AWARE2ALL

D2.3 Passive safety simulation framework including models

Demonstrator 1

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Dissemination level		
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About AWARE2ALL

Facing to the challenge of future highly automated vehicles, where occupants can freely orient themselves to engage in non-driving activities. This new environment prompts questions about how car occupants will actually sit, what activities they will engage in, and how they will be informed through the HMI to keep them in the loop if necessary.

AWARE2ALL aims to pave the way towards Highly Automated Vehicles (HAVs) deployment in traffic, by effectively addressing the changes in road safety and changes in the interaction of different road users caused by the emergence of HAV through the development of innovative technologies along with the corresponding assessment tools and methodologies.

AWARE2ALL will develop safety and HMI systems that will be interrelated through achieving a holistic understanding of the scene to ensure safe operation of the HAV. AWARE2ALL proposes a common conceptual universal safety framework for considering Human Machine Interaction (HMI). The project will be built on the results of projects funded under H2020 and other R&D programmes addressing the identification of new safety-critical situations and the most likely positions and postures considering the expected HAV applications.

The main objective of AWARE2ALL is to address the new safety challenges posed by the introduction of HAVs in mixed road traffic, through the development of inclusive and innovative safety (passive and active) and HMI (interior and exterior) systems that will consider the variety of population and will objectively demonstrate relevant improvements in mixed traffic safety.

AWARE2ALL includes 16 partners from 6 EU Member States (ES, DE, GR, NL, FR and SE) and 2 associated countries (TR, CS) and it is complemented by the International Advisory Board (IAB) representing key stakeholders that covers the full research and industrial development automotive value chain, more specifically in the CCAM field.

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Executive Summary

Deliverable D2.3 purpose is to show the technologies developed for use within Demonstrator 1. For greater understanding, background of the Use-Cases refined in D2.1 for application in Demonstrator 1 and relevant limitations and methods of assessment that apply are described throughout the initial chapters. Various design iterations of the applied technologies and their respective methods were implemented to pertinent load-cases existing in the Use-Cases for effectiveness evaluation and key performance requirements. Therefore, a summary of the initial vehicle and corresponding results through a crash phase is shown for the benefit of the reader. Following this, the tools and methods used to improve the two separate systems (vehicle architecture and restraint system) are shown. The respective results of developed technologies and extended assessments for refinement and optimization due in future work of Aware2All is described.

The vehicle architecture development of DLR's HAV, Urban Modular Vehicle Peoplemover (UMV PM), is described. The results of the initial re-design of the structure, accounting for numerous load-cases, have been conducted. The results of which are summarized in terms of occupant safety. Furthermore, the enhancement of DLR's tool (CS-OPT) for the optimization of the vehicle structure to improve crashworthiness is evidenced, utilizing a verified surrogate model of the UMV PM.

In addition, seatbelt designs were investigated via Sled tests, using the ViVA+ 50F Human Body Model (HBM), for identification of possible belt-designs to integrate into the UMV PM for safety enhancement. The study uses open-source models. As part of this study and the requirements stated in the Aware2All project, physically disabled occupants were created of the ViVA+ 50F. This Finite Element (FE) model will be released as part of D2.3. In addition, disabled variants of the THOR AV 50M and 05F Anthropometric Test Devices (ATD) were developed by Humanetics to support restraint system development to improve safety of a greater range of occupants.

The results and methods of developing and improving the restrain system within the UMV PM interior are shown with their relevance to Use-Cases of Demonstrator 1. The deployment and activation strategy of advanced belt systems and THI's adaptive airbag is described, and the successful results of the technology implementation are evidenced. The key areas to further enhance the restraint system are highlighted with potential measures to refine, inclusive of varying occupant sizes and orientations, in ensuing tasks of Aware2All.

D2.3 successfully presents the technologies developed, methods and tools of the passive safety framework of simulation models. Additionally, as commitment to supporting further scientific research, the ViVA+ 50F HBM disabled Finite Element (FE) model is delivered as part of this deliverable.

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Acronyms and terms

Acronym/Abbreviation	Definition
HAV	Highly Autonomous Vehicle
SUV	Sports Utility Vehicle
BIW	Body-In-White
BL	Baseline
NGC	Next Generation Car
UMV PM	Urban Modular Vehicle Peoplemover
FFRW	Full Frontal Rigid Wall
mPDB	Mobile Progressive Deformable Barrier
ATD	Anthropomorphic Test Devices
HBM	Human Body Model
UC	Use Case
REESS	Rechargeable Energy Storage System
UNECE (R)	United Nations Economic Commission of Europe (Regulation)
HIC	Head Injury Criterion
BrIC	Brain Injury Criterion
VC	Viscous Criterion
ASIS	Anterior superior iliac spine
AIIS	Anterior inferior iliac spine
CMS	Crash Mitigation Structure
THOR AV	Test Device for Human Occupant Restraint – Autonomous Vehicle
IR-TRACC	Infra-Red Telescoping Rod for the Assessment of Chest Compression

OLC	Occupant Load Criterion
XXM/XXF	XX=percentile number; Male / Female
ASMOS	Automated Surrogate Modeling for Vehicle Safety
CS-OPT	Car-Surrogate Optimizer
DOE	Design of Experiment
GP	Gaussian Processes
SVR	Support Vector Regression
OoP	Out-of-Position
CoG	Centre of Gravity
DAMAGE	Diffuse Axonal Multi-Axis General Evaluation
PMHS	Postmortem Human Subjects
NHTSA	National Highway Traffic Safety Administration
EuroNCAP	European New Car Assessment Program
ANCAP	Australasian New Car Assessment Program
US NCAP	United States New Car Assessment Program
kph	Kilometers per hour
SBD-X	Seatbelt Design – (variant)
SLL	Shoulder belt Load Limiter
BLL	Buckle Load Limiter
ALL	Anchor Load Limiter
SPT	Shoulder Pretensioner
BPT	Buckle Pretensioner
APT	Anchor Pretensioner
TTF	Time To Fire

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1. Introduction

In this document, D2.3, the developed technologies and corresponding framework will be presented, aiming to meet the requirements of Demonstrator 1. As Demonstrator 1 is a purely virtual demonstrator via Finite Element simulations, the pertinent information related to the development of implemented methods and necessary assumptions will be presented alongside initial results obtained in the development stages which will be refined within verification stages of the Aware2All project.

As part of the deliverable D2.3, an open-source model utilized in a restraint system development will be published and can be downloaded at Aware2All Zenodo.

A brief description of key criterion used to assess and develop passive safety systems will be presented as well as an overview of the use-cases. The document is structured to provide the reader the background of the technology platform to which the systems are applied (with key constraints and targets), followed by information required to assess the developed technologies, the methodology implemented in each system and evidenced by initial performance in comparison to the originally implemented systems.

Purpose of the deliverable

The purpose of the deliverable is to evidence that technologies have been implemented to improve passive safety systems of an autonomous pod vehicle which are applied within Demonstrator 1.

Component models will be calibrated by using measurement results from THI's airbag testbench from parallel projects (e.g., VorSAFe-Plus) and new measurements.

The passive safety system will be defined for different future vehicle configurations (interior configurations with different seating positions and occupant activity possibilities) in new accident configurations. The design of the new occupant protection system will include controllable restraint and airbag systems for the occupants in various configurations (relaxed, multi body-sizes) and address the safety challenges imposed with rearward facing occupants and structural limitations provided by the architecture of an autonomous pod. The technologies presented can therefore be summarized as adaptable systems for rearward- and forward-facing seating positions and seat-integrated safety systems with adapted body-in-white and interior design changes.

Intended audience

The intended audience of deliverable 2.3 are the project consortium members, the technical advisory board and members of the public. Deliverable 2.3 provides information of the current safety systems created, simulation platforms and the remaining work to be continued in succeeding tasks and work packages (namely Task 2.4 and WP5).

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2. Demonstrator 1 Use-Cases

The use-cases are set with a prioritization for research of Highly Autonomous Vehicles (HAV) which consider the operational domain of the vehicle, weather conditions, potential occupants (user-personas) and many other factors (a more detailed description is available in D1.2). The preliminary definition of use-cases provides operational bounds and scope of Demonstrator 1 and safety developments of T2.3. For instance, inner-city environment provides the maximum speed of a vehicle at 50 kilometers per hour (kph). The use-cases were further refined in D2.1, based on the output of D1.2. This was completed to ensure that key aspects for passive safety improvements are addressed within the Aware2All timeframe whilst ensuring factors pertinent to passive safety are represented and achievable in finite element crash simulations. Each use-case utilizes the Full-Frontal Rigid Wall (FFRW) and Mobile Progressive Deformable Barrier (mPDB) load-case, each differing with occupant position and orientation defined in the 'scenario'. To ensure coverage of as many use-cases and respective scenarios as possible whilst conforming to the Aware2All requirements within the feasibility of the project, the safety technologies of T2.3 will limit the number of use-cases completed. The limitation of implemented use-cases reduces repetition of work whilst still enabling key aspects to be considered, researched and analyzed in subsequent work-packages. To this end, the objective is to improve and extend the safety of under-represented occupants within emerging HAVs. Therefore, the safety systems developed encompass a wider variety of occupants (such as averaged-sized females and occupants with disabilities) as well as unconventional seating arrangements (such as reclined and rearward facing seats) presented by a HAV shuttle.

In this regard, it is important to note that the side impact use-case (UC1.5) will not be conducted within Aware2All. However, vehicle design changes have considered this load-case by reinforcement to the side structure and additional connections to the front structure for a holistic approach to crashworthiness improvement. Furthermore, due to the complexity of the tasks in designing and implementing new vehicle structures and restraint systems, the vehicle structural modifications and optimizations will be completed for the FFRW and mPDB load-cases to mitigate the loading experienced within the occupant cabin. The restraint system design and optimization will focus on the FFRW load-case as it provides the largest longitudinal acceleration to the occupants, thereby increasing the demand of the restraint system to effectively manage the occupant injury risk in various seating configurations (out-of-position) and an extended range of occupant's physical anthropometry. The HAV used in Demonstrator 1 is from the Next Generation Car (NGC) technology platform of DLR, the Urban Modular Vehicle Peoplemover (UMV PM)[1,2] .

Deliverable 2.3 is a documentation of technology development for implementation into Demonstrator 1. Due to the nature of Demonstrator 1 and the focus of passive safety systems in a crash event, the use-cases (defined in D1.2) are refined for simulation purposes. The relevant information on technology development related to the use cases is summarized in D2.1.

1 Münster, Marco und Kopp, Gerhard und Friedrich, Horst und Siefkes, Tjark (2020) Autonomes Fahrzeugkonzept für den urbanen Verkehr der Zukunft. ATZ Automobiltechnische Zeitschrift, 122 (122), Seiten 26-31. Springer. doi: 10.1007/s35148-020-0216-7 <https://doi.org/10.1007/s35148-020-0216-7>. ISSN 0001-2785.

2 Münster, Marco (2020) Vorgehensmodell zur Grundkonzeption eines Fahrzeugkonzepts und Entwicklung neuartiger kraftflussoptimierter Karosseriestrukturen für elektrifizierte Fahrzeuge (Procedure model for the basic conception of vehicle concepts and development of new body structures optimized for electrified vehicles). Dissertation, Universität Stuttgart.

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2.1. Use-Case refinement

This section provides a brief overview of the use-cases used in the structural technology development and/or the restraint system development of T2.3. It is important to note that this approach enables preliminary investigation to other use-cases and scenarios. For example, the opposed facing occupancy of the UMV PM (UC1.3) can be initially evaluated by qualitative methods through a combination of forward- and rearward-facing occupant simulations (UCs 1.2 and 1.1). Thereby providing insights of important developments of vehicle interior design or occupant interactions. The use-cases implemented in Task 2.3 are as follows:

Use-Case 1.1

Rearward-facing occupancy in mPDB and FFRW load-cases. Conducted with a representative occupant model of a 50^{th} percentile male (50M) and female (05F/50F) with the inclusion of a female occupant with a physical disability (loss of upper limb). The occupants are in an upright seating position and posture within the UMV PM.

Use-Case 1.2

Forward-facing occupancy in mPDB and FFRW load-cases. Conducted with a representative occupant model of a 50^{th} percentile male (50M) and female (05F/50F) with the inclusion of a female occupant with a physical disability (loss of upper limb). The occupants are in an upright seating position and posture within the UMV PM.

Use-Case 1.4

Forward-facing occupancy in mPDB and FFRW load-cases. Conducted with a representative occupant model of a 50^{th} percentile male (50M) and female (05F/50F) with the inclusion of a female occupant with a physical disability (loss of upper limb). The occupants are in a reclined seating position and posture within the UMV PM.

To maintain validity of the simulations, a robust and scientific approach to the development and analysis must be adhered to. In this regard, the occupant representation will be controlled by the most viable application of Anthropomorphic Test Devices (ATD) and/or Human Body Model (HBM) to the specific load-case.

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3. Background and requirement overview

For the development of passive safety systems, various constraints and boundaries apply. This is especially prevalent for virtual assessment with the application of available and validated models, materials and processes. Chapter 3 provides an overview of the models used in the development of passive safety technologies and design constraints, where relevant.

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3.1. User-Persona & Occupant models

As part of the Aware2All scope, user personas have been defined for consideration in the restraint system design and occupant injury criteria. Namely, the assessment extends the assessment of the 50th percentile male (50M) to also include the 5th percentile female (05F) and 50th percentile female (50F). These include the addition of a physically disabled occupant by modelling of a loss of upper limb to assess and improve the performance of relative restraint systems.

Occupant safety will be assessed either through kinematic, body part deformations and loads, or tissue strain data, or a combination thereof. This is dependent on the model selection that best represents the user persona in the load-cases. The selection of ATD or HBM is informed from the load-case selection (for validity of the occupant model) and occupant model availability.

Occupant metrics, for ATD, are defined by their respective test procedure for the specific dummies and their instrumented channels (accelerometers, springs, force transducer, etc.). The definitive criteria for Demonstrator 1 are established at a later stage in the project, namely after initial results to highlight key areas of interest. A general summary, as defined by the Adult Occupant Protection Protocol by Euro NCAP (2023)[3] is provided in Table 1.

Table 1. Summary of Driver and Passenger Injury Criteria for ATD application

Body Region	Criteria	Unit	Load-case
Head	HIC	-	FFRW, mPDB
	Res. Acc. 3ms exc.	g	FFRW, mPDB
	BrIC / DAMAGE		FFRW, mPDB
Neck	Shear	kN	FFRW, mPDB
	Tension	kN	FFRW, mPDB
	Extension	Nm	FFRW, mPDB
Chest	Compression	mm	FFRW, mPDB
	Viscous Criterion	m/s	FFRW, mPDB
Abdomen	Compression	mm	mPDB
Lumbar	Observational	kN, Nm	mPDB
Pelvis	Acetabulum compression	kN	mPDB

[3] European New Car Assessment Programme. (2023, December 5). Euro NCAP assessment protocol – adult occupant protection (Version 9.3). https://www.euroncap.com/media/79871/euro-ncap-assessment-protocol-aop-v93.pdf

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	Submarining	-	FFRW, mPDB
Femur	Femur Compression	kN	FFRW, mPDB
	Knee slider compression	mm	mPDB
Lower leg	Tibia Index	-	mPDB
	Tibia compression	kN	mPDB
	Interaction	-	FFRW

Based on this information, various occupant models have been selected for implementation within T2.3 passive safety development for Demonstrator 1. These are as follows:

1. THOR AV-50M, THOR AV-05F (HUM)
2. VIVA+ 50F
3. VIRTHUMAN (ESI)

The Test device for Human Occupant Restraint (THOR) for Autonomous Vehicles (AV) is the next in series based upon the THOR ATD. The THOR test dummy is currently used in mPDB test protocols of EuroNCAP and ANCAP, therefore the THOR AV ATDs (male and female) are deemed appropriate for the frontal crash occupant safety and restraint performance assessment of Demo 1. The THOR AV model permits larger pelvic angles for reclined seating configurations and its NTHSA biofidelity ranking for rear facing has been evaluated in hardware tests. The model has been validated through a series of physical tests[4,5,6]. The THOR AV-50M in 3 stages of reclined positions are shown in Figure 1.

Figure 1. Humanetics THOR AV-50M reclined positions

[4] Wang, Z., "Biomechanical Responses of the THOR AV ATD in Rear Facing Test Conditions," SAE Int. J. Adv. & Curr. Prac. in Mobility 4(6):2089-2105, 2022, https://doi.org/10.4271/2022-01-0836

[5] Wang, Z. J., Loeber, B., Tesny, A., Hu, G., & Kang, Y. S. (2021). Neck biofidelity comparison of THOR AV, THOR, and Hybrid III 50th dummies. Proceedings of the International Research Council on the Biomechanics of Injury (IRCOBI) Conference 2021, 136-156

[6] Wang, Z. J., Zaseck, L. W., & Reed, M. P. (2022). THOR AV 50th percentile male biofidelity evaluation in 25° and 45° seatback angle test conditions with a semi-rigid seat. Proceedings of the International Research Council on the Biomechanics of Injury (IRCOBI) Conference 2022, 288-308.

