OSCCAR:

FUTURE OCCUPANT SAFETY FOR CRASHES IN CARS

Future collision type matrix

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Primary Author(s)	Jan Dobberstein | Mercedes-Benz AG Daniel Schmidt | Robert Bosch GmbH Martin Östling | Autoliv Magdalena Lindman | Volvo Cars András Bálint | Chalmers University of Technology Patrick Höschele | TU Graz
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CONTRIBUTORS

Name	Organization	Name	Organization
Martin Östling	Autoliv	András Bálint	Chalmers University of Technology
Jan Dobberstein	Mercedes-Benz AG	Patrick Höschele	TU Graz
Daniel Schmidt	Robert Bosch GmbH	Corina Klug	TU Graz
Thomas Lich	Robert Bosch GmbH	Magdalena Lindman	Volvo Cars
Lisa Sulzberger	Robert Bosch GmbH		

FORMAL REVIEWERS

Name	Organization	Date
Nils Lubbe	Autoliv	2021-07-12
Jorge Lorente Mallada	TME	2021-07-13

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ABBREVIATIONS AND DEFINITIONS

Term	Definition
AD	Automated driving
ADAS	Advanced driver assistance systems
AEB	Autonomous emergency braking
BASt	Federal Highway Research Agency (Germany)
CADaS	Common Accident Data Set
CAE	Computer-aided engineering
CARE	Crash database containing police-reported data from road crashes with personal injury in EU-28 as well as EFTA (Norway, Iceland, Switzerland, Liechtenstein)
Delta-v	change in velocity of a colliding vehicle before and after the collision
EC	European Commission
EFTA	European Free Trade Agreement
EU-28	EU countries in 2017, i. e., the current 27 EU countries plus the United Kingdom
Fatal crash	A crash in which at least one person died within 30 days as a result of the crash
FEM	Finite element model
Fleet penetration	Share of vehicles in use equipped with a specific system
GIDAS	German In-Depth Accident Study: the name of a project collecting in-depth crash data as well as the name of the resulting database
HBM	Human Body Model
highD	Highway Drone Dataset
HLRS	High Performance Computing Unit of University of Stuttgart
IIHS	Insurance Institute for Highway Safety (USA)
Inherently avoided crash	A crash whose main cause was a violation of traffic rules and would therefore be avoided by default by automated vehicles
Injury crash	A crash in which at least one person was injured
LS-Dyna	Finite element Simulation software LS-DYNA
LTAP LD	Left-turn across path - lateral direction
LTAP OD	Left-turn across path - opposite direction
MAIS	Maximum AIS (Abbreviated Injury Scale)
Motorway pilot	Automated driving functionality addressing motorway front-to-rear-end conflict situations, defined in D1.1
MY	Model year
NCAP	New Car Assessment Program
NHTSA	National Highway Traffic Safety Agency (USA)
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
openPASS	Open Plattform for the Assessment of Safety Systems
PCM	Pre-Crash Matrix: a subset of GIDAS consisting of cases with sufficient information for simulation
PDO crash	Property damage only crashes: those crashes where nobody was injured
RSS	Responsibility-Sensitive Safety

Term	Definition
SCP	straight crossing path
STRADA	Swedish Traffic Accident Data Acquisition: Swedish national crash database
THOR-50M	Test Device for Human Occupant Restraint fifty percentile male
THW	Time Headway
Urban robo car	Automated driving functionality addressing conflict situations in urban-like intersections, defined in D1.1
V&V	Verification and validation
VCTAD	Volvo Cars Traffic Accident Database, in-depth crash database containing crashes with the involvement of a Volvo car
VKT	Vehicle Kilometers Travelled: a form of exposure data, indicating driven distance

1 EXECUTIVE SUMMARY

The objective of Work Package 1 (WP1) within OSCCAR is to predict future traffic scenarios as well as future crash configurations for automated vehicles based on current crash data. Human error in terms of performance limits, lack of attention or lack of obeying traffic rules is estimated to contribute to the majority of road crashes. Since automated vehicles are expected not to show human imperfections, they are expected to be involved in considerably fewer crashes. Yet, automated vehicles are expected to be involved in unavoidable collisions within their Operational Design Domain (ODD). The crash configurations as well as the crash pulses derived from those remaining road crashes serve as an input for occupant protection measures in other OSCCAR work packages.

A first analysis of future crash configurations of automated vehicles was reported in OSCCAR WP1 deliverable D1.1 [1]. By assuming some crashes linked to, e. g., violation of traffic rules, and an inherent avoidance of those crashes by automated vehicles on the one hand and performing pre-crash simulations with a conceptual collision avoidance function on the other hand, remaining crashes for urban intersections and motorways were identified. Out of these remaining crashes, representative test-scenarios were derived by cluster analysis and presented as final results of D1.1.

The OSCCAR WP1 deliverable D1.3 provides a comprehensive outlook from accident research perspective on potential challenges for occupant safety of automated vehicles beyond the state-of-the-art. It covers the substantial work on crash pulses – selecting them from predicted crash configurations and transferring them into useful acceleration time series data for occupant simulation. By using openPASS, a novel traffic model is used to amend the initial D1.1 findings on potentially remaining crashes of automated vehicles where traditional crash data is limited. Finally, the EU weighting completes the new methodology and provides EU figures based on the local and national results.

In the course of the OSCCAR project, D1.3 has progressed against D1.1 and the state of the art by answering three main questions, as described below in more detail:

- What crash configurations in D1.1 should be used for OSCCAR in-crash test cases and what are their corresponding crash pulses? This question is closely linked to the need for a method to generate generic, yet realistic crash pulses. The minimal requirements are on the one hand to predict crash pulses based on current vehicle structures, which are representative enough for the analysis of future occupant restraint principles. On the other hand, if feasible, the crash pulses need to be generic because of unknown future vehicle structures and its relation to vehicle safety of automated vehicles. Herein, we present in section 3 a method to select and generate generic crash pulses recommended to be used when developing restraint system for automated vehicles. These pulses were compared with standard frontal load cases in occupant simulation studies and showed overall lower injury risk results. In a parallel approach, car-make specific crash pulses were derived in order to improve the match between the different steps, e. g., the car make selection for the pre-crash simulation, the pulse-generating in-crash finite element (FE) simulation, and the in-crash occupant human body model (HBM) simulations.
- Can the limitations of the motorway scenario analysis identified in D.1.1 be remedied by using a different method: stochastic traffic simulation? The D1.1 simulations were based on re-simulation of real-world accidents and gave first insights into future collision statistics and crash configurations. Yet, the authors identified limitations in the D1.1 simulations based on reconstructed pre-crash trajectories, especially for motorway situations. These were the lack of surrounding traffic before the accident, limitations in the generic model of the automated driving function represented by an emergency braking function, and crash data sets possibly not covering specific ODD's, unique scenarios, and more. For those motorway situations, we

applied herein a recently developed open-source method of stochastic traffic simulations. The simulations address future, yet unknown, traffic and possible crashes, both arising from individual traffic maneuvers and interactions of hundreds of thousands of drivers with mixed behaviours (cooperative, aggressive). In section 5, we discuss the methodology, its validity and advantages, and present the simulation results for future motorway traffic. Especially the results from on-ramp scenarios amend the previous D1.1 findings leading to moderate overlap cut-in configurations. Due to the multi-agent character of these traffic scenarios, such collisions cannot be obtained from currently available crash data. In summary, from our stochastic simulation results, we could confirm the initial assumptions of automated vehicles being involved in road crashes relevant for the development of future occupant protection principles – at least in mixed traffic with conventional and automated traffic participants.

- How many accidents will be avoided or mitigated by automated vehicles on a European level? So far, previous results in D1.1 of expected crash configurations were based on different statistics of national or regional level. Aggregation of all information of different levels and countries onto a single, European level is desired and delivered. In section 6, we present a comprehensive method as well as the final OSCCAR WP1 figures regarding the number of avoided and mitigated crashes at various levels of fleet penetration of the automated driving vehicles. For instance, our method indicates that more than 50 000 crashes in the European Union and the UK (EU-28) can be avoided or mitigated from a hypothetical fleet penetration of 30% of the urban robo car and motorway pilot systems analyzed in WP1. Full market penetration of automated vehicles would give even larger benefits: complying to traffic rules alone would avoid up to 350 000 crashes in EU-28, which is 32% of all crashes in EU-28. Additionally, we discuss how the crash frequency in traffic simulations should be calibrated to appropriately represent motorway traffic in EU-28 and provide, as we argue, reasonable settings.

Based on the results of this work, the other OSCCAR work packages received a basis for evaluating future interior use cases with virtual assessment methods focusing on the use of active human body models. Connecting different domains of safety assessment led within the entire OSCCAR project to a new methodology for integrated virtual safety assessment which allows to manage the complexity arising with automated vehicles in terms of, e. g., new crash configurations, pre-crash behavior, and new seating positions.

In future work, the various models used in this traffic simulation approach must be further refined and validated, considering, e. g., more detailed traffic observation data whenever available or more sophisticated driver behavior mechanisms. The OSCCAR WP1 approach should be considered for future research and development in the field of safety of automated vehicle concepts as well as occupant safety solutions. While OSCCAR made use of a wide range of existing data sources, future European research activities should include harmonized data acquisition methods of both, traffic and crash situations, to enable improvements of the predictions elaborated in OSCCAR WP1. For instance, additional to the inherently avoided 350 000 crashes each year in the EU by automated vehicles complying with traffic rules, it was identified that the avoidance potential in equally many further crashes requires further investigation by, e. g., pre-crash simulation methods as in D1.1. A correct assessment of these cases would give an even more precise outlook regarding the potential safety benefit of automated vehicles in the EU-28.

2 OBJECTIVES

First, the objectives for WP1 are listed and it is identified which are addressed in the different deliverables (D1.1 – D1.3). Second, the objectives are compared to recent literature, published after D1.1 was finished (April 2019 [1]), to confirm their relevance in the present day. Third, based on the initial objectives, the state of the art in previous OSCCAR WP1 deliverables and the literature, the specific objectives and contribution to knowledge provided by D1.3 are specified. Finally, partner contributions to D1.3 are listed.

2.1 Objectives of WP1

The objective of Work Package 1 (WP1) within OSCCAR is to predict future traffic scenarios as well as future crash configurations for automated vehicles based on current crash data. This includes methodology development, crash data analysis, virtual simulation and result interpretation.

The following objectives and research questions were addressed in OSCCAR WP1 (in brackets: the WP1 deliverable(s) covering the activity):

- Macroscopic crash data analysis (D1.1): what safety impacts and crash data trends are influencing future crash numbers?
- Modelling use cases for automated driving functions for accident prediction (D1.1): how can we specify relevant situations by analyzing crash data for an assumed generic automated driving functionality? For instance, analyzing urban intersection crashes and their causation factors with respect to a fully automated driving capability in an urban ODD. What effects of the automated driving functions modify crash configurations relevant for automated vehicles?
- Microscopic crash data analysis (D1.1): how can relevant boundary conditions of automated driving (road geometry, road surface condition, weather, etc.) be represented in analyzing/filtering crash databases?
- Counterfactual pre-crash (D1.1) and traffic simulation (D1.3): what kind of automated driving functionalities can be incorporated in scenario or traffic simulation for the pre-crash phase? What can we learn regarding changes of crash configuration distributions?
- Result analysis and crash configuration selection (D1.3): how do we derive a limited number of relevant crash configurations for the ”OSCCAR test case matrix” [3] from the population of accidents that are expected to remain?
- Generic pulse creation (D1.3): which crash pulse (i. e., in-crash acceleration time series) can be made available to all OSCCAR partners to incorporate generic, yet realistic crash behavior of modern vehicle structures in the identified relevant crash configurations?
- EU level weighting (D1.3): given the limited geographical coverage of datasets used for the analysis (e. g., pre-crash matrix (PCM) data from the crash database GIDAS (German In-Depth Accident Study), how can we conclude what the results represent on EU level?

Figure 1 shows on a top level, how the activities and results are connected. It illustrates, too, how WP1 results were reported in different deliverables and how they build up upon each other, e. g., the generic crash pulses described in section 3 of D1.3 are based on D1.1 crash configurations; or the D1.3 traffic simulations were conducted using the D1.2 openPASS traffic simulation approach. For a more detailed understanding of the work flow and the used crash data sources please find further overviews in Figure 4 in section 4.1 and Figure 35 in section 6.1.

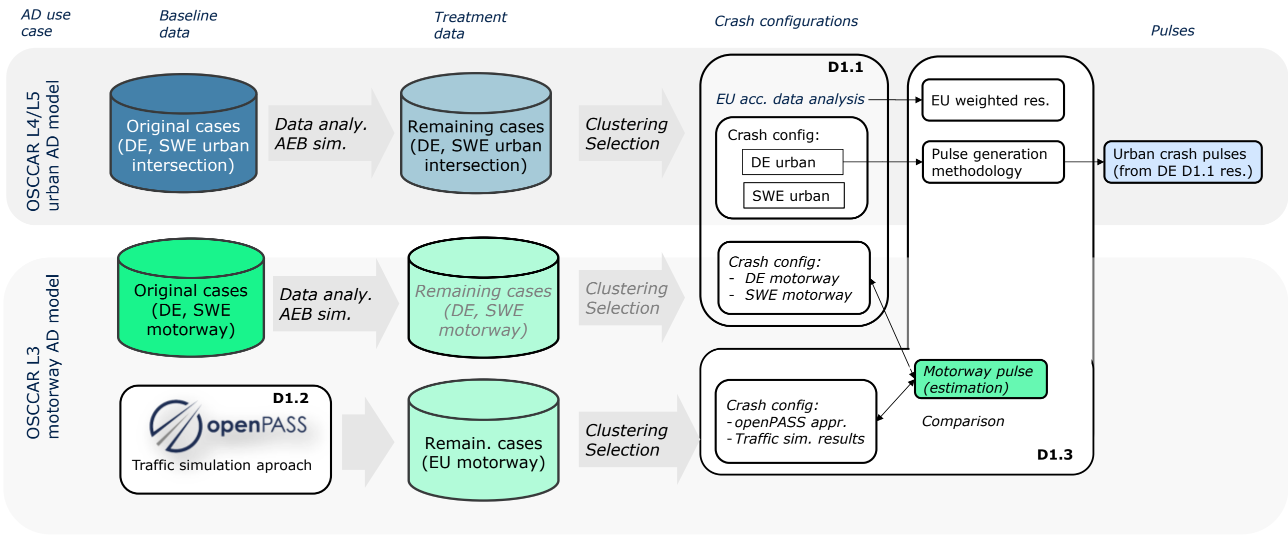


Figure 1: Overview of OSCCAR WP1 activities how to predict remaining crashes and determine future crash configurations

2.2 Relevant studies in safety assessment of automated vehicles

Deliverable D1.1 was written and finalized in April 2019 including a comprehensive literature review. Hence, this section lists and summarizes studies published thereafter in the dynamic research field of safety of automated driving that were brought up and discussed in project-internal WP1 expert meetings during the course of the project. It focuses on novel methodologies and results of safety impact assessment of automated driving and considerations of using crash data for deriving new passive safety requirements for automated vehicles.

In addition to the studies presented in this section, the UN Regulation on Automated Lane Keeping Systems was published in 2020 which is a milestone for introducing automated vehicles in real world traffic [4]. However, due to the scope of the regulation (automated driving lane keeping systems limited to motorway traffic up to 60 km/h), the requirements in terms of assessment scenarios were not further discussed in OSCCAR WP1.

2.2.1 BASt project report “Potential societal benefits by increasing vehicle automation”

The objective of this research project funded by the Federal Highway Research Institute of Germany (BASt) was to assess the potential of automated driving functions to improve road safety [5]. For identifying the benefits with respect to road safety, methods incorporating the characteristics of automated driving functions were used. For a generic motorway chauffeur, changes in frequency of the occurrence of accident scenarios are analyzed by using traffic simulations. This takes into account that automated driving functions continuously control the behavior of the vehicle (e. g. keeping sufficient distances), which, in contrast to active safety systems, leads to lower frequency of conflicting situations in the first place. Furthermore, the change of severity of motorway accidents was analyzed by using accident re-simulations of both real GIDAS cases and synthetic cases from stochastic variation based on the parameter distributions from real-world data. After determining the effectiveness of the automated driving functions, these effects are projected to the national level. The results indicate that a generic motorway chauffeur at a market penetration of 50% has a potential for reducing about 30% of all accidents with personal injuries on German motorways. More specifically, for cut-in situations, accident re-simulation showed a reduction of accident occurrence by 40% and of MAIS2+ injury severity (maximum abbreviated injury scale) by 42%, when generic automated vehicles were involved as followers. However, a share of rear-end accidents was expected to remain. Besides the use of an injury risk function, this impact assessment purely focused on accident avoidance by using traffic scenario simulation, but did not further investigate the influence of passive safety of automated vehicles.

2.2.2 White paper “Safety first for Automated Driving”

The goal of this white paper, written by experts from twelve companies involved in the development of automated driving functions, both OEMs and suppliers, was to provide an overview of a guidance about the generic steps for developing and validating safe automated driving systems [6]. The paper focuses on harmonizing requirements towards these functions in terms of leading principles, which forms the basis from which the “safety by design” methods and verification and validation (V&V) strategies are derived, with the aim to address the identified risks in a systematical way. It uses four development examples to illustrate the methods, including examples similar to the use cases analyzed in OSCCAR D1.1 (“urban robo car” and “motorway pilot”).

Most of the principles focus on the function development, but some points are relevant for the OSCCAR assessment scope: the authors of the paper identify the challenge to consider complex mixed traffic scenarios as well as currently unknown situations. These situations might arise from the interaction of human drivers with automated vehicles or between multiple automated vehicles. As a solution to this challenge, stochastic multi-agent traffic simulations are proposed, to predict future critical situations. Furthermore, the authors formulate the requirements with regard to passive safety that a) the vehicle layout should accommodate for modifications to crash scenarios due to vehicle automation and b) “occupant protection shall be ensured even when the customer has new uses for the interior that are made possible through automated driving systems” (p. 20 in [5]). These requirements are fully in line with the OSCCAR approach, e. g., with openPASS as a framework for stochastic traffic simulations. In addition, setting up and using the OSCCAR test case matrix [3] is a complementary method to the methods discussed in the paper.

2.2.3 IIHS paper on humanlike errors of autonomous vehicles

The objective of the analysis by IIHS [7] is to break down accident numbers based on police reported US crash data by different types of driver errors. It found that 94% of all crashes are caused by human errors. It is then analyzed more closely which of these crashes can be assumed to be prevented by automated vehicles [8]. By understanding the contributing factors in crashes, this study shows which errors must be avoided and what role automated vehicles could have in future traffic in order to display their safety potential. The authors conclude that, in addition to errors related to “sensing/perceiving” and “incapacitation” (33% of crashes), avoiding errors in “planning”, “executing” and “predicting” are crucial for development of automated driving functions. The OSCCAR approach investigates the impact of automated driving functions beyond the analysis of accident causation factors; in OSCCAR, we assume the technology to be capable of planning or execution tasks without humanlike error and identify what crashes automated vehicles will be exposed to in mixed traffic – although complying to traffic rules. Hence, the focus in OSCCAR with regard to unavoidable accidents is mainly on crashes caused by other traffic participants (see description of automated vehicles in D1.1).

2.2.4 Waymo study on "Reconstructed Fatal Crashes within an Autonomous Vehicle Operating Domain"

This study was published by the automated driving company Waymo looking into how autonomous technology performs in scenarios that led to fatal crashes by human drivers [11]. The authors used the term "autonomous", but in terms of functionality, the scope is the same of what OSCCAR calls "automated vehicles". For that purpose, the authors collected information on fatal crashes that took place in Chandler, Arizona between 2008-2017, matching to conditions of the ODD of Waymo vehicles (n = 72 crashes). All these cases were simulated with the Waymo vehicle in both the initiator and the responder role. Simulation of the "initiator role" means that the automated driving function by Waymo could avoid, e. g., a reconstructed version of a real-world fatal crash by obeying the speed limit - and not running a red light, as the initiator did in originally. The Waymo system avoided the collision in all cases. Furthermore, in the "responder role" they aimed to understand how well autonomous driving systems perform in response to mistakes made by humans. The system avoided 82% of these scenarios; 10% were mitigated and 8% remained unchanged. The mitigated cases were "Left-turn across path" situations. This study is fully in line with the approach taken for an urban ODD in OSCCAR D1.1 where one or both accident participant roles in car-to-car crashes were exchanged with a generic automated driving function: either by assuming inherent avoidance of humanlike errors as coded in the crash data or by counterfactual simulation with pre-crash trajectories of the respective intersection crashes. Furthermore, unavoidable simulated collisions occurred in three scenarios in the Waymo study: Front-to-Rear (with automated vehicle hit at the rear), Intersection, and Head-On. These crash configurations match with the relevant ones identified and used in OSCCAR D1.1.

2.2.5 Conclusions from literature study

All studies covered in this additional review support the approach of OSCCAR WP1 and lead to results including crashes expected to remain, hence the results are similar or consistent to what was found in OSCCAR WP1, e. g., in terms of motivating the need for traffic simulation (2.2.2), the overall assessment methodology (2.2.4) or similar exemplary crash configurations resulting from simulation (2.2.1, 2.2.4). In total, the additional studies confirm the early OSCCAR WP1 findings presented in D1.1 and are aligned with the points addressed in D1.3.

2.3 OSCCAR WP1 results in D1.3

This deliverable D1.3 picks up various activities, where at an earlier stage of the OSCCAR project, intermediate results were needed and covered in D1.1. In the beginning of OSCCAR WP1, various approaches and perspectives on the required crash configurations were discussed. One key requirement from the OSCCAR project plan towards the D1.1 methodology was to have results that allow for reasonably good estimations of unavoidable crashes at the earliest possible point in the project. Hence, the goal of D1.1 was to propose crash configurations that automated vehicles would be exposed to in mixed traffic. Those crash configurations were later used within OSCCAR, e. g., at the WP2 workshop on protection principles in April 2019 [9] and the T2.4 sled test series in WP2 [12]. The final OSCCAR WP1 deliverable D1.3 builds on and extends those early and intermediate findings and confirms and completes the methodological results presented in D1.1.

WP1 deliverable D1.1 covered in detail the background and the goals of the methodology development to predict future relevant crash configurations for automated vehicles in mixed traffic consisting of both human driven vehicles and automated vehicles. It also described the results of related research projects (like AdaptIVe [33]) and assessment concepts (e. g., the concept of Responsibility-Sensitive Safety (RSS) [2]) that determined potential safety impacts of automated driving functions as well as detailed descriptions of automated driving functions under development and safety assurance approaches according to the NHTSA Voluntary Safety Assessment.

Furthermore, different methods based on crash data analysis and pre-crash simulation were discussed with regard to their applicability in OSCCAR. Hence, based on this state-of-the-art, D1.1 finalized the requirements towards the OSCCAR assessment methodology and included its first implementation. The results in D1.1 can be considered as draft figures or intermediate results. Limitations of this initial analysis were already discussed in detail in section 8 of D1.1; further insights for potential improvement of D1.1 results were provided by WP2 in project-internal meetings.

Here, in the OSCCAR WP1 deliverable D1.3, the shortcomings of D1.1 are addressed and the final results of the OSCCAR WP1 approach are described. Specifically, the main improvements are as follows:

- Comprehensive methodology on detailed selection of crash configurations (section 4): The results in terms of clustered crash configurations from D1.1 were further processed to determine a limited number of relevant points in the test case matrix for further development.
- Generic crash pulse generation (section 4): Based on the novel crash configurations, there were no crash pulses available to be used in FE simulation studies in the project. This issue was addressed by developing a method that fits a polynomial model to multiple input data and predicts a generic pulse based on the model. These pulses were compared with preliminary results from FE simulation studies with public standard pulses, evaluating a WP2 protection principle.
- Stochastic traffic simulations to determine motorway crash configurations (section 5): The initial results of automated vehicles on motorways in D1.1 showed that an analysis exclusively based on PCM crash data, taking at most two vehicles into account, does not reflect all potentially critical situations in traffic. Consequently, relevant remaining crashes or entire scenarios might be neglected. Hence, a multi agent stochastic traffic simulation approach was established in order to model future mixed traffic and identify virtual accidents occurring in traffic with generic automated vehicles.
- Weighting previous WP1 results to a European level (section 6): The initial results concerning the remaining crashes are based on data collected in regions of limited geographical coverage (i. e., parts of Germany and in Sweden). To ensure the relevance of the results on a European level, a data weighting method for OSCCAR was developed and applied. Additionally, the multi-agent traffic simulation mentioned in the previous bullet was calibrated based on German motorway data. Therefore, the crash rate of passenger cars on motorways in the EU was estimated to assess the relevance of the corresponding parameter on a European level.

2.4 Partner contributions in OSCCAR WP1 deliverable D1.3

Mainly Mercedes-Benz contributed to section 2 with an update to the literature review, the status of WP1 in difference to D1.1 and the remaining issues addressed by the methodology (section 3). The OSCCAR partners Autoliv, Volvo Cars Corporation and TU Graz contributed to section 4 by describing the work on selecting crash configurations and deriving generic and specific crash pulses. The partners Bosch and Mercedes-Benz wrote section 5 on the openPASS simulation study, based on the simulation work conducted by University of Stuttgart (HLRS). Section 6 covers mainly the work of Chalmers with input from Bosch and Volvo Cars Corporation. In section 7, all involved OSCCAR WP1 partners contributed to the summary and the discussion of the WP1 results, based on a draft by Mercedes-Benz.

3 METHODOLOGY

3.1 Overview of methodologies

As described before, this deliverable D1.3 summarizes various activities following up on the first OSCCAR WP1 deliverable D1.1 containing intermediate results on prediction of remaining crashes. In extension to Figure 1 with the overview of OSCCAR WP1 methodologies, we display in Figure 2 the necessary additions (red boxes) to the final results of WP1 covered. The following sections 3.2 to 3.4 below summarize the individual steps.

