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Machine and Vehicle Systems

Predicting Safety Benefits of Automated Emergency Braking at Intersections

Virtual simulations based on real-world accident data

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Cover:
Left-turn across path scenario with oncoming traffic, with Intersection AEB (see Section 3.2.4)

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ABSTRACT

Introduction: Intersections are a global traffic safety concern. In the United States, around half of all fatal road traffic accidents take place at intersections or were related to them. In the European Union, about one fifth of road traffic fatalities occur at intersections.

Intersection Automated Emergency Braking (AEB) seems to be a promising technology with which to address intersection accidents, as information retrieval by on-board sensing is operational on its own, and, in critical situations, braking is initiated independent of driver reaction. This is not the case for Vehicle-to-Everything (V2X) communication, which requires all conflict-involved vehicles to be equipped with this technology and drivers to respond to an initiated warning. The objective of this thesis is to evaluate the effectiveness of a theoretical Intersection AEB system in avoiding accidents and mitigating injuries. As it will take several decades for a new safety technology to penetrate the vehicle fleet and full coverage of all vehicles may never be achieved, the technology benefit is here analyzed as a function of market penetration. Finally, this research assesses whether a set of test scenarios can be derived without compromising the variance of real-world accidents.

Methods: Data from the United States National Automotive Sampling System / General Estimates System and the Fatality Analysis Reporting System was used to compare the capacity of on-board sensing and V2X communication to save lives. To investigate Intersection AEB in detail, the German In-Depth Accident Study (GIDAS) data and the related Pre-Crash Matrix (PCM) were utilized to re-simulate accidents with and without Intersection AEB using different parameter settings of technical aspects and driver comfort boundaries. Machine learning techniques were used to identify opportunities for data clustering.

Result: On-board sensing has a substantially higher capability to save lives than V2X communication during the period before full market penetration of both is reached. The analysis of GIDAS and PCM data indicate that about two thirds of left-turn across path accidents with oncoming traffic (LTAP/OD) and about 80 percent of straight crossing path (SCP) accidents can be avoid by an idealized Intersection AEB. Moderate to fatal injuries could be avoided to an even higher extent. Key parameters impacting effectiveness are vehicle speed and potential path choice; to increase effectiveness, these should be limited and narrowed down, respectively.

Conclusion and Limitations: Intersection AEB is effective in reducing LTAP/OD and SCP accidents and mitigating injuries However, intersection accidents are highly diverse and accurate performance evaluation requires taking variations into account. The simulations were conducted using ideal sensing without processing delays and an ideal coefficient of friction estimation.

Keywords: Intersection; junction; straight crossing path; left turn across path; AEB; accident avoidance; injury mitigation; V2X; market penetration

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Ulrich Sander

Gothenburg, August 2018

LIST OF APPENDED PAPERS

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Boran, C., Bostrom, O., Jacobson, B.J.H., Lie, A., Sander, U., 2012. Saving lives with V2X versus on-board sensing systems - Which will be more effective? Technology leadership brief. SAE Tech. Pap. 11. doi:10.4271/2012-01-9017

Contributions: Sander designed the study, conducted the analysis, prepared the results, and authored the manuscript. Boran, Bostrom, Jacobson and Lie contributed to interpretation of the results and formulation of conclusions.

II Sander, U., 2017. Opportunities and limitations for intersection collision intervention - A study of real world "left turn across path" accidents. Accid. Anal. Prev. 99, 342–355. doi:10.1016/j.aap.2016.12.011

Contributions: Sander designed the study, conducted the analysis, prepared the results, and authored the manuscript.

III Sander, U., Lubbe, N., 2018. The potential of clustering methods to define intersection test scenarios: Assessing real-life performance of AEB. Accid. Anal. Prev. 113, 1–11. doi:10.1016/j.aap.2018.01.010

Contributions: Sander designed the study, conducted the analysis, prepared the results, and authored the manuscript. Lubbe discussed and interpreted results with Sander and contributed to writing of introduction, background and conclusion.

IV Sander, U., Lubbe, N., 2018. Market penetration of intersection AEB: Characterizing avoided and residual straight crossing path accidents. Accid. Anal. Prev. 115, 178–188. doi:10.1016/j.aap.2018.03.025

Contributions: Sander designed the study, conducted the analysis, prepared the results, and authored the manuscript. Lubbe discussed and interpreted results with Sander and contributed to writing of introduction, background and conclusion.

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LIST OF ABBREVIATIONS

ACAT	Advanced Crash Avoidance Technology
AD	Automated Driving
ADAS	Advanced Driver Assistance System
ABS	Anti-lock Braking System
AEB	Automated Emergency Braking
AES	Automated Emergency Steering
AIS	Abbreviated Injury Scale
CMB	Collision Mitigation by Braking
Delta-V	Delta Velocity
DSRC	Dedicated Short Range Communications
Euro NCAP	European New Car Assessment Programme
FARS	Fatality Analysis Reporting System
FOV	Field of View
GIDAS	German In-Depth Accident Study
GPS	Global Positioning System
LTAP / LD	Left Turn Across Path / Lateral Direction
LTAP / OD	Left Turn Across Path / Oncoming Direction
MAIS2+F	Maximum AIS of level 2 and higher and fatalities
NASS / CDS	National Automotive Sampling System / Crashworthiness Data System (United States)
NASS / GES	National Automotive Sampling System / General Estimates System (United States)
NDS	Naturalistic Driving Study
NHTSA	National Highway Traffic Safety Administration (United States)
PDOF	Principal Direction Of Force
P.E.A.R.S.	Prospective Effectiveness Assessment of Road Safety

PCM	Pre-Crash Matrix
SCP	Straight Crossing Path
TCS	Traction Control System
TTC	Time-to-collision
US NCAP	United States New Car Assessment Program
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VRU	Vulnerable Road User

LIST OF SYMBOLS

α	Level of significance for confidence intervals
$\hat{\beta}_i$	Estimate for the i-th coefficient in logistic regression
γ	Angle between longitudinal vehicle axis and look-ahead point (P_x, P_y)
δ	Road wheel angle (angle of the wheel in the vehicle coordinate system)
δ'	Required road wheel angle to reach look-ahead point (P_x, P_y)
$\delta_{ii'j}$	Number of possible combinations between i and i' for the j-th object in case of co-presence
ε	Coefficient of restitution for an impact
κ	Curvature of the vehicle trajectory at a given look-ahead distance
κ'	Required curvature to reach look-ahead point (P_x, P_y)
μ	Coefficient of friction
ω	Wheel angular velocity
ω_{iz}	Immediate pre-crash rotational velocity of vehicle i around z-axis
ω'_{iz}	Immediate post-crash rotational velocity of vehicle i around z-axis
c_1	1^{st} inverse mass substitution
c_2	2^{nd} inverse mass substitution
c_3	3^{rd} inverse mass substitution
c_f	Cornering stiffness of the front tire
c_r	Cornering stiffness of the rear tire
d	Displacement during an impact
$d_{ii'}$	Euclidean distance between i and i'
e	Error value for longitudinal controller of the driver model
e_v	Number of vehicles being equipped with a safety feature for market penetration modelling
$freq_{p[cl]}$	Case frequency for each cluster in population
$freq_{s[cl]}$	Case frequency for each cluster in sample

$freq_{p[total]}$	Total case frequency in population
$freq_{s[total]}$	Total case frequency in sample
g	Gravitational acceleration
k	Stiffness parameter to obtain overlap position
m_i	Mass of vehicle i
n_i	Distance between center of gravity of vehicle i and *n*-axis
s	Look-ahead distance
$s_{ii'j}$	Similarity between i and i' for the j-th object
t	Time
t_i	Distance between center of gravity of vehicle i and *t*-axis
$u_{throttle}$	Control variable for gas pedal input
u_{brake}	Control variable for brake pedal input
v_{cin}	Immediate pre-crash speed in the center of gravity of vehicle i in the *n*-direction
v'_{cin}	Immediate post-crash speed in the center of gravity of vehicle i in the *n*-direction
v_{cit}	Immediate pre-crash speed in the center of gravity of vehicle i in the *t*-direction
v'_{cit}	Immediate post-crash speed in the center of gravity of vehicle i in the *t*-direction
v_{pin}	Speed of impact point of vehicle i in *n*-direction
v_{pit}	Speed of impact point of vehicle i in *t*-direction
v_{pn}	Relative speed of impact point in *n*-direction
v_{pt}	Relative speed of impact point in *t*-direction
v_{wx}	Longitudinal wheel velocity in wheel coordinate system
v_{wy}	Lateral wheel velocity in wheel coordinate system
v_x	Longitudinal speed in the vehicle coordinate system

v_y	Lateral speed in the vehicle coordinate system
x_i	Observed value for the i-th explanatory variable
y_i	Value for the i-th quantitative variable
$y_{i'}$	Value for the i'-th quantitative variable
z	$(1-\alpha/1)$-quantile of standard normal distribution
DV	Velocity change during an impact
E	Effectiveness
I_{acc}	Number of accident cases
${I_{acc}}^{+}$	Number of accident cases with a specific feature present
${I_{acc}}^{-}$	Number of accident cases with a specific feature not present
I_{inj}	Number of specific injury cases
${I_{inj}}^{+}$	Number of specific injury cases with a specific feature present
${I_{inj}}^{-}$	Number of specific injury cases with a specific feature not present
I_{iz}	Inertia of vehicle i around z-axis
K_p	Coefficient of the proportional term (proportional gain)
K_i	Coefficient of the integral term (integral gain)
K_d	Coefficient of the differential term (differential gain)
N	Change of momentum in n-direction
N_f	Normal force on the front axle
N_r	Normal force on the rear axle
N_v	Number of vehicles for market penetration modelling
OR	Odds ratio
$\hat{P}$	Estimate for the risk of MAIS2+F injury
P_{both}	Probability of both of two vehicles being equipped with a feature
$PDOF_{tnz}$	Principal direction of force in the t,n,z-coordinate system
P_e	Probability of a vehicle equipped with a feature

P_{ne}	Probability of a vehicle not being equipped with a feature
P_{none}	Probability of none of two vehicles being equipped with a feature
P_{one}	Probability of one of two vehicles being equipped with a feature
P_x	x-coordinate of the look-ahead point (P_x, P_y)
$P_x{}'$	x-coordinate of the nearest point on given trajectory to (P_x, P_y)
P_y	y-coordinate of the look-ahead point (P_x, P_y)
$P_y{}'$	y-coordinate of the nearest point on given trajectory to (P_x, P_y)
R	Risk
R_t	Turning radius
R_{we}	Effective rolling radius of wheel
RR	Relative risk
RR_{ie}	Relative risk for the concept of induced exposure
$S_{ii'}$	Similarity between i and i'
S_x	Longitudinal tire slip
S_y	Lateral tire slip
T	Change of momentum in *t*-direction
V_a	Number of vehicles involved in an accident
$V_a{}^+$	Number of vehicles involved in an accident with a specific feature present
$V_a{}^+{}_{ref}$	Number of vehicles involved in an accident with a specific feature present, involved in a feature independent scenario
$V_a{}^-$	Number of vehicles involved in an accident with a specific feature not present
$V_a{}^-{}_{ref}$	Number of vehicles involved in an accident with a specific feature not present, involved in a feature independent scenario
V_r	Number of registered vehicles
$V_r{}^+$	Number of registered vehicles with a specific feature present

V_r^-	Number of registered vehicles with a specific feature not present
WB	Wheelbase of a vehicle

1 INTRODUCTION

1.1 Background

Around 1.25 million people are killed each year in road traffic and for over ten years there has been no substantial decrease in this figure. Road accidents are the leading cause of death for younger people aged between 15 and 29 years (World Health Organization, 2016).

Global perspective

Vehicle design and technology play an important role in achieving traffic safety improvements (European Transport Safety Council, 2018). However, to date, in around 75 percent of the countries of the world basic international vehicle safety standards are still not met, such as having safety belts, electronic stability control, or protection for front, side and pedestrian impacts (World Health Organization, 2016). The United Nations World Forum for Harmonization of Vehicle Regulations has therefore provided a legal framework which member states can adopt to reduce road accidents and mitigate injuries. Furthermore, initiatives such as the Global New Car Assessment Program (Global NCAP) offer emerging markets support and guidance in initiating assessment programs to promote vehicle safety technology, which in turn will increase usage of safer vehicles. In its Road Map 2020, Global NCAP included anti-lock brakes (ABS) for motorcycles and Automated Emergency Braking systems (AEB) for other vehicles, AEB being highly recommended for all new models produced or imported (Global NCAP, 2015).

In the United States

In 2015, over one third of all people fatally injured in road traffic accidents in the United States were passenger car occupants; this is followed by light-truck occupants (28 percent), and vulnerable road users (18 percent) (NHTSA, 2017a). Of all crashes involving at least one vehicle, approximately 50 percent took place at intersections or were intersection related, while about 20 percent of all fatal crashes took place at intersections (NHTSA, 2017b).

The United States National Highway Traffic Safety Administration (NHTSA) included in their vehicle safety priority plan Vehicle-to-Vehicle (V2V) communication to provide driver warnings in common crash types such as rear-end, lane change, and intersection crashes (NHTSA, 2015a). V2V communication should complement crash avoidance technologies based on on-board sensing and is seen as an enabler for vehicle-to-infrastructure communication (V2I). NHTSA's strategic goals of 2016 to 2020 include the establishment of proactive safety, safety systems which prevent crashes, as the industry norm (NHTSA, 2016). Another strategic goal is to inform and stimulate customers to buy safer cars. Here, the US New Car Assessment Program (US NCAP) is said to have been improved based on comments received in public meetings. So far, besides crashworthiness evaluation of passenger cars, the US NCAP includes a checklist of active safety features such as lane departure warning and forward collision warning (NHTSA, 2016).

In Europe

According to the European Road Safety Observatory, the main accident types in Europe that need to be addressed to reduce fatal and serious injuries are head-on accidents, run-off-road accidents, intersection accidents, and accidents involving vulnerable road users (European Commission, 2016a). Of all road traffic fatalities in Europe, car occupants comprised over 50 percent. Twenty percent of all road traffic fatalities in Europe happen at intersections and 34 percent of the intersection fatalities are car occupants (European Commission, 2016a, 2016b).

The European Transport Safety Council (ETSC) stated that the key priorities of vehicle safety include Intelligent Speed Assistance, Alcohol Interlocks, Seat Belt Reminders, and Autonomous Emergency Braking (AEB). To date, vehicles that just meet the minimum EU legal requirements would receive zero of five stars in the European New Car Assessment Programme (Euro NCAP). For automation and cooperative intelligent transport systems, ETSC includes in their priority list vulnerable road user protection and intersection safety (European Transport Safety Council, 2018).

Analysis of the German In-Depth Accident Study (GIDAS, Otte et al., 2003) indicated that close to 30 percent of all crashes and twelve percent of crashes involving a fatality were car-to-car crashes. Within car-to-car crashes, about a third happened at intersections with around 25 percent of the occupants being severely to fatally injured. The most frequent intersection accident types (Figure 1) were 'straight crossing path' (SCP, 13 percent of all car-to-car crashes), left turn across path / oncoming direction (LTAP/OD, 10 percent of all car-to-car crashes), and left turn across path lateral direction (LTAP/LD, 7 percent of all car-to-car crashes) (Paper II).

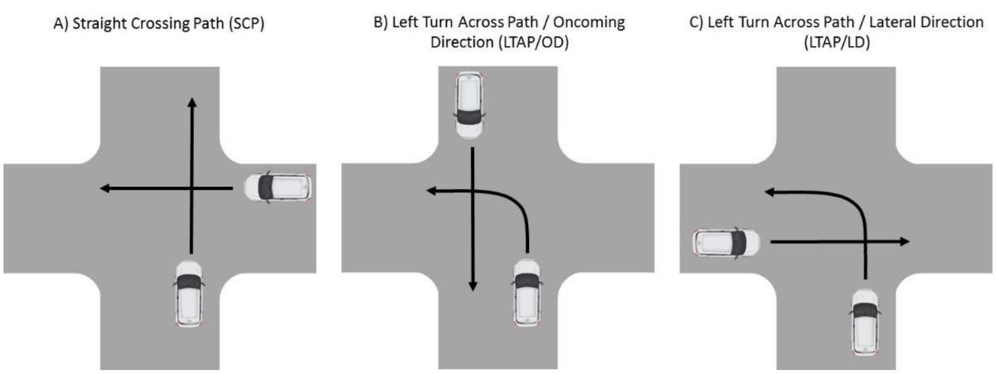

Figure 1: Most frequent intersection accident types: A) straight crossing path; B) left turn across path / oncoming direction; C) left turn across path / lateral direction. The classification is based on the principal design of intended vehicle paths, the pictograms shown give only examples of intersection layouts (see Appendix A).

Car-to-motorcycle crashes accounted for eight percent of all crashes. More than fifty percent of those were related to intersections, with the two leading scenarios being SCP (31 percent of all car-to-motorcycle crashes) and LTAP/OD (22 percent of all car-to-motorcycle crashes) (Paper II). Another GIDAS study indicated that round 20 percent of all crashes happened between a car and a bicycle and about one-third of these took place at intersections (Ranjbar, 2014). The term ‘left turn across path’ (LTAP) is relevant for right-hand traffic. For countries with left-hand traffic it should be interpreted as ‘right turn across path’. This interpretation is valid throughout the entire thesis, even where not explicitly stated.

Euro NCAP has put on their 2025 roadmap the testing of crossing and turning maneuvers which may include car, motorcycle, cycle, and pedestrian targets (Euro NCAP, 2017). Test protocols are expected to be released in 2019 with an implementation of testing in 2020. The start of scenario definition for testing of vehicle-to-everything (V2X) communication measures is not scheduled before 2021, as current uncertainties about a V2X standard may take a few years to resolve.

In conclusion, intersections are a major safety concern and many NCAP driven activities are planned or already ongoing to prevent accidents at intersections or to mitigate the outcome where they cannot be prevented.

Vehicle Technology

Vehicle technology to prevent or mitigate accidents (active safety) has developed quickly in the last decade. Active safety systems that have been assessed as highly effective are Electronic Stability Control (Lie, 2012; Lie et al., 2006), car-to-car Rear-end AEB (Fildes et al., 2015; Isaksson-Hellman and Lindman, 2016), car-to-pedestrian/cyclists AEB (Edwards et al., 2014; Lindman et al., 2010; Rosén, 2013), and Lane Departure Warning (Cicchino, 2017; Sternlund et al., 2017), which address some of the most frequent and harmful accident types.

However, for intersection conflicts, where vehicles approach laterally or head-on, only a few vehicle manufacturers offer advanced driver assistance systems; these include for example Volvo (Volvo IntelliSafe) and Audi (Audi Turn-Assist) with emergency braking in LTAP/OD scenarios and Daimler (Mercedes BAS Plus with Cross-Traffic Assist) and Lexus (Lexus Front Cross Traffic Alert) with warning and brake support for the Mercedes BAS Plus in SCP scenarios. To the author’s knowledge, no vehicle manufacturer offers to date a support function that addresses both SCP and LTAP/OD. The challenges for the two scenarios reside in different aspects: Whereas head-on approaching vehicles in LTAP/OD scenarios may be visible for a forward-looking sensor, the vehicles are initially not on a collision course. The conflict becomes apparent after one vehicle initiates the physical turning process, although indicator signaling, lane selection, or navigation route may give a prior indication. The lateral approaching vehicles in the SCP scenario however require a much broader field-of-view of environment sensing, potentially solved by the fusion of several sensors located at various positions and orientations on the vehicle. Here, vehicles can be initially on conflicting courses, but may turn off during the approach phase.

Since in SCP and LTAP/OD scenarios the vehicles are on intersecting, but not identical or merging, paths, the conflict can be resolved by the concept of temporal avoidance instead of spatial avoidance. With spatial avoidance, one of the vehicles would need to come to a stop before the path intersection. With temporal avoidance the arrival of one vehicle at the intersection corridor is delayed until the other vehicle has left the intersection corridor. Thus, temporal avoidance substantially increases the opportunities for crash avoidance. On the other hand, this also raises the risk for driver-experienced false-positives, system activations which are evaluated as unnecessary, as drivers may feel comfortable with small passing time gaps. Another alternative intervention for SCP and LTAP/OD is to prevent drivers from entering the intersection corridor by accelerating from standstill in case of a pending conflict. Here, besides the activation of the AEB system, the gas pedal might be decoupled from the propulsion system to prevent system override by the driver. Besides preventing a vehicle from entering an intersection, or braking to stop or braking to delay the arrival at the path intersection, automated steering or steering support is another alternative to escape a pending conflict, especially if only a small steering intervention is necessary to avoid an accident.

A challenge for intersection driver support systems is the potential obstruction of conflicting vehicles by surrounding traffic, road furniture such as road signs, guide posts, or light and utility poles, and road adjacent objects, such as buildings and fences. Particularly in densely built-up urban areas there is a high risk that sensors cannot track other vehicles or persons in time to avoid collisions. Here, vehicle-to-vehicle (V2V) communication technology can provide warnings to drivers or provide input to an AEB system which otherwise would not be available. After decade-long research, NHTSA foresees two main applications of the V2V technology: First, the Intersection Movement Assist (IMA), which warns the driver when entering an intersection when there is a potential collision with another vehicle; Second, the Left Turn Assist (LTA), which warns a driver making a left-turn when there is a potential collision with an oncoming vehicle (NHTSA, 2016). NHTSA estimates that with correct responses from the driver to the situation, up to 25 percent of intersection crashes can be prevented each year by a 100 percent market penetration of IMA and LTA.

Vehicle technology to prevent and mitigate injuries in cases where a crash cannot be avoided (passive safety) has evolved continuously over recent decades. The development of vehicle design and restraint systems has followed the main principles of crash protection (Haddon, 1970) to retain the structural integrity of the passenger compartment, and to ensure that the occupant is held inside the vehicle, and that impact forces are spread over wide contact points with energy being dissipated over available distances (European Commission, 2016a). Frampton and Lenard (2009) identified major functional requirements for crashworthiness improvements, which are still valid to date: reduction of seat belt loads (particularly for seniors), reduction of loads to the leg, head and chest protection in near-side crashes, and reduction of lateral recursion in far-side crashes. Here, the implementation of adaptive and integrated safety measures is seen as an important approach to improve front and side impact occupant protection (Michalke et al., 2011; Wallner et al., 2010). This, however, even with the presence of advanced passive safety technologies, requires that driving speeds and thus initial kinetic energy must be limited to a level that occupants can withstand without sustaining serious or fatal injuries.

Infrastructure

Besides enhancements of vehicle technologies to prevent accidents, improvements to infrastructure design have been considered necessary, as road design deficiencies contribute substantially to road traffic injuries (World Health Organization, 2017). For intersections, the implementation of well-designed roundabouts is seen as one of the most effective measures, as severe to fatal accidents can be substantially reduced (Brilon and Stuwe, 1993; Hu et al., 2014; Mandavilli et al., 2009; Maycock and Hall, 1984). Design guidelines have been put into place to ensure that main principles of a modern roundabout are kept, such as entering traffic having to yield, the speed of vehicles being reduced, and traffic being deflected in an appropriate entry path (Massachusetts Highway Department, 2006; Robinson et al., 2000).

However, studies have shown that cyclists were exposed to higher injury risk at large roundabouts, where speeds are not sufficiently reduced at the entry points (Reid and Adams, 2010; Reynolds et al., 2009). Secondly, roundabouts can cause tailbacks if traffic on approach roads is unequal, as priority and demands cannot be controlled (Robinson et al., 2000). Other recommendations for safer intersection design which may be introduced instead or prior to rebuilding intersections to roundabouts include grade separation through over- or underpasses, time separation using signal control of intersections, ensuring an unrestricted view, and implementing measures that enforce speed reduction such as raised platforms or driver awareness, i.e. vehicle-triggered warnings (Massachusetts Highway Department, 2006).

Vision Zero

The long-term goal of Vision Zero is that no-one is killed or seriously injured as a consequence of road traffic accidents within the road traffic system (Belin et al., 2012). Despite increased motorization, some countries that have subscribed to the Vision Zero framework have succeeded in reducing road traffic death and injuries (World Health Organization, 2016). Vision Zero is based on a key principle: The human prerequisites to withstand external forces or other violence in traffic accidents should be the basis for the design of the road transport system. From this principle, various design measures can be derived, such as dividing highways to absorb human error, rebuilding crossroads to roundabouts to reduce speed at vehicle path intersection, reducing or adjusting speed limits, and designing safer cars (Lindberg and Håkansson, 2017). One of the cornerstones of road safety strategy is speed, and thus energy management (ITF, 2017). Small differences in speed can have a substantial impact on the occurrence and severity of road accidents and injuries (European Commission, 2016a).

These measures must complement each other, such that, for example, law and road design consider limitations of technological advancements in car safety such as maximum addressable speed, and car technology takes into account potential human error and infrastructure conditions by limiting allowable speeds.

Therefore, it is necessary to understand at an early stage the capabilities and limitations of vehicle technology to prevent accidents and mitigate injuries. Vehicle engineers can optimize active safety functions and communicate necessities for high system efficiencies to road authorities. Law makers can evaluate the expected benefit and make regulatory decisions on vehicle equipment rate already when the technology hits the market. Further, road design changes can be evaluated to adapt to the limitations of vehicle technology.

Intersection accident analysis

Intersection accidents and measures for prevention have been analyzed under different aspects including characteristics and probability of occurrence (Abdel-Aty and Haleem, 2011; Kusano and Gabler, 2015), scenario clustering (Nitsche et al., 2017), driver behavior (Liu et al., 2014; Nobukawa et al., 2012), causation and contributing factors (Engström et al., 2013; Sandin, 2009; Simon et al., 2009), elderly drivers (Charlton et al., 2013; Gelau et al., 2011; Zhou et al., 2015), algorithm design for intervention systems (Brännström et al., 2011, 2010, 2009; Kaempchen et al., 2009; Maile et al., 2015), and sensor and communication technology (Abdulla et al., 2016; Aycard et al., 2011; Tsukada and Fukushima, 2011).

Specifically, the benefit of Intersection Advanced Driver Assistance Systems (I-ADAS) in SCP and LTAP/OD accident scenarios for crash avoidance and injury mitigation have been analyzed in virtual simulation with fixed Time-to-collision (TTC) algorithms based on US data (Scanlon et al., 2017a, 2017b, 2016). Likewise, virtual simulation was used to identify the effectiveness of collision mitigation by braking (CMB) in crash avoidance and fatality reduction for intersection path crashes (Van Auken et al., 2011a).

The Transportation Research Laboratory in the UK, on behalf of the European Commission, evaluated the benefit of active and passive vehicle safety technologies (European Commission, 2015). While evaluation was made of rear-end and pedestrian AEB systems, no AEB system addressing crossing paths in intersection accidents was investigated. Junction cameras and intersection assistance were mentioned for harmonization purposes, as there is a requirement for SUVs in Japan to be equipped with small mirrors on the bonnet to help see crossing pedestrians and bicyclists. However, it was noted that the infrastructure in Japan is different to that of Europe.

1.2 Overall aims and scope of the thesis

Aims of the thesis

The first overall aim of this thesis is to assess the potential real-life benefits of different design parameters for an Intersection AEB to specify system requirements and guide designers toward effective real-life systems. The work on this objective includes:

- analysis of real-life accident data (Papers I – IV)
- comparison of on-board sensing with V2X communication (Paper I)
- identifying opportunities to define test scenarios for effectiveness assessment (Paper III)
- assessment of sensor field-of-view and algorithm parameters (Paper II & IV)
- evaluation of the effect of one or both conflict participants being equipped with an Intersection-AEB (Paper II & IV)

The second overall aim of the thesis is to demonstrate the real-life effect when introducing an Intersection AEB system to the market. The work on this objective included the assessment of characteristics of remaining accidents as a function of market penetration (Paper IV).

Whereas the first aim covers technical aspects of an Intersection AEB, the second aim gives the background needed to make decisions on regulatory aspects for vehicle standard or optional equipment. Both aspects together allow the evaluation of a specific technology with a specific market penetration, i.e. to identify whether a simpler technology with a higher market penetration has a larger effect on accident avoidance and injury mitigation than a more sophisticated technology with a lower market penetration.

In this thesis, an Intersection AEB system is defined as an AEB system that intervenes when a conflict is identified between crossing vehicles or oncoming vehicle on crossing path and when steering within comfort boundaries for both vehicles as well as braking within comfort boundaries for the opponent vehicle will not solve the conflict. Road infrastructure information may be used additionally for decision making but is not essential to ensure principal functionality. This means that even in environments other than junctions or intersections the Intersection AEB may be activated when the above described conflict is present.

The third overall aim of the thesis was to describe an effectiveness assessment framework for active safety functions called PRAEDICO in greater detail than in the appended papers. PRAEDICO was not published in a separate method paper as the framework has been developed continuously during the PhD studies. The assessment framework to date includes choice of metrics (how effectiveness is measured), specification of target population by selection of relevant scenarios, and virtual simulations of pre-crash phases or other driving sequences with or without specified active safety systems. The virtual simulation comprises driver model(s), vehicle model(s), an environment model, and the safety system under investigation. In case the virtual simulation predicts a collision, crash characteristics are calculated, and the occurrence of occupants injured at a specified severity is estimated by an injury risk function. Finally, results are weighted to be representative for a specified region and the effectiveness metrics are presented as a function of market penetration.

Chapter 3 and specifically Section 3.2 presents the process flow within the framework and the utilized models.

Scope of this thesis

In an initial step, different accident scenarios are studied to identify the potential of V2X communication versus on-board sensing in saving lives. The two most frequent intersection accident scenarios with crossing paths, SCP and LTAP/OD, are then analyzed. According to GIDAS data weighted to be representative for the German national accident statistics in 2016, SCP and LTAP/OD together account for over 60 percent of all intersection accidents. Together with a third scenario, left-turn across path / lateral direction (LTAP/LD), over 80 percent of all intersection accidents are covered. During the pre-crash phase, the lateral approach of the conflict-involved vehicles in LTAP/LD is similar to SCP. Thus, demands to sensor field-of-view are similar. However, the speed of the turning vehicle is generally lower compared to the straight going vehicle. Some results of the SCP analysis might be applicable for LTAP/LD, but this has not been verified.

Rear-end accidents may happen in intersections, but in those scenarios the vehicle paths are not intersecting. All rear-end collisions were summarized in one category (Appendix A) and are not considered in this thesis. It is assumed that Rear-end AEB systems will address these scenarios.