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VIVA+ 50F[7] is an open source HBM developed in EU project VIRTUAL *(Grant number 768960).* The model has been validated against Postmortem Human Subjects (PMHS) data for torso and abdominal regions as well as through frontal and rear sled tests. However, the sled tests were at a lower acceleration value than expected in the UMV PM crash tests of FFRW and mPDB. The VIVA+ HBM is available as a standing and seated (driving posture) model. The VIVA+ 50F is the base model which has been morphed to create the 50M. The VIVA+ HBMs are shown in Figure 2.

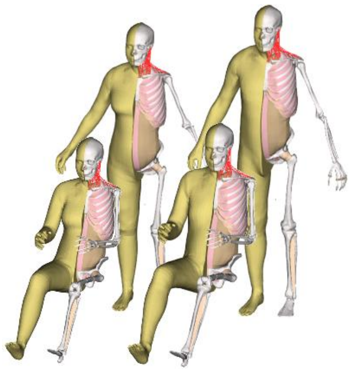

Figure 2. VIVA+ HBM (Left: 50F. Right: 50M)

VIRTHUMAN[8] is a computationally inexpensive HBM. The model couples the basic multibody structure with deformable segments, representing the behavior of related soft tissues and resulting in a short calculation time. After the validation of body parts in known impact scenarios, its response has been tuned to experimental corridors gathered from literature. Several energy level impacts from different directions were considered to test its robustness and correct biofidelic performance. The VIRTHUMAN occupant model, shown in a passenger position of a conventional vehicle, is provided in Figure 3.

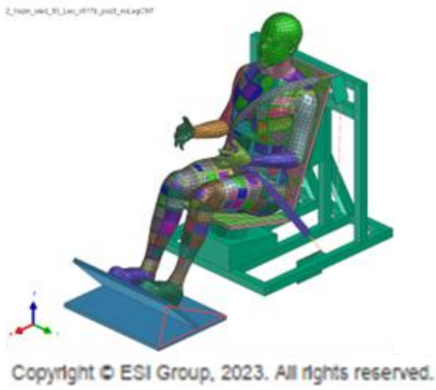

Figure 3. ESI VIRTHUMAN [8]

7 John, J., Klug, C., Kranjec, M., Svenning, E., & Iraeus, J. (2022). Hello, world! VIVA+: A human body model lineup to evaluate sex-differences in crash protection. Frontiers in Bioengineering and Biotechnology, 10. https://doi.org/10.3389/fbioe.2022.918904

8 Luděk Kovář, Jana Hluchá, 2019, https://doi.org/10.1016/B978-0-12-816713-7.00015-5).

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3.2. Vehicle Structure

The vehicle used within Demonstrator 1 of Aware2All is the UMV Peoplemover due to the unique occupant orientations and internal structure that the vehicle presents, reflecting the possible designs of HAV shuttle vehicles of the future. The UMV PM 2+2 prototype is shown FIGURE 4

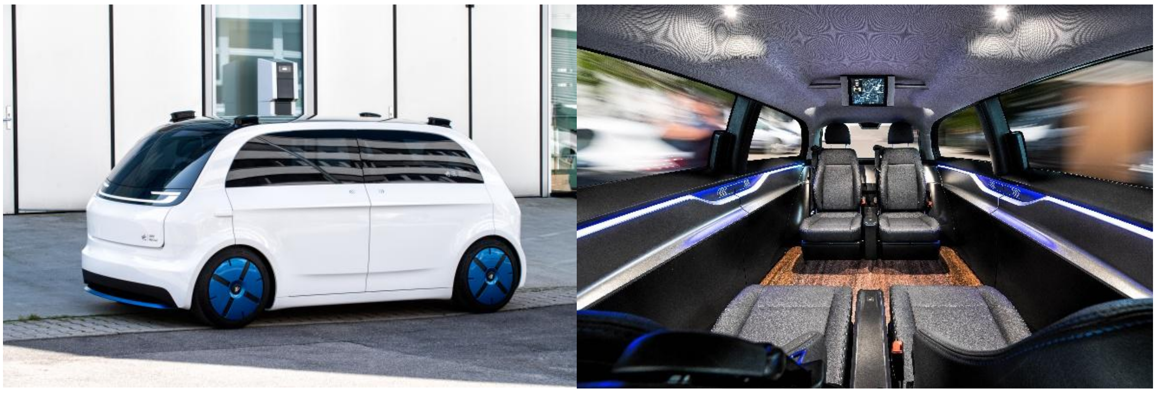

Figure 4. NGC UMV PM 2+2 Prototype (DLR, 2019) (left: Exterior. Right: interior configuration)

The UMV PM is a fully autonomous shuttle, therefore some requirements of the M1 classification for crash safety do not apply, namely steering wheel displacement. Similarly, some aspects are not required to be tested in the virtual environment within the scope of Aware2All, such as the door unlocking mechanisms post-crash. On the other-hand, relevant criteria pertinent to the vehicle and crash performance are of importance, especially for the proper function of restraint systems to be within an operable acceleration range. These are highlighted in the regulations UNECE R.137[9] and UNECE R.94[10]. This therefore includes, but is not limited to, the Rechargeable Energy Storage System (REESS) integrity retention, minimal occupant cabin intrusion and protection of various restraint system housings to ensure proper operation.

Unique challenges arise in the development of an effective crash structure of a HAV shuttle design, largely owing to the reduced energy absorbing structure space. As part of Task 2.3, the crash structure must be adapted in a way to reach an acceptable crash pulse to minimize occupant acceleration for optimum restraint system performance whilst managing to distribute the load of the crash throughout the vehicle structure to mitigate intrusions, protect packaging space and to maintain integrity of the REESS, in compliance with UNECE R137[9], UNECE R94[10].

The UMV Technical Platform enables exchange of modules to alter the vehicle Body-In-White (BIW) to fit the desired requirements for specific operations. Therefore, the elements that form the modules, alongside their manufacturing methods, form the initial constraints of permissible design changes. An example of the UMV platform strategy is presented in Figure 5.

[9] UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE. (2020). UN REGULATION NO. 137 – UNIFORM PROVISIONS CONCERNING THE APPROVAL OF PASSENGER CARS IN THE EVENT OF A FRONTAL COLLISION WITH A FOCUS ON THE RESTRAINT SYSTEM [2020/576]. OFFICIAL JOURNAL OF THE EUROPEAN UNION, L 136, 18–44.

[10] UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE. (2012). REGULATION NO. 94 – UNIFORM PROVISIONS CONCERNING THE APPROVAL OF VEHICLES WITH REGARD TO THE PROTECTION OF THE OCCUPANTS IN THE EVENT OF A FRONTAL COLLISION. OFFICIAL JOURNAL OF THE EUROPEAN UNION, L 254, 77–163.

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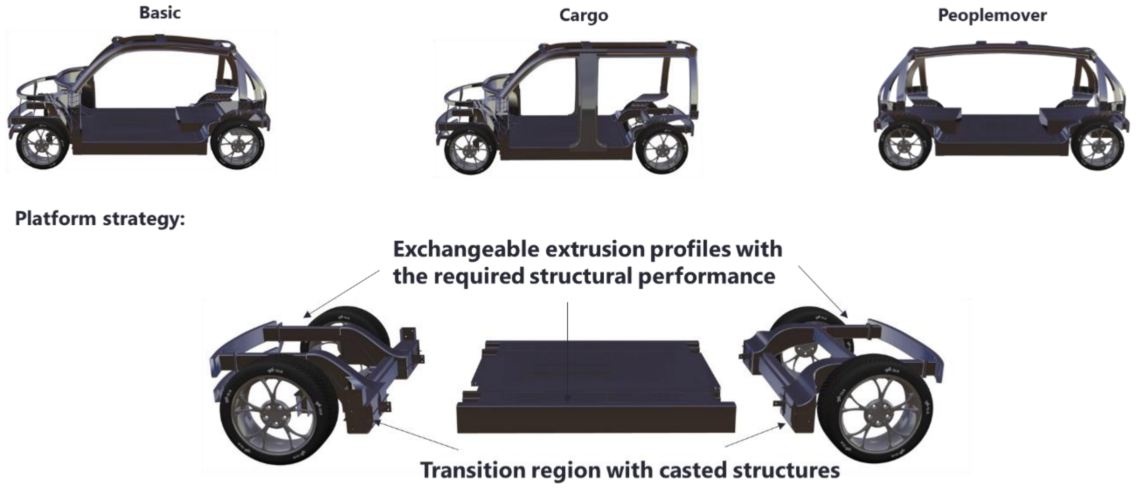

Figure 5. DLR UMV Technology Platform

The crash concept of the UMV PM is to distribute the crash energy through two main load-paths with secondary load-paths in support. The vehicle contains a cast component over the wheel arch and a press hardened A-Pillar. The main crash energy distribution paths for the front and rear are shown in Figure 6.

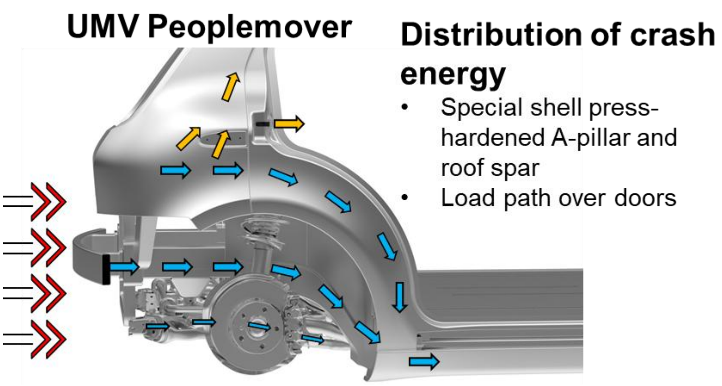

Figure 6. UMV PM Crash Energy Distribution Path

The cast wheel-arch provides structural reinforcement and provides a stiff and strong structure that is capable of withstanding high forces from the impact energy of a vehicle collision. The design is to protect the occupant cabin from intrusion whilst transferring the crash energy downwards into the vehicle sill (protecting the REESS in the central floor) and to distribute loads upwards into the press-hardened A-Pillar.

The design changes that can be implemented in T2.3 must adhere to specific constraints and design requirements (manufacturing, package spacing, material selection) as provided by the vehicle concept development team of DLR. The material selection, component changes and additions are implemented in the optimization framework of the UMV PM at a later stage which adhere to a select pool of verified and validated material descriptions and their respective manufacturing requirements (such as permissible thickness).

3.3. Restraint System

For the restraint system development activities, a simplified and partly rigidified sled model of the UMV PM interior is employed. The crash pulse of the full UMV PM is applied to the sled in order to simulate the deceleration experienced by the occupants. The anchorage and key fixing locations of the restraint system (e.g. slip-ring, airbag housing location) are defined considering the available packaging space within the UMV PM, as identified in November 2023 during the T2.3 workshop (DLR, THI). The sitting posture is defined within the THOR AV ATD adjustment limits and targeting a 'natural' and feasible sitting posture in alignment with EuroNCAP protocols[11,12]. The posture of the ATD is set within the tolerances of EuroNCAP frontal impacts testing protocol for passengers, changes to the dummy positioning were implemented for reclined and rearward passengers as these positions are not currently incorporated in regulatory or consumer testing. The posture of occupants for the reclined and rearward occupants was identified within the T2.3 Workshop and provided key data points such as knee distance from side wall, maximum seat rail and seatback positions, possible seat-pan and seatback angles and slip-ring locations.

The airbag system will be designed and optimized for the 'worst-case' of the use-cases, thus the FFRW test case, as this provides the most severe longitudinal acceleration pulse to the occupants. The entire restraint system (airbag and seatbelt) will be designed for both the upright position (18° seatback angle) of forward- and rearward-facing occupants and reclined position (45°) seatback angle of a forward-facing passenger.

The models utilized for the development and assessment of the restraint system will be the THOR AV-50M, THOR AV-05F (provided by HUM) and a HBM that shall fit the criteria of a 50th percentile female, either the VIVA+ 50F (available in LS-DYNA) or the VIRTHUMAN (provided by ESI, available in VPS). The airbag implemented is an adaptive airbag system developed and provided by THI.

Conventional vehicles in a crash scenario possess multiple occupant and restraint system load-paths that are not present within the UMV PM shuttle design. Specifically, there is no footrest to provide a lower load-path through the occupant legs that help support the occupant position and lessen the demand of the restraint system to restrain the occupant excursion. Additionally, the lack of a central console, windscreen and steering-wheel showcases unique challenges in the airbag design due to the lack of direct support for the airbag to stabilize the position and counteract the forces, generated by the airbag during the deployment phase and imposed by the occupant during the retention phase. Thus, novel systems based on roof deployment were investigated, aiming to maintain airbag integrity, position and performance for occupants in out-of-position postures. Furthermore, the seatbelt system is seat integrated, which requires specific firing and load limiting strategies to protect the belt components, to ensure that the occupant is properly restrained and that the increased loading through the seat structure is effectively managed to avoid integrity or excessive deformation issues.

[11] European New Car Assessment Programme. (2022). Full Width Frontal Impact Testing Protocol (Version 1.2.1). Retrieved from https://cdn.euroncap.com/media/67284/euro-ncap-frontal-fw-test-protocol-v121.pdf

[12] European New Car Assessment Programme. (2023). MPDB Frontal Impact Testing Protocol (Version 1.1.4). Retrieved from https://cdn.euroncap.com/media/67284/euro-ncap-frontal-fw-test-protocol-v121.pdf

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4. Virtual Passive Safety Development Plan and Tool Creation

Demonstrator 1 output is to provide a dataset of results for various occupant models in a set selection of defined load-cases. To enable efficient development of separate vehicle systems, the restraint systems and crashworthiness performance are initially developed separately until a greater maturity of models and results are achieved, at which point the two systems can be consolidated to conduct the use-case assessments as described in D2.1 within WP5.

The developments, although initially separated due to the technical disciplinary differences, are linked together through the T2.3 development. The aspects that contribute to the construction and finalization of T2.3 are grouped into working modules. The modules are highlighted with participating partners in a general overarching flow in Figure 7.

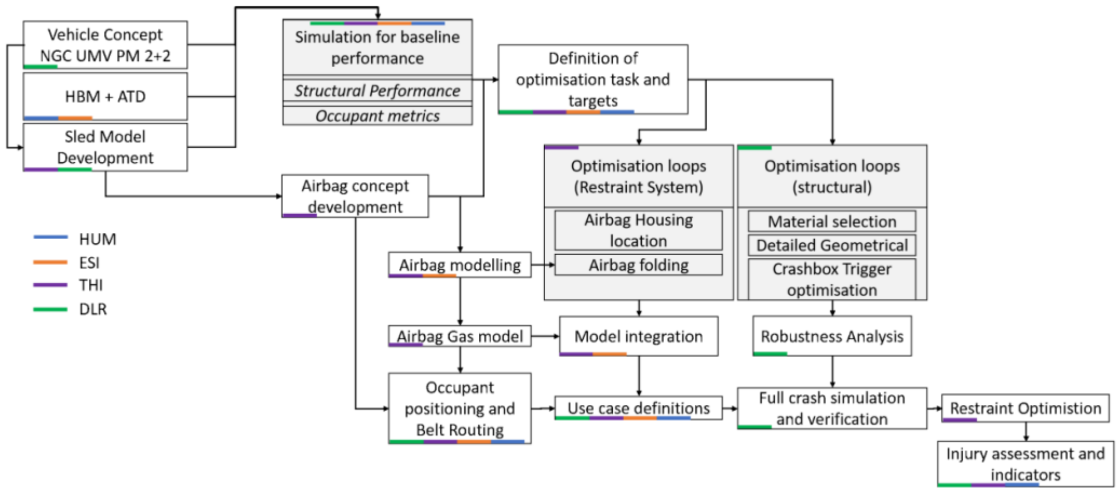

Figure 7. D2.3 Modular Workflow

The grey boxes in Figure 7 represent modules and their tasks that are repeated until a satisfactory result is created that can be utilized in the following module. For example, structural performance and occupant metrics are established for the baseline model, for each seating orientation and crash case (requiring multiple simulations). These steps are repeated once more with the second design iteration of the UMV PM, thus highlighting targets and critical cases that will advise on the correct setting of optimization tasks and targets for the restraint system and passive safety systems respectively.

The methodology which is commonly shared between the passive safety system development, of the restraint system and structural components are the application and assessment of the HBMs and ATDs used as occupant model and in which use-case they will be employed. The selection of the correct HBM and ATD is of extreme importance to maintain verification and robustness in the methodology and assessment of the safety systems. The occupant model must be able to provide the necessary data throughout FEA to correctly and accurately capture the occupant injury criteria, kinematics and positioning which are detailed in the use-cases (provided in D1.2).

