D5.6 Overall SAFE-UP impact

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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 the final report of the work performed in SAFE-UP T5.4 of WP5: "Safety assessment methodologies", applies the methods and approaches described in D5.8 (Kovaceva et al., 2023) and presents the results to estimate the overall safety impact of the demonstrators. The aim of 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.

A general framework for assessing the safety benefit of the SAFE-UP safety technologies was proposed in D5.1 (Mensa et al., 2021), that is 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.) (*P.E.A.R.S.* [no date]) initiative and combining the results of these simulations with results from physical testing in a Bayesian statistical approach developed in the EU project PROSPECT. The work in T5.3 and T5.4 has followed the structure of the framework described in D5.1 (Mensa et al., 2021) and has been directed towards specifying how this structure may be applied to the four SAFE-UP demonstrators. The final structure of the individual assessment framework for each demonstrator can be found in D5.8 (Kovaceva et al., 2023).

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 are implemented in SAFE-UP Demonstrator 1 (abbreviated as **Demo 1**). The occupant protection is 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 is 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.

Additionally, a main goal of SAFE-UP is to address the protection of Vulnerable Road Users (VRUs), primarily pedestrians and bicyclists, also in adverse weather conditions that could 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. The weather filter filters perception inputs of good (nominal) weather conditions into degraded inputs, representing a specified weather. 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. However, results of the individual assessment of Demo 2 showed negligible safety benefits, such this demonstrator was not further included in the overall assessment.

The third SAFE-UP demonstrator (**Demo 3**) includes an Autonomous Emergency Braking and Steering system (AEB+S). 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). 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 was 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 be covered by physical testing.

The fourth SAFE-UP demonstrator (**Demo 4**) focuses on understanding the safety benefit potential of Cooperative Intelligent Transport Systems (C-ITS). Various 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 (Bálint, Labenski, et al., 2021) 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 addresses the identified scenarios. Additionally, traffic and connectivity simulations assess delays in warnings sent to cars in situations with many participants.

Applying the assessment frameworks developed individually for each demonstrator (D5.8 (Kovacheva et al., 2023)) led to the assessment results in D5.3 (Parera et al., 2023) (Demos 2, 3 and 4) and D5.4 (Mensa et al., 2023) (Demo 1). Within this deliverable the results are combined to compute the effectiveness not only with respect to the scenarios in which the technologies are being assessed, but also with respect to the larger categories of accident type (e.g., car-to-pedestrian crashes) or with respect to all fatalities or killed or severely injured in road traffic within the EU. It was found that, when adding an in-lane evasion functionality to a generic AEB and V2X communication to increase the vehicles sensing capabilites, an additional 8% to 16% of killed or severely injured pedestrians or cyclists can be avoided in scenarios where the VRU crosses the street, and 5 to 16% of the fatalities for cyclist crossing scenarios, even though the AEB is already very effective and avoids the majority of cases. Furthermore, it was shown that using the improved restraint systems developed in SAFE-UP and including an AEB in reclined sitting positions does not increase the injury risk in comparison to state-of-the-art restraint systems without AEB, thus allowing passengers to assume the reclined sitting position.

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List of abbreviations

Abbreviation	Meaning
AV	Autonomous Vehicle
AD	Autonomous Driving
B-CLwSO	Bicyclist crossing from left with sight obstruction
B-CLwoSO	Bicyclist crossing from left without sight obstruction
B-CRwSO	Bicyclist crossing from right with sight obstruction
B-CRwoSO	Bicyclist crossing from right without sight obstruction
B-TurnL-SD	Bicyclist at turn left, same direction
C2P	Car-to-Pedestrian
C2B	Car-to-Bicyclist
CA	Consortium Agreement
CAV	Connected Automated Vehicles
D	Deliverable
EC	European Commission
GA	Grant Agreement
KSI	Killed or severely injured
MaaS	Mobility as a Service
OEM	Original Equipment Manufacturer
P-CLwSO	Pedestrian crossing from left with sight obstruction
P-CLwoSO	Pedestrian crossing from left without sight obstruction
P-CRwSO	Pedestrian crossing from right with sight obstruction
P-CRwoSO	Pedestrian crossing from right without sight obstruction
P-TurnL-SD	Pedestrian at turn left, same direction
PM	Person Month
R&D	Research and Development
SC	Steering Committee
SotA	State of the Art
TTC	Time-to-Collision
T	Task

VRU	Vulnerable Road User
WP	Work Package

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1. Introduction

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). D5.2 (Bálint, Schindler, et al., 2021) has been published describing the initial work of the task and the initial methodology, while D5.8 (Kovaceva et al., 2023) is describing the final methodology for the safety benefit assessment.

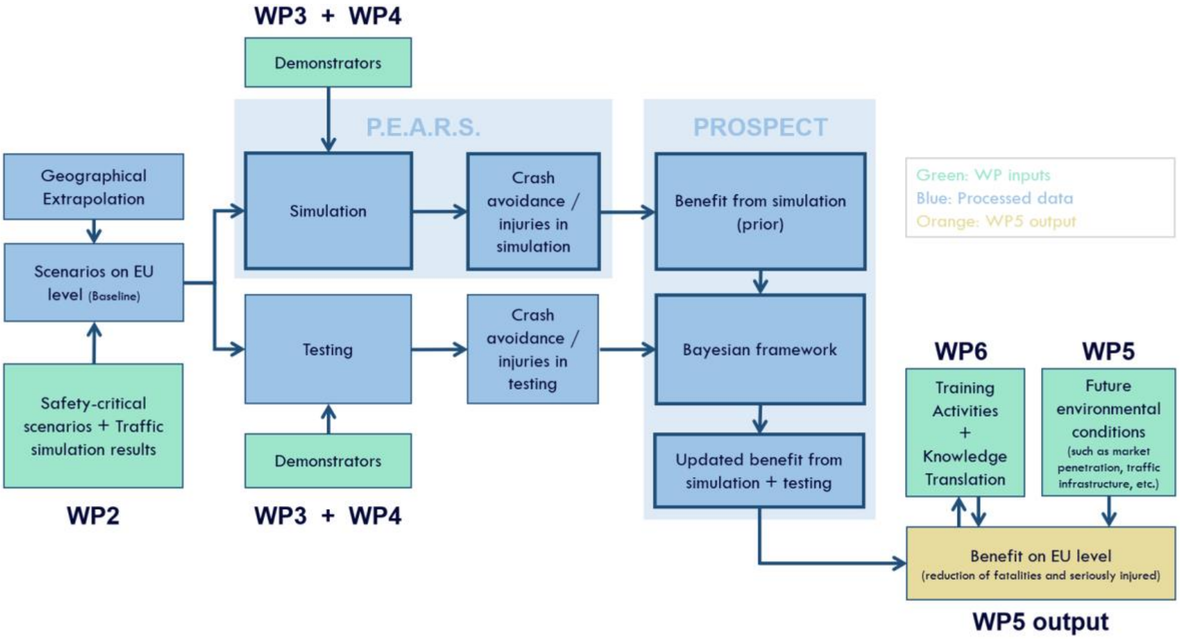

Figure 1: The safety impact assessment framework for SAFE-UP as defined in D5.1 (Mensa et al., 2021).

