D5.2 SAFETY IMPACT ASSESSMENT – INTERMEDIATE REPORT

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Related Work Package	WP5
Version/Status	1.0 | Submitted to the EC
Issue date	30/Nov/2021
Deliverable type	R
Dissemination Level	PU
Project Acronym	SAFE-UP
Project Title	proactive SAFEty systems and tools for a constantly UPgrading road environment
Project Website	www.safeup.eu
Project Coordinator	Núria Parera | Applus IDIADA
Grant Agreement No.	861570

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement 861570.

Document Distribution

Version	Date	Distributed to
0.4	23/11/2021	Coordination Team
1.0	30/11/2021	Submission in the EC System
1.0	17/03/2022	Approved by the EC

Acknowledgment

We thank all SAFE-UP project partners for supporting the work that led to this document and for their active participation in project meetings. Special thanks go to the reviewers for their valuable insights and suggestions!

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Executive summary

The aim of the SAFE-UP project is to improve traffic safety by developing tools and innovative methods that proactively address the safety challenges of future mobility systems. This deliverable, which is an intermediate report of the work performed in SAFE-UP task T5.3, specifies methods and approaches that will be used for the assessment of the safety impact of the SAFE-UP safety technologies implemented in four demonstrators. The aim with the demonstrators is not the delivery of a ready-to-use product but rather to understand the safety potential and the limitations of the safety technologies. This report describes work in progress – the work in T5.3 is ongoing and will end in January 2023. The final methodology for safety impact assessment will be reported in Deliverable D5.8.

A general framework for assessing the safety benefit of the SAFE-UP safety technologies was proposed in D5.1, built on knowledge from research publications and experience from previous projects and adapted to the specific needs of SAFE-UP. Two essential elements in the framework are detailed pre-crash and in-crash simulations according to the principles of the Prospective Effectiveness Assessment for Road Safety (P.E.A.R.S.) initiative and combining the results of these simulations and results from physical testing in a Bayesian statistical approach developed in the EU project PROSPECT. The work in T5.3 has followed the structure of the framework described in D5.1 and has been directed towards specifying how this structure may be applied to the four demonstrators. The demonstrator-specific aspects of the assessment method are described to a varying level of detail, due to of the time planning in SAFE-UP with different starting times for the demonstrators.

To improve the occupant protection in case of a collision and reduce the increased risk of injury for occupants in new seating positions, e.g., reclined seatback, WP4 in the SAFE-UP project is investigating an occupant monitoring system and an adaptive restraint system. The relevant technologies will be implemented in SAFE-UP Demonstrator 1 (abbreviated as **Demo 1**). The occupant protection will be evaluated virtually using both female and male Human Body Models (HBMs) in new seating positions. In addition to the HBM simulations, occupant protection for specific seated positions will be demonstrated in a sled test using Anthropometric Test Devices (ATDs). Furthermore, it is investigated how a (co-)simulation platform could be used for safety performance assessment of car occupant protection measures, including those considered in Demo 1.

As the last activity related to Demo 1, preliminary results are provided regarding the potential of increasing belt use rates and improving belt fit for belted car occupants, showing that 100% safety belt use in the EU could avoid close to 2 000 car occupant fatalities each year and that the injuries of more than 225 000 car occupants annually could potentially be mitigated or avoided by ideal belt fit. These results indicate a large potential for systems that can detect missing belt use or incorrect belt fit such as those based on occupant monitoring or sensors, coupled with Human-Machine Interaction (HMI) that prompts occupants to use seat belts and improve belt fit, as proposed in SAFE-UP D4.2. The development and completely functional demonstration of a system of this kind is out of scope for SAFE-UP; however, our results, which are planned to be further investigated and made more accurate

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in D5.8, clearly indicate that this is a topic well worth investigating in future projects aimed at improving car occupant safety.

Additionally, a main goal of SAFE-UP is to address the protection of Vulnerable Road Users (VRUs), primarily pedestrians and bicyclists, also targeting weather conditions that could adversely affect sensor performance (e.g., rain). Improved sensors implemented in a prototype vehicle are used in the second demonstrator in SAFE-UP (**Demo 2**). This vehicle undergoes physical testing in various weather conditions, including adverse weather conditions (e.g., precipitation of different intensity); the test results support the development of a filter representing reduced sensor performance in rain which in turn is included in pre-crash simulations. These simulations enable a quantification of the reduction of crashes and (serious) injuries resulting from the ability of an Autonomous Emergency Braking (AEB) system for VRU protection to address scenarios with adverse weather conditions.

The third SAFE-UP demonstrator (**Demo 3**) includes an Autonomous Emergency Braking and Steering system (AEB+S) with full functionality for all weather conditions. The scenarios to be addressed by Demo 3 are selected by considering the theoretical possibility of avoiding crashes by braking and steering (under given boundary conditions for these actions). The most relevant scenarios for adverse weather conditions are covered first, and the range of addressed scenarios will be extended in later work. Representations of the safety systems for VRU protection are integrated in a co-simulation platform (i.e., different simulation tools coupled in an overall simulation) which will be used to obtain results for safety benefit assessment. The results are complemented by physical testing of the Demo 3 vehicle and further simulations addressing aspects and parameter combinations that are not feasible to cover by physical testing.

The fourth SAFE-UP demonstrator (**Demo 4**) focuses on understanding the safety benefit potential of Cooperative Intelligent Transport Systems (C-ITS). All the possible communication interactions, such as timely warnings to both VRU and driver as well as actuation of safety systems like AEB for VRU protection are considered. However, the primary focus is on timely warnings which could avoid emergency situations. The selection of scenarios for Demo 4 was based on the crash data analysis presented in D2.6 and considering the state-of-the-art safety systems for VRU protection and the added value of C-ITS in various scenarios based on expert assessment. Physical testing of the Demo 4 vehicle will address the identified scenarios. Additionally, traffic and connectivity simulations will assess delays in warnings sent to cars in situations with many participants.

Finally, elements of the assessment are highlighted that are not specific to a single demonstrator, i.e., are relevant for all demonstrators. This includes details of physical testing, the combination of test results and simulation results, as well as data weighting methods to extrapolate results from locally collected data to an EU level. The statistical approach from the PROSPECT project is applied in that test results and simulation results are combined in a Bayesian statistical approach, and further details of this approach are described in this report. The importance of data weighting is illustrated by preliminary results, showing that unweighted results (such as those presented in D2.6) underestimate the performance of the active safety systems by almost 6% on a European level.

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List of abbreviations

Abbreviation	Meaning
AEB	Autonomous Emergency Braking
AES	Autonomous Emergency Steering
CARE	EU Community database on road crashes, including data from police-reported crashes in EU and EFTA member states and the United Kingdom
CAV	Connected and Automated Vehicle
C-ITS	Cooperative Intelligent Transport Systems
D	Deliverable within SAFE-UP (e.g., D5.2 denotes SAFE-UP deliverable 5.2)
Demo	SAFE-UP demonstrator (e.g., Demo 1 denotes SAFE-UP Demonstrator 1)
EU	European Union, including the member states in 2021
GIDAS	German In-Depth Accident Study
HMI	Human-Machine Interaction
IR	Infrared, a camera type used in the occupant monitoring system
KSI	Killed or Seriously Injured
MAIS	Maximum Abbreviated Injury Scale, indicates injury severity
OMS	Occupant Monitoring System
SOTA	State-of-the-art
T	Task within SAFE-UP (e.g., T5.3 denotes SAFE-UP task 5.3)
ToF	Time-of-flight, a camera type used in the occupant monitoring system
TTF	Time to Fire, used for in-crash occupant protection systems like airbags
VRU	Vulnerable Road User – applied to pedestrians, cyclists and PTW riders
WP	Work Package within SAFE-UP (e.g., WP5 denotes SAFE-UP work package 5)

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1. Introduction

This deliverable is an intermediate report, describing work in progress in SAFE-UP task T5.3: Method development for impact assessment for Demos 1-4. The output from T5.3, i.e., the final methodology for safety benefit assessment will be reported in Deliverable D5.8.

A general framework for assessing the safety benefit of the SAFE-UP safety technologies was proposed in SAFE-UP Deliverable D5.1 (Mensa, et al., 2021), see Figure 1. Work in T5.3 has been directed towards understanding and implementing the various elements of the framework (i.e., the boxes in Figure 1 as well as the connections between the boxes).

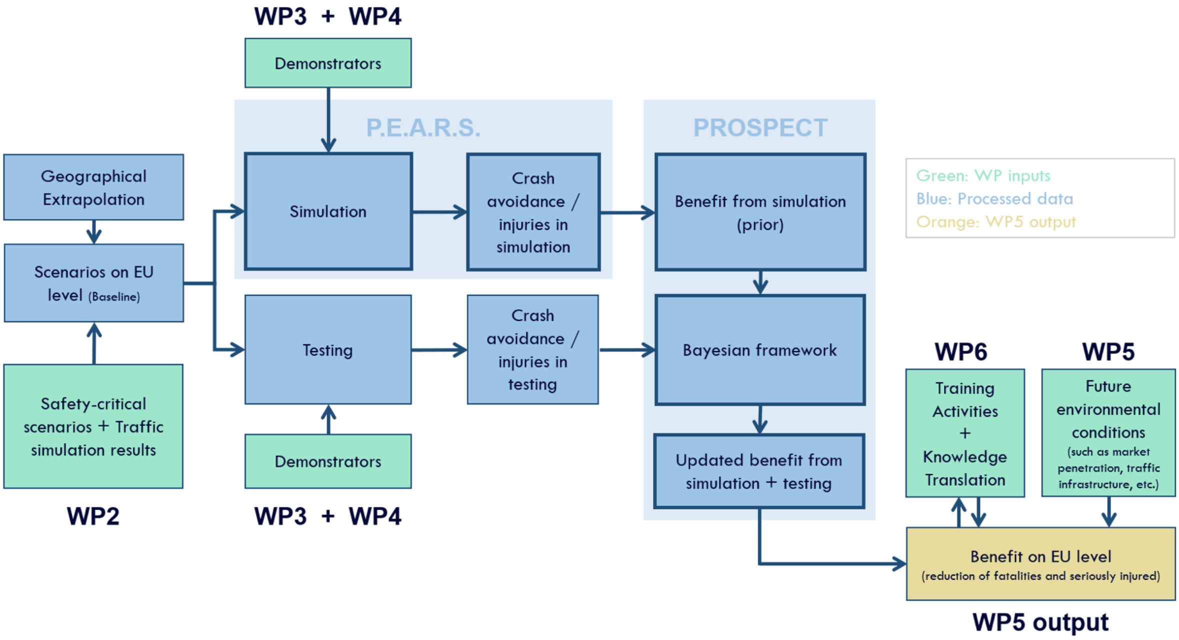

Figure 1 The preliminary safety impact assessment framework for SAFE-UP as defined in D5.1

As noted in D5.1, the relevant assessment activities may differ between demonstrators. The sections in this report are therefore organized as follows. Sections 2-5 are demonstrator-specific, addressing Demos 1 to 4 respectively. Each of these sections begins with a brief overview of the safety technologies included in the corresponding Demo and the corresponding research questions that the safety benefit assessment is meant to address, followed by the details of the virtual simulations and physical testing that have been performed or are planned to assess the safety benefit of the technologies included in the demonstrator. Section 6 deals with aspects of the assessment that apply to several demonstrators at the same time, as detailed above. This deliverable ends in Section 7 with the conclusions and an outlook, indicating topics that need to be explored and decisions to be made before the safety benefit assessment is finalized.

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2. Technologies for Demonstrator 1

This section describes the technologies included in Demonstrator 1 as well as the currently planned activities for their testing, simulation, and impact assessment.

2.1 Overview of Demonstrator 1

Demonstrator 1 aims to advance the occupant protection system and reduce the risk for severity of occupant injuries in new seating positions by implementing an occupant monitoring system and an adaptive restraint system. The occupant monitoring system consists of cameras and the processing hardware that will be installed in a mock-up vehicle, as well as the corresponding algorithms that will be developed by THI. It will showcase how the occupant monitoring system detects and classifies occupant size, positions, and postures. Real-time seat belt usage detection is not in the scope of this project but may be eventually accessed during data collection for training and testing the developed algorithms.

The adaptive restraint system will be investigated by virtual HBM simulations with occupant in new seating configurations (e.g., reclined seatback) and posture (e.g., crossed legs) assuming no knowledge (reference simulation) and full knowledge (adaptivity optimisation simulations) of the occupant characteristics (shape, position, and posture) and the crash configuration characteristics (delta velocity, impact angle and opponent). By this the improvement of the occupant protection system when using an occupant monitoring system can be assessed. Additional to the HBM simulations, a few selected seated positions will be demonstrated in sled test at IDIADA's facilities using an ATD. The occupant use cases were defined in D4.1 (Odriozola, et al., 2021) and further refined in D4.2 (Östling, d'Addeta, Lübbe, Silva, & Zimmer, 2021) and D2.6 (Bálint, et al., 2021). The workflow in Demo 1 is illustrated in Figure 2 below.