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As highlighted in D1.2, the use-cases are defined as “Essential”, “Additional” and “Secondary”. The essential use-cases are used directly in Demonstrator 1, whereas those marked “additional” and “secondary” are considered but are not directly implemented into the design and optimization tasks of T2.3 and Demonstrator 1. This means that the assessment of vehicle and restraint system design is not optimized for non-essential load-cases (T2.3), but where possible the results will be shown in demonstrator 1.

A summary of the use-cases, their weighting, prioritization and FE modelled aspects of Demonstrator 1 is provided in D2.1. More details of the use-cases are provided in D1.2. It is worth noting that the occupant models are used to represent the user-personas where suitable: the average male (50M), Karina (50F + disability) (50DF) and Uma (05F elderly). For the purposes of safety system development of the UMV PM within the LS-DYNA environment, the THOR AV-50M, THOR AV-05F, VIVA+ 50F and disabled variations were implemented. The ranking of the use-cases is provided below with the selected scenarios for restraint system and structural development. The restraint system development uses the FFRW cases due to the largest longitudinal acceleration, providing the largest demand and challenges of the belt and restraint system to the occupant. The vehicle structure is assessed and developed for both the FFRW and mPDB cases to maintain structural integrity.

For each case considered, baseline assessment of the passive safety systems is conducted to gather a ‘first status’ of the vehicle and restraint system performance which feeds to critical requirement identification of both the structure and restraint system. The baseline, where relevant, acts as a comparative guide for passive safety developments and target setting.

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4.1. Occupant Model Adaptation & Assessment methods

VIVA+ HBM

To evaluate the crashworthiness performance of the passive safety systems, occupant metrics must be calculated. Therefore, the relevant data must be extractable from all ATD and HBM models. The THOR AV ATDs provided by Humanetics have established methods and sensor systems implemented for the user to extract the probability of injury risks which are verified and validated to their physical counterpart. By performing the established set-up and data extraction methodology, injury risks for bodily regions can be calculated and compared between each load-case scenario considered within Demonstrator 1.

To enable the use of VIVA+ HBM, a few modifications to the original v1.0.1 model were created to enhance the data extraction of the model. Namely, the addition of cross-sections across the pelvis anterior superior- and anterior inferior iliac spine (ASIS-AIIS) and the C1 vertebrae to enable investigation of loading forces across the pelvis and neck respectively. The enhancements assist in identifying key metrics, such as NIC, belt loading force experienced by the occupant and to numerically identify whether there is belt-slippage or submarining. The injury criteria calculable on the VIVA+ HBM is shown in Figure 8.

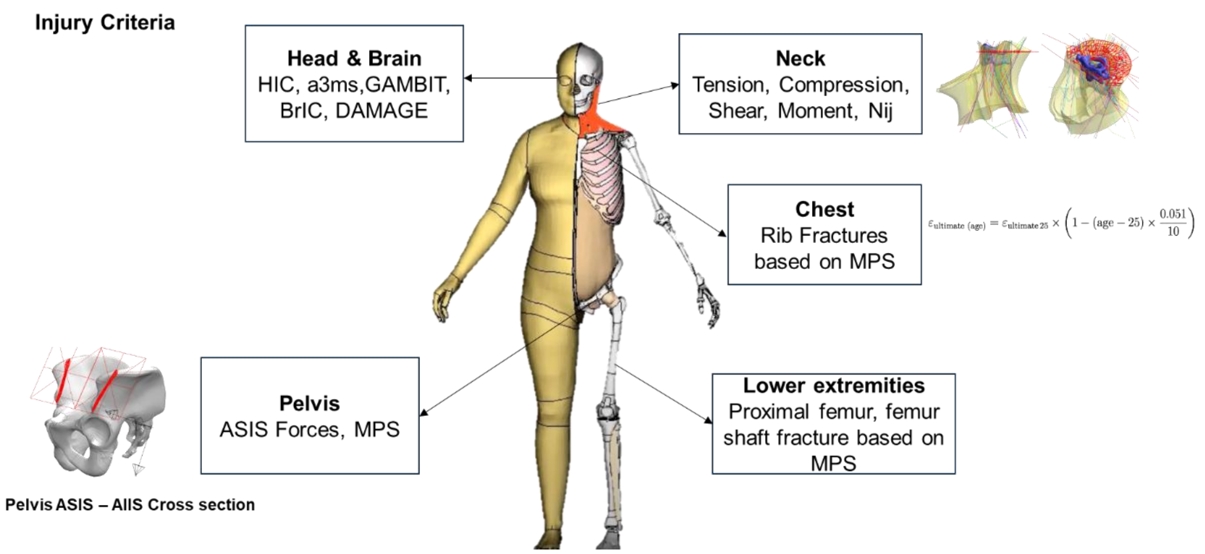

Figure 8. VIVA+ HBM Injury Criteria

Similarly to the injury assessment of ATD occupant models, the VIVA+ has a specific methodology that is implemented to rapidly extract kinematic and kinetic information that enables the calculation of injury predictions. Some methods are different to that of an ATD, such as analyzing maximum principal strain of the ribs to identify the risk of rib fracture. The formulas for injury risk prediction are based on that of a middle-aged female and male, depending on body region, from PMHS data.

To align with Aware2All occupant descriptions, such as physical disability (loss of upper limb). The VIVA+ 50[D]F was created in which the left arm of the VIVA+ 50F model was removed at the shoulder joint. The shoulder joint was chosen for numerical stability and robustness of the model. Figure 9 shows the original and disabled VIVA+ model used for T2.3.

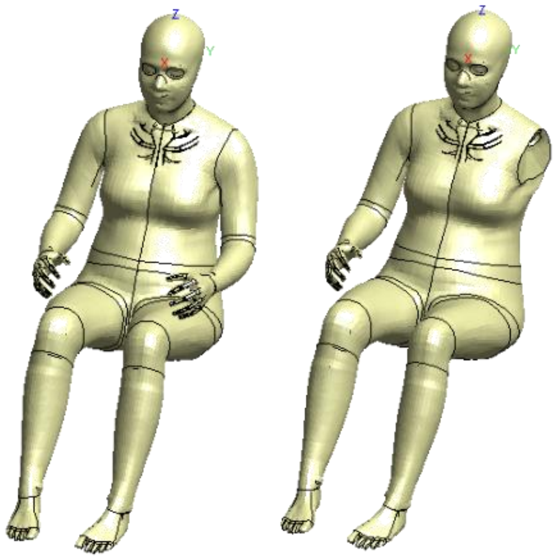

Figure 9. VIVA+ HBM (Left: original [VIVA-50F]. Right: Physically disabled modification [VIVA-50DF])

VIVA+ Posture & Positioning

The VIVA+ HBMs are available in standing and seated postures for pedestrian and occupant assessment respectively. As the restraint system is developed as part of T2.3, the seated posture is selected. However, the seated posture of the HBM is in a driving posture of a conventional vehicle. To align with the permissible seating positions and postures of the UMV PM, the posture of the HBM has been modified. Positioning the VIVA+ HBM can be handled by numerous pre-processing software, including the open-source PIPER tool. Metadata is required to position and articulate the joints of the HBM from the original position of the model. The metadata is formed of key landmarks of the HBM and contains joint data used for articulation and positioning. The ANSA pre-processor was used for the positioning and joint articulation of the VIVA HBM. The HBM posture can be achieved through joint articulation (pre-processor) without the need for numerical analysis, or by the marionette method which requires numerical analysis. The latter requires more computational time due to the necessity of invoking the solver for analysis, however internal contacts and material descriptions of the HBM are respected. On the other hand, pre-processor articulation is very quick and the mesh of the model is 'smoothed' and morphed after the articulation. However, pre-processor articulation is generally only recommended for small variations in joint angles.

As the seating position of the UMV PM can be considered a large variation to the conventional driving position, the marionette method was employed. Following the joint positioning of the HBM, a seat-squash procedure is required to ensure the correct position of the HBM within the seat. This provides the seat cushion deformation and the correct seating location of the occupant. There are pre-processor and numerical analysis methods to conduct the seat-squash procedure. For contact handling, internal stress and deformation of the cushion and HBM flesh, numerical analysis is recommended. However, this method can take considerably longer in comparison to the pre-processor's iterative method. Therefore, an alternative process was created as part of the initial study of restraint systems (Chapter 5.2: VIVA+ 50F Seatbelt Design Exploration) with the VIVA+ HBM, to reduce the computational time whilst yielding the same results.

The process consisted of a combination of pre-positioning and articulation within the ANSA pre-processor, utilizing the metadata of the VIVA+ HBM. A boundary-prescribed motion (BPM) was used to position the occupant in the desired location within the seat. At this stage of the process, the HBM skin was rigidified to enhance computational efficiency. Once in position, the nodal data of the foam and HBM was exported for input within the third stage of the process. To finalize the position of the occupant and stabilize the contact between the seat-foam and deformable HBM flesh, a gravitational load was applied. The HBM and seat are then prepared for use in transient analysis. The process conducted is summarized visually in Figure 10.

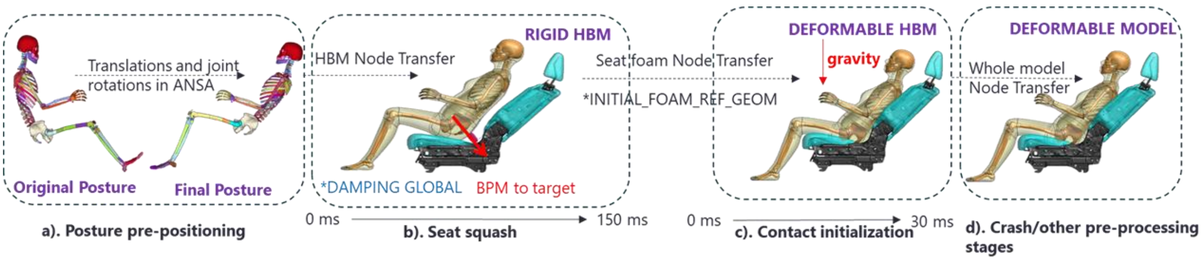

Figure 10. VIVA+ Positioning Process

THOR AV ATD

Occupant kinematics are crucial when evaluating the robustness and safety of a restraint system. Stable and continuous engagement between the belt and the occupant's bony structure during a crash phase prevents uncontrolled occupant movements, which could result in potentially more injurious interactions with unforeseen areas of the vehicle interior or other occupants, and, in the worst case, lead to occupant ejection.

A disability involving the loss of an arm could present challenges for effective upper body retention. To virtually assess the severity of these challenges, a disabled version of the THOR AV FE-model was created. Due to the mechanical complexity of the ATD shoulder system and the goal of generating reproducible results in hardware, the arm was removed at the point where the upper arm is attached to the shoulder joint.

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Figure 11. Disabled THOR AV 5th Female (right) 50th Male (left)

THOR AV Posture & Positioning

The THOR AV FE model can be positioned by pre-processor (joint articulation) or through numerical analysis. The angles permitted for joint articulation are defined within the model tree and whether numerical analysis is required to achieve the desired occupant position. The THOR AV FE models are available in 25°, 45° and 60° reclined positions for HAV assessment without articulation requirements. In this project, the desired seating position of the THOR AV models were achieved through joint articulation applied to appropriate model (25°, 45°). The seat-squash procedure of the THOR AV models was handled within the LS-DYNA environment by explicit analysis.

4.2. Vehicle Architecture

DLR has created a digital twin of their existing vehicle prototype of the NGC UMV PM 2+2 for use in the Aware2All demonstrator 1. Consequently, safety technology is developed and applied in virtual space to the vehicle within Aware2All. Some components of the digital twin do not contain those present in the physical prototype due to the prospective use and operation of the UMV PM. For example, the digital twin does not possess the central joystick controller that is in the physical prototype as the UMV PM, by design, will be a fully autonomous shuttle.

The original design, noted in this document as the baseline, was used to inform decisions on structural changes to enhance the safety and overall crashworthiness of the vehicle by identification of critical structural performance. Thus, the baseline UMV PM contains no structural development that was conducted within Aware2All. The development of safety structures is built by the initial results of the baseline model, noted throughout the rest of the document as UMV PM V2.

The developments are orienteered towards the front-module for the essential use-cases of FFRW and mPDB. In addition, structural changes have also been implemented with thought given to other crash scenarios, such as side barrier or pole impact, although they are not within the scope of Aware2All to be optimized or assessed.

After the baseline performance is established and improvements to the structure (internal and external) have been created, a surrogate model of the vehicle will be generated manually or by using DLR's own software ASMOS (Automated Surrogate Modeling for Vehicle Safety)[13]. The surrogate model will contain the full vehicle front structure relevant for the FFRW and mPDB cases, whilst the rear axle, vehicle mass and inertia are retained to provide comparable crash kinematics. The surrogate model is significantly less computationally expensive in comparison to the full vehicle model, allowing efficient calculation of the vehicle in defined crash loads for the optimization and refinement stages of the passive safety systems. A summary of the ASMOS tool is shown in Figure 12.

The component changes of the frontal structure are limited by verified and validation materials within the DLR database, as well as their respective manufacturing constraints. The refined structural design (UMV PM V2) will be optimized using DLR's optimization framework, CS-OPT[14].

The optimization will alter selected part thicknesses and materials, using key performance metrics (received by the baseline simulation) as targets and constraints. The optimization process performs a Design of Experiment (DOE), which provides the sample data serving as the foundation for the optimization process. Surrogate models are generated from the DOE and Gaussian Processes (GP) and Support Vector Regression (SVR) are used, alongside hyperparameter tuning methods, to assess the predictive accuracy of the models. The optimization process is built to handle continuous, mixed, discrete and constrained optimization problems. Thus, the optimization process will attempt to converge to a feasible solution with the discrete and continuous variables provided (material and part thicknesses respectively) to achieve the optimization target whilst providing the confidence level

[13] Lualdi, Pietro und Schäffer, Michael und Sturm, Ralf (2022) A simplification and optimization approach for vehicle crashworthiness analysis: application on the NCAP MPDB crash test. In: Advances in Structural Dynamic Simulation. Advances in Structural Dynamic Simulation - NAFEMS, 2022-03-29 - 2022-03-30, Online.

[14] Lualdi, Pietro (2024) Surrogate model-driven structural optimization for improved vehicle crashworthiness. DLR-Forschungsbericht. DLR-FB-2024-1. Dissertation. Universität Stuttgart. 195 S. doi: 10.57676/r9p0-zs60 <https://doi.org/10.57676/r9p0-zs60>.

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of the solution. The provided solution output is integrated to the full vehicle model to be verified with a full vehicle crash simulation.

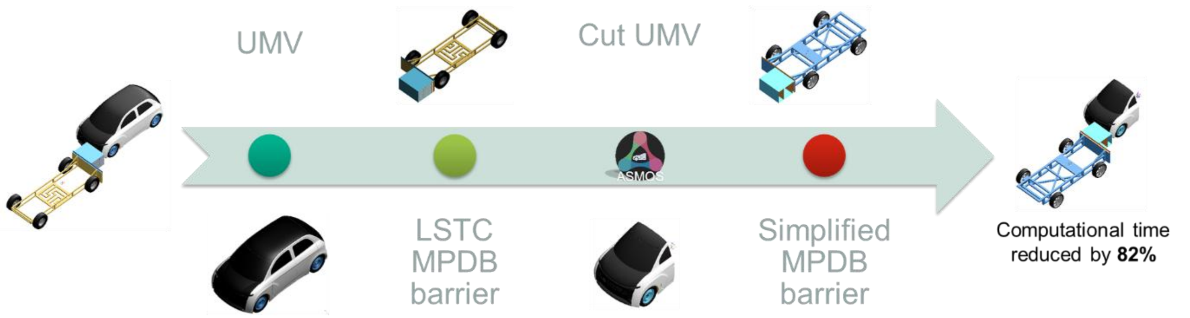

Figure 12. DLR ASMOS flow

A particular challenge of the complex optimization task is dimensionality. As dimensionality increases, the search space (for a solution) grows exponentially, making the optimum solution more expensive and difficult to identify. Therefore, to reduce the number of dimensions, the independent variables used in the optimization definition are applied to key structural components and parts which are critical for a stable and effective crash management of the FFRW and mPDB load-cases.

Model Conversion

Currently, the UMV PM digital twin is held within code for the LS-DYNA environment. The VIRTHUMAN reduced HBM is held within Virtual Performance Solutions (VPS) code (PAMCrash) of ESI and therefore the vehicle model (as part of T2.3 and Demonstrator 1) is to be converted to facilitate the integration of VIRTHUMAN in the demonstrator 1 dataset.

The complex task to convert the complete vehicle and restraint system is conducted in two parallel phases by ESI and their self-developed conversion toolset. The first phase involves converting the vehicle model, including joints, assemblies and airbags (for the vehicle wheels). The second phase focuses on converting the airbag model for integration into the Demonstrator 1 models. The airbag simulation of the integrated systems in VPS is assumed to already be deployed (but not fully inflated) for use in the crash simulations. Thus, the folding procedure and initial deployment of the airbag within the vehicle is not required. The conversion will apply to the finalized model, i.e. after optimization tasks and system integrations are completed.