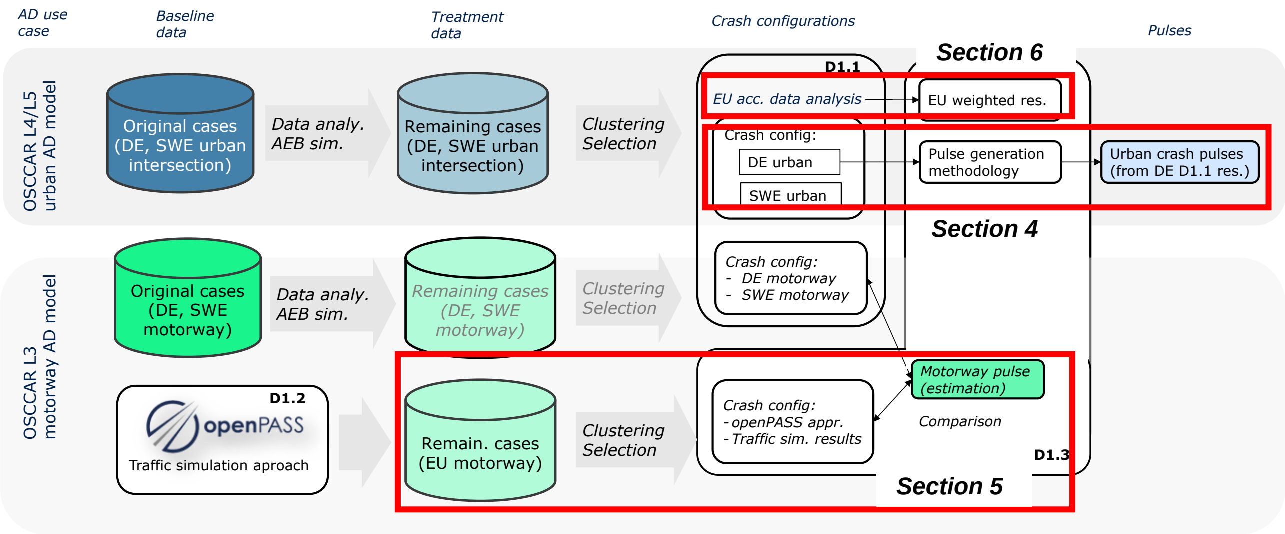


Figure 2: Overview of OSCCAR WP1 methodology and red boxes indicating the three main pillars covered in D1.3 (crash configurations & pulses, traffic simulations, and EU weighting)

3.2 Method to obtain crash configurations & pulses

The method to derive crash pulses from predicted crash configurations in section 4 comprises both data analysis and simulation activities. It extends the intermediate results of OSCCAR WP1 deliverable D1.1 regarding the crash configurations and describes a novel method to calculate generic crash pulses (central red box in Figure 2). The single steps covered in this field are:

- Clustering of result parameters
- Selection based on severity estimation of the occupant
- CAE structure crash simulation
- Mathematical fitting
- Selection of generic pulses
- Application of generic pulses in occupant simulation

3.3 Method of stochastic traffic simulations for crash configurations

For motorway predictions, a novel traffic model based on openPASS is used to amend the initial findings of D1.1 on potentially remaining crashes of automated vehicles. The D1.3 method is necessary especially in those traffic scenarios where traditional crash data is limited (lower red box in Figure 2). The single steps covered in section 5 are:

- Scenario definition
- Model selection and calibration
- Traffic simulation study
- Result analysis
- Comparison with time-series data simulation
- Requirements for further traffic research & validation

3.4 Weighting method to EU level

The weighting methodology in section 6 was developed in OSCCAR WP1 to upscale the results from both D1.1 and traffic simulations described in section 5 to EU level (upper red box in Figure 2). The main steps are:

- Up-scaling from time-series sample to national level
- Up-scaling from national data to EU level
- Calculation of EU traffic crash rates
- Weighting of traffic simulation results to EU level

4 CRASH CONFIGURATIONS & PULSES

Using Swedish and German datasets, OSCCAR D1.1 [1] reported on predicted crash configurations that a conceptual automated vehicle could be exposed to in mixed traffic on motorways and in urban intersections. Those were identified in two steps to model the potential impact of an automated vehicle on current crash data. First a filter was applied on a selected dataset of existing crashes to identify and remove crashes that an automated vehicle would inherently avoid. Inherent avoidance is hereby defined as the avoidance of a previous crash by respecting traffic rules and sufficiently adapted driving to the traffic conditions. Second, detailed treatment simulations were executed using an emergency intervention by a conceptual AEB crash avoidance system to include the potential intervention of an automated driving function in order to avoid crashes. The crashes that remained after these two steps were clustered by collision velocities and collision angles defining the crash configuration (see Figure 3 for definitions applied to the data). Thereby, typical crash configurations for an automated vehicle in rear-end crashes on motorways and in urban intersection crashes were defined. These well-defined crash configurations, including impact velocities, can be used to generate crash pulses by vehicle-to-vehicle simulations, see section 4.3. Such generated crash pulses can then be used when designing and assessing occupant restraints for future automated vehicles.

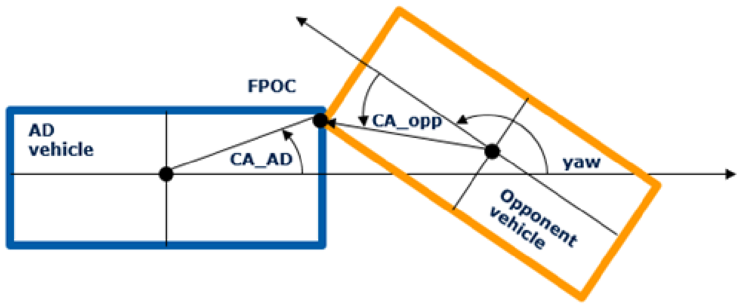


Figure 3: The configuration of each crash was described by its collision angles based on the first point of contact (FPOC): the collision angle of the automated vehicle (blue, CA_AD), the collision angle of the conventional vehicle (orange, CA_opp), and the relative impact angle (yaw) between both vehicles. The local coordinate system of each vehicle is faced forwards [1]. Vehicle shape was simplified rectangular shapes, for future development more realistic vehicle shapes could be used.

In this section, we present two different approaches to generate crash pulses to be used when assessing occupant restraint systems: 1) based on German data from GIDAS and *generic* crash pulses and 2) using Swedish crash data from STRADA and Volvo Cars Traffic Accident Database (VCTAD) with the aim to generate *specific* crash pulses that match the car make selection. To generate crash pulses, collision angles and velocities are needed. For the collision velocity, D1.1 reported on median collision velocities for each cluster of crash configurations; however, higher (75- or 90- percentiles) coverage from the impact velocity distributions were deemed more relevant when assessing occupant restraint performance (D1.1 page 75).

For approach 1), generating *generic* crash pulses from collision data, a flow chart is presented in Figure 4 (right part, see dotted frame). A method to derive higher impact velocities was developed and applied, see section 4.1.2. Additionally, the clustered German intersection crashes were selected for further analysis and generation of *generic* crash pulses to be used in OSCCAR WP2 sled testing, see OSCCAR D2.5 [12]. This was done using an open access computer-aided engineering (CAE) vehicle model of a Honda Accord Model Year (MY) 2011 [13], see section 4.2. Implementing the lessons learned from the simulation of the Honda Accord MY 2011 and widening the analysis to more and more recent vehicle models, further simulations were run on the German intersection dataset. Vehicle simulations on selected crash configuration were analyzed and combined to generate a set of generic crash pulses, see section 4.3. Finally, the “worst case” crash pulses were identified, i. e., most critical crash configuration, based on occupant response using human body models (HBM) in terms of HBM kinematic and injury prediction, see section 4.4.

For approach 2), selected crash configurations from D1.1 were used in car-make specific FE simulations to derive crash pulses to be used in human body model (HBM) simulations, see section 4.5. Both the generic and the specific approaches and how they are related are visualized in the flow chart below (Figure 4) that summarizes how crash pulses were created in OSCCAR WP1 and used in OSCCAR WP2.

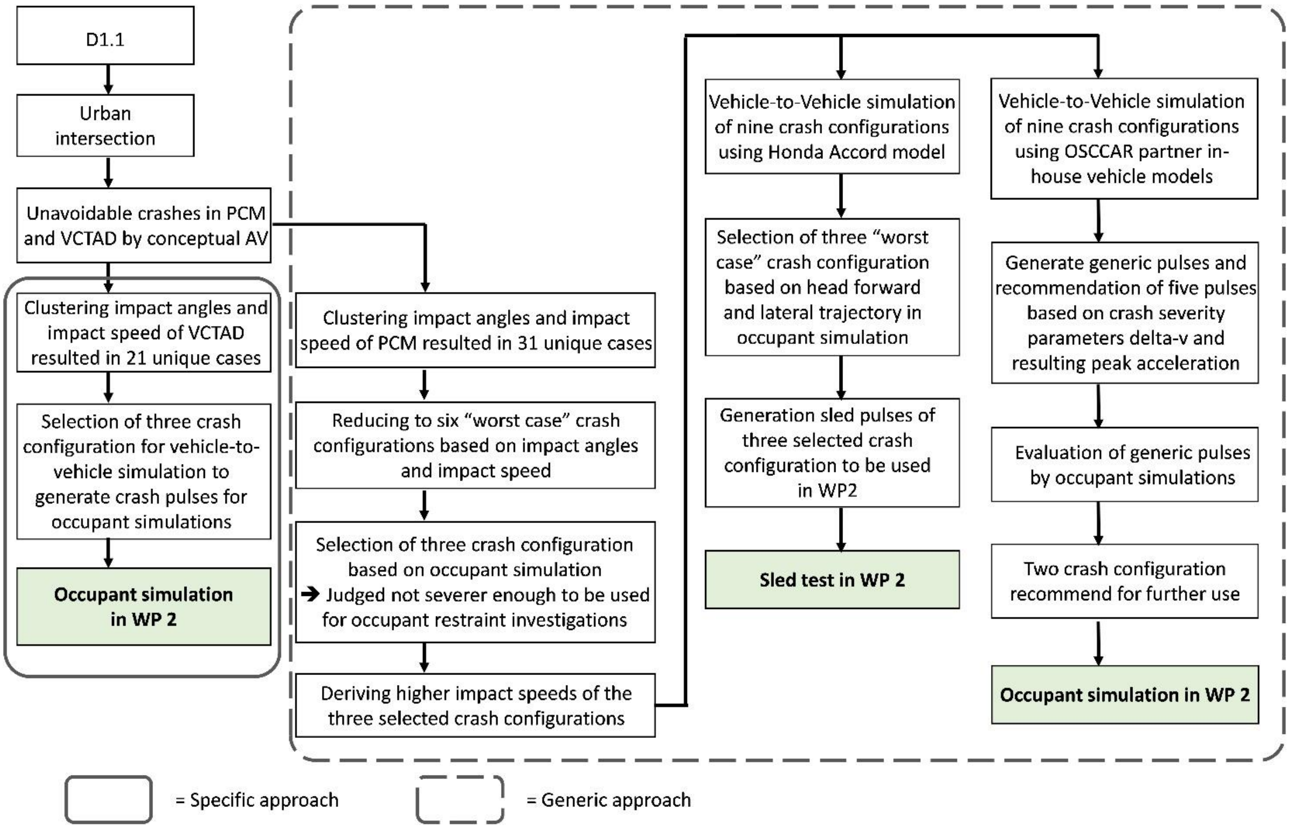


Figure 4: Flow chart how crash pulses were created in OSCCAR WP1 and used in OSCCAR WP2

4.1 Selecting crash configurations for occupant restraint system evaluation

4.1.1 Deriving crash configurations based on German data

Vehicle to vehicle crash simulations were run to generate crash pulses (i. e., time series of x, y, and z-acceleration experienced during the crash). However, only a subset of the 31 crash configurations (clusters) from the unavoidable German urban intersection crashes reported in D1.1 were used. The 31 crash configurations shown in Figure 5 were derived by first clustering each crash scenario by collision angles, i.°e., straight crossing path (SCP), left turn across path opposite direction (LTAP OD) and left turn across path lateral direction (LTAP LD), followed by an additional cluster based on collision velocities of each crash scenario cluster.

Expert judgement was used taking collision velocity and configuration into account to identify the six most severe crashes, i. e., those that would generate the highest accelerations within each crash configuration. These six crash configurations are highlighted by yellow marked velocities in Figure 5. Two of the crash configurations were not selected at all, LTAP OD3 and LTAP LD2 as the automated vehicle impacted the opponent car rearward of its geometrical center which is expected not to generate high accelerations even for the highest crash speeds listed in Figure 5.

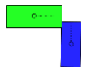
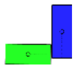
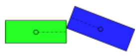
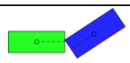
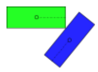
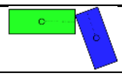
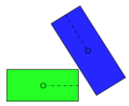
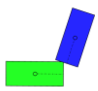
Crash scenario	Crash configuration	Visualisation	AD_CA [deg]	MD_CA [deg]	yaw [deg]	vAD [km/h]	vOPP [km/h]	Case ID
SCP	SCP1		-20	28	89	55	29	SCP1_55_29
						30	20	SCP1_30_20
						37	49	SCP1_37_49
	SCP2		19	-34	271	43	31	SCP2_43_31
						23	53	SCP2_23_53
						18	25	SCP2_18_25
LTAP OD	LTAP OD1		9	20	160	21	57	LTAPOD1_21_57
						0	79	LTAPOD1_0_79
						0	50	LTAPOD1_0_50
						0	30	LTAPOD1_0_30
						40	21	LTAPOD1_40_21
	LTAP OD2		4	-21	214	45	19	LTAPOD2_45_19
						18	17	LTAPOD2_18_17
	LTAP OD3		-20	-129	231	31	26	LTAPOD3_31_26
						5	17	LTAPOD3_5_17
						86	30	LTAPOD3_86_30
LTAP LD	LTAP LD1		10	23	110	48	13	LTAPLD1_48_13
						23	12	LTAPLD1_23_12
	LTAP LD2		24	127	123	12	15	LTAPLD2_12_15
						53	28	LTAPLD2_53_28
						32	26	LTAPLD2_32_26
						50	8	LTAPLD2_50_8
						20	30	LTAPLD2_20_30
						32	10	LTAPLD2_32_10
						42	16	LTAPLD2_42_16
						67	14	LTAPLD2_67_14
						23	20	LTAPLD2_23_20
						11	5	LTAPLD2_11_5
	LTAP LD3		22	-7	252	1	31	LTAPLD3_1_31
						0	47	LPATLP3_0_47
						0	72	LTAPLD3_0_72

Figure 5: Clusters of unavoidable intersection crashes after conceptual simulations of automated vehicles. Yellow marked impact velocities were used in vehicle-to-vehicle simulation

The six selected crash configurations were used in vehicle-to-vehicle simulations using the NHTSA LS Dyna open access CAE model of a Honda Accord 4-door midsize sedan MY2011, weight 1623 kg [8]. This model, that was previously validated to full frontal 56 km/h load case, can be found at [10]. Simulations were set-up according to the six selected crash configurations (Figure 6) and executed in LS-Dyna.

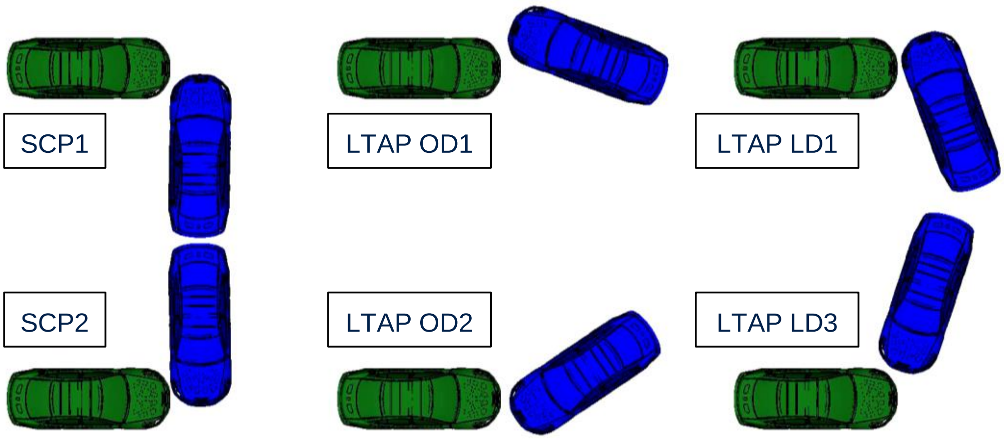


Figure 6: The Honda Accord 4-door MY2011 in the six selected crash configurations

Despite the different crash configurations, the simulations resulted in similar crash pulses especially for the x-component of the crash pulses all being below 150 m/s^2 (except short duration peak values at 100 ms), see Figure 7. Base on the results from these six simulations, three crash configurations were selected to best represent the most severe acceleration in x and y direction (accelerations in z direction were negligible in all simulations):

1. SCP1_55_29, red curve in Figure 7.
2. LTAP OD1_40_21, dark blue curve in Figure 7.
3. LTAP OD2_45_19, light blue curve in Figure 7.

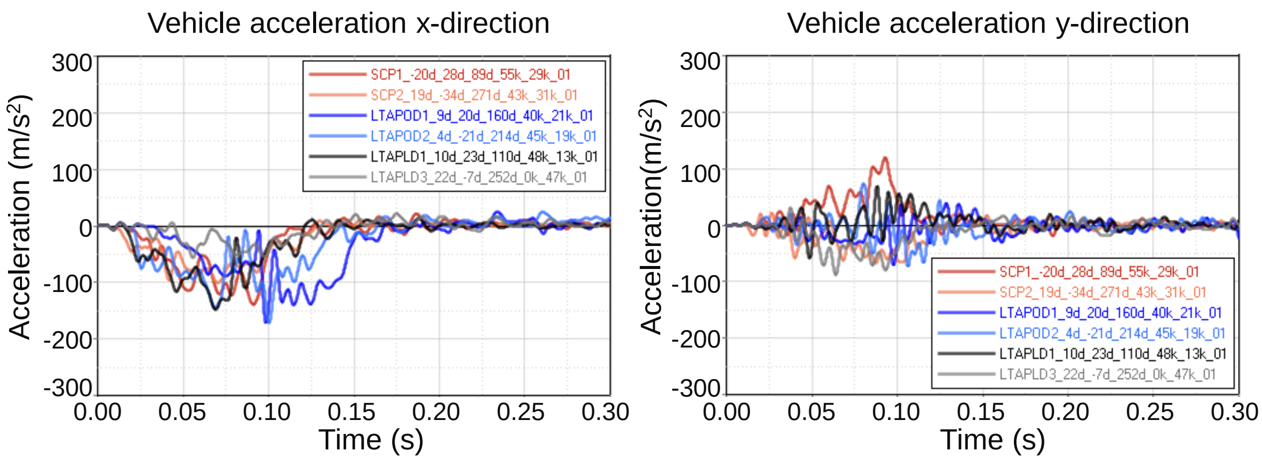


Figure 7: Crash pulses in x- and y-direction for the six crash configurations

4.1.2 Deriving crash configurations with higher collision velocity based on clustered German intersection crashes

State-of-the-art occupant restraint system are typically developed for high velocity collision conditions, e. g., US NCAP 56 km/h full frontal barrier [14] and Euro NCAP 50 km/h full width frontal crashes [15]. In general, these crash conditions result in vehicle crash pulses peaking at 300 m/s^2 or above. However, when analyzing the crash pulses coming from the six intersection crash configurations, those are all well below 300 m/s^2. These intersection crashes therefore represent frequent medium severity crash conditions which could be used to address the need to improve occupant protection in medium and low speed conditions [16][17][18][19]. However, in the OSCCAR project severe injuries in severe crashes were to be evaluated. Therefore, the three selected crash configurations clusters in section 4.1.1 were further investigated using bivariate distributions of collision velocities for all the crashes in each cluster [20]. For each of the three selected crash configurations the velocities of both the automated vehicle and the opponent vehicle were plotted as a scatter plot together with the contour lines covering 10% (inner circle) to 90% (outer circle) of the crashes, see Figure 8. Each blue point represents one crash. The plots were then used to retrieve the maximum and median velocity values of both vehicles at the 90- percentiles contour line (covering 90% of the crashes); see pink points in Figure 8. Vehicle to vehicle simulations were again performed for all these nine conditions (three crash configurations and three collision velocity combinations) and vehicle crash pulses were derived.

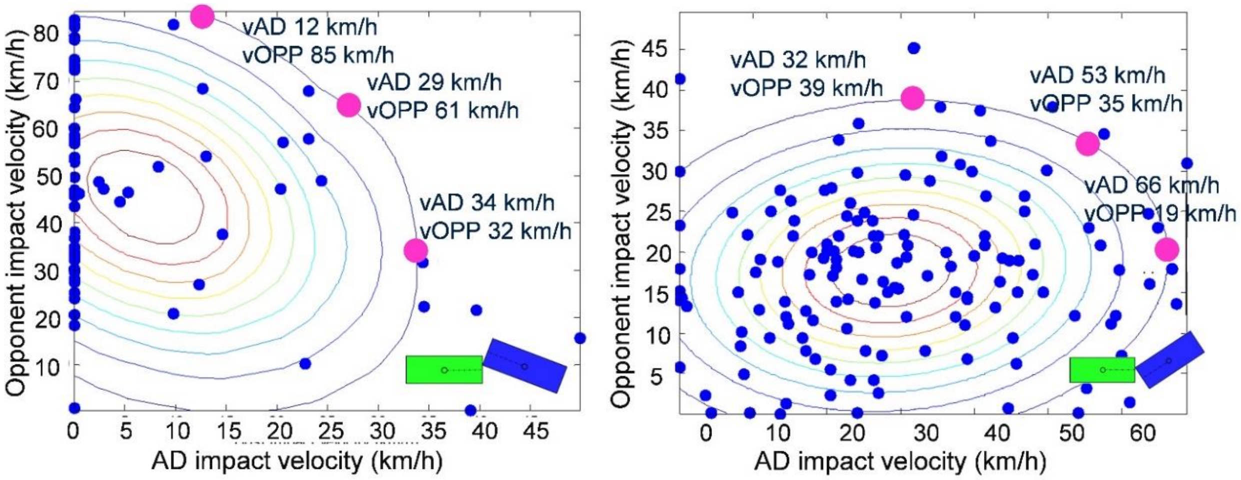


Figure 8: Bivariate distributions of impact velocities, left panel: LTAP OD1 right panel: LTAP OD2

4.1.3 Deriving crash configurations based on Swedish data

Three crash configurations (Figure 9) were selected from the analysis in D1.1 where data from Swedish crash databases were used for creating baselines for pre-crash simulations with a conceptual AEB as treatment [21]. By clustering and grouping predicted remaining crashes in the Straight Crossing Path (SCP) conflict situation, a limited number of crash configurations was identified. Out of these, the following crash configurations were selected for further evaluation of occupant restraint systems.

- The near-side configuration represents a lateral impact to the front right corner when stand-still, by another car traveling at 77 km/h.
- The far-side configuration is a lateral impact to the front left corner, by another car in 52km/h, when traveling in 31km/h.
- The frontal configuration is an impact with almost 50% left side overlap when traveling in 57km/h into another car's right front side.

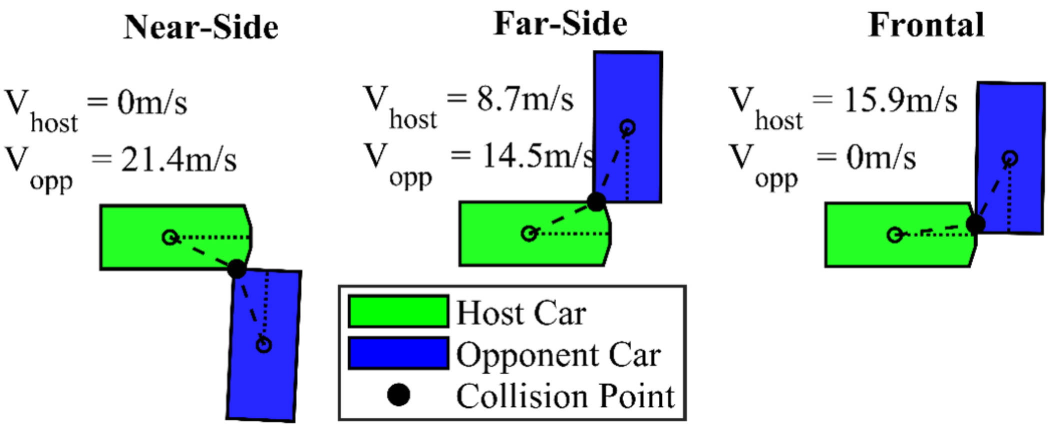


Figure 9: Crash configurations selected from the analysis of Swedish data in D1.1

The selected crash configurations (Figure 9) originate from clusters #1, #2, and #4 in [21] accounting for largest shares (10.2%, 10% and 6%) of the predicted crashes. (Cluster #3 was not chosen due to its similarity to #2.) For side impacts, the highest opponent speed was selected and for the frontal impact, the highest host speed was chosen.

4.2 Creating a crash pulse to be used in sled tests

The crash pulses from nine vehicle-to-vehicle simulations (section 4.1.2) were used for occupant simulation with the Test Device for Human Occupant Restraint fifty percentile male (THOR-50M) as human surrogate. The target was to select the most severe impact velocity per crash configuration in terms of lateral and forward displacement of the occupant head (measured at center of gravity), chest (at the first thoracic vertebra, T1) and pelvis (at H-point). The crash conditions were intended to be used in an automated vehicle interior with the occupants facing each other, therefore the vehicle crash pulses of 3 degree of freedom (acceleration in x and y as well as z-rotation) were picked at the center of either right or left rear seat positions, depending on expert judgement of which position gives a higher risk of sliding out of a state-of-the-art 3-point belt system, see Figure 10.

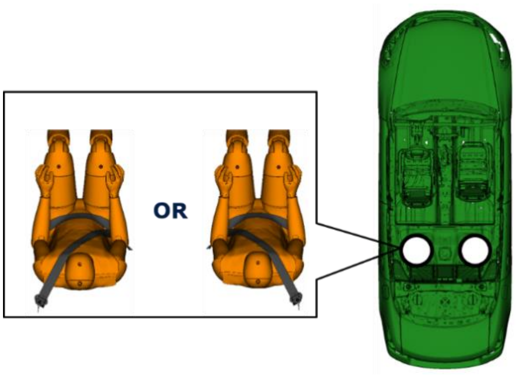


Figure 10: Vehicle crash pulses were taken from left and right side of the rear seat and occupants were positioned either in left or right seat with traditional belt routing.

For the occupant simulation a system CAE model including Humanetics THOR-50M model v1.6 seated in a position corresponding to a seat back angle of 23°, the semi rigid seat [24] and a seat integrated concept seat belt were used (Figure 11). The concept seat belt consists of a seat-integrated double retractor 3-point belt with a belt guide and shoulder belt retractor with pre-tensioner and load limiter of 4 kN installed in the seat back, a lap belt retractor with pre-tensioner and buckle pre-tensioner in the seat pan and a crash locking tongue . Previous to the simulation the system CAE model was validated to mechanical sled test using a 50 km/h full frontal crash pulse. The 50 km/h crash pulse was selected because it had been used with the semi rigid seat when it was developed [24].

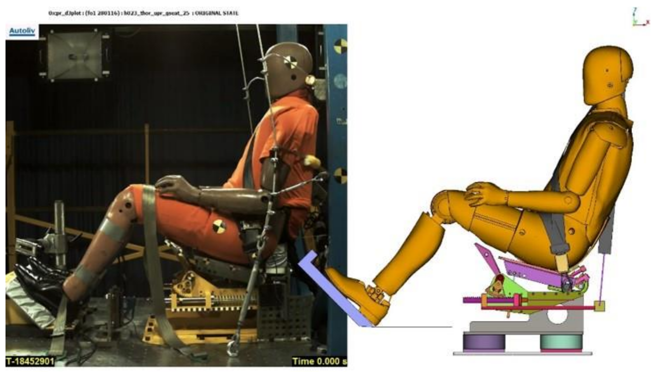


Figure 11: THOR-50M in system model

All nine crash configurations derived from vehicle-to-vehicle simulation were simulated and additionally the full frontal 50 km/h crash pulse was evaluated as well. Occupant head, chest (T1) and pelvis lateral and forward displacement for each crash pulse is shown in Figure 12.

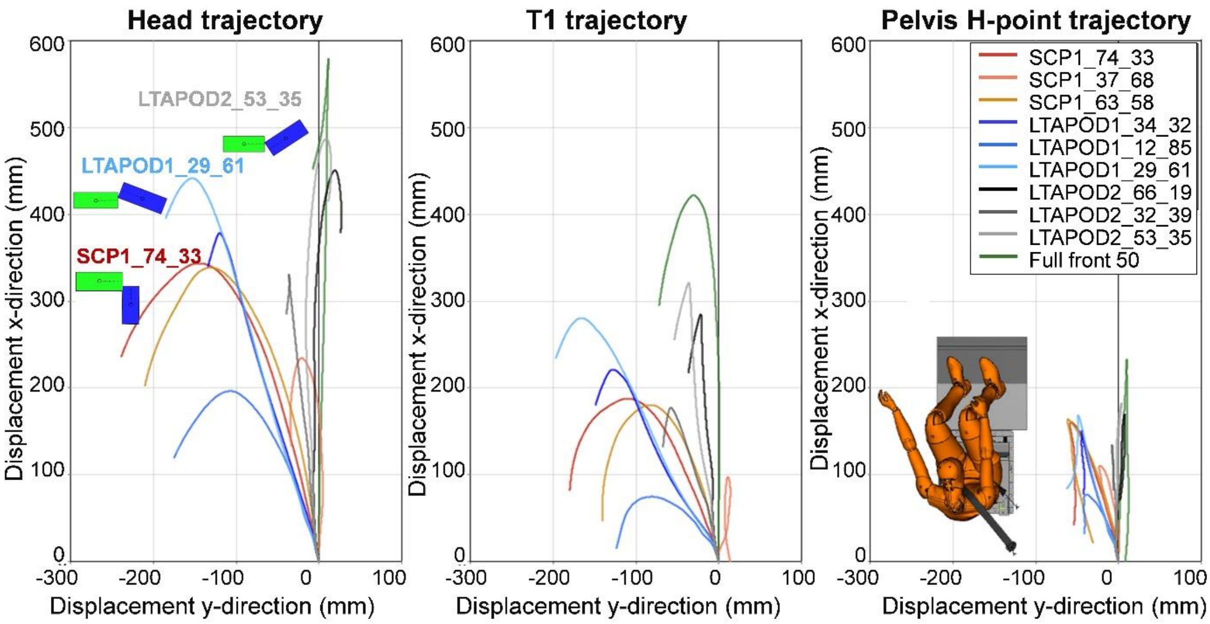


Figure 12: THOR-50M – Head, T1 and pelvis forward displacement

Based on those results, four crash configurations were selected as worst cases in terms of either largest lateral head displacement (indicates risk for sliding out of the seat belt) in SCP1_74_33 or largest forward head displacement (indicates most severe crash pulse) in LTAPOD2_53_35 km/h and full frontal 50 km/h or a combination of lateral and forward head displacement in LTAPOD1_29_61.