The task T5.4 is sub-divided in three subtasks, two for the active and passive safety systems (T5.4.1 and T5.4.2, respectively) and another one for the overall assessment (T5.4.3). The implementation of the method presented in D5.8 (Kovaceva et al., 2023), i.e., the results generated in sub-tasks T5.4.1 and T5.4.2, are reported in Deliverables D5.3 (Parera et al., 2023) and D5.4 (Mensa et al., 2023), respectively. The present deliverable 5.6 brings together the results of those two deliverables by presenting a methodology to calculate the mutual benefit introduced by the developed technologies.

The main aim of this deliverable is to demonstrate the combined benefit of the developed SAFE-UP technologies in terms of reduction of KSI injuries and fatalities on EU level.

The safety benefit of Demo 2 is negligible, see D5.3 (Parera et al., 2023). Therefore Demo 2 is omitted from the overall assessment and any of the discussions in this document.

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1.1 The overall assessment

Within this deliverable, the following technologies are assessed regarding their safety benefit for road traffic in terms of their potential to reduce KSI number:

- Demo 1 involves investigating an adaptive restraint system to enhance occupant protection for occupants in new seating positions, such as reclined seatback.
- Demo 3 involves a combined AEB+S system, which can employ emergency braking and steering manoeuvres sequentially to avoid collisions with pedestrians and cyclists.
- Demo 4 focuses on evaluating the potential safety benefits of Cooperative Intelligent Transport Systems (C-ITS) with the primary focus on timely warnings to avoid emergency situations.

The framework depicted in Figure 1 is applied individually to each technology to calculate its safety benefit. The specifics of the implementation of this framework are described in D5.8 (Kovaceva et al., 2023) This deliverable combines the results of the individual assessments to estimate the total numbers of reductions of KSI in road traffic in the EU. This process is termed the “overall assessment”.

1.2 The overlap problem

The framework shown in Figure 1 involves the definition of relevant scenarios, in which the safety performance is being assessed. The analysis which scenarios can be considered the most relevant ones, based on the highest frequency of crashes of a specific accident type, is provided in D2.6 (Bálint, Labenski, et al., 2021). Table 1 summarizes which technology is assessed in which scenario. In this table, Demo 1 is omitted, since the scenarios in which it is assessed (Car-to-Car crashes), are different from the scenarios for Demo 3 and Demo 4 (Car-to-Pedestrian (C2P) or Car-to-Cyclist (C2B)).

Table 1: List of scenarios and whether they are relevant for the assessment of a specific technology, and whether more than one technology is assessed in a specific scenario (overlap).

Scenario name	VRU type	Relevant for Demo 3	Relevant for Demo 4	Overlap of scenarios
P-CLwSO	Pedestrian	Yes	Yes	Yes
P-CRwSO		Yes	Yes	Yes
P-CLwoSO		Yes	No	No
P-CRwoSO		Yes	No	No
P-TurnL-SD		No	Yes	No
B-CLwSO	Cyclist	Yes	Yes	Yes
B-CRwSO		Yes	Yes	Yes
B-CLwoSO		Yes	Yes	Yes
B-CRwoSO		Yes	Yes	Yes
B-TurnL-SD		No	Yes	Yes

As can be seen from Table 1, there are several scenarios which are relevant for the assessment of more than one technology. This report refers to this situation, i.e., more than one technology being assessed in a given scenario, as “overlap” in that scenario.

On the one side, if no overlap is present, this means that only one technology will contribute to a specific type of scenario. Crashes of this scenario type can be avoided by no other technology included in the assessment. On the other side, P-CLwSO, for example, is relevant to both Demo 3 and 4. Either technology may contribute to the avoidance of crashes in the P-CLwSO scenario category: Demo 3 may intervene through evasive steering, possibly providing a benefit in cases with late detection due to sight obstructions, while Demo 4 provides a benefit due to earlier detection based on information from C-ITS. Since several assumptions for market penetration rate of the investigated technologies should be used, including 100% (optimistic), the case that both technologies are present and contribute at the same scenario needs to be investigated. The task to combine results for the effectiveness is termed the “overlap problem”.

Due to technical reasons, different baseline approaches for the simulations were used (approach C2 for Demo 3 and approach B for Demo 4), see D5.8 (Kovaceva et al., 2023). Furthermore, this also means that both technologies had to be simulated in separate simulations. Therefore, a case-by-case analysis to solve the overlap problem is not possible, indicating that an approach is needed which combines the results for the effectiveness of the individual technologies on a higher level of abstraction.

1.3 Scope

The overall assessment is limited by the following facts:

- Evasive manoeuvres might convert a frontal crash to a side crash. Possible changes in injury severity, either decreases or increases, were out of the scope of the methods developed within SAFE-UP.
- The safety benefit of Demo 2 was not included in the overall assessment since the benefit was considered to be negligible due to preliminary results.
- A case-by-case analysis on whether both Demo 3 and 4, only one of both, or none contributed to an accident avoidance, was not possible, since different baseline approaches had to be used.
- All weighting factors that describe the share of a specific crash type within a larger group (e.g., share of fatalities in urban C2B scenarios in the total road traffic fatalities) are computed using all available data, including data from recent years.
- Absolute numbers for crashes are taken from the year 2016.
- All calculations are done with numbers on EU level, if possible.

2. Method

To describe the method to conduct the overall assessment in mathematical terms, the following symbols and notations are introduced:

- $N_{avoided,x}^{y,fatal}$, $N_{avoided,x}^{y,KSI}$: number of avoided fatalities or KSI cases of scenario type "x", avoided by technology "y", on EU-level
- N_x^{fatal}, N_x^{KSI}: number of fatalities or KSI cases of scenario type "x", on EU-level
- $p_x^{y,fatal}, p_x^{y,KSI}$: percentage of fatalities or KSI cases of scenario type "x", avoided by technology "y", in the total number of fatalities or KSI cases of scenario type "x", i.e., $p_x^{y,fatal} = N_{avoided,x}^{y,fatal}/N_x^{fatal}$. Can be interpreted as the probability that for scenario "x", technology "y" avoids any given fatality or KSI case, e.g., $p_{P-CLwSO}^{Demo3,fatal}$.
- p_x^{fatal}, p_x^{KSI}: the probability that for scenario "x", a fatality or KSI case is avoided by any of the SAFE-UP technologies, on EU-level, e.g., $p_{P-CLwSO}^{fatal}$.
- $N_{avoided,x}^{fatal}$, $N_{avoided,x}^{KSI}$: number of avoided fatalities or KSI cases of scenario type "x", avoided by any of the SAFE-UP technologies, on EU-level

The following symbols and notations are introduced on crash-participant level or EU level:

- p_z^{fatal}, p_z^{KSI}: the probability that a fatality or KSI case in a scenario with the crash-participant type "z" is avoided by any of the technologies, on EU-level, e.g., p_{C2P}^{fatal}. "z" can be any of C2P, C2B or C2C.
- N_z^{fatal}, N_z^{KSI}: total number of fatalities or KSI cases with crash-participants type "z".
- $N_{z,avoided}^{fatal}$, $N_{z,avoided}^{KSI}$: number of avoided fatalities or KSI cases of within the group "z", avoided by any of the SAFE-UP technologies, on EU-level. "z" can be any of C2P, C2B or C2C.
- p^{fatal}, p^{KSI}: the probability that a fatality or KSI case within the EU in road traffic accidents is avoided by any of the SAFE-UP technologies
- N_{tot}^{fatal}, N_{tot}^{KSI}: total number of fatalities or KSI cases within the EU in road traffic accidents
- $N_{tot,avoided}^{fatal}$, $N_{tot,avoided}^{KSI}$: number of fatalities or KSI cases avoided by any of the SAFE-UP technologies, on EU-level.