4.3. Restraint System Development Methodology

As described in Figure 7, the restraint system development has multiple stages covering the construction of the model, concept development, FE development, parameter tuning and integration.

The UMV PM internal structure has been rigidified to decrease computational time. The crash pulse is applied to the vehicle Centre of Gravity (CoG) as recorded by FFRW tests. In the case of when the pulse is too high for effective and safe deployment of restraint systems (over 50G), a generic pulse of FFRW obtained through literature is used. The seat structure has remained deformable for the occupant positioning and restraint system.

The anchorage and housing locations were defined so to inform decisions for the complete restraint system design to abide by requirements and constraints set by the vehicle interior configuration. The main requirements can be summarized as a seat integrated seat-belt system with an over-the-shoulder slipring, no angled footrest and roof-mounted airbag. To align realistic positions and anchorage locations, a workshop between THI and DLR was conducted to take all necessary measurements for the restraint system and to ascertain 'realistic' sitting postures and positions within the vehicle. The 'realistic' seating postures are used for 'relaxed occupancy' and 'occupants engaging in non-driving tasks', conforming as closely as possible to EuroNCAP forward testing protocols for passengers and within permissible allowances of the UMV PM. Using the constraints provided by DLR in respect to housing locations and anchorage locations, the belt pathing and airbag concepts were developed.

The belt-pathing and airbag concepts were implemented with the THOR AV 50M (50th percentile male) model. Initially the restraint system was developed and optimized for the 50th male, followed by a review of effectiveness for a diverse range of occupants, including the 5th female occupant (THOR AV 5F).

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5. Passive Safety Technology - Baseline

The development of effective passive safety technology requires an energy absorbing structure to effectively manage and distribute the forces of a crash from critical regions and to reduce the acceleration exhibited within the occupant compartment. The restraint system is designed to reduce the loads experienced by the occupant across multiple body regions to reduce the overall fatality risk and severe injuries. Therefore, the development of passive safety technologies can be separated into two main branches. The structural elements external to the occupant cabin, and the restraint system constituents within the occupant cabin.

Therefore, the stages of development have been separated into the Baseline (BL) vehicle which contains no alterations to improve crashworthiness of the UMV PM and iteration of design with implemented technologies, henceforth called UMV PM V2. The BL is used for comparison and to identify key areas of interest for vehicle crashworthiness. As can be seen by Figure 7, the restraint system and vehicle model are initially developed separately (with transference of necessary data) until integration into one 3D numerical model. Therefore, it is worth noting that the restraint system developments utilized the key specifications and constraints given for the UMV PM interior, as well as using the BL vehicle crash pulse. The systems are integrated, verified and optimized (structure and restraint system) within T2.4 for evaluation in WP5.To assess the function of both systems, the original structure and restraint systems of the UMV PM is used for comparison against the developed technologies. Relevant criterion is used to quantify the original structure and ensuing evaluations. The development of the safety system technologies is an iterative process and the initial assessment and proof of improvement is therefore provided in D2.3. The full assessment of the finalized safety technologies implemented in Aware2All is assessed in WP5.

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5.1. Baseline UMV PM structure

Dummy models were not included in the UMV PM assessment for computational efficiency; however, a representative mass of 75kg has been added by a connection of spring elements to provide a mass distribution throughout the vehicle of mid-size occupants within the initialization of the crash.

To provide the necessary curve data for restraint system input and to assess the baseline performance, 16 accelerometers were added to the vehicle. These were mounted at the base of each crash can, the center top surface of the motor, the bases of the A-, B- and C-Pillars, between each pair of seats, at the head support of each seat and at the vehicle CoG. This is demonstrated in Figure 13 by the coordinate axes within the vehicle.

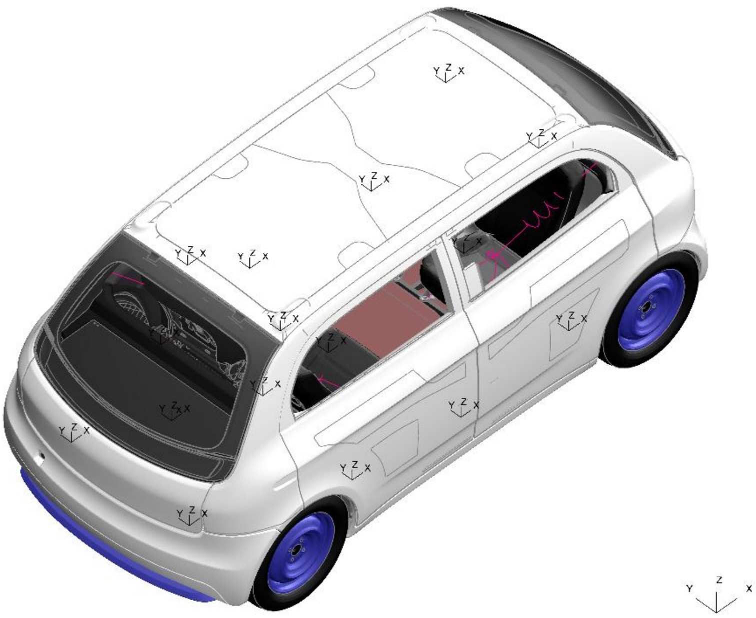

Figure 13. UMV PM Accelerometer locations

The accelerometers are passed through the appropriate channel frequency class (CFC) filter and those of the occupant cabin linked to the vehicle structure are averaged to provide the acceleration components in and about the X-, Y- and Z-axes. Global and part data is also recorded to identify the crash energy distribution throughout the vehicle, which is used to identify the required structural improvements and to assess the overall performance.

Full Frontal Rigid Wall (FFRW)

The FFRW test was conducted at 50kph. Initial assessment of the BL was conducted using the positioned accelerometers to ascertain the generic pulse data and nodal plot data to identify critical regions for development.

It was found that sufficient kinetic energy was not absorbed before the cast wheel arch was engaged, resulting in a large acceleration peak experienced within the occupant cabin. Additionally, the lower

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load path was insufficient to maintain integrity, particularly when combined with the upper structure, leading to an upward trajectory of the front module. A compounding result is that the long rail buckles downward due to the loading condition, rather than initiating a stable crushing response. Together, these factors increase the risk of occupant cabin intrusion, contact with the rearward-facing seats, and the potential for the front structure to detach from the vehicle floor within the transition regions. (Figure 5). Furthermore, the maximum resultant acceleration of the 50kph impact exceeded 50G, formed of longitudinal (x-direction) and vertical (z-direction) accelerations. In addition, troughs in x-acceleration were visible at approximately 17ms and 36ms into the crash phase, which coincides with the unstable collapse of the long rail and mounting module at the front of the vehicle.

Despite this, the resulting load-path was successfully distributed through the reinforced A-Pillar and vehicle sill to maintain the REESS integrity. The longitudinal pulse of the UMV PM BL is shown in FIGURE 14.

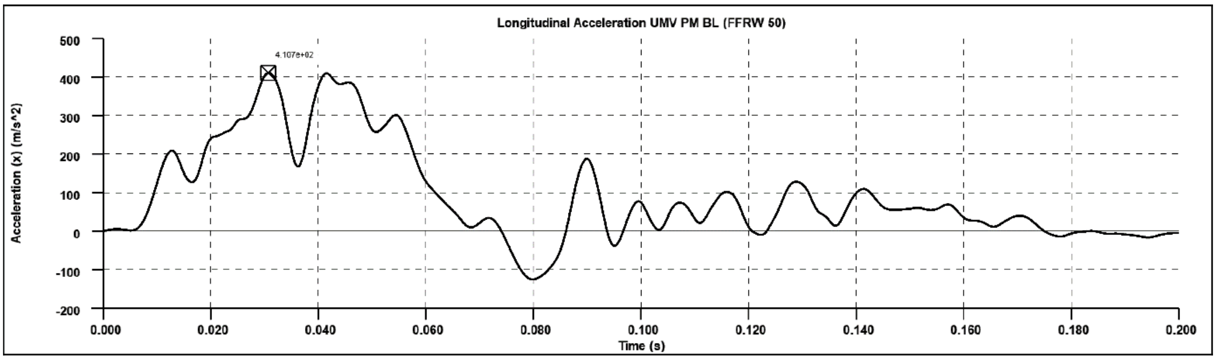

Figure 14. FFRW 50kph UMV PM BL longitudinal Acceleration

Mobile Progressive Deformable Barrier (mPDB)

Similarly to the FFRW assessment, the frontal structure indicated insufficient energy absorbing capability with a similar deformation response observable with the FFRW tests. However, a key aspect is that the mPDB passes underneath the cast structure of the front module assembly, thus increasing the demand upon the crash absorbing elements of the front module and decreasing the crash compatibility. The vertical alignment of the UMV PM to the mPDB is shown in Figure 15.

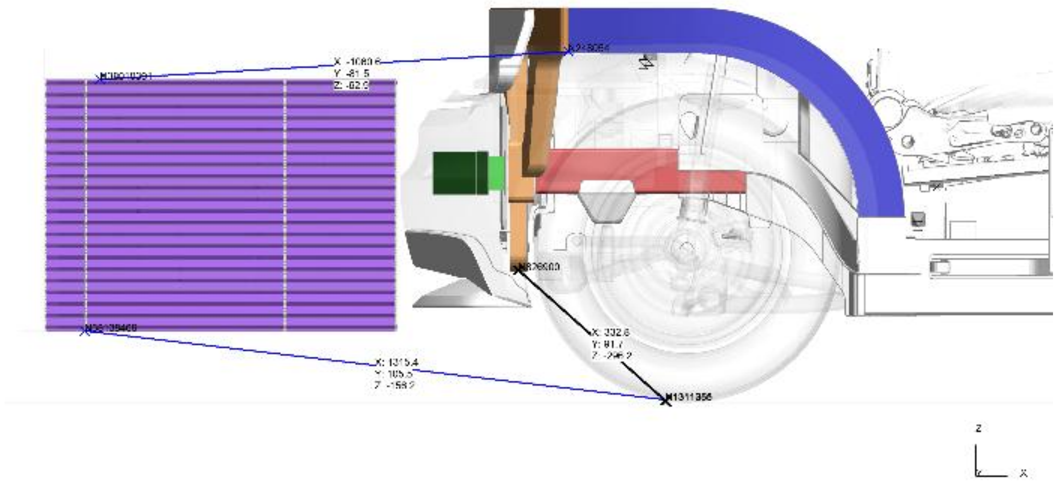

Figure 15. mPDB & UMV PM vertical alignment

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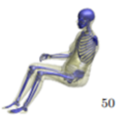
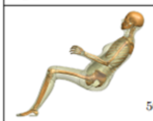
5.2. Baseline Restraint system

Two studies were conducted simultaneously for the first stage of restraint system development. The THOR AV dummy models were used in the UMV PM model and the VIVA+ 50F and 50DF were seated in a sled model of open-source NHTSA seat model with modifications to replicate the seat height of the UMV PM. The VIVA+ 50F and 50DF simulations were conducted to identify potential strategies for restraint system of a HAV (with consideration to disabled occupants) and support the development of the technologies within the UMV PM. The THOR AV models were integrated to the UMV PM Sled model to create the baseline performance of the UMV PM restraint system for evaluation of developed technologies.

VIVA+ 50F Seatbelt Design Exploration

The study has been conducted to identify the robustness and applicability of the VIVA+ HBM for Aware2All requirements and to examine the differences between the disabled and non-disabled response with varying seatbelt designs[15].

For the study, open source models were used for potential dissemination to the scientific community. The occupant model is the openly available VIVA+ HBM, and the seat model is from the National Highway Traffic Safety Administration (NHTSA) Honda odyssey[16]. In line with the UMV PM interior, the floor of the NHTSA seat had been lowered to provide the expected seat posture of the UMV PM. In each case, the seatbelt system was seat integrated to replicate the UMV PM seatbelt pathing restrictions. In total, five virtual sled tests were conducted for forward facing occupancy without foot support, 4 in an upright seated position and 1 in a reclined position. The 5 tests constituted of 50F and 50DF with three different belt designs. This is summarized in Figure 16.

HBM postures	Foot support	Seat belt design	Cases
 50F standard	×	Ⓐ	②
	×	Ⓑ	④
 50 DF standard	×	Ⓑ	⑤
	×	Ⓒ	⑥
 50F reclined	×	Ⓑ	⑦

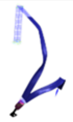
Seat belt design	SLL¹	BLL	ALL	SPT TTF	BPT TTF	APT TTF
 Ⓐ	2.5 kN	-		12 ms	-	
 Ⓑ		4 kN			12 ms	22 ms
 Ⓒ						

Figure 16. VIVA+ 50[D]F and restraint system investigation summary

Where, SLL - Shoulder belt Load Limiter, BLL - Buckle Load Limiter, ALL - Anchor Load Limiter, SPT - Shoulder Pretensioner, BPT - Buckle Pretensioner, APT - Anchor Pretensioner, TTF - Time To Fire.

[15] HARRISON, ANDREW (2024) INITIAL EVALUATION OF UNDERREPRESENTED OCCUPANTS IN HIGHLY AUTONOMOUS VEHICLES USING VIVA+ HUMAN BODY MODEL. 7TH INTERNATIONAL SIMBIO-M CONFERENCE, 2024-09-24 - 2024-09-25, ONLINE.

[16] BRIDGES, W.; GANESAN, V.; BARKI, G.; JAYAKUMAR, P.; DAVIES, J.; UMASHANKAR, S.K.M.: INTEGRATED SEAT BELT SYSTEM MODEL DEVELOPMENT. AVAILABLE FROM: HTTPS://WWW.NHTSA.GOV/CRASH-SIMULATION-VEHICLE-MODELS

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The pulse used for the sled test is the OSCAAR Sled Pulse[17] as presented in Figure 17. Seatbelt design A (SBD-A) is the standard 3-point seatbelt, Seatbelt design B (SBD-B) is an advanced 3-point seatbelt system as it utilizes BLL, ALL, BPT and APT. Seatbelt design C (SBD-C) is a 4-point restraint which shares the same belt loading and firing time parameters as B, with an additional belt strap across the occupant's right shoulder that share the limiting values. This denotes that the ALL and BLL, for example, of SBD-B is equivalent to that of SBD-C.

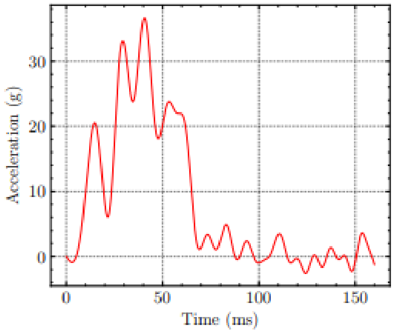

Figure 17. OSCAAR Frontal Crash Pulse (Höschele et al. 2022)

The VIVA+50DF and 50F were positioned and the seatbelt was pathed over the occupant body and chair in the same process and defined locations to minimize effects of belt pathing influences on the occupant response. The VIVA+ HBM occupant models were positioned by the method described by Figure 10, from the 'driving posture' into the 'normal sitting posture' and 'reclined sitting posture', shown in Figure 18.

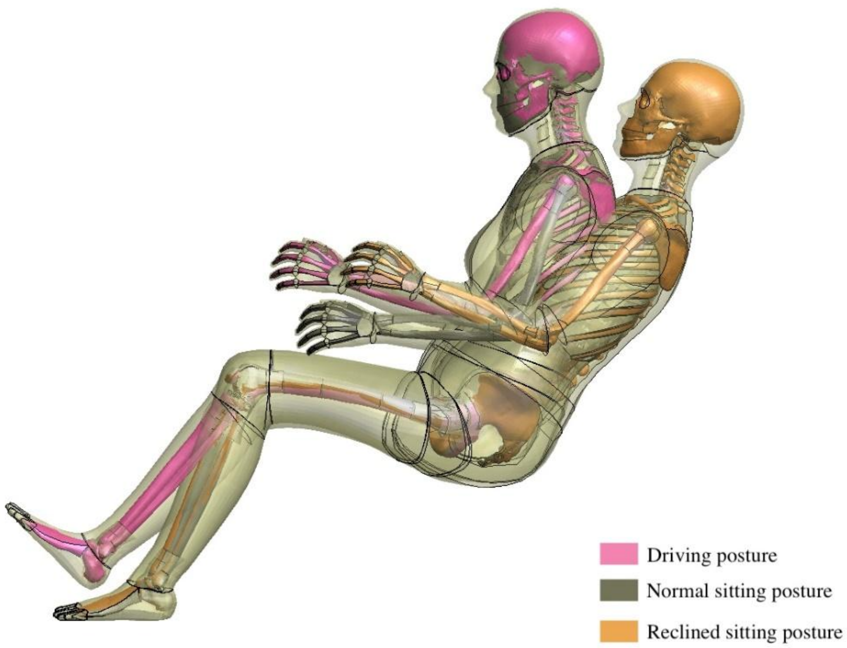

Figure 18. Sitting posture of VIVA+ HBM in case study

[17] Höschele, P.; Smit, S.; Tomasch, E.; Östling, M.; Mroz, K.; Klug, C.: Generic Crash Pulses Representing Future Accident Scenarios of Highly Automated Vehicles. SAE International Journal of Transportation Safety, Vol. 10, No. 2, pp. 09–10–02–0010, 2022.