This thesis is also limited to the investigation of car-to-car accidents, for three reasons: First, car-to-car accidents are more frequent than for example car-to-motorcycle accidents, though not more harmful; second, the path prediction and threat assessment algorithm used for the papers included in this thesis were based on comfort boundaries, and comfort boundaries for motorcyclists, cyclist and pedestrians have been studied to a much lesser extent than those for car drivers; and third, the thesis aimed to include the interaction effect in cases where both conflict partners are equipped with an Intersection AEB. Designing an AEB for a two-track vehicle is easier to realize than for a single-track vehicle as roll stability is of less concern (Schwab, 2012).

Automated evasive steering was not investigated. The GIDAS-based Pre-Crash Matrix (PCM) data utilized in Papers II to IV only codes trajectories of the conflict opponents, road infrastructure, and non-moving objects. Thus, information about surrounding traffic is not available. It is assumed that as long as the path is not changed and the following traffic keeps an adequate distance, no collision will occur other than that with the original conflict opponent. This does not hold for a change of the path where free space around the vehicle is crucial and needs to be taken into consideration. Steering interventions without free space information may create other conflicts with outcomes even worse than those of the initial conflict. Alternatives are driver-initiated steering support, where the driver is still in charge of the steering action or automated steering within the own lane. Though the algorithm utilized in Papers II to IV evaluated accident avoidance by steering to the left and to the right, possible avoidance by steering acted only as an inhibitor for I-AEB activation. Intersection AEB was not activated until steering alone could no longer avoid the conflict.

Automated emergency acceleration was also not investigated. Accelerating a vehicle in a critical situation increases the kinetic energy and thus can make the situation potentially more dangerous. Moreover, for the vehicles involved in the PCM data sample (all have a combustion engine) the acceleration capabilities are not known. On the other hand, for electrified vehicles, where propulsion torque is initially high and constant over a wide range of engine revolutions-per-minute, and torque can be directed to each wheel independently, an acceleration in conflict situations can lead to crash avoidance (Arikere, 2015).

The proposed Intersection AEB systems investigated in this thesis do not issue any warning to the driver at any time. Most AEB systems already deployed in the market such as car-to-car Rear-end AEB, issue a driver warning before an automated system intervention. This warning could be of visual, audible, or haptic nature, or any combinations of these. Additionally, application of V2X communication to date is intended to warn rather than to automatically intervene. However, much more research is necessary to understand and model driver reaction to warnings and their frequency of occurrence and V2X communication was excluded from the scope of this research during its progress. Developing an own driver model was beyond the objectives of this thesis. Instead, to investigate the potential of driver warning, a study was conducted alongside this thesis assessing the time span between warning release and the last point of braking required to avoid the collision (Sander and Lubbe, 2016).

1.3 Research Questions

The research questions underlying this thesis are:

- How does V2X communication compare to on-board sensing and can it be as effective as a stand-alone sensing alternative?
- How effective can an Intersection AEB system based on on-board sensing be in avoiding acccidents?
- What is the capability of these systems to mitigate injury in cases where an accident cannot be avoided?
- What parameters have a substantial influence on the performance of an Intersection AEB system?
- How does the effectiveness in avoiding accidents and mitigating injuries change as market penetration increases?
- Can a set of test scenarios be defined which is representative for the utilized sample of accidents?

1.4 Main contributions to scientific knowledge

Papers I to IV included in this thesis have made the following novel contributions to the scientific knowledge which had not been previously published:

Paper I contributes with a quantification of lives saved in the Unites States through the introduction of four different safety systems based on-board sensing and V2X communication as a function of market penetration.

Paper II contributes with computation of benefit estimates in avoiding LTAP/OD accidents with an Intersection AEB system based on German accident data; it includes an assessment of the impact of different specifications for the algorithm, sensing and actuation hardware on the safety benefit.

Paper III contributes with an application of machine learning techniques to cluster SCP and LTAP/OD accident data and a demonstration of high variance and correlation of scenario relevant characteristics.

Paper IV contributes with a computation of benefit estimates in avoiding SCP accidents and mitigating moderate to fatal injuries as a function of market penetration; a comparison of different I-AEB specifications and market penetration rates is made.

The development of PRAEDICO contributed to engineering science knowledge through concepts described in Section 3.2.

1.5 Outline of the thesis

The thesis is structured in Chapters as follows:

- **Chapter 1** describes the relevance of intersection accidents and the objectives and scope of the thesis.
- **Chapter 2** gives an overview of different effectiveness assessment methods and how they can be combined.
- **Chapter 3** describes the applied research methodology and gives insight into the continuous enhancement of data analysis and the development of the simulation framework named PRAEDICO, and provides a statistical analysis of the results.
- **Chapter 4** presents a summary of the attached Papers I to IV.
- **Chapter 5** discusses the findings.
- **Chapter 6** summarizes the conclusions of the work conducted.
- **Chapter 7** offers avenues for future research, research which could not be covered in this thesis but is nonetheless important.

2 EFFECTIVENESS ASSESSMENT

In road traffic safety research, two types of quantities are of fundamental importance: a) the risk of being involved in an accident when participating in road transportation and b) the risk of being injured or killed when being involved in an accident (Hautzinger et al., 2007). The risk of accident involvement or injury can be generally investigated with epidemiological methods applied to study a risk of disease, where the disease is equivalent to a number of incidents that happen under a given timespan and space. Here, Hautzinger et al. distinguish types of data: target population, for which the conclusions are representative, study population, from which the data is taken, and sample, which is the collected data from a subset of the study population.

2.1 Accident involvement risk

For the calculation of the accident involvement risk, generally two types of samples are necessary, one from for example a national register or mobility study to give information about the exposure (such as registered vehicles or journeys undertaken) and one from for example accident studies that detail the quantities of incidents (such as police reported accident vehicles or journeys resulting in accidents) (Hautzinger et al., 2007). The relative risk describes the ratio of two risks and is used as a measure of effectiveness. In epidemiology, relative risk is used in cohort studies and randomized controlled trials. In case-control (observational) studies, odds ratios are used as an alternative measure of association between exposure and outcome (Woodward, 1999). Relative risk and the odds ratio can differ substantially from each other. However, for small probabilities, when the number of incidents is small compared to the exposure size, the relative risk approaches asymptotically the odds ratio.

There are some major issues when dealing with relative risk and odds ratio: One such issue is the availability of both incident and exposure data. In Section 2.1.5 a method is described to bypass the lack of exposure data. Another issue is the confounding of variables. When an association is observed between incidents and exposure due to the influence of a third variable, this latter variable is *confounding*. A method to address confounding is stratification, which means separation of the data by confounding variables into different groups.

2.1.1 Risk

The risk R for a vehicle of being involved in an accident can be described as follows:

$$R = {}^{V_a}\!/_{V_r}, \tag{1}$$

where V_a is the number of vehicles involved in an accident (or journeys involving an accident) and V_r is the number of registered vehicles (or journeys undertaken) in a given time period (Hautzinger et al., 2007).

2.1.2 Relative risk

When the population of registered and accident involved vehicles can be categorized by using a specific characteristic, for example an active safety system, then relative risk RR between the sub-populations can be calculated. The relative risk RR expresses the ratio between two risks, for example the risk for vehicles equipped with an active safety system (+) versus the risk for a vehicle not equipped with an active safety system (-):

$$RR = \frac{R^+}{R^-} = \frac{\left({V_a}^+ / {V_r}^+\right)}{\left({V_a}^- / {V_r}^-\right)}. \tag{2}$$

In case $RR < 1$, the active safety system has a positive effect on the risk of being involved in an accident. With $RR = 1$, the safety system has no effect and with $RR > 1$, the safety system has a negative effect.

2.1.3 Confidence intervals for relative risk

The natural log (ln) of RR is normally distributed, so it can be used to derive the confidence intervals for the relative risk. Using a Wald normal approximation interval for large sample sizes, it follows:

$$\ln(RR) = \pm z \cdot \sqrt{\frac{1}{{V_a}^+} - \frac{1}{{V_r}^+} + \frac{1}{{V_a}^-} - \frac{1}{{V_r}^-}}, \tag{3}$$

where z is the $\left(1 - {}^{\alpha}/_{2}\right)$-quantile of the standard normal distribution and α is the level of significance. For a common level of significance of α=5 percent, z is 1.96. This means that 95 percent of the area under a normal curve lies within 1.96 times of the standard deviation of the mean.

2.1.4 Effectiveness

The effectiveness E characterizes the change to accident occurrence, for example the presence of an active safety system compared to non-presence. Thus, it describes the deviation of RR from unity:

$$E = 1 - RR = 1 - \frac{R^+}{R^-} = \frac{R^- - R^+}{R^-}. \tag{4}$$

In epidemiology the corresponding term is *attributable risk* (Woodward, 1999). It is noted that the computed effectiveness E is dependent on the selected target population (see Section 2.3.4).

2.1.5 Induced exposure

In case exposure data such as the number of registered vehicles or the number of vehicle trips is not available, a concept called 'induced exposure' can be used (Thorpe, 1964). In one variant of induced exposure, for example for the evaluation of the effectiveness of an active safety system (*risk factor* in the terminology of epidemiology), in addition to an active safety system relevant accident type, an active safety system independent accident type (denoted as '*ref*') must be chosen as reference. The assumption of independence requires then that the risks for vehicles equipped and vehicles not equipped with the active safety system under investigation are equal for the independent accident type:

$$ {{V_a}^+}_{ref} \Big/ {V_r}^+ = {{V_a}^-}_{ref} \Big/ {V_r}^-. \tag{5}$$

With Eq. (5) in Eq. (2) a relative risk RR_{ie} for the concept of induced exposure can be calculated:

$$RR_{ie} = \frac{\left({V_a}^+ / {V_a}^+_{ref}\right)}{\left({V_a}^- / {V_a}^-_{ref}\right)}. \quad (6)$$

The effectiveness E is then calculated according to Eq. (4) with RR_{ie} instead of RR. With the substitution of the exposure with a safety system independent accident type, RR_{ie} is formally not a risk ratio anymore, but an odds ratio. Thus, the confidence interval can be computed based on an odds ratio (OR):

$$\ln(OR) = \pm z \cdot \sqrt{\frac{1}{{V_a}^+} + \frac{1}{{V_a}^+_{ref}} + \frac{1}{{V_a}^-} + \frac{1}{{V_a}^-_{ref}}}. \quad (7)$$

Similar to the risk ratio RR, the odds ratio OR is better approximated by a normal distribution in its natural logarithm. As mention in Section 2.1, with a small incident size (rare event) the OR is an adequate approximation for the RR.

The application of induced exposure requires that the system independent accident type is carefully chosen. Most often, the focus is put on multi-vehicle crashes where the driver of a vehicle did not actively cause the crash, for example the struck vehicle in a rear end crash. Alternatively, crashes were selected where the driver was not at fault. However, likely bias was identified even in these accident types with regard to vehicle size and driver age and gender (Keall and Newstead, 2009).

2.2 Injury risk

Theoretically an injury risk can either be computed based on all accidents, independent of the occurrence of any constraints such as injury occurrence (Hautzinger et al., 2007). However, such data is practically unavailable. Thus, it is common to compute conditional injury risks from databases with sample criteria such as, at least one person must be injured in an accident, or, the accident must have been reported to an insurance company. In this case, it must be clearly stated that the computed risk ratios or effectiveness are only valid for the constraints given by the sample criteria. The following risk, relative risk, and effectiveness equations are formulated for the conditional injury risk.

2.2.1 Risk

The risk of being injured *R* is defined as follows:

$$R = {I_{inj}} / {I_{acc}}, \quad (8)$$

where I_{inj} is the number of specific injury cases and I_{acc} the number of all accident cases involving personal injury.

2.2.2 Relative risk and effectiveness

When a specific risk factor such as a passive safety system is investigated, the relative risk RR is computed as follows:

$$RR = \frac{\left({I_{inj}}^{+} / {I_{acc}}^{+}\right)}{\left({I_{inj}}^{-} / {I_{acc}}^{-}\right)}, \tag{9}$$

where (+) indicates cases with passive safety system in place and (-) without the system.

The confidence intervals and the effectiveness can be calculated according to Eq. (3). In contrast to the accident involvement risk, all quantities in Eq. (9) are now available in one dataset.

There may be bias in risk estimates derived from only one dataset as confounding could be present due to vehicle or crash related factors. Here, matched-pair cohort methods can be applied to produce unbiased estimates (Cummings et al., 2003a, 2003b).

2.3 Effectiveness assessment of active safety

The assessment of the effectiveness of road traffic safety features or functions has gained high priority among a variety of stakeholders (Page et al., 2015). Vehicle manufacturers and safety system suppliers have a keen interest in the functionality being optimized for a given cost target right from market introduction. This way customers are more likely to choose their product and cost-intensive design changes at a later stage can be prevented. Here, providing information to customers through independent organizations such as NCAP programs plays an important role. Regulatory requirements set minimum standards and do not allow for a differentiation of system performance in real-life (European Transport Safety Council, 2018). The NCAP organizations themselves have a keen interest in effectiveness estimates; on the one hand to make decisions for future roadmaps, and on the other to verify that their rating strategy had the desired effect on real-life injury occurrence. Similarly, lawmakers and road authorities need to understand the benefit of safety systems or measures to be able to decide on mandatory vehicle safety equipment and infrastructure measures such as speed limits and road design in order to further reduce road deaths and injuries. With high-dimensional data such as data from Naturalistic Driving Studies (NDS), the application of novel methodologies might be required for analysis, which is of general interest to universities and research institutes. One aspect that is relevant for all stakeholders is the interaction of drivers with and the adaption to safety systems. Technical systems are generally set to a standardized specification with little option for personal preferences. Drivers however have diverse abilities to cope with various traffic situations, diverse feelings of comfort, and diverse responses to any kind of information and interaction. Thus, effectiveness assessments allow for comparison of expected and experienced behavior.

2.3.1 A priori and a posteriori knowledge

Similar to philosophy, the distinction between *a priori* and *a posteriori* knowledge is often made with regard to effectiveness assessment. Whereas *a posteriori* or retrospective assessment is interpreted as an assessment based on observed real-life data, *a priori* or prospective assessment is used for the assessment before observation (Eichberger, 2010). This means that *a posteriori* always gives a true picture of the effectiveness (when measurements are not biased and methods are applied correctly). This is not necessarily true for *a priori*, as the models and constraints utilized may not truly reflect physical reality. This said, sometimes it is desirable to reduce the complexity of the real world into simplified models to be able to study effects that otherwise would be hidden in high-dimensional models.

2.3.2 A priori assessment

Different methods can be applied to conduct an *a priori* assessment such as virtual simulation, driving simulator studies, augmented reality testing, controlled physical testing, Field Operational Testing (FOT), or crash data analysis. In virtual simulation all aspects are considered as mathematical and/or physical models, whereas the driving simulator studies replace a driver model by a human driver. In augmented reality testing the vehicle model is replaced with a physical car, but the real driver is confronted with a virtual conflict scenario. In controlled physical testing, all aspects are physical; however, the conflict scenario is predefined by parameters such as conflict opponent trajectories and environmental conditions. Similarly, in FOTs all aspects are physical but exposed to real-life conditions, thus controllability is limited. Crash data analysis is often undertaken as an initial step to identify the quantity of potential addressable crashes in a given data sample (Jermakian, 2011; Najm et al., 2007). Each method is used for a specific purpose. In general, the more physical hardware involved, the higher the costs, reducing flexibility in testing the variants of an initial design. Thus, virtual simulation tends to be a method of choice when initial settings for safety system parameters need to be evaluated and the potential safety benefits of the system needs to be predicted both for the short and long term (Sander, 2016). However, Coelingh et al. (2007) demonstrate the complexity of predicting the real-life safety benefit of active safety systems, as aspects such as accident occurrence and injury protection for the ego vehicle and if appropriate, for opponent vehicle(s) have to be considered. For this reason, virtual simulation approaches may substantially differ from each other with regard to level of detail, completeness, and representativeness (Alvarez et al., 2017). One critical aspect is the selection of the scenarios, which then defines the target population: When the target population includes scenarios that are lying beyond the boundaries of what can be addressed by a safety system under investigation, the expected benefit is low. Vice versa, when the target population contains only scenarios that can be handled by the safety system, the expected benefit is high. Results of studies that use different target populations must therefore not be compared with each other. For example, the Advanced Crash Avoidance Technologies (ACAT) Program in the United States contained the evaluation of four different technologies. However, as the target populations addressing each technology were not comparable, each ACAT project should be viewed as an independent, stand-alone analysis (Funke et al., 2011).

To date there is no standardized method that describes a best practice for the assessment of the effectiveness of active safety or driver assistance systems using virtual simulation. For this reason, the 'Prospective Effectiveness Assessment for Road Safety' (P.E.A.R.S.) initiative was started in 2012 (Page et al., 2015). This initiative aims to derive a harmonized framework and to identify aspects and processes that can be covered by one or more ISO standards.

Two main approaches can be observed when virtual simulation is applied: a) re-simulation of scenarios similar to the original course of events (for example, collected in in-depth accident studies) and b) simulation of artificial scenarios generated from identified characteristic variable distributions and their dependencies in different types of data. The scenarios can be either crashes, near-crashes or normal driving sequences. Some key studies are outlined below to describe the variety of approaches and if available, to give estimated effectiveness figures for comparison with *a posteriori* assessments.

<u>*Re-simulation of scenarios*</u>

Re-simulation of scenarios is a common practice and has been widely used to predict the effectiveness of a safety system.

Lindman et al (2010) used GIDAS data in a virtual simulation environment to predict the benefit of Pedestrian AEB in a Volvo car of model year 2010 with technology-accurate algorithm and sensing models. The authors estimated a reduction in pedestrian fatalities of around 24 percent. In a follow-up study, a low-speed Rear-end AEB system was evaluated and compared to the benefit of the same system in the real-world (Lindman et al., 2012). Crash avoidance and mitigation rates of 19 percent and 68 to 75 percent were estimated, respectively.

Eichberger et al. (2010) evaluated the effectiveness of ESC, Anti-lock Braking System (ABS), Brake Assist, and Evasive Maneuver Assistant (EMA) by re-simulating 217 fatal accidents of the Austrian in-depth accident database ZEDATU (RCS-TUG study). Additionally, the effectiveness of 39 other active safety systems was evaluated based on subjective analysis of the pre-crash phase. The results indicated that EMA is the most promising safety system with a potential to avoid around 20 percent of fatal accidents. When the overall reduction of fatalities was assessed, the authors identified collision warning systems as most effective with a reduction of up to 40 percent. In a follow-up study, these results were broken down for vehicle categories such as motorized two-wheelers, passenger cars, light trucks, and trucks and busses (Eichberger et al., 2011).

An Advanced Collision Mitigation Brake System (A-CMBS) was investigated by Van Auken et al. (2011) to determine its effectiveness in terms of crash avoidance and fatality reduction using reconstructed accidents. Four different accident types were selected as the A-CMBS was designed to address them: intersecting path collisions, rear-end collisions, head-on collisions, and car-to-pedestrian collisions. The utilized databases were the US National Automotive Sampling System / Crashworthiness Data System (NASS/CDS), the Pedestrian Crashworthiness Data System (PCDS), and the Fatal Analysis Reporting System (FARS). It was estimated that approximately 8 percent of all accident and four percent of all fatalities could be avoided with the A-CMBS system in 2005.

Kusano and Gabler (2012) analyzed the effectiveness of a Pre-Crash System (PCS) by comparing the injury severity outcome of a set of car-to-car rear-end crashes from NASS / CDS with and without the PCS system available. A system activation at a TTC of 0.45 seconds was assumed with a deceleration level of 0.6 g. The reduction of moderately to fatally injured drivers due to PCS implementation was assessed to be around 36 percent for the striking car and 28 percent for the struck car.

The safety potential of three different Pre-Collision System (PCS) algorithms were investigated in 1396 car-to-car rear-end crashes from the National Automotive Sampling System / Crashworthiness Data System (NASS/CDS) (Kusano and Gabler, 2012). The vehicles' pre-crash trajectories were derived from the stored data of event data recorders. The authors concluded that, depending on the PCS algorithm, around 3 to 8 percent of the crashes and 29 to 50 percent of the moderate to fatal injuries can be prevented.

Rosen (2013) analyzed 543 car-to-pedestrian and 607 car-to-bicyclist accidents from the GIDAS-based PCM database and evaluated the extent of injury mitigation based on different settings for a pedestrian and bicyclist AEB system. Depending on system specifications, the accident avoidance rates varied between 0 to 52 percent and 1 to 31 percent for pedestrian and bicyclists, respectively.

Gorman et al. (2013) re-simulated about 3,000 collisions from NASS/CDS with varied driver steering input and reaction times to assess the effectiveness of a Lane Departure Warning (LDW) system. The authors concluded that approximately 30 percent of all road departure crashes can be prevented by LDW.

A sample of 100 reconstructed car-to-pedestrian crashes from the crash investigation database of the Centre for Automotive Safety Research (CASR) at the University of Adelaide in Australia and the laboratory of accident mechanism (LAB) of the French Institute of Science and Technology for Transport, Development, and Network (IFSTTAR) was used to evaluate the potential of a Pedestrian AEB for crash avoidance (Hamdane et al., 2015). Using virtual simulation with a varying range of parameters, the authors estimated that about 50 percent of the accidents can be avoided using a 35° field-of-view sensor and AEB triggering at 1 s TTC. With a TTC of 1.5 s, the percentage could be increased to 80 percent crash avoidance.

Finally, Scanlon et al. (2017a) investigated the potential of an Intersection Advanced Driver Assistant System (I-ADAS) for avoidance and mitigation of SCP accidents. With arbitrary chosen TTC activations of 1 to 3 seconds with 0.5 second steps, the pre-crash simulation of 448 SCP crashes from the National Motor Vehicle Crash Causation Survey estimated a crash avoidance potential up to 59 percent and injury mitigation potential of 79 percent. In another study, Scanlon et al. (2017b) used 501 reconstructed LTAP/OD accidents to assess the effectiveness of the I-ADAS. It was estimated that up to 25 percent of the accidents could be avoided if the driver of the turning vehicle received a warning three seconds before the crash. Up to 71 percent of the crashes were assessed to be avoidable by an AEB function.

Generation of artificial scenarios

Like the re-simulation of scenarios, the generation of artificial scenarios based on real-world data has been widely used to analyze the effect of crash prevention technologies.

McLaughlin et al. (2008) analyzed thirteen rear-end crashes and sixty rear-end near crashes collected in a NDS to investigate the effect of a collision avoidance system. The point in time when the driver of the rear vehicle needed to initiate the bakes to avoid the collision was identified from the vehicle kinematics. Then, the point in time for braking was varied to create artificial scenarios and the effect of different algorithms for collision avoidance were simulated. From the results conclusions were drawn regarding the effect of the collision avoidance system on the driver reaction, though no quantitative figures were given.

The effectiveness of Lane Departure Warning (LDW) in the prevention of lane departure crashes was studied by Gordon et al. (2010) using crash data from NASS/CDS, the National Automotive Sampling System General Estimates System (NASS/GES), and Naturalistic Driving Studies (NDS). Additionally, road parameters were derived from geo-referenced data. Artificial crash databases were generated from virtual driving scenarios with and without LDW. The results showed that about one-third of the lane departure accidents could be avoided with LDW. Further, a greater benefit in rural areas compared to urban areas was identified.

The Safety IMPact Assessment TOol (SIMPATO) was developed to evaluate the safety benefit of different active safety and driver assistance functions such as Rear-end AEB and emergency steering assist (Van Noort et al., 2013). Conflict scenario descriptions were derived from the GIDAS data. The warning was issued when TTC was less than three seconds and driver reaction times were set to 0.5 seconds. Qualitative results were only given in examples of simulated single cases.

Kates et al. (2010) presented a method to estimate the benefit of a Pedestrian AEB with warning. Stochastic simulation was used to generate traffic scenarios that involved both collisions and non-collisions. The method was further developed with decision modelling of the pedestrian to enter the road and surrounding traffic (Helmer, 2014; Helmer et al., 2013, 2012). Specific benefit estimates were not presented.

Woodrooffe et al. (2013) analyzed the effect of a Forward Collision Avoidance and Mitigation system (F-CAM) including FCW and CMB for commercial vehicles using about 10,000 rear-end conflicts with delayed driver reaction time, so that artificial collisions took place. For a 100 percent fitment rate of F-CAM it was assessed that the reduction of annual fatality and injury rates in rear-end truck collisions would be about 24 and 25 percent, respectively.

Tanaka (2015) presented a method to generate traffic accidents from traffic scenarios involving a road environment, vehicle dynamics and driver behavior models by implementation of a driver error. The simulation environment, called ASSTREET, was then used to assess the effectiveness of safety systems addressing car-to-car rear-end crashes, car-to-pedestrian crashes, and lane departure accidents in the US, Europe, and Japan (Morales Teraoka et al., 2014, 2013, Tanaka et al., 2012, 2011; Tanaka and Mochida Teraoka, 2014). Specific estimate figures were not given.

Counterfactual simulations involving 37 rear-end crashes and 186 rear-end near crashes from the SHRP II naturalistic driving project were conducted with delayed driver reaction time, so that the conflict scenarios were artificially altered (Bärgman et al., 2015a). A model of driver glance behavior was used to define the probability of crash occurrence and injury severity. The authors did not include quantitative figures.

Yanagisawa et al. (2017) used a Monte Carlo simulation model to estimate the crash probability in vehicle-to-pedestrian conflicts. NASS/GES and FARS crashes were used in combination with a pre-crash avoidance and mitigation system (PCAM). Based on the simulation results, the authors concluded that up to 78 percent of the vehicle-to-pedestrian crashes can be avoided and up to 96 percent of the severe to fatal crashes can be mitigated by a PCAM system.

General principles of effectiveness assessment by virtual simulation

The effectiveness assessments based on virtual simulations reviewed above used some general principles described by Carter and Burgett (2009), Page et al. (2015), and Engström and Wege (2016), outlined as follows:

1. Definition of evaluation purpose and metrics on which the safety feature effectiveness is measured. The character of the safety feature may include active or passive vehicle safety technology, infrastructure measures, driver behaviour change, or any combination.
2. Selection of data sources and relevant traffic situations for the safety feature. Constraints on the selection of traffic scenarios have to be considered when the results of the simulations are interpreted, as these affect the target population.
3. Definition of models representing driver, vehicle (dynamics), environment, and safety feature under evaluation.
4. Simulation of baseline (or reference) scenarios where the safety feature under evaluation is not in place. Baseline scenarios can be a representation of recorded or reconstructed scnearios, altered scenarios, i.e. with regard to driver behavior, or synthetically generated scenarios from given distributions. The baseline is a representation of the exposure in Section 2.1 and may contain normal driving scenarios, near-crashes, crashes, or any combination of these.
5. Simulation of potentially modified scenarios where the safety feature under investigation is in place.
6. Weighting of simulation results to eliminate sampling bias and to make the results representative for a specific population.
7. Comparison of baseline and potentially modified scenarios by computation of relative risk and effectiveness as presented in Section 2.1 and 2.2.

As virtual simulation gives information about both avoided and not avoided accidents, the datasets of scenarios where the safety feature is in place and is not in place are most often identical. Then it follows that ${V_r}^+ = {V_r}^-$. The equation to calculate the risk ratio RR then simplifies to:

$$RR = \frac{R^+}{R^-} = \frac{{V_a}^+}{{V_a}^-}, \tag{10}$$

and the effectiveness E of accident avoidance can be computed as follows:

$$E = 1 - \frac{{V_a}^+}{{V_a}^-} = \frac{{V_a}^- - {V_a}^+}{{V_a}^-}. \tag{11}$$

Influence of data selection on effectiveness

In case only accidents are selected for the baseline, the accident involvement risk in the exposure data equals one and the accident involvement risk in the incident data must be less than or equal to one. Thus, the computed effectiveness is between zero and one (or zero and 100 percent). It is, however, possible that a safety feature increases (unintendedly) the risk of accident involvement, resulting in a negative effectiveness (the relative risk is greater than unity).

2.3.3 A posteriori assessment

Though it may take several years after a safety feature has been introduced to the market for sufficient data to be available for an *a posteriori* assessment, this approach is the only alternative to get a 'true' representation of the effect in real-world. The term 'true' still must be evaluated against any bias that may result from sampling of exposure and incident data or idealization of driver behavior. A number of studies have conducted *a posteriori* evaluation of various active safety systems resulting either in coincident or deviant results compared to *a priori* evaluations.

Doyle et al. (2015) used insurance claims data to quantify the effect of low-speed Rear-end AEB. Claims losses with a specific vehicle with AEB were compared to vehicles of the same class without AEB. The authors concluded that claims for own damage for the vehicle with AEB were 10 to 15 percent lower than for the control cohorts.

Meta-analysis was used to assess the benefit of low-speed Rear-end AEB in car-to-car rear-end crashes (Fildes et al., 2015). Data from six different countries was aggregated, differentiated by AEB equipment status. Induced exposure was applied and vehicles being struck in the rear were used as the AEB non-sensitive control group. The overall effectiveness of low-speed AEB in crash avoidance was assessed to be 38 percent.

Isaksson-Hellman and Lindman (2016) also evaluated the crash mitigation effect of a low-speed Rear-end AEB system by comparing insurance claims involving a specific vehicle model with and without the system. Crash severity was estimated by car damage based on spare part demand. The authors estimated that low-speed AEB systems reduced crash occurrences by 27 percent, whereas low severity crashes were reduced by 37 percent. More severe crashes were not found to be reduced.

The effectiveness of Forward Collision Warning (FCW) systems with and without AEB using police reported crash rates was investigated by Cicchino (2016). Poisson regression was used to control for other factors that affect the crash risk such as driver age, gender, and insurance risk level. The regressions resulted in rate ratios for FCW alone and FCW with AEB against vehicle without those systems. FCW and FCW with AEB were estimated to be effective by reducing crash involvements by 23 percent and 39 percent, respectively. The author used the same method to assess the effect of Lane Departure Warning (LDW) on single vehicle, sideswipe, and head-on crashes (Cicchino, 2017). After accounting for driver demographics in the Poisson regression models, LDW was found to reduce the number of crashes by eleven percent and crashes with injuries by 21 percent.

Sternlund et al. (2017) estimated the benefit of LDW and Lane Keeping Assistance (LKA) systems using data from the Swedish Traffic Accident Data Acquisition (STRADA) database. Induced exposure was used to correct the exposure for crashes not sensitive to LDW/LKA. For all single vehicle and head-on crashes, the estimated benefit of crash reduction was 30 percent, for crashes with speed limits between 70 and 120 km/h the estimated benefit was 53 percent.