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2.1 Hierarchical assessment approach

The assessment procedure can be described as a hierarchical process, which is separated into several levels, shown also in Figure 2:

- Case-by-case level: most detailed level of the assessment. This is the level where the baseline-to-treatment comparison is done, comparing the results of the same concrete scenario with the investigated system and without the system. This level of assessment evaluates each technology individually, and for each scenario in which it is relevant. The process on this level is depicted by Figure 1. The outputs are the fatality and KSI avoidance rates $p_x^{y,fatal}$ and $p_x^{y,KSI}$ for each technology under investigation "y" in scenario "x", as well as the number of avoided cases $N_{avoided,x}^{y,fatal}$ and $N_{avoided,x}^{y,KSI}$. The results for this level of the assessment can be found in D5.3 (Parera et al., 2023).
- Scenario level: on this level, the outputs of the assessment on case-by-case level, separated by technology and scenario, are combined to calculate the combined safety benefit of all technologies for each scenario. The outputs are the KSI and fatality avoidance rates p_x^{fatal}, p_x^{KSI} for each scenario "x".
- Crash-participants level: on this level, the outputs of the assessment on scenario level are combined to calculate the benefits for specific groups of crash-participants, i.e., Car-to-Pedestrian (C2P), Car-to-Bicyclist (C2B) or Car-to-Car (C2C) to form the fatality and KSI avoidance rates p_{C2B}^{fatal}, p_{C2P}^{fatal}, p_{C2C}^{fatal}, p_{C2B}^{KSI}, p_{C2P}^{KSI}, and p_{C2C}^{KSI}.
- EU level: Finally, on the coarsest level, the safety benefit of the developed technologies is put into an EU-wide perspective by computing the share of the avoided fatalities and KSI cases in the number of all road traffic fatalities or KSI cases in the EU.

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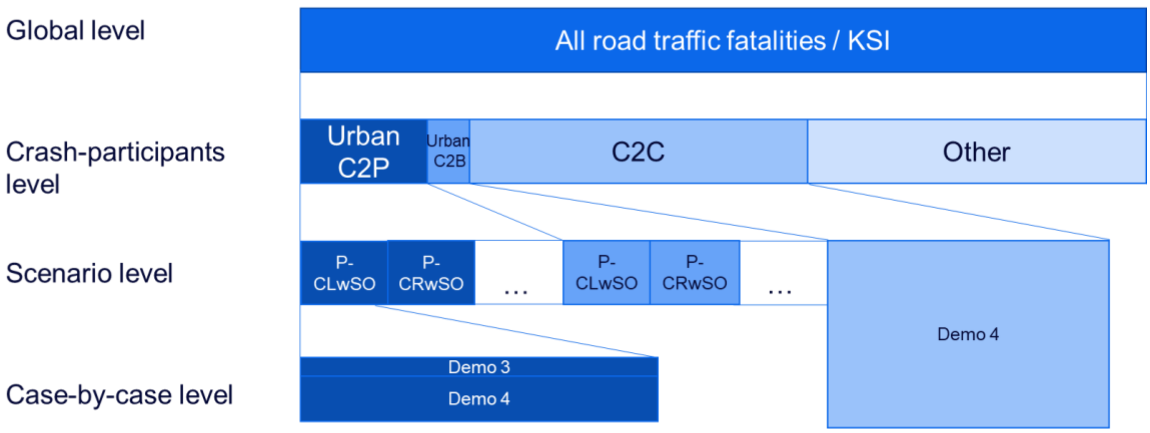

Figure 2: Relations between the individual levels of the assessment

2.2 Assessment on scenario level

To solve the overlap problem described in Section 1.2, the following models are available. Each of the models is applicable depending on the assumptions that can be made on the interactions between the investigated technologies. The inputs for the models are avoidance rates for a specific scenario and technology, i.e., the probability that any given KSI or fatality of the specified scenario can be avoided by a technology. The outputs are the probabilities that a given KSI or fatality can be avoided by one or more of the technologies. The relevant models to combine those probabilities can also be found in (Ross, 2009).

2.2.1 Additive model

The “additive model” is the model with the strictest requirements. It assumes that the two technologies which are evaluated avoid different crashes in disjoint subsets within the set of concrete scenarios of a given scenario type “x”, see Figure 3.

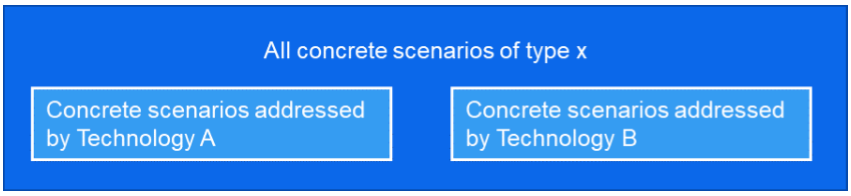

Figure 3: Example: Technologies A and B address disjoint, i.e., non-overlapping, subsets of concrete scenarios of type x.

For example, the two technologies could be a low-speed AEB that works only below 40 km/h ego-vehicle speed and an AES that works only above 40 km/h.

If the above-mentioned requirements are fulfilled, the avoidance probabilities can simply be added:

$$p_x^{fatal} = p_x^{y1,fatal} + p_x^{y2,fatal}.$$

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2.2.2 Independent model

For the application of the “independent model”, it is required that the activation of one technology does not exclude the activation of the other technology. There can be concrete scenarios where only one technology contributes, and there can be scenarios where both technologies contribute, see Figure 4 (if the addressed concrete scenarios were not overlapping, the additive approach would be applicable).

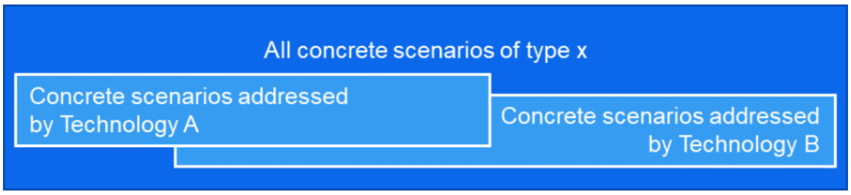

Figure 4: Concrete scenarios In some concrete scenarios, only one technology contributes. In others, both might become active.