Due to the small lateral head displacement in LTAP OD2 that vehicle crash pulse could be used directly in a sled test. But both SCP1_74_33 and LTAPOD1_29_61 vehicle crash pulses resulted in large lateral head displacement which means that the y-acceleration component needs to be included when running sled tests. The sled is limited to acceleration in one direction so to replicate the lateral displacement of the head the sled is mounted with a pre-defined angle in y direction, see Figure 13.

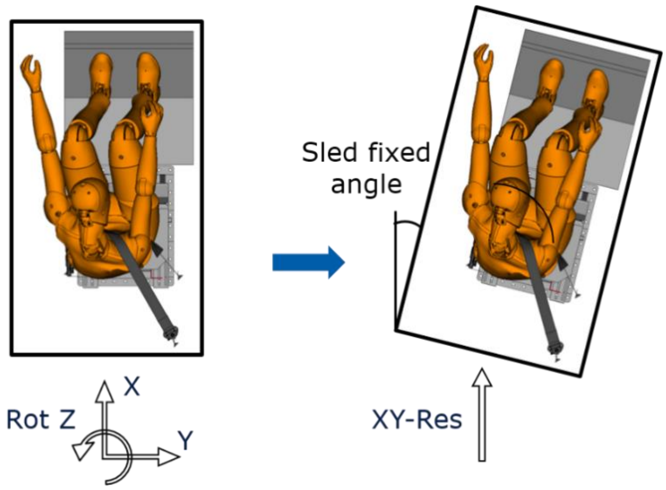


Figure 13: THOR-50M – Going from vehicle simulation to sled test with fixed angle

To find the sled angle that best matched the head lateral displacement of SCP1_74_33 and the LTAPOD1_29_61 vehicle simulations, simulations were performed with the fixed angle at 15° and 20° for the SCP1_74_33 and 10°, 15° and 20° for the LTAP OD2_29_61, see Figure 14. A fixed sled angle at 15° matched best the head displacement from the vehicle simulations for both crash pulses.

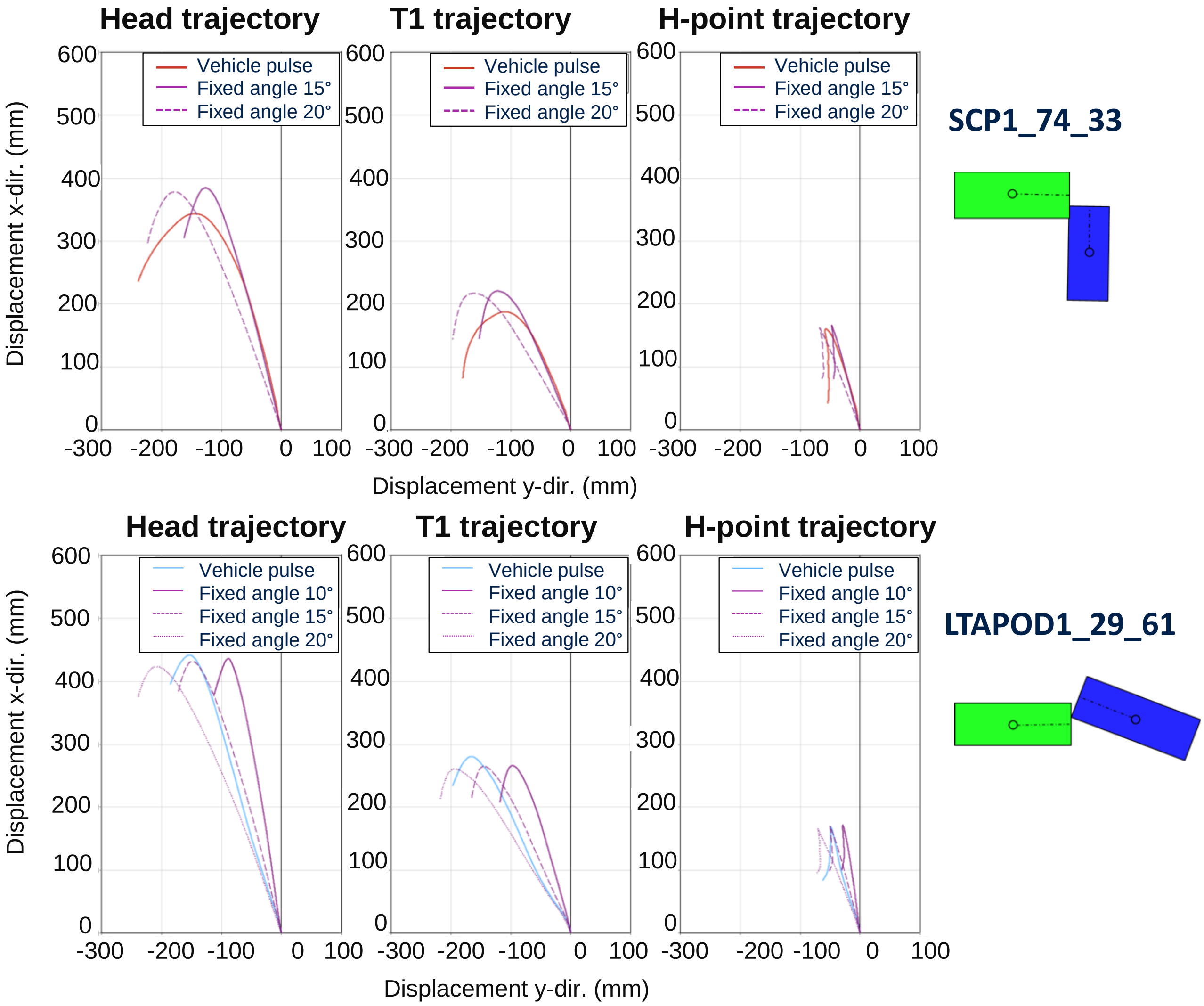


Figure 14: THOR – Head, T1 and pelvis kinematics for SCP1 and LTAP OD2 compared to fix angle simulations

In total, four sled crash pulses were created to be used in sled test in WP 2 [12], see Figure 15

1. SCP1_74_33, 15° fixed angle
2. LTAP OD2_53_35, 0° fixed angle.
3. Full frontal 50 km/h, 0° fixed angle.
4. LTAP OD1_29_61, 15° fixed angle

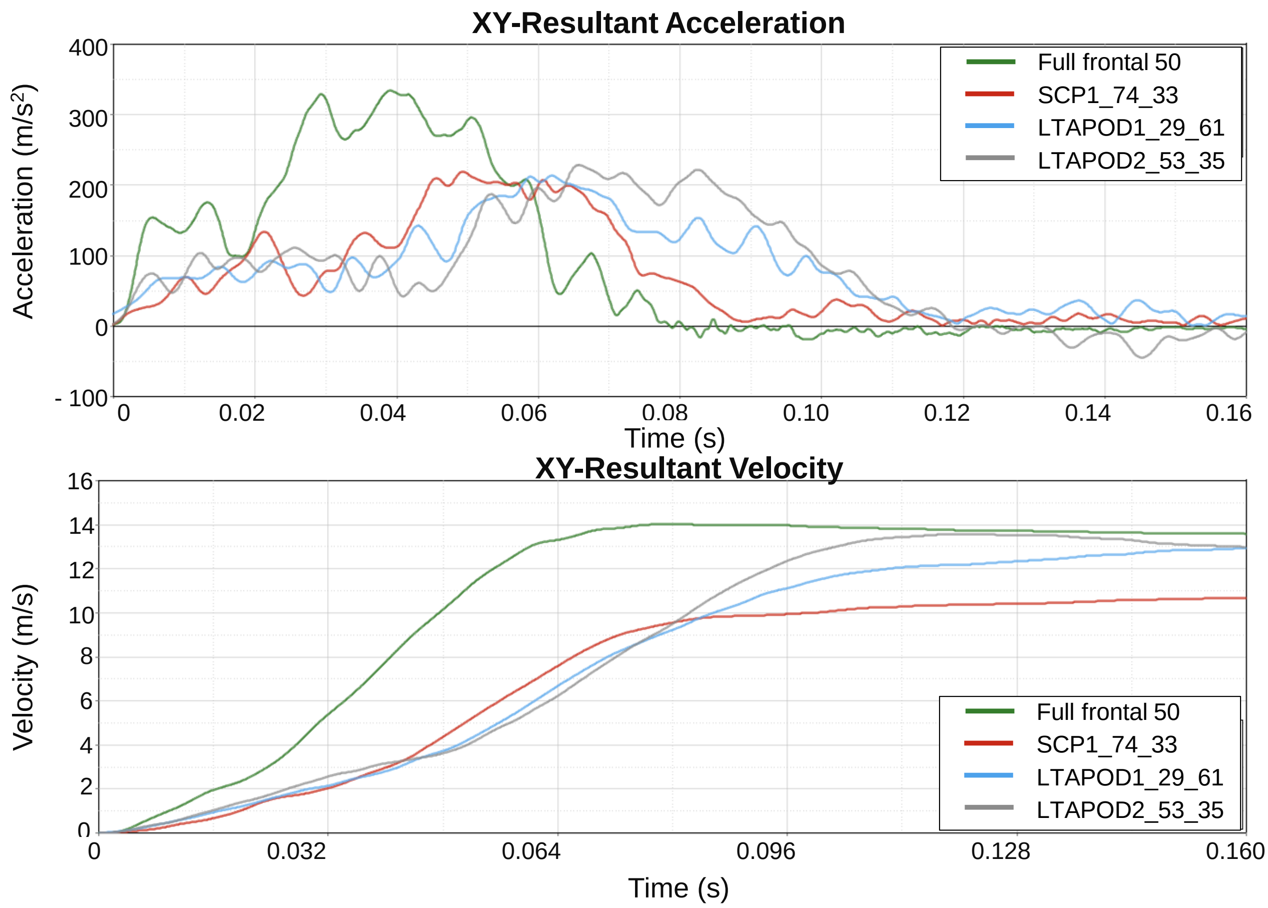


Figure 15: Sled crash pulses acceleration (top) and delta velocity (bottom) for the four crash configurations

4.3 Generic crash pulses using a sample of vehicle to vehicle crash simulation results

After implementing the lessons learned from the simulation of the Honda Accord MY 2011 (mainly done with the purpose to generate crash pulses to the sled tests performed by WP2), and widening the analysis to more recent vehicle models, further vehicle to vehicle simulations were run on the three selected urban intersection crash configurations, SCP1, LTAP OD1 and LTAP OD2, for the three selected configurations of Figure 5 (outcome of 3.1.1), and their corresponding collision velocity combinations from the 90- percentile contour plots, which are shown in Figure 8.

These vehicle-to-vehicle simulation were run by OSCCAR partners using their state-of-the-art vehicle models. The output from those simulations were used to generate generic crash pulses using Legendre polynomials [28]. By this procedure, the individual acceleration signals were parameterized and finally a set of generic pulses were derived for a vehicle mass of 1717 kg (average mass of 110 vehicles tested by Euro NCAP in the years 2015 to 2019) [28] and an averaged deformation energy. The generic crash pulses were generated using both an acceleration-based approximation and a velocity-based approximation. The acceleration-based method described the direct approximation of the acceleration signals. The velocity-based method described an approximation of the velocity signals and indirect calculation of accelerations by differentiation [28]. An exemplary result for the full frontal 56 km/h impact where the generated generic crash-pulse is compared to the corridors from the individual OEM simulation results is shown in Figure 16 and

Figure 17. The full frontal impacts were added as reference to compare the proposed crash configurations with the highest severity with state of the art tests.

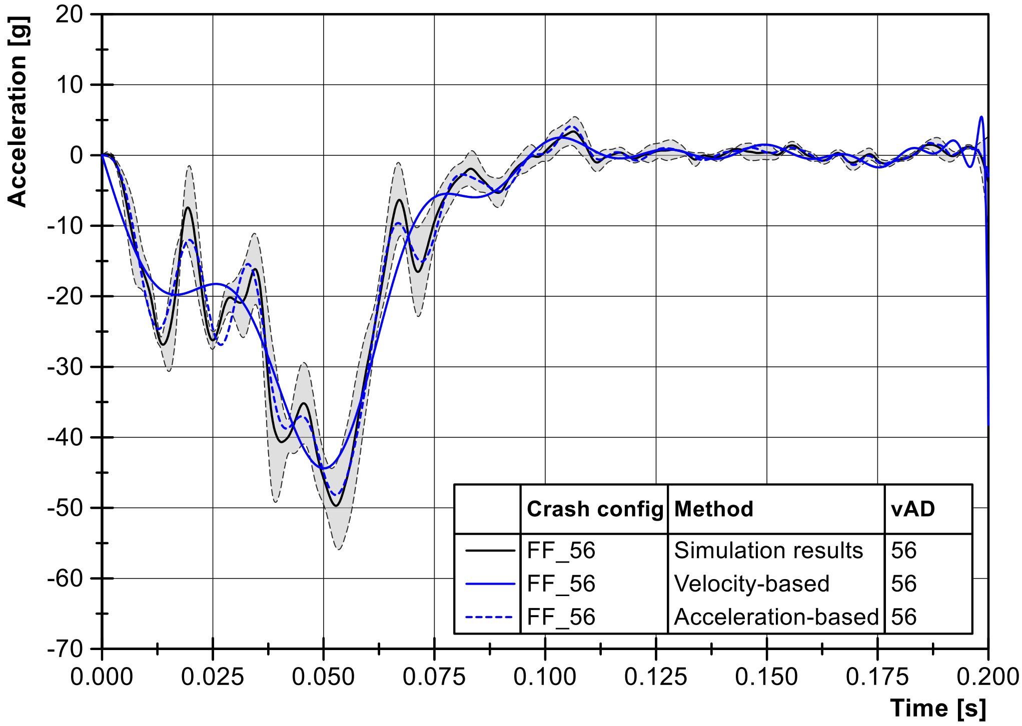
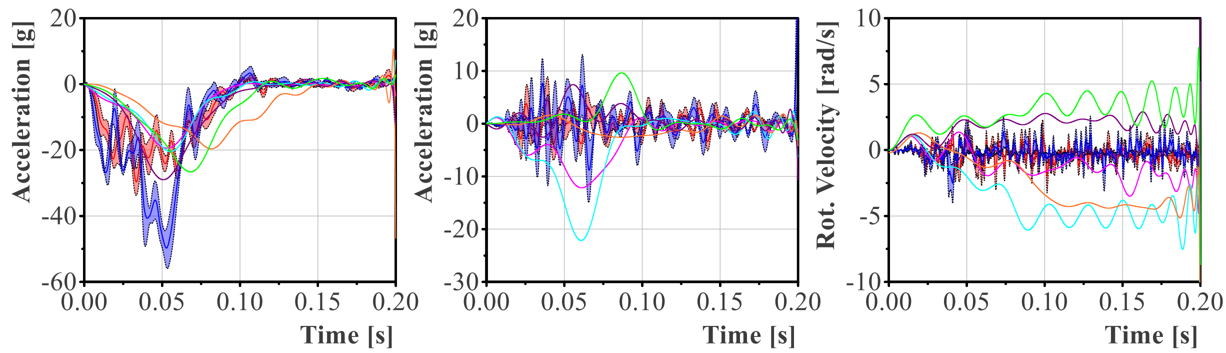
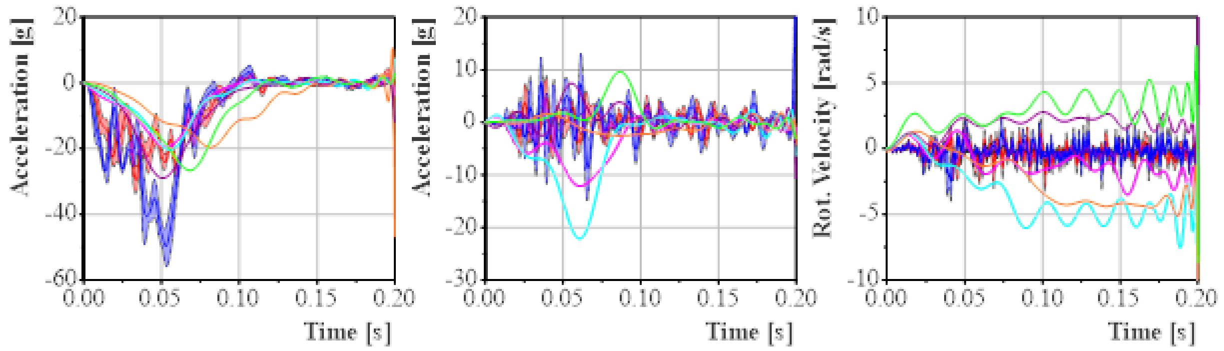


Figure 16: Translational x-acceleration for crash configuration FF_56 against a rigid wall for the mean of simulation results (black) with one standard deviation corridor and generic crash pulses for velocity-based (solid blue) and acceleration-based (dashed blue) method with a vehicle with a mass of 1717 kg.

For the acceleration-based method a higher number of basis functions was needed for the signal approximation leading to overfitting and an unrobust behaviour. The velocity-based method was recommended for further investigations. Additionally, a study by Iraeus and Lindquist has shown that the pulse duration and Delta-v values are more relevant for a risk of rib fracture [28].



	Crash configuration	Method	vAD	vOPP	Configuration
	FF_40	Simulation results	40	-	Rigid Wall
	FF_56	Simulation results	56	-	Rigid Wall
	SCP_74_33_hh	Velocity-based	74	33	Heavy/heavy
	SCP_63_58_hh	Velocity-based	63	58	Heavy/heavy
	LTAPOD1_29_61_hh	Velocity-based	29	61	Heavy/heavy
	LTAPOD2_66_19_hh	Velocity-based	66	19	Heavy/heavy
	LTAPOD2_53_35_hh	Velocity-based	53	35	Heavy/heavy



	Crash configuration	Method	vAD	vOPP	Configuration
	FF_40	Simulation results	40	-	Rigid Wall
	FF_56	Simulation results	56	-	Rigid Wall
	SCP_74_33_hh	Velocity-based	74	33	Vehicle/vehicle
	SCP_63_58_hh	Velocity-based	63	58	Vehicle/vehicle
	LTAPOD1_29_61_hh	Velocity-based	29	61	Vehicle/vehicle
	LTAPOD2_66_19_hh	Velocity-based	66	19	Vehicle/vehicle
	LTAPOD2_53_35_hh	Velocity-based	53	35	Vehicle/vehicle

Figure 17: Mean of simulation results with one standard deviation corridor for crash configuration FF_40 (red) and FF_56 (blue) against a rigid wall and generic crash pulses for velocity-based method for recommended crash configurations with two vehicles with a mass of 1717 kg. First column – translational x-acceleration. Second column – translational y-acceleration. Third column – rotational z-velocity. vAD – velocity of the automated vehicle. vOPP – velocity of opponent vehicle.

Based on the severity parameters Delta-v (calculated according to ISO 12353-3 without the definition of t-0 and t-end, a pulse length from 0 to 160 ms was considered) and resulting peak acceleration five crash configurations were recommended to be used in further OSCCAR investigations [28]:

1. SCP1_74_33, largest Delta-v for SCP1
2. SCP1_63_58, highest peak acceleration for SCP1
3. LTAP OD1_29_61, largest Delta-v and peak accelerations for LTAP OD 1
4. LTAP OD2_66_19, largest Delta-v for LTAP OD 2
5. LTAP OD2_53_35, highest peak acceleration for LTAP OD 2

4.4 Evaluating the generic crash pulses

The generic crash pulses identified in 3.3 were evaluated in occupant simulation using a system CAE model including the semi rigid seat and a seat-integrated concept seat belt. The concept belt consists of a seat-integrated double retractor 3-point belt with a belt guide and shoulder belt retractor with pre-tensioner and load limiter of 4 kN installed in the seat back, a lap belt retractor with pre-tensioner and buckle pre-tensioner in the seat pan and a crash locking tongue. This time the occupant simulations were made using the SAFER HBM [25] in two positions. An upright position with the seat back in 23° to the vertical and a reclined position with the seat back 48° to the vertical, see Figure 18. The evaluation was done in two steps. First the crash pulses generated by the velocity-based method and the acceleration-based method (see section 4.3) were compared in terms of HBM kinematics and seat and seatbelt interaction with the target to identify which of the crash pulses to be used in further studies, e. g., OSCCAR deliverable 2.4 [26]. After this step there followed an investigation of the five recommended crash pulses (based on the severity parameters Delta-v and resulting peak acceleration, see section 4.3) with the target to identify the worst crash pulses in terms of HBM kinematics and injury prediction.

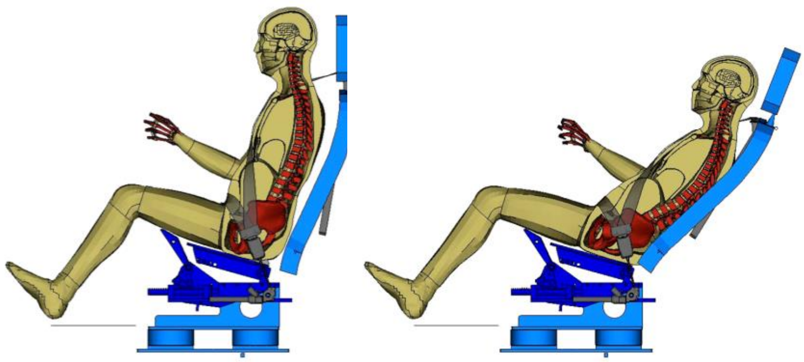


Figure 18: SAFER HBM in upright (left) and reclined (right) position

4.4.1 Comparison of velocity-based and acceleration-based intersection crash pulses

The objective of this investigation was to select if the velocity-based or the acceleration-based crash pulses should be used in further studies. Simulation was done with SAFER HBM in both the upright and the reclined position. Two crash pulses and two seat positions (SCP1_74_33, driver's seat with driver seat belt geometry and LTAP OD2_53_35, passenger seat with passenger seat belt geometry, see Figure 19 and Figure 20) were investigated in terms of SAFER HBM kinematics (head, T1 and pelvis trajectories), seat interaction (pelvis accelerations) and belt interaction (belt forces). These criteria were selected to be the ones most influenced by variation in the crash pulses.

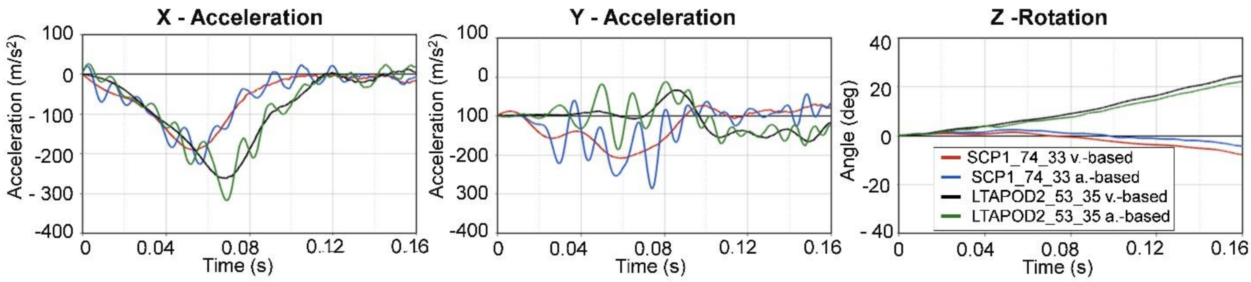
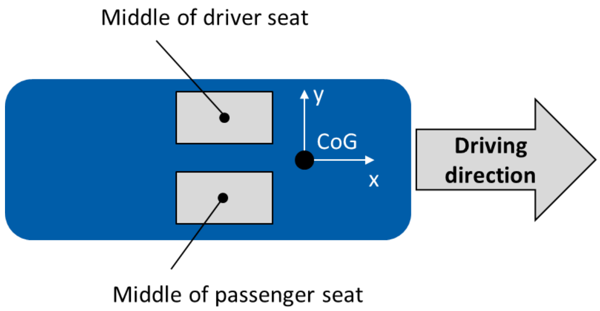


Figure 19: SCP1_74_33 and LTAP OD2_53_35 crash pulses

The SAFER HBM was positioned according to a generic interior geometry defined with input from vehicle-to-vehicle simulations, see Figure 20.



	Driver seat (CoG → DS)		Passenger seat (CoG → PS)	
	Mean	SD	Mean	SD
x [mm]	- 273.7	94.1	- 273.7	94.2
y [mm]	390.3	21.6	-385.2	19.8
z [mm]	-149.7	65.8	-147.3	69.6

CoG – center of gravity
DS – driver seat
PS – passenger seat

Figure 20: Generic vehicle geometry

Simulation using the velocity-based and the acceleration-based crash pulses yielded similar results. In terms of kinematics, i. e., trajectories of head, T1 and pelvis, almost no difference was noticed, Figure 21 and Figure 22. For pelvis acceleration and belt forces, a noisier signal was noticed for the acceleration-based crash pulses compared to the velocity-based crash pulses. But overall, no major differences were seen. Therefore, it was recommended to use the velocity-based crash pulses in further work.

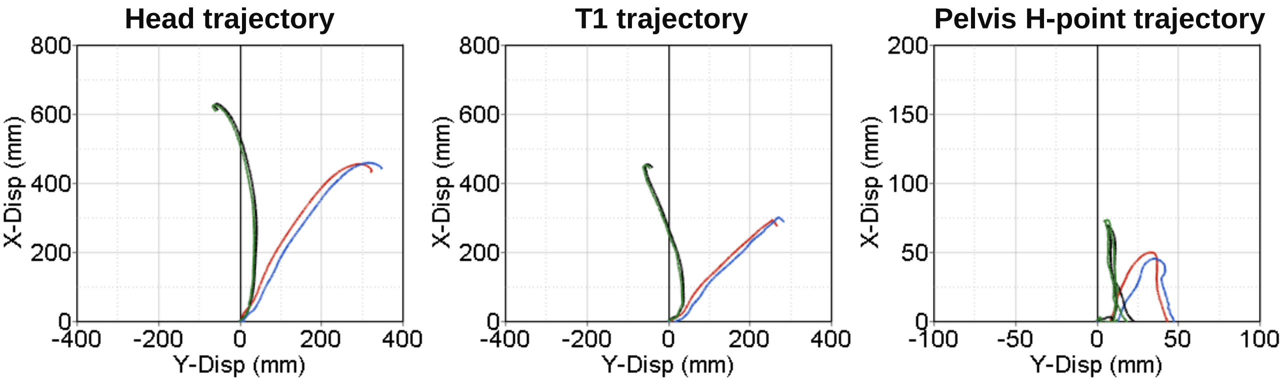


Figure 21: Upright position: Head, T1 and pelvis trajectories

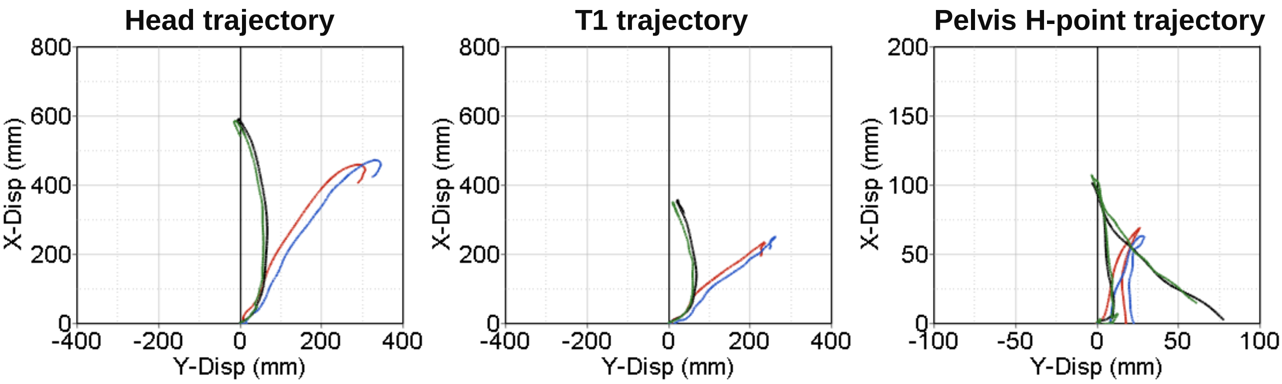


Figure 22: Reclined position: Head, T1 and pelvis trajectories

4.4.2 Derivation of “worst-case conditions” for intersection crash pulses

The objective of this investigation was to derive the worst-case intersection crash configuration out of the five recommended crash pulses, see section 4.3.1, with respect to occupant position (driver or passenger) and belt geometry (outboard and inboard geometry) in terms of head excursion, head resultant acceleration, neck tension forces, risk of rib fractures, forces to pelvis from the lap belt and compression forces and flexion moment of the lumbar spine. Simulations were run with the SAFER HBM in upright and reclined positions. This evaluation will also be published during 2021 [27].