2.3.4 Comparison of a priori and a posteriori assessments

Table 1 to Table 6 present effectiveness figures of one selected metric from the above-mentioned quantitative virtual simulation-based *a priori* and *a posteriori* studies for Rear-end AEB, Pedestrian AEB, Lane Departure Warning, and Intersection AEB.

A high number of *a priori* and *a posteriori* effectiveness studies have been conducted for Rear-end AEB (Table 1 and Table 2).

Table 1: A priori effectiveness figures for Rear-end AEB

	A priori assessment			
Authors	Lindman et al. (2012)	Van Auken et al. (2011)	Kusano and Gabler (2012)	Woodrooffe et al. (2013)
Metric	Crash avoidance	Crash avoidance	Crash avoidance	Fatality reduction
Remarks	AEB operates up to 30 / 50 km/h.	Ideal sensing; System parameters not exactly described.	Evaluation for FCW, Brake Assist, and AEB;. AEB operates from relative speed greater than 15 km/h	Analysis for commercial vehicles; FCW and CMB
Effectiveness	19% / 19%	65%	up to 8%	24%

A priori Rear-end AEB studies vary substantially in their assessed effectiveness (Table 1).

Table 2: A posteriori effectiveness figures for Rear-end AEB

	A posteriori assessment			
Authors	Doyle et al. (2015)	Fildes et al. (2015)	Isaksson-Hellman and Lindman (2016)	Cicchino (2016)
Metric	Own and third-party damage reduction	Crash avoidance	Crash avoidance	Crash avoidance
Remarks	Analysis based on insurance claims data; Low-speed AEB	Meta-data analysis; Low-speed AEB	Analysis based on insurance claims data; Low-speed AEB	Analysis based on insurance claims data; FCW and AEB.
Effectiveness	7%	38%	27%	39%

However, Lindman et al. investigate a close to production system, whereas Van Auken et al. simulate a prototype system, resulting in a much higher number of avoided crashes.

Kusano and Gabler assume that the AEB system operates only if the relative speed between the vehicles exceeds a given threshold. As most Rear-end accidents happen at lower speeds, the overall crash avoidance rate is smaller compared to other studies. The assessed crash avoidance potential derived from recent *a posteriori* Rear-end AEB studies are of the same magnitude (Table 2).

For the effectiveness evaluation of Pedestrian AEB, only *a priori* studies have been found. With similar system specifications, the effectiveness of fatality reduction is within the same magnitude. The studies using crash avoidance as effectiveness metric investigate system parameter ranges and thus, the effectiveness results span a wide range (Table 3 and Table 4).

Table 3: A priori effectiveness figures for Pedestrian AEB

	A priori assessment			
Authors	Lindman et al. (2010)	Van Auken et al. (2011)	Rosen (2013)	Hamdane et al. (2015)
Metric	Fatality reduction	Fatality reduction	Fatality reduction	Crash avoidance
Remarks	FCW and AEB.	FCW and AEB.	AEB only; System only performant in daylight.	AEB only; Ideal system without processing time.
Effectiveness	24%	19%	21%	up to 83%

Table 4: A priori effectiveness figures for Pedestrian AEB (continued)

	A priori assessment
Authors	Yanagisawa et al. (2017)
Metric	Crash avoidance
Remarks	AEB only; Constant pedestrian motion; .
Effectiveness	10% - 78%

For Lane Departure Warning systems, the estimated effectiveness for crash avoidance was substantially higher in Sternlund et al.'s study than in Cicchino's and the referenced a priori assessments (Table 5). However, the lower 95% confidence limit in Sternlund et al.'s work was identified at 11 percent effectiveness and the results represented an LDW system from only one vehicle manufacturer. Further, when the target population was adjusted to all head-on and single vehicle crashes, the effectiveness was estimated at 30 percent with a lower limit of six percent.

Table 5: A priori and a posteriori effectiveness figures for Lane Departure Warning

	A priori assessment		*A posteriori* assessment	
Authors	Gordon et al. (2010)	Gorman et al. (2013)	Cicchino (2017)	Sternlund et al. (2017)
Metric	Crash avoidance	Crash avoidance	Crash avoidance	Crash avoidance
Remarks	Considering speed and sensor performance.	Driver step response; Driver reaction time set to 0.38 s and 1.35 s; Foru trajectory models.	Insurance claims	For crashes with speed limit within 70 to 120 km/h; Road markings present; No snow condition;
Effectiveness	32%	30%	18%	53%

Intersection AEB systems have been investigated so far with *a priori* assessments as only a few vehicle manufacturers have such systems in the market, and this only for a short period of time. Van Auken et al. are detailed on the utilized method, but little information is given about the specification of the investigated collision mitigation system. Thus, it cannot be explained why the effectiveness is small compared to Scanlon et al. (Table 6).

Table 6: A priori effectiveness figures for Intersection AEB

	A priori assessment		
Authors	Van Auken et al. (2011)	Scanlon et al. (2017a)	Scanlon et al. (2017b)
Metric	Collision Avoidance LTAP/OD	Collision Avoidance LTAP/OD	Collision Avoidance SCP
Remarks	Collision mitigation system addressing rear-end, head-on, and crossing path crashes.	System activation up to 3s TTC.	System activation up to 3s TTC.
Effectiveness	8%	up to 71%	up to 74%

The selected studies differ in the definition of target population, AEB and LDW system specifications, and driver reaction models. Further, many studies use more than one metric to measure the effectiveness. In this comparison, however, only the metric which was most commonly present across the studies was chosen for display.

A priori studies can be generally divided into two categories:

a) Studies that investigate theoretical or early prototype systems. These studies are characterized by a variation of system parameters in specific ranges to assess the influence on system effectiveness. Models are often simplified and processing delays and measurement errors are neglegted.
b) Studies that use close-to-production systems for effectiveness evaluation. Here, models have much higher granularity and system parameters are set to actual ranges or values.

In general, *a priori* studies face the difficulty of driver behavior modelling in case such a model is necessary for the assessment objective. Some studies mentioned before use simplified driver models, where drivers respond to system interaction or intervention in a 'perfect' way. Also, an idealization of the sensor model is quite common. This must be taken into consideration when system effectiveness is interpreted. It is also possible that utilized models are inadequate or even ill-defined. Thus, it is important that both specified target population and simplifications or idealizations that may lead to a deviation from real-world performance are clearly stated in the methodology description. The reliability of virtual simulation results is dependent on the quality of input data and the validation and verification of models and processes. Therefore, these aspects have to be critically reviewed and if necessary improved.

2.3.5 Virtual simulation and expert opinion

Despite the challenges of *a priori* assessment by virtual simulation, this approach has numerous advantages. Compared to an approach based on expert opinion and case-by-case analysis as presented for example by Strandroth et al. (2012), virtual simulation is less prone to subjective assessment. Further, virtual simulation is repeatable, and, though automated processing, results based on changed assessment rules can be derived with little effort. Building up, completing, or modifying an assessment framework including virtual simulation does not only enable computing overall results, but also fosters the understanding of the roles of models, their interconnections, and their functionality and limitations.

2.3.6 A modified Deming cycle

Due to their different strengths and weaknesses and thus fields of application, *a priori* and *a posteriori* assessment should be not seen as competing but complementary. Considering the different characters of *a priori* and *a posteriori* studies (as described in Section 2.3.4), an assessment process sequence is suggested:

Before a safety system is specified, *a priori* assessment can offer initial insights into the strengths and limitations of different safety system design alternatives (planning phase). With the results of *a priori* studies, specifications for safety systems can be generated to allow a more detailed analysis of a close-to-hardware design (doing phase). In-depth observation of the safety system in the market enables *a posteriori* assessment (studying phase). This assessment can be based on the observation of only one specific system design or a system category such as AEB and LDW including solutions from different automotive manufacturers. The data from *a posteriori* assessments in turn can then be used to refine the system specific *a priori* evaluation process (acting phase). The knowledge of potential bias between *a priori* and *a posteriori* assessment results can be used in the definition of an *a priori* assessment for a new safety system proposal (planning phase). The sequence of assessments then represents a modified Deming cycle (William and Gregory, 1998) with the stages plan-do-study-act (Figure 2).

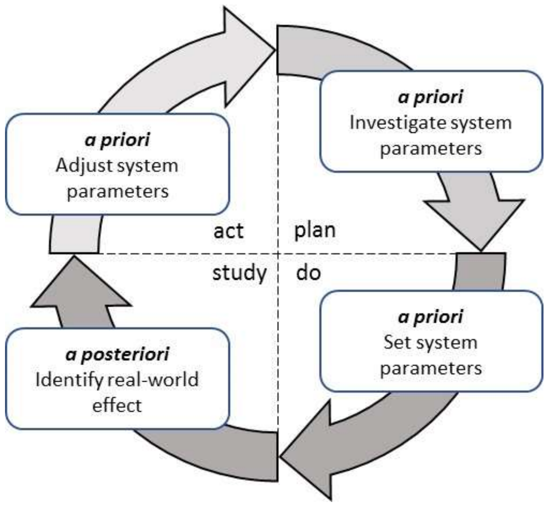

Figure 2: Modified Deming cycle adapted to a priori and a posteriori effectiveness assessment

3 METHODS

This chapter provides the background to the different phases of the research process, to the data and methods utilized, and their dependencies.

3.1 Research Process

The aim of this research was to identify and quantify parameters that have a substantial impact on the effectiveness of an Intersection AEB in avoiding accidents and mitigating injuries. As described in Section 3.1.1 below, the research was organized into four stages, guided by specific research topic. Each subsequent stage was dependent on answering the research questions related to the topic of the previous stage. Further, each stage is divided into four phases: definition, procedure-design, analysis, and interpretation (Graziano and Raulin, 2014). Within these phases, several activities took place (Figure 3). Section 3.1.3 then gives information about the applied methods *case collection* and *computer simulation,* and how they relate to each other.

3.1.1 Research stages

The research strategy was developed from the current state of knowledge as described in the introduction. Four main research stages were identified and reported in individual papers, each dealing with a specific research topic and guiding the subsequent stage:

<u>Stage 1, research topic:</u> How does V2X communication compare to on-board sensing with regard to saving lives?

The first stage addresses the initial research question "How does V2X communication compare to on-board sensing and can it be as effective as a stand-alone sensing alternative?". Both NHTSA in the United States and the European Commission have put focus on V2X communication as a traffic safety feature for injury mitigation (European Commission, 2016c; Harding et al., 2014; NHTSA, 2014). Though communication can be seen as another type of environment sensor, the data transmitted can be substantially different to what cameras or radars can identify. Further the data has to be correctly received and interpreted to enable driver information or automated intervention. The answer to this question led to the next phase of in-depth investigation of on-board sensing:

<u>Stage 2, research topic:</u> What are the opportunities and limitations of Intersection AEB based on the variation of main design parameters?

The second stage addresses the research questions "How effective can an Intersection AEB system based on on-board sensing be in avoiding accidents?" and "What parameters have a substantial influence on the performance of an Intersection AEB system?" for LTAP/OD scenarios. During the course of this research, only a few published studies have been identified that deal with an estimated effectiveness of Intersection AEB (Scanlon et al., 2017a, 2017b, 2016; Van Auken et al., 2011b). Though there might be inhouse studies available to vehicle manufacturers or safety system suppliers, shared knowledge is limited. Design parameters are generally seen as intellectual property and therefore kept confidential. But besides design parameters, market penetration is also important to predict the effect on injury mitigation. This research circumvents confidentially issues by describing the effect of parameter variation in combination with other fixed parameters that may not represent the most ideal settings. The answer to this question led to a more in-depth analysis of the dataset to identify data variance and influence on crash avoidance:

Stage 3, research topic: Is it possible to reduce the variation of real-world crashes into a set of test scenarios without substantial reduction of the variance present in the data?

The third stage addresses the research question "Can a set of test scenarios be defined which is representative for the utilized sample of accidents?" for both SCP and LTAP/OD scenarios. To date, no test scenarios have been defined for Intersection AEB testing. Euro NCAP, however, has mentioned the implementation of intersection test scenarios in their road map for 2020 (Euro NCAP Strategy Working Group, 2015). Thus, there is a high interest in system effectiveness derived from specific scenarios being representative of effectiveness in the real world. Paper I has shown the importance of market penetration. Further, injury mitigation is generally judged equivalently important as accident avoidance. Both aspects led to the following investigation:

Stage 4, research topic: How does the effectiveness of Intersection AEB with regard to crash avoidance and injury mitigation change with increased market penetration?

The fourth stage addresses three research questions for SCP scenarios: "How effective can an Intersection AEB system based on on-board sensing be in avoiding accidents?", "What is the capability of these systems to mitigate injury in cases where an accident cannot be avoided?" and "How does the effectiveness in avoiding accidents and mitigating injuries change as market penetration increases?". The introduction of active safety systems to 95 percent of the vehicle fleet will take many years (IIHS, 2012). Though the fitment of active safety systems to new vehicles can reach very high percentages (Krafft et al., 2009), older cars will be replaced slowly and thus remain on the roads for some time. However, according to Statistics Sweden (statistiska centralbyrån, SCB) data from 2017, the median vehicle mileage is reached after five to six years, whereas the 90-percentile mileage is reached in up to 15 years. This means that the majority of road traffic consists of newer vehicles (Strandroth, 2015). On the other hand, accident involvement risk and driving distance are not linearly related and risk decreases with increased yearly driving distance (Hakamies-Blomqvist et al., 2002). Younger and older drivers are more likely to drive older cars and have a higher probability of getting fatally injured in intersection crashes (Lombardi et al., 2017). Thus, it becomes relevant to understand the effect of active safety systems during their market penetration time period.

3.1.2 Research phases

For each research stage, research activities are organized in four different research phases (Figure 3). In the definition phase, the research question(s) based on the knowledge gap is/are refined into objectives for the study. A literature review is then conducted to even refine the objectives further. The following phase is the procedure-design phase. Here, the identification of relevant data sources and selection of cases relevant for the study objective is covered. Following data selection, different types of procedures are defined: a) computation of weighting factors to make the selected cases representative for the corresponding national statistics, b) frequency and distribution analysis of selected variables to identify potential bias, for example unimodal versus bimodal distribution, and c) identification of miscodings and if necessary, recoding. Then, statistical models are generated and if appropriate, simulation models are generated or updated based on the results of previous studies. These statistical models are developed for different purposes such as to determine the probability of vehicles equipped with a safety system being involved in a crash and the probability of moderate to fatal injury in case an intersection crash cannot be avoided. In the analysis phase, simulations are executed with different parameter settings and merged with the results from the statistical analysis and modelling. For example, simulation results are weighted with the factors from the statistical analysis and combined with the probability models of occurrence. In the final phase, the interpretation of results is aided through identifying appropriate visualization. In comparison to the research methodology of Graziano and Raulin, an observation phase is dismissed, as the data have already been collected (see Section 3.1.3).

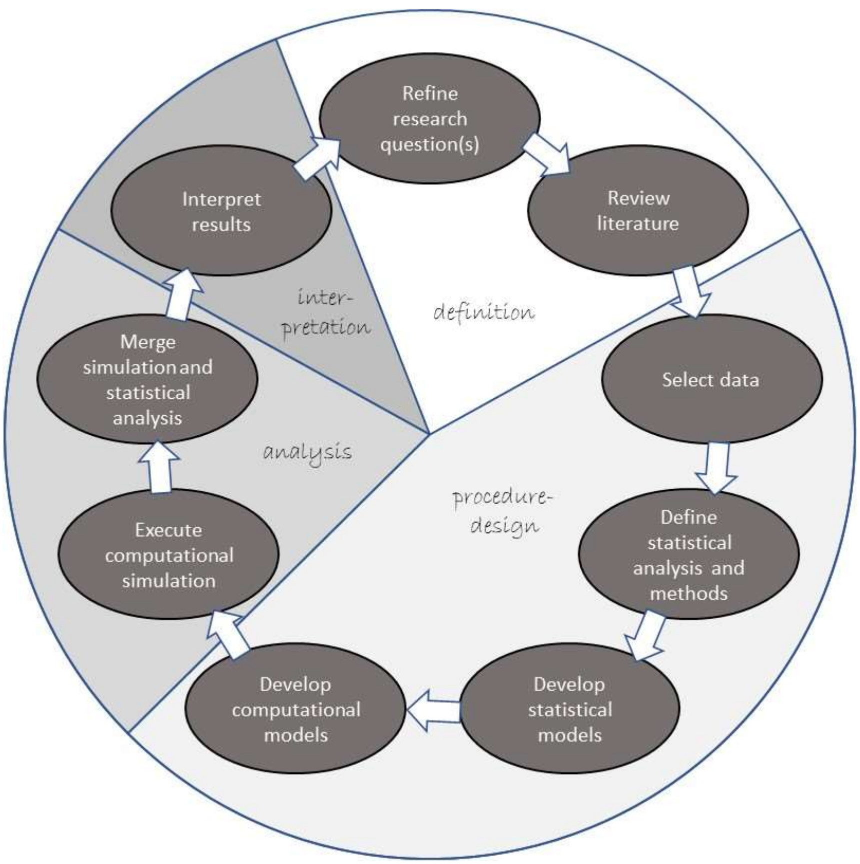

Figure 3: Research process adapted from Graziano and Raulin. Activities grouped in research phases. When the interpretation of results is completed, the outcome is used to refine the research questions for the following stage.

3.1.3 Research methods

Two different approaches have a long history in scientific research, deduction and induction. In the former, assumptions are formulated, often by mathematical equations, and consequences of the assumptions are deduced, e.g. by mathematical derivation. However, for complex problems it is often impossible to find analytical solutions, or a solution may only be valid for specific conditions. Induction may be interpreted as collecting observations (case collection) and analyzing them to identify relationships. Here, the access to data and the time frame necessary to retrieve sufficiently large data is a limiting factor. A third approach has been established with the rise in the processing power of computers: computer simulation (Waldrop, 1994). The limitation of deduction, that a derivation can be mathematically challenging, is addressed by numerical methods. Also the limitation of induction, that necessary data might be not available, is overcome as simulation produces its own data (Harrison et al., 2007). Graziano and Raulin (2014) also name scientific modelling as another approach, where the model does not need to be of a physical nature. The approach is similar to computer simulation as the model should represent reality, but not duplicate it. In that sense, computer simulations usually build upon models. This thesis utilizes case collection and computer simulation as research methods.

Case collection

The cases that are underlie this thesis were not self-collected but gathered from state-funded and industry/state-funded research programs. Whereas the United States NASS and FARS data is open access, the German GIDAS data is only available to funding member organizations.

NASS comprises different data systems, The Crashworthiness Data System (CDS) with a general focus on passenger vehicle crashes and specifically injury mechanisms, and the General Estimates System (GES) with a less detailed but higher sample size to investigate the overall crash situation and identify trends. NASS/GES data is sampled through police accident reports and as such is restricted to the data collected by different police jurisdictions. GES focusses on crashes of high interest and concern. Thus, at least one travelling vehicle must have been involved and material damage at least must have occurred (Committee on Classification of Motor Vehicle Traffic Crashes, 2017). Every year about 400 police jurisdictions in 60 areas across the United States collect a random sample of 50,000 police accident reports. NASS/CDS data collects about 5,000 crashes a year involving passenger cars, light trucks, vans, and utility vehicles. Trained investigators go out to the accident site and record evidence on-scene such as crash damage and skid marks. Follow-up investigations are conducted by interviewing crash-involved persons and collecting medical information. From the crash damage, impact constellations, and vehicle stiffness category, the change of velocity (delta-V) during the crash is estimated (Brach and Brach, 1998; Hampton and Gabler, 2010; Sharma et al., 2007). Special crash investigations on specific topics such as crash causation and crash injury research has been conducted. The FARS is a census of all fatal crashes occurring in the 50 States and the District of Columbia. The information about fatal crashes is taken from police reported accidents and complemented with driver records, vehicle registration files, roadway files of each State, and death certificates. NASS/GES and FARS data is used in Paper I.

The German In-Depth Accident Study (GIDAS) has been collecting in-depth accident data on the spot in two regions in Germany, Hanover and Dresden, since 1999. Approximately 2,000 cases per year are recorded in which at least one road traffic participant is injured, undertaken according to a detailed sampling plan (Hautzinger et al., 2004). The database includes all types of road participant accidents, among others pedestrian-to-bicyclist accidents. The random sampling scheme allows extrapolation of analysis results from the sample to Germany by weighting. On-scene evidence such as tire marks, end positions of vehicles and persons, liquid puddles, and splinter fields are recorded and used to reconstruct the accident which is done in the vast majority of cases using the software PC-Crash (Cliff and Montgomery, 1993; Cliff and Moser, 2001).

From 2011, using a subset of the GIDAS data, the Pre-Crash Matrix (PCM) has been coded by converting road traffic participant pre-crash trajectories from accident reconstruction into a time-series format (Erbsmehl, 2009; Schubert et al., 2013). In this database, vehicle pre-crash path coordinates and speed profiles are given in 10 millisecond time steps. Road infrastructure information and objects obstructing sight are taken from accident sketches, converted into a digital format as lines and polygons and added to the PCM information. Additionally, vehicle specific information such as the moments of inertia with respect to the principal axis, track width, wheelbase, and center of gravity height are taken from PC-Crash, as they were not present in the GIDAS database. The length of the pre-crash time-series data is about five seconds for each case, though road infrastructure information is not available for all cases around the starting position. This is due to the generation of time-series information from older GIDAS cases, where the scene sketches covered a closer area around the crash location, but not the run-in path of the vehicles in a five second time span. The PCM only contains environment information that is included in the sketch, thus information about moving objects such as other road traffic except the collision opponents is not available. GIDAS and PCM data were used for Papers II, III, and IV.

<u>*Computer simulation*</u>

A computer simulation can be defined as a computational model of system behavior coupled with an experimental design (Harrison et al., 2007). The computational model defines the relevant system components such as parameters and variables and how they change through the definition of processes. The experimental design then defines the initial conditions of a simulation, the criteria under which the simulation is terminated, the output of the simulation, and the variations of parameter settings. Where stochastic models are used, simulations must be repeated many times with different starting values to ensure that the range and probability of selected values corresponds to their probability density function.

Though there are many aspects to the use of computer simulation, two are of specific interest: predicting accident evolution with a specific safety system present to evaluate the influence of system parameters such as braking capabilities, and also evaluating the consequences of system-independent parameters such as vehicle speed. One challenge in computer simulation is finding the right balance between simplicity and perfection. It is desirable for computer simulation to give a good representation of real world processes; however, with more complex models, it is more difficult to understand the influences: “After all, the perfect computation simply reproduces Nature, does not explain her” (Anderson, 1977). The description of the framework for the assessment of the effectiveness of active safety systems, which includes the computational model of system behavior, is presented separately in Section 3.2.

Verification and validation

Both the data and the computer simulation process were verified and validated in the assessment framework; details of this procedure can be found in the Section 3.2 below.

3.2 PRAEDICO

PRAEDICO is the framework developed in this thesis to assess the effectiveness of active safety systems. The name stands for 'PRediction of Accident Evolution by Diversification of Influence factors in COmputer simulation' and is also Latin for the English expression 'I make known'.

The output of PRAEDICO is manifold and covers aspects such as number or percentage of avoided crashes and mitigated injuries, number or percentage of system activations, pre-crash speed reduction, and objects within sensor field-of-views at specific points in time.

The framework includes the following partitions: experimental design, data selection, scenario definition, pre-crash simulation, crash computation, and statistical analysis (Figure 4).

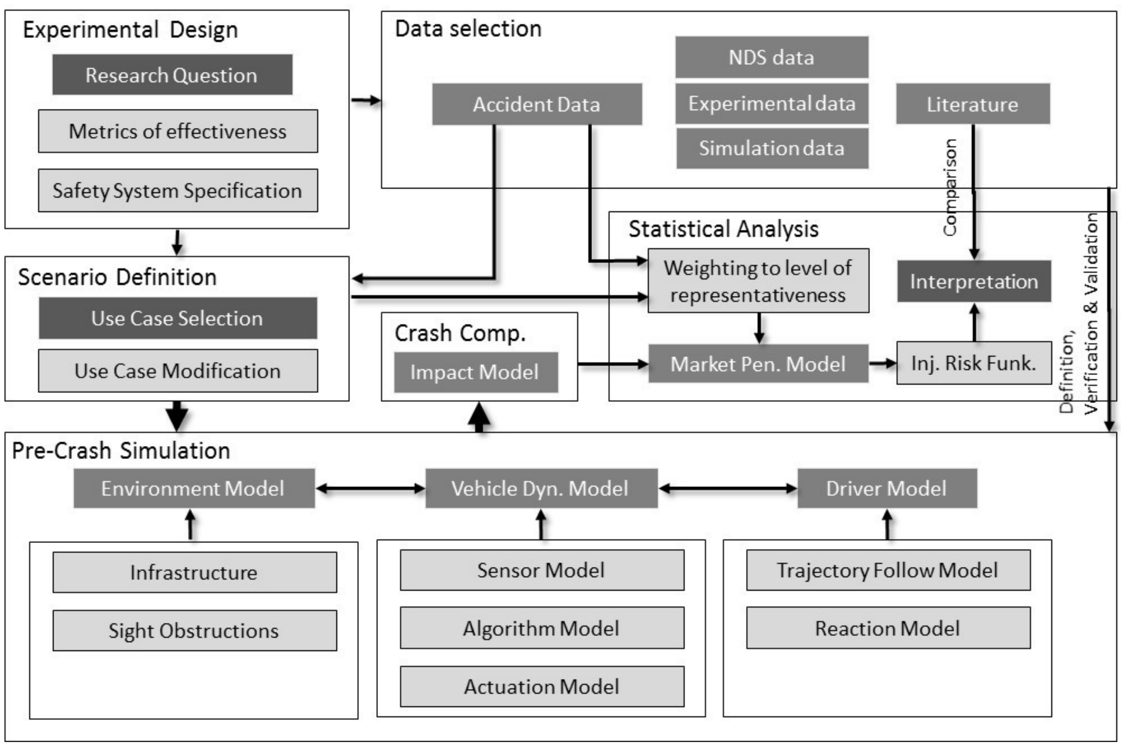

Figure 4: PRAEDICO framework - With the definition of the experimental design, data source(s) and relevant scenarios are selected and defined. Pre-crash simulations are conducted on the selected scenario cases, using an environmental model, a vehicle dynamics model, and a driver model. The vehicle dynamics model can be equipped with an active safety system that either can warn the driver or initiate automated braking. The pre-crash simulation outputs, if vehicles are passing each other, come to a stop or crash with each other. When a crash takes place, a crash computation is conducted. In the statistical analysis, weights are computed to make the results representative for a specific region. If relevant for the analysis objective, a market penetration and injury risk model are

considered to compute metrics such as avoided accidents and mitigated occupant injury as a function of market penetration.

PRAEDICO was built to allow assessments beyond the scope of this thesis. First, it is possible to simulate not only car-to-car accidents, but also all other accident types where at least one passenger car is involved. Second, it is possible not only to simulate intersection accidents, but all types of accidents except those where dynamic loss of control is involved. If loss of control is not present, trajectory information can be translated into steering wheel and gas- and brake-pedal input. This does not generally hold for loss of control situations. Third, also driver reaction to warning can be simulated, so that the driver reaction model randomly selects a reaction time from a given distribution. However, this does not reflect the current state-of-the-art on driver modelling, where it has been shown that driver reaction depends on the relative kinematics of the conflicting vehicles (Markkula et al., 2016).

Validation of the PRAEDICO framework has been done by scrutinizing results as reasonable and through comparison to results from similar studies. Further, the appendix of Paper IV contains results from a re-simulation of the original accident data without an added safety system. The distribution of specific variables from GIDAS and re-simulation were compared, and it was concluded that the mean and standard deviation match appropriately.

The PRAEDICO framework was used in Papers II to IV.

3.2.1 Experimental design

In this thesis, the elements of experimental design (Section 3.1.3, Computer simulation) were set in different ways: The metrics suitable for measuring the effectiveness of a safety system of the simulation and the variation of specification of a safety system were determined according to the research questions underlying each stage. The active safety system to be evaluated was defined along with the addressed target population. The initial conditions for each simulation were taken from case collection data. Termination criteria for simulations were pre-defined and identical across all conducted simulations. The criteria included a) all vehicles having come to a standstill without a collision, b) the maximum simulation time having passed without a collision, and c) the vehicles having collided with each other. The maximum simulation time was set in the pre-processing to ensure that the vehicles had passed each other in cases where they have not stopped to standstill and have not collided with each other. Re-simulation of scenarios (see Section 2.3.2) was chosen for Papers II to IV. Stochastic modelling was not utilized.

3.2.2 Data selection

The data used for Papers I to IV (Section 3.1.3, Case collection) were in large part based on real-world accidents. GIDAS and PCM data was used to specify vehicle models, the environment model, and driver model. Other data types were utilized to characterize and parameterize the active safety system (sensor, algorithm, and actuation model). For example, experimental and NDS data were analyzed to parameterize the driver comfort threshold for lateral and longitudinal acceleration (Bärgman et al., 2015b; Dingus et al., 2006; Moon and Yi, 2008) and for steering wheel velocity (Thalhammer, 2008). Internal data was used to specify sensor models and actuation model. German national accident statistics were utilized to compute weights to make the simulation results representative to Germany.

The different data types included a) parameters that were kept constant throughout a batch simulation of scenarios (such as sensor parameters) and b) parameters that were updated with each scenario simulation (such as vehicle dimensions and trajectories).

In general, when using a specific data format, all type of driving events such as normal driving, near-crashes or crashes can be utilized as input to PRAEDICO.

3.2.3 Scenario definition

Based on the 44-Crashes report from General Motors (North America Operations Crash Avoidance Department, 1997), Najm et al. (2007) developed a pre-crash scenario typology for crash avoidance that has been widely adopted in road safety research. The classification from Najm et al. is based on NASS/GES and NASS/CDS database variables, thus it is not easily possible to transfer the classification scheme to other databases. In Europe, the description of accident scenarios according to the report of the German insurers (Gesamtverband der Deutschen Versicherungswirtschaft e.V., 2016) is frequently used as a basis for pre-crash scenario classification (Wisch et al., 2012).

For this thesis, a new accident scenario classification was developed combining parts of the classification logic from Najm et al. and using the accident scenario description from the German insurers. The classification is done in two steps: In the first step, the accident type is selected based on crash participant types. This step is necessary as PRAEDICO requires that one participant is a passenger car, and either a kinetic model (for passenger cars and trucks) or kinematic model (for motorcyclists, bicyclists, and pedestrian) is selected for simulation of the other participant. In the second step, the pre-crash maneuver is defined based on technical vehicle condition, driver condition, vehicle stability, and / or relative motion of the conflict participants to each other. Specific scenarios are selected to define the target population (Section 3.2.1).