An example would be if the vehicle is equipped with both an AES and AEB system. In that example, the AEB might activate, but an AES might additionally be activated if the AEB activation alone does not suffice to avoid an accident.

Using the assumption required for the independent model, the combined avoidance rate is expressed as the probability that at least one of the systems avoids the accident:

$$p_x^{fatal} = 1 - \left(1 - p_x^{y1,fatal}\right) * \left(1 - p_x^{y2,fatal}\right).$$

2.2.3 Same crashes model

If the required assumptions for the previous models are too strict, and cannot be plausibly justified, the “same crashes model” can be applied. It can be used in cases where the activation of one system excludes the usage of another system, and when the systems are equally likely to activate in any concrete scenario, e.g., when the same sensor and similar activation strategy is used, see Figure 5.

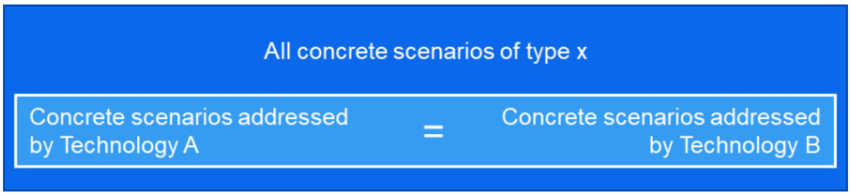

Figure 5: Both systems address the same concrete scenarios.

A typical example could be an AEB and forward collision warning (FCW) system, where only one of both is activated if crashes are imminent. With this model, the higher avoidance rate of the two systems is used, corresponding to the assumption that the “better” system will avoid the accident:

$$p_x^{fatal} = \max\left(p_x^{y1,fatal}, p_x^{y2,fatal}\right).$$

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2.2.4 Application to SAFE-UP technologies

Since Demo 1 addresses different scenarios than Demo 3 and Demo 4, there is no overlap to be solved and its effectiveness is integrated additively into the assessment at the EU level.

For Demo 3 and 4, Table 1 lists the scenarios for which the overlap problem must be solved: P-CLwSO and P-CRwSO for C2P cases, and all C2B cases (B-CLwSO, B-CLwoSO, B-CRwSO, B-CRwoSO and B-TurnL-SD).

The most appropriate model to be applied to combine the effectiveness of Demo 3 and 4 is the independent model, due to the following reasoning:

- The main benefit of the addition of C-ITS to an AEB is that in cases, where the VRU would be detected shortly before a crash, it can now be detected earlier, thus allowing an earlier activation by the AEB.
- The addition of AES provides a benefit in cases where the VRU is detected shortly before the crash, by offering a further option for action to avoid the accident.
- While C-ITS improves the environment perception, AES adds a further avoidance strategy. Thus, both technologies can be active during the same concrete scenario and their activation is not mutually exclusive.

The combined avoidance rate is then expressed by the probability that at least one of the technologies provides a benefit:

$$p_x^{fatal} = 1 - \left(1 - p_x^{Demo3,fatal}\right) * \left(1 - p_x^{Demo4,fatal}\right)$$

and

$$p_x^{KSI} = 1 - \left(1 - p_x^{Demo3,KSI}\right) * \left(1 - p_x^{Demo4,KSI}\right),$$

while $N_{avoided,x}^{y,fatal}$ and $N_{avoided,x}^{y,fatal}$ are results of the individual assessment in D5.3 (Parera et al., 2023). The combined number of avoided fatalities or KSI cases has to be estimated using the computed combined avoidance rates p_x^{fatal} and p_x^{KSI}:

$$N_{x,avoided}^{fatal} = N_x^{fatal} * p_x^{fatal}$$

and

$$N_{x,avoided}^{KSI} = N_x^{KSI} * p_x^{KSI}.$$

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2.3 Assessment on crash-participant level

In the first step, the number of avoided fatalities and KSI cases is summed up for each group z:

$$N_{z,avoided}^{fatal} = \sum_{\substack{scenarios\ x \\ for\ group\ z}} N_{x,avoided}^{fatal}$$

and

$$N_{z,avoided}^{KSI} = \sum_{\substack{scenarios\ x \\ for\ group\ z}} N_{x,avoided}^{KSI}.$$

Furthermore, those numbers are divided by the total number of fatalities or KSI cases in the respective group z:

$$p_z^{fatal} = N_{z,avoided}^{fatal} / N_z^{fatal}$$

and

$$p_z^{KSI} = N_{z,avoided}^{KSI} / N_z^{KSI}.$$

2.4 Assessment on EU level

After applying the previous assessment steps, the EU number of avoided fatalities and KSI cases can be computed in the following way:

$$N_{tot,avoided}^{fatal} = N_{C2P,avoided}^{fatal} + N_{C2B,avoided}^{fatal} + N_{C2C,avoided}^{fatal}$$

and

$$N_{tot,avoided}^{KSI} = N_{C2P,avoided}^{KSI} + N_{C2B,avoided}^{KSI} + N_{C2C,avoided}^{KSI}.$$

The final avoidance rate is computed by the following expressions:

$$p^{fatal} = N_{tot,avoided}^{fatal} / N_{tot}^{fatal}$$

and

$$p^{KSI} = N_{tot,avoided}^{KSI} / N_{tot}^{KSI}$$

2.5 Scaling according to market penetration rate

Using the scaling factor mp to represent the market penetration rate, the actual benefit under consideration of market penetration rate is simply expressed by the following equations:

$$p_{mp}^{fatal} = mp * p^{fatal}$$

$$p_{mp}^{KSI} = mp * p^{KSI}.$$

3. Results

In this chapter, the method in the previous chapter is applied to calculate the overall safety benefit of SAFE-UP in terms of fatality and KSI reduction.

To compute the share of avoided fatalities and KSI cases within a specific scenario type, the total numbers of such cases in the scenario type is required, which are shown in Table 2 for scenarios relevant to Demo 3 and Demo 4. Those numbers are taken from D5.3 (Parera et al., 2023). Furthermore, the corresponding numbers for the investigated Demo 1 scenario are shown in Table 3, taken from D5.4 (Mensa et al., 2023).

Table 2: Number of fatalities and KSI cases on EU level for 2016 for Demo 3 and 4 scenarios.

Scenario type x	N_x^{fatal}	N_x^{KSI}
P-CLwoSO	154.2	2369.2
P-CRwoSO	211.1	3244.0
P-CLwSO	146.3	2247.7
P-CRwSO	213.9	3286.5
P-TurnL-SD	46.7	718.1
B-CLwoSO	68.9	1824.8
B-CRwoSO	99.9	2647.3
B-CLwSO	31.6	836.5
B-CRwSO	56.7	1501.8
B-TurnL-SD	8.2	216.5

Table 3: Number of fatalities and KSI cases on EU level for 2016 for the Demo 1 scenario.