In addition to the intersection crash pulses, two challenging full front crash pulses in 40 km/h and 56 km/h were also evaluated and used as a reference, see Figure 23.

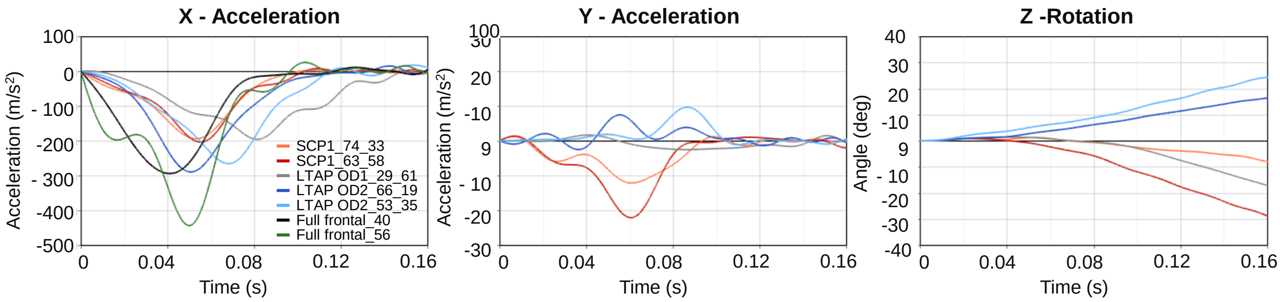


Figure 23: Generic crash pulses x-acceleration (left), y-acceleration (mid) and z-rotation (right) for the five recommended intersection crash pulses and two full front crash pulses

Among the intersection crash pulses, SCP1_63_58 with the occupant in the driver seat resulted in the largest head displacement, highest risk for rib fracture and risk for slipping out of the seat belt and highest forces to the pelvis and was therefore selected as a worst-case condition. LTAP OD2_66_19 with the occupant in the passenger seat yielded the largest head accelerations, highest neck tension forces and highest lumbar spine flexion moment and compression forces and was selected as another worst-case condition. Although the two intersection crash configurations are judged as worst-case conditions, when compared to the result from the simulations from the 56 km/h full frontal crash pulse most of the measurements were lower in the intersection cases. However, there is one exception, lumbar spine flexion moment and compression force were similar in LTAP OD2_66_19 and 56 km/h full frontal crashes. Even though the full frontal crash pulse generated higher measurements with the HBM, the intersection crash configurations should be considered in future research and development of safety in automated vehicles and the development of occupant safety solutions as those represent frequent crash modes for automated vehicle compared to the full frontal crash mode.

4.5 Car-make specific crash pulses from vehicle-to-vehicle crash simulations

Based on the prediction of future crash configurations using Swedish crash data, an approach that attempts to improve the way that the different phases in the overall project fit together was used. For these steps:

- car make selection for the pre-crash simulation,
- pulse-generating in-crash FE simulation, and
- in-crash occupant HBM simulations,

similar vehicles from the same car make were selected, and by this some inconsistency in the overall results are expected to be reduced.

Crash pulses for the crash configurations described in Figure 9 were generated by simulating car to car impacts using a mid-sized station wagon FE car model of the same car make and of a model that is representative for the cars in the baseline input data for pre-crash simulations that was reported in D1.1.

The simulation environment used - previously validated against physical crash tests - was described in [22]. The vehicle motions during the in-crash simulation are illustrated in Figure 24

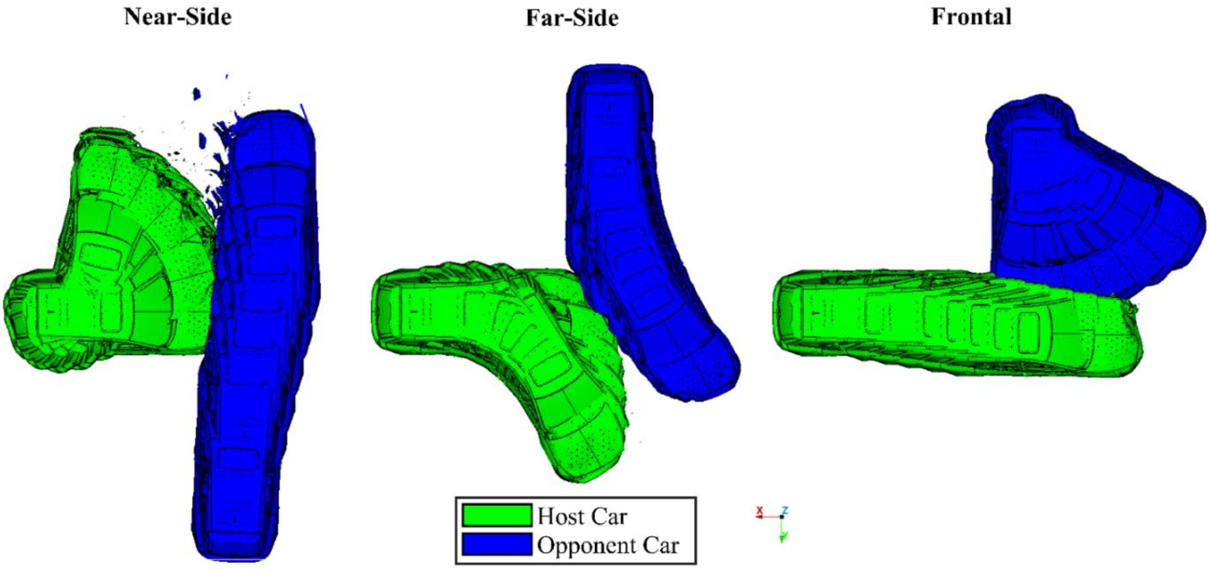


Figure 24: Illustration of vehicle motion during car-car in-crash FE simulations.

The crash pulses resulting from the three FE simulations can be described as being of relatively low-severity. The crash severity metrics for each crash configuration are presented in Table 1.

The z-rotation of the Near-Side impact reached up to 5.8 rad/s, the peak lateral acceleration was 262.9 m/s² (=26.8 g) in the Far-Side impact and in the Frontal crash, the peak resultant acceleration was 224.6 m/s² (=22.9 g) while the resultant Delta-v was 5.8 m/s.

Table 1: Crash severity metrics per crash configuration, adapted from [23]

		Near-Side	Far-Side	Frontal
Crash Configuration	Host Collision Point Angle [°]	-48.3°	48.1°	17.5°
	Opponent Collision Point Angle [°]	42.4°	-42.7°	-48.4°
	Opponent Yaw Angle [°]	87.4°	-90.3°	-90.9°
	Host speed [m/s]	0	8.7	15.9

	Opponent speed [m/s]	21.4	14.5	0
Crash severity	ΔV resultant [m/s]	7.9	1.7	5.8
	Peak x-acc. [g]	11.8	5.1	22.7
	Peak y-acc. [g]	-18	26.8	7
	Peak resultant acc. [g]	21.3	26.9	22.9
	Peak z-rot. velocity [rad/s]	5.8	-4.4	0.7

These results were used for the occupant in-crash HBM simulations as described in D2.4. In order to investigate the effect of sitting postures on kinetic and kinematic responses, 35 occupant posture combinations were studied in the three different crash configurations that are described in Figure 9 and are more in detail defined by the metrics in Table 1.

5 CRASH CONFIGURATIONS OF AUTOMATED VEHICLES IN MOTORWAY TRAFFIC

First results on future crash configurations of automated vehicles in motorway traffic were reported in Deliverable D1.1 [1] based on PCM simulations. To overcome the limitations of the approach of PCM simulations, especially the limitation of having only two participants without any dynamic sight obstructions, it was argued already in D1.1 sections 2 and 8.2.3, the need of developing and applying a more complete traffic simulation. This section describes the simulation approach itself (section 5.1), the simulated traffic scenarios (section 5.2), the driver model of the individual vehicles (section 5.3), the validation approach (section 5.4), as well as the simulation setup and the selected parameters (section 5.5). The results of the simulation are presented and discussed in section 5.6 and an overall conclusion is given in section 5.7. Prior to the work presented herein, the software architecture of the openPASS framework for integrated safety assessment used in these simulations was described previously in detail in Deliverable D1.2 [30].

5.1 Stochastic traffic simulation approach with openPASS

Why are traffic simulations needed in OSCCAR for determining future accidents including automated vehicles? In D1.1, carefully selected real-world accidents formed the basis for estimating future collisions of automated vehicles. In the multi-dimensional approach of D1.1, crash configurations with potential involvement of automated vehicles were re-simulated by equipping one or both collision participants with a collision avoidance system. For urban intersections, this approach worked fine and future crash configurations were used in several tasks within OSCCAR. However, for motorway collisions, this procedure did not work in a similar fashion, mostly due to a generic collision avoidance system unsuited for velocities of motorways, lacking a distance adapting behavior (see D1.1 section 8.2.3). In addition, the trajectories do not necessarily accurately represent the traffic situation right before the collision because of (i) limiting to only those vehicles directly involved in collisions and (ii) uncertainty of trajectory reconstruction. On a statistical level, the approach is limited by the number of cases, i.e. only about 100-200 real-world accidents are available in GIDAS with PCM. In D1.1, we concluded with the need for another, more advanced approach for determining future crash configurations with automated vehicles on motorways. In this study, we aim for a complementary approach by using a stochastic traffic simulation with a human driver behavior model on the one hand and a realistic, yet generic collision avoidance system for the automated vehicle on the other hand. Especially in the case of motorway traffic, we can overcome the main obstacles of the previous D1.1 approach by shifting from an “accident” perspective to a “traffic” perspective. Please note, although stochastic traffic simulations have some advantages over accident re-simulations for some research questions, traffic simulations have some drawbacks ranging from increased simulation efforts to potential issues in representativity. For a more detailed discussion on benefits and drawbacks of both simulation approaches, see, e. g., reference [31] and references therein.

The stochastic traffic simulation platform for OSCCAR was developed in D1.2 [30] based on the open-source framework of openPASS. It accounts for the above-mentioned requirements of a stochastic traffic simulation by simulating multi-agent traffic scenarios in realistic traffic conditions and incorporating human-like imperfections leading to accidents. The development of openPASS and how it was used for first examples in prospective safety assessment of automated driving functions was described by Fahrenkrog et al [32]. In this previous study, the authors aimed at evaluating the entire range of potential effects from normal driving via critical situations up to the moment of the collision. The main objective of [32] was to analyze how an automated driving function performs compared with a human driver model in pre-defined scenarios in which the proprietary human driver model combines human cognitive processes with stochastic process modeling. Therefore, the driver model aims to cover the driving ability of human drivers including accident prevention strategies as well as faulty behavior. Due to the research questions of Fahrenkrog et al., the use of openPASS focuses on determining the collision-avoidance potential of the human driver model in interaction with the automated driving function as precise and statistically robust as possible. But it does neither focus on reproducing realistic accident statistics nor the remaining crash configurations of future automated vehicles. In OSCCAR, we build on the previous findings and expand the application of stochastic openPASS simulations to potentially remaining crash configurations of future automated vehicles.

Even though automated vehicles will comply to traffic rules, we aim to predict collisions including involvement of automated vehicles in mixed traffic situations. Compared to the previous openPASS study of Fahrenkrog et al, there is a fundamental difference of the traffic-based approach in OSCCAR. In the scenario-based simulations of the previous study, scenario agents perform pre-defined, mostly critical maneuvers in exactly controlled conditions of well-known traffic conflicts, such as, e. g., [32]. The traffic-based approach within OSCCAR starts with a stochastic traffic generated by perfect drivers, i. e., drivers with perfect knowledge of the instantaneous situation and perfect but simplified reaction patterns. On top of the perfect traffic, we add driver imperfections based on first principles, mostly imperfect knowledge of the surrounding vehicles. Tuning the model parameters, we find a realistic motorway traffic (see, e. g., [34] and section 5.6.1). Instead of describing a *specific scenario* as in the scenario-based simulations, e. g., “passive cut-in maneuver”, an *OSCCAR traffic scenario* is defining, e. g., “free-flow traffic at an on-ramp” and is generating all potential specific scenarios itself. In this exemplary OSCCAR traffic scenario lane changes of different agents may or may not lead to safety critical or non-critical cut-in situations, depending on the traffic situation and the distribution of driver characteristics.

Ideally, the virtual traffic simulation modeled with openPASS is similar to real traffic - including the frequency and characteristics of accidents occurring in the traffic scenarios under investigation. However, this approach is highly ambitious by implicitly promising a fully validated model for all kind of macroscopic and microscopic traffic situations. If fully implemented and validly parametrized, it could be the ideal closed-loop simulation solution for all kinds of future assessment of automated driving functions. For instance, it could be used for testing of new automated driving functions and, at the same time, answer questions on how many collisions would be expected to remain for the system under test. Finally, these remaining collisions could serve as a forecast of the load cases that have to be addressed by future occupant protection systems.

Please note, in OSCCAR, we exemplarily applied an initial version of such an integrated openPASS traffic model which has not yet reached a development maturity and validation level to live up to all of these expectations. The current shortcomings in software functionality and limited possibilities for verification and validation of such a model against real traffic and realistic accident occurrence are discussed in sections 5.4 and 5.5. Yet, we believe to have reached a maturity level to draw first conclusions on potential future crash configurations of automated vehicles in mixed motorway traffic.

5.2 Traffic scenarios in openPASS simulations

In general, the motorway traffic is rich in different traffic scenarios and each traffic scenario itself consists of a wide range of specific scenarios. A stochastic traffic simulation has the advantage to only use a traffic scenario as an input while the specific scenarios within the traffic scenario emerge from first principles of the driver model. The traffic scenarios for the OSCCAR simulations were identified by building on three pillars: previous publications, critical analysis of traffic and accident statistics, as well as expert knowledge (for a summary see D1.1). In the following paragraphs, we will describe the selected OSCCAR traffic scenarios in more details. In general, the selected OSCCAR traffic scenarios are following the scenario analysis in the EU-FP7 project AdaptIVe covering the most relevant shares of car-to-car/truck accidents on motorways [33].

The first OSCCAR traffic scenario is a regular three-lane motorway with a speed limit of 120 km/h (Figure 25). The first traffic scenario is motivated by the capabilities of the openPASS framework including an advanced driver behavior modelling (see section 5.3 for details). We expect only a few collisions in this traffic scenario as the driver parameters are chosen such that there is a collision after about 1 million simulated kilometers (see section 6). The aim of the first traffic scenario is a reproduction of reasonable distances between two collisions. A statistical analysis of crash configurations in this traffic scenario will remain elusive as the simulated distance would need to reach more than a billion kilometers and the simulation resources are limited in OSCCAR. For the other traffic scenarios, we aim for more critical simulations with potentially more collisions and options for statistical analysis of crash configurations.

The second traffic scenario is free traffic at a motorway on-ramp (Figure 25). Combining different publicly available data sources for German motorway traffic (e.°g., BASt traffic data [42]) and accidents statistics (e.°g., DESTATIS Unfallatlas [43][45]) showed that approximately 40% of all accidents on German motorways with personal injury occur at or nearby motorway on-ramps or exits [34]. In addition, cut-in scenarios are a widely discussed specific testing scenario for automated vehicles. A free-flow motorway traffic at an on-ramp fits all these inputs. To increase the criticality of the simulated on-ramp scenario, we use a challenging traffic volume in the incoming lane combined with a short merging zone. With these adjustments, we hope to find the collision numbers above the measured accident statistics while the crash configurations may change only a little. Moreover, in our simulations, we do not set a speed limit. Yet, we expect an average velocity well below 120 km/h given the rather challenging traffic volume (for the actual velocity distribution see section 5.6.1).

The third OSCCAR traffic scenario is motivated by the fact that accidents at the end of traffic jams account for approximately 20% of all car accidents on motorways, as the GIDAS analysis in AdaptIVe showed [33] and which was confirmed based on analysis of German “Unfallatlas” data [34]. Following these findings, the third OSCCAR traffic scenario addresses traffic jams (Figure 25 right). Technically, we use a three-lane motorway without a speed limit but use a sample of slow-moving cars on all lanes to mimic the end of a traffic jam (so called scenario cars).

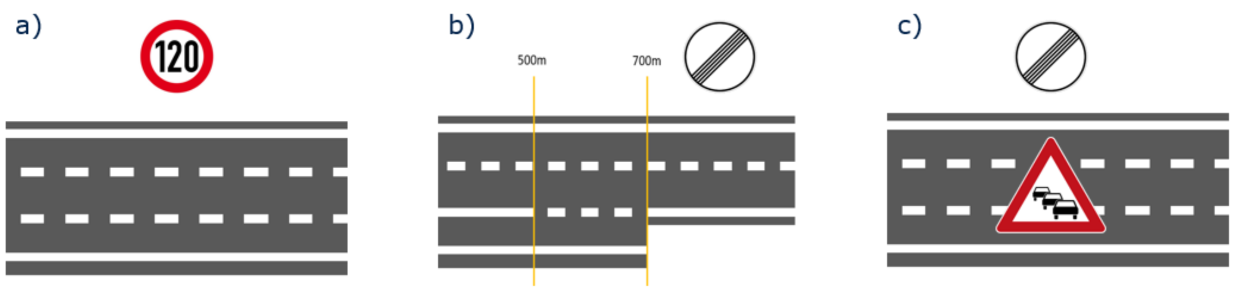


Figure 25: Sketches of traffic scenarios used in openPASS simulations (adapted from [30])

5.3 Driver behavior model

The driver behavior model is the essential part in a stochastic traffic simulation approach [32] and covers the cognitive processes of a human driver. Basically, the driver behavior model enables the simulated vehicles to decide on their own actions and, most importantly, it can make a mistake at every level of the decision process. Thereby, the origin for possible critical behavior and collisions in the simulation is not pre-defined but incorporated in the driver behavior and a result of mistakes based on first principles.

The concept definition of the relevant cognitive processes for a human driver as well as the driver model development were conducted independently but aligned with OSCCAR as part of the research cooperation platform Tech Center i-protect in several projects by Mercedes-Benz AG, Robert Bosch GmbH and Dresden University of Technology [34]. The openPASS driver models were published with the same open-source license as the openPASS platform itself, whereas the OSCCAR specific models are publicly available in the hlrs-branch of the openPASS repository [36]. The driver model development was finally integrated into the overall OSCCAR openPASS toolchain (D1.2 [30]).

In the following paragraph, we give a brief overview of the driver model architecture [38]. All cognitive driver models were included in the algorithm level of the sensor-algorithm-dynamics architecture of the openPASS platform. From the "sensor" module basic information about the environment as, e.°g., on road and surrounding vehicles is passed to the information acquisition submodule of the driver model. In the next steps, the driver model performs a situation assessment and deducts possible actions and executes those actions. Failures or mistakes can occur at every level of the driver model (see red bolts in Figure 26). For the purposes of this study, driver failures are generally implemented by modulating the update frequency of the information acquisition, i. e., mimicking a "look away time". If the driver is modeled to look away and does not obtain new information, the mental model will extrapolate based on the last available information. This might lead to delayed reactions, critical situations and, possibly, collisions.

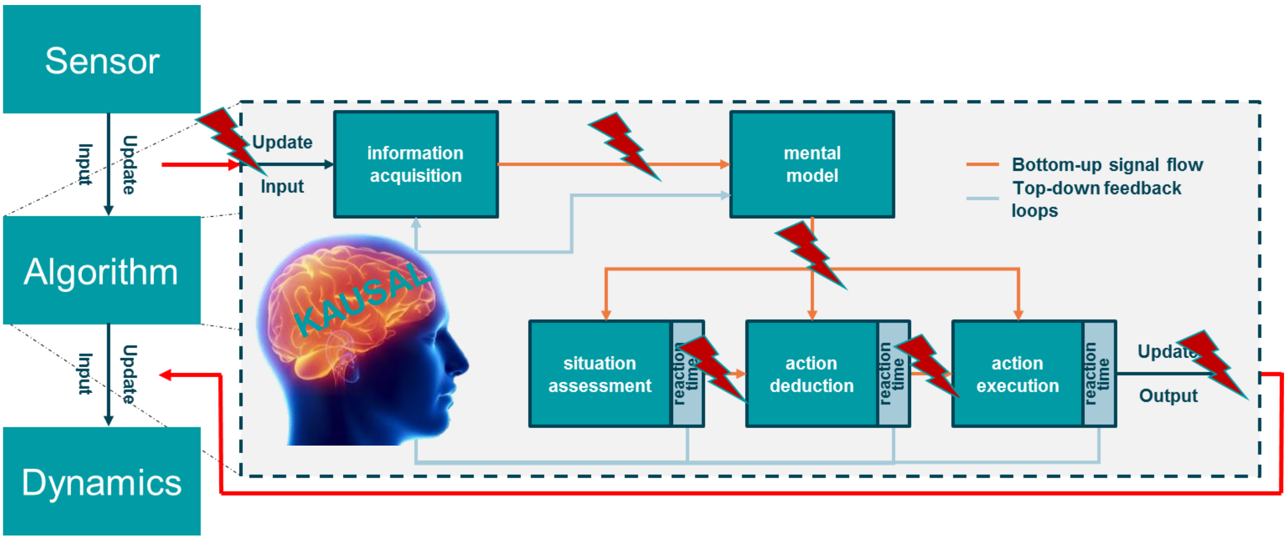


Figure 26: Schematic architecture of the driver model (adapted from [38])

For the stochastic traffic simulations, we make use of the openPASS inherent stochastics module and choose for each vehicle in the simulation its own set of parameters. The simulation as a whole is set up by specifying the distributions of all stochastically chosen parameters. The specifications of the driver can be summarized as follows.

- Model parameter: the driving style is defined by both physical (e. g., desired velocity) and model-specific parameters (e. g., driver style) that lead to variations between rather slow, cautious drivers as well as rather fast, risk-taking drivers.
- Normal driving capabilities: the driver is capable of car following and lane changing in longitudinal traffic, complying to traffic rules and showing cooperative behavior at merging lanes. The submodules for action deduction were adopted from the open-source traffic

simulator SUMO [39]. In normal traffic situations and without any failure options in the driver model, i. e., with a perfect driver, the simulated traffic is free of collisions, as it is usually the case in traffic simulators.

- Behavior in critical situations: if needed, drivers might switch from normal driving within the range defined by their comfort deceleration/acceleration to a TTC triggered emergency braking. Emergency steering is not implemented.
- Failure induction: a subset of drivers in the simulation has the previously described ability to introduce (stochastic) failures in the driver model. The most prominent part is by modulating the information acquisition which is solved technically by an avert view and reaction time. Consequently, imperfect information is used for the action deduction and the driver behavior may lead to critical situations, e. g., low distance.

After describing the human drivers, we now modify the technical driver model for modelling generic automated vehicles. Aligned with the D1.1 approach, a generic automated driving function complies to traffic rules and is carefully dealing with surrounding traffic. Consequently, the automated vehicles in the openPASS simulation framework are implemented as a version of the failure free drivers. Functionally, the automated vehicle is identical to a human driver, being able to perform car following and lane change maneuvers. However, the parameters for these functions are different for the automated vehicle and the human drivers. In general, the driver parameters of the automated vehicle reflect an idealized conservative driving style with slower mean velocities and larger time gaps to preceding vehicles; the automated vehicles are supposed to represent a robust and well-designed system behavior.

In Table 2, the main driver parameters are shown as an overview for the human car and truck drivers as well as the automated vehicles. The main characteristics of the driver models are described by the *velocity wish* ("VelWish" in Table 2 modelled as normal distribution with mean and standard deviation), the *desired time headway* ("THW" in Table 2 modelled as log-normal distribution with mean and standard deviation), the *driving style* ("Speed gain/Keep right"), the *compliance with traffic rules* ("Traffic rules"), and the *source for failures* ("Failures"). The exact parameters used in the simulations to model human drivers and automated vehicles can be found along with the OSCCAR demonstrator software of the simulation platform as described in D1.2 [30].

Table 2: Overview of basic driver characteristics in the openPASS simulations. The parameters VelWish and THW are modelled as normal and log-normal distributions, respectively

	VelWish	THW	Speed gain / Keep right	Compliance to traffic rules	Failures
Conventional car	135±10 km/h	1.0±0.3 s	high/low	normal	Driver can take eyes off the road
Conventional truck	88±7 km/h (max 90 km/h)	1.9±0.3 s	low/high	normal	Driver can take eyes off the road
Automated vehicle	110 km/h	2.0 s	low/low	high	-

5.4 Validation of motorway traffic

The stochastic simulations of motorway traffic have been validated in several individual steps. While the first steps consist of the general infrastructure of motorways and the selection of traffic scenarios (see sections 4.1 and 4.2), the more challenging steps address the validation of the (human) driver behavior model of section 4.3. As there is no formal validation process for highly complex stochastic simulations, especially for parameters with only indirect and multi-purpose impact on simulation results, we describe our validation steps mostly in qualitative terms.

In the following paragraphs, we address the validation of the driver model in a three-step process: on a functional level, on the level of macroscopic traffic characteristics and on the level of collisions. Figure 27 illustrates these validation steps in detail. Red marked are such requirements which are either not yet covered by the simulation software (especially the functionality in critical situations) or the real-world data is lacking to focus on, e. g., traffic scenario specific crash rates by adjusting driver or traffic parameters. An ideal forth validation step for the overall model (i. e., “the model represents the real world appropriately”) is omitted due to the shortcomings on the previous levels.