A description of the accident scenario classification is given in Appendix A.

3.2.4 Pre-Crash Simulation

Pre-crash simulation has become an important technique in assessing the functionality of an advanced driver assistance or active safety system (Alvarez et al., 2017). Several commercial products are available that offer passenger vehicle dynamics simulation in a road infrastructure environment with interfaces to implement active safety function algorithms, and sensor models, and include IPG CarMaker (Unger et al., 2016), TASS PreScan (Fredriksson and Nilsson, 2015), or VIRES Virtual Test Drive (Freij, 2013). However, none of these was found to be suitable for the current research as these commercial products allow only one vehicle to be equipped with an active safety system. Additionally, in some commercial products the driver model could only follow the centerline of a road, thus the road would have been aligned to a trajectory, which may not correspond to real-world conditions. As the research aims focus on the avoidance and mitigation of intersection accidents by AEB, the probability of conflict scenarios where both vehicles are equipped with an active safety system increases with market penetration. Thus, it is not sufficient to equip either the one or the other with a safety system; the interaction between the system responses would have be missing.

For this reason, a proprietary pre-crash simulation environment was developed by the author of this thesis for PRAEDICO. It consists of three parts: time-independent pre-processing and post-processing, both in Matlab, and time-dependent processing in Simulink.

Pre-processing

Pre-processing was dependent on the database type and information available in the databases. Different graphical user interfaces (GUIs) were used to select databases and scenarios, and to specify model parameters (see Appendix B). In the following, the pre-processing for the GIDAS data and the PCM data is described. Data from the selected accidents were read out from GIDAS and PCM and converted and saved into a Matlab structure file (Figure B.1).

The following information was obtained from the GIDAS database:

- accident type
- identification of vehicle (e.g. which vehicle number is turning, which is going straight)
- time of the accident and light conditions
- environmental character (e.g. how built up the surrounding area is)
- precipitation
- cloud density
- sight distance when fog is present
- speed limit
- road surface type and condition
- driver age, gender, and physical condition.

The following information was obtained from the PCM database:

- vehicle specifications (e.g. wheelbase, trackwidth, center of gravity position, intertias)
- vehicle trajctories in time-series format
- road edges, lane and road marking
- objects that potentially can act as sight obstruction.

When both GIDAS and PCM data have been loaded from the database, plausibility checks were conducted to ensure that is possible to generate physical models out of the data; for example, the wheelbase must be shorter than the vehicle length and the trackwidth must be smaller than the vehicle width. The center of gravity position was verified with data from NHTSA's measured vehicles inertial parameters (Heydinger et al., 1999). Further validation of the input data was done by data segregation, for example by data separation between turning and straight heading vehicle, followed by a comparison of the expected and actual cumulative distribution functions. Finally, additional parameters such as effective tire rolling radius and tire cornering stiffness were computed.

As the trajectories in the PCM database are coded in discrete positions in 10 millisecond time steps and the simulation is run in 1 millisecond time steps, intermediate positions were derived by piecewise polynomial interpolation of filtered original positions. Further, the trajectories of the vehicles coded in the PCM database end when squared boundary boxes around vehicles or vulnerable road users interfere with each other. When an AEB system is influencing vehicle kinematics, vehicles may hit each other in different areas or pass each other. Thus, it is necessary to extend the given trajectories. The trajectories were extrapolated by carrying forward the change of distance and heading angle in local polar coordinates.

To run a pre-crash simulation, it is necessary to set parameters for general processing (Figure B.2), sensor models (Figure B.3), algorithm design (Figure B.4), and driver models (Figure B.5). Parameters from the databases such as vehicle characteristics, trajectories, and environment definitions and parameters set in the GUIs were forwarded to Simulink for processing.

Processing

For the processing of the pre-crash simulation, six types of models were defined in Simulink: a driver model, vehicle model, sensor model, path prediction and threat assessment model, decision model, and environment model. The signal flow between the models is shown in Figure 5.

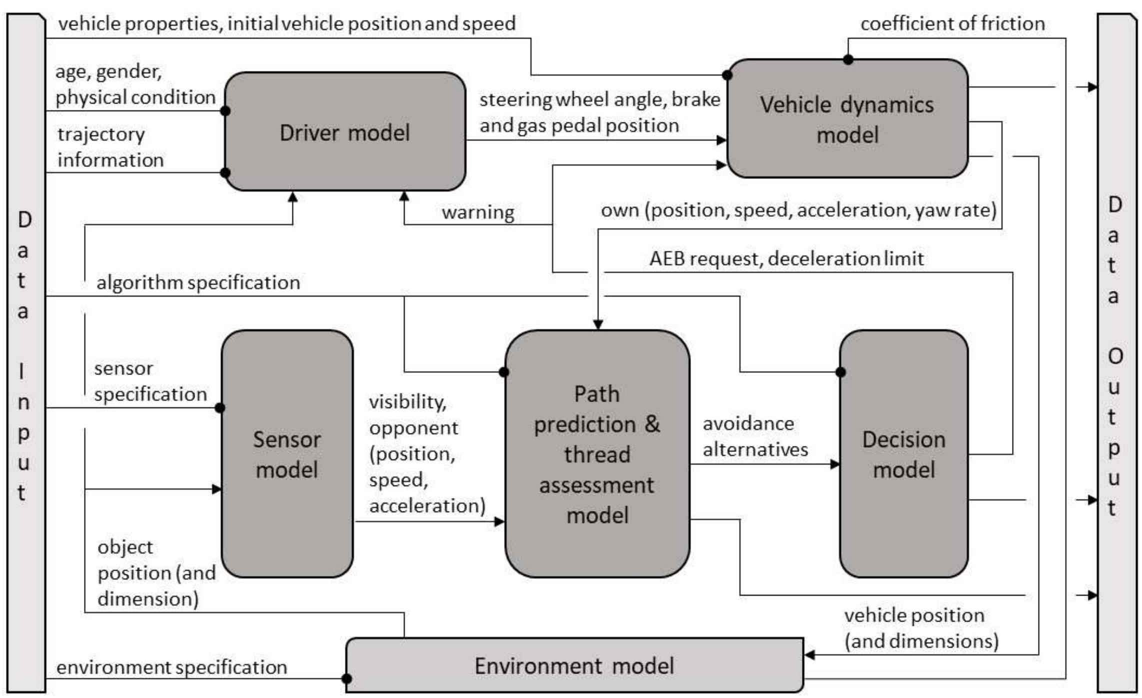

Figure 5: Data flow between simulation models. Parameter-flow (time-independent) is marked with ——● and variable-flow (time-dependent) with ——▸.

Driver model

As long as no intervention from the active safety system is issued, the driver model has a path- and speed-follow task: to convert the trajectory of the vehicle into a steering wheel angle, and gas and brake pedal position. In a first approach the driver model was designed as an inverse plant model of the vehicle model (open-loop control / feedforward). This could be done as the model of the vehicle is known. However, difficulties arose when an AEB intervention was issued and the vehicle was braked while the driver model still had control over the lateral dynamics via the steering input. For this reason, two separate closed-loop (feedback) controllers were designed, a longitudinal dynamics controller for the speed profile and a lateral dynamics controller for the path.

A PID controller was used to control the vehicle speed. Control variables for gas pedal $u_{throttle}$ and brake pedal u_{brake} were computed separately:

$$u_{throttle}(t) = K_p \cdot e(t) + K_i \cdot \int_0^t e(t')dt' + K_d \cdot \frac{de(t)}{dt}, \tag{12}$$

$$u_{brake}(t) = -\left(K_p \cdot e(t) + K_i \cdot \int_0^t e(t')dt' + K_d \cdot \frac{de(t)}{dt}\right), \tag{13}$$

with e as error value of the vehicle speed and K_p, K_i, and K_d as the coefficients of the proportional, integrated, and differential terms, respectively.

The logic for gas and brake pedal is set as follows:

- If current gas pedal position plus $u_{throttle}(t)$ is greater than/equal to zero, then the new gas pedal position is current gas pedal position plus $u_{throttle}(t)$. The brake pedal position is set to zero.
- Otherwise, gas pedal is set to zero and the new brake pedal position is current pedal position plus $u_{brake}(t)$.

Both gas and brake pedal position are limited to the range [0;1].

For the lateral controller, a linear bicycle model is used to predict the position of the vehicle at a specific look-ahead time. The current curvature κ of the path is calculated as follows:

$$\kappa = \delta \Big/ \left(WB + \left(\frac{N_f}{c_f} - \frac{N_r}{c_r}\right) \cdot \frac{{v_x}^2}{g}\right), \tag{14}$$

with δ as the average of the left and right road wheel angle, WB as the wheelbase, N_f and N_r as the normal force on the front and rear axle respectively, c_f and c_r as the cornering stiffness of the front and rear tire respectively, v_x as the longitudinal speed, and g as the gravitational acceleration.

It is assumed that the curvature $\kappa = 1/R_t$ (with R_t being the turning radius) is tangentially aligned to the longitudinal axis at the center of gravity (0,0), see Figure 6.

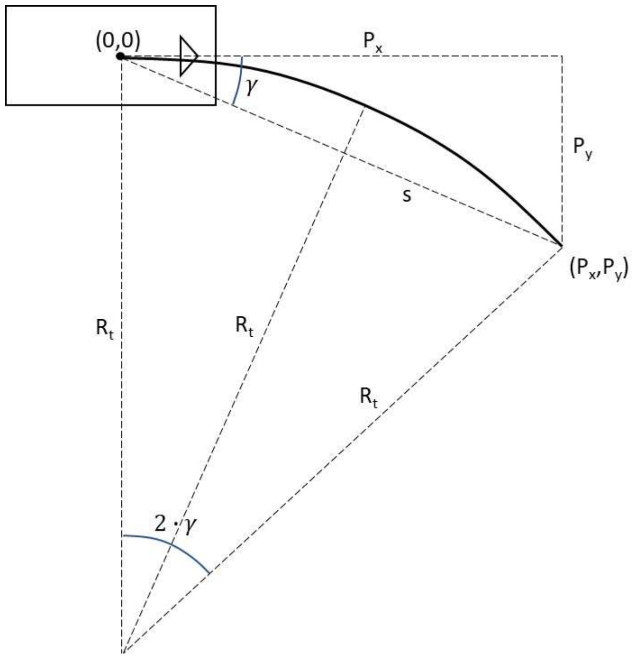

Figure 6: Definition of (P_x,P_y) by look-ahead distance s and steering curvature κ=1/R_t

Then the point (P_x,P_y) that will be reached at a look-ahead distance s is computed:

$$\begin{pmatrix} P_x \\ P_y \end{pmatrix} = s \cdot \begin{pmatrix} \cos(\gamma) \\ \sin(\gamma) \end{pmatrix}, \tag{15}$$

with:

$$\gamma = \operatorname{asin}\left(\frac{s \cdot \kappa}{2}\right), \tag{16}$$

where γ is the angle between the longitudinal axis of the vehicle and point (P_x,P_y).

The nearest point to (P_x,P_y) on the trajectory is then identified as ($P_x{}'$,$P_y{}'$) and the required curvature κ' to ($P_x{}'$,$P_y{}'$) is computed:

$$\kappa' = \frac{2 \cdot P_x{}'}{\left(P_x{}'\right)^2 + \left(P_y{}'\right)^2}. \tag{17}$$

The new average road wheel angle δ' is then calculated from the required curvature κ' according to *Eq. (14)*:

$$\delta' = \kappa' \cdot \left(WB + \left(\frac{N_f}{c_f} - \frac{N_r}{c_r}\right) \cdot \frac{{v_x}^2}{g}\right). \tag{18}$$

The lateral controller is only valid for $P_x \geq P_y$ and $P_x > 0$. To make the controller more efficient, the look-ahead distance was set to be speed dependent with a minimum of one meter. The road wheel angle was limited to +/- 0.44 radians.

When a warning is issued, the driver model sets the maximum value of one for the brake pedal after a reaction time randomly selected from a specified time distribution (Figure B.5).

Driver warning was not considered in this thesis. The trajectory following part of the driver model was verified by comparison of the input trajectory and the simulated trajectory.

Vehicle model

The vehicle dynamics model was modelled in the software Dymola using the Modelica language (Fritzson, 2015). For the usage in Simulink, it was translated to a Functional Mockup Unit (FMU) for co-simulation using the CVODE solver for stiff and non-stiff ordinary differential equation systems (Blochwitz et al., 2012). The implementation in Simulink is done via Functional Mockup Interface (FMI). The vehicle dynamics model uses the coordinate system according to ISO8855:2011. It is initialized before the start of each simulation with specific properties such as weight, trackwidth, wheelbase, center of gravity position, inertias around the main axes, tire specification, and the initial start position, orientation, and velocity.

The vehicle model started as a linear model with a non-linear tire model. The first simulations of real-world accidents showed that it was not always possible to follow the pre-crash trajectories in cases where the driver braked and steered immediately before the crash. The vehicle model was then updated to a two-track model with a 'semi-empirical' brush tire model. The tire model is semi-empirical in that the combined-slip characteristics are based on the theory of brush-model mechanics, while the pure slip part was modelled empirically (Svendenius, 2007).

To enable steering with fully engaged brakes, an ABS was defined. Additionally, a Traction Control System (TCS) and an ESC system were implemented to ensure that the vehicle is capable of following a given trajectory.

Suspension and damping were added to achieve a more realistic load transfer. The current vehicle dynamics model is structured in four sub-models: chassis, suspension, steering, and 'brakes, propulsion, and tires' (Figure 7).

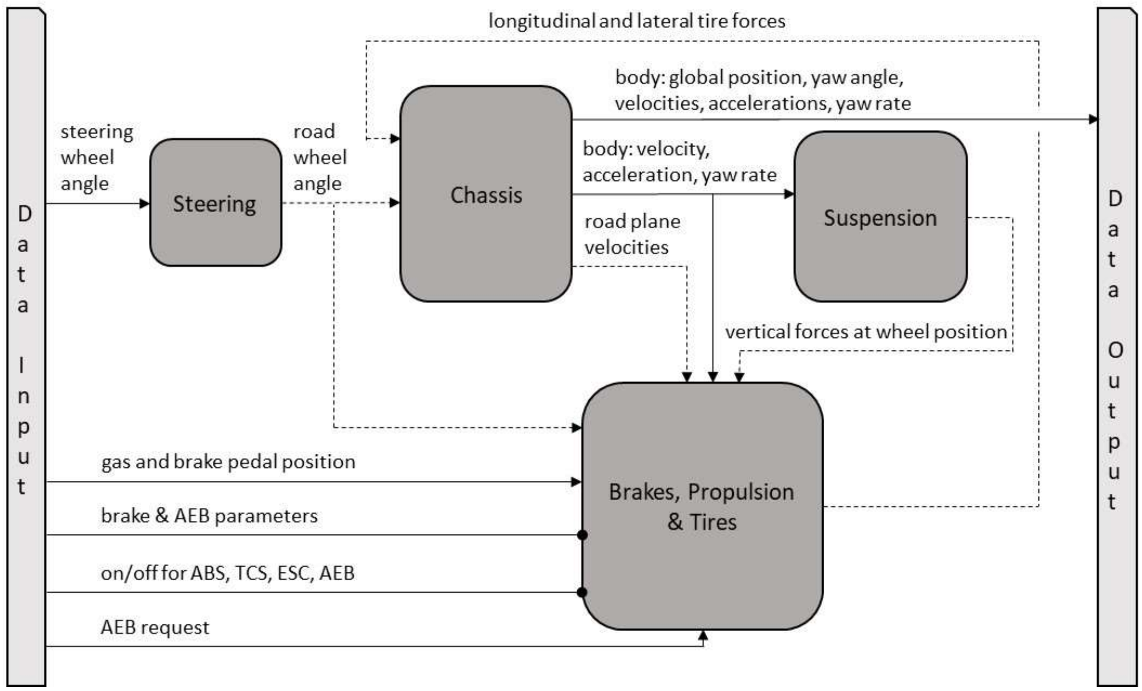

Figure 7: Top-level-structure of the vehicle dynamics model. Parameter-flow (time-independent) is marked with ——● and variable-flow (time-dependent) with ——▸. Vectorized connection statements are shown with a dashed line.

The 'chassis' model contains equations for the sum of forces in x- and y-direction, the sum of momentum in around the x-, y-, and z-axis in the vehicle coordinate system, and the tire velocities in the x- and y-direction in the local tire coordinate system.

The 'suspension' model formulates the equations for the sum of forces in the z-direction including the load transfer forces due to roll and pitch.

The 'steering' model converts the steering wheel angle into a road wheel angle.

The 'brakes, propulsion, and tires' model contains as the name indicates sub-models for brakes, propulsion, tires, road interface, and AEB, ASB, TCS, and ESC controllers (Figure 8).

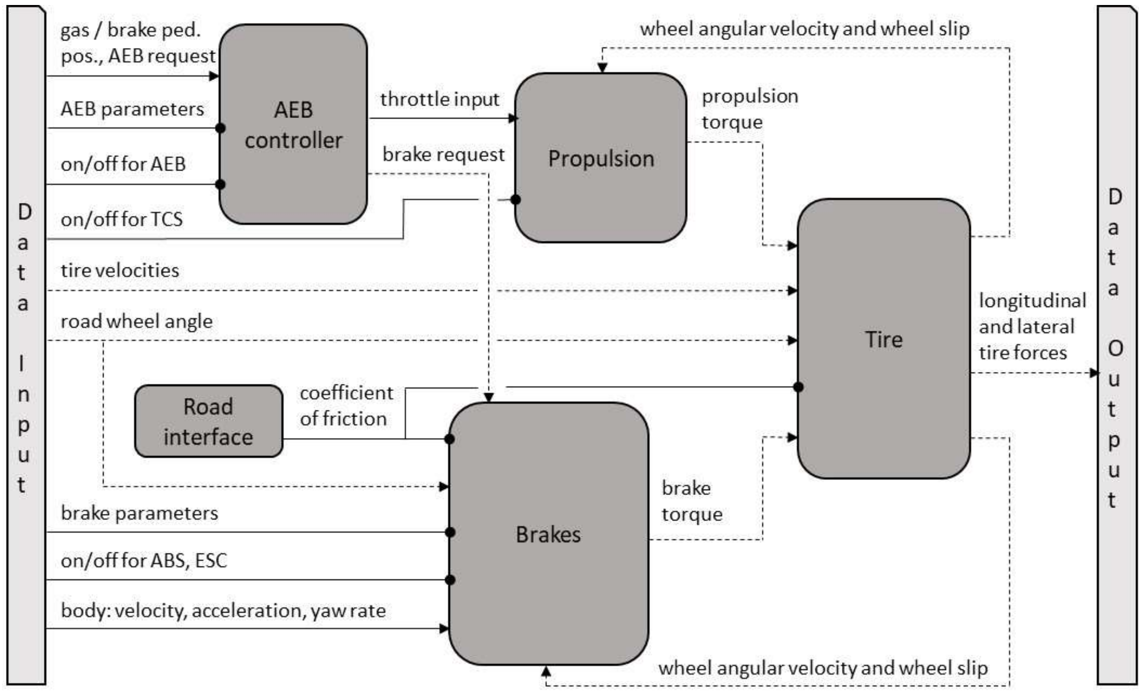

Figure 8: Structure of the brakes, propulsion, and tires model. Parameter-flow (time-independent) is marked with ⟶● and variable-flow (time-dependent) with ⟶. Vectorized connection statements are shown with a dashed line.

The 'road interface' model propagates the current coefficient of friction information to the tires and the ESC controller in the brakes model.

The 'tire' model defines the relation between tire slip and forces in the x- and y- directions in the local tire coordinate system. It is commonly assumed that tire forces in the x,y-plane reach their maximum at the transition from partial to full sliding. In the semi-empirical brush tire model, this point is reached when the normalized slip, the ratio between actual slip and limit slip, reaches unity (in the following called 'optimum slip'). At full sliding, when the normalized slip is greater than unity, the adhesive tires forces become zero. To represent the tire more accurately at higher slip values, velocity dependency was included in the friction coefficient (Svendenius, 2007).

For the tire slip, physical definitions according to *Eq. (19)* and *Eq. (20)* are used:

$$S_x = -\frac{v_{wx} - \omega \cdot R_{we}}{\max(v_{wx}, \omega \cdot R_{we})}, \tag{19}$$

$$S_y = -\frac{v_y}{\omega \cdot R_{we}}, \tag{20}$$

where S_x and S_y are the longitudinal and lateral slip, respectively, v_{wx} and v_{wy} are the longitudinal and lateral wheel velocities, ω is the wheel angular velocity, and R_{we} is the effective rolling radius. Note, that different definitions for S_x and S_y have been established. To avoid a singularity of S_x and S_y, the angular velocity ω was set to a minimum value greater than zero.

The 'propulsion' model translates the gas pedal position into a wheel torque on either the front axle, rear axle, or both axles. For all studies in this thesis the propulsion torque was sent to the front axle. Only forward propulsion was considered; the vehicle dynamics model is not developed for reversing.

The model contains the 'TCS controller', which limits the slip of the front wheels close to the optimum slip to achieve maximum traction forces. In case the actual slip exceeds the optimum slip during acceleration (acceleration creates positive slip due to slip convention in *Eq. (19)* and *Eq. (20)*), traction control becomes active. A proportional controller was specified to reduce the propulsion torque. The error signal is set to zero in case the actual slip falls below the optimum slip.

The 'AEB controller' acts as a switch between gas and brake pedal input and AEB system input. The AEB system input comprises two Boolean inputs stating whether AEB and brake acceleration limit is active or not. If brake acceleration limit is true, then the specified brake limitation value is considered. AEB, ESC, ABS, and TCS can be switched on or off. The model is prepared to accept a road wheel angle on the rear axle wheels; the value however is set to zero. Thus, the vehicle is only steered by the front axle wheels.

The 'brakes' model itself contains four models: 'brake rate limiter', 'ABS controller', 'ESC controller', and 'actuator' (Figure 9).

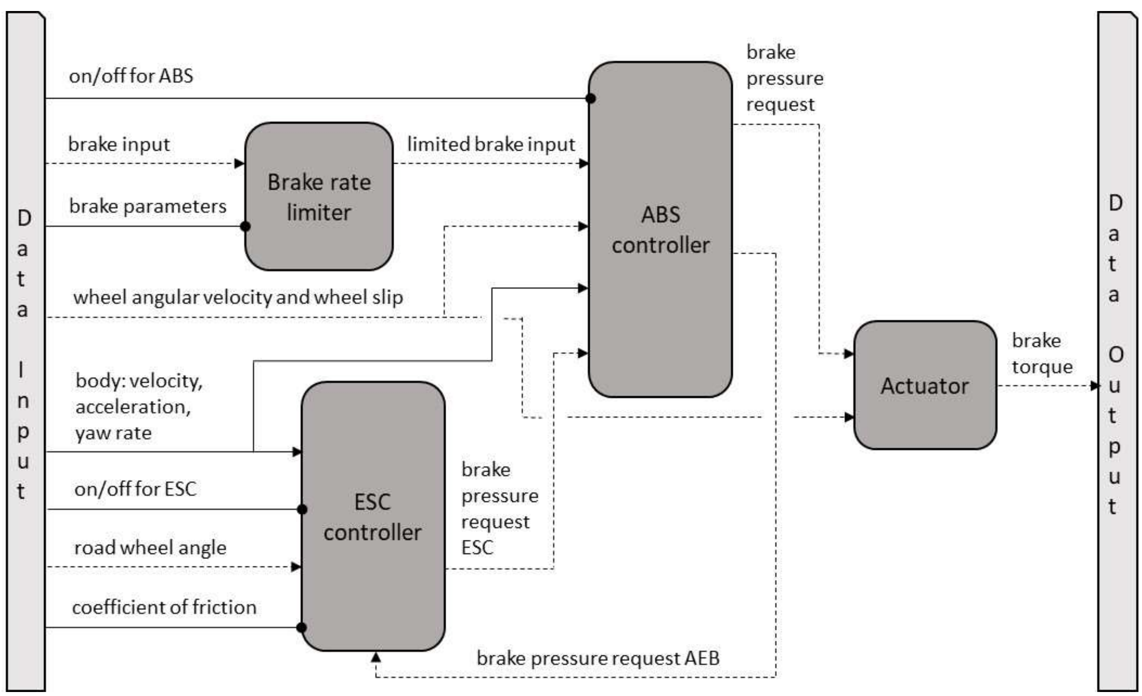

Figure 9: Structure of the brake model. Parameter-flow (time-independent) is marked with ——● and variable-flow (time-dependent) with ——▸. Vectorized connection statements are shown with a dashed line.

The 'brake rate limiter' model receives the parameters for brake delay and brake jerk defined in the pre-processing (Figure B.4).

Similar to the 'TSC controller' model, the 'ABS controller' model was specified to limit the negative slip of the tire when braking to the optimum slip, where maximum traction forces can be achieved. In case the actual slip falls below the optimum slip, the system error is reduced by a PI-controller. The system error is set to zero in case the actual slip exceeds the optimum slip.

The 'ESC controller' model was implemented using a linear bicycle model to estimate the reference yaw rate. If the difference between actual yaw and reference yaw exceeds +0.025 and -0.025 radians/s, the 'ESC controller' brakes either the front right or front left wheel, respectively, to reduce oversteering. Understeering is not handled by the ESC controller.

The 'actuator' model computes the brake torque based on axle position, wheel rotational velocity, brake pressure, brake disk diameter, brake pad area, brake pad coefficient of friction, and brake caliper piston diameter.

The verification of the vehicle model was done in two steps: In a first step, specific test cases involving vehicle acceleration, deceleration, and steering were generated in Dymola. The behavior of the vehicle in the test scenarios was analyzed and if necessary, the model was corrected. In a second step, an interface to CarMaker was built (Figure B.2), so that the vehicle dynamics simulation could be conducted with a generic CarMaker model using identical properties such as dimension, wheelbase, trackwidth, and center of gravity position. Though the validation against similar specified CarMaker models is not a scientific proof of model correctness, alternatives are limited: For each simulated scenario, the vehicle models are parameterized according to the actual vehicle specification in the data source. As these number up to 730 in one study, detailed validations against, for example, real vehicle behavior is not feasible.

Sensor model

The 'sensor' model represents an environment sensor and is based on a mathematical description of the two-dimensional sensing area by field-of-view (opening angle) and range (minimum and maximum sensing distance). The sensor can be placed at any position relative to the center of gravity with a defined rotation angle from the longitudinal vehicle axis. A sampling frequency is specified to define the number of samples per second where the sensor retrieves information from the environment (Figure B.3).

In the planar environment, an object is in general represented by a polyline and a vehicle or person is represented by a surrounding rectangular box.

Figure 10 shows the structure of the sensor model. The 'in field-of-view' model computes subsequently if any edge of an object is within the field-of-view and if this edge is obstructed by the object itself or by another object. A vehicle becomes visible to the sensor if either one edge or one side of the surrounding rectangle is within the sensing area. The former definition is used for a radar sensor, the latter for an image sensor such as a monovision or stereovision camera. With the given sampling frequency, the sensor registers the position of objects in the 'data logger' model. Two samples are necessary to compute a velocity; with three samples the acceleration can be computed. After a specific number of continuous samples of position retrieval, specified in the pre-processing, an object is tracked.

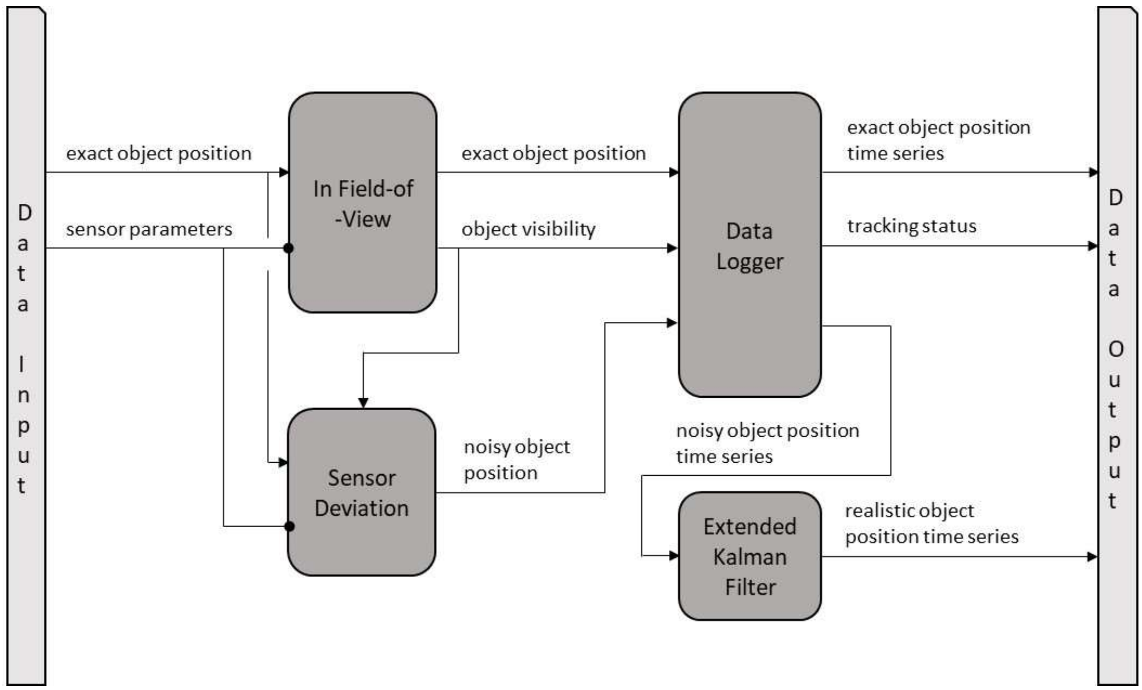

Figure 10: Structure of the sensor model. Parameter-flow (time-independent) is marked with ⟶● and variable-flow (time-dependent) with ⟶.

The sensor can either retrieve the exact object position (optimal sensing) or the object position with added white Gaussian noise (realistic sensing). The noise is derived from the standard deviation of angle and range measurements for each type of sensors in the 'sensor deviation' model. An 'Extended Kalman Filter' (EKF) model was developed following Danielsson (2010) to reduce the noise in the measurements to retrieve realistic object position time series data. However, divergence of the EKF was observed in the application of many real-world pre-crash scenarios. Most likely the divergence was introduced due to a first-order linearization of the non-linear system. Here, an unscented Kalman filter (UKF) could have been a valid alternative. Using an unscented transformation, posterior mean and covariance can be captured accurately to the third-order and thus improve the performance of the UKF (Wan and Van Der Merwe, 2000).