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VIVA+ 50F Seatbelt Design Study Results

Initial visual kinematic indicates potential advantages of SBD-B over SBD-A by observing the occupant excursion in the seat. Although a similar kinematic response is otherwise observable, it is predicted that with the shared load limiting of independently acting belt limiters that a greater distribution of load across the occupant pelvic and torso region will be apparent. This is evidenced between Case 2 (SBD-A) and Case 4 (SBD-B) in which the probability of more than 1 fractured rib is consistently less with SBD-B than SBD-A. In addition, SBD-B of case 4 reduced the pelvic loading in comparison to SBD-A by 30%, however the loading of the pelvis of SBD-B was still too high to achieve 'safe' values. SBD-B of Case 4 also reduced other injury likelihoods across the neck and head region in the upright position, although marginally. The general kinematics of the upper regions between the two Cases remained comparable. Figure 19 shows the probability of injuries by injury criterion of the Cases: 2, 4, 5, 6 and 7. The data was normalized by injury criteria of the respective region for ease of comparison. The injury criteria of the Hybrid-III 50M ATD were used as limiting values for calculating injury risk in the head and neck regions, against which the results were normalized. However, the likelihood of rib fracture is a probability metric based on the maximum principle strain within the rib cage and therefore does not need to be normalized. It is known that the Hybrid-III 50M limits cannot be directly applied to the VIVA+ 50F HBM; however, they provide a suitable reference for comparison between seatbelt designs.

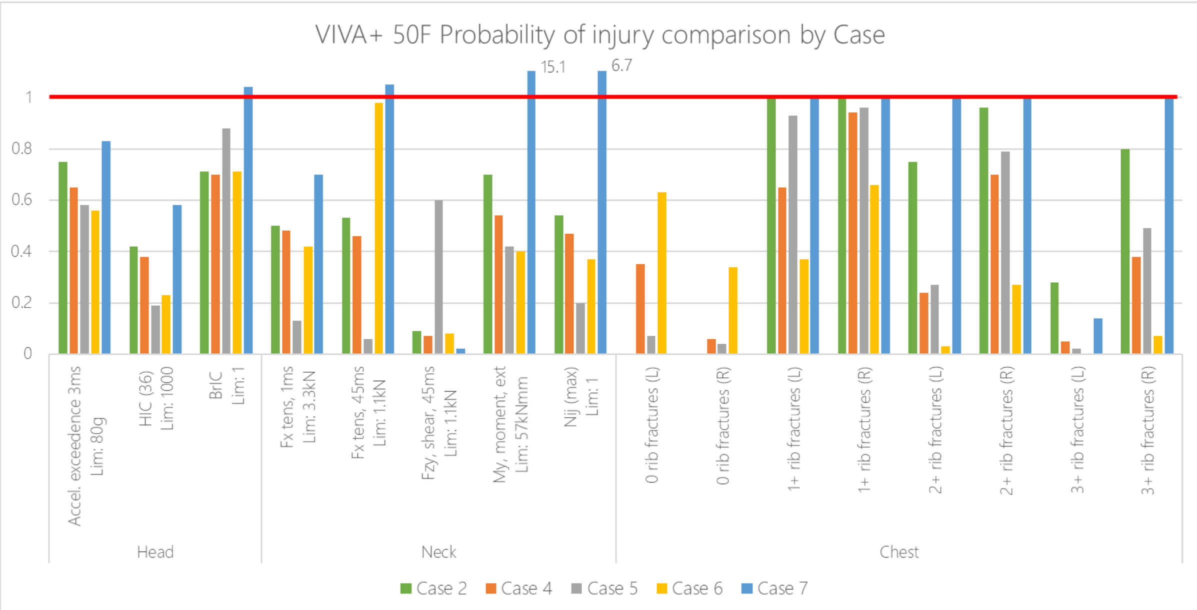

Figure 19. VIVA+ 50F Probability of injury comparison by Case (Open-source Sled Study)

The SBD-B was employed on the 50DF occupant model with the shoulder belt passing over the side of the occupant with the missing limb (case 5). The results indicate that the SBD-B is insufficient in restraining the 50DF occupant as the shoulder belt slips from the shoulder at approximately 75ms. This permits a rotational movement of the occupant about the vertical axis. The rotational motion, compounded with lack of torso restraint, results in a larger seat excursion in the lateral direction of the seat and an increased torso compression. The larger rotation of the torso could be the cause of the increased injury risk of BrIC and Neck shearing. The kinematic response of the 50DF with SBD-B is shown in Figure 20.

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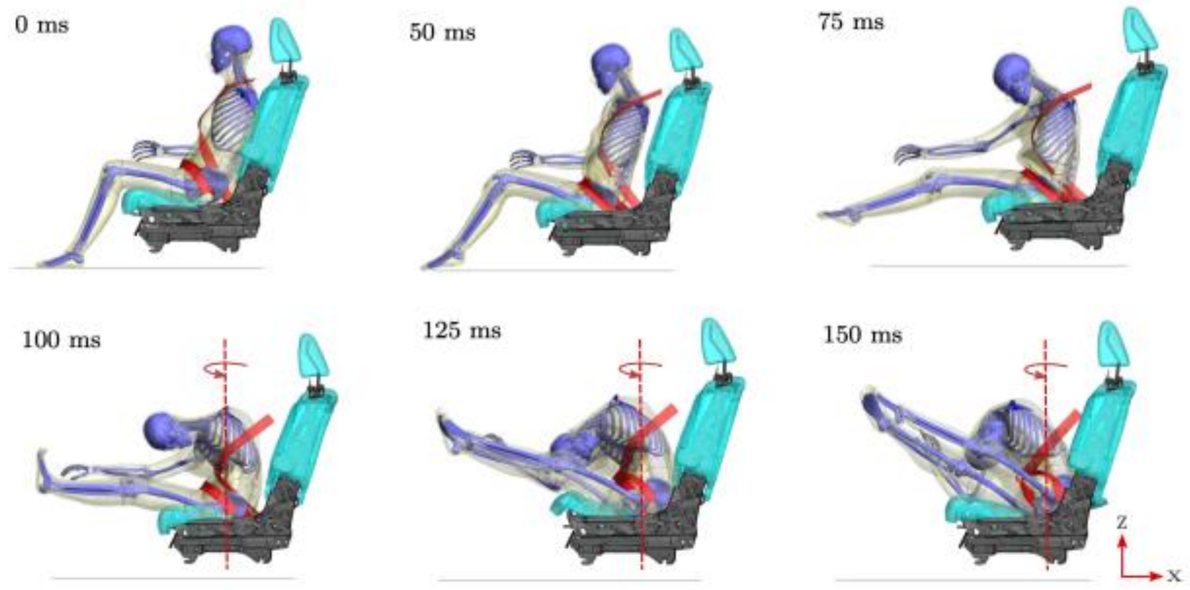

Figure 20. VIVA+ 50DF Sled Kinematic Response SBD-B (Case 5)

To counteract the rotational movement of the occupant, SBD-C was investigated with the 50DF. Initially, the SBD-C appears to be more effective in restraining the 50DF occupant more effectively. The shoulder belts of SBD-C do not slip off the occupant, the seat excursion is reduced and no rotations about the vertical axis are immediately noticeable. In the initial stages of the crash pulse, the loading to the pelvis appears to be similar between the belt systems with similar kinematics of the lower extremities. An overlap of the response is presented in Figure 21. However, as shown in Figure 19, the neck tension forces increase substantially in comparison to other belt designs, warranting further investigation for mitigative solutions.

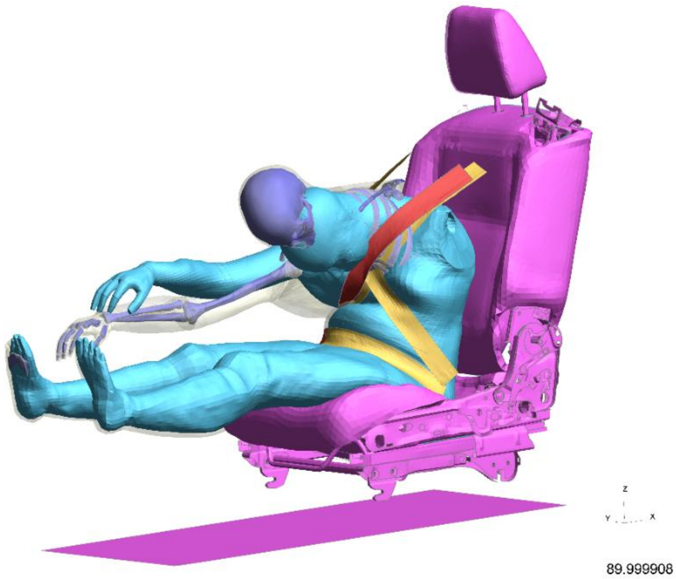

Figure 21. VIVA+ 50DF kinematic at 90ms of SBD-B (red belt and skeletal view) and SBD-C (opaque view with yellow belt)

The reclined position with SBD-B (case 7) resulted in considerably higher loadings in the head, neck and chest regions. The results indicate that seat-integrated 3-point seatbelts, which are not adapted for reclined positions, could cause severe injuries to the occupant or cause the restraint system to fail the evaluation. The high loading is due to the shoulder belt moving upward to the occupant's neck, as well as exhibiting a 'clotheslining' effect, where the occupant is caught by the seatbelt, increasing loading and acceleration in all upper regions. Figure 22 shows the shoulder belt moving into the neck and the lap belt slipping above the pelvis bone.

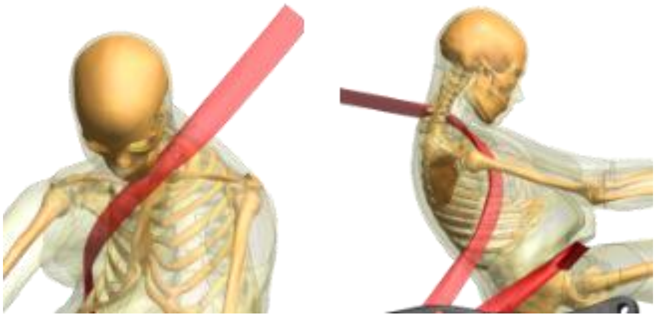

Figure 22. VIVA+ 50F Reclined Response with SBD-B (Case 7)

It should also be noted that the model is not validated with the crash pulse utilized. Therefore, the results from this assessment need to be validated against existing models or PMHS data, which is out of scope within Aware2All. Nonetheless, the results of the VIVA+ HBM provide insights into the implementation of restraint system strategies within the UMV PM.

THOR AV - UMV PM

For the baseline approach, THOR AV 50M occupants were positioned in the UMV PM in opposed seating configurations. The seatbelt was applied with the agreed fixing locations as conducted by the T2.3 Workshop. Initial pulses provided by the UMV PM FFRW tests were applied (Figure 14) without the use of airbags to identify the occupant kinematic response and to identify requirements of the entire restraint system.

With the original seatbelt anchorage locations, load-limiter definitions and pre-tensioner forces, large occupant excursions of the forward-facing passengers were observed. In addition to this, the 'leg-lift-off' resulted in hard contact of the vehicle interior of the opposed seating structure. Furthermore, the torso angle reached throughout the crash phase showed signs of occupant self-contact of the head striking the knee.

The rearward-facing occupant exhibited large vertical pelvic excursion from the seat throughout the crash-phase. The occupant excursions from the seat as well as contact with hard-points of the interior provided insights to the requirements of the airbag design and belt-system parameters which have been developed upon.

The occupant ATDs were placed according to the load cases already defined to develop the restraint systems. To reduce the computing time of the simulations, only one dummy was used for the development, and the interaction with the other occupants was subsequently checked in combined simulations. For reasons of simplicity, only one dummy is shown in the shuttle in each of the immediately following figures. Figure 23 shows the occupants sitting forwards for UC1.2.

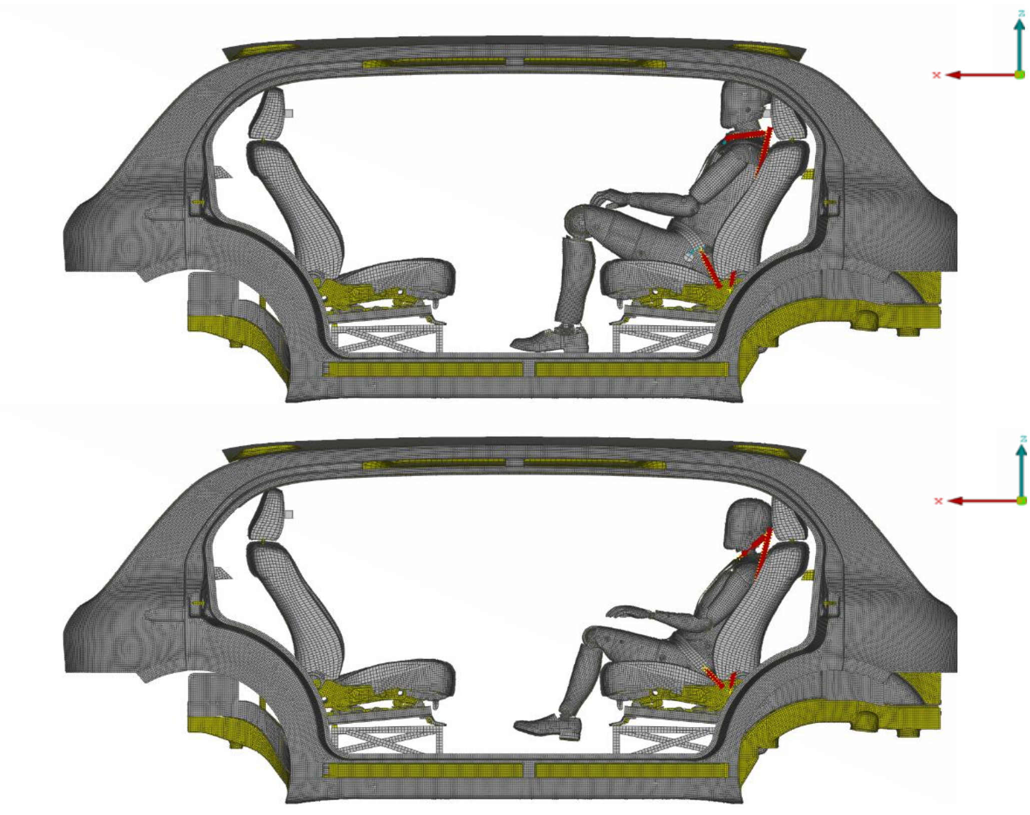

Figure 23. Occupants in forward facing orientation (UC1.2)

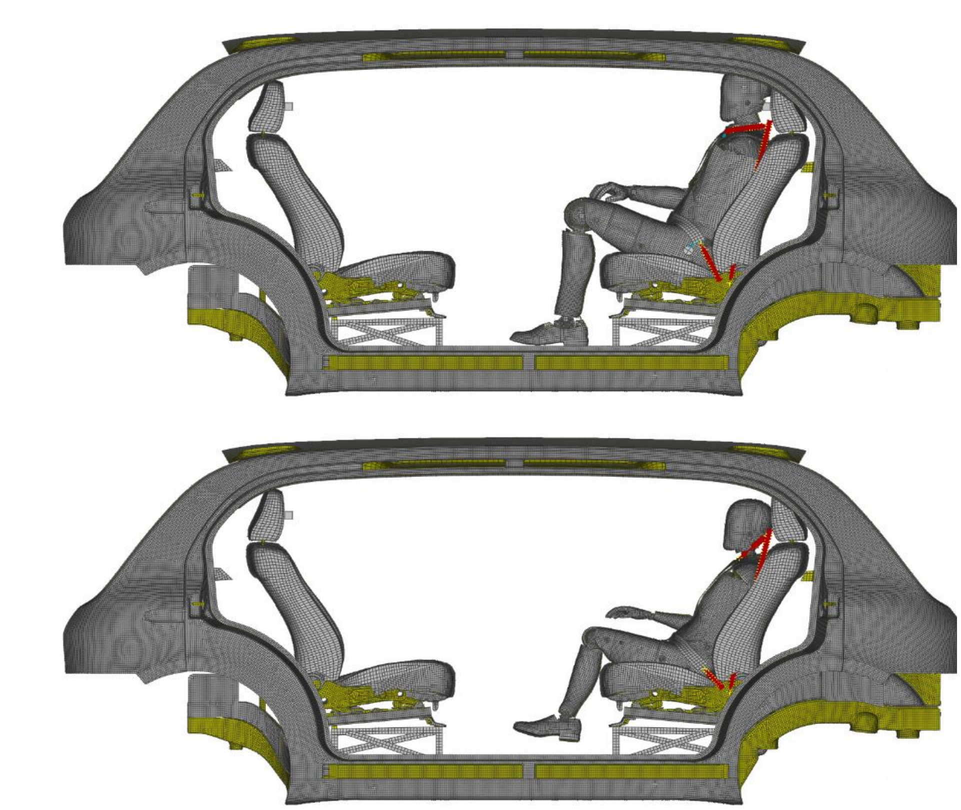

Figure 24. Disabled occupants in Forward Facing Orientation (UC1.2)