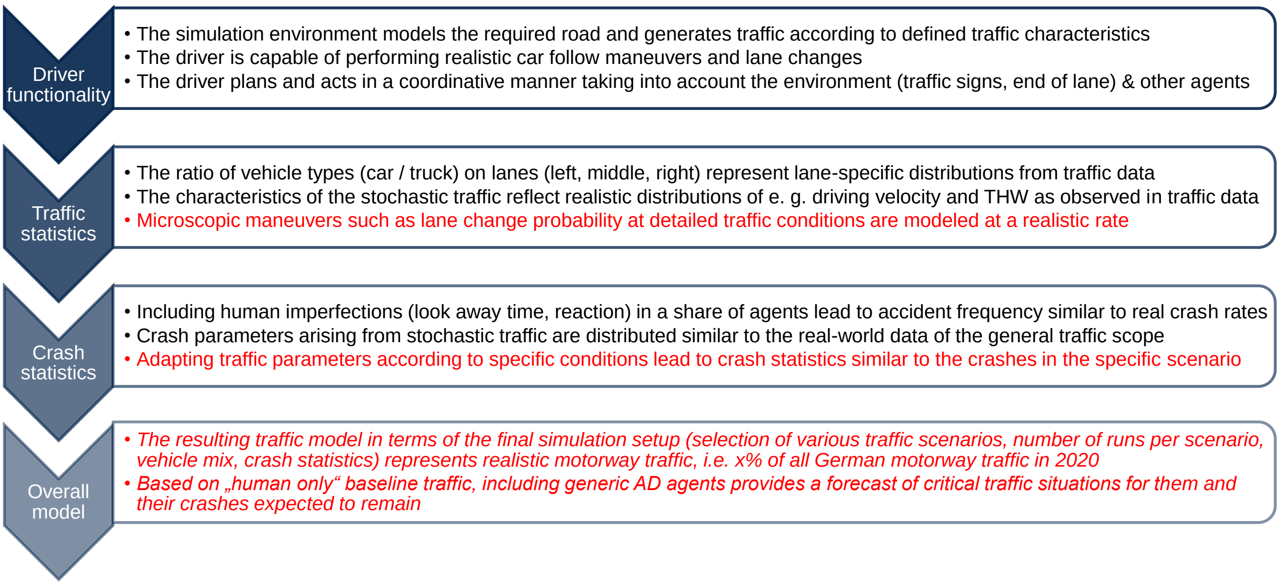


Figure 27: Visualization of the requirements towards the traffic model / the simulation approach on the different levels. Red marked = shortcomings leading to the overall model not representing real-world motorway crashes

The first validation step of the human driver behavior model is a functional validation for all potential tasks on the motorway. As described in section 5.1, the main functional tasks of vehicles on motorways are “car following” and “lane change" as well as complying to implicit (e. g., obligation to drive on the right side) or explicit traffic rules (e. g., speed limit). In addition, the drivers have the ability to perform emergency braking maneuvers. Most of the functional tasks have been originally adapted from the SUMO simulation framework and offer a parametrization per vehicle driver to perform each task individually [32][34]. For instance, each driver has a parameter TGapWish (*desired time headway*) determining the distance to a preceding vehicle in the car following task. After careful review of all functional tasks, no major tasks for generating motorway traffic are missing in the current version of the OSCCAR openPASS framework.

The second validation step is dealing with the parametrization of the simulation that is finally determining the traffic. This validation step was performed by an iterative process where, after starting with an educated guess for all driver model parameters, traffic characteristics of the simulation were tested against real world data. More specifically, in an iterative process and accounting for all specific traffic scenario set ups (e. g., regular motorway traffic scenario uses three-lane motorway with speed limit at a given traffic volume), the best driver model parameters were found to match macroscopic traffic characteristics as, e. g., velocity and time headway distributions, lane occupancy, etc. Here, different data sources were used for real world data, e. g., BASt traffic data [42] and highD-dataset [35]. The entire process and its results are described in detail in reference [34]. In total, the stochastic simulation approach generates with our parametrization of the driver model on average a traffic that could be considered as “realistic” (for details see also the traffic results in Table 4 and in section 5.6.1). Considering the large variances of macroscopic traffic characteristics for different traffic situations, we are confident that our simulations generate at least a subsample of all real-world motorway traffics.

The third validation step accounts for human driver imperfections which are the root for driver mistakes and, consequently, critical situations and collisions. Driver imperfections should not affect the previously validated macroscopic free-flow traffic characteristics, e. g., traffic volume and density, vehicle type distributions or velocity distributions, as there is only a small share of drivers with imperfections and, in addition, the imperfections alter the driver behavior occasionally. The key driver imperfections are the reaction time and a “look away time”. During the latter, the driver is not paying attention to other traffic participants, either by in-vehicle distractions or by focusing on other parts of the traffic (e. g., read-ward traffic). For this validation step, the driver model parametrization is mostly built on literature. For instance, the human reaction time is modelled by a lognormal distribution with mean and (lognormal) standard deviation, with mean typically in the range of 1 s and the standard deviation in the range of 300 ms [41]. A cross-validation before starting the main simulation study for OSCCAR openPASS simulation results proved the macroscopic traffic characteristics were unaffected by the driver imperfections [34]. It is worth noting that the automated vehicles in our simulations have no comparable feature and should consequently do not cause collisions.

All in all, it appears plausible that our driver behavior model and its parametrization is sufficiently valid for answering the OSCCAR specific research questions with the openPASS stochastic traffic simulation framework. Especially for the regular free-flow motorway traffic, all aspects of the traffic scenario have been explicitly tested in the validation process. However, for the most challenging traffic scenarios (on-ramp and traffic jam), specifically chosen to generate more than realistic collision numbers (see discussion in section 5.2), the driver behavior model and its parametrization might be overstretched. For both traffic scenarios, we will analyze and state our interpretation of the simulation results extremely carefully. As both traffic scenarios are not fully validated, we will avoid discussing, e. g., shares of remaining crash configurations, but we hope to learn about trends of future remaining collisions in mixed traffic.

5.5 Simulation study for motorway traffic scenarios

After describing the approach for stochastic traffic simulations in 5.1, the simulated traffic scenarios in 5.2, and the details of the driver modelling in 5.3, we will address all other aspects of the simulation study in this section. First, we discuss the configuration of the traffic within the simulation itself. Thereafter, we deal with the setup of the simulation study, from baseline and treatment simulations to the number of simulation runs. Finally, we explain the openPASS approach for identifying collisions and how those collisions could by analyzed in section 5.6.

The backbone of each simulation is regular traffic. The traffic consists of many individual vehicles, each vehicle with its own set of stochastically chosen parameters. The vehicles are spawned at the beginning of the road, where the traffic volume per lane is the same for each lane. The traffic volume on motorways is calculated from German accident and traffic characteristics and is typically found below 2 000 vehicles per hour per lane with accidents occurring on German motorways mostly at traffic volumes of around 750 vehicles per hour per lane [34][42]. For the OSCCAR simulations, the traffic volume follows the previous findings and is fixed to 750 vehicles per hour per lane and, for convenience, all traffic scenarios were simulated with the same traffic volume. The distribution of vehicle types with human car drivers (conventional cars), human truck drivers (conventional trucks), and automated cars may vary from lane to lane. The share of trucks on German motorways is typically, as a yearly average, in the range of 5% to 20%, depending on the location and with large variances during a week [42]. In the traffic simulation, each setup has a fixed share of trucks among all vehicles in the same ranges (see Table 2). With more and more vehicles being spawned in the simulation environment, the differences in speed and behavior as well as the individual choices for interactions (overtaking, changing to the favored right lane, etc.) leads to realistic traffic situations including conflicts and accidents. All traffic scenarios start with a three-lane motorway, and in the on-ramp traffic scenario, the number of lanes is reduced after 700 meters from three to two lanes. Consequently, the vehicles spawned on the right lane are forced to change the lane. The other traffic scenarios keep the three-lane motorway for the entire simulation (for sketches see also Figure 25).

For each traffic scenario, we perform a “baseline” and a “treatment” simulation, where the baseline simulation is traffic of conventional vehicles while the treatment simulations include automated vehicles, too. The simulations in this study assume a share of 50% automated vehicles among all cars, referring to the expected mixed traffic of the late 2040s and 2050s (see section 5 in D1.1). To simulate millions of vehicles, the number of simulation runs is set to 50 000 per traffic scenario per baseline or treatment simulation. Only for the traffic jam scenario, we reduced the number of runs to 1 000 per baseline or treatment simulation after finding a huge number of collisions (for a detailed discussion, see 5.6.2). For technical reasons, the simulation time is limited to 120 s per simulation run. In Table 2, all simulation parameters for all traffic scenarios are displayed.

Table 2: Number of runs and distribution of vehicle types for all traffic scenarios

Traffic scenario	#runs	AD	Share of conventional cars	Share of conv. trucks	Share of automated cars
Regular motorway traffic (A)	50 000	no (baseline)	93.4%	6.6%	0
	50 000	yes (treatment)	62.4%	6.6%	31.0%
On-ramp traffic (B)	50 000	no (baseline)	80.0%	20.0%	0
	50 000	yes (treatment)	53.0%	20.0%	27.0%
Traffic jam (C)	1 000	no (baseline)	93.4%	6.6%	0
	1 000	yes (treatment)	62.4%	6.6%	31.0%

The three different traffic scenarios are set up by configuring the road infrastructure and the scenario. For the regular motorway traffic, it is only a three-lane motorway with a speed limit of 120 km/h, the previously motivated traffic volume of 750 vehicles per hour per lane and a fixed distribution of vehicles types based on [42]. Everything else within the simulation is initiated by the driver model itself. The on-ramp traffic scenario is different by its road infrastructure (two-lane motorway plus on-ramp lane without speed limit) and has a modified distribution of vehicle types. The traffic jam scenario, in contrast to the regular motorway traffic scenario, has the same road infrastructure – a three-lane motorway – but no speed limit and, in addition, a scenario pre-configured in the OpenSCENARIO configuration file. The OpenSCENARIO configuration describes a pack of 24 slowly moving cars (so called scenario cars with a design velocity of 30±5 km/h in a normal distribution) equally distributed on all three lanes to mimic the end of a traffic jam.