For the studies in this thesis only optimal sensing was utilized; however, depending on the weather and light conditions, the sensor range was reduced. It was further assumed that, alongside position, velocity and the acceleration, also the orientation and thus the yaw rate of tracked objects can be identified.

The sensor model was verified by visualization of the sensor field-of-view and color-coding the visibility of objects in it (Figure 11). Further, in the analysis mode all sensor signals were stored and available for analysis (Figure B.2).

Path prediction and threat assessment model

In general, path prediction means a forecasting of the geometric path without time parameterization. However, if time parameterization is included, a trajectory is generated. The algorithm used in the appended papers estimates the vehicle's upcoming trajectories based on the assumption of constant turn rate and acceleration (CTRA). As such, when lateral motion is present, the model assumes that the vehicle is following a clothoid. Schubert et al. (2008) showed that a CTRA model delivered the least error for trajectory prediction, especially in urban areas, compared to models based on either constant velocity or constant turn rate and velocity.

When the predicted trajectories of the ego and tracked vehicle intersect in the time-space, a collision course is identified, and the tracked vehicle becomes a target vehicle. With the identification of a collision course, escape alternatives are investigated. The alternatives comprise: ego vehicle braking, ego vehicle steering to the left or right, target vehicle braking, and target vehicle steering to the left or right (Figure 11).

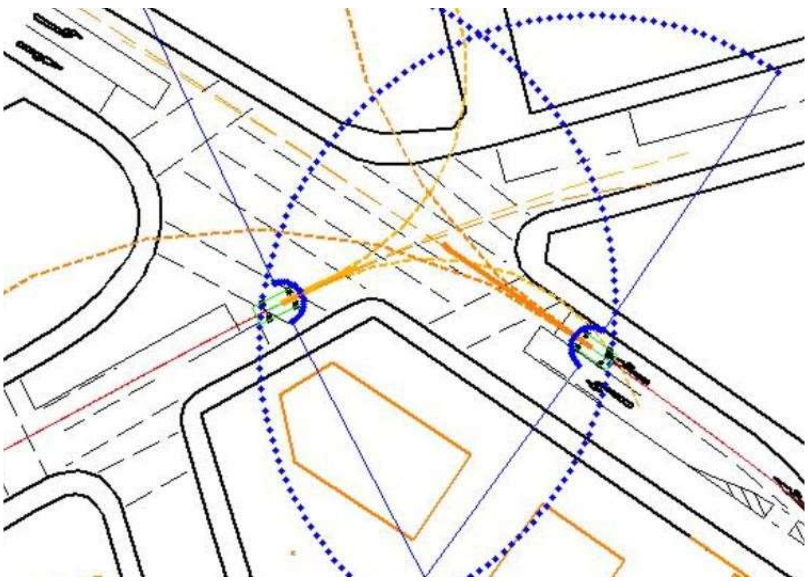

Figure 11: Visualization of escape alternatives when vehicles are on conflict course in a Straight Crossing Path (SCP) scenario. Escape by braking is shown with a thick orange line. Escape by J-steering to the left and right is shown by a short-dashed orange line. The path prediction is visualized with a long-dashed orange line.

Avoidance by braking and steering is defined by three parameters: a) longitudinal vehicle acceleration, b) lateral vehicle acceleration, and c) steering wheel rate. For braking, a longitudinal vehicle acceleration threshold is considered. For steering, two alternative maneuvers are selectable: In the J-steering maneuver, the steering wheel angle is increased with the specified steering wheel rate until a lateral acceleration threshold is reached. In the S-steering maneuver, a sinusoidal steering input is considered so that a pre-defined lateral offset to the planned path is achieved. For all the avoidance alternatives, the thresholds can be set either on comfort boundaries or physical limits (Figure B.4).

When a specific longitudinal and lateral acceleration is reached during driving, people feel uncomfortable (Bärgman et al., 2015b). The threshold is termed the comfort zone boundary and is subjective to each car occupant (Figure 12).

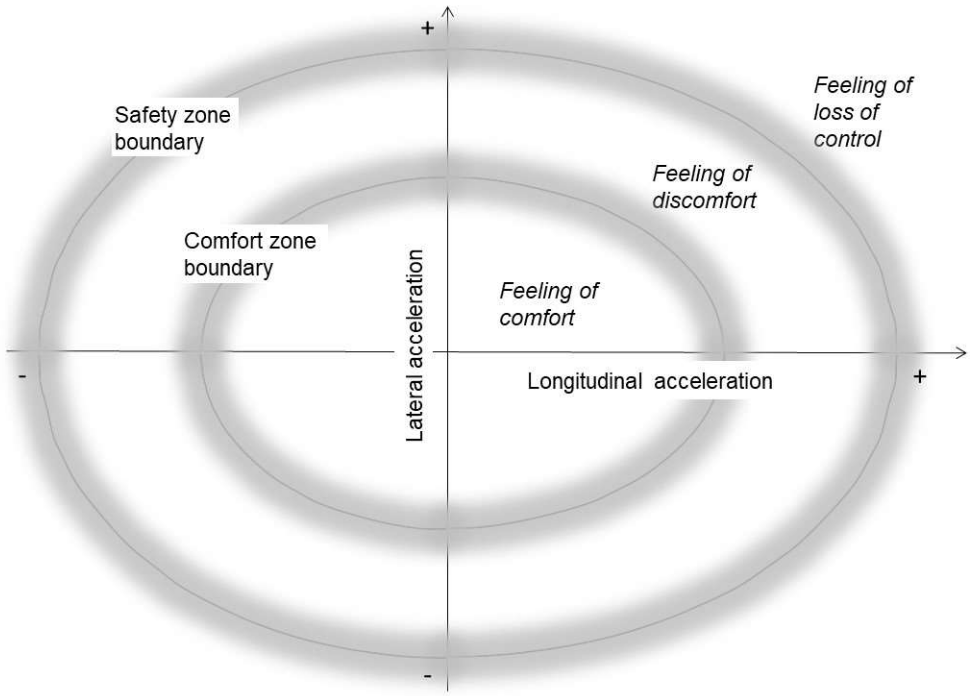

Figure 12: Qualitative representation of comfort zone boundaries and safety zone boundaries depending on longitudinal and lateral acceleration. Boundaries are not sharp but have a transition band.

Normal driving usually takes place below the comfort zone boundary in the area of feeling of comfort (Ljung Aust and Dombrovski, 2013). Under time pressure or other forms of stress, car drivers may exceed the threshold into the area of feeling of discomfort. This area is confined by the safety zone boundary. The safety zone boundary is also a subjective threshold and does not necessarily coincide with the physical limits. It is furthermore the threshold where the driver is no longer capable of having safe control over the vehicle; a loss of control is probable. Bärgman et al. (2015b) additionally defined a dread-zone boundary lying between the comfort zone boundary and the safety zone boundary. This zone boundary is rarely exceeded by car drivers. Paper II investigated the effect of comfort zone boundary settings. Further, for Papers II and IV the exceedance of comfort zone boundaries was used as an enabler for AEB intervention.

Whereas the physical limit for braking only considers the coefficient of friction of the road-tire interface, for steering vehicle stability the maximum possible road wheel angle (the angle of the steerable wheel in the vehicle coordinate system) are also taken into account.

The approach of avoidance alternatives within comfort boundaries or physical limits is similar to the work of Kaempchen et al. (2009), Brännstrom et al. (2010), and Dörffel (2011). One essential input is an estimate for the coefficient of friction. For all papers in this thesis it was assumed that the true coefficient of friction of the road-tire interface is known.

Based on the theory of a field in which the car can safely travel (Gibson and Crooks, 1938), a safety zone around the rectangle enclosing the vehicle outer shape was introduced. Any intrusion into the safety zone from the outside would be assessed as uncomfortable by the driver. A similar approach has been taken by Petrovskaya and Thrun (2008). For all papers in this thesis, the safety zone was set to 20 cm all around the vehicle.

Verification of the path prediction and threat assessment was done by visualization of the predicted paths and escape alternatives (Figure 11).

<u>*Decision model*</u>

The ‘decision’ model investigates whether any of the escape path alternatives of the ego vehicle or the target vehicle will be successful in avoiding a crash. A parameter setting in the algorithm GUI determines which of the escape path alternatives are considered for decision making. Additionally, ego vehicle speed and gas and brake pedal input can be included in the decision-making process. In Paper II, the effect of inclusion of different escape path alternatives was investigated. In Papers III and IV, AEB intervention was activated where none of the escape alternatives leads to crash avoidance. For warnings, the decision making is based on different sets of escape alternatives (Sander and Lubbe, 2016).

<u>*Environment model*</u>

Through the ‘environment’ model the information on the road infrastructure and surrounding objects is shared. As environment information is retrieved through different kind of sensors, the level of detail of the environment model and the sensor model must reflect each other’s requirements. The environment model provides information regarding the coefficient of friction of the road-tire interface and the position and orientation of other surrounding vehicles. The PCM data includes only trajectory information on the conflict-involved vehicles, thus the constitution of the surrounding moving traffic is not available. Stationary traffic, parked vehicles and buildings are considered as potential sight obstructions. Road edge and road marking information was not used due to lack of completeness in the PCM data.

The environment model was verified by visualization of road marking, road edges, and objects such as other vehicles, houses, and fences, and compared against a subsample of scene sketches.

<u>*Simulation results*</u>

At the end of each simulation, the following data is stored as time-series data for each vehicle: position and orientation, longitudinal and lateral velocities, yaw rate, road wheel angle, collision status, collision course status, TTC, escape alternatives status, signal status for AEB and warning, and the escape trajectories.

Post processing

When the pre-crash simulation of all selected cases has finished, the results are post-processed to generate necessary information for further analysis. Where a collision occurred, the process includes the computation of the contact point in the vehicle coordinate system, the collision angle in a global coordinate system, and the determination of impact side and speed. This information is then used to conduct a crash computation.

3.2.5 Crash Computation

The crash computation determines two important characteristics: The magnitude (delta-V) and the direction (principal direction of force, PDOF) of the change of velocity during the impact. In GIDAS, the principal tool for accident reconstruction is the software PC-Crash, which uses the Kudlich-Slibar rigid body impulse model among other less frequently used models. To validate and verify the simulation results against the reconstruction results coded in GIDAS, the Kudlich-Slibar model was utilized for crash computation. The post-crash trajectories were not calculated.

The Kudlich-Slibar model is a momentum-based collision model allowing for both sliding and full impact (Kudlich, 1966). It postulates that the momentum is exchanged in an infinitesimal time step at the time of maximum compression. The pre-crash simulation is stopped when the outer rectangles enclosing the vehicles intersect with each other (collision condition). The position of the vehicles at maximum compression is computed by moving the vehicles along their velocity vector for a calculated displacement as described below (Figure 13A).

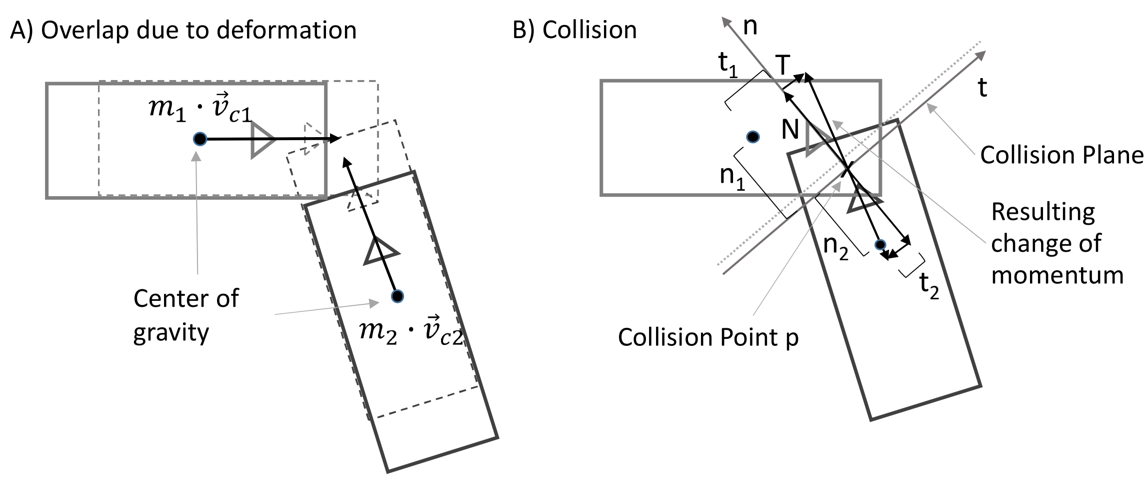

Figure 13: A) Displacement of vehicle bounding rectangles along velocity vector to compute position at maximum compression. B) Computation of the change of momentum during the collision.

A simple model is used to derive the displacement d from the longitudinal speed v_x:

$$d = 1 - \mathrm{e}^{-\left(v_x/k\right)}, \tag{21}$$

with $k = 27.4$. The parameter k was chosen to obtain overlap positions that approximately correspond to real-life crashes.

The orientation of the impact plane is aligned to the line through two intersection points (dotted line in Figure 13B). Similar to the default setting of the reconstruction software PC-Crash (Cliff and Montgomery, 1993; Steffan, 2009), the plane is then shifted parallelly through the impact point p, which is represented by the center of gravity of the overlapping area of the cars (continuous line in Figure 13B). A coordinate system t-n-z (tangential-normal-z) is placed with the origin at the collision point and with the t-axis parallel to the impact plane. A similar approach was used by Kolk et al. (2016).

The equations for conservation of momentum of both vehicles are:

$$m_1(v'_{c1t} - v_{c1t}) = T, \tag{22}$$

$$m_1(v'_{c1n} - v_{c1n}) = N, \tag{23}$$

$$m_2(v'_{c2t} - v_{c2t}) = -T, \tag{24}$$

$$m_2(v'_{c2n} - v_{c2n}) = -N, \tag{25}$$

$$I_{1z}(\omega'_{1z} - \omega_{1z}) = T \cdot n_1 - N \cdot t_1, \tag{26}$$

$$I_{2z}(\omega'_{2z} - \omega_{2z}) = -(T \cdot n_2 - N \cdot t_2), \tag{27}$$

where:

- m_i is the mass of vehicle i
- v_{cit} and v_{cin} are the immediate pre-crash velocity of the center of gravity of vehicle i in the t-direction and n-direction, respectively
- v'_{cit} and v'_{cin} are the immediate post-crash velocity of the center of gravity of vehicle i in the t-direction and n-direction, respectively
- T and N are the change of momentum in the t-direction and n-direction, respectively
- I_{iz} is the inertia of vehicle i around the z-axis
- ω_{iz} and ω'_{iz} are the immediate pre-crash and post-crash rotational velocity of vehicle i around the z-axis, respectively
- t_i and n_i are the distance between the center of gravity of vehicle i and the t-axis and n-axis, respectively.

The velocities of the impact point v_p in the *t*,*n*,*z* coordinate system are computed from the velocities of the centers of gravity v_c (Figure 13B) as follows:

$$v_{p1t} = v_{c1t} + \omega_{1z} \cdot n_1, \tag{28}$$

$$v_{p1n} = v_{c1n} + \omega_{1z} \cdot t_1, \tag{29}$$

$$v_{p2t} = v_{c2t} + \omega_{2z} \cdot n_2, \tag{30}$$

$$v_{p2n} = v_{c2n} + \omega_{2z} \cdot t_2, \tag{31}$$

where v_{pit} and v_{pin} are the velocities of the impact point of vehicle i along the t-axis and n-axis, respectively.

The speed of vehicle 1 and vehicle 2 at point p is then defined as:

$$v_{pt} = v_{p1t} - v_{p2t}, \tag{32}$$

$$v_{pn} = v_{p1n} - v_{p2n}. \tag{33}$$

The following definitions are introduced to simplify the equation for the change of momentum in the tangential (T) and normal (N) directions:

$$c_1 = \frac{1}{m_1} + \frac{1}{m_2} + \frac{{n_1}^2}{I_{1z}} + \frac{{n_2}^2}{I_{2z}}, \tag{34}$$

$$c_2 = \frac{1}{m_1} + \frac{1}{m_2} + \frac{{t_1}^2}{I_{1z}} + \frac{{t_2}^2}{I_{2z}}, \tag{35}$$

$$c_3 = \frac{t_1 \cdot n_1}{I_{1z}} + \frac{t_2 \cdot n_2}{I_{2z}}. \tag{36}$$

The change of momentum, (T) and (N), is then derived from Eq. (22) to Eq. (31) using Eq. (32) to Eq. (36):

$$T = \left(\frac{v_{pn} \cdot c_3 + v_{pt} \cdot c_2}{{c_3}^2 - c_1 \cdot c_2}\right) \cdot (1 + \varepsilon), \tag{37}$$

$$N = \left(\frac{v_{pn} \cdot c_1 + v_{pt} \cdot c_3}{{c_3}^2 - c_1 \cdot c_2}\right) \cdot (1 + \varepsilon), \tag{38}$$

where ε is the coefficient of restitution ranging from 0 to 1 and is defined based on the relative speed of the vehicles (Bürger et al., 1998):

$$\varepsilon = {}^{2.5}\!/_{(v_{c1} - v_{c1})}. \tag{39}$$

The coefficient of friction between the cars is set to $\mu = 0.8$ as it gave the best results in model validation.

If $T \leq \mu \cdot N$, then the vehicles get stuck during the collision.

If $T > \mu \cdot N$, then the vehicles slide along each other:

$$N = \left(\frac{v_{pn}}{\mu \cdot c_3 + c_2}\right) \cdot (1 + \varepsilon), \tag{40}$$

$$T = \mu \cdot N. \tag{41}$$

The resulting change of momentum P for each vehicle is:

$$P = m_{1,2} \cdot DV_{1,2} = \sqrt{T^2 + N^2}, \tag{42}$$

where DV_1 and DV_2 are the changes of velocity during the impact (delta-V) and m_1 and m_2 are the masses of vehicle 1 and 2, respectively.

The resulting principal direction of force is:

$$PDOF_{tnz} = -atan\left({}^{T}\!/_{N}\right). \tag{43}$$

As the $\mathrm{PDOF_{tnz}}$ values are computed in the t,n,z-coordinate system, a transformation is conducted to show them in the respective vehicle-specific coordinate system.

After the crash computations are conducted, all results are exported for further statistical analysis in the statistics software R.

The impact model was verified for a random selected sample of car-to-car SCP scenarios. The vehicles were positioned relative to each other using the contact point and the impact angle. The initial momentum was calculated from vehicle mass and speed, assuming that the direction of the momentum was along the vehicle's longitudinal axis. The calculated delta-V and PDOF were compared to the values coded in GIDAS.

3.2.6 Statistical Analysis

Besides the quantitative statistics used to describe the data, identify coding mistakes and investigate variable correlations, four main applications of statistical methods have been used throughout this thesis:

1) Weighting adjustment
2) Cluster analysis
3) Market penetration
4) Injury probability

Weighting adjustment

Ideally, a selected data sample is a perfect representation of the population it was taken from. This is however rarely the case, as non-response may lead to over- or under-representation of specific characteristics. In accident data collection, non-response means that some types of accidents might not be reported, for example because of lower injury severity. Further, data may be biased because of the region or time period sampled. Though accident data collection does not have the problem of self-selection (found in online surveys, for example), accident participants can still decline the usage of their personal data. Reliable conclusions cannot be drawn from a biased data sample; it is thus necessary to correct for any lack of representativeness.

Weighting adjustment is a commonly applied method to minimize bias (Hautzinger et al., 2004). Auxiliary variables for weighting adjustment are selected based on their correlation with variables for which the results should be representative. A common technique is *hyper-cube* or *n-dimensional* weighting, where *n* stands for the number of auxiliary variables. For each combination of categories of the auxiliary variables, a cluster is created in the sample and the population. By comparing the relative frequencies ($freq$) in the sample (index s) and population (index p), a weight is computed for each cluster (index $[cl]$) (*Eq. (44)*). To avoid incorrect interpretation of weighted data, especially when methods of inferential statistics are used, the weights are normalized so that the sample size remains the same after weighting:

$$weigth_{s[cl]} = \left(\frac{freq_{p[cl]}}{freq_{p[total]}}\right) \Big/ \left(\frac{freq_{s[cl]}}{freq_{s[total]}}\right). \tag{44}$$

A weighting adjustment was conducted in Papers II to IV to make the simulation results based on GIDAS and PCM data representative for Germany. As GIDAS is a sample of the accidents recorded in the German national accident statistics and PCM in turn is a sample of the GIDAS, a two-stage weighting was applied: First, weighting PCM data to GIDAS data, and second, weighting GIDAS data to the national accident statistics. With this, different sets of auxiliary variables that needed weighting in PCM and GIDAS were selected. Detailed information on data weighting can be found in the supplementary information of Paper IV.

Cluster analysis

Though different methods for data clustering have been developed, the common goal is to identify groups where the objects in one group are more similar to each other than to those of other groups. This is especially valuable to identify patterns and compress data. In this thesis, three different cluster algorithms are utilized to identify internal data structures of SCP and LTAP/OD accidents and thus, to identify possible test scenarios: Hierarchical clustering and partitioning around medoids (where centroids are restricted to members of the data set) as representatives of distance- or similarity-based clustering, and latent class clustering as a representative of model-based clustering.

For distance-based clustering, Gowers coefficient of similarity was used, as it allows for distance calculations where dichotomous, quantitative, and qualitative variable are present in a dataset (Gower, 1971). The similarity coefficient between i and i' is defined as the average score taken over all possible combinations:

$$S_{ii'} = {\sum_{j=1}^{J} s_{ii'j}} \Big/ {\sum_{j=1}^{J} \delta_{ii'j}}, \tag{45}$$

where $s_{ii'j}$ = 1 when the values of a variable match and $s_{ii'j}$ = 0 when there is a mismatch for dichotomous and qualitative variables, and

$$s_{ii'j} = 1 - \left(|y_i - y_{i'}| \Big/ R_j \right) \tag{46}$$

for quantitative variables, where R_j is the range of the variable y in the sample or the population and $\delta_{ii'j}$ is the number of possible combinations in case of co-presence.

The similarity matrix $S_{ii'}$ is positive semi-definite when missing values are not present. Thus, a true Euclidean representation with distances $d_{ii'}$ can be derived:

$$d_{ii'} = \sqrt{1 - S_{ii'}}. \tag{47}$$

For latent class clustering, a probabilistic model is used to describe the distributions in the data instead of distance measures. The main assumption is that the data is composed of a mixture of underlying probability distributions and each component in the probability distribution stands for a cluster. Thus, by knowing or assuming the underlying distributions for each cluster, the problem of finding the clusters can be reduced to a parameter estimation problem. Using the maximum likelihood method, the unknown parameters are estimated using the Expectation-Maximization algorithm. More detailed information on cluster analysis can be found in Paper III.

Market penetration

In an updated study from the Highway Loss Data Institute, it is shown that as recently as 2016 only one percent of registered vehicles in the United States were equipped with Rear-end AEB (HLDI, 2017). About seven percent of new vehicles were equipped with Rear-end AEB as standard, while for 38.5 percent of new vehicles Rear-end AEB was only available as an optional extra with the take-up rate being unknown. It is predicted that in 2045 about 95 percent of registered vehicles will be equipped with this feature. In Sweden, the equipment rate of new cars with ESC increased from 15 percent to 90 percent in four years through consumer initiatives and through the request of the government to manufacturers and importers to no longer sell cars without ESC (Krafft et al., 2009). Nevertheless, it will take many years to replace the older vehicles in the fleet with new vehicles equipped with ESC.

The probability that one or both vehicles involved in a crash is equipped with a safety system is dependent on the market penetration of the safety system.

Let e_v be the number of vehicles equipped with a safety system and N_v be the total number of vehicles. The probability P_e of picking a vehicle equipped with the safety system is then:

$$P_e = \frac{e_v}{N_v}. \tag{48}$$

The probability P_{ne} of picking a vehicle not equipped with the safety system is:

$$P_{ne} = \frac{N_v - e_v}{N_v}. \tag{49}$$

Assuming that most of the vehicles sustaining an accident will be repaired and put back into the fleet, and, further, taking into account that accidents are rare events so the number of vehicles involved in an accident is substantially smaller than the total number of vehicles (in a given time period), the probabilities are seen as independent of each other. Thus, the joint probabilities are:

neither vehicle equipped:

$$P_{none} = \frac{(N_v - e_v)^2}{{N_v}^2}, \tag{50}$$

one vehicle equipped:

$$P_{one} = 2 \cdot \frac{(N_v - e_v) \cdot e_v}{{N_v}^2}, \tag{51}$$

both vehicles equipped:

$$P_{both} = \frac{{e_v}^2}{{N_v}^2}. \tag{52}$$

Papers I and IV used the probability model for market penetration. For different market penetration stages, as used in Paper IV, the outcomes of the simulation results for neither vehicle equipped, first vehicle equipped, second vehicle equipped, and both vehicles equipped were combined with the corresponding probabilities and summed. As the probability that either the first or the second vehicle is equipped is equal, each of them has the half probability of P_{one}.

Injury probability

Where a collision cannot be prevented by a safety system, injuries to the occupants may occur. Specifically, in intersection crashes an Intersection AEB may not only reduce the impact speed, but also lead to a change of impact side or area. A common practice to estimate the effect of active safety systems on injury mitigation is the application of a dose-response model using injury risk functions as a link between dose and response (Alvarez et al., 2017). Input to a dose-response model is the impact severity, and the response is the injury outcome (Kullgren, 2008). Reduction of injured occupants can be achieved by reducing 1) the number of collisions, 2) the impact severity, and 3) the injury risk at given severity (Kullgren, 1998). The first two reduction opportunities are usually addressed by active safety systems though crash avoidance and speed reduction, respectively. However, changes to impact side or impact area may increase or reduce the impact severity. The third reduction opportunity is typically addressed by passive safety measures. To assess the number of incidents for a given injury level, injury risk functions are necessary.

Petitjean and Trosseille (2011) have identified two methods as best performing approaches to derive injury risk functions from biomechanical experiments: survival analysis and logistic regression. For censored data, the authors recommend survival analysis; and real-world traffic accident data are typically censored. However, when the outcomes are censored binary injury information (injured / not injured), logistic regression and survival analysis try to maximize similar likelihood functions (McMurry and Poplin, 2015). Therefore, a multivariate logistic regression model was used in Paper IV to estimate the probability of a moderate to fatal injury (expressed as MAIS2+F; see Gennarelli and Wozine, 2008). The MAIS2+F injury level was chosen to address injuries with long-term consequences: Stigson et al. (2015) and Tingvall et al. (2013) have shown that injuries at the higher MAIS3+F level (severe to fatal injury) give rise to only 14 percent of long-term consequences, whereas 63 percent of injuries with long-term consequences are covered at the MAIS2+F level.

Candidates for the independent variables in the logistic regression function were chosen following the process described by Flannagan et al. (2018). Wald chi-squared statistics were used to select those variables out of the candidate variables for which the null hypothesis is rejected and a relationship is identified. Akaike's information criterion (Akaike, 1974) was used to test whether the inclusion of a non-significant variable gives an improved model compared to a model without the variable.

The application of logistic regression yielded an analytical expression for the occupant injury risk as a function of independent variables in the GIDAS dataset. It was assumed that this has the following form:

$$\hat{p} = 1 \Big/ \left(1 + e^{-\left(\sum_{i=0}^{r} \hat{\beta}_i \cdot x_i\right)}\right), \tag{53}$$

where $\hat{p}$ is the predicted risk of MAIS2+F injury, $\hat{\beta}_i$ is the estimate for the i^{th} coefficient, and x_i is the observed value of the i^{th} explanatory variable in the regression model (i = *0 ... r*). To estimate $\hat{\beta}_i$, the method of maximum likelihood was used (Dobson and Barnett, 2008).

The best model included the intercept, 'occupant age' (continuous variable), 'vehicle model year' (categorical variable: $<$ 2003, $\geq$ 2003), 'impact type' (categorical variable: front, nearside compartment hit, nearside no compartment hit, far-side), 'delta-V' (continuous variable), 'accident location' (categorical variable: urban, rural), and the interaction between 'impact type' and 'delta-V'. Only belted occupants were considered in the model.

For the estimation of MAIS2+F injured occupants it was assumed that all vehicles are of the second category of vehicle model year (≥ 2003).

More detailed information on the developed injury probability function can be found in the supplementary information of Paper IV.

4 SUMMARY OF PAPERS

This chapter gives an overview of this thesis to indicate how the included papers relate to each other. This is followed by a summary of the overall results and of each individual paper, and finally the research questions are answered.

Paper I to Paper IV build upon each other so that the outcome of each paper is considered in the papers which follow (Figure 14).

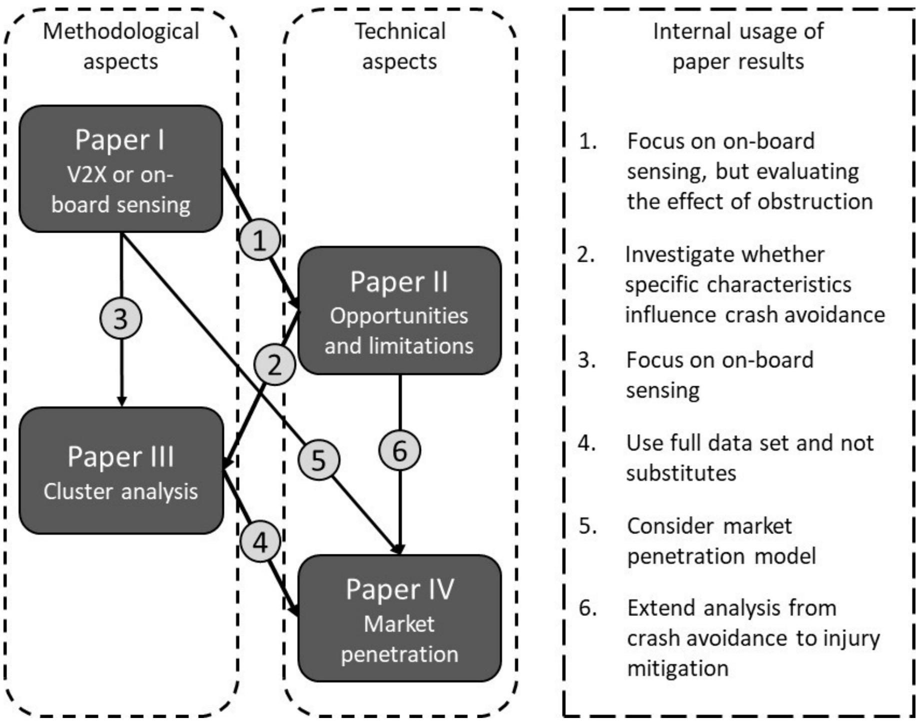

Figure 14: Overview of the individual papers and how the results of the previous papers were used in the following paper (internal usage).