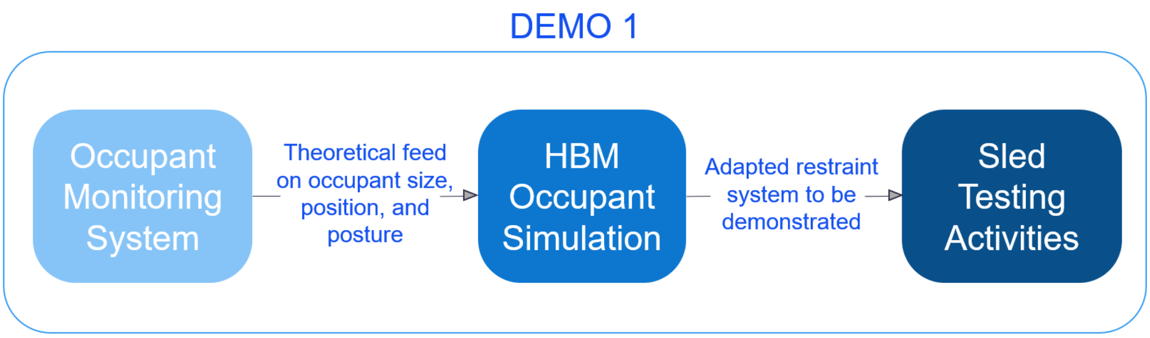

Figure 2 Overview of SAFE-UP Demonstrator 1

Some research areas, such as the link between classification of occupant sizes and used HBM sizes in the simulations or the accuracy needs for the adaptive restraint systems in terms of exact occupant position will not be addressed within the activities in Demonstrator

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1. Those challenges are out of the scope for SAFE-UP and will need to be addressed once the project is completed.

The research questions for Demo 1, as stated in D5.1, are as follows:

RQ1. *"What are the implications in terms of head, neck, chest, pelvis and lumbar spine injuries of new seating position compared to current consumer test position with SOTA occupant protection systems in selected crash configurations?"*

RQ2. *"Can the implications of the new seating position be addressed by an improved occupant protection system including enhanced restraint functions and occupant monitoring system?"*

The next sections describe in more detail each of the Demonstrator 1 components. Section 2 is concluded with the description of a co-simulation platform that is relevant to both Demonstrators 1 and 3, described in Section 2.5.

2.2 Occupant monitoring

The Occupant Monitoring System (OMS) is composed of multiple submodules, as illustrated in Figure 3, that process the acquired data from multiple sensors (cameras) to generate as output the required information about the occupants. This information will be used by the Human-Machine Interaction (HMI, to secure safer seating position) and the occupant protection system (in case of a crash to activate the actuators in an optimal way).

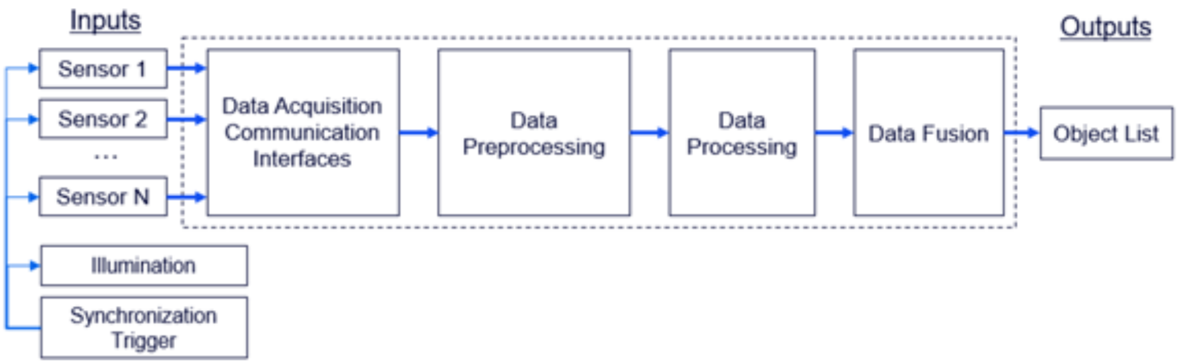

Figure 3 OMS Architecture

The chosen sensors for the OMS are the image-based ones, because they provide data with ample information and high resolution as compared to other technologies (e.g., RADAR, ultrasonic, pressure sensors). The main sensors for the system are cameras that can capture monocular images with depth information (e.g., time-of-flight (ToF) cameras), which allows the use of deterministic algorithms (i.e., occupancy detection only with depth information / point clouds) in contrast to the state-of-the-art methods for 3D human pose estimation that are based on deep neural networks (He, Yan, Fragkiadaki, & Yu, 2020; Iskakov, Burkov, Lempitsky, & Malkov, 2019). As complementary sensors, Infrared (IR) cameras equipped with large field-of-view lenses (i.e., fisheye models) will be combined to

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the time-of-flight cameras to improve the detection performance in specific tasks (e.g., clothes and materials of different colours) and overcome problems with occlusions.

Figure 4 illustrates the locations to be used for the cameras which were fixed based on tests to minimize possible occlusions and avoiding the standard location of actual restraint systems (e.g., airbag deployment regions). C1 and C4 are the ToF cameras, the first one detects the passengers on front seats and the latter one the passengers on back seat.

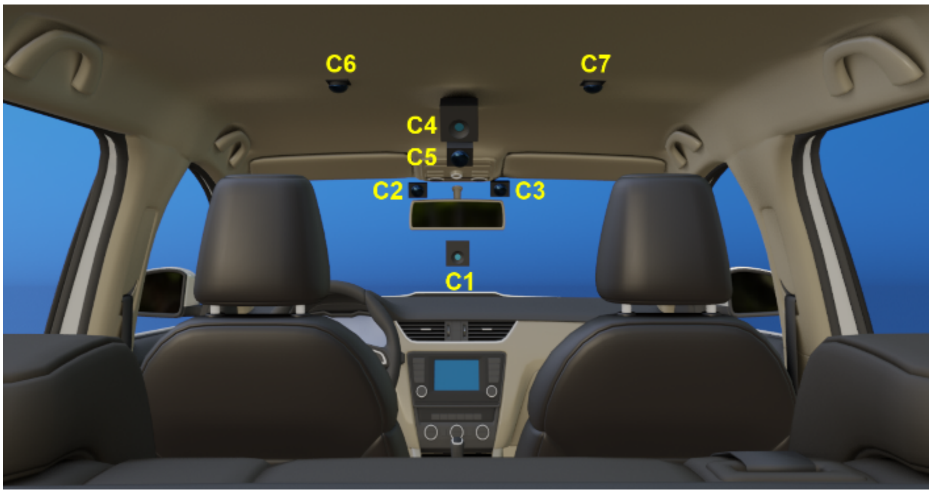

Figure 4 Camera Locations

To increase the robustness of the detection system for the desired use cases, some additional IR cameras are installed (C2, C3 and C5), C2 and C3 cameras generate redundant and complementary data optimized for the front row but can also monitor the back row, C5 is a complementary camera just for the back seat. Although this was not the intention and the interior of the vehicle is not optimized for a living room style configuration (see Figure 5), the C6 and C7 cameras shown in Figure 4 were also installed considering this environment.

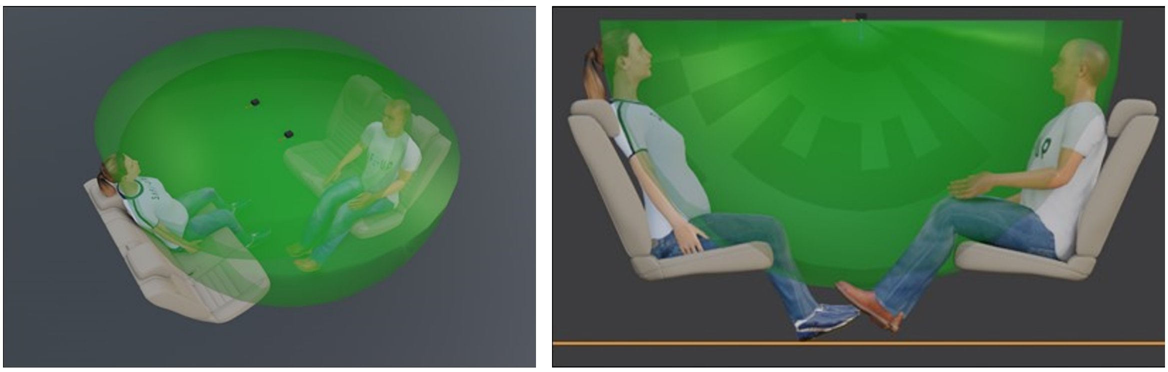

Figure 5 Occupant monitoring in a living room style configuration

The final application will output images from the cameras with 3D posture detected by a real-time algorithm as shown in Figure 6 and will produce an object list as output with the

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following data: occupant detected (yes or no), occupant position, spatial volume used and posture (3D key-points), camera occluded (yes or no).

For testing the outputs of the occupant monitoring system, annotated data of specific collected test cases will be used as ground truth to evaluate and validate the developed detection models. The evaluation metric is based on the comparison of the ground truth (e.g., mean squared error of the 3D key-points) and system outputs considering the detection methods, camera type, and camera position, seat position.

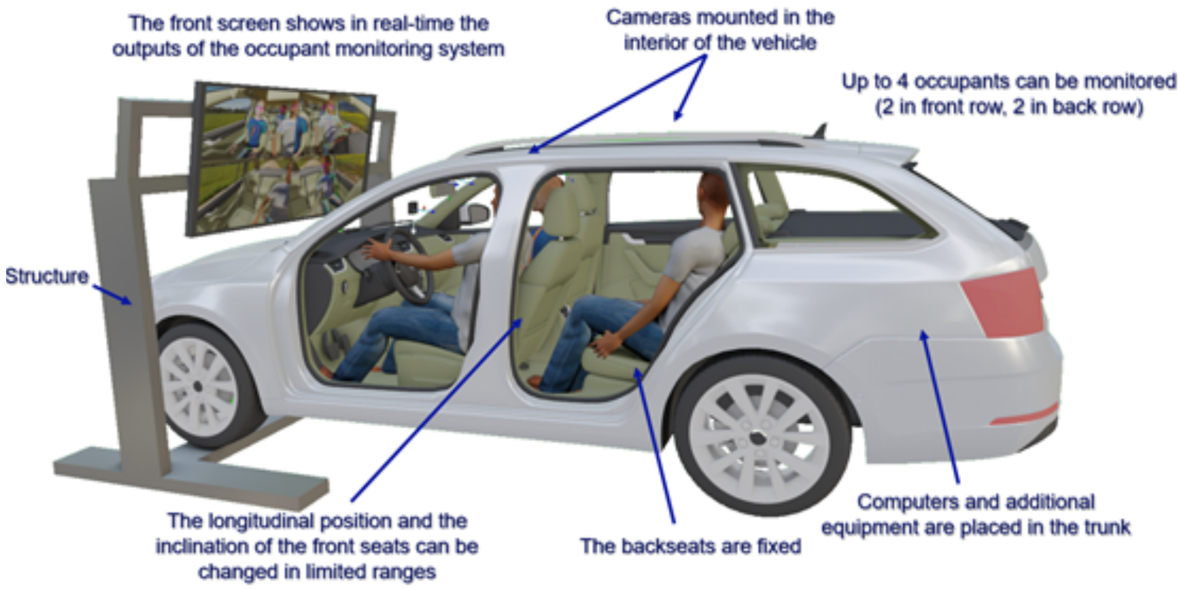

Figure 6 Final presentation for Demo 1

2.3 Human Body Model simulations

This section describes the potential impact of using Human Body Model (HBM) simulations in SAFE-UP in terms of improving adaptive restraint systems.

2.3.1 Improving occupant protection by HBM simulations

Injury risk evaluation with ATDs (Anthropometric Test Devices) are used in protocols (ECE and Euro NCAP) and in the development of restraint systems. The injury assessment for ATDs is based on injury risk curves, giving a statistical prediction of injury risk, based on mechanical measurements in the form of a criterion or indicators (force, acceleration, displacement). To derive an injury risk curve for the ATD, the mechanical measurements are mapped on to injury outcomes of human subjects or tissue specimens under comparable loading conditions. Regulatory crash testing using ATDs has contributed to the reduction of road fatalities in the past years (EC, 2018), by creating a limited number of standardized “abstract” scenarios for assessment. To further decrease the numbers of road fatalities, a step towards the real-world situation, by using HBM, might be necessary.

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In contrast to ATDs, virtual HBMs realistically represent the anatomical structure of humans including bones, flesh, skin, fat, and soft tissue. The high model detail allows a direct assessment of the injury mechanism based on the strain applied to the respective body region, assuming a biofidelic response of the HBM. As HBMs represent a specific human, based on the reference used to model the HBM, the assessment outcome is deterministic. Therefore, also the HBM tissue-based injury prediction needs to be transferred to a probability of injury (Forman, et al., 2012), as is currently the case for ATDs. The process of injury risk evaluation based on HBM assessment outcomes is currently under development. In addition to the improvement of injury risk prediction, HBMs can also represent the kinematic response realistically (more human-like) for different anthropometries (Larsson, et al., 2019). Using HBM in virtual testing enables researchers to investigate several individual postures, anthropometries, and impact situations, e.g., for the development of occupant restraint systems. This can eventually result in restraint systems developed for real humans in realistic scenarios and impact the number of road fatalities by providing improved restraint systems and strategies. (Wismans, Happee, & van Dommelen, 2005).