	N_x^{fatal}	N_x^{KSI}
C2C Head-on scenario	611	1106

3.1 Safety assessment results for individual Demos

In this section, the results regarding the effectiveness of Demos 1, 3 and 4 from D5.3 (Parera et al., 2023) are summarised to be processed in the method.

3.1.1 Demo 1

In T5.4.2, a study was performed that estimates how many occupants would not be killed or seriously injured (KSI) in frontal head-on car-to-car crashes in EU when some improved restraint systems are introduced. In this benefit analysis, results from simulations with human body models were combined with accident data to estimate the benefit introduced with improved restraint systems. The improvements in the restraint system are referred to as “Demo 1”.

The results from simulations with an updated and seated VIVA+ model that was restrained by either a state of the art (SOTA) restraint system or an improved restraint system and the effectiveness are presented in D5.4 (Mensa et al., 2023). Figure 6 shows the initial positions of the occupant model.

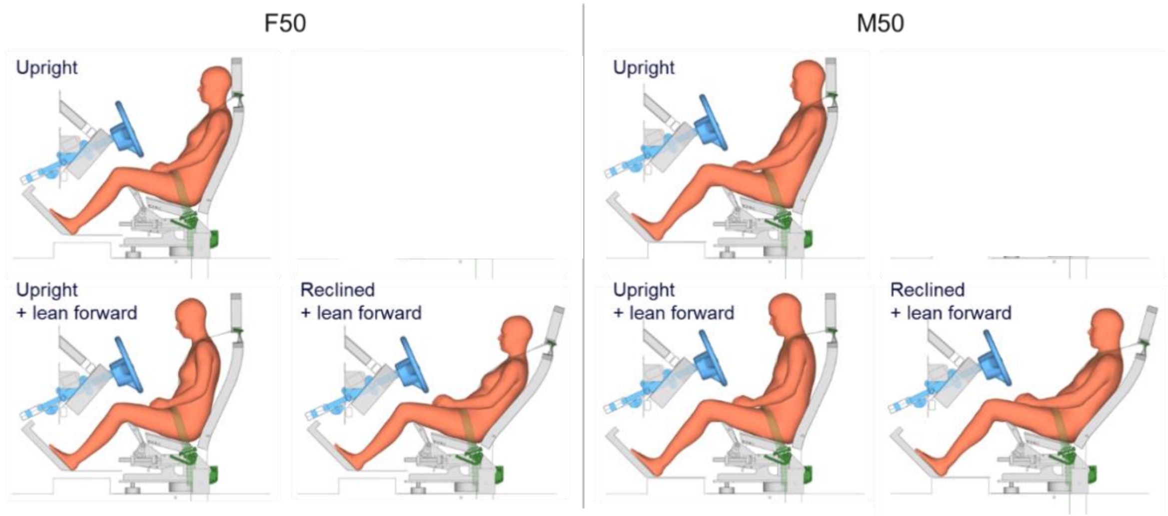

Figure 6: Seated F50 (left) and M50 (right) occupant model in the seat model and in initial positions. Upright (left) and reclined (right) and leaning forward positions (bottom right and left).

The simulations were done using the VIVA+ 50th percentile female (F50) and male (M50) occupant models. The two occupants were simulated in upright positions, in upright + lean forward and reclined + lean forward positions, which are the result of autonomous emergency braking (AEB) before the crash.

Table 4 presents the effectiveness of Demo 1 in terms of KSI cases. If all vehicles were equipped with the improved SAEF-UP system and all occupants were reclined, the effectiveness of the improved restraint systems is 2.6% over current systems without AEB (the improved system would save 29 KSI annually at the EU level).

It was not possible to compute the corresponding numbers for the fatalities, since appropriate risk functions were not available and could not be established within the scope of the SAFE-UP project, see D5.4 (Mensa et al., 2023).

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Table 4: KSI occupants and the overall effectiveness for different cases compared to current.

Case	**Occupants injured**	$\boldsymbol{N^{Demo1,K}_{avoided,x}}$	**Effectiveness compared to current (%)**
Upright seating position with SOTA restraint system without AEB (current)	1106	-	-
Leaning forward seating position with SOTA restraint system with AEB	629	477	43.2
Leaning forward seating position with improved restraint system with AEB	438	668	60.4
Reclined seating position with improved restraint system with AEB	1077	29	2.6

3.1.2 Demo 3

Table 5 presents the effectiveness of Demo 3 with respect to the following research question:

RQ 2b: “What is the additional safety benefit provided by a combined ‘VRU AEB+S’ with ideal decision-making (refer to as ‘idealized VRU AEB+S’), at a market penetration rate of 9.6% / 27.5% / 100% in car to VRU collisions on urban roads in terms of KSI reduction on EU level in 2025 compared to a pure ‘VRU AEB’ implementation?”

The numbers $N^{Demo3,fatal}_{avoided,x}$ and $N^{Demo3,KSI}_{avoided,x}$ therefore represent the additional safety benefit added through the AES functionality, and they are computed by subtracting the number of fatalities or KSI cases avoided by VRU AEB+S from the number of fatalities or KSI cases avoided by the idealised VRU AEB+S.

The highest percentage of additionally avoided fatalities can be observed in scenarios with side obstruction, where the VRU is coming from the right. In general, the additional benefit was higher for scenarios with an obstruction. The highest additional benefit of almost 1% can be observed for the KSI case reduction in P-CLwSO.

All reductions were below 1%, which is a low number, considering that these numbers were calculated with respect to the respective scenario type. When calculating the reduction with respect to all road traffic fatalities and KSI cases, the additional benefit is further decreasing. One important aspect that must be mentioned here, is that the safety benefit additional to AEB was investigated. As can be seen in Figure 5, the number of fatalities and KSI avoided by AEB is already large.

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Table 5: Additional benefit of Demo 3 in terms of avoided fatalities and KSI cases. Included are the benefits by AEB only as the basis for comparison.

Scenario type x	$N_{avoided,x}^{Demo3,fatal}$	$p_x^{Demo3,fatal}$	$N_{avoided,x}^{Demo3,KSI}$	$p_x^{Demo3,KSI}$	Avoided fatalities by AEB only	Avoided KSI by AEB only
P-CLwoSO	0.0	0.00 %	1.8	0.08 %	153.0	2339.9
P-CRwoSO	0.1	0.05 %	3.2	0.10 %	206.9	3140.9
P-CLwSO	0.2	0.14 %	22.2	0.99 %	125.6	1812.8
P-CRwSO	0.6	0.28 %	0.7	0.02 %	194.9	2911.4
Total Pedestrian	**0.9**		**27.9**		**229.4**	**5512.6**
B-CLwoSO	0.1	0.15 %	0.8	0.04 %	60.9	1108.2
B-CRwoSO	0.0	0.00 %	0.0	0.00 %	27.2	2275.7
B-CLwSO	0.0	0.00 %	0.0	0.00 %	94.1	645.9
B-CRwSO	0.2	0.35 %	5.1	0.34 %	47.2	1482.9
Total Cyclist	**0.3**		**5.9**		**680.4**	**10205.0**
Total Pedestrian+ Cyclist	**1.2**		**33.8**		**909.8**	**15707.6**

3.1.3 Demo 4

Table 6 presents the effectiveness of Demo 3 with respect to the following research question:

"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?"