If a collision occurs in a simulation, the crash configurations were logged as event parameters in the simulationOutput.xml (see Figure 28 for an example) and contain most importantly collision point angles, relative yaw angles, and collision velocities as in section 3. Furthermore, the openPASS framework estimates internally the Delta-v [40], i. e., the estimated velocity change due to the collision, as a simple collision severity indicator from the crash configuration and vehicle characteristics. The colliding vehicles are removed in the time step after the collision and the traffic simulation may continue and further collisions may occur. However, due to the immediate elimination of colliding vehicles, no multiple collisions in terms of follow-up collisions are seen in the openPASS simulations. As results for all simulation runs, the mileage driven, the type of vehicles and the collision parameters are stored in the simulationOutput.xml (example shown in Figure 28). Additionally, for runs with collisions, the trajectories of all vehicles in the simulation run (X/Y positions and yaw angle of all vehicles) were logged to CSV files.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        <Agents>
            <Agent Id="0" AgentTypeGroupName="Ego" AgentTypeName="EgoAgent" VehicleModelT
            <Agent Id="2" AgentTypeGroupName="Common" AgentTypeName="ModularDriverAD" Veh
            <Agent Id="3" AgentTypeGroupName="Common" AgentTypeName="ModularDriverAgent"
            <Agent Id="6" AgentTypeGroupName="Common" AgentTypeName="ModularDriverAgent"
```


Figure 28: Exemplary simulation output file with a collision logged as an “Event”

5.6 openPASS simulation results of motorway traffic

The openPASS simulations were by design highly parallelizable and consequently carried out on different machines. As described in section 5.5 a total of 202 000 individual simulation runs were carried out. One run consists of a single openPASS simulation of a motorway section of 4.5 km length and a total simulation time of 120 s. As discussed previously, the short simulation time was chosen to avoid effects of memory overflow or long writing and processing times of the simulation output to and from the hard drive. On average, 80-100 vehicles were simulated per simulation run.

A detailed analysis of the simulated traffic is given in section 5.6.1. In the following section 5.6.2, the simulated accident statistics of free-flow motorway traffic and our interpretation is described. We conclude analyzing the openPASS simulations in sections 5.6.3 and 5.6.4 by carefully analyzing the crash configurations of the not fully validated traffic scenarios “on-ramp” and “traffic jam”, respectively.

5.6.1 openPASS traffic analysis

Our data set of openPASS simulations consists of three motorway scenarios: (A) a regular, free-flow, three-lane motorway, (B) a two-lane motorway with on-ramp, and (C) a three-lane motorway with traffic jam (see section 5.5). Each scenario was simulated twice, with and without generic automated vehicles (baseline vs treatment). As discussed previously, the main idea for doubling the simulation effort is to identify possible non-trivial effects of automated vehicles by comparing the treatment simulations (with automated vehicles) with the baseline simulations (without automated vehicles). While the traffic scenarios “free-flow” (A) and “on-ramp” (B) were simulated in a total of 100 000 runs, the traffic scenario “traffic jam” (C) was simulated in 2 000 runs. All main traffic characteristics are shown in Table 3. In this sub-section, we analyze the simulated traffic in general and try to justify the main traffic characteristics by rough estimates in addition to the model justifications of section 5.4.

Table 3: Main traffic characteristics and simulation overview

Scenario	#runs	distance [km]	#vehicles	#human cars	#human trucks	#automated cars
Regular motorway traffic (A)	50 000	7 824 911	3 837 646	3 590 200	247 446	no
	50 000	7 934 278	3 863 994	2 413 123	249 032	1 201 839
On-ramp traffic (B)	50 000	5 881 650	3 394 504	2 719 006	675 498	no
	50 000	5 916 099	3 416 949	1 813 236	680 926	922 787
Traffic jam (C)	1 000	102 675	68 780	64 603	4 177	no
	1 000	103 207	69 593	43 792	4 298	21 503

The total number of simulated vehicles is close to 15 million. This number is obtained from the traffic volume and the simulation time. By design of the simulations, the traffic volume is set to 750 vehicles per hour per lane to induce a reasonable number of interactions between vehicles. In combination with the three-lane or two-plus-one-lane motorways, the traffic volume is 2 250 vehicles per hour for all traffic scenarios. The simulation time was set to 120 s for each scenario. Consequently, the number of vehicles per simulation is about 2 250*120/3600 = 75 vehicles. For 50 000 simulation runs, we expect per (sub-) scenario a total of 75*50 000=3.75 million vehicles. Checking with Table 3 shows for both sub-scenarios A about 3.8 million vehicles and for both sub-scenarios B about 3.4 million vehicles – an excellent result given the simplicity of our estimate, neglecting, e. g., initially spawned vehicles or delaying of runtime spawning due to crowded lanes.

The driving distance of all vehicles can be derived in a similar simplistic way. Assuming for the regular motorway an average driving speed of 120 km/h and a simulation time of 120 s, we end up with a maximum driving distance of 4 km per vehicle. Yet, we need to reduce this driving distance by a factor of two as we have a constant spawning rate of vehicles for all of the simulation time (a car spawned at, e. g., t = 110 s had only the chance to drive for 10 s before finishing the simulations). Multiplying an assumed driving distance of 2 km per vehicle with 3.75 million vehicles derived above, we expect a total distance of 7.5 million km. For the sub-scenarios in A, we measure a total driving distance of 7.8 and 7.9 million kilometers – again, an excellent result. Deriving the total distance for the other scenarios is more challenging, because of an – *a priori* – unknown average velocity. For both, the on-ramp and the traffic jam, the vehicles are required to, at least partially, significantly reduce their velocity.

As a third and last macroscopic measure of our simulated traffic, we analyze the distribution of vehicle types. Taking as example the on-ramp scenarios, by design of the on-ramp scenario simulation (see Table 2), we expect 20% trucks among all vehicles. For both, the baseline and treatment simulations, we find for trucks a share of 19.9%. The remaining 80.1% of vehicles are cars. In the case of treatment simulations, the group of cars consists of the two populations of conventional cars and automated cars with a designed distribution of 2:1 (see Table 2). From Table 3, we find for the simulation results a distribution of conventional to automated cars of 1.96:1.

Before concluding the traffic analysis, we want to have a closer look into some vehicle characteristics such as driving velocity and time headway which were analyzed for 10 000 randomly chosen vehicles of the treatment simulation in the on-ramp scenario. By design, there are twice as many conventional cars as automated cars. The driving velocity for conventional cars and automated vehicles is shown in Figure 29. Although the velocity wish for conventional cars with 135 ± 10 km/h (dashed line in Figure 29) is considerably larger than the velocity wish of automated vehicles (110 km/h), the final velocity in our rather crowded simulation setup is for both populations very similar. For conventional cars, the velocity reduction is explained by the surrounding vehicles, especially the slower automated vehicles and trucks. Only 17% of the conventional cars are unaffected by automated vehicles or trucks and have a driving velocity above 110 km/h. In contrast, the automated vehicles are less affected by the surrounding traffic with almost 40% of automated vehicles driving close to the velocity wish above 105 km/h. Comparing the average velocities of both car populations, we find an almost identical average driving velocity indicating the crowded traffic in the on-ramp traffic scenario.

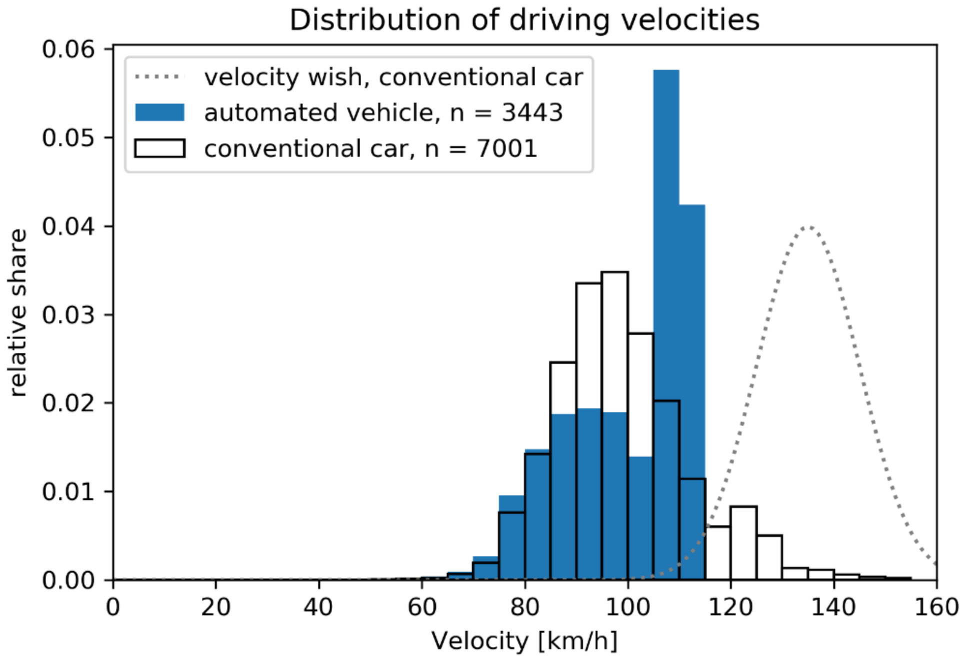


Figure 29: Distribution of driving velocity for automated vehicles and conventional cars (about 10 000 randomly chosen vehicles of the on-ramp scenario). The velocity wish of conventional cars (dotted line) and automated vehicles (v=110 km/h) is reduced due to surrounding traffic

Analyzing for the same vehicles the time headway, i. e., the time gap between two following vehicles, we find the distribution displayed in Figure 29. For the conventional cars, with a time gap wish of 1.0 s and a standard deviation of 0.3 s in a log-normal distribution, the actual time headway peaks at about 1.5 s with almost no occurrences below 0.5 s and a broad tail above 2.0 s. In contrast, the distribution for automated vehicles is fundamentally different: it has a narrow peak at about 2.0 s. It originated from the configuration of the automated vehicles which wish a fixed time gap of 2.0 s. Accordingly, we find almost no time headways below 2 s. Yet, on the right side of the peak, the distribution has again a long tail, comparable to the tail of conventional cars. On German motorways, we see the same characteristics of the time headway – in Figure 30 exemplarily displayed for all vehicles classified as class “Car” in the highD dataset [35]. Please note, the highD dataset observed all types of motorway traffics including low and high traffic volumes, possibly not all comparable to the traffic volume in the OSCCAR simulations. Mimicking the time headway more realistically is an open task for future traffic simulations, requiring possibly a more sophisticated car following model.

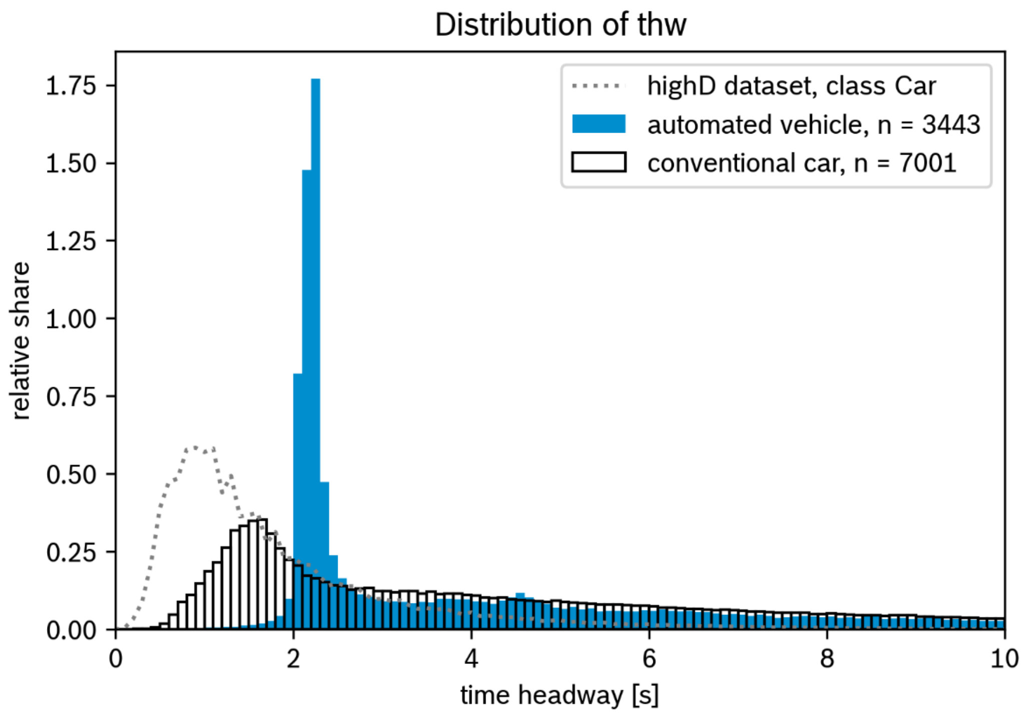


Figure 30: Distribution of the time gap between two following vehicles (time headway) for automated vehicles and conventional cars (blue and white bars, respectively). The distribution is constructed from about 10 000 randomly chosen vehicles of the on-ramp scenario, the same vehicles as for Figure 29. The dotted line shows a time gap distribution obtained from the highD dataset of German motorway traffic

All in all, a first glance at the traffic characteristics of the simulations on macroscopic and microscopic level is very promising with respect to our aim of simulating realistic traffic.

5.6.2 openPASS crash statistics

After discussing the simulated traffic in the previous section, we will address the crash statistics in this section. The overall crash statistics are displayed in Table 4. This table shares the same overall structure as Table 3 with all three scenarios, each one with and without participation of automated vehicles. In contrast to Table 3, the columns in Table 4 show if automated vehicles were present (AD), the total travelled distance within the scenario (distance [km]), the number of identified collisions (#collisions) and the travelled distance per collision (vehicle kilometers travelled, abbreviated VKT/collision [km/accident]). In the following paragraphs, we will discuss the overall accident statistics in detail.

Table 4: Accident statistics on scenario level

	AD	distance [km]	#collisions	VKT/collision [km/accident]
Regular motorway traffic	no	7 824 911	8	980 000
	yes	7 934 278	10	790 000
On-ramp traffic	no	5 881 650	155	38 000
	yes	5 916 099	210	28 000
Traffic jam	no	102 675	689	150
	yes	103 207	631	165

For the first scenario, the regular motorway traffic, we find in almost 8 million km travelled distance only 8 and 10 collisions for simulations without and with automated vehicles, respectively. The distance between two collisions (VKT/collision) is consequently close to 1 million km per collision. This VKT/collision is a realistic value assuming regular traffic on motorways (see, e. g., section 6.2.4). Given only a few collisions, a detailed analysis of crash statistics similar to the analysis in 5.6.3 and 5.6.4 is omitted for the regular motorway traffic scenario. No differences between simulations without and with automated vehicles can be drawn. All crash configurations are either of the type “left-front (45°) to right-rear (-135°)” (n = 15) or “right-front (-45°) to left rear (135°)” (n =3). There are four generic automated vehicle agents involved in collisions, all of them have impacts to their rear corners.

The “regular traffic” scenario with automated vehicles shows ten collisions which is 25% more collisions than the baseline simulations without automated vehicles (eight collisions). However, assuming validity of general simple statistics for binomial distributions, the confidence interval for eight collisions out of 50 000 simulation runs predicts 3 to 17 collisions. Consequently, ten collisions of the treatment simulations are right in the middle of the confidence interval and could be interpreted as statistical noise. Thus, a prediction for collision probabilities of automated vehicles on regular motorways is avoided. All in all, we find for the regular motorway traffic a collision statistic in line with the previous traffic analysis; both indicating a well-chosen set of parameters for all types of drivers.

In the on-ramp scenario, we find the number of collisions increased by more than an order of magnitude. In particular, we find a collision every 28 000 to 38 000 km. The increased number of collisions is understood to be due to the setup of the scenario of an on-ramp with large traffic volumes and a short merging zone, reflecting the design of the traffic scenario with many conflict situations. The full discussion on the collision statistics of the on-ramp scenario is found in section 5.6.3. Yet, the driver model was never fully validated for the forced lane change of this scenario.

The accident analysis of the traffic jam scenario as the third scenario shows an unclear message. With only a fraction of driven distance, i. e., almost two orders of magnitude less, we find about two orders of magnitude more collisions than the regular motorway scenario. The VKT/collision is consequently reduced to only about 150 km per collision. Real-world distances between two crashes at the end of traffic jams are difficult to estimate – yet, we would expect orders of magnitude more VKT/collision. Therefore, an analysis of the collision statistics has only limited reliability. Most likely, the driver model, calibrated for regular motorway traffic, is overburdened with the traffic jam scenario reaching its limits in the low travelling speeds in combination with frequent lane changes. For full transparency, we display the results in section 5.6.4.

5.6.3 Crash configurations of the on-ramp scenario

In this section, we analyze in detail the collision statistics and crash configurations of the on-ramp traffic scenario. We compare conventional vehicles with automated vehicles and discuss key findings. First, we analyze the first point of contact for the collisions and in a second step we estimate the severity of the collision by discussing Delta-v. For the on-ramp scenario with large traffic volumes and a short merging zone, the forced lane change from the on-ramp lane to a regular lane on the two-lane motorway is by far the most critical type of event. As described in Table 4, the on-ramp sub-scenarios show 210 and 155 collisions with and without automated vehicles in the simulation, respectively. For the detailed discussion of the crash configurations, we analyze the treatment simulation including automated vehicles with a total of 210 collisions and 420 involved vehicles (174 conventional cars, 144 trucks, and 102 automated vehicles).

Having the forced lane change to the left from the on-ramp to the motorway lanes as the most critical type of event, the first point of contact is typically on the left side of the vehicle's front for the following vehicle and on the right side of the vehicle's back for the preceding vehicle (Figure 31). For all following figures, the conventional and automated vehicles are shown by white and blue bars, respectively. Please note that, to compare the first point of contact and corresponding angles for very different vehicle geometries, the vehicle coordinates have been transformed such that the four corners of the vehicle are at ±45° and ±135°. The prominence of the peaks at the left-front and right-back corners indicates only very little front to rear-end collisions in the on-ramp scenario. In addition to the key findings of OSCCAR Deliverable D1.1 with a focus on front to rear-end collisions (i. e., in the analysis of Swedish data, only the conflict situation Same Direction - Rear-end Frontal was included in the baseline data for pre-crash simulations, while the conflict situation Same Direction – Lane Change was not considered for simulation in this project), we find here almost exclusively lane change collisions, independent of the vehicle type. Combining both findings from D1.1 and the current study, we assume to expect future automated vehicles being involved in more than one accident type on motorways.

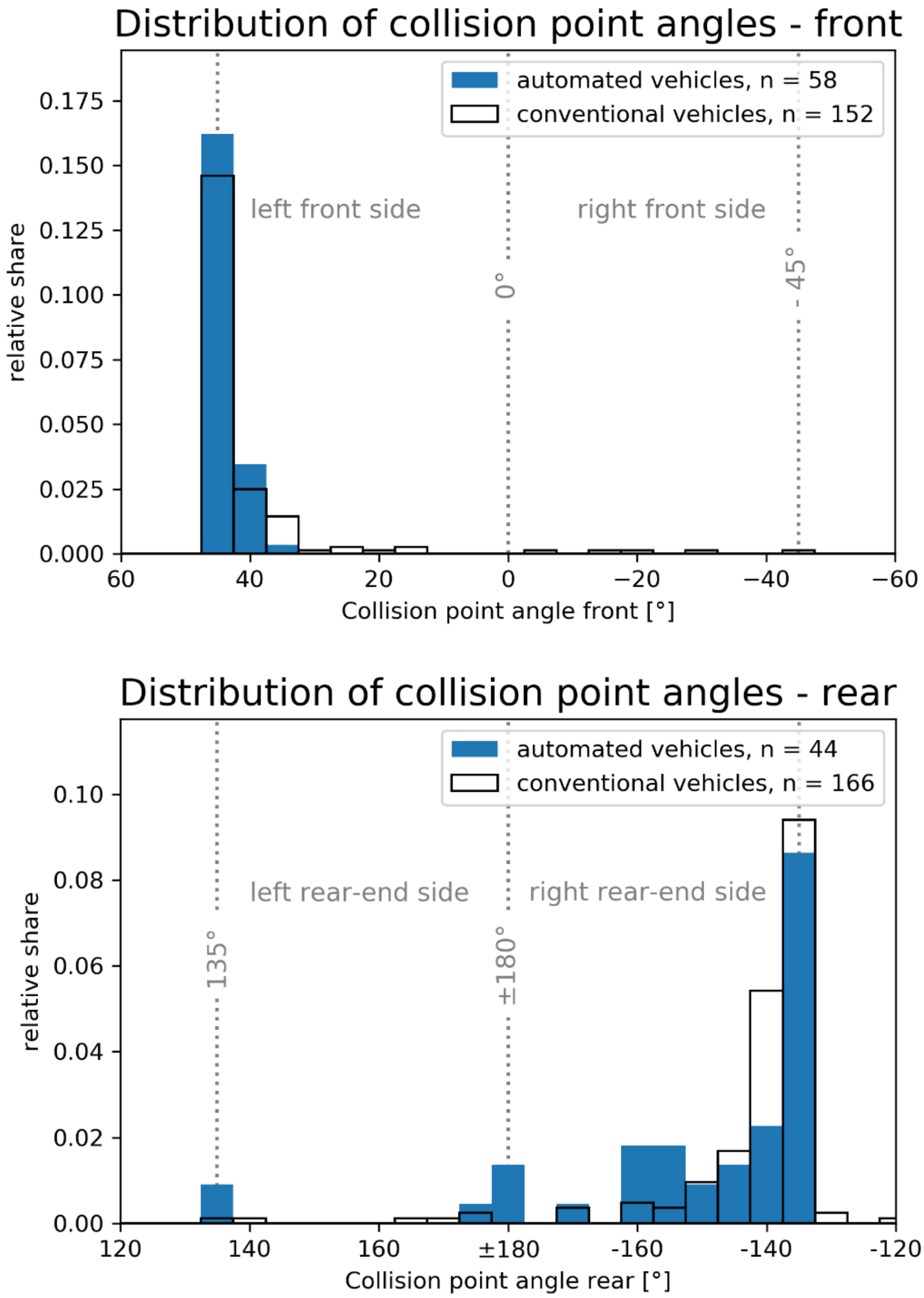


Figure 31: Collision point angle of conventional and automated vehicles in the on-ramp scenario. With the forced lane change to the left at the end of the on-ramp, the collision point angles are mostly on the left front side corner (top panel) and the right rear-end side corner (bottom panel)

The severity of the collisions is estimated by a discussion of Delta-v, i. e., the change in velocity of a colliding vehicle before and after the collision (see section 3, too). In the openPASS simulations, we calculated the Delta-v by assuming a generic elastic deformation and a basic impact calculation (i. e., a partially elastic/partially inelastic collision) accounting implicitly for the masses of the involved vehicles. For the on-ramp scenario, we find the distribution for automated and conventional vehicles in Figure 32. Except for a few collisions, almost all collisions show only small Delta-v below 20 km/h. Neglecting secondary collisions, we would expect no life-threatening injuries for both, conventional and automated vehicles. Interestingly, the most prominent bin for conventional vehicles is [0 km/h, 1 km/h) - a bin completely unpopulated by automated vehicles. In other words, automated vehicles could support avoiding collisions with minimal differences in collision velocities and consequently minimal Delta-v.

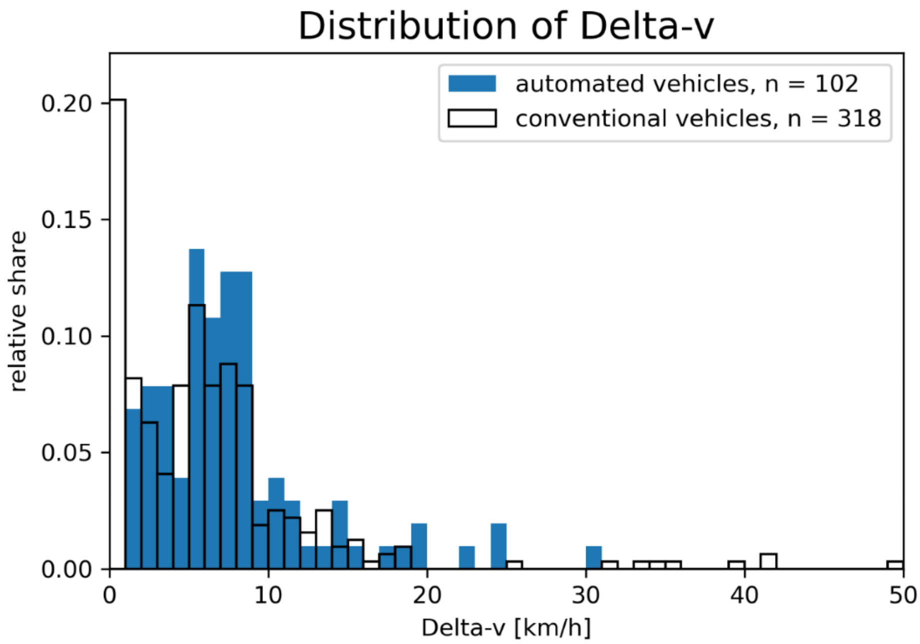


Figure 32: Delta-v distribution for conventional vehicles (human drivers) and generic automated vehicles in the on-ramp scenario

5.6.4 Crash configurations of the traffic jam scenario

After discussing the collisions of the on-ramp scenario, we analyze the traffic jam scenario in detail. This scenario was designed to introduce a traffic scenario with more critical situations and collisions than regular motorway traffic. Finally, we found a collision about every 150 km, a number obviously far from reality. Recalling the limitations during simulation validations in section 5.4, we assume the validity of the driver behavior model and its parametrization are probably overstretched by, e. g., the large difference between the actual velocities in traffic jam and the vehicles' velocity wish. Nonetheless, we analyze the crash configurations and Delta-v as in the previous traffic scenario and try to learn some general information in addition to the previous findings.

In the traffic jam scenario, we find in 1 000 simulation runs a total of 631 collisions, i. e., one collision in more than every second simulation run. 631 collisions include 1262 collision partners, thereof 758 conventional vehicles, 117 trucks, 245 automated vehicles, and 142 slowly moving cars that generate the traffic jam (scenario cars). As described previously in section 5.5, the 24 scenario cars per simulation run represent the end of a traffic jam on the three-lane motorway by “blocking” all lanes driving with a design velocity of 30±5 km/h. The other traffic participants are spawned at a distance of at least 500 m before the last scenario car with regular motorway cruising velocities and are forced to brake and adjust to the traffic jam.

In the traffic jam scenario, we find a large number of collisions with a contact point angle as displayed in the histogram in Figure 33. In the top panel of Figure 33, we show the collision point angles at the vehicle front, in the bottom panel the same angle at the vehicle back. In contrast to the on-ramp scenario, the distribution of the contact point angles lacks the strong asymmetry towards the left-front/right-rear corner and shows front-to-rear-end collisions (peak at 0°/180°), too. Interestingly, there are 655 collisions at the vehicle front and only 607 collisions at the vehicle rear-end. This asymmetry is explained by the existence of side collisions of two vehicles driving on parallel lanes and the definition of "front” being every contact point at the front half of the vehicle (collision point angles between -90° and 90°). Technically, the vehicle front would be considered between -45° and 45° in normalized coordinates. As we analyze the very first point of contact and use rectangular vehicles, even a side collision would have for one collision partner a first contact point at one of the front corners at ±45° (see Figure 33). Differences between automated and conventional vehicles are considered insignificant given the collisions number being too large by orders of magnitude for the entire traffic scenario.

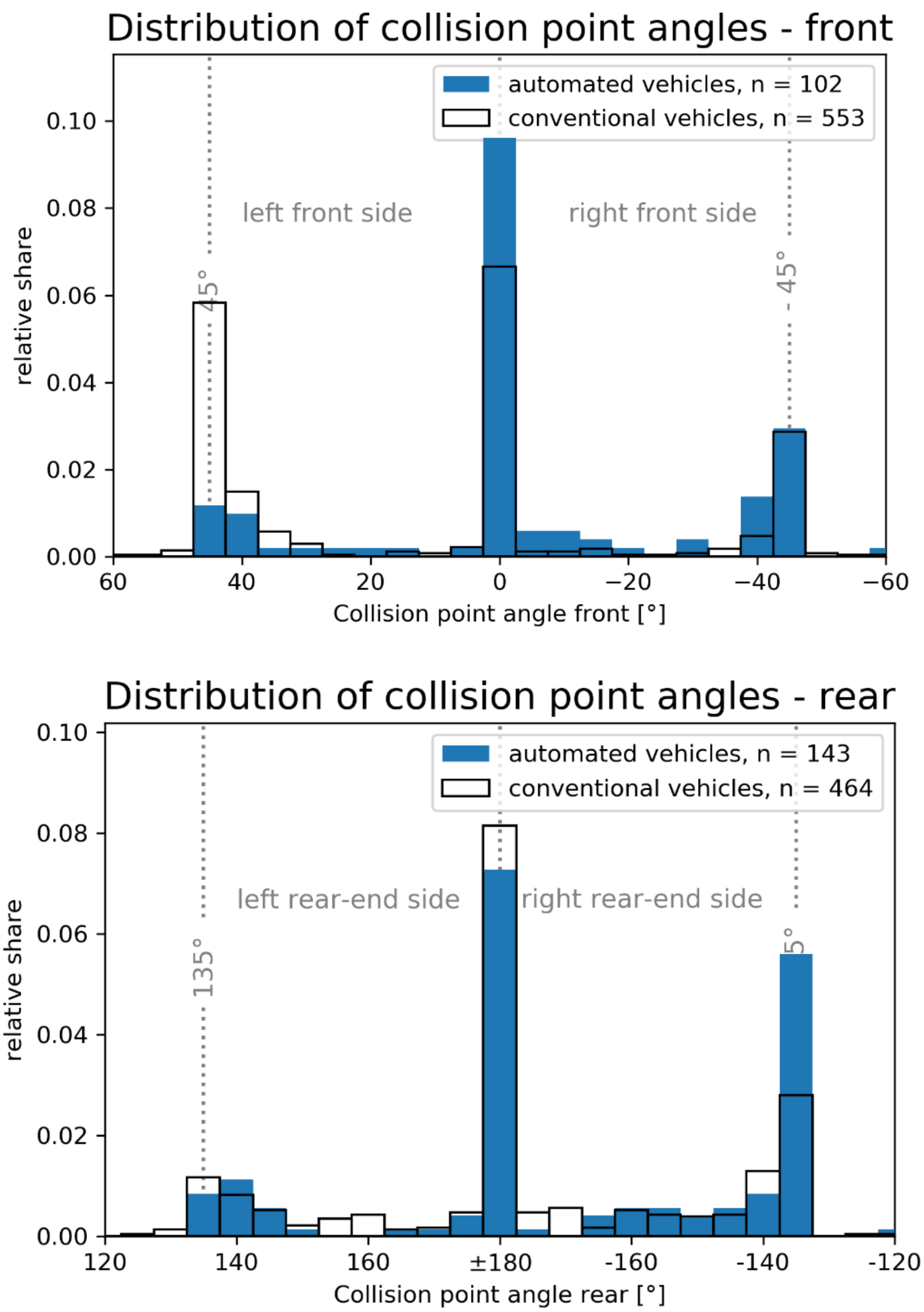


Figure 33: Distribution of collision point angles of conventional and automated vehicles (white and blue bars, respectively) in the traffic jam scenario. Top panel for front half of the vehicle and bottom panel for rear half of the vehicle

The severity of the individual collision is, on average, expected to be increased (see Figure 34) compared to the on-ramp scenario. In the on-ramp scenario (Figure 32), almost all of the 420 collision participants had a Delta-v of below 20 km/h. In the traffic jam scenario, 31% and 33% of conventional and automated vehicles, respectively, experience a Delta-v above 20 km/h. This high number of collisions at high severity is understood by the transition between regular motorway traffic with velocities at 90-120km/h and a traffic jam with velocities of ~30 km/h. In the on-ramp traffic scenario, all vehicles are approximately at the same velocity. Again, collisions with very small Delta-v seem to be avoided by the automated vehicle.

The crash configurations and the expected severity of the traffic jam scenario can only give some general information on this traffic scenario due to the obviously limited vehicle model and/or parametrization. Consequently, we consider the differences between baseline and treatment simulations as insignificant. Despite all unknowns in the simulations, we conclude to find all types of collisions on motorways (front-to-rear-end, lane change, and side collisions) in the traffic jam scenario simulations.

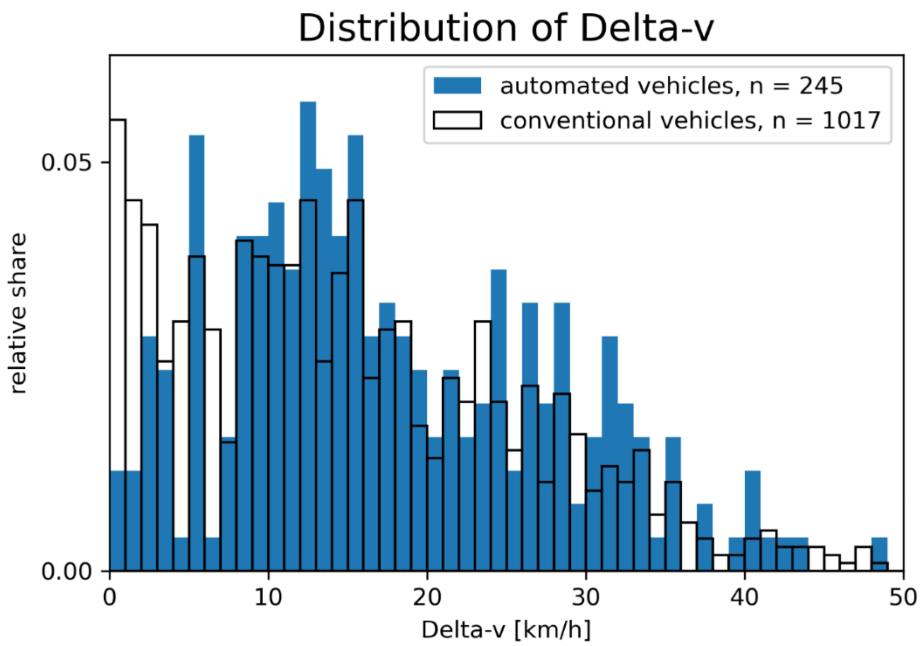


Figure 34: Delta-v distribution for conventional vehicles (human drivers) and generic automated vehicles in the traffic jam scenario.

5.7 Summary of traffic simulation results

The aim of the simulation study presented herein is to demonstrate the potential of stochastic traffic simulations in the context of prospective safety assessment and give first results for future crash configurations in mixed traffic on motorways. Crash configurations of future vehicles can be estimated by stochastic traffic simulations, both for driver assistance systems and for automated vehicles. The founding building block is the development of a driver behavior model that not only generates realistic traffic but also has implemented the underlying psychological mechanisms for human mistakes on various levels of the driving tasks. After an iterative fine-tuning of all parameters of the driver model in various limits of the simulation, the stochastic traffic simulation can reproduce, e. g., a realistic number of collisions on motorways as well as realistic traffic flow.

In OSCCAR WP1, we applied a fully parametrized stochastic traffic simulation within the openPASS framework to three different traffic scenarios. Each of the traffic scenarios addresses different research questions. The first traffic scenario is a regular, free-flow three-lane motorway traffic, without any pre-defined obstacles or challenges for the driver model. It addresses the question of a realistic number of collisions in the simulations. The second traffic scenario is an on-ramp scenario onto a two-lane motorway. This scenario is challenging because of a large number of vehicles on the on-ramp lane and, at the same time, a short merging lane forcing the drivers to perform possibly risky lane changes. The third traffic scenario is mimicking a traffic jam with the drivers approaching the end of the traffic jam. The third traffic scenario addresses another challenging scenario with risky situations due to possibly large velocity differences. While the free-flow traffic scenario is well validated for macroscopic traffic characteristics as well as accident statistics, the other traffic scenarios lack the same quality of the validation process. Especially for the traffic jam scenario, the crash avoidance potential of all kinds of drivers is below what is observed in reality and showing the need for further improvements in the implemented driver functionalities and parametrization. All analysis of simulation results was performed while keeping the validation level in mind.

We identified in section 5.6.1 several characteristics of regular traffic with partly expected and partly surprising results. For instance, and as expected, we found the distribution of vehicle types exactly as defined in the simulation set-up which suggests the numbers of vehicles within the stochastic nature of the simulations are sufficiently large. Another expected result is the number of vehicles and the driving distance given the number of simulations, simulation time per run, and the mean traffic volume. A rather surprising result is the distribution of driving velocities for conventional and automated cars, since the last ones are way less affected by dense traffic compared to conventional vehicles. While conventional cars have a larger velocity wish compared to automated cars, the peak of the observed velocity distribution of automated cars in dense traffic is much higher than for conventional cars. Yet, the mean velocity of both populations is almost identical.

For observed collisions in the simulations, we identified three major outcomes: (i) the number of collisions for our driver model is realistic in the regular free-flow motorway traffic scenario, (ii) forcing drivers to lane changes results in lane change collisions including the involvement of automated vehicles, and (iii) automated vehicles are expected to be involved in all kinds of collisions including front-to-rear-end and lane change collisions. The first outcome is again a sign for the high quality of the openPASS simulation framework, its parametrization and validation. The other outcomes are completing the previous OSCCAR WP1 picture of crash configurations of future automated vehicles on motorways. While the simulations presented herein show promising results, the overall simulation study has limitations. Besides the limitations due to incomplete validation for some traffic scenarios, a major limitation is the fact that the simulation study consists of a large number of vehicles and millions of driven kilometers, but the numbers are still too small to identify a significant impact of automated vehicles on the overall collision statistics. In addition, the automated vehicles in our simulation study are roughly modelled, generic automated vehicles without careful researching the optimal vehicle parametrization. While the first mentioned limitation could be overcome by huge simulation efforts, the second limitation is only overcome by detailed modelling and parametrization of all relevant automated vehicle driving functions.

6 WEIGHTING TO EUROPEAN LEVEL

6.1 Weighting methodology and available data

The approach described in the previous sections yields estimates regarding the effectiveness of the systems on a local level, representing the data collected and generated in a specific region. The goal of this deliverable as well as the OSCCAR work in general is to obtain results that are most relevant on EU level and represent the potential effect of systems in the context of the crash population in the EU. Therefore, a weighting methodology was developed in WP1 that aims to upscale the results from both D1.1 and from the traffic simulation approach described in section 5 to the EU. The results are weighted in order to adjust for differences between the local/regional and EU traffic. A cornerstone of the method is an overview and best use of the available data sources on EU level, including both crash data and exposure data, which are discussed next. This method, illustrated in Figure 35 below, is described in this section.

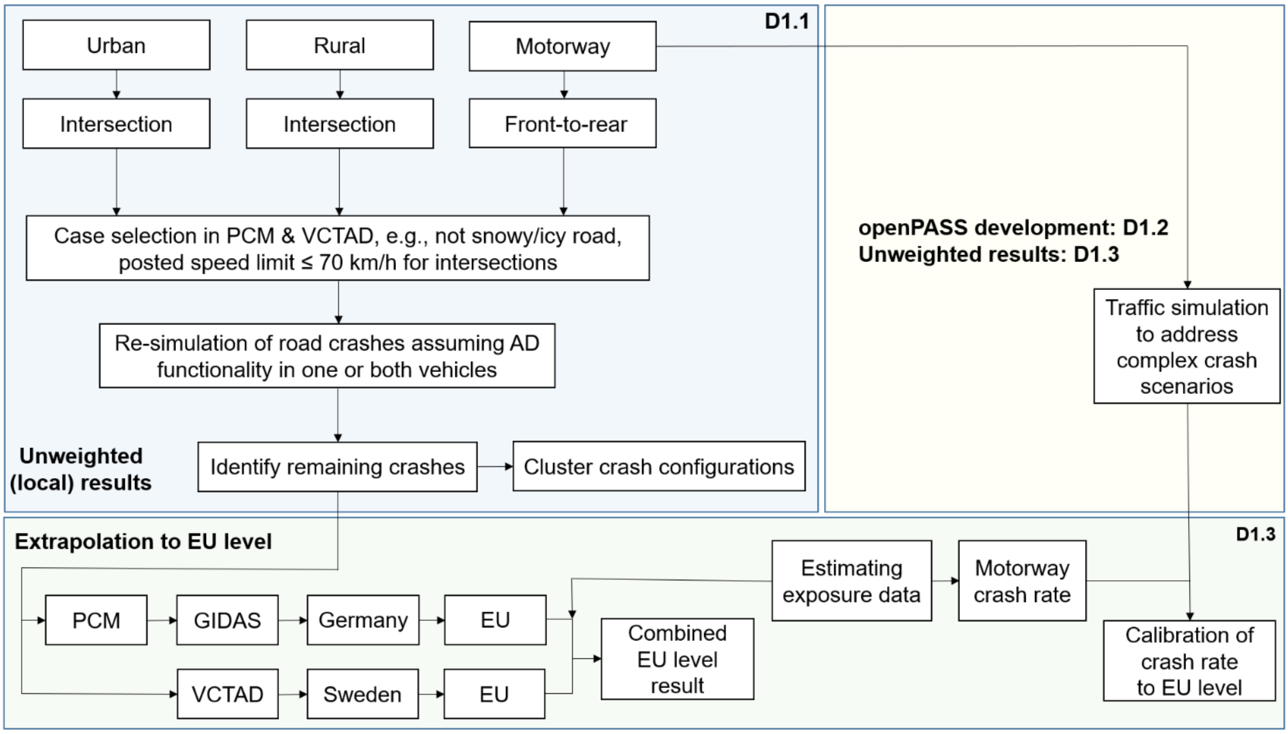


Figure 35: Illustration of the main steps of the weighting method

Note that the United Kingdom (UK) is included in the analysis, because it was in the EU in the first part of the project when the overview was prepared and a substantial part of the analysis was performed. To clarify this in the notation, EU-28 is used to denote the current EU countries plus the UK. For simplicity and to emphasize that most parts of the method could be completely analogously applied for the current state of the European Union, EU-28 will at several places be referred to as EU.

6.1.1 EU level crash data in CARE and variable selection

The CARE database [46] contains police-reported data from road crashes with personal injury in EU-28 as well as EFTA (Norway, Iceland, Switzerland, Liechtenstein). Data are collected independently by the different countries and are integrated into CARE using a framework of transformation rules to get harmonized variables. Relevant reports based on CARE are published annually used to follow up trends in road crashes within the EU. The most relevant ones for the OSCCAR WP1 work are the Annual Accident Report [47] and fact sheets on car occupants [48], motorways [49] and junctions [50].