Further, HBMs offer the possibility to undertake a continuous assessment of pre- and in-crash, which is not possible with current hardware ATDs. As demonstrated in González-García, Weber, & Peldschus (2020) considering pre-crash kinematics can influence the results of the in-crash simulation. To perform a proper prediction of the HBM kinematics at the moment of collision, active models which simulate the pre-crash behaviour are required. Different controller strategies are used (Wochner, 2019) to depict the human muscle response to external forces and apply that on the HBMs. Controller and HBMs are validated (tuned) based on volunteer data in low velocity and low-g sled tests or vehicle tests. (Huber, Kirschbichler, Prugger, & Steidl, 2015; Östh, Ólafsdóttir, Davidsson, & Brolin, 2013).

2.3.2 HBM activities in SAFE-UP

The existing active HBMs are validated on the basis of upright sitting volunteers (mostly male) – see e.g., THUMS v5 and v6 (Daichi , Yuko , & Masami , 2017; Daichi , Yuko , Noritoshi , & Masami , 2018). As automated driving enables the vehicle occupants to sit in a reclined sitting position, the active HBMs should also be capable of predicting the pre-crash kinematics in these new sitting postures. Therefore SAFE-UP aims to:

- run a volunteer study to create a dataset on occupant kinematics in reclined sitting positions in pre-crash manoeuvres (braking, steering, combined), and
- enhance an active HBM using the data obtained to actively predict the human pre-crash kinematics.

These goals are reached in five steps:

1. Available volunteer data (Reed M. P., Ebert, Jones, & Park, 2021) in reclined sitting positions are used to enhance an HBM (with the VIF controller) to roughly predict the pre-crash kinematics in reclined sitting positions. These results will be used in WP4 (Task 4.3) and WP5.

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2. A volunteer study is conducted to supplement and enhance the existing study with, e.g., belt data, interaction with the environment (seat contact forces) and trajectories for the thorax. The study will be performed on a test track in a vehicle, which is equipped with automated driving and “driving robot” functions. It is therefore capable of accurately repeating driving manoeuvres. It is planned to have a balanced proportion of male / female volunteers.
3. The used HBM is validated / tuned with the volunteer data of the SAFE-UP study.
4. The updated active HBM is used for pre-crash kinematic prediction for the pre-crash pulses which are derived in T4.2.
5. Transition of the pre-crash kinematics to in-crash models with the VIF transition tool from OSCCAR.

Within the HBM simulations conducted in T4.3, future scenarios will be investigated, with a focus on using information about occupant size, position, and posture from the occupant monitoring system to optimise the adaptive restraint systems. The investigations will be conducted for future scenarios, including seating positions, occupant postures and crash cases as well as restraint system functionalities expected in automated driving vehicles, which were defined in T4.1 (Odriozola, et al., 2021) and T4.2 (Östling, Architecture of Passive Safety Systems, 2021). The defined cases also include a state-of-the-art reference scenario (System Layout 1), including a state-of-the-art restraint system and the standardized seating position. The target for the optimization of the restraint system and the novel principles in future system layouts, is to meet as minimum, today’s safety standard (represented by System Layout 1) as well as more complex future scenarios. For an aligned assessment within all investigated situations, several injury criteria were defined in T4.2.

2.3.3 Contribution of HBMs to safety benefit assessment

The HBM simulations in SAFE-UP will contribute to improving occupant safety in the following aspects:

- Using improved models to better predict injury risk.
- Optimization of the adaptive restraint system based on “real” human response.
- Optimizing adaptive restraint systems for realistic crash scenarios.
- Ensuring safety in a higher variety of sitting postures.
- Ensuring safety for a higher variability of anthropometries and human individuals.
- Safeguarding new seating positions.

A numerical output from HBM work in WP4 is expected to be a quantification of the risk of an injury of a given severity (e.g., AIS5+ or AIS2+, as needed) under different boundary conditions (regarding occupant size, sitting postures, etc.) in different crash configurations.

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It requires further work in T5.3 to explore how to quantify the effect of a potential injury risk reduction for the number of seriously or fatally injured people in Europe.

2.4 Sled testing

Besides the occupant monitoring and the HBM simulation activities, Demo 1 plans to demonstrate the performance of adaptive restraint systems in sled test facilities. Thus, according to representative test cases defined in SAFE-UP, selected seating positions will be physically tested using an ATD within a generic sled test environment. The final seating positions will be reproduced in both the simulations and physical testing to assess the restraint system performance according to the selected situations.

The main objective of the Demo 1 physical testing activities is to show the adaptiveness of the restraint systems in representative seating positions when those are connected to an occupant monitoring system that can provide information about the occupant state and position within the vehicle prior to the crash.

Therefore, the initial plan includes a series of sled tests for frontal in-crash load-cases comparing both current SOTA restraint systems and the adaptive restraint system actuators activated according to the optimisation work performed in task 4.3. Activation times and strategies for the different restraint actuators will then depend on the outputs of the OMS as explained in Section 2.2 (SAFE-UP T4.4), and the HBM simulation described in 2.3.2.

A generic LS-Dyna system simulation model including the previously explained adaptive restraint systems will be developed by Autoliv in Task 4.3. A physical representation of the system simulation model will be replicated in a sled test setup at IDIADA. The sled test setup will include a generic seat, seat belt with possibility for both B-pillar and belts in seat installed belt guide. Further, it comprises of a driver airbag, a steering wheel with a collapsible steering column and a knee bolster, see Figure 7 below.

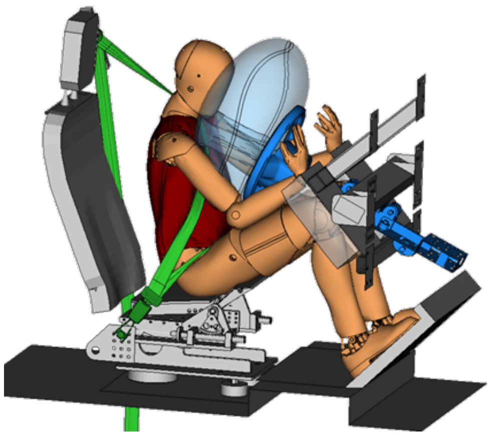

Figure 7 The sled test setup planned for SAFE-UP

The fore-aft position of the seat will be defined according to the selected seated positions to be studied, as well as for the seat-back angles and seatbelt position. The sled testing matrix, set-up and detailed parameters are currently being defined in Task 4.3 activities and will be

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finalized in T4.5. Thus, the final conditions to be followed when conducting the Demo 1 sled tests in T5.4 may differ slightly to what has been described above.

2.5 Application of (co-)simulation for safety performance assessment

The technology of Demo 1 is sensitive to the occupant position prior to the crash. Therefore, a simulation method for safety performance assessment must consider both pre- and in-crash phase and for each phase all relevant elements. Figure 8 below shows a framework that covers all domains relevant for integrated safety performance assessment. It consists of the following main elements:

- **Scenario-based pre-crash simulation.** The pre-crash simulation covers the phases from normal driving up to the time of crash. It consists of the vehicle under test (vehicle dynamics, driver, sensor(s), safety technology algorithm(s), actuators) and its surroundings (traffic, infrastructure, environment).
- **Vehicle in-crash simulation.** This simulation is started once a collision is detected. It provides the accelerations resulting from the crash which will then be transferred to the vehicle interior and occupant simulation.
- **Continuous vehicle interior and occupant simulation (pre- and in-crash).** This is the final simulation element of the framework. Here, the occupant will be loaded with the pre- and in-crash accelerations. The pre-crash accelerations are relevant for the occupant's position at the time of crash. This position has an influence on the injury severity. The same applies to the in-crash accelerations.
- **Determination of injury severity.** Based on the output (displacements, velocities, accelerations, forces) of the previous simulation, the injury severity is measured using injury criteria, such as, e.g., HIC or chest deformation. Each injury criterion value can then be used to calculate a respective injury risk. Finally, the individual injury risks are combined to an overall injury risk, which can then be used for comparing simulation results and assessing the safety performance.

This framework can be used for a small number of cases providing a high level of detail. However, if many cases should be investigated in a scenario-based testing approach, a significant reduction of calculation time is required. Especially the high-fidelity models for in-crash simulations (vehicle in-crash simulation and vehicle interior and occupant simulation) are computationally too expensive. Therefore, for a large-scale study, the following high-fidelity models could be replaced by surrogate models to reduce computation time:

- For the vehicle in-crash, a black-box model could be used. Its input are parameters describing the crash configuration (relative speed, angle, offset). Its output is, same as for the high-fidelity model, accelerations over time.

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- For the interior and occupant simulation, a split up between pre- and in-crash could be performed. The pre-crash simulation surrogate model could be a simplified physics-based model that provides mainly the thorax and head movement resulting from the applied pre-crash accelerations. The in-crash simulation surrogate model could also be a black-box model that integrates the vehicle in-crash model and provides resulting injury values based on crash configuration, head position at time of crash and restraint system settings. The modified framework including the surrogate models is shown in Figure 9 below. The surrogate models need milliseconds to seconds for one run while a simulation run with the high-fidelity models needs about 24 hours for the same task.

This acceleration of computing performance comes at a price: the surrogate models need a training phase to fit the initially unknown internal parameters to the actual problem that should be approximated. To do so, simulations with the high-fidelity models must be performed to generate the training data. In an exemplary study to show the feasibility of this method, a training dataset with about 100 simulation runs was used and showed satisfactory results. In the case that several hundred crashes should be studied, this approach is still much faster than using the original, high-fidelity models. More details on this study and the method in general can be found in Hay et al. (2021) and Wimmer et al. (2021).

Another critical point that should be mentioned is the fact that surrogate models always represent a certain physical system with its specific properties. If different systems should be assessed, e.g., different vehicle models, a separate surrogate model must be trained for each of these systems. This also implies, that the respective high-fidelity models to generate the training input must be available, which might be a difficulty in this project. Finally, it should be stated that this is only one possibility to assess the performance of integrated vehicle safety systems. The final method to be used also depends on the activities and results from other work packages.

The technologies related to occupant monitoring may enable a higher rate of belt use in general as well as a higher proportion of occupants using their belts correctly. Section 2.6 makes a preliminary assessment of improved belt use on a European level.

2.6 Preliminary assessment of improved safety belt use

An important element of car occupant protection is the (correct) use of the safety belt. A study by the National Highway Traffic Safety Administration (NHTSA, 2019) estimated that the use of safety belt in passenger vehicles saved 14,955 lives in 2017 in the United States, and that 100% safety belt use would have saved additional 2,549 lives. These estimates suggest that improved safety belt use could potentially save hundreds or thousands of lives in the EU as well. Considering that the technologies in Demo 1 (such as occupant monitoring and/or sensors) could possibly be used in safety systems improving belt use rates, a small study within SAFE-UP has been conducted to get an initial estimate of the safety benefit potential of an assumed 100% safety belt use on EU level.

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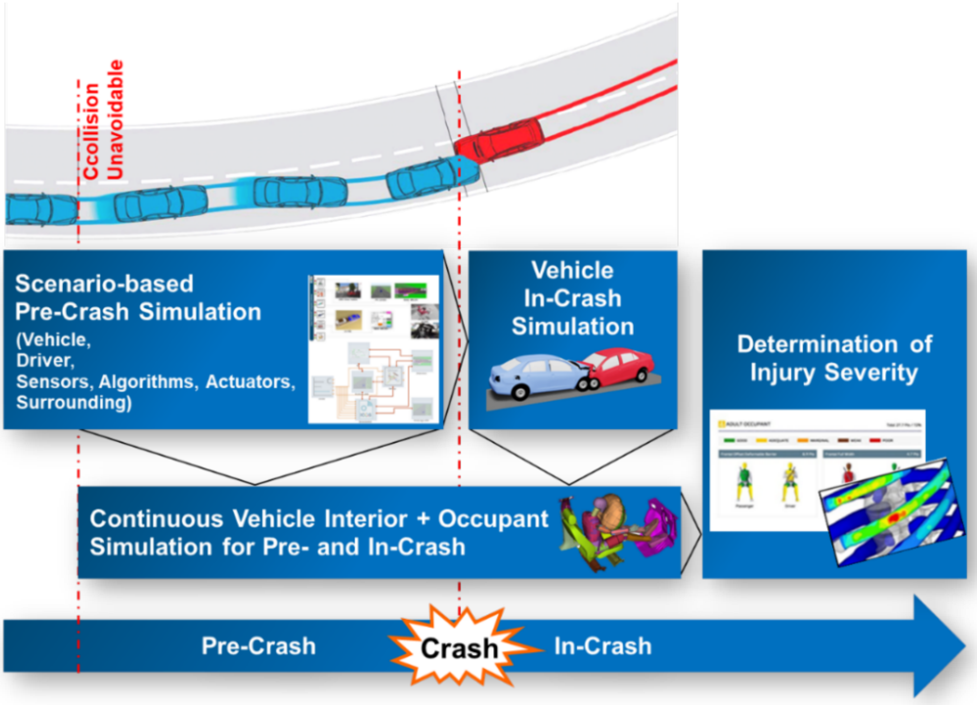

Figure 8: Simulation framework combining all relevant simulation domains for integrated safety assessment covering a complete car-to-car crash scenario from normal driving to in-crash.