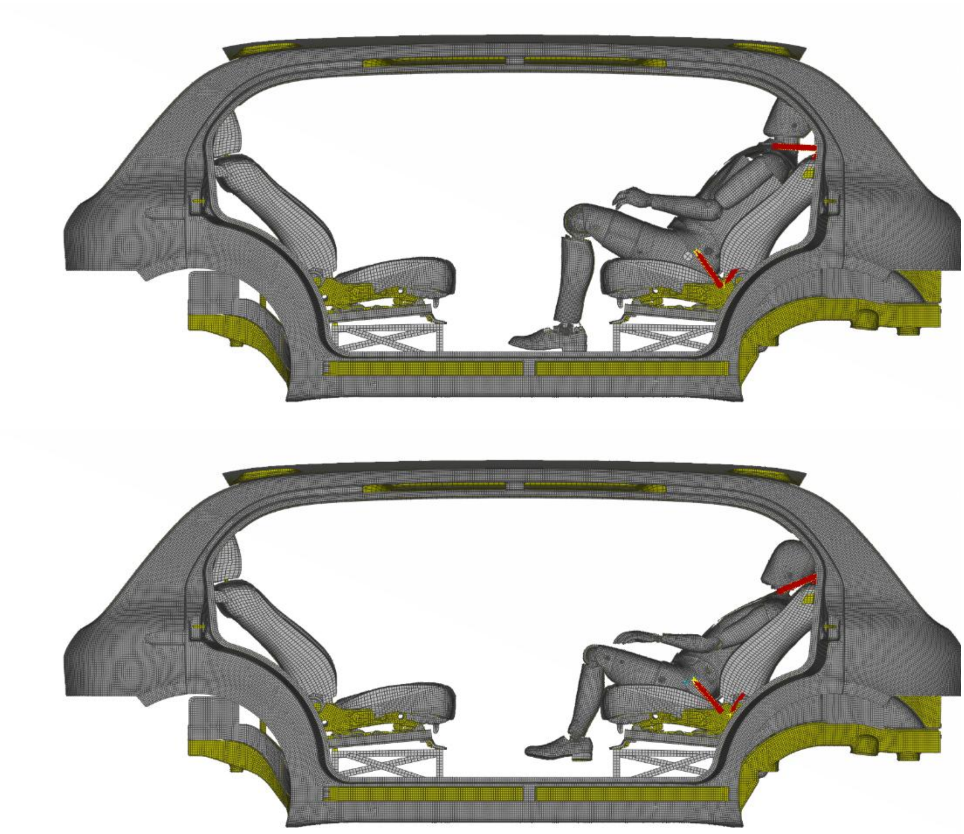

Figure 25. Occupants in Forward Facing, reclined (45°), orientation (UC1.4)

In each case from Figure 23, Figure 24 and Figure 25, the Baseline FFRW 50kph pulse was applied to the simplified UMV PM sled model. Similar kinematic results to that of the VIVA 50F study (5.2: VIVA+ 50F Seatbelt Design Exploration) were observed. The results will be shown collectively with the restraint system technology results in Section 6.

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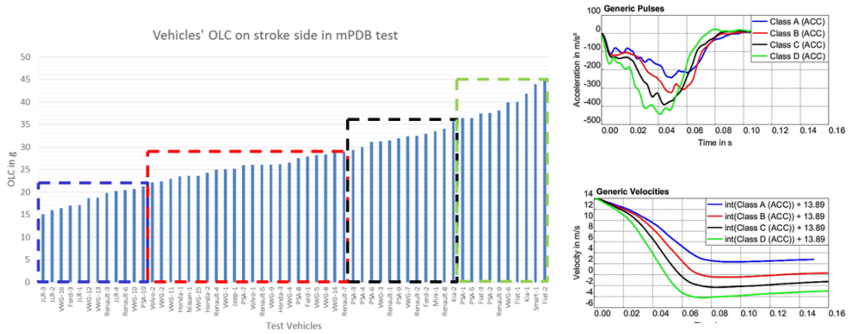
6. Passive Safety – Technology Development

This section provides information regarding the development and initial outcomes of the passive safety system technologies implemented within the scope of Aware2All. The following chapters highlight the key challenges addressed with respect to the vehicle architecture and the complete restraint system, as outlined in the Baseline Vehicle. (section 5).

6.1. Vehicle Architecture Development

Targets were identified to reach class C for the mPDB crash cases of the UMV PM as defined by E.Sadeghipur (2019)[18].



Class	OLC Range	No. Data	$OLC_{generic}$
A	≤ 22g	12	18.8g
B	22g < ≤ 29g	22	25.5g
C	29g < ≤ 36g	12	32.0g
D	> 36g	10	39.0g

Figure 26. Generic Pulse for Knee Mapping Sled test Procedure 2020 (E. Sadeghipour 2019)

The structural developments of a new design (UMV PM V2) aim to increase kinetic energy absorption in both load cases and reduce intrusion risk by extending the effective crash structure, implementing new components, and enhancing the performance of load-path distribution within the constraints set for the UMV PM packaging and configurations.

Firstly, the front structure extended the crash-can length from 89mm to 176mm and increased the average depth of the crash beam by 4mm. In addition, a lower crash beam and crash can were added to transfer a greater load through the lower load path, which is especially critical for the mPDB load case. The lower crash elements provided 136mm and 24mm to the crash can and crash beam, respectively. Furthermore, the interior configuration of the crash elements was selected based on numerous studies for high-energy absorption within a short crush length. An open-cell hexagonal profile was chosen for the crash cans, and extruded reinforcement ribs span the length of the crash beams. The extension of the crash elements maximized the space available under the bodywork while still allowing sufficient space for a deformable component designed for pedestrian impact. These adaptations were facilitated by alterations to the cast-mounted structure of the front module. Following the manufacturing constraints of the part, the vertical span was extended to accommodate the lower crush elements and their connection to the axle, and sufficient pockets for the main (upper) crash cans were introduced. Reinforced connecting brackets were added to the vertical mounting module to resist the bending moment observed in the Baseline vehicle.

With consideration to other use-cases as per the M1 vehicle class requirements, the side structure was also changed to better withstand loads generated by pole and barrier side impact tests. A particular challenge arose to create a strong, well-connected B-Pillar due to the central opening mechanisms of the doors which slide along the vehicle to allow passengers to embark and disembark the vehicle (Figure 4). Nonetheless, a new pressed inner-structure, B-Pillar reinforcement sheets were introduced at the seam of the door with reinforcement cross beams diagonally and horizontally fixed across the span of the door. In addition to supporting the retention of integrity, the reinforcements were also designed to provide better distribution of crash loads from the wheel arch through the BIW of the vehicle. The vehicle sill was modified with an open-cell extrusion spanning its length to

[18] E.Sadeghipur 2019, published in: Euro NCAP, "Euro NCAP Sled Test Procedure for Assessing Knee Impact Areas," Version 4.0.1, Euro NCAP, 2020.

encompass and protect the new door closing mechanisms, while retaining the load transfer around the battery pack. A simplified rendition of the updated load-path from a frontal collision is provided in FIGURE 27.

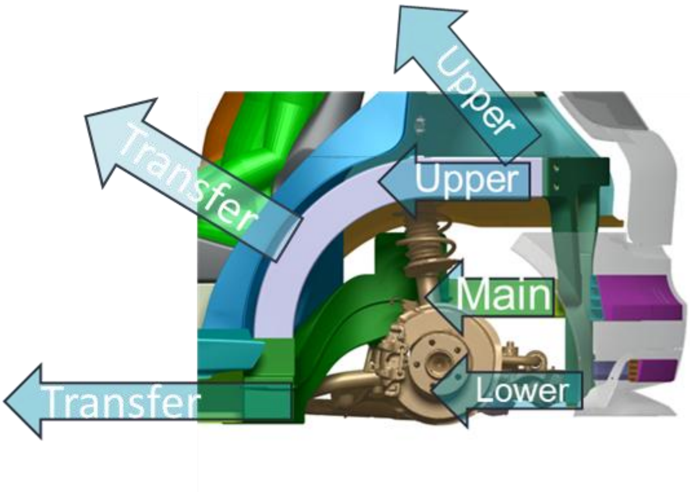


Figure 27. UMV PM V2 Frontal Load-Path Rendition

To maintain the vehicle mass and its distribution, the addition and alteration of components were measured, and the thickness and material selection were carefully monitored. Further refinement of the material selection and thickness will be made during the optimization stage of T2.4 for the successful development of Demonstrator 1.

Structural Development Results

To align with restraint system development, the UMV PM V2 FFRW at 50kph test was conducted. The longitudinal pulse from the CoG of the vehicle is presented in Figure 28.

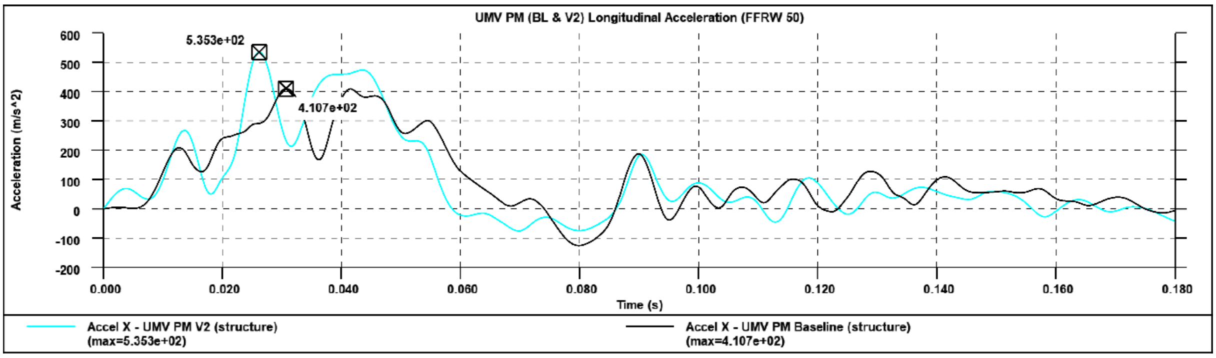


Figure 28. FFRW 50kph UMV PM BL & V2 designs, Longitudinal Acceleration

It can be seen in Figure 28 that the UMV PM V2 shows a higher longitudinal acceleration at the vehicle's CoG than the Baseline. The pulse also indicates the collapse of crash management systems at 15ms and 30ms by a steep decline in acceleration immediately following the initial peaks. It can be seen that the general shape of the curve indicates earlier engagement in the FFRW impact due to the added Crash Management Structure (CMS); however, the collapse of components is more severe, as highlighted by the greater amplitude between the peaks. Nevertheless, the purpose of the investigation was to provide an overview of the system's performance and to identify regions relevant for optimization. This model successfully provided insights into the energy absorption distribution of the components and identified critical areas for reinforcement. Specifically, a similar deformation was observed in the long-rail elements of the UMV PM V2 as in the Baseline, where the

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failure was bending-dominant rather than providing a crushing response. As a result, a comparable response of the frontal structure was noted, where, as the crush length increases, the frontal components follow an upward arc trajectory. In combination with the engagement of the reinforced cast wheel arch, this resulted in the firewall impacting strongly against the seatback of the rearward-facing seats, with significant flexure of the seatbacks observed from the sudden deceleration of the vehicle. This could lead to adverse effects on the restraint system's function and an increased load directly applied to the occupant.

The structural integrity of the rearward-facing seats presents unique challenges. Firstly, maintaining vehicle integrity during a severe frontal crash pulse with restricted packaging space; secondly, reducing the longitudinal pulse enough to decrease seatback flexure without inducing intrusions or seatback-vehicle contact. Within the seat model, the seatback flexure around the seat-adjustment motor axis (located on one side of the seat), which connects the seatback to the seat pan, exhibits larger deflections on the side of the seat without the motor control system. As a result, the seatback twists around the local vertical axis, and the side without the motor control unit makes hard contact with the vehicle interior. This behavior is undesirable as it compromises the safety of the occupant and the restraint system. Therefore, a two-step approach to mitigating this effect must be implemented. The first step is to minimize the intrusion of the firewall in line with the seatback, reducing the risk of collision due to intrusion. The second step is to reinforce the seat structure to reduce flexure and provide protective housing over the belt system components. It is important to note that while contact with the firewall is not observed in the 30 kph impact, significant flexure of the seatback remains, which would detrimentally affect the performance of the entire restraint system.

The seat motor addition has been made to each occupant seat within the vehicle. Furthermore, a surrogate vehicle model was generated using the methods described in Section 4. The UMV PM was cut through a vertical plane offset from the door seam. All parts rearward to this plane were removed, except for the rear suspension system to maintain proper vehicle dynamics throughout the crash phase. The UMV PM V2 inertia and mass was retained in the Surrogate vehicle model to conserve the initial crash state and crash behavior between the vehicle models. The side view of the surrogate vehicle model is shown in Figure 29.

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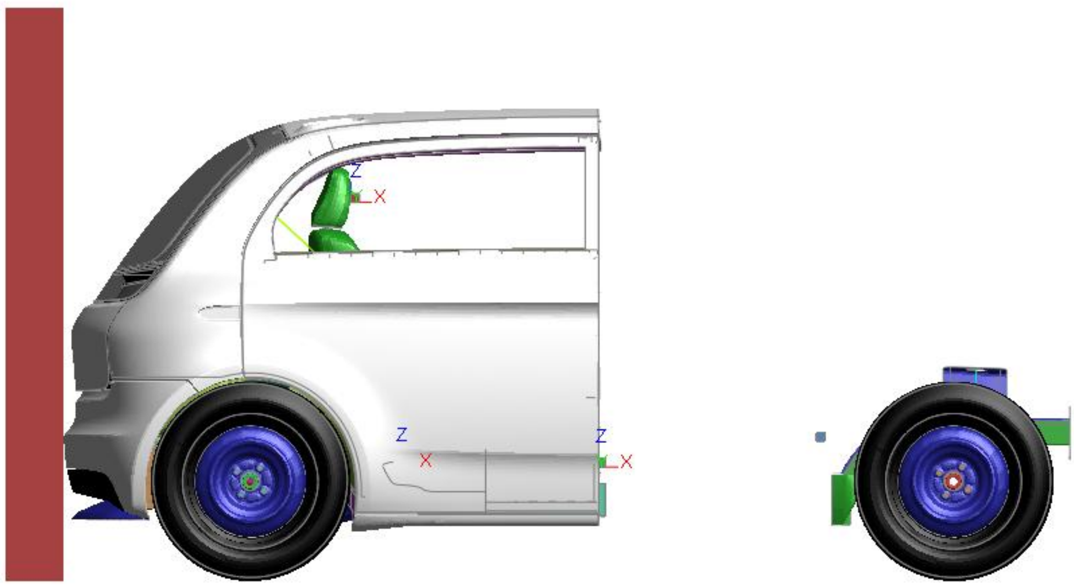

Figure 29. UMV PM Surrogate Vehicle Model

The Surrogate vehicle model has been created with a maximum of 26 continuous variable parameters (section thickness) of the CMS. Approximately 16 additional discontinuous variables (material) are available for the selected parts. However, due to the complexity of the optimization task and to ensure manufacturability, the number of material variables in the optimization process will be limited for each part. Similarly, the range of thickness for the continuous variables is established to be within manufacturable ranges.

The number of elements in the vehicle model, using the surrogating method, was reduced from approximately 2 million to 1.1 million. This reduction is crucial for computational efficiency within the CS-OPT framework, as the explicit solver is invoked throughout the feedback loop. For 180 ms of simulation time with the same CPUs, the calculation time of the surrogate model was approximately 64% shorter. While creating a surrogate model can lead to unrealistic or dissimilar behavior compared to the full model, it is important to verify that the surrogate model behaves similarly to the full vehicle simulation. One method of verification is to ensure the energy balance of the simulations is correct. The vehicle energy balance plots for the surrogate and full vehicle simulations in the FFRW 50 load case are shown in Figure 30. In which K.E, I.E and T.E are kinetic energy, internal energy and total energy respectively.