The numbers $N_{avoided,x}^{Demo4,fatal}$ and $N_{avoided,x}^{Demo4,KSI}$ therefore represent the additional safety benefit added through the V2X functionality, and they are computed by subtracting the number of fatalities or KSI cases avoided by pure AEB from the number of fatalities or KSI cases avoided by the AEB+V2X technology.

First, it has to be mentioned that the scenarios P-CLwoSO, P-CRwoSO and P-CLwSO were not simulated and assessed. Since the effectiveness was higher for B-CRwSO than for B-CLwSO, it was assumed that analogously, the same holds true for P-CRwSO and P-CLwSO, such that copying $p_x^{Demo4,fatal}$ and $p_x^{Demo4,KSI}$ to P-CLwSO represents a lower bound for the true effectiveness. By using the average of the ratios of the effectiveness between B-

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CRwSO to B-CRwoSO and B-CLwoSO to B-CLwSO, the effectiveness for P-CLwoSO and P-CRwoSO is estimated. Such copying of the effectiveness to previously not included scenarios is necessary, since the alternative of assuming 0% effectiveness for the not-simulated scenarios would lead to a significant under-estimation of the total effectiveness. By multiplying $p_x^{Demo4,fatal}$ with the respective N_x^{fatal} for the missing scenarios (analogously for KSI), the number of avoided cases is estimated.

It can be seen in Table 4, primarily in the cyclist scenarios, that adding V2X provides more benefit in cases with sight obstructions than in cases without, which is proof that at least in simulation, the technology achieves the intended benefit by providing more information in scenarios with limited visibility. Furthermore, the additional benefit due to V2X even in scenarios without sight obstruction was around 60% of the additional benefit in scenarios with sight obstruction, which should not be neglected when assessing the technology. Similar to Demo 3, it can be seen that also for Demo 4, the AEB was already able to avoid a significant portion of the crashes.

Furthermore, no additional safety benefit can be observed in the turning scenarios involving pedestrians. This could be due to the fact that cyclists are moving at higher speeds and that those speeds are the relevant aspect that require V2X communication for avoidance.

Table 6: Additional benefit of Demo 4 in terms of avoided fatalities and KSI cases. The numbers $\boldsymbol{p_x^{Demo4,fatal}}$ and $\boldsymbol{p_x^{Demo4,KSI}}$ for the scenarios marked by the green background were copied from P-CRwSO. Included are the benefits by AEB only as the basis for comparison.

Scenario type x	$N_{avoided,x}^{Demo4,fatal}$	$p_x^{Demo4,fatal}$	$N_{avoided,x}^{Demo4,KSI}$	$p_x^{Demo4,KSI}$	**Avoided fatalities by AEB only**	**Avoided KSI by AEB only**
P-CLwoSO	9.2	5.99 %	198.4	8.37 %	147.6	2162.9
P-CRwoSO	12.6	5.99 %	271.7	8.37 %	202.0	2961.5
P-CLwSO	14.5	9.91 %	288.4	12.83 %	140.0	2052.0
P-CRwSO	21.2	9.91 %	421.7	12.83 %	188.5	2778.7
P-TurnL-SD	0.0	0.00 %	0.0	0.00 %	46.7	718.1
Total Pedestrian	**57.6**		**1180.2**		**724.3**	**10673.1**
B-CLwoSO	6.7	9.72 %	211.5	11.59 %	58.8	1504.9
B-CRwoSO	8.1	8.11 %	242.3	9.15 %	89.6	2337.4
B-CLwSO	4.9	15.51 %	134.9	16.13 %	24.9	652.1
B-CRwSO	7.9	13.93 %	234.3	15.60 %	46.7	1203.7
B-TurnL-SD	0.3	3.66 %	6.3	2.91 %	7.8	207.5
Total Cyclist	**27.9**		**829.3**		**227.8**	**5905.6**

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Scenario type x	$N_{avoided,x}^{Demo4,fatal}$	$p_x^{Demo4,fatal}$	$N_{avoided,x}^{Demo4,KSI}$	$p_x^{Demo4,KSI}$	Avoided fatalities by AEB only	Avoided KSI by AEB only
Total Pedestrian+Cyclist	**85.5**		**2009.5**		**952.1**	**16578.7**

3.2 Application of the hierarchical assessment approach

3.2.1 Assessment on scenario level

On this level of the assessment, the independent approach from Section 2.2 is applied to combine results from Demo 3 with Demo 4, shown in Table 7. The general tendencies can be observed again, i.e., the effectiveness is higher in scenarios with sight obstruction compared to without sight obstruction, and the benefit is also higher if the VRU is coming from the left. Fatalities and KSI cases avoided by Demo 1 are added at the crash-participant level, since no combination with other Demos on scenario level is necessary.

It has to be noted that the main contribution to the avoided cases comes from Demo 4, which can be seen by comparing the effectiveness of both Demos, see Table 5 and Table 6.

Table 7: Combined effectiveness results.

Scenario type x	$N_{avoided,x}^{fatal}$	p_x^{fatal}	$N_{avoided,x}^{KSI}$	p_x^{KSI}
P-CLwoSO	9.2	5.99 %	200.1	8.44 %
P-CRwoSO	12.7	6.04 %	274.6	8.47 %
P-CLwSO	14.7	10.03 %	307.8	13.69 %
P-CRwSO	21.7	10.16 %	422.3	12.85 %
P-TurnL-SD	0.0	0.00 %	0.0	0.00 %
Total C2P	**58.4**		**1204.7**	
B-CLwoSO	6.8	9.86 %	212.2	11.63 %
B-CRwoSO	8.1	8.11 %	242.3	9.15 %
B-CLwSO	4.9	15.51 %	134.9	16.13 %
B-CRwSO	8.1	14.24 %	238.6	15.89 %
B-TurnL-SD	0.3	3.66 %	6.3	2.91 %
Total C2B	**28.2**		**834.3**	

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Scenario type x	$N^{fatal}_{avoided,x}$	p^{fatal}_{x}	$N^{KSI}_{avoided,x}$	p^{KSI}_{x}
Total C2P+C2B	**86.6**		**2039.1**	

3.2.2 Assessment on crash-participant level

The number of fatalities and KSI in urban C2P, urban C2B and C2C in car-involved crashes with 2 participants are shown in Table 8. While the additional benefit was for some scenarios even higher than 10%, the benefits are below 10% if the number of avoided fatalities or KSI cases is put into the perspective of the total number of fatalities or KSI cases within respective crash-participant group.

Since no estimate of avoided fatalities was possible for Demo 1, no corresponding effectiveness for C2C can be computed. The estimate on EU level for the avoided fatalities will therefore be an underestimate of the true reduction.

Table 8: Estimated avoided fatalities per crash-participant group and the corresponding effectiveness.