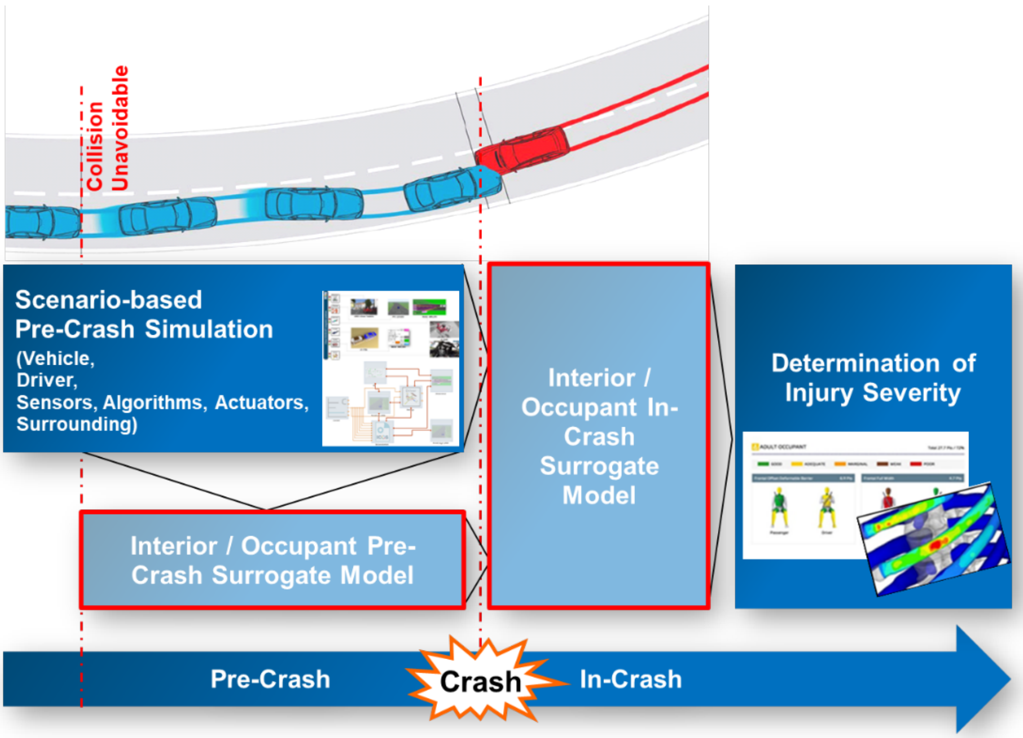

Figure 9: The modified simulation framework for car-to-car crashes with surrogate models (marked red) replacing all time-consuming high-fidelity models.

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Data from the World Health Organization (WHO, 2021) was used for understanding belt use by country for front seat occupants, see Figure 10 below. According to the same data source, the corresponding rate for the United States is 90.1%.

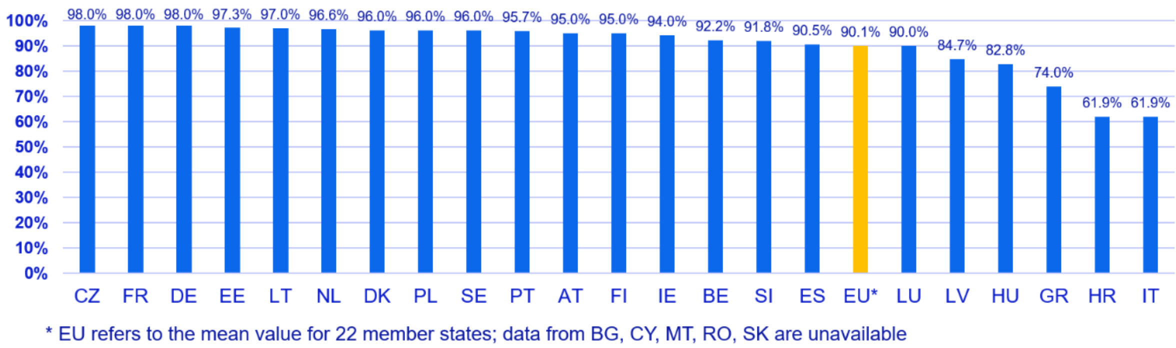

Figure 10 Belt use rates for front seat occupants in the European Union in 2017 (WHO, 2021)

These results indicate that while most EU countries have safety belt use rates above the US, the mean safety belt use rate for front seat occupants in the EU is equal to the safety belt use rate for front seat occupants in the US. Statistics from the International Road Traffic and Accident Database regarding year 2019 (IRTAD, 2020) reinforce this picture in that while most EU countries have better safety belt use rates compared to the US, the EU average is still around the US level due to a few countries having substantially lower seat belt use rates than the majority. In fact, the weighted average of EU seat belt wear rates for front seat occupants based on population data from the statistical office of the European Union (Eurostat, 2019) is 89.7%, which is slightly lower than the safety belt use rate for front seat occupants in the United States.

The above statistics indicating similar rate of unbelted front seat occupants in general in the EU and the US motivate our first Working Hypothesis, denoted by WH1, assuming that the rate of unbelted front seat occupants among car occupant fatalities is equal between the EU and the US. This work hypothesis will be investigated later in T5.3, by analysing data from CARE, which is the European community database on road crashes (CARE, 2021; CADaS, 2021). According to data from the National Highway Traffic Safety Administration (NHTSA, 2021), the total number of passenger car occupant fatalities in the United States in 2017 was 13 477 of which 5 064 (37.6%) were unrestrained while 7 173 (53.2%) were restrained and 1 240 (9.2%) had unknown restraint use.

Another working hypothesis used for the current analysis, denoted by WH2, is that the estimates regarding the share of unbelted fatalities that could have been saved by belt use is the same between the United States and the EU. Specifically, using the estimate mentioned at the beginning of this section that 100% safety belt use would have saved additional 2 549 lives (NHTSA, 2019) which is 50.3% of the 5 064 unrestrained car occupant fatalities, WH2 amounts to assuming that 50.3% of the unrestrained car occupant fatalities in the EU could have been saved by 100% safety belt use.

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Applying WH1 and WH2 on the EU level crash data statistics presented Table 4 in D2.6 (Bálint, et al., 2021) allows an estimate regarding the number of car occupant fatalities in the EU that could have been prevented by 100% safety belt use, see Table 1 below.

Table 1 Fatalities of car occupants in the EU in 2018 that could have been avoided by 100% safety belt use, under assumptions WH1 and WH2

Type of road user and restraint use	Fatalities
Car occupants, all	10 349
Unbelted car occupants	3 860
Unbelted car occupants that could have been saved by the safety belt	1 943

A target population of 2 085 fatalities in modern cars was identified in D4.1 (Odriozola, et al., 2021) that could be relevant for future vehicles and potentially feasible to address. The target population includes car occupant fatalities in modern cars in crashes involving exactly two cars or exactly one car and exactly one heavy goods vehicle, with crashes with parking vehicles excluded. An initial estimate of avoidable fatalities can be derived by using a rather strong and probably flawed working hypothesis (WH3) that the percentages of unbelted car occupants and those that could be saved by 100% safety belt use used in WH1 and WH2 for the general population of car occupant fatalities also apply to the target population. The corresponding results are provided in Table 2 below.

Table 2 Fatalities in the SAFE-UP target population for car occupants that could have been avoided by 100% safety belt use, under the (rather strong) assumption WH3

Type of road user and restraint use	Fatalities
Car occupants in the SAFE-UP target population	2 085
Unbelted car occupants in the SAFE-UP target population	778
Unbelted car occupants in the SAFE-UP target population that could have been saved by the safety belt	391

In addition to occupant fatalities, it can be investigated how many non-fatal injuries of car occupants occur without belt use. Statistics by the National Highway Traffic Safety Administration (NHTSA, 2021) estimate that of the 1 529 000 car occupants non-fatally injured in road crashes in the United States in 2017, there were 64 000 (4.2%) unrestrained, 1 333 000 (87.2%) restrained and 132 000 (8.6%) had unknown restraint use. We define WH4 as the assumption that the same shares of restraint use apply to non-fatally injured car occupants in the EU.

Furthermore, another aspect that could in principle be investigated by technologies related to Demo 1 (such as occupant monitoring) is belt fit for belted car occupants. A recent study

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based on an analysis of naturalistic driving data in the United States (Reed M. P., Ebert, Jones, & Hallman, 2020) found that front seat occupants had a non-ideal belt fit in 35% of the time. Our last work hypothesis, WH5, states that 35% of non-fatally injured belted car occupants had non-ideal belt use, and the results under this hypothesis are specified in Table 3 below.

Table 3 Non-fatally injured car occupants in the EU in 2018 without restraint or with incorrectly used restraint, under assumptions WH4 and WH5

Type of road user and restraint use	Non-fatally injured
Car occupants, all	649 016
Unbelted car occupants	27 259
Belted car occupants with non-ideal belt fit	198 080

The above analysis, based on various assumptions, has led to rough EU-level estimates regarding the potential of systems improving the rate of belted car occupants and the share of belted car occupants with ideal belt use, as follows.

1. Ensuring belt use of car occupants all the time could save close to 2 000 car occupants annually in the EU of which close to 400 are in the target population in SAFE-UP.
2. About 27 000 non-fatally injured car occupants in the EU are unbelted, and close to 200 000 non-fatally injured car occupants per year are belted but have non-ideal belt fit. Therefore, the injuries of more than 225 000 car occupants in the EU annually could potentially be mitigated or avoided by ideal belt use.

The above results are preliminary, and their correctness depends on the validity of assumptions WH1-5. The results suggest, in any case, that improving restraint use rates and belt fit for belted car occupants has substantial safety benefit potential to be exploited, and the technologies related to SAFE-UP Demo 1 could theoretically be used for this purpose. Further discussion is required within the SAFE-UP project how much this potential can be demonstrated within the project and which aspects need to be addressed in future studies and projects.

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3. Technologies for Demonstrator 2

Demonstrator 2 is addressing improved sensor performance in adverse weather conditions which, according to D2.6, mainly includes precipitation. The development of Demo 2 is described in greater detail in the deliverable D3.2 (Löffler, et al., 2021); what follows here is a brief overview of the demonstrator and those Demo 2 activities that are most relevant for the safety benefit assessment. The parts below may therefore include sentences or paragraphs taken from D3.2, without further indication.

3.1 Overview of Demonstrator 2

As indicated in D5.1 (Mensa, et al., 2021), Demonstrator 2 has the following sensor components, all with raw data access but without object data output (see also D3.1 (Nikolaou, et al., 2021) and D3.2 (Löffler, et al., 2021)):

- prototype high resolution radar (front rear center, 2*front corner, rear center 2*rear corner),
- video sensors (stereo video camera at windscreen), and
- prototype lidar sensor (roof mounted).

All measurement data are collected and stored by the central processing unit (Car PC) inside the vehicle, see Figure 11.

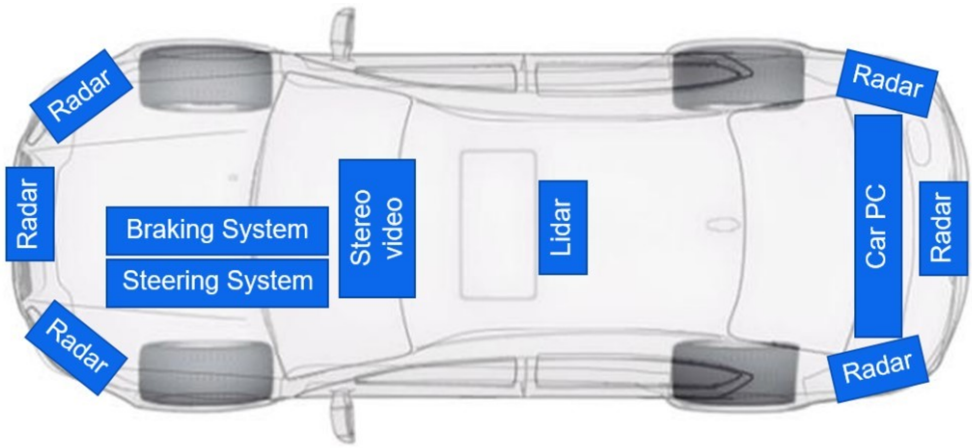

Figure 11 Demo 2 Physical architecture diagram

The research question specified in D5.1 for Demo 2 is related to a comparison between the safety benefit of an (unspecified) active safety system and the same system with all-weather VRU detection:

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RQ3. *“What is the safety performance of an active safety system with an ‘all-weather VRU detection system’ at a penetration rate of 9.6% / 27.5% / 100% in Car to VRU collisions on urban roads in terms of MAIS 5+ injury reduction on EU level in 2025 compared to the 2016 numbers and the same safety system with SOTA VRU detection system?”*

3.2 Physical testing at THI test lab

As shown in D3.2 (Löffler, et al., 2021) there was a physical testing of Demo 2 inside the THI indoor lab using rain and fog with different intensities for analysing the weather effect on pedestrian detection of the different sensor types. A more detailed description of the indoor lab can be found in Section 3.2 of D3.2. The 4A pedestrian dummy was used, which is certified also for NCAP testing. The measurement setup of the first measurement campaign is shown in Figure 12 below, followed by images of the Demo 2 vehicle under testing rain and fog conditions (Figure 13).