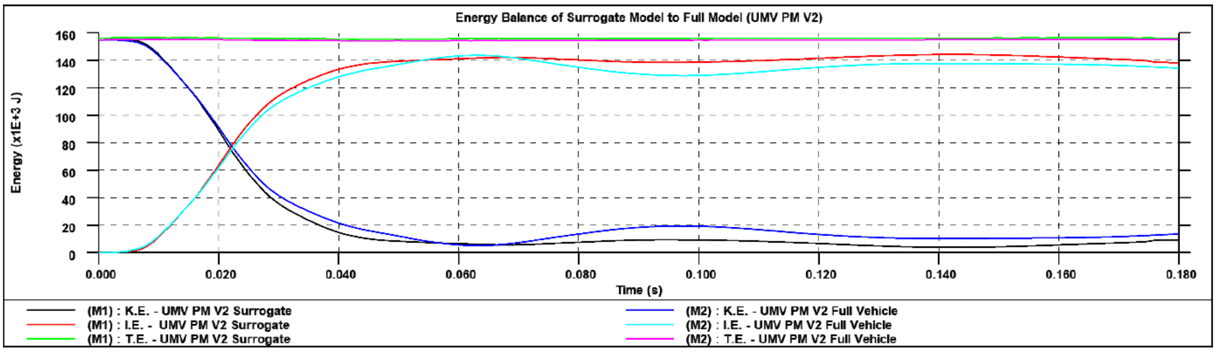

Figure 30. UMV PM V2 Surrogate Model Verification

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Furthermore, the required variables and respective ranges, sampling strategies and assessment methods of the surrogate vehicle have been built into the CS-OPT tool. An overview of the optimization process is shown in Figure 31.

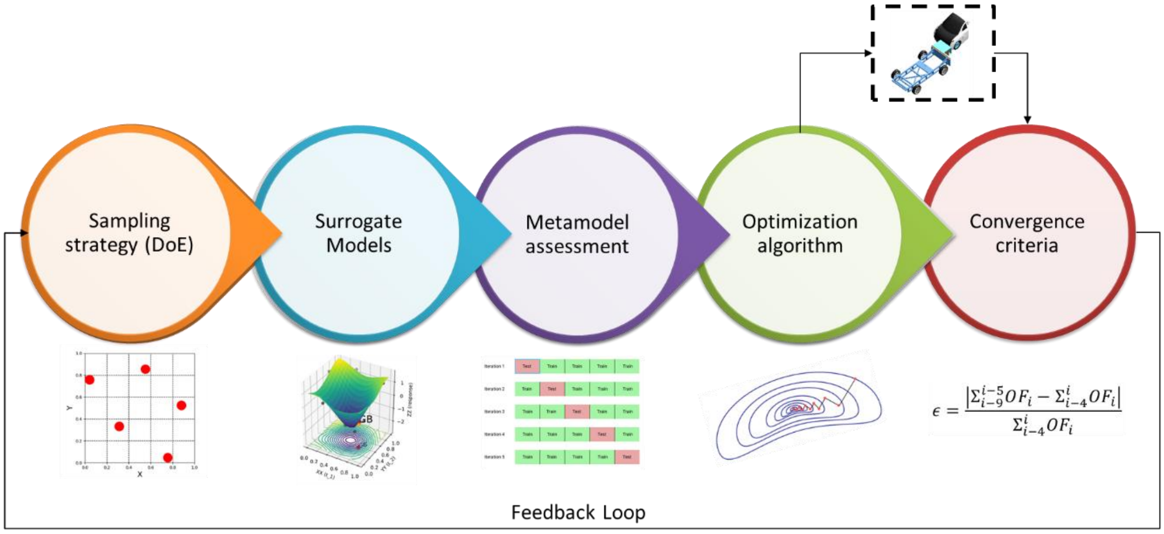

Figure 31. CS-OPT Optimization loop overview

The CS-OPT tool will be used throughout T2.4 to optimize the front CMS to meet structural targets, namely intrusion requirements and Occupant Load Criterion (OLC) for assimilation with the developed restraint system technology.

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6.2. Restraint System Technology Development

There are challenges in the development of the restraining systems for a HAV. Comparing a conventional vehicle with a driver and passengers in a two- or three-row seating configuration, such as a mid-size car, van, or SUV, and an autonomous vehicle, as in the shuttle developed in Aware2All, there are differences in the position of the restraint systems and the passengers themselves, as well as the lack of reaction surfaces (windscreen, dashboard, footwell area) that interact with the occupant's lower limbs and that can be effectively used by airbags to distribute the load over multiple load paths, supporting the reduction of occupant excursion. In future interior designs with four seats, two seats will be positioned across each other. Figure 32 shows the two types of cars (conventional and HAV) and the load paths in a crash from the occupant through the restraint systems to the car structure. As can be seen, there are differences in the load paths, as shown by the red arrows. Movements are illustrated with blue arrows.

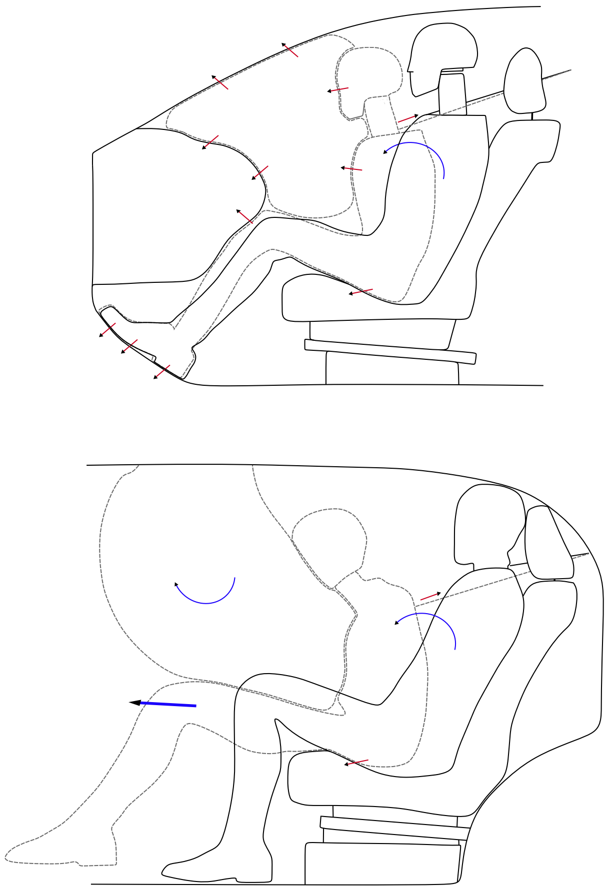

Figure 32. Load paths in crash (conventional vehicle above, HAV vehicle interior below)

First, it is essential to consider the load path in a conventional vehicle, particularly in the first row of seats. The occupants are seated facing the dashboard, which is a critical factor in the expected injuries and the design of the restraint systems. The restraints and load paths are first transferred from the occupant to the seatbelt. The ignition and deployment of the airbag extend the restraint system. The energy generated by the movement and impact of the head is transferred to the airbag,

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which is held in position and supported by the instrument panel and windshield, allowing the airbag to fully deploy and absorb the occupant's energy throughout the restraint phase. The occupant sits on the seat and rests their hands on the sloping floor structure specially installed in the vehicle. The occupant's legs transfer energy to the floor structure during the accident. The slight forward movement of the occupant also results in contact between the lower half of the dashboard and the knees, which also provide support and absorb energy, reducing the energy to be absorbed by the restraint systems.

Looking at the interior of the future, the sloped floor and dashboard have been removed. The occupant now sits in the shuttle with their feet directly on the floor, facing an empty space and the next passenger. In the event of a crash, the occupant will also experience forward motion. Due to the absence of the footrest, neither support effect nor energy absorption can be realized, and the occupant moves further away from the seat in the x-direction, i.e. pelvis excursions tend to increase. When the airbag deploys, the coupling with the occupant is achieved due to its size, but since there is no dashboard and windscreen support, the airbag volume displaces and rotates away, as indicated by the blue arrows, and therefore cannot absorb the energy of the impacting occupant without moving itself.

The occupant is therefore not optimally restrained and additional energy must be dissipated via the seatbelt, resulting in larger loading on the occupant’s anatomy.

The position of the airbag is strongly influenced by the design of the vehicle interior. The shuttle was assessed during the workshop between THI and DLR at the DLR facility in a first step. Measurements were also carried out at the workshop with the physical UMV PM prototype and the information gathered was subsequently transferred to the demonstrator's digital twin. In addition to the challenges mentioned in Figure 32, further challenges related to the airbag arose. For example, the position of the airbag is not trivial, nor is the attachment for proper functioning and restraint of the occupant. Since there is no dashboard directly in front of the occupants, using a solution similar to those found in current vehicles is impossible. To effectively position the airbag and protect the occupants, a detailed examination of the shuttle was conducted to identify suitable locations for the airbag and assess their viability. Each side of the shuttle has two sliding doors, which form a B-pillar in the center but offer little space for the integration of airbags due to the package of the doors. Another option is the floor. However, an airbag deployed from the floor is impossible due to the limited space. Especially if there are four occupants in the shuttle or objects on the surface between the seats, the deploying airbag will injure the occupants. Another and final option is the greenhouse. Both the airbag and the gas generator can be placed here.

To ensure sufficient occupant restraint with low inflation times, the decision was made to use four separate airbags, which can be deployed based on load direction and occupant characteristics, such as size and weight. In the simulation of the baseline variant with a THOR AV 50M dummy and no airbag installed, the dummy's kinematics were analyzed to derive the airbag's shape. To prevent the head from striking the legs and causing serious injuries, the design favored an 'L'-shaped airbag. This configuration prevents the legs from moving upward, keeping the head and neck from being displaced too far, thereby minimizing injuries. The L-shape was evaluated in various forms and variations, with adjustments made to the airbag's length, height, width, and the angle of the contact surface. These adjustments aimed to reduce neck bending and strain, head acceleration upon airbag impact, and chest compression due to the airbag's volume. Furthermore, considering different groups of individuals, the airbag needed to be positioned at an optimal distance from the

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occupant—neither too close nor too far. These variations ultimately led to the design of the airbag described below.

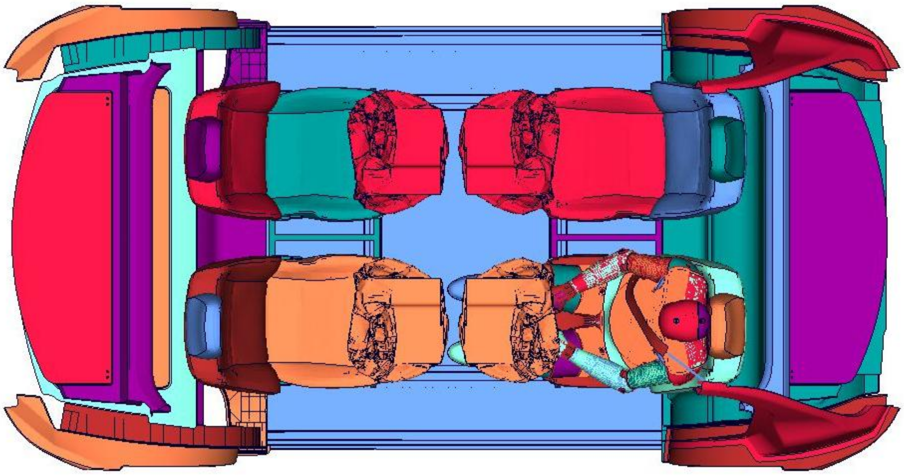


Figure 33. Airbag Placement (topview) within the UMV PM

A volume of 110 liters can be achieved at maximum expansion, used for the THOR 5F, which represents the fifth percentile female occupant. As there is a monitor on the greenhouse between the occupants in the real shuttle, providing information during the journey, the airbags are arranged around the monitor. In Figure 33, the top view illustrates the placement of the four airbags within the shuttle. The airbags are folded, and there is one occupant situated inside the shuttle.

As described in Figure 33, the airbag attached to the greenhouse moves away from the occupant in the opposite direction due to the deceleration during the crash and contact with the occupant. Although this ensures restraint during the coupling phase, a short time later, the occupant slips off the airbag and suffers serious injuries. To counteract this, the airbag contains a support (seen in Figure 34). The support is stitched to the back of the airbag and attached to the top of the greenhouse. It ensures a certain amount of movement of the airbag but limits the movement to such an extent that the occupant is restrained, and injuries are reduced.

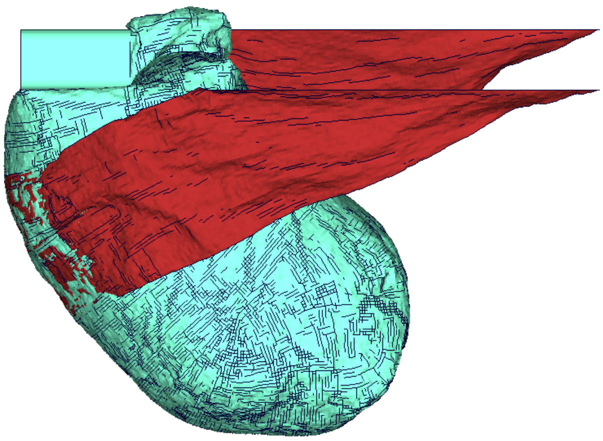


Figure 34. L-Shaped Greenhouse Deployed Airbag Support

In the baseline configuration, the airbag is inflated using a single-stage gas generator. It is inflated upon detecting a severe crash within a set ignition time, which is typically determined by the vehicle manufacturer and remains independent of the specific occupants in the vehicle (male, female, weight, etc.). Subsequently, the airbag is deflated through the existing vent holes by the energy of the impact. In the optimized version, a contact sensor is integrated at the contact surface of the airbag.

Due to the integrated contact sensor and the additionally installed adaptive inflation and deflation valve, the inflation and deflation of the airbag can be controlled in the event of a crash, and therefore, it can be used for different groups of people, different sizes and weights, and out-of-position. Thus, addressing the requirements of the passive safety system development of Aware2All.

The airbag contains two components developed by N. Shirur: a capacitive contact sensor[19] on the surface of the airbag (represented in Figure 35) and an adaptive pressure valve to control the airbag pressure[20].

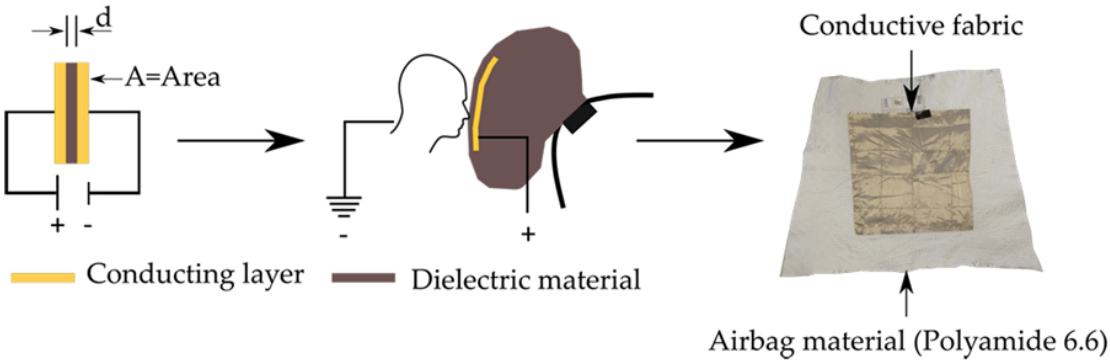
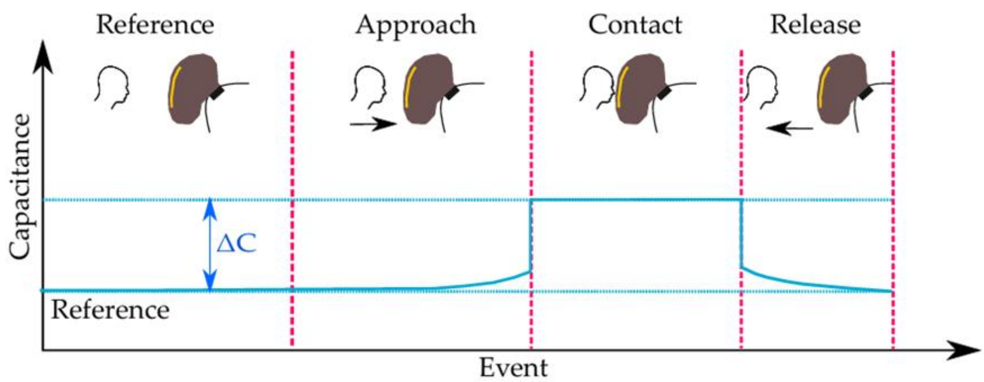


Figure 35. Concept capacitive contact sensor on airbag surface [19,20]

According to Shirur [19] the contact sensor detects the change in capacitance caused by the occupant approaching the airbag, which can result in a voltage drop at the sensor. Figure 36 shows this behavior as an example.



[19] SHIRUR, NAVEEN, ET AL. TACTILE OCCUPANT DETECTION SENSOR FOR AUTOMOTIVE AIRBAG. ENERGIES, 2021, 14. JG., NR. 17, S. 5288.

[20] SHIRUR, NAVEEN, ET AL. 3D SIMULATIONS AND LABORATORY EXPERIMENTS TO EVALUATE A DYNAMIC AIRBAG VALVE. INTERNATIONAL JOURNAL OF CRASHWORTHINESS, 2024, 29. JG., NR. 2, S. 378-388.