Crash-participant type z	N^{fatal}_{z}	$N^{fatal}_{z,avoided}$	p^{fatal}_{z}	N^{KSI}_{z}	$N^{KSI}_{z,avoided}$	p^{KSI}_{z}
Urban C2P	2261	58.4	2.58 %	23703	1204.7	5.08 %
Urban C2B	456	28.2	6.18 %	12079	834.3	6.91 %
C2C	4901	-	-	51612	668	1.29 %

3.2.3 Assessment on EU level

In the final assessment step, the assessment on EU level, all the previous results are combined to form one estimate for the reduction of fatalities and one for KSI. To compute the effectiveness on the EU level, the sum of the number of avoided KSI cases or fatalities for each crash-participant group is divided by the number of KSI cases or fatalities that occur in road traffic on EU level. This corresponds to a weighted sum of the effectiveness shown in Table 8 - the weights are shown in Table 9.

Table 9: Relative share of the number of fatalities or KSI of a certain crash-participant type with all the number of all fatalities or KSI due to road accident in the EU, and effectiveness by EU level.

Crash-participant type z	w_z^{fatal}	w_z^{KSI}	$p_z^{fatal} * w_z^{fatal}$	$p_z^{KSI} * w_z^{KSI}$
Urban C2P	12.7 %	12.8 %	0.33 %	0.65 %
Urban C2B	2.6 %	6.5 %	0.16 %	0.45 %
C2C	27.5 %	27.9 %	0.00 %	0.36 %

Since the weights in Table 9 are the smallest for those crash-participant groups in Table 8 where the effectiveness is the highest, the final estimates for the reduction KSI cases or fatalities are significantly maller than for example for urban C2P or C2B. It can be seen, that the C2P group shows the largest potential for EU-wide avoidance.

The first row in Table 10 shows this weighted sum under the assumption, that a 100% market penetration of SAFE-UP systems is reached within the EU, while the other rows represent ambitious (27.5%) and conservative (9.6%) assumptions for the market penetration rate.

It has to be noted that, since the number of avoided fatalities cannot be estimated for C2C collisions, the estimates for the fatality reduction represent an underestimate.

Table 10: Fatalities and KSI avoided by SAFE-UP demonstrators and their relative share in all fatalities or KSI due to road accident in the EU, scaled by different assumptions for the market penetration rate.

Market penetration	N_{tot}^{fatal}	$N_{tot,avoided}^{fatal}$	p^{fatal}	N_{tot}^{KSI}	$N_{tot,avoided}^{KSI}$	p^{KSI}
100 % (optimistic)	17798	86.6	0.49 %	184892	2707.1	1.46 %
27.5 % (ambitious)		23.8	0.13 %		744.4	0.40 %
9.6 % (conservative)		8.3	0.05 %		259.9	0.14 %

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4. Discussion and conclusions

4.1 General discussion of overall effectiveness

While the results of the effectiveness assessment were computed on different assessment reference levels to put them into different perspectives through the hierarchical approach, it can be argued that the assessment on the scenario level is the most meaningful, since it puts the number of avoided fatalities or KSI into the perspective of only those types of scenarios, for which the safety systems were designed. On the scenario level, it was found that Demo 3 and Demo 4 combined can avoid 8% to 16% of the KSI, and 6% to 15% of the fatalities in the crossing scenarios (with only minor effectiveness of up to 4% in the turning scenarios B-TurnL-SD and 0% for P-TurnL-SD), assuming a 100% market penetration rate of the systems. For the crossing scenarios, these are promising numbers (calculated based on the results of virtual simulations), considering that AEB alone (without added V2X or evasion) is already very effective. All benefits considered in the calculation were additional benefits to an already existing generic AEB, i.e., the numbers for the additional benefit were calculated by subtracting the number of fatalities or KSI avoided by AEB from the number of fatalities or KSI avoided by AEB and the investigated functionality. This renders reaching notable benefits additional to AEB a non-trivial task, which can nonetheless be achieved, as was shown in this deliverable.

Furthermore, it must be noted that all considerations were lower bound estimates, meaning that the true effectiveness can be higher. For example, for Demo 1, no estimate for the number of avoided fatalities could be computed, such that this number was assumed to be 0. For Demo 4, it was found that additional benefits are also possible in cases without sight obstructions, even though it was assumed in the initial definition of relevant scenarios that only scenarios with sight obstructions would be of interest. This suggests that there are also other types of scenarios which were not included in the assessment, such as non-urban C2P and C2B scenarios, which is another argument that the most meaningful perspective to consider avoidance rates is on the scenario level.

4.2 Safety-related effects by SAFE-UP technologies not included in the overall assessment

In the following sub-sections, various safety-related effects by SAFE-UP are discussed which could not be included in the overall assessment, either because they were out of the scope of the project, or because their influence became apparent at a later stage of the project. The true overall safety benefit on crash-participant and EU level is therefore higher than what was estimated.

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4.2.1 Demo 1

As part of the passive safety systems assessment, sled test activities were carried out with a THOR-reclined in T.5.4.2 (see D5.4 (Mensa et al., 2023)), with the main objective to physically demonstrate that the optimization in the restraint systems carried out throughout simulations activities in T4.3 (D4.4 (Becker et al., 2022)) was effective. This was evaluated by conducting 6 sled tests and using their results, considering a reference restraint system and an optimized restraint system, combining different airbag's ventholes and knee bolsters to determine the best possible optimized configuration for reducing the injuries criteria on the THOR-reclined at a greater extent. The tests with the reference systems were repeated twice and results showed that a certain repeatability could be assured by obtaining similar values in head resultant acceleration, but some differences could be observed in acetabulum and femur resultant forces. These sled tests helped to understand the limitations of the conventional restraint systems and gave evidence on the need of an improved system, which can reduce the injury values of an occupant's seated in a high reclined position.

By following the Euro NCAP MPDB assessment protocol, it could be observed that by using the reference restraint system, critical values above the lower performance limit were obtained in head and pelvis, and the femurs' resultant forces were above the higher performance limit. The optimized restraint system improved the injury values in those body regions of the THOR-reclined. Among the ventholes of 40 mm and 45 mm, the latter resulted to better retain the head after the impact. In addition, a knee bolster of 60 gramm/liter was also tested to be compared with the one of 30 g/L, and results showed greater femur loads with the 60 g/L knee bolster. For this reason, the greatest reduction of injury criteria was seen with the optimized configuration with a venthole of 45 mm and a knee bolster of 30 g/L. Consequently, the optimization of the restraint systems resulted to be efficient in reducing occupant injury risk prediction on the THOR-reclined.

4.2.2 Demo 3

In cases where AES fails to avoid the accident, the collision impact location is changed to be on the side of the vehicle, with many cases showing impact locations at the rear half of the vehicle's side. As the current state of research lacks the knowledge of how this change in crash constellation effects the resulting accident severity, no final statement can be given in this regard. However, side impact locations behind the A-pillar may result in a reduced accident severity. Additionally, side crashes at the rear part of the vehicle may also be avoided by the pedestrian, who can abruptly stop his movement after a passing vehicle is detected. For a final assessment of the AES safety benefit, these two effects would have to be compared to the AEB velocity reduction in cases where no full accident avoidance is possible.