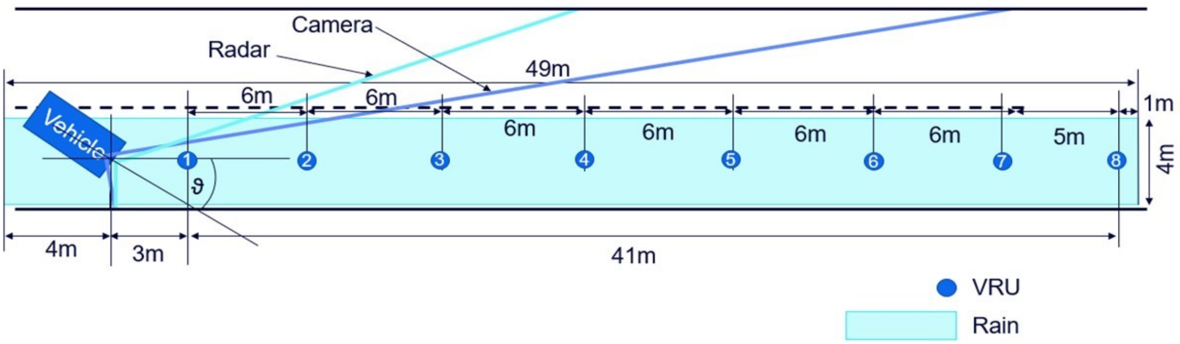

Figure 12 Measurement setup of the first measurement campaign (static measurements) inside the CARISSMA test hall

Figure 13 Demo 2 in rain and fog condition testing

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The baseline measurements are performed in the test lab of THI and, as described in Section 4.2 of D3.2, the resulting data are used to develop a corresponding weather filter algorithm to be used in software simulating adverse weather conditions. This filter enables the Demo 3 car to simulate adverse weather perception influence at the test track driving and will also be used in the traffic simulations in WP2. A more detailed description of the first measurement campaign can be found in Section 5.1 of D3.2.

A second measurement campaign was performed with the sensor setup of Demo 3 vehicle (sensors closer to serial production). As in the first measurement campaign, the pedestrian target from 4A was used, this time in addition to the bicycle target and the Powered Two-Wheeler (PTW) target from 4A. The measurement results are still in post-processing; for a more detailed description of the second measurement campaign, the reader is referred to Section 5.2 of D3.2.

A third dynamical test campaign is planned for end of November 2021, and the results will give input to virtual simulation performed by CARIAD, as detailed in Section 3.3 below.

3.3 Simulation of collision avoidance under adverse weather conditions

In T3.2, influences of adverse weather conditions (rain and fog) on sensors (radar, lidar, and camera) are analysed. Based on measurements with various weather conditions in the test hall of THI, several pre-crash simulations will evaluate the intervention of AEB in car-to-VRU conflict situations.

While most state-of-the-art pre-crash simulations assume ideal sensor detection ranges, sensor detection ranges in simulations of this project are to be adapted using results from the measurements conducted in the THI test hall. Beside the changed sensor detection ranges due to adverse weather conditions, the simulation takes further scenario parameters into account (e.g., road friction coefficient).

The simulated scenarios are selected based on the crash data analysis of T2.1 that identified use cases for adverse weather conditions. As an output of this simulation analysis, the collision avoidance potential using adapted sensor detection ranges is to be assessed in comparison to the ideal sensor detection ranges.

Generally, the sensor degradation effect due to adverse weather conditions will be defined for the different sensor technologies. This results in an updated sensor fusion concept for minimizing the degradation effect and creating a higher effectiveness for VRU detection, leading to a higher conflict avoidance potential for Connected and Automated Vehicles (CAVs).

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3.4 Link to advanced intervention systems

A close cooperation in the development of Demos 2 and 3 can be found in all related tasks of the project. Although the specific scopes of these demonstrators are quite different, they share the common ground of addressing crashes that can only be detected very late in time with SOTA technology. Demonstrator 2 has the goal to address this by enabling an earlier detection of VRUs under adverse weather conditions, while the goal of demonstrator 3 is to achieve complete crash avoidance by advanced intervention systems, e.g., AES, even when a detection of a crash can only be achieved at a very late point in time. The late detection can have several reasons, one being bad visibility due to adverse weather conditions, and another one being sight obstructions hiding the VRU. Because of this link between the two demonstrators, crash scenarios relevant for adverse weather have been selected for the initial Demo 3 scenario selection.

Additionally, even though each demonstrator uses its own vehicle, the Demo 3 vehicle is also used for adverse weather testing. This enables further insights into the effect of adverse weather conditions on different levels of object perception, as the Demo 3 vehicle has access to object-level sensor data, while the Demo 2 vehicle only has access to raw sensor data.

4. Technologies for Demonstrator 3

Demonstrator 3 includes all-weather advanced intervention systems. The development of Demo 3 is described in greater detail in the deliverable D3.3 (Löffler, et al., 2021); what follows here is a brief overview of the demonstrator and those Demo 3 activities that are most relevant for the safety benefit assessment. The parts below may therefore include sentences or paragraphs taken from D3.3, without further indication.

4.1 Overview of Demonstrator 3

Demo 3 develops advanced vehicle dynamics intervention functions to avoid or mitigate critical events, featuring combined trajectory control algorithms for both emergency braking and steering.

A Bosch development vehicle as shown in Figure 14 is used as the Demo 3 integration platform. The vehicle contains several sensors and actuators with enhanced interfaces as well as a computing platform including a Robot Operating System (ROS) framework.

Figure 14 Demo 3 integration platform. A Bosch development vehicle featuring a radar/video sensor set and steering and braking interfaces with enhanced dynamics

The general layout of the Demo 3 software is summarized in Figure 15 below. This figure shows the main functionalities that are needed for the demonstrator.

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The sensor input (2) block processes the measurements coming from the vehicle sensors. The object fusion and tracking (3) function provides tracked objects (e.g., VRUs) to the other functions that need this information. The VRU intent & trajectory prediction (5) predicts the intent and trajectory of VRUs.

The path planner (8) plans a path based on the predicted VRU trajectories and a global route, provided by the global planning (7). This global planning needs the current location of the vehicle, provided by the localization (4) module.

The trajectory generator (9) generates trajectories based on the planned path and the predicted VRU trajectories. The trajectories are evaluated on their risk for a collision, which is provided by the crash prediction and avoidance function (6). After a safety decision performed in (10), the vehicle control (11) generates the outputs to control the vehicle to follow the generated trajectory.

Note that the scenario selection & baseline simulation block (1) is not connected to any other block in Figure 15, as it is a supportive activity to define the actual scenarios and not a software module.

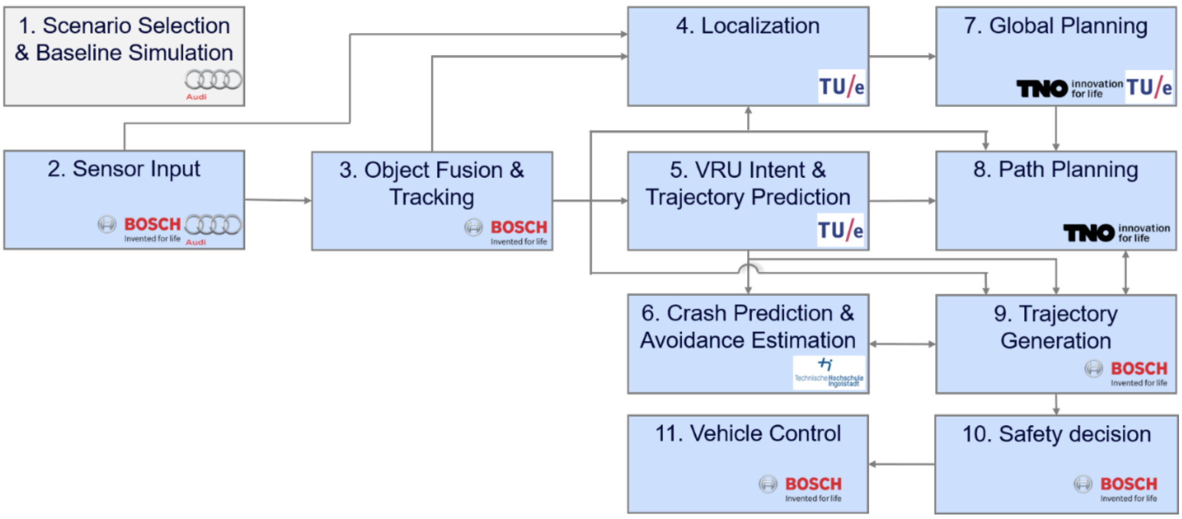

Figure 15 High level interaction layouts between functionalities (light blue) and inputs needed from other work packages (grey block)

A detailed description of the Demo 3 hardware and software architecture and technical specification can be found in the deliverable report D3.1 (Nikolaou, et al., 2021).

The research question in D5.1 for Demo 3 addresses the added value of the all-weather aspect and autonomous steering and braking compared to SOTA systems:

RQ4. "What is the safety performance of an 'all-weather VRU AEB+S' at a penetration rate of 9.6% / 27.5% / 100% in Car to VRU collisions on urban roads in terms of MAIS 5+ injury reduction on EU level in 2025 compared to the 2016 numbers?"

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4.2 Scenario selection summary for Demo 3

With the main goal of Demo 3 to develop advanced crash avoidance systems including autonomous emergency steering (AES) as a novelty, special focus is given in understanding the potential field of effect of such a system, especially in comparison to current state-of-the-art advanced driver assistance systems addressing VRU crashes. Therefore, a simulation analysis to quantify a theorical field of effect is performed as part of the Demo 3 development.

The goal of the following Demo 3 scenario selection process is to identify scenarios that cannot be avoided by state-of-the-art systems and have the theoretical potential to be avoided by AES. These scenarios are then used to steer Demo 3 development towards a real-world benefit by directly addressing crashes that are not yet covered by any avoidance system.

The scenario selection method is based on a simulation of generic implementations of Autonomous Emergency Braking (AEB) und Autonomous Emergency Steering (AES) systems. Based on an assessment of the crash avoidance potential, crash clusters are formed and specified by their parameter distributions. Figure 16 shows an overview of the simulation process.

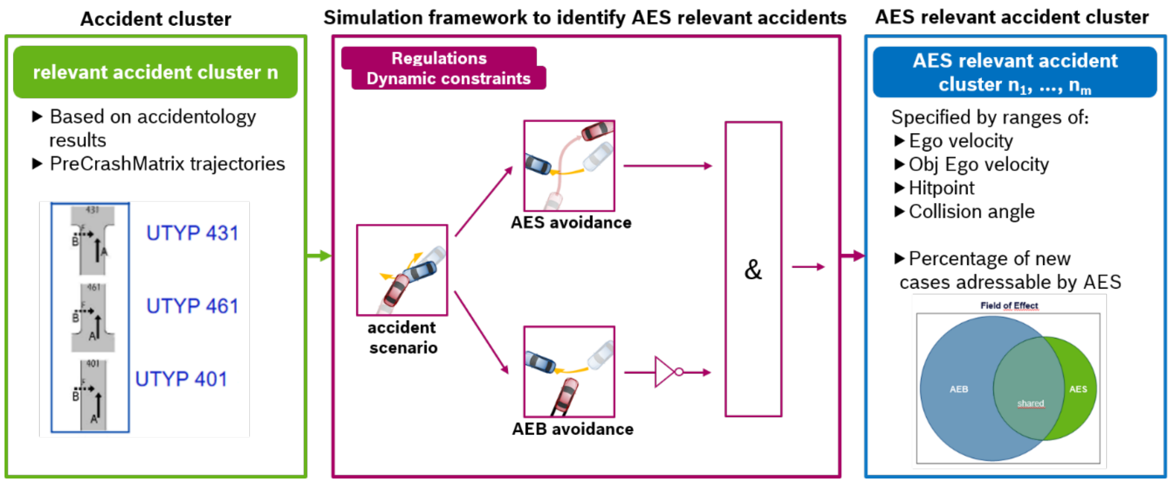

Figure 16 Overview of the simulation process for scenario selection. Clusters derived from crash data are used to simulatively assess the crash avoidance potential of an AES manoeuvre and build clusters of AES relevant traffic situations

To be able to generate useful and realistic simulation results, several assumptions must be made, and these are shown in Figure 17. The most limiting factors for the AES fields of effect are expected to be the available free space, the allowed lateral dynamics, and the trigger time of the system. The AES system under investigation is seen as an SAE Level 2 system (Synopsis, 2021) and needs to fulfil the legal requirements of the UNECE R79 regulation (UNECE, 2018), resulting in the following general simulation assumptions:

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1. In accordance with the UNECE R79 regulation, the AES manoeuvre is limited to evade within the current ego lane only.
2. Based on Bosch controllability studies (Schneider, Schmitz, Ahrens, Löffler, & Neukum, 2018), the lateral dynamic interventions are limited to a maximum lateral acceleration value of 5 m/s^2.
3. Sensor characteristics are considered by a field of view model only, sensor detection or situational uncertainties are not considered.
4. AES manoeuvres are performed by steering only. A combination of AES and AEB is not considered in this initial step.
5. The system trigger time is limited by a Bosch internal approach, which only allows it to trigger if an avoidance manoeuvre by the driver is no longer estimated to be feasible.