4.1 Overall results

Paper I aimed to identify whether V2X communication is a comparable alternative to on-board sensing in terms of saving lives and thus whether the work to follow should focus on V2X communication or on-board sensing. As the results showed that V2X communication is not an equivalent substitute when market penetration is taken into account, however reasonable a complement, the following papers focused on-board sensing. The work in this paper also revealed that intersection accidents were treated by different system approaches: LTAP/OD by forward collision avoidance and SCP by side-view assist. Another difficulty was found in determining whether only one or both cars in an intersection accident needed intervention to avoid a collision. This lead to the development of the pre-crash simulation within PRAEDICO, as no other commercial simulation tool at that time allowed more than one car to be equipped with a safety system.

In Paper II it was then investigated whether a forward-looking sensor in combination with an Intersection AEB function would be suitable to address LTAP/OD. Furthermore, the effect of different algorithm settings on effectiveness avoiding accidents was studied. The results led to further developments of the algorithm and the vehicle brake model. Additionally, the results indicated that initial speed of the turning vehicle has an influence on accident avoidance when a certain threshold is exceeded. The direct influence of other variables on crash avoidance could not be identified. This lead then to the decision to study the accident data more in detail.

Paper III utilized different clustering methods, hierarchical clustering (HC), partitioning around medoids (PAM), and latent class clustering (LCC), to identify groups in the data that differ from each other. Applying principal component analysis, the study revealed the high diversity of intersection accident descriptors. The clusters generated by an all-embracing set of cluster variables using HC, PAM, and LCC were found to have a weak structure. A reasonable structure could only be found when the number of input variables was reduced. However, for all sets of variables the simulation results within a cluster showed divergence regarding crash avoidance. It was evaluated that crash avoidance as a binary outcome variable is not adequate to reflect the similarities and differences between scenarios. Hence, it was decided to extend the pre-crash simulation of Intersection AEB with a crash computation and prediction of injury mitigation.

Paper IV investigated the extent to which Intersection AEB can avoid crashes and mitigate moderate to fatal crashes in SCP scenarios. An impact model was developed based on the Kudlich-Slibar rigid body impulse model. The outcome of the crash computation, namely the change of velocity during the impact, was then used as an input to the injury risk function. In SCP scenarios, both vehicles are heading straight and therefore both the vehicle approaching from the left and the vehicle approaching from the right use an identical function to address the conflict. This means that adding the market penetration model used in Paper I enabled the assessment of the expected benefit as a function of market penetration.

Table 7 gives an overview of data and methods and Figure 15 shows a summary of the main results of the papers included in this thesis.

Table 7: Data and methods overview for thesis papers.

	Paper I	Paper II	Paper III	Paper IV
Data	NASS/GES & FARS (United States)	GIDAS & PCM (Germany)		
Accident Scenario	Rear-end Turning Lane Change Lane departure	Intersection (LTAP/OD)	Intersection (SCP & LTAP/OD)	Intersection (SCP)
Technology	V2X communication and on-board sensing	On-board sensing		
Effectiveness Assessment	Estimation of addressable accidents	Estimation of avoided crashes		Estimation of avoided crashes and mitigated injuries
	Data analysis	Pre-crash simulation		
				Crash Computation
Statistical Analysis	Data Weighting			
			Cluster Analysis	
	Market Penetration			Market Penetration
				Injury Probability

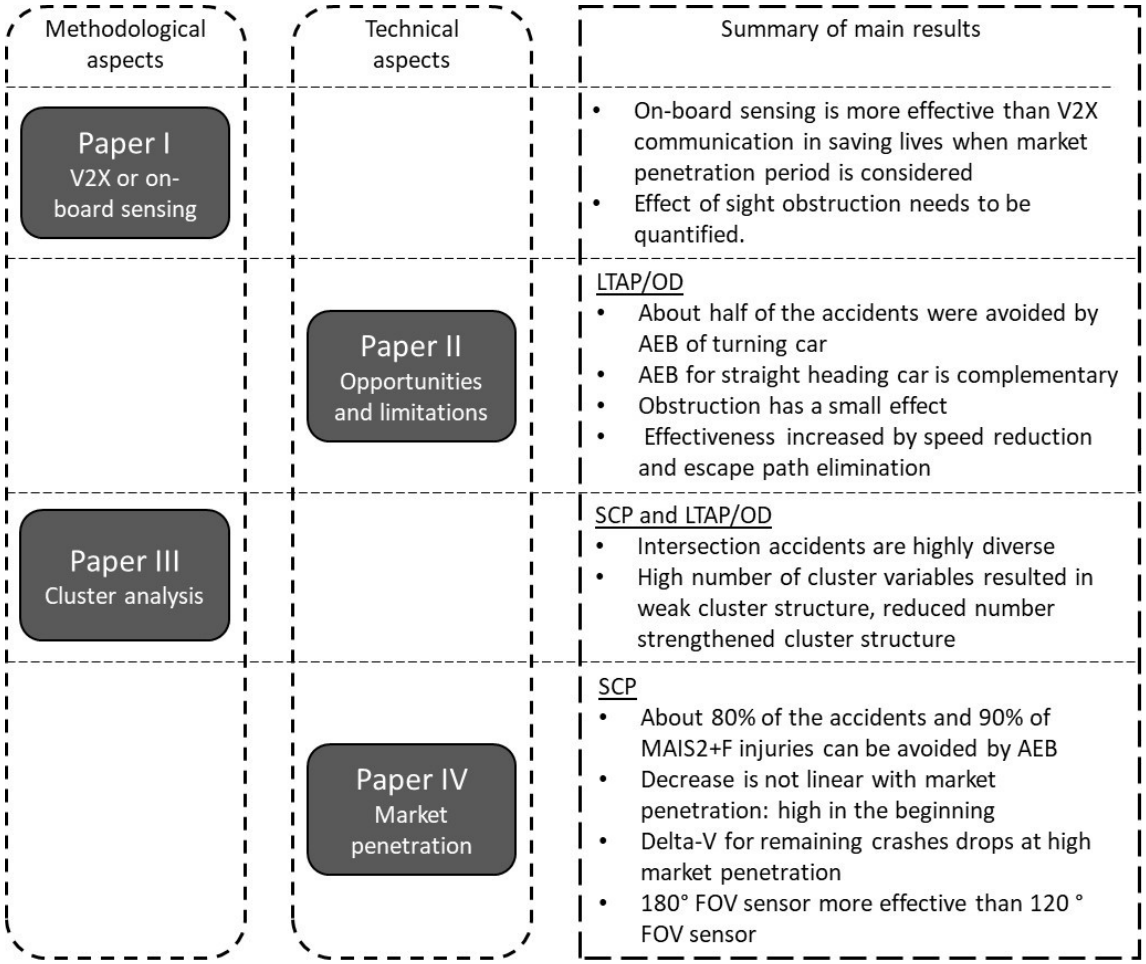

Figure 15: Summary of the main results of the papers included in this thesis.

4.2 Answers to research questions

This section provides compact answers to the research questions formulated in Section 1.3.

1st research question: How does V2X communication compare to on-board sensing and can it be as effective as a stand-alone sensing alternative?

Answer: During the time period of market penetration, V2X communication will not be as effective as on-board sensing in saving lives. The benefits of V2X communication will not compensate for the shortcoming that another vehicle equipped with V2X communication is required to exchange information.

2nd research question: How effective can an Intersection AEB system based on on-board sensing be in avoiding accidents?

Answer: Assuming ideal sensing and coefficient of friction estimation, Intersection AEB will be able to prevent up to two thirds of LTAP/OD and 80 percent of SCP accidents.

3rd research question: What is the capability of these systems to mitigate injury in cases where an accident cannot be avoided?

Answer: Assuming ideal sensing and coefficient of friction estimation, Intersection AEB will be able to reduce the number of moderate to fatally injured occupants by 90 percent in SCP scenarios.

4^{th} research question: What parameters have a substantial influence on the performance of an Intersection AEB system?

Answer: For the Intersection AEB algorithm used here that investigates escape alternatives from a pending conflict, initial speed of the vehicles and the kind of possible escape maneuver have a leading effect on the system performance.

5^{th} research question: How does the effectiveness in avoiding accidents and mitigating injuries change as market penetration increases?

Answer: For SCP scenarios, the decrease of accidents and injuries as a function of AEB market penetration is not linear. At low market penetration, accident avoidance and injury mitigation rates are relatively high. With higher market penetration, the reduction flattens out.

6^{th} research question: Can a set of test scenarios be defined which is representative for the utilized sample of accidents?

Answer: Intersection accidents are highly diverse. Using different data clustering methods, accident scenarios grouped into one cluster yielded different crash avoidance outcomes when an Intersection AEB system was present. Where one data point of each cluster is selected as test scenario (for example the medoid), the derived set of test scenarios is not representative of the whole data sample. Thus, with the methods applied, it was not possible to generate a set of representative test scenarios.

Summary of Paper I: Saving lives with V2X versus on-board sensing systems - Which will be more effective?

Introduction: Theoretically, infrastructure systems such as vehicle-to-vehicle and vehicle-to-infrastructure (V2X) communication can prevent the majority of accidents by gathering and combining the speed, locations, and travel directions of traffic participants, and intervening to control vehicle motion in critical situations to help avoid collisions. However, during the phase-in, many vehicles and road infrastructure points will not have those communication systems in place and thus the information exchange will be limited. On-board sensing systems such as cameras and radar sensors may not detect all potential hazards due to weather conditions or hazards being hidden, but they are effective in many situations and can help prevent crashes without depending on communication with infrastructure or other vehicles.

Objective: This paper evaluates and compares the effectiveness of communication and on-board sensing technology in saving lives as a function of market penetration. Various implementation scenarios and system capabilities are investigated.

Method: The maximum potential crash reduction of three on-board crash avoidance systems based on data from the National Automotive Sampling System General Estimates System (NASS/GES) and the Fatality Analysis Reporting System (FARS) was taken from a published study and compared against potential crash reduction figures based on V2X communication. The investigated crash avoidance systems were: forward collision warning/mitigation, side view assist, and lane departure warning/prevention. It was assumed that on-board sensor systems were only effective in clear weather conditions whereas V2X systems were also effective in inclement weather. The effect of vehicle obstruction could not be taken into account, as the information was not available in the NASS/GES and FARS data. Fleet and infrastructure penetration was defined in two scenarios: a realistic scenario with a five-year offset to introduction and an annual increase of 4 percent and a fast scenario with immediate introduction and 6 percent annual increase. The crash population was based on the equipment rates of vehicles with on-board sensing and V2X communication. On-board sensing was defined as functional as long as at least one vehicle was equipped whereas V2X was defined as functional only when both vehicles or vehicle and infrastructure were equipped.

Results: When a 100 percent market penetration was assumed, the ability of a V2X communication system to avoid fatal crashes was overall higher than the ability of the on-board systems. However, when the effectiveness of on-board and V2X communication systems during the market penetration period was taken into account, substantially more lives could be saved with the on-board technology in both scenarios. To achieve the same results as on-board systems in the first scenario, V2X needed to be introduced with an annual increase of 6.5 percent.

Discussion: V2X communication is strongly dependent on the degree to which it is implemented in the vehicle fleet and the infrastructure; however, the inability to assess sight obstruction may lead to an overestimation of the effectiveness of on-board systems. Thus, the potential of V2X communication systems to address scenarios with obstructed hazards is a complement to on-board sensing. The results for the side view assist were not meaningful for intersection crashes, as the data coding did not allow an identification of straight crossing path scenarios.

Summary of Paper II: Opportunities and limitations for intersection collision intervention - A study of real world 'left turn across path' accidents

Introduction: Turning across the path of oncoming vehicle (LTAP/OD) accidents are frequent and dangerous. To date, relatively few car manufacturers have introduced Automated Emergency Braking (AEB) systems to address this type of conflict situation, but it is foreseeable that these scenarios will be part of the Euro NCAP 2020 rating.

Objective: This paper investigates the effect of different algorithm and brake settings on the ability to prevent LTAP/OD crashes through utilizing Intersection AEB. The capabilities of crash avoidance are analyzed for both the turning and the straight heading vehicles. Characteristics having an influence on intervention success are presented.

Method: The German In-depth Accident Study (GIDAS) and the GIDAS-based Pre-Crash Matrix (PCM) data were queried for LTAP/OD accidents. Pre-crash simulations using the trajectories of vehicles involved in 384 LTAP/OD real-world accidents were conducted within the PRAEDICO assessment framework. An AEB system was specified that takes the decision for intervention on the basis of the ego and conflict vehicle driver's options to avoid a pending crash by either braking or steering. To assess the effect on the safety benefit, AEB system parameters were varied, covering parameters such as driver comfort boundaries (based on longitudinal and lateral acceleration), expected steering maneuvers to avoid conflict (steering away and steering to achieve a specified lateral offset), and intervention response characteristics (brake delay and ramp up). Additionally, the effect of sight obstructions on accident avoidance was analyzed.

Results: Nine out of ten collisions were caused by the driver of the turning vehicle. The reference simulation indicated that the AEB system in the turning vehicle has the potential to prevent approximately half the collisions. An AEB system implemented in the straight heading vehicle was less effective. The variation of the drive comfort boundaries had a substantial impact on the ability to prevent crashes: the lowest activation thresholds resulted in about twice the effectiveness of the highest threshold. The effectiveness of the turning vehicle's AEB system increased substantially when spatial limitations for the collision-avoidance steering maneuver were known. AEB interventions rarely result in collision avoidance for turning vehicles with speeds above 40 km/h or for straight going vehicles with speeds above 60 km/h. State-of-the-art field-of-views of forward looking sensing systems designed for Rear-end AEB interventions were capable of addressing turning across path situations.

Discussion: To date, the focus in left turn across path accidents has been on the turning vehicle. Since most accidents were caused by the turning driver disregarding the right of way, this is a natural approach. Also, the effectiveness of AEB intervention for crash avoidance is much higher for the turning than for the straight going vehicle. Nevertheless, most accidents that can be avoided by an AEB system of the straight going vehicle cannot be addressed by the turning vehicle's AEB system, so the systems complement each other. To increase the effectiveness of an Intersection AEB, the avoidance abilities of both vehicles by steering needs to be reduced to those that are physically possible. This information could be provided by sensors detecting free space in or around the road environment or geographical information shared via vehicle-to-everything (V2X) communication.

Summary of Paper III: The potential of clustering methods to define intersection test scenarios: Assessing real-life performance of AEB

Introduction: Intersection accidents are frequent and harmful. The accident types ‘straight crossing path’ (SCP), ‘left turn across path – oncoming direction’ (LTAP/OD), and ‘left-turn across path – lateral direction’ (LTAP/LD) represent around 95% of all intersection accidents and one-third of all police-reported car-to-car accidents in Germany. The European New Car Assessment Program (Euro NCAP) has announced that intersection scenarios will be included in its rating from 2020. How these scenarios are to be tested has not been defined.

Objective: This paper investigates whether clustering methods can be used to identify a small number of test scenarios sufficiently representative of the accident dataset to evaluate Intersection Automated Emergency Braking (AEB). Accidents that were identified as similar to each other were re-simulated to reveal whether the AEB system performance in crash avoidance is homogeneous in each cluster.

Method: Data from the German In-Depth Accident Study (GIDAS) and the GIDAS-based Pre-Crash Matrix (PCM) from 1999 to 2016, containing 784 SCP and 453 LTAP/OD accidents, were analyzed by principal component methods to identify variables that account for the relevant total variances of the sample. Three different data clustering methods were applied to each of the accident types: two similarity-based approaches, namely Hierarchical Clustering (HC) and Partitioning Around Medoids (PAM), and the probability-based Latent Class Clustering (LCC). The optimum number of clusters was derived for HC and PAM using the average silhouette width. The PAM algorithm was both initiated with random start medoid selection and medoids from HC. For LCC, the Bayesian Information Criterion (BIC) was used to determine the optimal number of clusters. The set of variables for clustering was further varied to investigate the influence of variable type and character. The medoids of the resulting cluster were used as test scenarios. We quantified how accurately each cluster variation represents real-life AEB performance using pre-crash simulations with PCM data and a generic algorithm for AEB intervention.

Results: The usage of different sets of clustering variables resulted in substantially different numbers of clusters. The stability of the resulting clusters increased with prioritization of categorical over continuous variables, though none of the identified clusters had an average silhouette width of 0.7 or higher, indicating that the cluster grouping is partially random. For each different set of cluster variables, a strong in-cluster variance of avoided versus non-avoided accidents for the specified Intersection AEB was present. The medoids were not representative for the Intersection AEB behavior in each cluster.

Discussion: Utilizing three of the most common cluster analysis methods and different sets of variables, it was impossible to reduce the diversity of intersection accidents into a set of test scenarios without compromising the ability to predict real-life performance of Intersection AEB. Although this does not imply that other methods cannot succeed, it was observed that small changes in the definition of a scenario resulted in a different avoidance outcome. There were no dominant variables that determine the success or failure of crash avoidance.

Therefore, we suggest using limited physical testing to validate more extensive virtual simulations to evaluate vehicle safety.

Summary of Paper IV: Market penetration of Intersection AEB: Characterizing avoided and residual straight crossing path accidents

Introduction: Car occupants account for one third of all junction fatalities in the European Union. Studies have shown that driver warning can reduce intersection accidents by up to 50 percent; adding Autonomous Emergency Braking (AEB) delivers a reduction of up to 70 percent. However, these findings are based on an assumed 100 percent equipment rate, which may take decades to achieve.

Objective: This study investigates the relationship between intersection AEB market penetration rates and avoidance of accidents and injuries in order to guide implementation strategies in combination with technical specifications. Additionally, residual accident characteristics such as impact configurations and severity are analyzed to provide a basis for future in-crash protection requirements.

Method: We determined which accidents could have been avoided through the use of an Intersection AEB system with different sensor field-of-views (180° and 120°) by means of re-simulating the pre-crash phase of 792 straight crossing path (SCP) car-to-car accidents recorded in the German In-Depth Accident Study (GIDAS) and the associated Pre-Crash Matrix (PCM). We used a statistical model to define whether, depending on the market penetration, neither, one, or both vehicles were equipped with an Intersection AEB. Correspondingly, each accident was simulated with all possible equipment combinations. Intersection AEB was activated when neither of the conflict opponents could avoid the crash through reasonable braking or steering reactions. For not-avoided accidents, we used the Kudlich-Slibar rigid body impulse model to calculate the change of velocity during the impact as a measure of impact severity and the principal direction of force. An injury probability function was developed to determine the frequency of moderate to fatal (MAIS2+F) injured occupants in the remaining accidents.

Results: Accident avoidance over market penetration is not linear but exponential, with higher gains at low penetration rates and lower gains at higher rates. A 180° field-of-view sensor substantially increased accident avoidance and injury mitigation rates compared to a 120° field-of-view sensor. Further, for the wider field-of-view sensor at 100 percent market penetration, about 80 percent of the accidents and 90 percent of the MAIS2+F injuries could be avoided. For the remaining accidents, AEB intervention rarely affected side of impact. The median change of velocity (delta-V) of the remaining crashes reduces only marginally with up to 50 percent market penetration rates, but the reduction increased with higher penetration rates. With 100 percent market penetration, one quarter of the vehicles still involved in straight crossing path accidents sustained a delta-V higher than 17 km/h.

Discussion: Intersection AEB is very effective. Enabling a fast initial implementation of systems with wide field-of-view sensor(s) and ensuring a high market penetration over the longer term is essential to achieve high crash avoidance and injury mitigation rates over time. However, systems with smaller field-of-view sensors can be more effective in accident prevention and injury mitigation than those with wider field-of-view sensors if they achieve a substantially higher market penetration. The standards for in-crash protection must be high to mitigate injury in the unavoidable residual accidents as it is not expected that their severity will decrease until a high market penetration of Intersection AEB is reached.

5 DISCUSSION

Different aspects of an Intersection AEB and the consequences on the road infrastructure and driver behavior are examined to put the work presented here into a broader context.

5.1 Global impact

Every year, around 1.25 million people die in road traffic, most of them in low- and middle-income countries (World Health Organization, 2016). The African region has the highest number of road traffic fatalities, whereas high-income countries in the European region have the lowest. In Africa, the road traffic death rate per 100,000 population is around ten times of the best performing countries in Europe. Around half of the fatalities are among pedestrians, cyclists, and motorcyclists. With this in mind, a car-to-car Intersection AEB specified on the basis of data from a European high-income country arguably may not have a strong impact on road safety globally. Furthermore, such a system seems to address a first-world problem only, as advanced technology is necessary. However, this might be true on a short-term perspective, but arguably not over the long-term. Short-term objectives for low- and middle-income countries are still focused on changing key risk factors such as speeding, drunk driving, and seat belt and helmet usage and many countries have already introduced corresponding laws. Many newly industrializing nations, however, have demonstrated that they take development steps very rapidly. In a study on the future of driving in developing countries, the Institute of Mobility Research in Germany has concluded that a car-culture favorability is expected to increase over the next couple of decades in the BRIC countries (Brazil, Russia, China, and India) to the level of Japan or Europe (Ecola et al., 2014). In Brazil, China, and Russia, pro-automotive government policies are in place to strengthen the domestic car industry. The costs for car technology will decrease, so that new cars will become affordable in the emerging markets. Also, vehicle life-span has more than doubled in the last few decades. According to the United Nations Environment Programme, about 99 percent of all cars imported to Kenya are second-hand and most of them were shipped from either Japan or Europe. In developing countries, second-hand cars allow for mobility which in turn leads to an increased gross domestic product (National Research Council and National Academy of Engineering, 2003). Thus, there are several ways for new technology to be introduced to low- and middle-income countries.

5.2 Vision Zero

According to the Vision Zero approach, no one shall be killed or seriously injured within the road traffic system. As Section 1.1 discussed, a huge proportion of accidents involving seriously and fatally injured (MAIS3+F) road traffic participants occur at intersections or are related to intersections. The results in Paper IV for mitigated occupant injury refer to a moderate to fatal injury level (MAIS2+F). MAIS2+F was chosen as the injury severity level under three aspects: 1) to consider a broader range of injuries with long term consequences, 2) to use an injury risk function with smaller confidence intervals (out of 22,765 passenger car occupants, 1,348 sustained MAIS2+F injury level and 503 sustained MAIS3+F injury level), and 3) to give better predictions for the remaining injured occupants (out of 2282 car occupants in the SCP PCM sample, 99 were MAIS2+F injured, 20 were MAIS3+F injured, and 4 were fatally injured). That is, a reduction of MAIS3+ injured occupants has not been estimated. However, it can be assumed that accident avoidance and injury mitigation capabilities are reduced with higher speeds and that injury severity increases with speed. Consequently, it is expected that the reduction of MAIS3+ injured occupants is less than the reduction of MAIS2+F injured occupants.

5.3 Data usage

The analysis for Paper I was based on a study conducted by Jermakian (2011) using NASS/GES and FARS data. Both databases are compiled from police-reported data and lack to some extent details on the environment, the vehicle, the crash constellation, and pre-crash information. In general, police reported data is prone to underreporting of accidents with lower severity outcome. Thus, the published number of crashes that can be addressed by a specific crash avoidance technology has a substantial range of uncertainty. For the forward collision warning system, only rear-end crashes were considered, though an oncoming vehicle in an LTAP/OD scenario is also in the field-of-view of a forward-looking sensor. The side-view assist considered lane-changing crashes but excluded straight crossing vehicles. That is, the analysis from Jermakian did not provide information on the avoidance of intersection crashes. The applied method for market penetration could also have been applied to any artificial dataset to show relative changes. However, the NASS data was chosen to emphasize a real-world relevance and give absolute numbers.

German in-depth accident data was used for Papers II to IV and therefore the results are not expected to be globally representative. Speed limits and how well they are adhered to, road layout, traffic signalization and density, and road user behavior are all characteristics that vary from country to country and influence the effectiveness of an Intersection AEB. However, differences within countries may be reduced in the future with the adoption of Vision Zero. Specifically, Vision Zero defines among other measures a) limits for tolerable speed the human can handle in case a crash happens, b) requirements for road design to permit human error, and c) measures to influence road user behavior. For countries such as China and India, Shaikh and Sander (2018) presented a method illustrating how pre-crash time-series data, as used for this thesis, can be generated out of the corresponding in-depth accident data. Many countries, especially low- and mid-income countries, do not conduct sufficient data collection and analysis as recommended by the OECD to be able to monitor the current performance in road safety. Here, a recently developed ISO standard for organizational road safety management (European Commission, 2016d), ISO 39001, is a valuable tool to accelerate the implementation of processes to monitor periodically the status of safety measures.

5.4 Virtual simulation

The results of this thesis are predominantly based on virtual simulation. In general, virtual simulations are of low cost. Once a microcomputer and relevant software is available, there are almost no additional costs in running as many simulations as are necessary other than building up the simulation framework. As stated in Section 2.3.2, virtual simulations may vary in level of detail and representativeness. For this thesis, both aspects have been chosen in such a way that an initial *a priori* assessment to investigate system parameters according to the modified Deming cycle (Section 2.3.6) is possible. This means that simplifications are intentionally chosen and an accurate replication of the real-world was not intended. Consequently, the quantifications of effectiveness presented here should not be interpreted as single results, but in the context of each other and how they have been generated. Effectiveness values are not directly comparable to those that can be achieved in real-world by using real sensors and signal processing. However, the results give a good indication of what to prioritize to ensure that Intersection AEB systems are optimally effective within given constraints. Currently, one constraint is the assumption that the car is driven by a human driver and the exact intended path of the ego vehicle and conflicting vehicle(s) is not known to the active safety algorithm.

An important aspect in the application of virtual simulation is the definition of a target population. The specified Intersection AEB system intended for LTAP/OD scenarios may also mitigate injures in other crash types such as lane departure or lane change / overtaking crashes with oncoming traffic (vehicle-to-vehicle head-on crashes). These scenarios however were not simulated; consequently, the real-world overall benefit of the Intersection AEB might be greater than the one derived from the narrowed target population of LTAP/OD crashes.

5.5 AEB specification and infrastructure dependencies

Brännström et al. (2014) predicted an interesting potential of Intersection AEB in SCP scenarios. Their analysis showed that the slower vehicle has always the greatest opportunity to avoid the collision. With a target vehicle speed of 50 km/h and an ego vehicle speed below 50 km/h, avoidance by braking is still possible when avoidance by steering would no longer succeed. Thus, an AEB system would be able to prevent those collisions. The results of Paper IV confirm this prediction.

As presented in Paper IV, the effectiveness of Intersection AEB in LTAP/OD scenarios as a function of market penetration has been investigated, but results have not been published. Similar to SCP scenarios, effectiveness in avoiding crashes was found to increase faster at low market penetrations than at high market penetrations. Interestingly, for LTAP/OD scenarios, the proportion of front, left side, and right side impacts does not remain constant. With increased market penetration, the availability of Intersection AEB for the left-tuning vehicle led to a change of front-to-right side impacts into front-to-front impacts, in doing so reducing the proportion of moderate to fatal injured occupants.

Scanlon et al. (2017a) estimated that up to 60 percent of the investigated SCP crashes could be avoided and up to 80 percent of the severe to fatal injured drivers could be prevented with an AEB activation at three seconds prior to collision. Though three seconds TTC is prone to activations when not necessary, the effectiveness for crash avoidance and injury mitigation are below the ones estimated in Paper IV. It is assumed that the difference is affected by Scanlon et al. simulating either of the vehicles equipped with I-ADAS, but not both. For LTAP/OD scenarios, Scanlon et al. (2017b) estimated a crash avoidance benefit of around 60 and 70 percent when possible sight obstruction was included and excluded, respectively. These estimates are above the benefit as assessed in Paper II. However, Scanlon et al. did not investigate the opportunities of the driver of the turning vehicle to escape the conflict by steering. The results for an S-steering maneuver in Paper II match the magnitude of effectiveness of Scanlon et al. for the I-ADAS without sight obstruction.

The effectiveness of a CMB system in LTAP/OD accidents was assessed by Van Auken et al. (2011b) at around 8 percent. The report does not state clearly whether the CMB system was introduced to the turning vehicle, the straight-heading vehicle, or both. Considering that the CMB system was primarily designed to address rear-end crashes, it is assumed that the target population focusses on the straight-heading vehicle only. In this case, the magnitude of the assessed effectiveness would be in a similar range to that of the Intersection AEB for the straight-heading vehicle in Paper II.

An important influence on the effectiveness of an Intersection AEB is the field-of-view of the sensor(s). Whereas for the LTAP/OD scenario a forward-looking sensor with up to 70° will cover most of the opponent vehicles at the time when a decision for intervention is made (Paper II), SCP scenarios require 180° to achieve a similar coverage (Paper IV). The LTAP/OD scenario could thus theoretically be addressed with existing hardware for Rear-end AEB systems, but straight crossing paths scenarios could not. On the other hand, a sensor platform specified for SCP will be also functional for LTAP/OD. Most likely, there will be not 'one' AEB addressing intersection crashes in the future, but variants with different levels of coverage. Still, the market penetration rate should be considered when an assessment is made: A system with a sensor field-of-view of 120° can be more effective than one with a sensor with a field-of-view of 180°, if the achievable market penetration is correspondingly higher (Paper IV) and not set by default to 100 percent. Thus, it is of utmost importance to plan and conduct *a posteriori* assessments according to the modified Deming cycle (Section 2.3.6) already for the early Intersection AEB systems that hit the market. A follow-up allows for prompt real-world performance identification and if necessary. system parameter adjustments and refinements of consumer organization rating and lawmaking

Another important parameter which impacts the effectiveness of Intersection AEB is vehicle speed. At higher speeds, avoidance by steering might still be possible when avoidance by braking is no longer possible. As driver path intentions are not known to the algorithm and environment information is not considered in the decision to activate the AEB, all steering opportunities to avoid a crash are considered as valid intended paths, as long as comfort boundaries for longitudinal and lateral acceleration are not exceeded. This means that, for example, turning right or left at an intersection is an escape path from a conflict course when vehicles approach in a straight crossing path scenario. Thus, if braking is initiated while comfort escape steering is still possible, there is a high risk of generating unnecessary activations. For LTAP/OD, avoidance opportunities for the turning vehicle were rare when the speed exceeded 40 km/h. For the straight going vehicle the speed threshold was a little higher and less distinct. To address these issues, among others two approaches are obvious: A first approach is a reduction of the permissible speed in intersections. Besides improving traffic flow, speed reduction lowers injury risk where a collision cannot be prevented. A second approach is based on eliminating implausible paths by either using map data shared through cloud services in combination with the sensor information (Polychronopoulos et al.,

2005) or visual path prediction using semantic segmentation and labeling of a scene to identify turning lanes, traffic islands, road edges, and more (Huang et al., 2016). The elimination of implausible paths is highly effective in increasing the crash avoidance potential compared to other algorithm parameter optimizations (Paper IV), but prone to wrong decisions due either to out-of-date map data or misclassifications. Additional information about a selected path may be retrieved from an indicator signal. However, a confirmation of the intended path is more likely when an indicator is set than if an indicator is not set. Thus, a combination of speed reduction and elimination of implausible paths is anticipated to be necessary to improve performance further.