The set of harmonized data variables in CARE is called the Common Accident Data Set (CADaS), see the CADaS glossary [51]. CARE contains variables about the crash and the environment as well as the vehicles and people involved. Variables marked with (H) indicate high reliability and those marked with (L) indicate low reliability. For the purposes of weighting, it is important to use variables that are common in CARE and the in-depth data to be weighted (i. e., PCM and VCTAD), are of sufficient quality (i. e., have high reliability according to the CADaS glossary), and are known sufficiently often (proportion of "unknown" is below a threshold, e. g., <20%). These aspects were also pointed out in section 8.2.2 of the OSCCAR deliverable D1.1 [1].

Once groups of crashes are defined in terms of variable combinations (e. g., car-to-car crashes with serious injury outcome on a motorway at daylight), a weight for each considered group is computed as follows:

$$weight = \frac{Number\ of\ corresponding\ cases\ in\ EU\ level\ data}{Number\ of\ corresponding\ cases\ in\ the\ in{-}depth\ data}\ .$$

The analysis is then conducted by assigning the weight to each crash in the analyzed in-depth data that belongs to the given crash group. As a result, if certain groups of crashes are overrepresented in the analyzed in-depth crash data (e. g., crashes with an icy road surface have a substantially larger proportion in Swedish national data compared to the EU level), then the corresponding cases will be assigned a smaller weight. However, those crashes that are relatively less common in the in-depth data compared to the EU level data (e. g., fatal crashes) will get a larger weight.

In fact, cases belonging to very uncommon categories with close to zero cases in the in-depth data would get extremely large weights (e. g., fatal crashes in urban environment at dusk/dawn). This approach is problematic, because this way a single simulation result (which could be affected by some specific and potentially atypical features) would determine a substantial part of the overall results. To avoid such issues, i. e., very small group sizes, sufficiently broad groups need to be defined, by choosing a low number of variables for the weighting and combining variable values.

A variable that is generally highly relevant for weighting (because of its relevance to most in-depth analyses) is crash type. However, the crash type variables in CARE are classified in the CADaS manual to have low reliability, and the corresponding variables have a large percentage of other/unknown categories due to the difficulty of harmonizing this variable between the different countries. To ensure that an adjustment to crash type distribution is made, the weighting process will include an intermediate step: instead of directly weighting the in-depth data towards the EU, it will be first weighted towards national statistics where crash type can be included in the weighting process, and the national results in Germany and Sweden are then weighted to the EU.

6.1.2 Weighting to country level

Weighting to national level uses crash location and crash type for both Germany and Sweden, and additionally, crash severity (in terms of the most serious injury in the crash) for Germany and the posted speed limit for Sweden. The weighting procedures are discussed separately below.

6.1.2.1 Weighting from PCM to Germany

PCM is a subset of GIDAS consisting of cases with sufficient information for simulation. Therefore, PCM cases are first weighted towards GIDAS to adjust for the differences in the joint distribution of crash location, crash severity, and crash type between these two datasets. The corresponding weights are then multiplied by the case weights corresponding to the GIDAS to Germany weighting, based on the same variables. This way, each crash is assigned a weight in PCM in such a way that weighted analysis of crashes represents results on German national level. Note that using the same variables for these two steps is a simplification: as discussed in [44], the bias PCM-GIDAS is not necessarily the same as GIDAS-Germany, which could motivate the selection of different variable sets.

6.1.2.2 Weighting from VCTAD to Sweden

Using the same method as detailed for PCM in section 6.1.2.1 would be problematic because VCTAD contains information about the injury severity of Volvo occupants only, which does not allow quantification of crash severity taking all involved road users into account. Therefore, weighting of the Volvo Car data to Swedish national level was based on crash location classified as Urban / Rural / Motorway, maximum posted speed limit classified as 10 to 50 km/h / 60 to 90 km/h / at least 100 km/h / Unknown or missing, and the crash type classification used in the Swedish national crash database STRADA to which crashes in the VCTAD database were re-classified. The posted speed limit is used in this step because it gives an (admittedly imperfect) indication of the collision speeds (which cannot be used for the weighting in this step because they are not available in STRADA). The VCTAD data contains synthetic cases that were generated from real-world cases to represent plausible variations of the observed crashes. Synthetic crashes were assigned the same weight as the underlying real-world cases that they were generated from.

6.1.3 Weighting to EU level and combining results

After the previously described steps, each crash in PCM and VCTAD is assigned a weight in such a way that weighted analyses of crashes are meant to represent the crash situation on German, respectively Swedish, national levels. Further weights can be obtained as a result of comparing the joint distributions of the following variables between Germany and the EU (with the considered variable values between parentheses):

- Crash severity (Fatal / Serious / Slight);
- Area type (Urban / Rural / Motorway);
- Junction type (Not at junction / At junction);
- Road surface (Dry / Wet or Damp / Icy).

Deriving further weights for Swedish data follows the same procedure, except that crash severity is not used in this step due to the mismatch between crash severity definitions detailed in section 6.1.2.2.

After multiplying the case weights from the previous step with those obtained when going from national to EU level, each crash in the in-depth databases is assigned a weight so that weighted analyses are meant to represent EU level results. Note, however, that due to various limitations of the datasets as well as the weighting process (detailed in section 0 below), the same analyses may provide potentially different results for EU-28.

In order to get a single, combined result on EU level, a weighted average of the PCM-based and VCTAD-based results was considered. The weights in this last step were defined by the exposure data by area type in the different countries for which estimates will be described in the section 6.1.4. More specifically, PCM-based results for motorway were multiplied by w_{GER}^{M} defined as

$$w_{GER}^{M} = \frac{E_{GER}^{M}}{E_{GER}^{M} + E_{SWE}^{M}},$$

and VCTAD-based results for motorway were multiplied by w_{SWE}^{M} defined as

$$w_{SWE}^{M} = \frac{E_{SWE}^{M}}{E_{GER}^{M} + E_{SWE}^{M}},$$

where E_{GER}^{M} and E_{SWE}^{M} denote the motorway-related exposure data for Germany and Sweden respectively, measured as the VKT by cars on motorways in the respective countries. As indicated above, these quantities will be estimated in the next section. The analogous coefficients that are used for combining the results for intersections (which are not on motorways) are defined as

$$w_{X}^{O} = \frac{E_{X}^{O}}{E_{GER}^{O} + E_{SWE}^{O}},$$

where the subscript $X \in \{GER, SWE\}$ denotes Germany or Sweden, and O in the superscripts stands for outside motorways. The corresponding exposure data can be computed from the total VKT by cars E_{GER}^{Total} and E_{SWE}^{Total} in the corresponding countries and the previously defined motorway-related exposure quantities E_{GER}^{M} and E_{SWE}^{M} as

$$E_{X}^{O} = E_{X}^{Total} - E_{X}^{M}.$$

The above method for the combination of results ensures that the estimate for EU-28 will be closer to results from countries that provide a larger portion of driven kilometers (and thereby the potential exposure to crash risk). Additionally, it provides a link to the weighting of traffic simulation data for which the comparison of the number of crashes to exposure (i. e., estimating the number of crashes per VKT, alternatively the average distance travelled between crashes) is a key parameter, see below.

6.1.4 Exposure data and motorway crash rates in Europe

Various forms of exposure data in Europe are available in different EU level reports. For example, the Eurostat Statistical Pocketbook 2019 [52] includes statistics for EU countries regarding passenger kilometers traveled in passenger cars. This is not the same measure as VKT, considering that a car may transport more than one passenger at the same time. The IRF World Road Statistics report [53] contains information about the VKT by cars on all roads for most EU countries in 2011. Combining these data sources, more specifically estimating VKT by cars in 2011 for those EU countries where the IRF report does not specify a value based on passenger kilometers allows the calculation of an estimate for VKT by cars in EU-28. Additionally, the figures from 2011 have been adjusted to the year 2017 (for which the number of crashes were queried) by assuming the increase in VKT from 2011 to 2017 as specified for passenger kilometers in cars in [52].

These results determine the quantities E_{X}^{Total} defined in section 6.1.3 for $X \in \{GER, SWE\}$. In order to obtain the weighting coefficients w_{X}^{M} and w_{X}^{O} for computing the combined results, it is necessary to estimate the motorway-related exposure by cars as well. Additionally, for calibrating the motorway-related traffic simulation parameters (see section 6.1.5), this information is needed on EU level as well, not only for Germany and Sweden. Data regarding the VKT by cars on motorways is substantially harder to find compared to the total VKT. The first step to get an estimate on EU-28 level was to find separate data for the largest EU-28 countries or regions from various sources:

- Data for France and Italy are available from Statista reports ([54],[55]); as not all motorways are toll roads in France, the corresponding estimate is adjusted by a factor representing the length of all motorways divided by the length of toll motorways (available from [56],[57]).

- Data for Great Britain, Spain and Sweden are publicly available online ([58],[59],[61]). The data from Great Britain is adjusted to the United Kingdom by multiplying the traffic volume estimate by a factor corresponding to the length of motorways in the UK [62] divided by the length of motorways in Great Britain. The estimate for Spain is adjusted by a factor representing the length of all motorways divided by the length of toll motorways (available from [60],[59]).
- An estimate for Germany for the year 2014 was obtained by the Federal Highway Research Institute (BASt); the report is publicly available [63].

All estimates are adjusted to year 2017 based on the change in passenger kilometers in cars between the data year indicated above and 2017 as specified in [52]. For those countries that had data from 2018, it was assumed that the change in passenger kilometers in cars between 2017/18 equals the value from 2016/17.

The VKT by cars on motorways divided by the total VKT by cars for these countries is then multiplied by the total VKT by cars for the other countries to estimate the VKT by cars on motorways for the other countries.

Dividing the number of crashes on motorways involving cars in EU-28 (queried from CARE) by the estimated VKT by cars on motorways gives the rate of crashes on motorways with personal injury per VKT for cars on EU level. Importantly, this rate does not include property damage only (PDO) crashes, i. e., those crashes without any injured people. However, crash severity is not known for the crashes observed in the openPASS simulations, hence such crashes can possibly be PDO. Therefore, one further step is needed to estimate the rate of all crashes (including PDO) per VKT.

In the final step, results from the Destatis yearbook [64] (also available from the online query tool provided by Destatis [65]) are used, indicating that the number of injury crashes in Germany on motorways in 2017 were 20 928 while the number of all crashes on motorways was 178 861; the corresponding figures for areas outside motorways are 281 728 and 2 464 237, respectively. These results indicate the following relationships:

$$\text{All crashes} \approx c^{Area} \text{ x Injury crashes,}$$

where the superscript $Area \in \{M, O\}$ denotes motorway or outside motorway, respectively, and the corresponding factors derived from Destatis data are $c^{M} = 8.55$ and $c^{O} = 8.75$.

Of course, the rate between injury crashes and all crashes may vary by country and may even depend on the definition of a road crash; however, using the above results give an approximation and an indication of the magnitude of the crash rate. The main steps in the process of estimating crash rates of cars by VKT on motorways in the EU-28 is illustrated in Figure 36 below.

Figure 36: Estimating crash rates of cars by VKT on motorways in the EU-28

6.1.5 Calibrating traffic simulation for results in EU-28

Different questions related to safety benefit have been investigated so far. These include the reduction of the number of crashes in the EU as a result of introducing automated driving functions in general, estimated by an investigation of the effect of advanced driver assistance systems (ADAS) and automated driving compared to current traffic (see the OSCCAR deliverable D1.1, section 5).

Additional information was obtained by simulations for very specific operational design domain (motorways and urban intersections) and field of effect, where the relative effectiveness by the investigated specific, yet generic automated driving function (essentially AEB plus obeying traffic rules) was estimated using the unweighted simulation results described in section 7 of deliverable D1.1. The weighting process of these results to EU level was described in Sections 6.1.1-6.1.4 above and the corresponding results are presented in section 6.2.

The last question investigated in this section is the method of how to scale up the results from the openPASS motorway traffic simulations described in the previous sections to EU-28 level. One way to approach this question is to ensure that simulation parameters are calibrated in such a way that the resulting simulation represents EU traffic in general. Having such a parametrization or calibration available and simulating a sufficiently large number of vehicle kilometers would directly give results that are representative to the EU and do not need to be weighted further. Note, however, that the time constraints in the OSCCAR project have not made it possible to follow the above approach and simulate a sufficiently large number of vehicle kilometers after the development of the corresponding openPASS simulation tool. In particular, substantial further research is needed to overcome data limitations and methodological challenges related to finding appropriate values for the other relevant simulation parameters (apart from crash frequency) as well as effectively simulate a large driving distance. Therefore, the current results, which were fine-tuned after a careful investigation of the German traffic situation on motorways and are thus based on parametrization according to motorway data in Germany, do not have sufficient statistical power and should be considered as a proof of concept. Consequently, it was decided that the results obtained this way will not be upscaled to EU level, to avoid the publication of potentially misleading estimates.

The general feasibility of obtaining results with sufficient statistical power depends on the computing capacity and may be challenging but possible in future projects. An essential ingredient for this, as argued above, is a calibration of the simulation in such a way that it can represent EU level traffic. One of the most basic and most important parameters for the calibration is the average distance driven between two crashes, which is the inverse of the crash rate per VKT as defined above. This was the motivation for a deeper investigation of this parameter, based on the method described in section 6.1.4, and a comparison with the analogous parameter in Germany. The corresponding results are described in section 6.2 below.

6.2 EU weighted remaining accidents

The weighted results will adjust the percentage reductions attributable to automated driving in the analysis based on crash simulation. However, to understand and quantify the effect of the relative reduction on EU level, the EU-28 level statistics about the absolute numbers of relevant crashes are presented first.

6.2.1 General crash statistics on EU level

The following results were based on an analysis of the CARE database. All results address the crash year 2017 as it was the most recent year for which almost all EU-28 countries had available data when the analysis was conducted. Exceptions are Lithuania, Ireland and Slovakia which had the latest results for 2015, hence that crash year is used for these three countries. Car-involved crashes are not coded in CARE for Slovakia hence the corresponding numbers are estimated from similar proportions observed in the other 27 EU countries to get an estimate for EU-28. General EU level statistics on crash numbers and fatalities for different levels of car involvement are presented in Table 5.

Table 5: Number of road crashes and fatalities in EU-28 in 2017 by car involvement according to the CARE database

	Crashes with personal injury	Fatal crashes	Fatalities
All	1 084 062	23 536	25 347
Passenger car-involved	878 864	17 323	18 899
Car-to-car	250 114	2 361	2 768

In order to quantify the relevance of the crash data-based simulations related to intersections and motorways in D1.1 on EU level, the crash location distribution of car-to-car crashes was investigated in CARE; see the results in Figure 37 below. The percentages are based on cases with both known area type and motorway information (which holds for ~90% of car-to-car crashes). The results show that the majority of car-to-car crashes happen in urban areas, but the majority of fatal car-to-car crashes and fatalities occurs in rural areas.

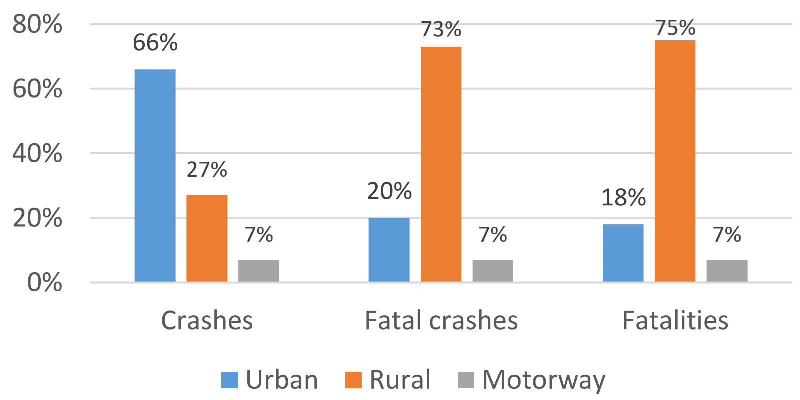


Figure 37: Area distribution of car-to-car crashes and fatalities in EU-28

The analyses in D1.1 included some further restrictions. For instance, crashes on icy or snowy roads were excluded. Those crashes amount for car-to-car crashes on EU level to 1.5% of crashes on motorways and 2.2% outside motorways (1.7% in urban areas and 3.5% in rural areas). For motorway crashes, front-to-rear collisions were analyzed. As this condition cannot be reproduced in CARE for car-to-car crashes, the proportion described in section 7.1 of D1.1, i. e., 77%, will be assumed for EU level results as well. For intersection crashes, cases were considered in the simulations in which the posted speed limit was at most 70 km/h. These speed restrictions account for 57% and 30% of car-to-car crashes with not icy/snowy road surface in urban and rural areas, respectively. Table 6 below summarizes the annual number of crashes on EU level that corresponds best to those addressed by the D1.1 simulations.

Table 6: Crashes in EU-28 in 2017 corresponding to those analyzed in D1.1 simulations

	Number of crashes	Proportion of all passenger car-involved crashes (n=878 864)
Motorway car-to-car front-to-rear crashes, not snowy/icy road	12 167	1.4%
Intersection car-to-car crashes, posted speed limit ≤70 km/h, not snowy/icy road	102 207	11.6%
Total	114 374	13%

As indicated in section 6.1, the results from PCM and VCTAD are first weighted separately to national and then EU level and a weighted average of the results (with weights based on exposure data) is computed to obtain a combined estimate. The corresponding results are presented in sections 6.2.2-6.2.3 followed by results on the crash rate per VKT by cars on motorways in EU-28 in section 6.2.4.

6.2.2 Weighted results for PCM and VCTAD

The analysis of PCM data in D1.1 considered four options depending on which of the main causer and opponent cars in a re-simulated crash are equipped with automated driving (AD) functions: (i) neither; (ii) the opponent; (iii) the main causer; (iv) both. If the automated vehicle(s) would ensure that the corresponding crash situation could not happen (e. g., because the automated vehicle(s) would obey traffic rules and would thus prevent those crashes where the main cause was a violation of traffic rules by the equipped vehicle), we say that the crash is inherently avoided. In all other cases, i. e., without obvious avoidance of the original crash, a detailed re-simulation is needed to know what the outcome would be, and there are three possibilities: the simulation can show that the crash is avoided, or it is mitigated in the sense of a speed reduction, or there is no intervention of the automated driving function resulting in no improvement compared to the original crash.

As indicated in section 6.1.2.1, a weighting method based on crash location, crash type and crash severity, was used to weight PCM data to German national level (with an intermediate step of weighting the data to GIDAS) and then to EU level. Re-weighting the crashes this way could potentially change the proportion of different outcomes in the simulation compared to the unweighted results - e. g., if a crash with a large weight is inherently avoided, that could increase the proportion of “Inherently avoided” outcomes compared to the unweighted results. The results weighted to EU level, are presented in Figure 38 below. The sample sizes in parentheses, taken from Table 6 above, indicate the number of crashes in EU-28 that the results apply to. For example, if all cars participating in the corresponding crash situations were equipped with automated driving functionality, the results for simulation (iv) would indicate the avoidance of 5428 and mitigation of more than 6739 injury crashes on motorways annually in EU-28. As the corresponding numbers for intersections would be 95 923 avoided and 6284 mitigated injury crashes, the total annual benefit of 100% fleet penetration of these two systems in EU-28 based on the analysis of German in-depth data would be the avoidance of 101 350 and mitigation of 13 024 injury crashes. Note that Figure 38 and the subsequent Figure 39 and Figure 40 below show results rounded to the closest integer percentage value while the benefits are calculated with more decimals.

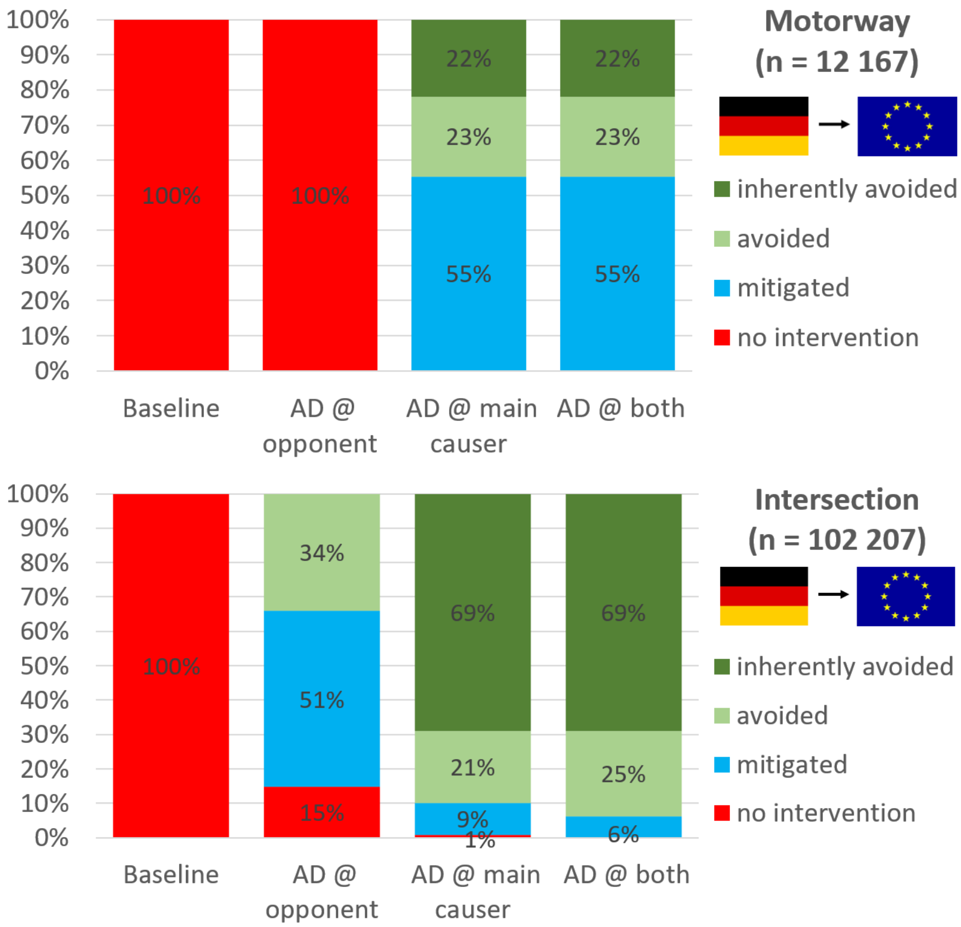


Figure 38: Results of PCM simulations of (i)-(iv) of motorway situations (above) and intersection situations (below) weighted to EU-28 level

Comparing the results in Figure 38 with the original, unweighted ones presented in sections 7.2.1 and 7.3.1 of the OSCCAR deliverable D1.1, we see that the differences are very small. A detailed comparison between weighted and unweighted results for both the PCM-based and VCTAD-based analyses, is provided in Table 7 and Table 8 below, which also include further decimals of the percentage reductions for the weighted results compared to the figures.

The simulations based on VCTAD data did not use the classification based on the “main causer” of the crash. Instead, the results are grouped depending on whether the host vehicle (i. e., a Volvo car), the opponent or both had automated driving functionalities. The results shown in Figure 39 below are similar to the unweighted results presented in sections 7.2.3 and 7.3.3 of deliverable D1.1; see Table 7 and Table 8 below.

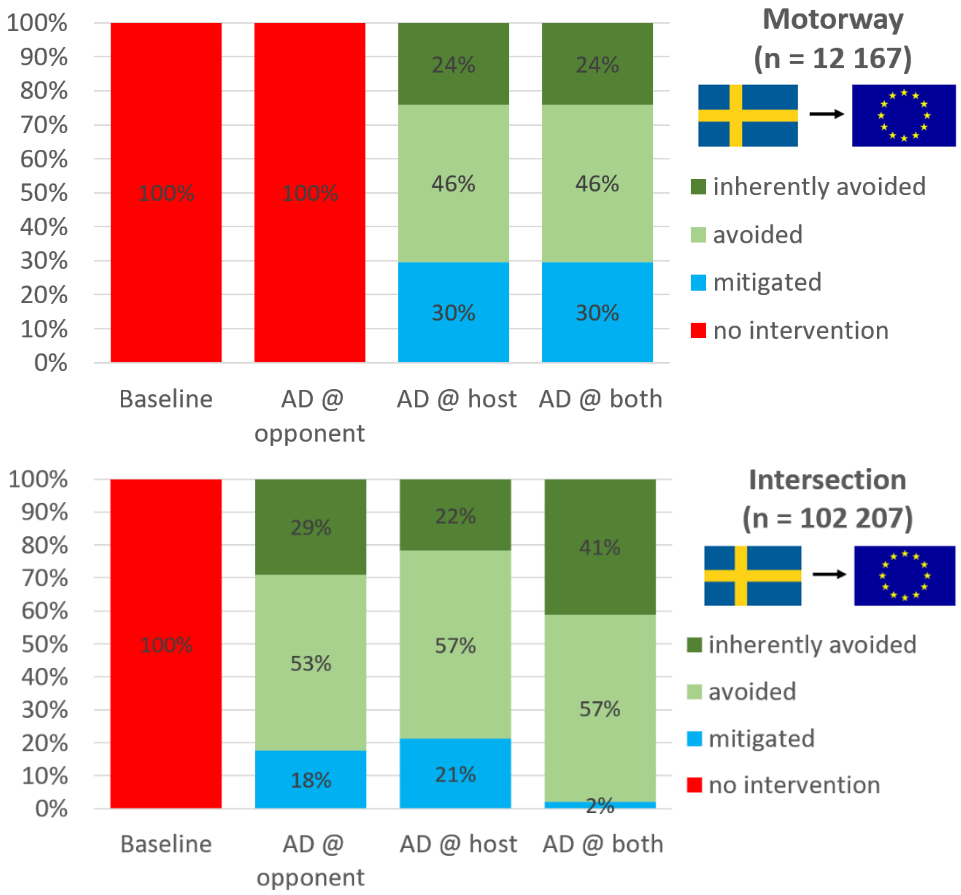


Figure 39: Results of VCTAD simulations of motorway situations (above) and intersection situations (below) weighted to EU-28 level

As above, the relevant relative reductions are referring to the number of crashes specified in Table 6. For example, these results indicate that all cars being equipped with automated driving functions would lead to the avoidance of 108 571 crashes (of which 100 011 in an intersection and 8560 on motorways) and mitigate 5803 crashes (2196 intersection, 3607 motorway).

The next tables summarize the PCM-based and VCTAD-based analysis results and allow comparisons between unweighted and weighted results. In these tables, “Inherently Avoided”, “Avoided”, “Mitigated”, and “No intervention” are abbreviated as “IA”, “A”, “M”, and “No”, respectively, and the sample sizes (i.e., the number of applicable crashes in EU-28) are indicated in the captions of the tables.

Table 7: Comparison of weighted and unweighted simulation results for motorway situations (n=12 167)

Analyzed data	Crash participant with automated driving function	Motorway, weighted to EU-28				Motorway, unweighted (D1.1)			
		IA	A	M	No	IA	A	M	No
PCM	None	0%	0%	0%	100%	0%	0%	0%	100%
	Opponent of main causer	0%	0%	0%	100%	0%	0%	0%	100%

	Main causer	21.89%	22.72%	55.39%	0%	24%	21%	55%	0%
	Both	21.89%	22.72%	55.39%	0%	24%	21%	55%	0%
VCTAD	None	0%	0%	0%	100%	0%	0%	0%	100%
	Opponent of host vehicle	0%	0%	0%	100%	0%	0%	0%	100%
	Host vehicle	24.09%	46.27%	29.65%	0%	25%	47%	28%	0%
	Both	24.09%	46.27%	29.65%	0%	25%	47%	28%	0%

Table 8: Comparison of weighted and unweighted simulation results for intersection situations (n=102 207)

Analyzed data	Crash participant with automated driving function	Intersection, weighted to EU-28				Intersection, unweighted (D1.1)			
		IA	A	M	No	IA	A	M	No
PCM	None	0%	0%	0%	100%	0%	0%	0%	100%
	Opponent of main causer	0%	34.08%	51.20%	14.72%	0%	37%	49%	15%
	Main causer	69.03%	20.79%	9.48%	0.70%	71%	19%	10%	0%
	Both	69.03%	24.82%	6.15%	0%	71%	22%	7%	0%
VCTAD	None	0%	0%	0%	100%	0%	0%	0%	100%
	Opponent of host vehicle	29.01%	53.35%	17.64%	0%	31%	50%	19%	0%
	Host vehicle	21.80%	57.00%	21.20%	0%	22%	55%	23%	0%
	Both	41.18%	56.67%	2.15%	0%	43%	54%	3%	0%

There are differences between PCM-based and VCTAD-based results, with the latter one showing higher avoidance potential for scenarios when both vehicles are equipped with AD technologies. This difference is analyzed in Section 5.3).

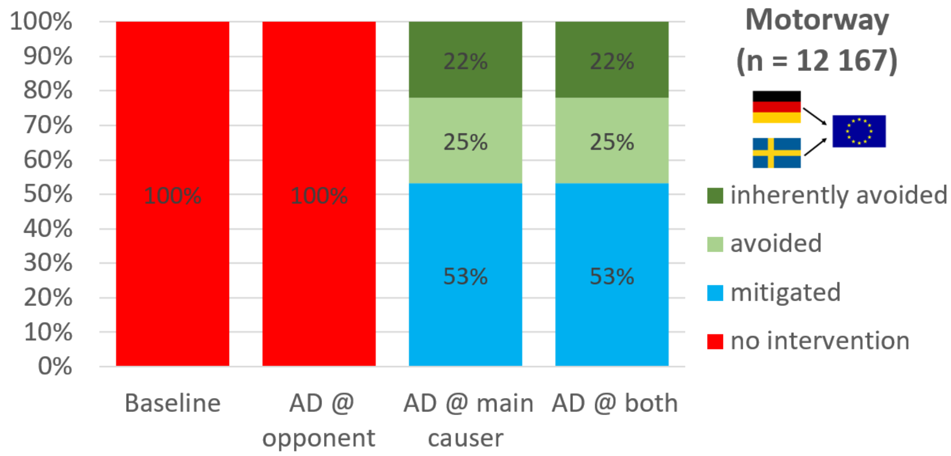
6.2.3 Combined weighting results

VKT-based factors are used for combination of results. Such results will be investigated on EU level in section 6.2.4. However, for specifying the coefficients for combining weighted German and Swedish results, it is enough to know the corresponding exposure data for these two countries.

The total VKT by cars in 2011 according to Table 3.3 in [53] was 608.8 billion VKT in Germany and 63.2 billion VKT in Sweden. Making an adjustment for the total traffic by cars between 2011 and 2017 defined by the increase of passenger kilometers in the same period gives an estimate of 636.9

billion VKT in Germany and 67.3 billion VKT in Sweden by cars on all roads in 2017. Results from a BASt project [63] estimate the traffic by cars on German motorways in 2014 as 169.7 billion VKT which is adjusted to an estimate of 173.3 billion VKT for 2017 using an increase of 2.1% as specified for passenger kilometer in the corresponding period in Germany in [52]. Statistics in [61] indicate that the traffic by cars on Swedish motorways is 16.3 billion VKT. Substituting $E_{GER}^{M} = 173.3 \times 10^9, E_{GER}^{Total} = 636.9 \times 10^9, E_{SWE}^{M} = 16.3 \times 10^9$, and $E_{SWE}^{Total} = 67.3 \times 10^9$ in the respective formulas in section 6.1.3 gives the following coefficients for combining results from PCM and VCTAD: $w_{GER}^{M} = 0.914$, $w_{SWE}^{M} = 0.086$ for motorway-related results, and $w_{GER}^{O} = 0.901$, $w_{SWE}^{O} = 0.099$ for the intersection cases.

The combined results are presented in Figure 40 below. Note that the exposure in Germany is substantially greater than the exposure in Sweden, especially for motorways. Consequently, the results for the cases that are comparable (i. e., when neither or both vehicles are automated) look rather similar to the PCM-based results presented in section 6.2.2. The result for those simulations where only one vehicle has an automated driving functionality is more difficult to combine; in the intersection case, the PCM-based results are combined with the average of the VCTAD results for host/opponent equipped with automated driving functions. For the motorway scenario, those cases are selected for VCTAD analysis where the host car is the striking vehicle in a front-to-rear crash which is in good agreement with the host car being the main causer; therefore, the corresponding results are combined using the coefficients for motorway as specified above.



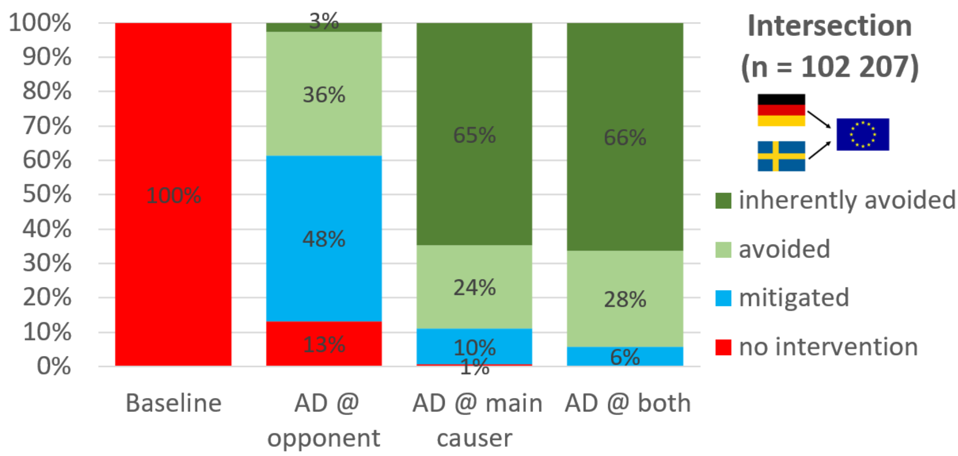


Figure 40: Estimated reduction of front-to-rear crashes on EU level for motorway situations (left) and intersection situations (right)

The bases that the above percentages refer to (i.e. the number of relevant crashes in EU-28) are the case numbers in Table 6, as before. The combined results assuming automated driving fuctionalities for both vehicles indicate the maximum benefit that could be achieved by the analyzed automated driving functionalities; assuming that all passenger cars would be automated vehicles, the results indicate a reduction of more than 100 000 crashes per year (see Table 9).

Table 9: Maximum annual benefit in EU-28, assuming that all passenger cars are equipped with both analyzed automated driving functionalities (urban robo car and motorway pilot)

	Avoided crashes	Mitigated crashes	% of all car-involved crashes avoided	% of all car-involved crashes mitigated
Motorway	5696	6471	0.6%	0.7%
Intersection	96 328	5879	11.0%	0.7%
Total	102 024	12 350	11.6%	1.4%