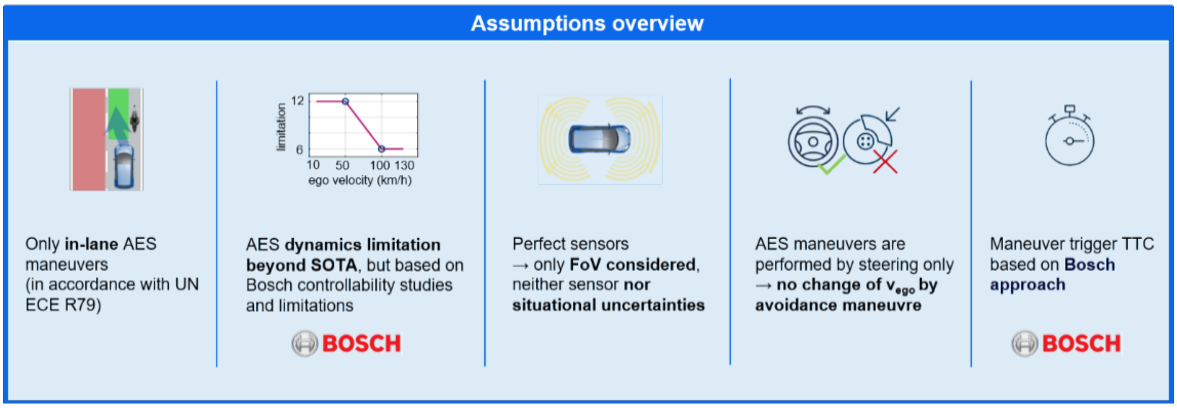

Figure 17 Simulation assumptions for the assessment of the crash avoidance potential of an AES manoeuvre

The initial step of the simulation is the extraction of time resolved ego and VRU trajectories and dynamics as well as lane information from the crash scenario. Based on the trajectories and dynamics, the Time-To-Collision (TTC) and the collision overlap are calculated for each timestamp and then fed into the calculation of the system trigger. At the timestamp where TTC falls below the system trigger threshold AES and AEB manoeuvres are initiated.

For the AEB manoeuvre, a longitudinal acceleration profile is used to calculate the vehicles future motion until stand-still.

For the AES manoeuvre, two trajectories are calculated for every crash scenario: One evading to the left and one to the right. Both trajectories end on the maximum lateral displacement possible (given by the ego lane information) and use the maximum allowed lateral dynamics.

For both manoeuvres, the vehicle dynamics of the component of motion which is not affected by the manoeuvre are assumed to be constant. For an AEB manoeuvre lateral dynamics are calculated with a model of constant acceleration, starting at the time of the system trigger. For the AES manoeuvres longitudinal dynamics are calculated respectively.

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The trajectories and dynamics of the ego manoeuvres are then used to perform collision checks with the pedestrian trajectory to decide if full collision avoidance or frontal collision avoidance can be realized.

For an initial Demo 3 scenario selection, the described method has been applied on a set of Pre-Crash-Matrix (PCM) cases in GIDAS of crossing pedestrians from the far side. The simulation results indicate a potential field-of-effect of ~10% sole AES avoidance potential, meaning cases that can be avoided by AES, but not by AEB. These ~10% of sole AES avoidance potential are the cases of interest for the Demo 3 development, as addressing these cases with novel avoidance functions would have a direct impact on total crash avoidance numbers. A detailed description of the database and the results can be found in the deliverable report D3.3 (Löffler, et al., 2021).

The Demo 3 scenario selection method will be applied on a wider range of relevant scenarios within the scope of the SAFE-UP project to further quantify potential AES relevant cases. Therefore, the generic AES and AEB implementations (as described above) will be incorporated into a holistic simulation toolchain, which will be described in detail in Section 4.3 below.

In a second step, the same method will be used to quantify the safety benefit of the novel Demo 3 crash avoidance functions by replacing the generic function implementations by the developed Demo 3 algorithms.

4.3 Application of simulation for safety benefit assessment

In general, an approach similar to that described in ISO/TR 21934-1:2021 (2021) will be used for the safety performance assessment:

1. Definition of the traffic safety evaluation scope. This has already been done in D5.1 (Mensa, et al., 2021). The relevant research question is re-stated as RQ4 in Section 4.1.

2. Establishment of a baseline. Here, an approach that generates synthetic cases will be used. The cases will be generated either by using the traffic simulation set up in T2.5 or by using an extension of the method described in Eichberger, Zukancic, & Wimmer (2015). In any case, the case generation should consider the information from the scenario selection described in the previous section and the results of D2.6 (Bálint, et al., 2021) describing typical Car to VRU crash scenarios, their frequencies, and parameters.

3. Virtual simulation without and with safety technology. Here, a co-simulation approach will be used for the pre-crash phase. It covers all relevant elements and is similar to the simulation framework architecture described in ISO/TR 21934-1:2021 (2021). The method for determining injury severity will depend on the resulting crash configurations. The simplest approach would be using impact speed-based injury risk curves, the most complex and time consuming would be using detailed finite element (FE) models of car and VRU. This approach is only feasible if a few cases should be considered due to the long calculation

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times of the detailed models. Furthermore, the respective FE models need to be available. A compromise with respect to simulation effort would be splitting up the in-crash simulation into two parts: First, the impact kinematics are determined. Using the resulting impact locations and speeds as inputs, a surrogate model of the actual impact can be used to determine the resulting injury values and injury risk. Obviously, this surrogate model needs to be trained on data obtained from a (limited) set of detailed simulations. This surrogate model can also be viewed as a more complex injury risk function with several input parameters (impact location and velocities) instead of impact speed only. However, also here the availability of the respective FE models is a limitation. A possible solution for the overall simulation framework for the safety performance assessment of VRU protection systems including the three different approaches for in-crash simulation is shown in Figure 18 below.

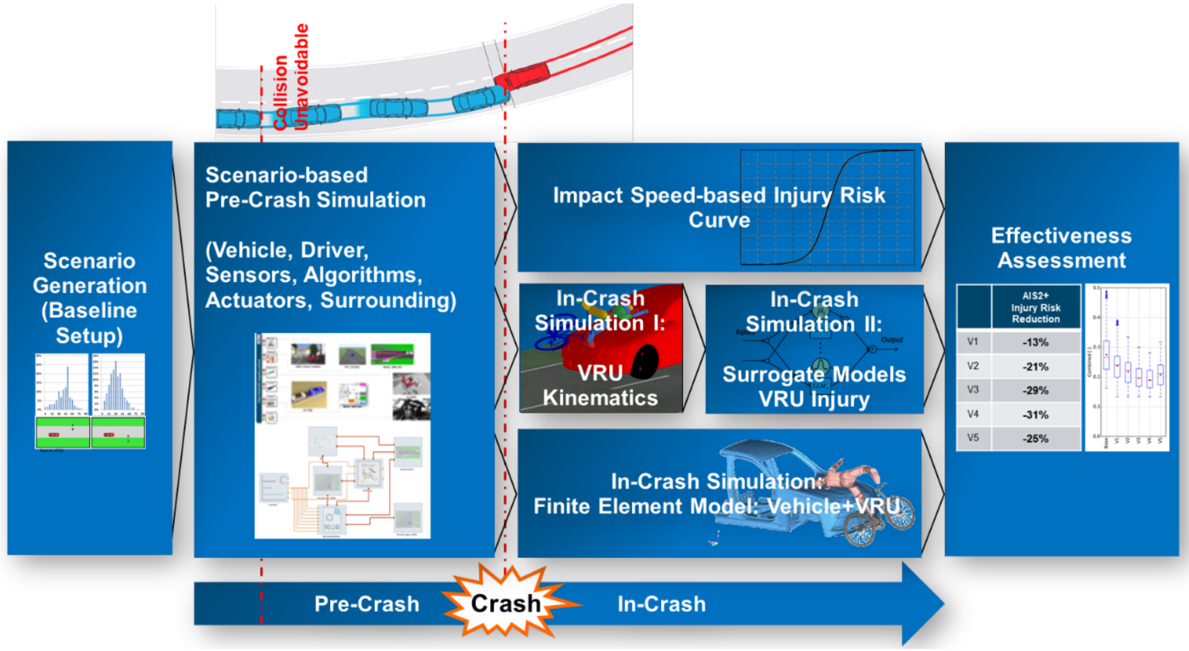

Figure 18 Possible configuration of an overall simulation framework for the safety performance assessment of active and integrated VRU protection systems

Another aspect that must be considered is the fact the AES part of the Demo 3 technology has the capability of changing a frontal collision (VRU is hit by the vehicle front) to a side collision (VRU hits the vehicle at the side). In such cases, the primary impact (VRU on vehicle) is most probably not the critical one, but the secondary impact on the road. For those impacts the methods for determining the injury severity described above are no longer applicable and methods for assessing the secondary impact must be developed. Even here, a first step could be VRU kinematics simulation and the second one an impact simulation but this time on the road, not on the vehicle.

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4. Estimation of the safety performance. Here, the results of the simulations with safety technology are compared to the simulation results without safety technology in terms of avoided crashes and reduction in injury severity.

4.4 Physical testing of Demo 3 vehicle

The Demo 3 vehicle is planned to be assessed in WP5 in the summer of 2022, and detailed planning of the testing will happen in T5.4.1 which starts in November 2021. More information regarding this testing can be found in Section 6.2.

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5. Technologies for Demonstrator 4

In this section, C-ITS-related systems are considered. Section 5.1 describes the different components of the relevant technologies. The development of Demo 4 is described in greater detail in the upcoming deliverable D3.4 (Nikolaou, Castells, Mallada, Gragkopoulos, & Tsetsinas, 2021); what follows here is a brief overview of the demonstrator and those Demo 4 activities that are most relevant for the safety benefit assessment. The parts below may therefore include sentences or paragraphs taken from D3.4, without further indication.

5.1 Overview of Demonstrator 4

Demo 4 focuses on understanding the safety benefit of a communication framework referred to as C-ITS, considering all the possible communication interactions that can take place, such as timely warnings (to both VRU and driver) as well as actuation of safety systems. The primary focus is related to the provision of timely warnings which will support the mitigation of critical situations. Since the approach should be considered on a holistic manner, the engagement of active safety solutions (such as an AEB VRU system) by communication framework will be also analysed.

Generally, Demo 4 is not aiming at delivering a ready to use product, but rather to assess the safety potential of the communication framework. There are several challenges that Demo 4 will not be able to address and that should be part of further work, such as the accuracy of the positioning of VRUs and vehicles, the integration of standard signals from the communication environment to the vehicle, or the assessment of the perception and acceptance of the warning messages by the targeted users. Additionally, tests will be performed in controlled environments, so aspects such as false activations will not be addressed. Those challenges will be defined more concretely in the final deliverable of Demo 4.

5.2 Updated research questions for Demo 4

In the D5.1, two initial research questions for Demo 4 were drafted. However, due to the fact that Demo 4 was launched after the issue of D5.1 those research questions were updated and reported in Section 2 of D3.4, as follows:

RQ5. "What is the safety benefit of a VRU C-ITS warning system on connected VRUs in supporting them to mitigate safety-critical events with passenger cars, triggered by a radio signal based (OBU, VRU-smart device) communication and detection system, in terms of KSI injury reduction on EU level in 2025 compared to the 2016 numbers for Car to VRU collisions on urban roads?"

RQ6. "What is the safety benefit of a VRU C-ITS warning system on vehicle drivers in supporting them to mitigate safety-critical events with connected and

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non-connected VRUs, triggered by a radio signal based (OBU, RSU, VRU-smart device) communication and detection system, in terms of KSI injury reduction on EU level in 2025 compared to the 2016 numbers for Car to VRU collisions on urban roads?"

RQ7. ""What is the safety benefit of a vehicle equipped with an active safety system (e.g., AEB) that is enhanced by a radio signal based (OBU, RSU, VRU-smart device) communication and detection system, in terms of KSI injury reduction in EU urban roads in 2025 compared to the 2016 numbers and the same safety system with SOTA VRU detection system?"

5.3 Scenario selection summary for Demo 4

The scenario selection method for Demo 4 needs to consider both the scope of Demo 4 and the research questions defined in Section 5.2.

From the research questions, two important aspects need to be considered: a need to focus on scenarios which are related to KSI injuries, and that the baseline case is a vehicle with an active safety system (e.g., AEB) with SOTA VRU detection system. It will therefore have to be taken into account which scenarios are aimed to be addressed nowadays by such systems. Three specific inputs were taken into account in this method:

1. The crash data analysis results performed in SAFE-UP, as described in D2.6.
2. The SOTA of active safety system with VRU detection, by considering the Euro NCAP 2020 VRU protocol (Euro NCAP Test protocol AEB VRU, Version 3.0.3), which addresses not only the activation of AEB VRU systems but also the warnings provided to drivers.
3. Considerations of C-ITS technology, identifying situations where communication may demonstrate a safety benefit potential such as the case where there are obstructions that hinder the VRU visibility by a vehicle or pedestrians crossing the street at non-designated locations.

Based on these three inputs, the method to define the scenarios addressed by Demo 4 (D3.4, Section 4) is shown in Figure 19. As a result of this work, a set of four scenarios for car to pedestrian conflicts and three scenarios for car to cyclist conflicts were selected. Several test runs were identified for each, addressing different speed combinations between the passenger car and the VRU.

More details on the scenario selection procedure as well as on the final scenarios for Demo 4 are provided in D3.4 (Nikolaou, Castells, Mallada, Gragkopoulos, & Tsetsinas, 2021).