A further performance enhancement could be achieved by increasing the maximum AEB acceleration above 1 g. One approach that has been proposed is the usage of a Vacuum Emergency Brake (VEB). Low-pressure from a vacuum tank is released into the space between a rubber plate and the ground in case the VEB is activated to create both a longitudinal friction force and a normal force additional to the tire forces. Jeppsson et al. (2018) showed through pre-crash simulation of GIDAS pedestrian accidents that the combination of pedestrian AEB and VEB led to an estimated fatality reduction of up to 87 percent, compared to 72 percent with a pedestrian AEB alone.

Though in Section 5.4 it is stated that results of an initial *a priori* effectiveness assessment are not comparable to the results of an *a posteriori* assessment, such a comparison was made for Rear-end AEB to identify the magnitude of difference. While the simulation results of an idealized Rear-end AEB system indicated that approximately 80 percent of the crashes could be avoided, the retrospective analysis of real-accident data (with first generation of Rear-end AEB systems) estimated a crash avoidance potential of up to 40 percent (Section 2.3.4). The difference can be explained by several aspects: besides the idealization of sensor performance and coefficient of friction estimation, the utilized algorithms were different. Most first generation Rear-end AEB systems used a TTC-based algorithm with limitations on characteristics such as TTC values, vehicle lateral offset, lane curvature, and driver brake and steering input. The introduction of 50 percent overlap in rear-end crashes for Euro NCAP in 2018 has since led to extended system performance and algorithm designs. For an AEB addressing intersection accidents, avoidance alternatives which include braking and steering as used in this thesis are evaluated as essential by the author. It is worth noting, however, that even if first generations of Intersection AEB systems in the real world have around half the accident avoidance effectiveness of the idealized system assessed in this thesis, the benefit to society is enormous. Additionally, whereas rear end-crashes commonly result in whiplash associated disorders (Jakobsson, 2004), the outcome of intersection crashes bear a high probability of threat to life (Sander and Boström, 2010; Sunnevång, 2016).

Although this thesis differentiates between Rear-end AEB and Intersection AEB, the objective is to have a single algorithm for all scenarios relevant to collision mitigation by braking or steering. Thus, the prefix is only used to differentiate between existing AEB systems addressing for example rear-end and VRU crashes.

An infrastructure measure that already combines speed reduction with narrowed down path alternative is the modern roundabout. A modern roundabout follows the principal guidelines of a high deflection angle at the entrance to reduce speed and a one-way traffic flow to allow only one driving direction (Massachusetts Highway Department, 2006; Robinson et al., 2000). A rotary differs from a roundabout in that the diameter size is much bigger, so that circulating speeds are much higher. There is an ongoing trend in Europe and the United States to replace classic intersection with roundabouts, as research has shown a substantial reduction in crash severity (Brilon and Stuwe, 1993; Hu et al., 2014; Mandavilli et al., 2009; Maycock and Hall, 1984). In Europe, south-western countries like France, Spain, and Portugal have the highest density of roundabouts per inhabitant. To ensure that Intersection AEB systems are effective at the merging points of roundabouts, the deflection of the entrance path should not happen too far from the entrance point, otherwise other vehicles will move outside a 180° sensor field-of-view towards the blind spot. Further, a minimum circular diameter is necessary so that opponent vehicles have a lateral approach. Otherwise, a vehicle entering a roundabout may end up in a similar conflict to that which a straight heading vehicle has with a left turning vehicle crossing the path in an LTAP/OD scenario. The straight-going vehicle cannot identify until a late point in time whether the oncoming vehicle is going to continue straight ahead or turn left, leading to a reduced opportunity for crash avoidance. If both the deflection angle and roundabout diameter are appropriate and the information is available that the ego vehicle is at the entrance of a roundabout, then Intersection AEB systems will have similar or even better performance at roundabouts compared to classic intersections. If these cannot be guaranteed, then specific sensor arrangements to address conflicts in roundabouts have to be considered.

If roundabouts cannot be built due to unbalanced traffic flow through the legs or because of environmental constraints (Robinson et al., 2000; Valdez, 2010), then a physical separation of directional lanes at a conventional intersection can increase Intersection AEB effectiveness by improving the clarity of vehicle path selection. However, this would require lane identification. Ego vehicle lane identification can be done using GPS techniques, map data, and sensor information (Knoop et al., 2012; Rose et al., 2014), but for opponent vehicle, lane estimation is far more challenging. Again, using V2X communication by ad-hoc or infrastructure networks, each other's lane position, heading information, and path prediction can be exchanged (Lytrivis et al., 2011). In Paper II it was shown that the evaluation of alternative avoidance routes for opponent vehicles is necessary to minimize unintended interventions.

Infrastructure layout and vehicle safety systems design should complement each other. Generally, infrastructure should be designed to limit kinetic energy to a level that humans can withstand without getting seriously injured or killed. When this cannot be ensured, vehicle safety systems should limit kinetic energy (for example through intelligent speed assistance), reduce the kinetic energy (for example through emergency braking), or lower the injury risk (for example through passive safety). Altering a vehicle's path by lane keeping or emergency steering will lower the risk of a crash, but may not affect the kinetic energy, when a crash cannot be avoided. Thus, as combination with kinetic energy reduction measures should be aspired.

5.6 Driver behavior and warnings

Physical conflict assessment in combination with comfort boundaries is an effective approach to identify the point in time for AEB activation. Where physical conflict assessment acts as an activator for the evaluation of avoidance strategies, for example by identifying that two vehicles are on a conflict course, the comfort boundaries describe the likelihood of deviating from the current motion: if comfort boundaries are exceeded, it is unlikely that this happened deliberately and thus it is likely that a driver will appreciate system support (Ljung Aust and Engström, 2011). On the other hand, comfort zone boundaries are a subjective sensation and vary among the population of car drivers. With comfort zone boundaries set equivalent to physical limitations, there will be no false-positive activations as interventions will always happen at the point of no return. The more the comfort zone boundaries deviate from physical limitations, the higher the probability that an activation will not be appreciated by the driver. A threshold of 5 m/s^2 for longitudinal and lateral acceleration seems to be a good starting point for effectiveness assessment based on current research (Bärgman et al., 2015b; Hugemann and Nickel, 2003; Moon and Yi, 2008). However, it has not yet been investigated how drivers react to interventions at this threshold, nor how many activations in non-critical situations would be generated by a representative driver sample. It is conceivable that comfort zone boundaries are set individually for each driver based on their normal driving behavior. This, however, could only be done for the ego vehicle and not for opponent vehicles for which driver behavior characteristics are unknown.

AEB interventions which take away the control over the vehicle from the driver are therefore the strongest form of system intervention. In Figure 16 the TTC is used as a measure of criticality for the situation, as the proposed algorithm (see Section 3.2.4) uses a safety zone around the vehicle and the identification of the collision course is then dependent on the intersection of the safety zones in time and space. A TTC can be computed as soon as a vehicle is on collision course with either another vehicle, a vulnerable road user, or an object. The frequency of occurrence for severe interventions should be reduced as much as possible, instead earlier driver warning and information should be initiated.

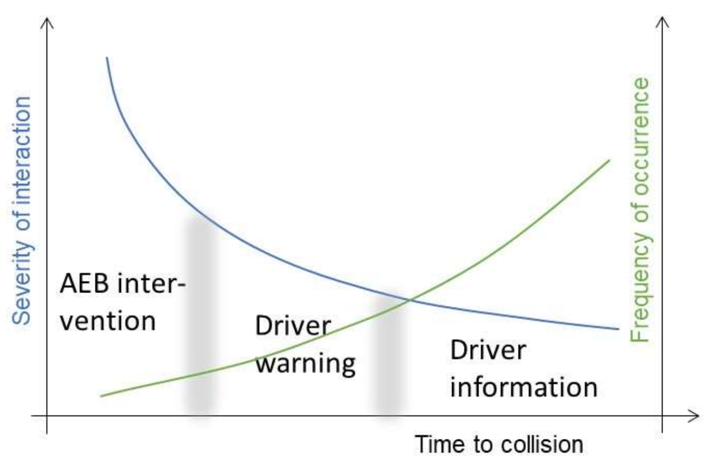

Figure 16: Severity of active safety intervention as a function of Time to collision (TTC)

Such interventions are used as a last resort in cases where the driver does not respond or respond quickly enough to a previously initiated warning. Using PRAEDICO, Sander and Lubbe (2016) showed that the available median time between the point in time when braking needed to be activated to avoid the collision and the collision itself was between 0.6 – 0.7 s and 0.2 – 0.6 s for the SCP and LTAP/OD scenarios, respectively, at the lowest activation threshold. At higher thresholds, the available time span was reduced substantially.

Warning may have a limited effect on crash avoidance, but still injury mitigation may be reached on a larger scale. Additionally, Ljung Aust et al. (2013) showed that forward collision warning influenced the response time in their study only when the event began to repeat. Thus, if warnings are given only to rare events, which accidents are, the driver may not respond to them as intended. On the other hand, if warnings are given without identification of a threat by the driver, the safety system might be seen as disturbing and eventually switched off. Another challenge lies in the localization of the threat after a warning, as in intersections conflict opponents can approach from different directions.

As a complement to AEB intervention and driver warning, early advisory information may be given to a driver as an additional driver support. Naujoks (2015) suggested that this kind of information should be issued to the driver about one to two seconds earlier than a regular driver warning through a visual signal. The direction from which the conflict arises should be included in the information content.

What is not clearly shown in Figure 16 is a driver support system with mild automated intervention capabilities acting during the phase when warning early advisory information is given. For this reason, the transitions between AEB, warning, and information have been drawn indistinctly. Such a system could act at a very early stage when a collision course is identified by slightly adjusting speed and heading to reduce the probability of conflict. An automated driving function plans an optimal trajectory based on sensor information and in case the driver trajectory diverges from the optimal trajectory, mild interventions are initiated to correct towards the optimal trajectory. If the mild interventions exceed the level at which they become noticeable to the driver, the driver should be informed of the reason for interaction.

5.7 V2X communication

The safety application of V2X communication technology is seen as most relevant for the following conflict scenarios: rear-end, lane change, overtaking with oncoming traffic, LTAP/OD, SCP, and traffic control device violation (Harding et al., 2014). One of the major benefits of V2X communication is the identification of threats which are not seen by on-board sensors due to physical obstruction. Additionally, it enables the transfer of information beyond position and speed that is otherwise not available, or limited, such as steering angle, yaw rate, physical dimensions and inertias, understeering coefficient, or processed data such as predicted paths or trajectories. Another advantage is the long signal propagation distance compared to an on-board long-range sensing system (Eichberger et al., 2017). However, to date the application of V2X communication focusses predominantly on information, geofencing, and to some extend driver warning. Thus, the effect of V2X communication is dependent on driver response to given information and warning. An intervention by AEB based solely on V2X communication is theoretically possible, but in this case the information provided needs to be very accurate and 100 percent market penetration is necessary. With limited information about the environment, an AES intervention based only on V2X communication is not possible.

Paper I describes the disadvantage of V2X communication being dependent on both vehicles or vehicle and infrastructure being equipped. In 2014, the US National Highway Traffic Safety Administration introduced an Advanced Notice of Proposed Rulemaking to support the mandatory introduction of V2X to accelerate the market penetration (NHTSA, 2014). However, another current issue is the lack of an international standard, resulting in usage of different frequencies of reserved radio spectrum of 5.8 – 5.9 GHz for V2V communication in the United States, Europe, and Japan. Additionally, the emergence of the 5th generation (5G) of mobile communication systems is evaluated as an alternative for vehicular communication and was recognized by the European Commission as the initial communication technology (European Commission, 2016c). A communication via 5G requires a continuous bandwidth of spectrum up to 100 MHz, which are only available above the 6 GHz spectrum.

Once the harmonization issues of the radio spectrum have been resolved, V2X will be a valuable complement to on-board sensing. In fact, as sight obstructions were underrepresented in the data sample that was used for the simulations, the resulting effectiveness figures are representative of an Intersection AEB that can partially circumvent the issue of obscured opponents. For LTAP/OD scenarios in GIDAS, six percent of the drivers of the straight-heading vehicle and 11 percent of the drivers of the turning vehicle stated that a sight obstruction was present. For SCP scenarios, 35 percent of the drivers of the left approaching vehicle and 38 percent of the drivers of the right approaching vehicle reported a sight obstruction. The drivers were interviewed separately and the principal component analysis in Paper III disclosed a high correlation between their statements. Simulations showed an effectiveness change due to sight obstruction of around 3 percent (LTAP/OD) and around 10 percent (SCP). Based on these figures it seems that the computed effectiveness for 100 percent market penetration are overestimated around 3 to 5 percent and 15 to 20 percent for LTAP/OD and SCP, respectively. However, there is a need for the information to be retrieved within tolerable delays and with a high degree of accuracy to enable usage for automated interventions and not only for warnings.

5.8 Automated driving

It is a common statement that in over 90 percent of all serious crashes human error is a leading cause (NHTSA, 2015b). This however neither means that there is a single cause nor that contributing factors are always non-driving related. Changing or replacing the driver will not resolve over 90 percent of the accidents. Contributing factors leading to an accident are manifold and most often occur as combinations. Sandin (2009) showed that for drivers without the right of way involved in an intersection crash, distraction and obstruction were most often present, when a traffic light / sign or the opponent vehicle was not observed. When they were observed, no clear patterns could be identified. However, in some situations, cognitive bias led to an incorrect interpretation and prediction of the development of the current situation. Engström et al. (2013) found that the most frequent contributing factor is a close encounter, where the driver of the accident-causing vehicle assumed they had the right of way, followed by visual occlusion and distraction.

Thus, there is the strong belief that when the human is taken out of the loop and replaced by control algorithms with undistracted and unobstructed sensing information about the environment, fewer road traffic crashes will happen. But it should be borne in mind that humans in general are very effective in avoiding crashes, otherwise they would not be such rare events. One of the biggest challenges for the technological development in automated driving is the interpretation of contextual information; to gain and link new knowledge to existing knowledge, to learn from experience and develop expectations from this. This means in turn, that automated driving will face challenges to be accident free. There is still the need for active safety systems that support the automated driving function in critical situations. The active safety systems must be independent to ensure that any misinterpretation or malfunction in the automated driving function is not propagated to the active safety function. An Intersection AEB developed to assist a human driver, therefore, still has a place in the domain of automated driving. However, with the substitution of the driver, the trajectory planning of the ego vehicle is known to the Intersection AEB algorithm. This allows for earlier conflict identification and increased crash avoidance probability. Ideally, fully automated vehicles would be separated from other traffic and communicate their planned trajectory, so uncertainties about driver path and speed selection are eliminated. Then sensor capabilities (such as accuracy of identification and location, processing delays) determine the effectiveness of fully automated driving.

5.9 AEB intersection testing

Intersection accidents are highly diverse and small deviations in the description of a scenario are sufficient to determine success or failure in crash avoidance (Paper III). For this reason, it was not possible to define a set of test scenarios that is representative of the sample of SCP and LTAP/OD accidents in GIDAS and PCM using hierarchical clustering, partitioning around medoids, and latent class clustering. Clustering is a commonly applied technique in statistical data analysis. Other methods such as artificial neural networks or rule-based machine learning were not applied due to time constraints. Nitsche et al. (2017) used a combination of partitioning around medoids and association rule mining and identified thirteen clusters for T-junctions and six clusters for crossroads. However, there were two fundamental differences between the approaches by Nitsche et al. and Paper III: Nitsche et al. used all type of intersection crashes involving at least one car for clustering. Further the average silhouette width (see Paper III) was used to identify the optimum number of cluster and an average silhouette width of 0.38 was valued as sufficiently strong. In contrast, Paper III uses already predefined data groups of car-to-car SCP and LTAP/OD accidents, which reduces the variation within each crash data sample. This paper also used the average silhouette to identify the optimum number of clusters; however, a value below 0.50 was judged to represent a weak structure that could be artificial.

To investigate the opportunities for data reduction, only linear Principal Component Analysis (PCA) was used. Linear PCA is an eigenvector method to model linear variabilities in higher dimensional data. However, the low variance per principal component and strong sensitivity to variable selection may point towards a non-linearity. Mapping the data into a higher dimensional space than the dimension of the input space using non-linear methods such as kernel PCA may result in greater classification power (Mika et al., 1999).

Generally, it is possible to generate significantly different clusters, for which the medoid can be used as a cluster representative, by reducing the number of cluster variables or by prioritizing qualitative variables over quantitative variables. However, information loss is inherent in this procedure and the results may not be representative for a given accident sample or population. On the other hand, stakeholders have different requirements and needs for testing: Vehicle manufacturers and safety system suppliers need to ensure that while the system is optimized for high effectiveness of different metrics, undesired activations and side effects are minimized in all possible conditions. Lawmakers will focus on scenarios that are frequent and contribute most to fatalities and severe injured. Consumer organizations will also focus on frequent and dangerous scenarios, but additionally highlight performance difference to support the customer choice for a safe vehicle.

To evaluate the appropriateness of test scenarios that are defined upon a reduced set of variables it is necessary to conduct *a posteriori* assessments at an early stage. Combining expected fleet penetration rates of the specific system with effectiveness rates from *a priori* assessments allows to estimate, at which point in time *a posteriori* assessments are feasible. To be able to conduct then such assessments with high quality, it is necessary to identify which vehicles are equipped with the specific system and whether the system was active or not. These aspects can be already planned before a system is introduced to the market.

5.10 Study limitations

Most of the limitations of the studies included in this thesis are at the same time their strength. Real accident data was used for re-simulation to cover the diversity of rare events. It would have been difficult to generate the variance in the data synthetically without consideration of a high number of parameters and their correlation. On the other hand, as mentioned in Section 2.3.2, the effectiveness can only be zero or positive, but not negative. Further, the assessment of false-positive activations is not possible as only true conflicts are present. As the data was derived from reconstructed accidents, neither was it possible to generate the trajectories of road users not involved in the crash, leading to an underestimation of sight obstruction due to moving objects.

Pre-crash and crash characteristics in GIDAS and PCM are derived by reconstructing accident data collected on-scene. Experts in the data collection teams use established reconstruction methods and regularly-held reconstruction workshops ensure a continuous increase in quality. On the other hand, the varying availability of on-scene evidence leads to error in the estimation of characteristics such as impact speed, initial speed, or collision angle. The error of those variables in GIDAS, however, is assumed to be of a random nature (Rosén and Sander, 2010). Averaging over a large sample size, random error will result in zero effect. Thus, the result might be imprecise, but not inaccurate. In contrast to this, systematic error has a specific direction and large number of observations show a resulting effect; results are inaccurate. In the same study, Rosén and Sander computed estimates for the error of impact speed in pedestrian accidents and concluded that the coded impact speed is normally distributed around the true impact speed with a standard deviation substantially less than 15 percent of the true impact speed.

The simulation models were simplified, especially for the sensor model optimal sensing (usage of ground truth data) and no processing delays were assumed. Therefore, it was not necessary to consider the uncertainty of trajectory prediction and threat assessment due to sensor measurement errors, as investigated by Runarsson and Granum (2014). A more advanced model for a radar sensor was presented by Bernsteiner et al. (2015). The authors superimposed noise due to component tolerances and temperature drift and effects of environmental conditions, such as weather influence on the threshold for object detection depending on the signal-to-noise ratio. Additionally, objects could be randomly lost for a certain time depending on their properties.

Further, the threat assessment algorithm was provided with the same coefficient of friction that was used for the road-tire interface. This means that ideal coefficient of friction estimation was used. In reality, however, an accurate estimation of friction would require a high friction utilization. Prokeš et al. (2016) showed that using a brush tire model and real-time recursive parameter estimation, a reliable estimation of friction in all investigated cases required over 90 percent of friction utilization. The German Research Association for Automotive Technology (FAT) conducted a research project to evaluate the potential of coefficient of friction estimation based on parameters such as road surface type, road surface condition, kind of tire, and vehicle speed (Forschungsvereinigung Automobiltechnik, 2017). Additional utilized parameters were measured road surface and air temperature, humidity, wiper activation, and data from a weather database. The application of the developed prognosis model indicated that around 99% of the measured coefficients of friction were in between the estimated lower and upper coefficient of friction. The mean range between lower and upper coefficient of friction was 0.34. Koglbauer et al. (2018) conducted a driving simulator study with 96 drivers to assess the subjective response to activations of a conventional AEB (not adaptive to road friction) and an advanced AEB (adaptive to road friction) in summer and winter sceneries. The authors concluded that the drivers trusted the adaptive AEB more and felt safer compared to the conventional AEB.

For both sensing and coefficient of friction estimation, continuous technology improvements are made. Thus, it was decided to not further investigate the current state of technology in detail.

The algorithm that analyzed avoidance opportunities was limited to either braking or steering. A combination of both was not considered, though it has been shown that this approach can be highly effective (Eichberger, 2010). Scanlon et al. (2015) identified that about 80 percent of drivers brake and steer immediately prior to a crash. In normal driving, car drivers aim for low lateral accelerations when longitudinal acceleration is high and vice versa; although, when negotiating a left turn across a path, drivers braked until the point in time when turning was initiated and accelerated afterwards (Nobukawa et al., 2012). Acceleration was also not considered as an avoidance alternative for the drivers. An analysis of GIDAS data showed that up to 10 percent of drivers (depending on scenario) accelerate the vehicle to escape a pending conflict but did not succeed.

The simulation model in PRAEDICO is designed for two-dimensional data which means data in a plane. Height information is only used for the vehicle dynamics model to calculate load transfer to the different wheels when longitudinal or lateral acceleration is present. Partwise obstruction due to objects with lower height is therefore not considered.

The statistical model for the probability of vehicles involved in an accident being equipped with a safety system is simplified in that only prior probabilities are used. Knowledge about the equipment status of the vehicles in accident data and in exposure data (such as vehicle registration information) was not incorporated.

The utilized injury risk function differentiates passenger cars by their model year ($<$ 2003 and $\geq$ 2003). Passive safety systems such as front and side airbags have not shown to be significant in the risk model development. The split of the dataset at even more recent model years was not possible due to a small number of newer vehicles. Therefore, the model is limited in the representation of recent advancements in passive safety. In consequence, the remaining percentages of MAIS2+F injured occupants are likely to be overestimated. To assess injury severity, finite element method (FEM) applied to vehicles and occupants has been used as an alternative to rigid body vehicle modelling in combination with conservation of momentum (Wimmer et al., 2017, 2015). The results of such an FEM analysis deliver dose and response to the modelled human substitute. In this approach, the injury risk function(s) may not contain vehicle parameters. However, vehicle design and passive safety functionality has to be considered in the vehicle FEM model, which can be a vast modelling effort.

The use of driver warning was not within the scope of this thesis, but the driver may still react to AEB intervention either by steering, braking, or accelerating. Any overriding of the AEB system or current steering course by the driver was not considered. It is also likely that drivers will adapt to an Intersection AEB system and change their behavior when approaching an intersection entrance. This however cannot be investigated with the utilized data.

Finally, the driver needs to trust the safety functions in a car and such trust cannot be validated in virtual simulation. Here, in-vehicle experience is necessary to design a safety system that anticipates driver behavior and explains circumstances for any kind of intervention.

5.11 Reproducibility of thesis results

From an ethical point of view, research should be committed to search for the truth (Resnik, 2005). This implies, that research should be conducted with integrity, objectivity, openness, and carefulness (Shamoo and Resnik, 2009). Other researchers should be able to utilize similar data and tools and, in the best way, confirm and extend previous research. However, even if methods are comprehensively described, access to data and tools may be limited.

The GIDAS data underlying most of the papers appended to this thesis is to date only accessible for project members. Alternatively, a subset of the GIDAS data is provided to the members of the IGLAD project (Bakker et al., 2017). The generation of pre-crash time-series data similar to PCM has been evaluated in a project of the German Research Association for Automotive Technology and might be adapted in the future (Forschungsvereinigung Automobiltechnik, 2015). Data can also be generated by stochastic processes and weighted according accident statistics to be representative for a specific region and year (Gordon et al., 2010; Helmer, 2014; Wimmer et al., 2017). Distributions of marginal distributions of key variables for SCP and LTAP/OD can be found in the supplementary information of Paper III. Further, Scanlon et al. (2016) presented a method to reconstruct pre-crash path and speed information using data from the National Vehicle Crash Causation Survey.

The simulation framework PRAEDICO developed by the author of the thesis is proprietary and not available to the public. On the other hand, parts of PRAEDICO were contributed to the development of openPASS, a cooperative open source project initiated by German vehicle manufacturers to design and access driver assistance systems, active safety, and automated driving (Tenzer et al., 2016). The simulation framework openPASS is available under the Eclipse Public License 1.0 via the webpage of the Eclipse Foundation (Eclipse Foundation, 2018).

5.12 Usage of the thesis results

Stakeholders such as vehicle manufacturers and suppliers, consumer organizations, lawmakers and road authorities, and research institutes have an interest in effectiveness assessments (Section 2.3). The simulation results from Paper II and IV indicate that about two-third and 80 percent of the LTAP/OD and SCP accidents can be avoided with Intersection AEB, respectively. These *a priori* effectiveness assessments however use idealized sensing systems and assessments of false positive activations were not conducted. Further, the dataset does not include other traffic participants except those involved in the accident, and thus an underestimation of sight obstruction is present. Adjusting for the idealization of the sensing system (as described in Section 5.5) and for the underestimation of sight obstruction (as described in Section 5.7), first generation of Intersection AEB may be able to avoid 20 to 25 percent and 30 to 40 percent of LTAP/OD and SCP accidents, respectively. With the continuous development of sensing system performance, crash avoidance rates may increase correspondingly. As mentioned in Section 5.4, the simulation results should be interpreted in context of their parameterizations, effects of variation, and dependencies on market penetration.

Examples of the external usage of the paper results are given in Figure 17.

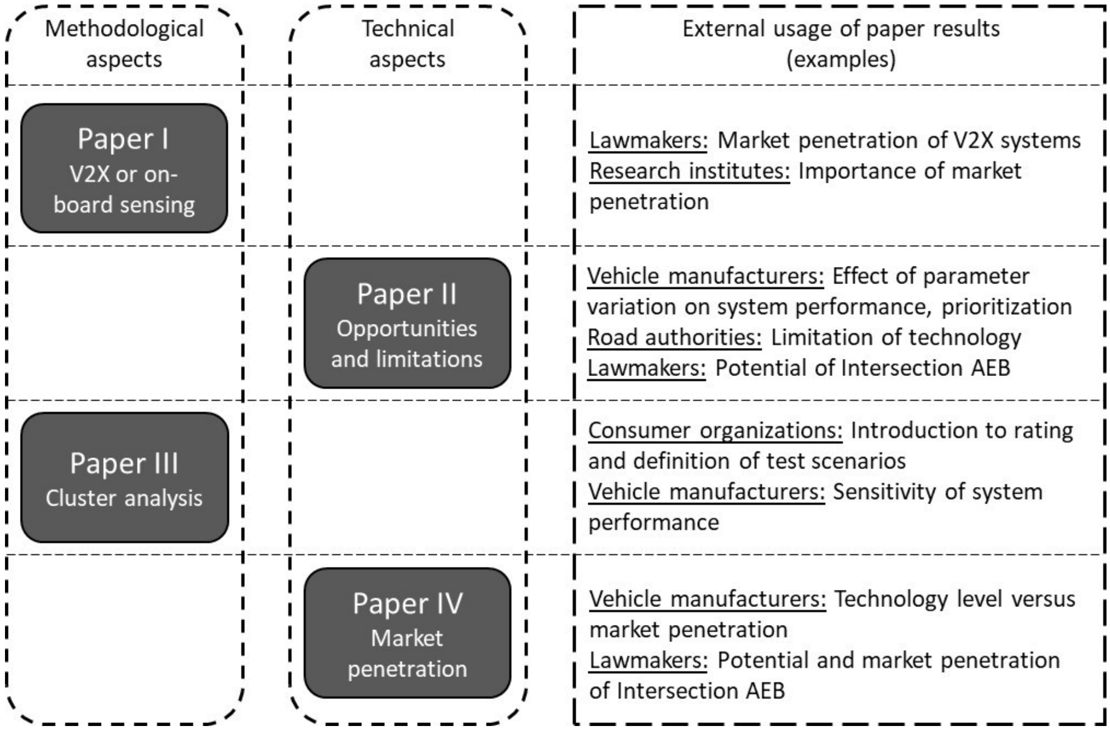

Figure 17: Overview of the individual papers and how the results of the papers can be used by different stakeholders (external usage)

Lawmakers in the United States have already identified the need for a fast introduction of V2X communication (Harding et al., 2014). Similarly, Euro NCAP has put a rating of Intersection AEB on the roadmap for 2020 (Euro NCAP Strategy Working Group, 2015). The results of this thesis verify the importance of these steps, as high benefits can be expected (Papers I, II and IV). Not only have estimated benefits been computed, but also how they depend on market penetration. Lawmakers can use these results to stimulate vehicle fleet exchange for higher market penetration rates. Consumer organizations will find information about scenario clustering in Paper III to define test scenarios. Vehicle manufacturers and safety system suppliers can use the results from different parameter setting of the investigated Intersection AEB for basic system specifications and identification of performance enhancements. Finally, parts of the PRAEDICO may be used for other assessment frameworks.