It is important to note that the maximum benefit could be achieved at a (close to) 100% fleet penetration of the analyzed automated driving technologies. According to the estimation of safety technology penetration in the overall vehicle fleet in the EU (Figure 13 in D1.1), getting close to that level may take over 30 years from market introduction of the technologies. For lower levels of fleet penetration, the estimated crash reduction will depend on simulation results with each of conditions (ii), (iii) and (iv). For example, if the urban robo car functionality is present in 30% of the vehicles and it is assumed that the presence of the system in the vehicles in intersection situations agrees with the general level of their fleet penetration, then both vehicles will have robo car functionality in 0.3 x 0.3 = 0.09 = 9% of intersection situations, corresponding to condition (iv). As 0.7 x 0.7 = 0.49 = 49% of intersection situations would occur between two vehicles without urban robo car functionality, we have a situation with exactly one equipped car in 42% of intersection cases (computed as 100% - 9% - 49%). If it is further assumed that in half of these situations it is the main causer being equipped with urban robo car functionality while in the other half the equipped vehicle it is the opponent of the main causer, conditions (ii) and (ii) apply to 21% of intersection situations each. Under all these assumptions, using the results in Figure 40, the aunnual number of intersection crashes in EU-28 avoided by the robo car function can be estimated as follows:

$$102\ 207 \times [9\% \times (66\% + 28\%) + 21\% \times (65\% + 24\%) + 21\% \times (3\% + 36\%)] = 36\ 120.$$

which is about 37% of the maximum crash avoidance potential of the robo car function as specified in Table 9 above.

Under the simplifying assumptions that the vehicles in the relevant crashes (i. e., main causer and opponent) are equipped with automated driving functionality independently with a probability corresponding to the general fleet penetration rate of the system and that the systems for motorway and intersection scenarios have the same fleet penetration rates, the annual safety benefit was estimated for 10%, 30%, and 50% fleet penetration, see Table 10. According to the estimates of delvierable D1.1, those fleet penetration values could correspond to years 2035, 2042, and 2047.

Table 10: Estimated annual benefit of the urban robo car and motorway pilot in EU-28 by fleet penetration

Fleet penetration of both automated driving technologies	Avoided crashes	Mitigated crashes	% avoided crashes of all car-involved crashes	% mitigated crashes of all car-involved crashes
10%	13 270	6089	1.5%	0.7%
30%	37 765	15 030	4.3%	1.7%
50%	59 534	19 657	6.8%	2.2%

Table 10 shows that, for example, more than 50 000 crashes annually in EU-28 could benefit from a 30% fleet penetration of both automated driving systems; more specifically, this fleet penetration level yields the avoidance of 4.3% and severity mitigation of further 1.7% of all car-involved crashes on EU level.

Note also that the results in Table 9 and Table 10 refer to the two specific automated driving functionalities that were simulated in detail. Results in section 5.4 of D1.1 indicate estimates related to inherently avoided crashes by automation in general. Specifically, it is estimated that at least 27% of injury crashes in urban environment would be inherently avoided as a result of vehicle automation and additional 39% require further investigation (i. e., a part of this 39% could also potentially be avoided). The similar shares for rural areas, respectively motorways, are 32% (resp., 29%) inherently avoided crashes and 41% (resp., 48%) potentially avoided crashes. Applying these reductions to those crashes that were not investigated in detail (i. e., those car-involved crashes that are not included in Table 6) gives the following results:

Table 11: Estimated annual crash avoidance in EU-28 assuming 100% AVs obeying traffic rules and adapting to driving conditions

	Avoided crashes	Further investigation	% of all car-involved crashes avoided	% of all car-involved crashes require further investigation
Urban	227 123	229 420	26%	26%
Rural	101 033	93 531	11%	11%
Motorway	21 505	26 165	2%	3%
Total	349 661	349 116	40%	40%

These results show the large potential of vehicle automation in that 100% fleet penetration of automated vehicles is estimated to lead to the avoidance of close to 350 000 crashes in EU-28 and potential avoidance of approximately 350 000 further crashes (where the assessment of the crash avoidance requires further study, e. g., detailed re-simulation of the corresponding crashes). As pointed out above, it is likely to take decades to get close to this level of automated vehicle fleet penetration, and only part of the potential benefit may be realized until that time.

6.2.4 Crash rate of cars on motorways by VKT

The estimation of crash rates follows the process illustrated in Figure 36. As described in section 6.1.4, we need the crash rate of cars on motorways as a foundation for a possible future weighting of traffic simulations to an European level. The first step is therefore to estimate the annual VKT for cars on all roads in EU-28. The second step is to estimate the similar quantity for motorways only. Once this estimate is available, it can be related to the annual number of car-involved injury crashes on motorways, queried from CARE, which can be used to indicate the number of all car-involved crashes on motorways using the relationship between crashes with personal injury and all crashes, estimated using data from Germany. These steps are described in this section.

6.2.4.1 Estimating VKT by cars on all roads

Comparing the VKT by cars on all roads for those EU countries where these data are available in [53] to the passenger kilometers travelled in passenger cars as specified in [52] gives the following relationship between passenger kilometers and VKT for year 2011 (corresponding to the average number of car occupants):

Passenger kilometers in cars = 1.434 x VKT by cars.

The same proportion between these two quantities is assumed for those countries (namely, Bulgaria, Czech Republic, Italy, Portugal, Slovak Republic) where VKT was not available. The resulting estimates for all EU-28 countries are adjusted to 2017 figures by assuming the same change for VKT between 2011 and 2017 as specified for passenger kilometers in [52]. This method gives an estimated traffic volume of 3403.6 billion VKT by cars in 2017 in the EU-28 considering all roads.

6.2.4.2 Estimating VKT by cars on motorways

As described in in section 6.1.4, the traffic volumes by cars on motorways for DE, ES, FR, IT, UK, and SE are based on (slight adjustments of) data from other sources while the estimates for the other countries assume the same ratio (19.9%) between motorway traffic by cars to all traffic by cars as observed for these six countries. The resulting estimates are presented in Figure 41 below.

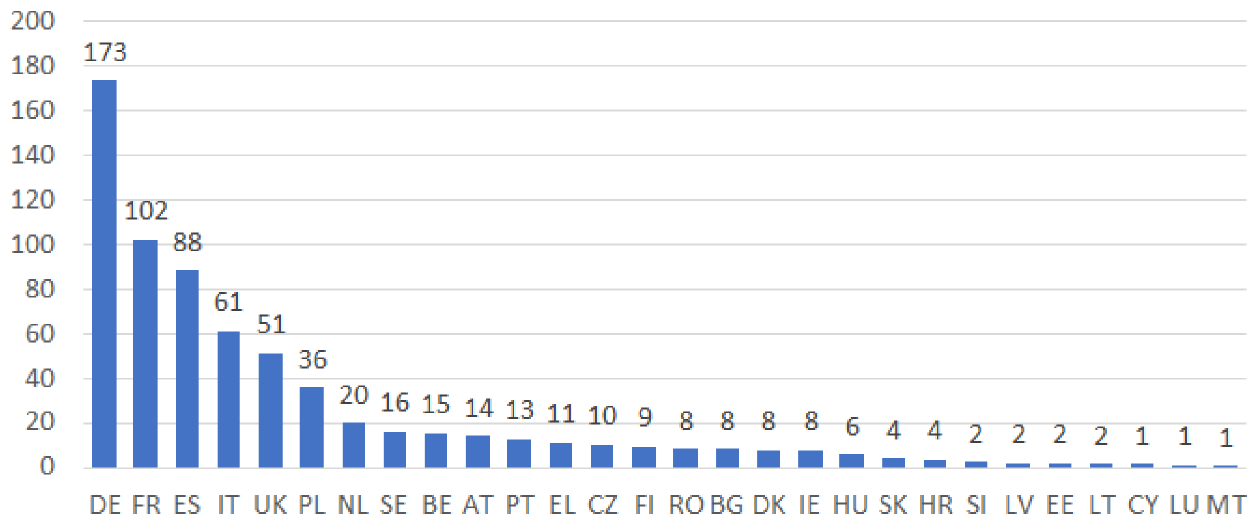


Figure 41: Estimated traffic volume of cars on motorways in EU-28 in 2017 (billion VKT)

The above estimates give a total motorway traffic volume of 677 billion VKT by cars in EU-28. Combining this result with the total estimated traffic volume by cars as specified at the end of the previous section, derives the traffic volume by cars in 2017 in EU-28 outside motorways as 3403.6 billion VKT – 677 billion VKT = 2726.6 billion VKT.

6.2.4.3 Rate of injury crashes and all crashes

The results presented above can be compared to crash data Table 5toestimate the rates at which cars are involved in a crash with personal injury. The total number of car-involved injury crashes is taken from Table 5, while the number of car-involved injury crashes on and outside motorways are retrieved by new queries in CARE. Assuming the relationship between all crashes and injury crashes on and outside motorways presented in section 6.1.4 yields the following estimates on the crash rates (and consequently, on the average distance travelled by cars between car-involved crashes):

Table 12: Estimated crash rates of passenger cars in EU-28 in 2017 by location

	Traffic volume by cars (billion VKT)	# car-involved injury crashes	# all car-involved crashes	Rate of car-involved crashes (# / billion VKT)	Average distance between crashes (VKT)
Motorway	677	58 892	503 320	743.5	1 345 046
Outside motorway	2726.6	819 972	7 172 185	2630.4	380 165
Total	3403.6	878 864	7 675 505	2255.1	443 436

As argued in section 6.1.5, these quantities can be used as calibration parameters for traffic simulation with the aim of representing traffic in EU-28. As specified in section 5, 980 000 VKT/collision was obtained in the openPASS simulations presented in section 5 for regular motorway traffic based on parameter calibration according to German data. While this result indicates a slightly higher frequency of crashes compared to that estimated for EU motorways in Table 12, the uncertainties related to the relatively small simulated driving distance and completeness of reporting in CARE suggest that the two crash rates are well aligned. Interpretation and further use of results in Table 12 as well as other results in section 6 should take into account the discussion points and limitations described in section 0 below.

6.3 Discussion and limitations of weighting to EU level

A method for extrapolating simulation results to EU level was presented in section 6. It includes EU level estimates regarding the percentage of avoided and mitigated car-to-car crashes on motorways and in intersections, assuming the automated driving functions in one or both crash-involved passenger cars. The results are based on a weighting method comparing the percentage of crashes under circumstances defined by combinations of variable values (e. g., crashes in a junction in an urban area on wet road with fatal outcome) in the in-depth database GIDAS-PCM and the EU community road crash database CARE. A similar weighting procedure is performed with the results from the VCTAD database, with slight differences regarding the chosen variables (e. g., using posted speed limit instead of injury outcome) due to the different structure of the databases. Both injury outcome and posted speed limit are used in the weighting to correct for differences in crash violence between the in-depth and EU level data. They are both imperfect for this purpose and, e. g., collision speed or Delta-v (i. e., change of velocity in the crash) would work better; unfortunately, these parameters are not available in national or EU level data.

The above methods provide two different EU level estimates: one based on GIDAS results and another one based on VCTAD results. While each estimate is meant to represent the effectiveness of the simulated automated driving functions on EU level, the results are not in complete agreement. There can be various reasons for these differences, including the following aspects: (1) different principles of sampling: GIDAS contains cases with personal injury while a substantial part of VCTAD cases includes property damage only crashes in addition to injury crashes, resulting in a larger percentage of cases in VCTAD with lower collision speed; (2) within the intersection scenario, GIDAS simulations address left turn across path scenarios (opposite direction/lateral direction: LTAP OD, LTAP LD) as well as straight crossing path (SCP) scenarios while the VCTAD simulations consider SCP only; (3) the implementation of the relevant automated driving functions were developed separately, hence while they are similar, they may not be the same; (4) differences and limitations of the weighting, e. g., possibly imperfect mapping between different variable definitions, considering a low number of variables and combined variable values to avoid extremely large weights.

A comparison of unweighted and weighted results revealed only small differences, suggesting that regarding the percentage reductions in crashes attributable to the urban robo car and motorway pilot systems in the considered specific situations, the unweighted analysis results may have provided a reasonably good approximation. Note, however, that this holds only for the specific research question addressed, and it is not necessarily the case in general that unweighted analysis results in PCM and/or VCTAD provide a similarly good (or even a reasonable) approximation of EU level results.

The two database-specific EU level estimates were combined into a single estimate using traffic volume by cars in the respective countries (i. e., Germany for PCM and Sweden for VCTAD) as weighting factors. These quantities were taken from other sources hence the relevance of the combined results depends also on the correctness and limitations of the corresponding data. The effect of the combined results on EU level was quantified at various assumed fleet penetration rates; in this step, it was assumed that the “main causer” and opponent are equipped with automated driving functionality independently with a probability corresponding to the general fleet penetration rate of the system. This may be a simplification considering that the probability of being involved in a relevant situation as main causer could possibly be affected by the equipment of the vehicle with safety systems.

Additionally, a detailed study of traffic volumes was conducted in order to relate the rate of crashes in openPASS traffic simulations to EU level and to provide an important calibration parameter for future traffic simulation activities. The traffic volume by cars on all roads was estimated using data from 2011 which then was adjusted to year 2017 by using the change in passenger kilometers in cars in the corresponding period. The estimation of traffic volume on motorways was estimated for all EU countries based of the relationship between the VKT by cars on motorways versus all roads in only six countries (i. e., DE, ES, FR, IT, SE, UK) – however, as these countries gave 73% of the VKT by cars in EU-28 in 2017, estimates based on these data may provide a good approximation.

The traffic volume estimates could then be related to the crash numbers to get the relevant crash rates. The CARE database contains crashes with personal injury hence the number of such crashes could be queried from CARE. However, the injury outcome of a crash is not available in traffic simulations, hence it was necessary to estimate the rate of all crashes, including property damage only. In the presented method, the number of all crashes was estimated from the number of injury crashes using the corresponding relationship in national statistics from Germany.

Comparing the average distance between crashes in the openPASS simulations to those resulting from the estimated crash rates indicates a 27% smaller average distance between two car-involved motorway crashes in the simulations which were calibrated using data from Germany compared to EU level. Note that the crash rate observed in the simulation is based on a relatively small driving distance and can therefore be considered as an approximate value. Additionally, part of the difference between the crash rates could be attributed to different reporting practices to CARE. In particular, while the reporting of fatalities in CARE may be reasonably complete, there can be country-specific differences regarding the completeness of non-fatal injuries (especially slight injuries). In Germany, 0.81% of reported crashes in CARE are fatal – this is the lowest such percentage in the EU while the EU average is 1.76%, and there are 10 countries with >4% of reported crashes being fatal (including e. g., Denmark and France). While there could be differences in the risk of fatality in a crash, such large differences in the proportion of fatal crashes to all crashes suggests a more widespread reporting of slight injuries in Germany compared to the EU average; a similar reporting for all EU countries would likely increase the estimated crash rates on EU level. Overall, taking all arguments above into account including the uncertainty about the crash rate estimates, the crash rate used in the openPASS simulation as presented in this deliverable may be an appropriate representation of EU level crash rates.

7 DISSEMINATION

The work in OSCCAR WP1 leads to dissemination in various fields. First of all, scientific papers were written on the methodology on how to select relevant crash configurations and use them for evaluation interior concepts of automated vehicles, which explain in more technical detail the content of section 3 [20][23][27][21]. In addition, a paper on the methodology for determining generic pulses was written [28]. The resulting data (the “OSCCAR pulses”) are made publicly available as an Annex to this paper.

Furthermore, the software development within the scope of OSCCAR did not only lead to D1.2, a software demonstrator deliverable, but shaped and motivated major contributions to the stochastic multi-agent simulation platform and the Eclipse open-source project openPASS, especially as input for the implementation of the modular driver model [34].

In the field of standardization, the OSCCAR work made use of recently introduced standards, OpenDRIVE and OpenSCENARIO, and contributed as a reference implementation. In addition, the previously introduced term “crash configuration” was established as a potential new standard term for use in the field crash data analysis when transferring a geometrical constellation of two vehicles to another simulation environment.

In cooperation with OSCCAR China, the WP1 results were discussed and shared, e. g. when explaining the idea of using openPASS to predict future crashes as well as in terms of OSCCAR crash pulses. After comparing the D1.1-based results with their analysis of Chinese crash data, the OSCCAR China project decided to use the generic crash pulses defined in OSCCAR for their occupant simulation.

8 DISCUSSION AND CONCLUSIONS

8.1 Discussion of WP1 results

In OSCCAR, the WP1 activity was dealing with future crash scenarios of automated vehicles. Within the task, new methodologies were developed and applied to provide adequate starting points in terms of crash configurations for challenging test cases (defined, e. g., in OSCCAR deliverable D2.1 [3]). These starting points enabled in subsequent step in the OSCCAR project virtual assessment of occupant protection in future automated vehicles.

Based on the comparison with previous results and projects (e. g., AdaptIVe), we established connections in OSCCAR, from automated driving functions to the evaluation of new interior concepts and the scope of passive safety. All WP1 methodologies fit seamlessly into methods of other OSCCAR work and altogether provide the required additional steps for the evaluation of future passive safety concepts for automated driving. The OSCCAR approach can be used to define future assessment of automated driving functions by determining, e. g., the injury risk for occupants in new challenging scenarios. Current functional assessment methods use the pass/fail criterion considering only collision avoidance. Injury assessment in terms of integrated safety could be included in pass/fail criteria of automated driving functions, e. g., by determining the remaining risk for occupants in new scenarios when running scenario-based assessments. With more advanced scenario catalogues for growing operational design domains, more insights will become available regarding system performance and limitations, which will allow to improve the prediction of remaining accidents as well.

For deriving future crash configurations, the developed modular and flexible approach aligned to the test case matrix [3] provides a way to reproduce load cases from real-world data. The approach using current car-to-car crash data at urban intersections (section 3) considers a challenging situational complexity of conflicts caused by human opponents. Finally, the predictions are an expansion of what is expected to happen in future mixed traffic of conventional and automated vehicles. Regarding the results, this approach leads to rather large crash velocities since most low-speed crashes are avoidable by automated vehicles. Despite the large predicted crash velocities, the occupant loading is expected to be still less severe than in current crash tests. The differences in terms of side load components and angled impacts highlight the need to consider omnidirectional occupant protection, especially when new degrees of freedom (rotated and reclined seats) are added for occupants of automated vehicles. The element of stochastic traffic simulations as used in section 5 within the WP1 approach could serve as an addition to established simulation approaches (e.g., crash re-simulation as presented in D1.1 [1]) or other accident research studies based on real crashes.

The OSCCAR results make it clear that traffic situations leading to unavoidable crashes – especially for conflict situations with an on-coming, cutting-in, or left-turning opponents – show the need for evaluating specific occupant protection principles for future decades. Furthermore, the method of clustering crash configurations and a further processing to generic crash pulses is transparent and universal and could be useful for other applications. For instance, for the upcoming discussions on how to include the beneficial effects of active safety and driver assistance technology in future crash tests and to consider lower speeds or more realistic crash angles for conventional vehicles modes. The method for deriving generic pulses can be used to vary pulses for other approaches or determine robust velocity-based pulses for purposes where a detailed acceleration-based pulse is not helpful. The data analysis behind the pulses could further be the basis for pulse prediction, supporting technologies which could consider the accident configuration and its severity for triggering restraint systems before the first contact of the vehicles.

With the stochastic traffic simulation approach, here with the open-source framework openPASS, OSCCAR successfully demonstrated a full tool chain and showed the feasibility of stochastic traffic simulations to investigate future accident scenarios. Two of the three selected traffic scenarios were used to create virtual crashes which were investigated in exemplary studies comparing the virtual crashes with the earlier agreed on “OSCCAR motorway pulse” based on D1.1 and literature. The motorway traffic simulations did not contain a crash pulse estimation since the “motorway pulse” (which was defined in WP2 of the OSCCAR project based on an educated assumption) already over-estimated the potentially more realistic crash pulses. Using Delta-v as crash severity indicator was sufficient for the comparison, but a pulse estimation method could be included into the traffic simulation model, too. Reflecting on the full traffic simulation tool chain, additional research questions were identified and first answers were presented in section 5, e. g, baseline parametrization, comparability with crash statistics and additional needs for traffic data to calibrate simulations. However, future work is required to deliver final answers to the identified research questions.

Comparable to all other simulation tools in the field, the OSCCAR stochastic traffic simulation method faces the challenge of how to validate the complex multi-dimensional model and parameter space. In OSCCAR WP1, we decided to face these challenges to avoid pre-defined crash scenarios for virtual assessment but use traffic scenarios instead. For the OSCCAR scope (motorway crashes and their collision characteristics), the multi-agent stochastic traffic simulation was deemed more appropriate. Compared to varying, e. g., many different but very specific cut-in parameters, stochastic simulations of a traffic scenario with many cut-ins could represent the broad range of various causation mechanisms of real-world crashes more realistically. Even if the traffic model is not fully validated for all of the simulated scenarios, the rather imperfect human behavior model, which is still causing more crashes than expected, provides a worse than realistic traffic. This is helpful for the OSCCAR WP1 objective (crash prediction) than an idealized driver behavior leading to only few collisions.

Another benefit of an open-source traffic model is creating the basis for future predictions. For instance, changes in traffic parameters could be easily addressed. Further refinements of the simulation matrix should be investigated by introducing different traffic scenarios. As an example, sudden stochastic cut-out maneuvers could be addressed by a traffic scenario with a traffic jam only on right-most lane. Additionally, this approach could identify currently unknown traffic conflicts worth being investigated in the context of automated vehicles. In addition, understanding human behavior in traffic remains an important and challenging research question. The reasons, circumstances and frequencies of driving errors or risk-taking maneuvers need to be addressed by any approach for safety assurance of automated vehicles. For motorway scenarios with limited driving tasks to be modeled, OSCCAR showed the feasibility of the overall approach.

In the final steps of the entire OSCCAR WP1 approach, a weighting method was applied to results presented in D1.1 to get EU level estimates regarding the portion of crashes in urban-like intersections (with posted speed limit ≤70 km/h) and front-to-rear-end crashes on motorways that could be avoided by generic automated driving functions. The variables used for the weighting process were selected with considerations to data availability in the relevant databases (GIDAS-PCM, VCTAD, national databases, and CARE) and used mostly crash location, crash severity, and accident type. In addition, a method based on exposure data was developed to combine results from all different databases and obtain EU level results at various levels of fleet penetration of the automated driving functions. Exposure data for cars on- and outside of motorways in the European Union was estimated to assess the relevance of the collision frequency of the motorway simulations on a European level and provide an important calibration parameter for future traffic simulations. Hence, the considerations on weighting from different inputs complete the methodological framework to predict future crash scenarios.

8.2 Conclusions

Automated vehicles are close to entering the market and are expected to avoid a large number of current road crashes. It is assumed that these functions perform more reliably and more effectively in traffic situations where human behavior leads to crashes. However, until a large market penetration of automated vehicles is reached, we will see mixed traffic scenarios and automated vehicles are expected to be involved in unavoidable crashes. Hence, protecting occupants in such crashes will be still needed for quite some time for all kinds of vehicles, but the crash configurations of automated vehicles could differ from those of conventional vehicles. In consequence, the crashes involving automated vehicles are expected to modify statistics of crash parameters compared to current crash data.

For our prediction of future crashes involving automated vehicles, we took into account conservative assumptions on crash avoidance and further investigated remaining crashes in two different infrastructures (motorways and urban intersections). OSCCAR WP1 showed that even with comparably small real-world data sets like crash databases and no full-scale traffic scenario prediction with realistic simulation models of automated driving functions, relevant aspects of future crash configurations can be identified. A detailed selection of crash configurations was found and served within OSCCAR as a strong basis for further development.

In another step, harmonized with later OSCCAR work, crash pulses for selected crash configurations were obtained. The OSCCAR methodology allows a creation of generic, yet still specific crash pulses. The crash pulses are generic in terms of being independent of car make specific crash structures, while being specific with respect to the crash configuration. Comparison with some selected car make specific crash pulses showed reasonably good agreement for the developed methodology and could serve in a broader field for a generic and efficient process to create crash pulses.

Due to the limitations of based solely on small crash data sets, we developed a methodology based on stochastic traffic simulation to create more situations leading to crashes in motorway traffic. The model development, the simulations and the resulting crashes pushed forward the methodology development in the field of accident research using non-crash traffic data. The crashes support the initially assumed crash configurations, even though the traffic model could not be fully validated within OSCCAR. Additionally, our considerations on weighting to EU level provide the opportunity to improve the quality of results in future similar research activities.

The first draft estimations from OSCCAR can be compared with future estimations based on additional insights or when focusing in more detail on boundary conditions of both driving functions (e. g., take-over request scenarios) and occupant protection. OSCCAR showed that a single, final conclusion for what kind of crashes will remain relevant for automated vehicles remains inaccessible. Potential variations of the ODD, seating positions, interior designs, etc. need to be considered for every single new occupant safety concept. Hence, the relevant crash configurations presented herein depend on the concepts for automated vehicles. But OSCCAR showed as well that the complexity is manageable without oversimplifying this task by relying on, e. g., existing load cases. From today's knowledge on road crashes, guiding assumptions for future crashes can be drawn. Still, experience from conventional restraint system development can be used for deriving new safety concepts, if test cases are systematically motivated based on future boundary conditions, such as new crash configurations.

Driven by the step-by-step progress in the field of automated driving starting with the introduction of first automated driving functions at the beginning of this decade, the application of the method developed in OSCCAR will provide more precise and hence better input for the development of occupant protection principles, needed for future automated vehicles.

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