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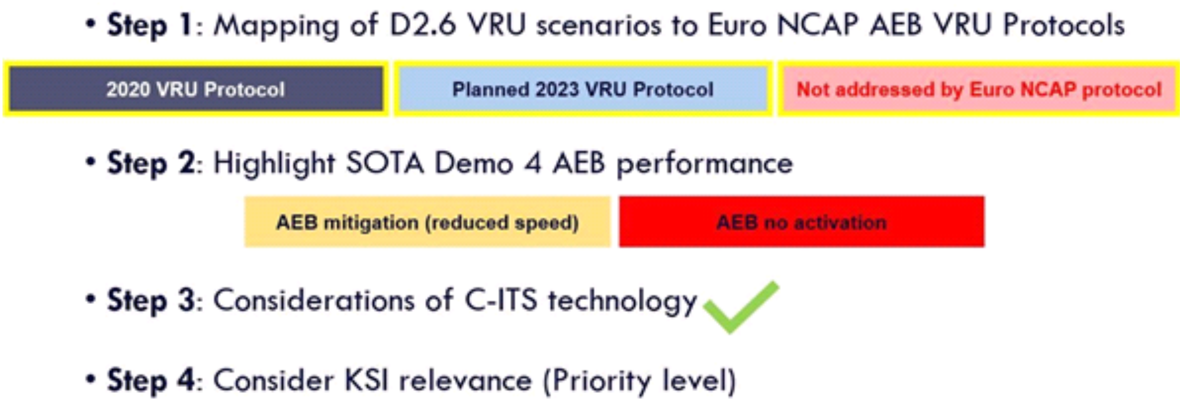

Figure 19 Method to define scenarios addressed by Demo 4 (source: D3.4)

5.4 Physical testing of Demo 4 vehicle

The Demo 4 vehicle by TME is planned to be assessed by WP5 in the summer of 2022, and detailed planning of the testing will happen in T5.4.1 which starts in November 2021. More information regarding this testing can be found in Section 6.2.

5.5 Simulating the delay in message transition

Traffic and connectivity simulations have been performed by CEA in which Line-Of-Sight (LOS) conditions without buildings and obstacles, as well as Non-Line-Of-Sight (NLOS) conditions in which communication is obstructed by other vehicles, obstacles, or buildings, have been considered in the simulations.

Future work will address the impact of network congestion on the performance of vehicle-to-infrastructure (V2X) technologies. More specifically, potential delays in warnings sent to cars in situations with many participants (e.g., many VRUs and/or many vehicles) will be assessed by the simulations so that risk assessment can be performed, and mitigation strategies can be considered.

These simulations will be reported in D3.9: Active safety system specification and risk analysis update. Although this work is not part of the Demo 4 development process, the simulation results regarding the delay together with the frequency of relevant situations (i.e., the simultaneous presence of many road users at sites of car-to-VRU crashes) could possibly allow a quantification of how much the performance of communication-based systems is reduced because of a delay in communication.

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6. Demonstrator-independent aspects

This section highlights elements of the assessment that are not specific to a single demonstrator, i.e., are relevant for multiple or even all demonstrators. This includes methods to extrapolate results from locally collected data to the EU level (with a case study presented in Section 6.1.1 and a corresponding sensitivity analysis described in Section 6.1.2), the description of physical testing at the IDIADA facilities (Section 6.2) as well as the combination of test results and simulation results (Section 6.3).

6.1 Future crash scenario outlook in IGLAD

An unweighted analysis of how the distribution of crash types changes with large fleet penetration of vehicles equipped with currently available active safety systems was presented in D2.6 (Bálint, et al., 2021). The method is based on papers by Östling and co-authors (Östling, Lübbe, Jeppsson, & Puthan, 2019; Östling, Jeppsson, & Lübbe, 2019) of which the first uses the weights provided in the database for the analysis of data from the United States, while the second presents unweighted analysis based on data from the German In-Depth Accident Study (GIDAS) database. Like GIDAS, the IGLAD database (IGLAD, 2021) does not specify weights for each case. Therefore, weighting methods need to be applied to make the results more representative for crashes in the EU rather than crashes in the sampling areas of the databases.

The representativeness of IGLAD data has been investigated by analysing distributions of basic variables in IGLAD (Bakker, et al., 2017). However, for the SAFE-UP project, a more recent and more detailed analysis is necessary; furthermore, in this case, a comparison with specific EU-level statistics based on data from the CARE database (CARE, 2021; CADaS, 2021) will be made, as described in Section 6.1.1 below.

6.1.1 Weighted results

For weighting the results from the IGLAD database to a European level, every case in IGLAD is classified into a specific category, according to the following variables: location of the crash (urban or rural), road surface condition (dry or not dry), relation to a junction (crash happened at a junction or not at a junction) and injury severity of the crash (fatal, severe, slight). All combinations of the variable values will be assigned a weighting factor corresponding to the number of crashes in CARE with the given combination of characteristics, divided by the number of corresponding crashes in IGLAD. To get analysis results that are meant to represent EU traffic, each analysed crash in IGLAD with specific values for these variables will be counted with a multiplication term specified by the weighting factor.

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The following weighting factors for each of the categories have resulted from the analysis of CARE and IGLAD (see Table 4 below):

Table 4. Weighting factors between IGLAD and CARE

Location	Road surface condition	Relation to junction	Injury severity Fatal	Injury severity Serious	Injury severity Slight
Urban	Dry	At junction	26.30	180.93	281.08
		Not at junction	36.56	222.08	466.82
	Not dry	At junction	75.25	179.99	288.32
		Not at junction	48.52	207.88	373.42
Rural	Dry	At junction	14.38	132.92	393.71
		Not at junction	28.83	244.40	579.37
	Not dry	At junction	33.57	209.80	298.22
		Not at junction	29.84	261.80	481.12

Each of the crashes in IGLAD is assigned its corresponding weighting factor. Afterwards, the analyses described in D2.6 (Bálint, et al., 2021) are performed again, this time using the weighted cases and therefore providing a better understanding of the situation in Europe.

Figure 20 shows unweighted results, i.e., the number of cases within the 7 main crash type categories between the baseline and future database. With the systems implemented, crash categories 2 (turning scenarios) and 3 (crossing scenarios) show the largest proportional reduction in the number of crashes by 40.2% and 36.2% respectively, while category 4 (crossing pedestrians) shows the lowest reduction with 19.4%. The difference between these results and the earlier unweighted results is that the analysis included in D2.6 (Bálint, et al., 2021) included the crash type distribution of all crashes in IGLAD while the current unweighted results in Figure 20 include the crash type distribution for car-involved crashes only. The motivation for this change is to highlight sharper contrasts between the current crash situation and the one including widespread fleet penetration of car-based safety systems.

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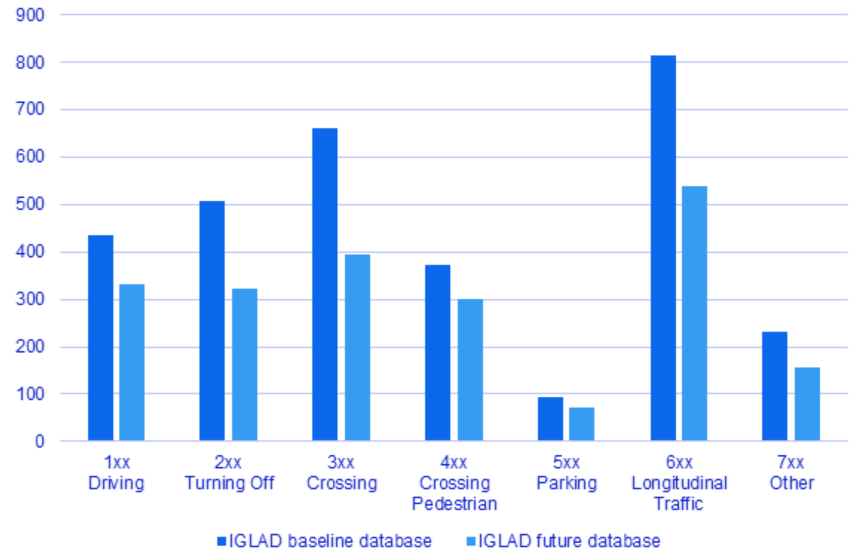

Figure 20. Crash distributions for the main crash type categories based on IGLAD

In comparison, Figure 21 shows the distribution within the main crash type categories for the weighted data. While crashes in longitudinal traffic (category 6xx) have a higher share on the European level compared to what is seen in the IGLAD data (30.0% compared to 26.1%), the percentage of those crashes that are avoided by the applied systems also has increased (41.6% instead of 33.6%). Overall, the systems show a reduction of crashes of 37.8% on a European level (in comparison to 31.9% when only considering IGLAD data). Pedestrian crossing scenarios (4xx) remain cases with the lowest percentage of avoided crashes, increasing their share in the overall crash distribution from 11.0% to 13.3%.

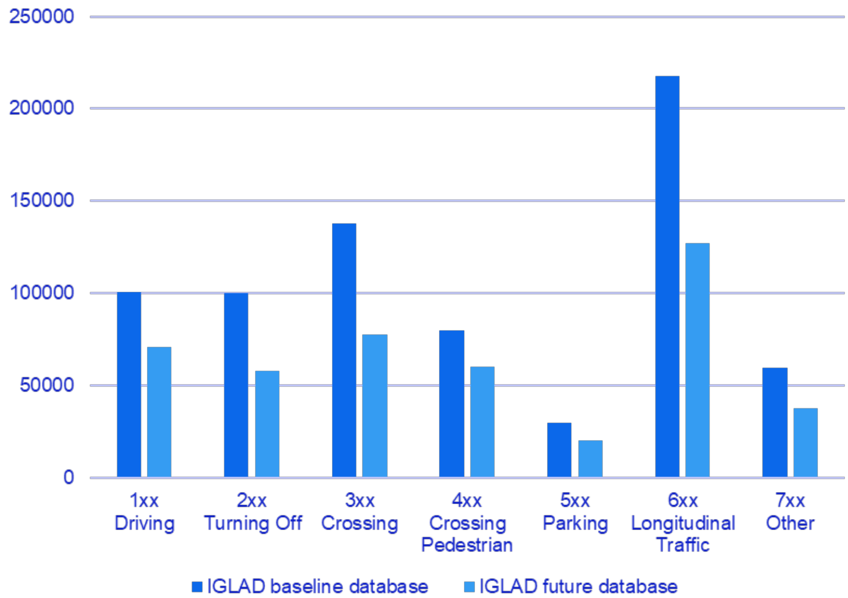

Figure 21. Crash distributions for the main crash type categories based on weighted IGLAD data

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Table 5 shows a more detailed overview over the main crash categories for IGLAD based data and Table 6 shows the same overview for the weighted IGLAD data.

Table 5. Overview of different crash types and the expected changes in the crash type distribution based on an analysis of IGLAD data

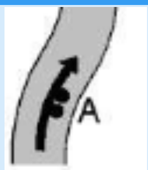
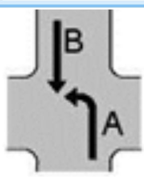
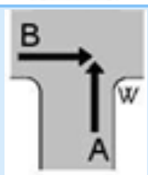
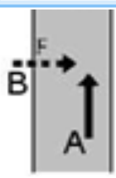
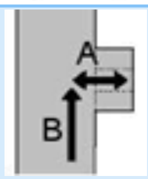
Main crash type	Illustration	Number of crashes in IGLAD sample	Share among crashes	Reduction	Share among future crashes	Change in share
1: Driving		434	14.0 %	23.7 %	15.6 %	+1.6
2: Turning Off		506	16.3 %	36.2 %	15.3 %	-1.0
3: Crossing		660	21.2 %	40.2 %	18.6 %	-2.6
4: Crossing Pedestrian		371	12.0 %	19.1 %	14.2 %	+2.2
5: Parking		94	3.0 %	23.4 %	3.4 %	+0.4
6: Longitudinal Traffic		813	26.1 %	33.6 %	25.5 %	-0.6
7: Other crash type	N/A	232	7.5 %	32.3 %	7.4 %	-0.1
SUM	N/A	3 110	100 %	31.9 %	100 %	N/A

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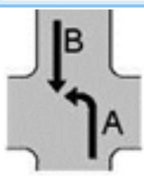
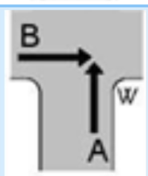
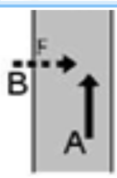
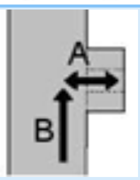
Table 6. Overview of different crash types and the expected changes in the crash type distribution based on an analysis of weighted IGLAD data

Main crash type	Illustration	Number of crashes in weighted IGLAD sample	Share among crashes	Reduction	Share among future crashes	Change in share
1: Driving		100 550	13.9 %	29.8 %	15.6 %	+1.7
2: Turning Off		100 060	13.8 %	42.1 %	12.9 %	-0.9
3: Crossing		137 511	19.0 %	43.7 %	17.2 %	-1.8
4: Crossing Pedestrian		79 653	11.0 %	24.9 %	13.3 %	+2.3
5: Parking		29 583	4.1 %	31.2 %	4.5 %	+0.4
6: Longitudinal Traffic		217 592	30.0 %	41.6 %	28.2 %	-1.8
7: Other crash type	N/A	59 743	8.2 %	36.9 %	8.4 %	+0.2
SUM	N/A	724 692	100 %	37.8 %	100 %	N/A

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The differences between the unweighted and weighted results show the importance of the weighting. While the general trends are similar (e.g., longitudinal scenarios having the highest share), the actual values differ quite substantially. Only using IGLAD data would underestimate the performance of the active safety systems by 5.9% on a European level.