For an initial estimation of how the changed impact location might affect the expected accident severity, Figure 7 and Figure 8 show the distribution of accident severities clustered in the categories minor, severe and fatal for different regions of both frontal and side car vs. pedestrian accidents, extracted from the GIDAS database and weighted to German national level.

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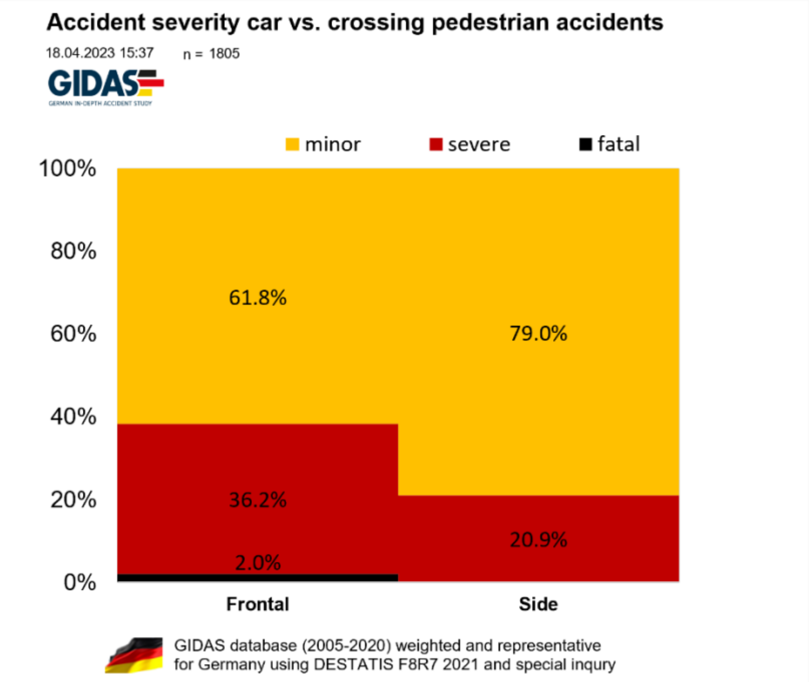
These results show that statistically, side crashes result in a lower number of severe accidents than frontal crashes (20.9% compared to 36.2%) and the number of fatal accidents is reduced to 0%, compared to 2% in frontal crashes. Furthermore, for side crashes that happen behind the first 50cm of the vehicle front, the number of severe accidents further reduce. Note that the database does not contain any useable data for side crashes happening behind 150cm of the vehicle front, which might be an indication that crashes where the pedestrian walks into the rear half of the vehicle's side are very unlikely to happen.

The reduced severity in side-crashes leads to the assumption made in the assessment, that assessing the injury or fatality risk in such cases by a risk function suited for frontal crashes represents a worst-case estimate.



GIDAS database (2005-2020) weighted and representative for Germany using DESTATIS F8R7 2021 and special inqury

Figure 7: Distribution of accident severities clustered in the categories minor, severe and fatal for frontal and side car vs. pedestrian accidents.

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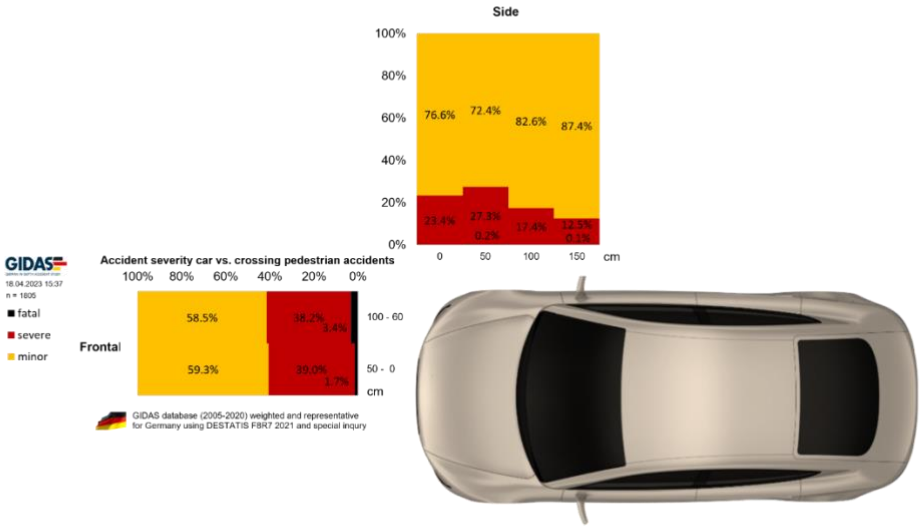

Figure 8: Distribution of accident severities clustered in the categories minor, severe and fatal for different regions of both frontal and side car vs. pedestrian accidents

4.2.3 Demo 4

Demo 4 shows the benefit of the V2X technology in AEB-related scenarios from three points of view; the VRU warning, the Driver warning and the AEB activation. However, the reactions and behaviours from the VRUs and Drivers upon the warnings triggered in each situation are not deeply analysed since human factors are out of the scope of the SAFE-UP project. The impact assessment has included only the AEB performance with V2X technology, which has demonstrated to perform slightly better than without such communication technology. However, in those cases where the AEB could not avoid the crash, the warnings triggered could help on mitigating or even avoiding the critical situation. A future work is required on the warning's reaction for safety-critical situations with V2X technology.

Furthermore, there are still several challenges that need to be addressed to improve the maturity level of this technology to make it ready for market introduction, especially when it comes to positioning accuracy, signal integration trough standard procedures and reliability of information. With higher maturity level of the ADAS systems with V2X technology integrated, better results on the injury risk and fatalities could be extracted.

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4.3 Conclusions and outlook

When adding an in-lane evasion functionality to a generic AEB and V2X communication to increase the field of view and aid the sensors for the generic AEB, an additional 8 to 16% of killed or severely injured pedestrians or cyclists can be avoided in scenarios where the VRU crosses the street, and 5 to 16% of the fatalities for cyclist crossing scenarios, even though the AEB is already very effective and avoids the majority of cases.

The evasion functionality converted some of the frontal crashes to side crashes, which can currently not be assessed, such that a worst-case assumption had to be made since side crashes seem to be less severe than frontal crashes. Furthermore, the safety systems seem to provide benefits in scenarios that were initially considered irrelevant. These arguments lead to the fact that the benefit assessment represents a lower-bound estimate, and the true benefits are possibly larger.

As an outlook regarding alternative sitting positions, the improved restraint systems of Demo 1, combined with an AEB, do not increase the injury risk as opposed to the upright seating position with a state-of-the-art restraint system without AEB, allowing reclined sitting in future mobility without changing the severity of car-to-car head-on crashes. The evasion functionality benefits from lateral evasion space, such that out-of-lane evasion seems promising under the requirement that regulations allow such manoeuvres, and, if it can be excluded that other traffic participants are endangered, e.g., those in oncoming traffic.

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