6 CONCLUSIONS

Intersection crash occurrence can be substantially reduced by introducing car-to-car Intersection AEB. The avoidance potential for straight crossing path (SCP) accidents is higher than for left-turn across path accidents with oncoming traffic (LTAP/OD). With a comfort boundary threshold of 5 m/s^2 for longitudinal and lateral acceleration, close to half of the LTAP/OD accidents can be prevented by the turning vehicle. When both turning and straight heading vehicles are Intersection AEB equipped, the percentage further increases. The settings of the comfort thresholds have a substantial impact on effectiveness: when comfort zone boundaries are reduced to 3 m/s^2 or increased to 7 m/s^2, the effectiveness correspondingly increases and decreases by more than 10 percent. A quick AEB response has a similar positive effect to lowering comfort boundaries, but without the risk of associated false activations. One challenge is the late identification of a collision course in a LTAP/OD scenario. Though about 90 percent of the accidents are caused by the turning vehicle, and thus there is a natural intention to have an AEB system available for the turning vehicle, AEB functionality implemented in the straight heading vehicle is a good complement; most of the accidents it can prevent were not addressed by the turning vehicle's AEB system. Additionally, reduction of kinetic energy by both conflict participants supports injury mitigation in cases where an accident cannot be prevented. In an SPC scenario, close to 80 percent of the accidents and 90 percent of the moderate to fatal injuries can be prevented. The main reason for the difference in performance compared to a LTAP/OD scenario is that both vehicles are initially on a conflict course.

Obviously, there are also differences to the sensor field-of-view requirements: Whereas for the LTAP/OD scenario a sensor with 70° field-of view covered about 95 percent of the opponent vehicles at the time of decision making, for SCP the sensor field-of-view had to be increased to 180°. Specific to intersection conflicts is the ability of both involved vehicles to avoid or mitigate a crash by AEB. This is not the case for rear-end crashes. For head-on crashes, both vehicles must be equipped with AEB to potentially avoid the crash by braking.

Besides technical specifications such as brake performance and processing delays, two main parameters were identified that have a substantial effect on the Intersection AEB performance: vehicle speed and exclusion of conflict escape paths. When vehicle speed is reduced, escape alternatives through steering become less favorable compared to braking and AEB activation can be initiated earlier. Further, the exclusion of escape paths other than the intended path reduced the available steering maneuvers to steering within the driver's own lane. Thus, with limited steering options, an AEB system can be activated earlier.

As it will take many years until Intersection AEB systems have penetrated the vehicle fleet to a full extent and as 100 percent market penetration may never be reached, the effectiveness of Intersection AEB was investigated at different market penetration stages. For SCP, the relative percentages of front, left side, and right side impacts will remain nearly constant. However, effectiveness in avoiding crashes and mitigating injuries was found to increase disproportionally quickly at low market penetrations and increase more slowly at higher market penetrations. The same behavior is expected for LTAP/OD crashes, though here the impact types will change over market penetration: The total number of remaining crashes decreases while the relative proportion of front crashes increases. Correspondingly, in right-hand traffic the relative percentage of right side impacts decreases, whereas the relative percentage of left side impacts remains constant. Negative consequences due to the change of impact constellation changes were not observed.

However, the average severity of the remaining SCP and LTAP/OD accidents was substantially reduced only at high market penetration rates. Thus, it is not foreseeable that the requirements for passive safety can be reduced in the near- to mid-term without negative consequences. Even with a 100 percent market penetration there will be still side impacts which involve high kinetic energy such as impacts with a delta-V higher than 30 km/h.

V2X communication has great potential to avoid and mitigate intersection accidents, especially as the limitations of on-board sensing such as sight obstruction and weather dependency are bypassed. However, this potential is dependent on the presence of communication technology integrated into other vehicles, a shortcoming that becomes relevant when possible market penetration time frames are investigated. Further, information about the environment, necessary to reduce the number of possible escape paths, may not be available. Thus, it is a valuable complement to on-board sensing, but a limited alternative on its own.

Intersection accidents are diverse and a reduction of description parameters without losing variance was not achievable. Grouping of intersection by means of different machine learning techniques accidents showed strong dependencies on the selection of clustering variables. With an increased number of cluster variables, the identified cluster structure tended to get weaker. Therefore, the testing of Intersection AEB in hardware tests will be challenging: small changes in the test setup lead to different avoidance outcomes. As hardware tests are usually limited in quantity due to effort and cost, virtual simulation is proposed as a method to conduct representative investigations of system performance in the real world. When a certain market penetration has been reached, *a posteriori* investigation should be conducted based on real-world data to gain an understanding of the true effectiveness and validate the method(s) used for *a priori* assessment(s).

7 FUTURE RESEARCH

Three main areas are particularly interesting for further research.

First, a similar analysis as described in Papers II to IV can be conducted with real-world accident data from India and China. The method for data generation has already been tested and published (Shaikh and Sander, 2018). The objective would be to identify whether the results generated on the basis of German accident data are of the same magnitude as those for other parts of the world, especially emerging markets.

Second, as mentioned in Section 2.3.6, the next steps in the modified Deming cycle could be taken. For a refined *a priori* assessment, some of the limitations described in Section 5.10 would be addressed by specifying a more realistic sensor model, coefficient of friction estimation, and algorithm settings. To find plausible algorithm settings, an estimation of false-positives is also necessary. This could be done by converting naturalistic driving sequences in intersections into the appropriate time-series format and running them in PRAEDCIO. Then also an *a posteriori* assessment could be planned before the market introduction of Intersection AEB. Such a plan could include evaluating a minimum number of vehicles involved in accidents to achieve a certain confidence level and identifying vehicles with Intersection AEB in relevant datasets.

Third, PRAEDICO was developed as a universal simulation framework that can handle all conflict types and scenarios as long as at least one passenger car is involved. SCP and LTAP/OD scenarios are not only frequent among car-to-car accidents, but also among accidents involving motorcycles and bicycles. Although the algorithm is applicable to those conflict partners, the comfort boundaries and path prediction models need to be adapted. Further research is necessary, particularly for safety systems addressing vehicle-to-motorcycle conflicts.

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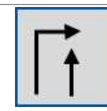
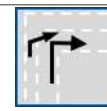
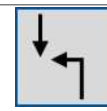
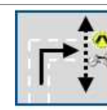
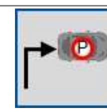
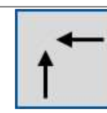
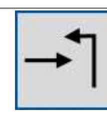
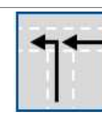
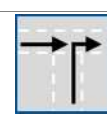
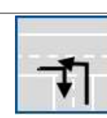
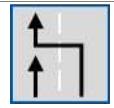
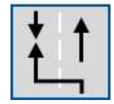
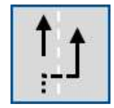
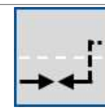
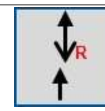
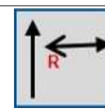
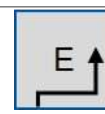
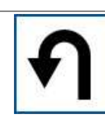
APPENDIX A

Scenario classification based on GIDAS variables.

ID	Nomenclature for RHD traffic	Description	GIDAS Variables	Pictogram
1	Technical Failure	Vehicle sustains a technical failure with the consequence of a conflict situation.	UTYP in (771, 772, 773, 774, 775) or (URSWIS in (50, 51, 52, 53, 54, 55) and TECHMAN equal 1); Exclusive for all following scenarios	
2	Vehicle Loss of Control	Vehicle loses stability and skids with the consequence of a conflict situation.	UTYP in (101, 102, 109, 111, 112, 119, 121, 122, 123, 129, 131, 132, 139, 141, 151, 152, 153, 159, 161, 162, 163, 169, 171, 172, 173, 179, 181, 182, 183, 189, 199) and SCHLEU equal 1	
3	Driver Loss of Control	Driver loses control over the vehicle and creates a conflict situation.	UTYP in (101, 102, 109, 111, 112, 119, 121, 122, 123, 129, 131, 132, 139, 141, 151, 152, 153, 159, 161, 162, 163, 169, 171, 172, 173, 179, 181, 182, 183, 189, 199) and SCHLEU in (2,97,99)	
4	Driver Incapacity	Driver is in drowsy or physically impaired and creates a conflict situation.	UTYP in (761, 762, 763)	
5	Straight On-Path / Same direction	Vehicle heads straight on-path and creates a conflict with a vehicle ahead.	UTYP in (201, 231, 541, 542, 549, 583, 584, 601, 602, 603, 604, 609, 611, 612, 613, 614, 619, 621, 622, 623, 624, 629)	
6	Straight On-Path / Pedestrian Longitudinal	Vehicle heads straight on-path and creates a conflict with a pedestrian moving in same or opposite direction.	UTYP in (671, 672, 673, 674)	
7	Straight On-Path / VRU Crossing	Vehicle heads straight on-path and creates a conflict with a pedestrian crossing the roadway.	UTYP in (272, 274, 341, 342, 343, 344, 349, 361, 362, 363, 364, 369, 371, 372, 379, 401, 402, 403, 404, 405, 409, 411, 412, 413, 414, 419, 421, 422, 423, 424, 429, 431, 432, 433, 434, 435, 436, 439, 441, 442, 443, 444, 449, 451, 452, 453, 454, 455, 459, 461, 462, 463, 464, 465, 469, 471, 472, 473, 479, 491, 492, 493, 494, 499)	
8	Straight On-Path / Parked Vehicle	Vehicle heads straight on-path and creates a conflict with a parked vehicle.	UTYP in (501, 502, 509, 581, 582, 589, 741, 742, 749)	

9	Turn Across Path / Same Direction	Vehicle turns across path and creates a conflict with another vehicle moving in same direction.	UTYP in (202, 203, 232)	
10	Turn Off-Path / Same Direction	Vehicle turns off-path and creates a conflict with another vehicle moving in same direction.	UTYP in (251, 252, 259)	
11	Left Turn Across Path / Opposite Direction	Vehicle turns left across path and creates a conflict with another vehicle moving in opposite direction.	UTYP in (211, 212, 281, 351, 354, 543)	
12	Turn On-Path / VRU Crossing	Vehicle turns on-path and creates a conflict with a VRU crossing a roadway.	UTYP in c(221, 222, 223, 224, 225, 229, 241, 242, 243, 244, 245, 249, 282, 283, 284, 285, 273, 275, 481, 482, 483, 484, 489)	
13	Turn On-Path / Parked Vehicle	Vehicle turning on-path and creates a conflict with another parked vehicle.	UTYP in (591, 592, 593, 594)	
14	Straight Crossing Path	Vehicle crosses intersection and creates a conflict with another straight crossing vehicle.	UTYP in (271, 301, 311, 321, 331, 353, 355)	
15	Left Turn Across Path / Lateral Direction	Vehicle turning left across path and creates a conflict with another vehicle approaching laterally.	UTYP in (215, 261, 302, 312)	
16	Left Turn Into Path / Lateral Direction	Vehicle turning left into path and creates a conflict with another vehicle approaching laterally.	UTYP in (322, 332, 352)	
17	Right Turn Into Path / Lateral Direction	Vehicle turns right into path and creates a conflict with another vehicle approaching laterally.	UTYP in (303, 304, 213, 214)	
18	Turn Off-Path / Lateral Direction	Vehicle turns off-path and creates a conflict with another vehicle due to lateral approach.	UTYP in (262, 286, 306, 323, 324, 326, 333, 334)	

19	Lane Change / Same Direction	Vehicle changes lanes and creates a conflict with another vehicle moving in same direction.	UTYP in (204, 233, 305, 313, 314, 315, 373, 374, 551, 552, 559, 631, 632, 633, 634, 635, 639, 641, 642, 643, 644, 645, 646, 649, 663)	
20	Lane Change / Opposite Direction	Vehicle changes lanes and creates a conflict with another vehicle moving in opposite direction.	UTYP in (325, 335, 661, 662, 664, 553, 554)	
21	Lane Departure / Same Direction	Vehicle departures from lane and creates conflict with another vehicle moving in same direction.	UTYP in (651, 652, 659)	
22	Lane Departure / Opposite direction	Vehicle departures from lane and creates a conflict with another vehicle moving in same direction.	UTYP in (681, 682, 683, 689)	
23	Backing-Up / Opposite Direction	Vehicle reverses and creates a conflict with another vehicle moving in opposite direction.	UTYP in (711, 712)	
24	Backing-Up / Lateral Direction	Vehicle reverses and creates a conflict with another vehicle moving in lateral direction.	UTYP in (571, 572, 579, 713, 714, 715)	
25	Evasive Maneuver	Vehicle makes an evasive maneuver and creates a conflict with another vehicle.	UTYP in (511, 512, 519, 521, 531, 532, 533, 534, 539)	
26	Object On Road	Vehicle is in conflict with an object on road.	UTYP in c(731, 732)	
27	Animal On Road	Vehicle is in conflict with an animal standing on or crossing roadway.	UTYP in (751, 752, 753, 759)	
28	U-Turn	Vehicle makes a U-turn and creates a conflict with another vehicle.	UTYP in (721, 722, 723, 724, 729)	
29	Parking	Vehicles is in conflict at a parking area.	UTYP in (561, 562, 569, 701, 702, 703, 709)	

30	Other	Vehicle is involved in other kind of conflict.	UTYP in (209, 219, 239, 279, 299, 359, 399, 599, 669, 679, 699, 719, 799)	OT

APPENDIX B

PRAEDICO GUIs for data selection and entry

Figure B.1: PRAEDICO main GUI of PRAEDICO. In this GUI three different actions can be selected: A) Select data source and convert data to a Matlab file. B) Select Matlab data file for pre-crash simulation. C) Select Matlab simulation result file for analysis.

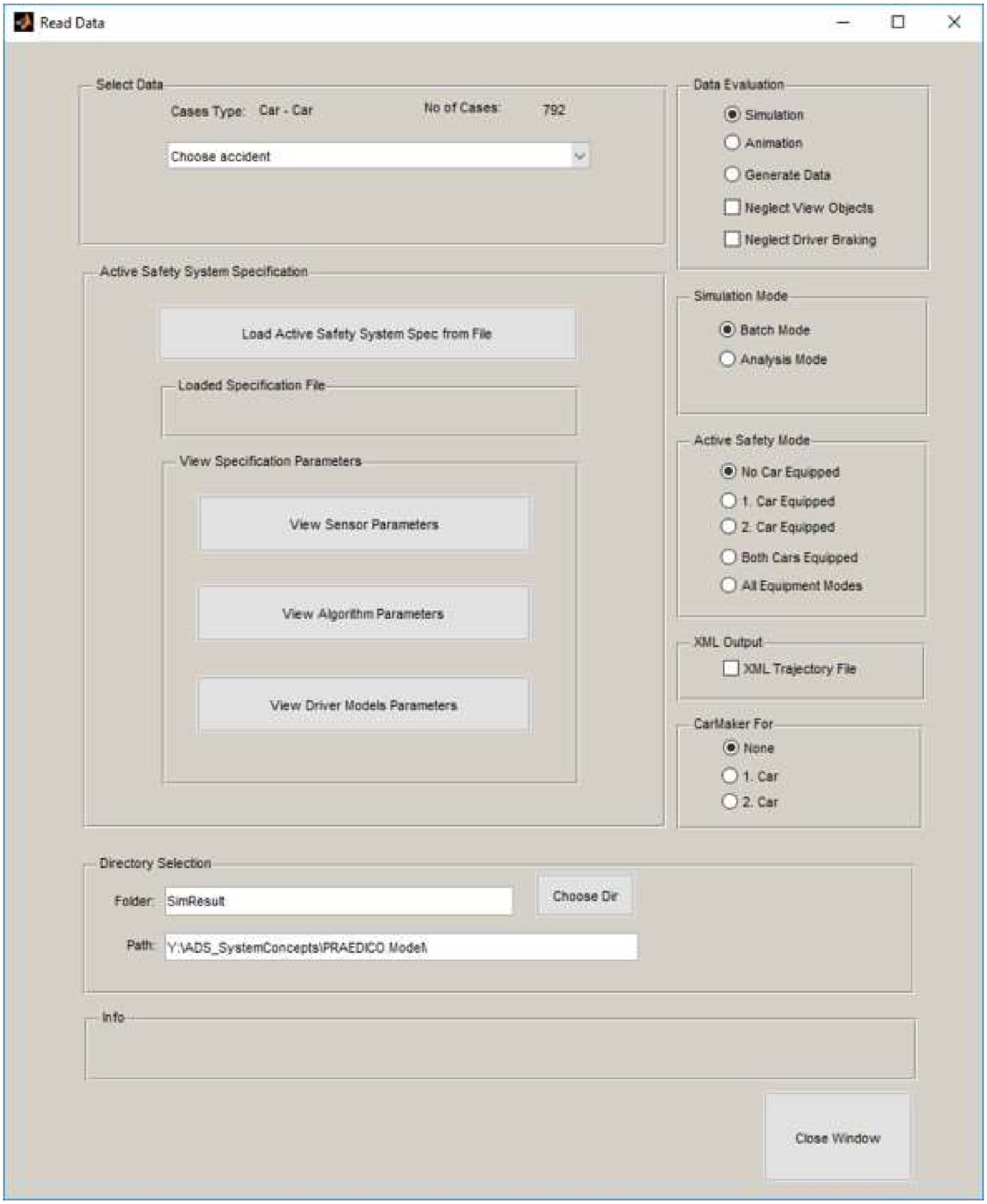


Figure B.2: PRAEDICO simulation GUI: In this GUI the global settings for the pre-crash simulation are done: A) Selection of cases to be simulated (all, selected cases, a single case). B) Selection of processing type (animation, simulation, export to proprietary data format for in-house simulation platform). C) Selection of analysis or batch mode. Analysis mode stores all simulation signals and generates a video. Batch mode only stores simulation results specified for the result file and video is disabled. D) Selection of which vehicle is equipped with the specified safety system. E) Trajectory output for driving robot used in physical testing. F) Selection to conduct pre-crash simulation in CarMaker. G) Load specification file for the active safety system or define manually the parameters of the sensors, algorithms, and driver model.

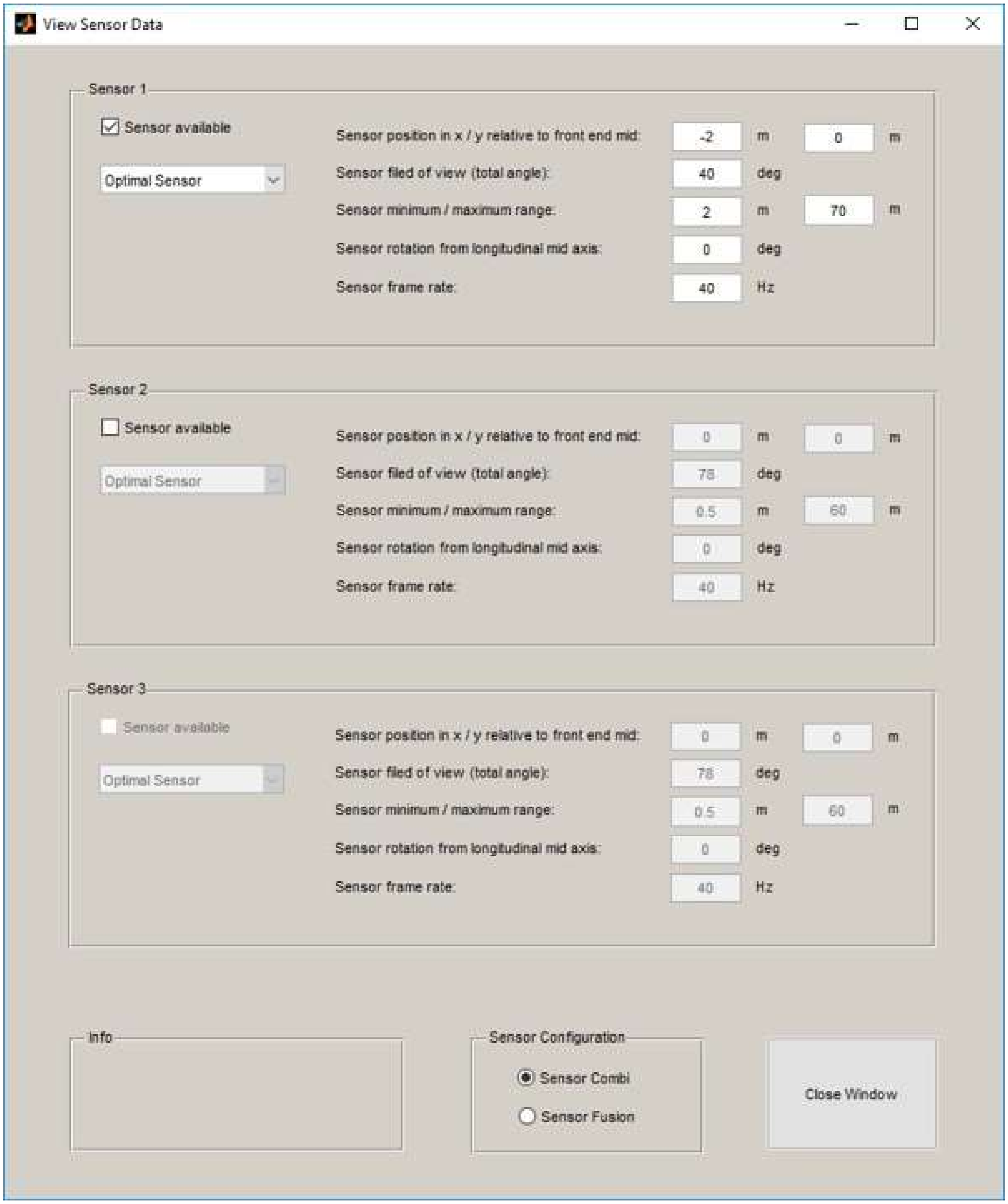


Figure B.3: PRAEDICO sensor model GUI: In this GUI the number and type of sensors are specified. For each sensor, information about the field-of-view, position and orientation, and the sample frequency is defined. Further, it can be chosen, if the sensor information will be combined i.e. to increase the field-of-view or fused, i.e. to reduce measurement uncertainty. The initial parameter setting can be overwritten and are saved together with the simulation results.

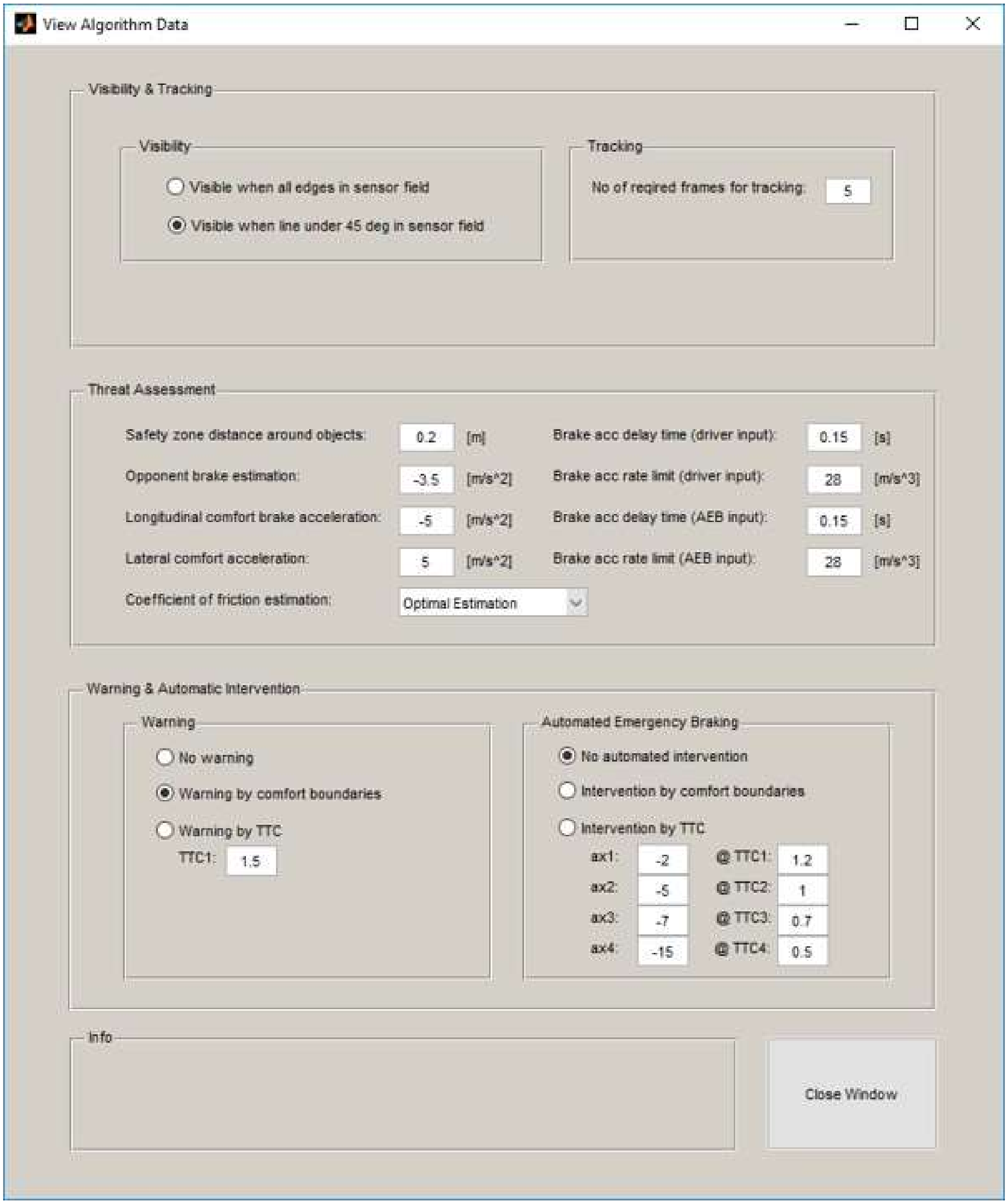


Figure B.4: PRAEDICO algorithm model GUI. In this GUI, visibility and tracking options are specified. Further comfort zone boundaries are set, the accuracy of friction estimation is defined, and the brake silent time and the brake jerk for the manual brake and AEB system are specified. Warning and AEB intervention can be either set as disabled, depending on comfort boundaries, or based on a fixed TTC. For AEB, a brake profile based on up to four acceleration levels at specified TTC can be defined. The initial parameter setting can be overwritten and are saved together with the simulation results.

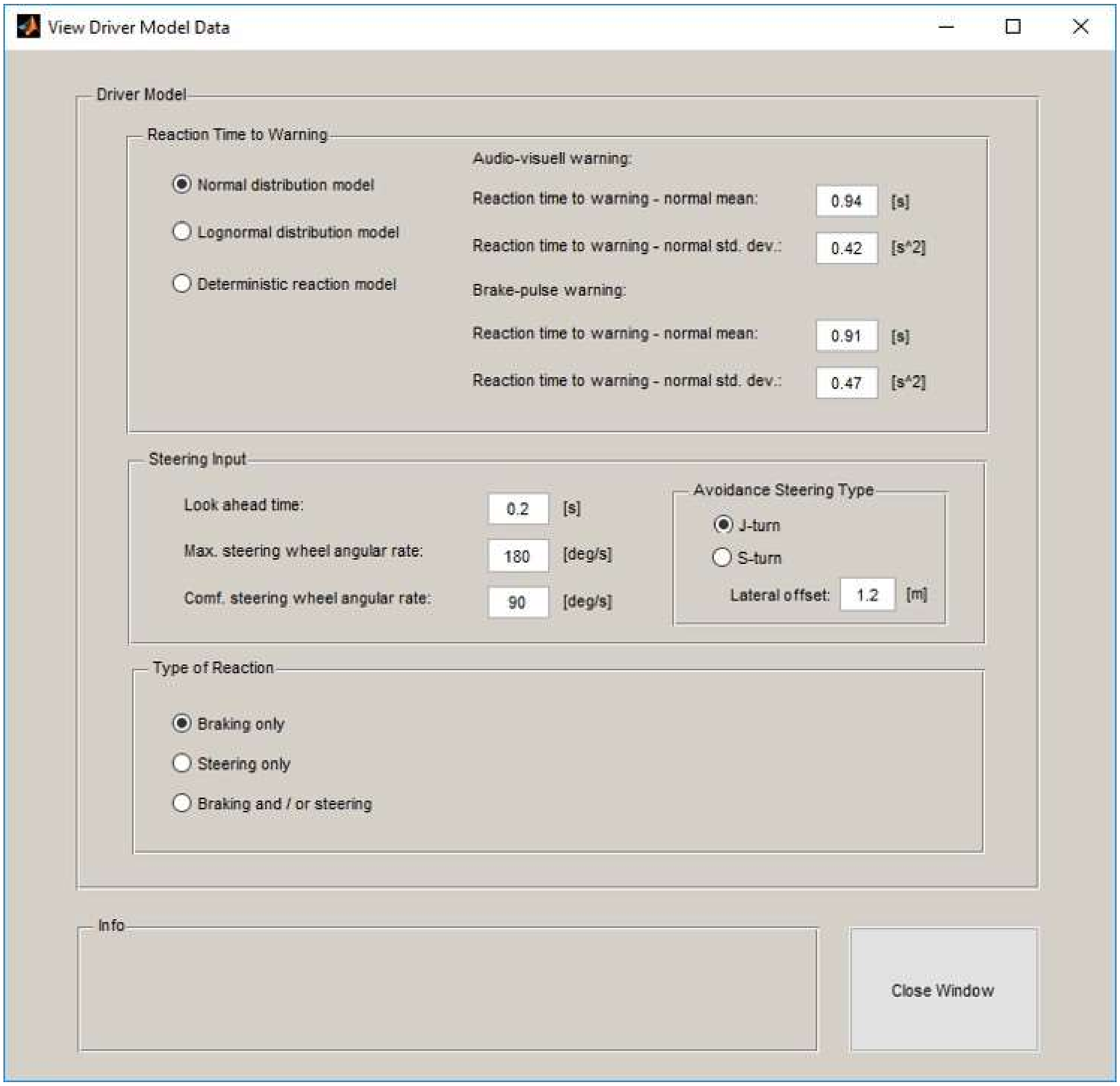


Figure B.5: PRAEDICO driver model GUI. In this GUI, the method for computation of a reaction time is defined. Further, the driver steering input for both, trajectory following, and conflict escape maneuvers are set. The look ahead time is used for path following. The steering angular rates describe how fast the driver rotates the steering wheel in an escape maneuver until comfort zone boundaries (comfort steering) or physical limits (max steering) are recached. The type of reaction describes, if a driver reacts to a warning by braking, steering, or braking and steering. The initial parameter setting can be overwritten and are saved together with the simulation results.