6.1.2 Sensitivity analysis

Table 4 shows that weighting factors in Section 6.1 were defined for all combinations of location (urban/rural), junction (at junction/not at junction), road surface (dry/not dry), and crash severity (fatal, serious, slight) and each crash with a specific combination of these variables was included with the corresponding weight in the analysis. Such weighting methods can be called *hypercube weighting*, considering that the cross-tables prescribing all combinations of the variables could be visualized as a hypercube. How would the results change if more, alternatively less, variables were added or some variables were replaced by others? More specifically, how would a change in the weighting method affect the overall reduction of future crashes compared to the original set, how would it affect the order of crash types by their estimated future frequency, and what would be the largest change between the current and the future relative frequency of a crash type?

The above questions are addressed in the sensitivity analysis conducted in T5.3, exploring the sensitivity of results to the specification of the weighting method, e.g., the variable selection for hypercube weighting. Which variable combinations can be considered are mainly determined by limitations in data availability in the in-depth data (too few cases for unusual variable combinations) and data quality in the regional data (unreliable variable values or too many unknowns for detailed variables such as crash type), as described in PROSPECT D2.3 (Kovaceva, et al., 2018) and OSCCAR D1.1 (Dobberstein, Lich, & Schmidt, 2019).

Apart from hypercube weighting with different variable combinations, tree-based methods (Kreiss, et al., 2015; Kreiss, Feng, Krampe, Meyer, & Niebuhr, 2015; Flannagan, et al., 2015), as well as specific weighting methods from previous projects such as PROSPECT (Kovaceva, et al., 2018) are also planned to be included in the sensitivity analysis. In cases where the marginal probability distributions of certain variables are available, but the weighting method requires the specification of the joint distribution of these variables, the iterative proportional fitting method (Niebuhr, Kreiss, & Achmus, 2013) may be used to estimate the joint distribution.

Finally, one way to check the quality of a weighting method is to select a variable V that is not used in the definition of the weighting method and compare the distribution of V within IGLAD and CARE, before and after the weighting. The purpose of weighting methods is to bring the distribution of crashes in the in-depth data closer to the regional crash population, so that analysis results of the in-depth data will give a better representation of the crashes in the larger region. Therefore, if the distributions of V in IGLAD and CARE are closer to each other after the weighting than they were before, that is a sign of the weighting method

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working well. Such quality checks will be conducted for the weighting methods considered for the sensitivity analysis, and the results will indicate which methods work best.

6.2 Physical testing of demonstrator vehicles

The physical testing of Demo 3 and Demo 4 will be undertaken at IDIADA's proving ground, specifically in the ADAS & CAV test track. An image of a selected part of the ADAS & CAV test track which represents an intersection can be seen in the following image (Figure 22).

Figure 22 Intersection part of ADAS & CAV test track

As stated in Section 4.2, currently the preliminary selected scenarios for Demo 3 are based around a car-to-pedestrian conflict situation where the pedestrian is crossing from the far-side. Considering a Left-Hand Drive (LHD) vehicle with the steering wheel on the left side that drives on the right side of the road, crossing from the far side means that the pedestrian will come from the left side of the road. More detailed information regarding Demo 3 and the corresponding scenario selection can be found in D3.3 (Löffler, et al., 2021).

On the other hand, Demo 4 scenarios are considering car-to-pedestrian and car-to-cyclist conflicts in obstructed and blind spot situations where the VRUs are approaching the vehicle from the near and far sides. This intermediate validation demonstration will consider a single scenario, named Demo_4_02, representing a VRU crossing from the near side with a vehicle obstructing the visibility within a non-designated crossing. For more detailed information regarding Demo 4 and the corresponding scenarios, see D3.4 (Nikolaou, Castells, Mallada, Gragkopoulos, & Tsetsinas, 2021). Both Demo 3 and Demo 4 scenarios will be further discussed in T5.4.1.

The equipment required for the physical testing of the selected scenarios is as follows:

- Proving ground. The CAV test track complies with all Euro NCAP requirements (dimensions, adherence, lane markings) and has all the necessary elements so that data and results can be reliable. The test track is divided into sections where different tests are undertaken. The main test are scenarios between two cars, car-to-car or Lane Keeping Assist (LKA) scenarios. Tests with pedestrians and cyclists are evaluated as well (e.g., VRU crossing, AEB tests).

- Euro NCAP pedestrian target. The official test targets defined by Euro NCAP for AEB tests will be used. They represent a 50th-percentile adult male pedestrian and a 6-year-old child pedestrian. The targets have been validated with several vehicles and are compatible with RADAR, LiDAR, and camera-based systems.
- Euro NCAP cyclist target. The test target which represents an adult cyclist will be used according to the test scenarios selected. The target is articulated, and it is compatible and detectable by RADAR, LiDAR, and camera-based systems.

Figure 23 AEB VRU test examples

- Positioning systems and inertial sensing system. To have relative positions and speeds between the test vehicle and the target with high accuracy, there is a need to install global positioning systems in both elements, with relative measurements. In this case, a differential GPS system with a multi-axis inertial system from OXTS (the RT 3002) will be used, combined with a Wi-Fi connection (the RT Range).
- Real-time image and sound. Real-time synchronised cameras and microphones will be used to get a time-synchronised representation of the warning signal. This equipment will be installed on-board of the subject vehicle to get a time reference of the warning events.
- Data logger. A data logger will be used for recording all the test data. The GPS time signal will be used as a synchronisation signal for all records, including data, video, and audio.

For system validation for Demo 4 in T3.5, the dummies used will be the ones available in IDIADA facilities. For the final testing in WP5 in T5.4.1, new dummies will be brought as defined in the grant agreement of SAFE-UP.

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The tests scenarios for T5.4 will be decided and defined in T5.4.1 which starts in November 2021. The scenarios selected will consider the requirements described in D5.1 (Mensa, et al., 2021) as inputs. The results of the physical tests will be used in WP5 as an input for impact assessment of active safety systems. Section 6.3 describes the general method for combining simulation results with physical test results.

6.3 Combination of simulation results and test results

As indicated in the Introduction, an essential element of the framework proposed in D5.1 is the combination of results from virtual simulations and physical tests. It is also motivated in D5.1 (Mensa, et al., 2021) that the method developed in the PROSPECT project based on Bayesian statistical methods is appropriate for this purpose. The details of the underlying mathematical models need to be specified, and it is likely that different modelling will be necessary for the Demo 1 technologies where in-crash occupant protection is analysed, and Demos 2-4 addressing both crash avoidance and the mitigation of crash severity. The latter setup is analogous to the PROSPECT setting where separate models were developed to address the crash avoidance and the crash mitigation aspects (Kovaceva, et al., 2018; Kovaceva, Bálint, Schindler, & Schneider, 2020).

Bayesian approaches require the specification of priors representing our state-of-knowledge before conducting an experiment, and it has been shown that such priors for the probability of crash avoidance can be defined based on the analysis of simulation results. The experiment in this setting is the physical testing, and the corresponding results are new data that are used to update our prior knowledge and obtain a posterior parameter distribution representing combined knowledge gained from simulation results and testing.

The computation of the posterior distribution may generally require an application of Markov Chain Monte Carlo (MCMC) methods, see Hoff (2009). However, under appropriate assumptions on priors and sampling models, a substantial simplification can be made. Specifically, modelling priors by Beta distributions ensures that the posteriors will belong to the same family of distributions; moreover, the posteriors can be computed directly after an adjustment of the distribution parameters. Having such a simplification gives substantial computational benefits and simplifies the interpretation of the statistical model. Therefore, it will be investigated whether Beta distributions (or other probability distributions with similar properties, called conjugate distributions) can be used for the modelling the relevant quantities (e.g., the probability of crash avoidance) for the SAFE-UP demonstrators.

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7. Conclusions and outlook

As described in the previous sections, the overall safety benefit assessment method has not changed compared to the preliminary framework specified in D5.1, but progress has been made regarding understanding and planning of the analysis for the elements of the framework. Further work in T5.3 will follow the path described in this report, performing the planned simulation activities, physical testing, and analysis of results. This work will culminate in reporting the final safety benefit assessment methodology, and final results regarding specific questions addressed in T5.3 (e.g., regarding the sensitivity analysis with respect to the extrapolation method from local data to the EU level) in D5.8.

Furthermore, there are several points detailed below that need to be considered when finalizing the assessment:

- Inclusion of future crash distribution in the assessment. Analyses described for the demonstrator technologies provide effectiveness within a scenario or a set of scenarios, hence the relative frequency of the scenario gives a weighting factor to the corresponding results. Future crash type distributions are investigated in T2.5 based on traffic simulations as well as in the case study for weighting methods described in Section 6. It is likely that the results will not be in complete agreement but will rather provide a range of potential changes in the crash distribution. This suggests that a range should be given as the safety benefit (e.g., regarding the number of saved lives) rather than a single value.
- Assumptions regarding the results from WP6 (training activities and knowledge translation). The effect of WP6 activities on the overall safety benefit of demonstrator technologies depends on several factors, e.g., from the scale, scope, and acceptance of training activities to their assumed effectiveness. A complete analysis of the effects is too complex and is out of the scope of this project, hence the inclusion of these aspects will primarily need to be based on assumptions. The precise form of these assumptions, to be described in D5.8, is yet to be determined, depending also on further developments in WP6.
- Uncertainty of crash data. Results in D2.6 regarding EU level statistics are based on an analysis of the CARE database that contains police-reported data from every crash with personal injury. Therefore, one can choose to use the results as they are assuming that the analysis results accurately represent the population of road crashes in the EU. On the other hand, as described in D2.6 and elsewhere (e.g., Kovaceva et al. (2018); Dobberstein, Lich, & Schmidt (2019)), there are indications of inconsistencies between countries in the level of reporting. Additionally, estimates have been provided in the PROSPECT project (Kovaceva, et al., 2018) regarding the rate of road crashes that are not reported by the police.

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It should therefore be considered whether it is necessary and feasible to include correction factors for underreporting of crashes in the assessment. Such underreporting would not affect the relative benefit (e.g., the percentage reduction of fatalities) within a scenario, but it would affect the absolute number of lives saved and injuries avoided. Additionally, if the distribution of scenarios changes in the future, having different underreporting rates for different scenarios could theoretically affect the overall relative reductions as well.

- Injury risk functions. For each analysis considering injuries of different severities, it is important to use an appropriate injury risk function that describes the risk of injury of a given severity (e.g., as specified in the research questions) for various values of a crash severity parameter (e.g., collision speed of the car). It is a major difficulty to find or construct a function that provides a sufficiently accurate representation of injury risk which may depend on the crash configuration, the age and gender of the victim of the crash, as well as several other factors. An additional challenge is to understand injury risk in those cases when an active safety system changes the trajectory of a crash-involved vehicle, resulting e.g., in a situation when a pedestrian (whose trajectory is assumed to be unchanged) bumps into the side of the car instead of being hit by the front of the car (as it happened in the original crash without the safety system). Injury risk functions may be found in the research literature (see e.g., the injury risk functions for pedestrians and cyclists specified in Kovaceva et al. (2018) or the risk curves in Craig et al. (2020) for car occupants) or can possibly be constructed by HBM simulation or crash data analysis if necessary.
- Future operational conditions (such as traffic infrastructure and market penetration of safety systems). The regulatory environment and the roadmap of consumer organizations (e.g., Euro NCAP) are factors beyond the control of the project that can strongly affect the ultimate EU level of safety benefit of the systems considered in the project, via accelerating the market penetration of safety systems. The research questions for the demonstrator technologies prescribe the analysis of safety benefit for specific values of the market penetration parameter, based on conservative, ambitious and optimistic scenarios defined in the grant agreement of SAFE-UP. Another way to approach the analysis would be to study which values of this parameter are necessary to achieve a desired/prescribed level of the overall safety benefit (e.g., a 10% reduction compared to the number of fatalities and seriously injured in 2016). Similar considerations apply to future changes in the traffic infrastructure and specifically for the assumed frequency of roadside units equipped with C-ITS technology.

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- Dependence of results for the different safety systems. It is easy to see that the safety benefit estimates for the different Demos could depend on each other. Informally, the same crash cannot be avoided twice, therefore, if the effect of different systems (e.g., all-weather AEB+S and a roadside unit-based C-ITS system) is overlapping, then the effects of systems cannot simply be summed to get the overall effect. Answering the research questions separately does not require the consideration of this effect and it could possibly prove to be an overly complex task to fully analyse the dependence within the timeframe of SAFE-UP – nevertheless, it is at least a relevant discussion point and possible limitation of the analysis that needs to be considered and described in the final report on the safety benefit assessment method (D5.8).

Considering that the safety benefit assessment is addressing systems that are still in a concept phase in a future traffic environment, it is unavoidable that the final results of the assessment will be based on a number of assumptions, e.g., concerning the above bullets. Nevertheless, it is the task of WP5 to choose reasonable forms of these assumptions to ensure that the results are as accurate as possible, clearly describe all assumptions made for the analysis, and indicate directions of future studies that could further improve the accuracy of the benefit assessment.

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