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Figure 36. Change in capacity due to occupant-airbag contact [19,20]

This behavior can be used to determine the distinction between groups of people and the occupant's position. The sensor installed on the airbag can control the adaptive pressure valve. According to Shirur et al. [20], this improves the restraint of the occupant compared to a standard gas generator (one and two-stage), depending on the information available.

The dimensions and conditions of the shuttle from the workshop were also used as the basis for the position of the seatbelt. A seat-integrated seatbelt should be used here. The advantage is that the D-ring coupled to the backrest enables good belt guidance even in a reclined position, as shown with the THOR AV 50M in Figure 37.

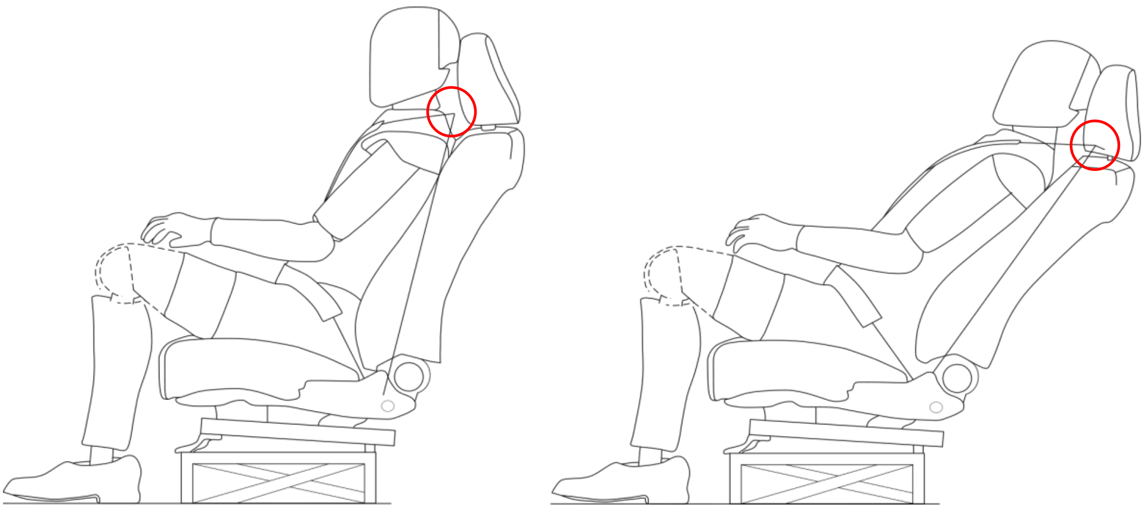

Figure 37. D-Ring Location UMV PM upright and reclined position

The D-ring must, therefore, be positioned on the upper edge of the backrest. Figure 37 shows two exemplary positions of the D-ring. The position of the D-ring is related to injuries to the occupant. If the D-ring is positioned too close to the occupant, the belt injures the neck region by cutting into it during the crash, resulting in the forward displacement of the occupant. If, on the other hand, the D-ring is positioned at the outermost position on the upper edge of the backrest, the shoulder belt slips off the occupant's shoulder during the crash, which means that the occupant is not restrained. The kinematic response can be seen in Figure 38. This position was determined iteratively and verified with simulations using a fifth percentile woman (THOR AV 5F). The left side shows the outermost position of the D-ring when sliding off the shoulder, between t = 100 ms and t = 150 ms after t_0. The right side illustrates the final position of the D-ring at the same time intervals, a slip off can be prevented.

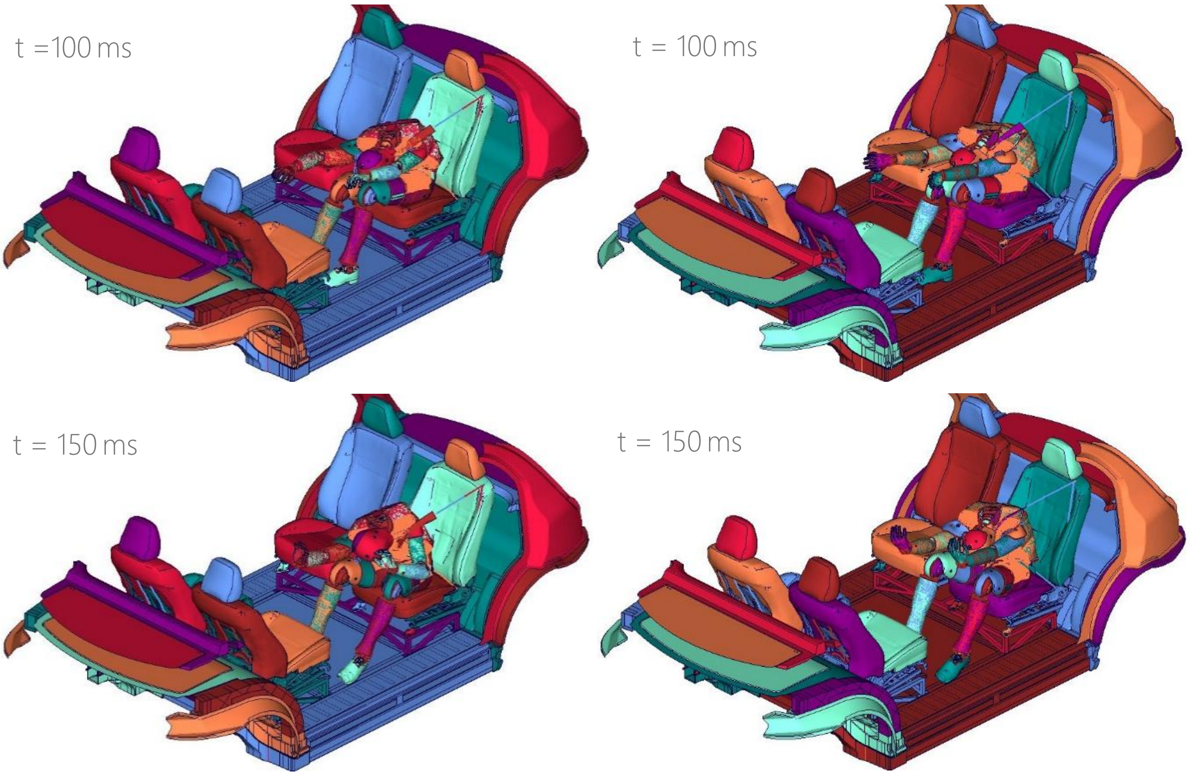

Figure 38. D-Ring Position and Occupant Kinematic Response

The final position of the D-ring was also simulated with the THOR AV 50M disabled to provide advice for disabled occupants. As mentioned in chapter 4.1 , the left arm was removed entirely. As shown in Figure 39, the shoulder belt slips off the upper body due to the absence of the shoulder region, and the occupant cannot be restrained sufficiently. One suggestion is that such a person sits in a different seat with the shoulder belt on the existing arm to ensure restraint.

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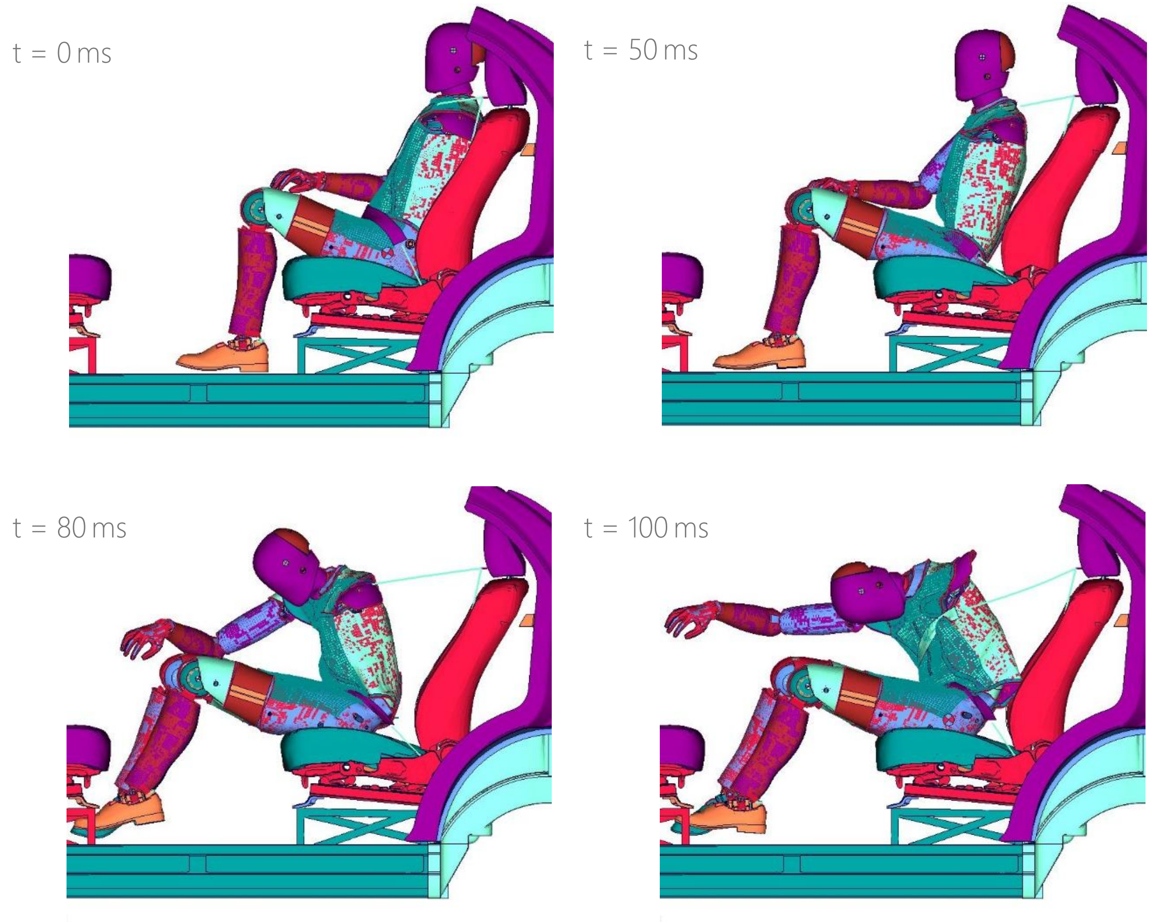

Figure 39. THOR-AV 50M Shoulder Belt Slip-off

As can be seen from the figure above (Figure 39), the upper body undergoes a complex movement, rotating around the vertical axis and also moving forward. One possible way to minimize this movement is by using a four-point seatbelt, as described in chapter 5.2: VIVA+ 50F Seatbelt Design Exploration. When evaluating this seatbelt configuration, a potential risk of strangulation was identified, especially with the reclined position, which informed the decision to retain the use of a three-point seatbelt. The movement sequence and the moment of potential strangulation are illustrated in Figure 40, using the THOR 50M as an example.

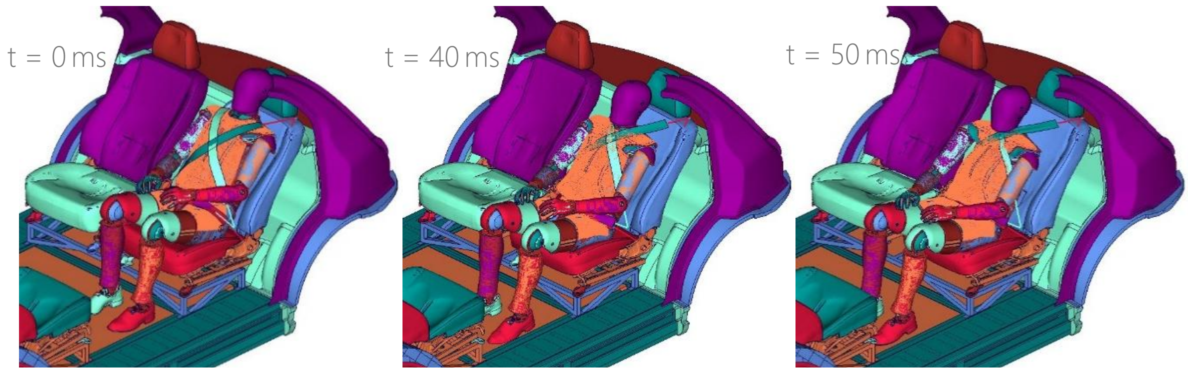

Figure 40. 4-Point harness strangulation risk in reclined position

6.3. Restraint System Technology Results

The results presented below are of the FFRW load-case presented in the use-cases for Demonstrator 1. Each result is presented with the corresponding use-case, such as forward-facing, rearward facing occupancy and reclined occupancy.

It is important to note that there are no published critical limits for injury assessment for the THOR AV Dummy as of the date of this document. The limit values for the THOR 50M are outlined in Craig et al.[21], which provide both a full and zero score ranking for US NCAP and Euro NCAP in the context of a full-frontal crash test conducted at a speed of 50 kph. In order to fulfill legal and minimum requirements, the zero-score rating is used to evaluate the simulation results, which are shown as a percentage, with the respective limit value corresponding to 100%. If a value is higher than 100%, it can be assumed that the limit value has been exceeded, and an injury is highly probable.

The following points are important in the evaluation of the developed system: the load limit values previously referenced are thus applicable exclusively to occupants positioned in the forward seat (50th percentile male). There are no limit values for rear-seated occupants in high-speed scenarios (30 and 50 km/h). Similarly, no limits have been defined for the 5th percentile female and those in a reclined position. The subsequent procedure involves the application of the limit values outlined in Craig et al.[21] to load cases 1.1 and 1.4 (rearward facing and reclined position, respectively). In 1.2, these are taken as a reference to obtain a first estimation.

For the 5th percentile woman, limit values for the 5th percentile hybrid III Dummy are used, in accordance to UN-R137[22]. It must be noted that this is not the optimal choice, however it is sufficient to provide an estimation and to evaluate the developed technologies at the current stage of virtual prototype development.

It is important to note that the restraint system development uses a rigid sled model and is therefore not dependent on the surround vehicle structure, external to the occupant cabin. As described in section 5, the pulse of the baseline structure of the FFRW 50kph simulation is used, with a peak longitudinal acceleration of approximately 40G, the limiting target for the structural optimization process with the new vehicle CMS (UMV PM V2). Henceforth in following chapters, the Baseline refers to the original seat structure and restraint systems of the UMV PM. In addition, the results from tests replicating that of UC1.1 and UC1.2 are used to inform decisions for the restraint system of UC1.3.

Forward Facing Occupancy (UC 1.2)

During the development of the Shuttle's restraint systems, submarining was identified in the load case of the forward seated occupant. The occupant slides below the lap belt and is not optimally restrained, inducing injuries, especially in the lower half of the upper body. This is partly due to the very flat design of the seat cushion. For this reason, only the values for the head and neck can be shown in the figure, as the loads on the thorax and pelvis are not correct in this case.

One of the main changes is adding a component to the seat structure. This plate is mounted at an angle of 25° to the starting position and forms a ramp to limit excessive forward movement and

21 CRAIG, M., ET AL. INJURY CRITERIA FOR THE THOR 50TH MALE ATD. NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION, 2020.

22 SAFETYWISSEN.COM. (N.D.). REGULATION NO. 137 - REV.2 - FULL WIDTH FRONTAL IMPACT (VERSION REV. 2). RETRIEVED JANUARY 22, 2025, FROM HTTPS://WWW.SAFETYWISSEN.COM/OBJECT/B04/B04.80K7388018SQD01X91957452W3UTCF63832377452/SAFETYWISSEN

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prevent submarining. For the simulation purposes of restraint technology development, the anti-submarining plate is assumed to be in position at the start of the crash pulse. The feasibility of deploying the plate pre-crash phase and/or deployment strategies will be evaluated in T2.4.

In addition, a conventional airbag was added to the vehicle via roof mounting, this was subsequently replaced by an adaptive airbag (described in chapter 6.2). At 30 kph speeds, the airbag is more likely to injure than protect the occupants, so it is only deployed at 50 kph. The Injuries for the forward-facing THOR AV 50M are shown in Figure 41. The head acceleration at 50 kph is notably high in this situation. The interaction between the head and the legs can explain this phenomenon. In the baseline simulations (excluding the airbag), the legs show an upward movement, while the upper body, including the head, experiences a downward motion. This dynamic interaction leads to a significant increase in head acceleration. The use of an airbag serves as a countermeasure to this effect. The findings reveal that implementing an adaptive airbag reduces head acceleration, neck loads, and chest compression compared to the conventional airbag.

Furthermore, the results demonstrate that using an airbag alone can significantly reduce acceleration and neck loads compared to the baseline.

The pelvis load remains at a notably elevated level across all versions. The harness is of particular significance in this regard, as the airbag's primary function is to reduce loads in the upper half of the body. The lower half of the body is only reduced via the belt, which leads to higher loads in the pelvis area due to the high crash pulse and the lack of load paths for reducing the energy generated in the crash compared to conventional vehicles.

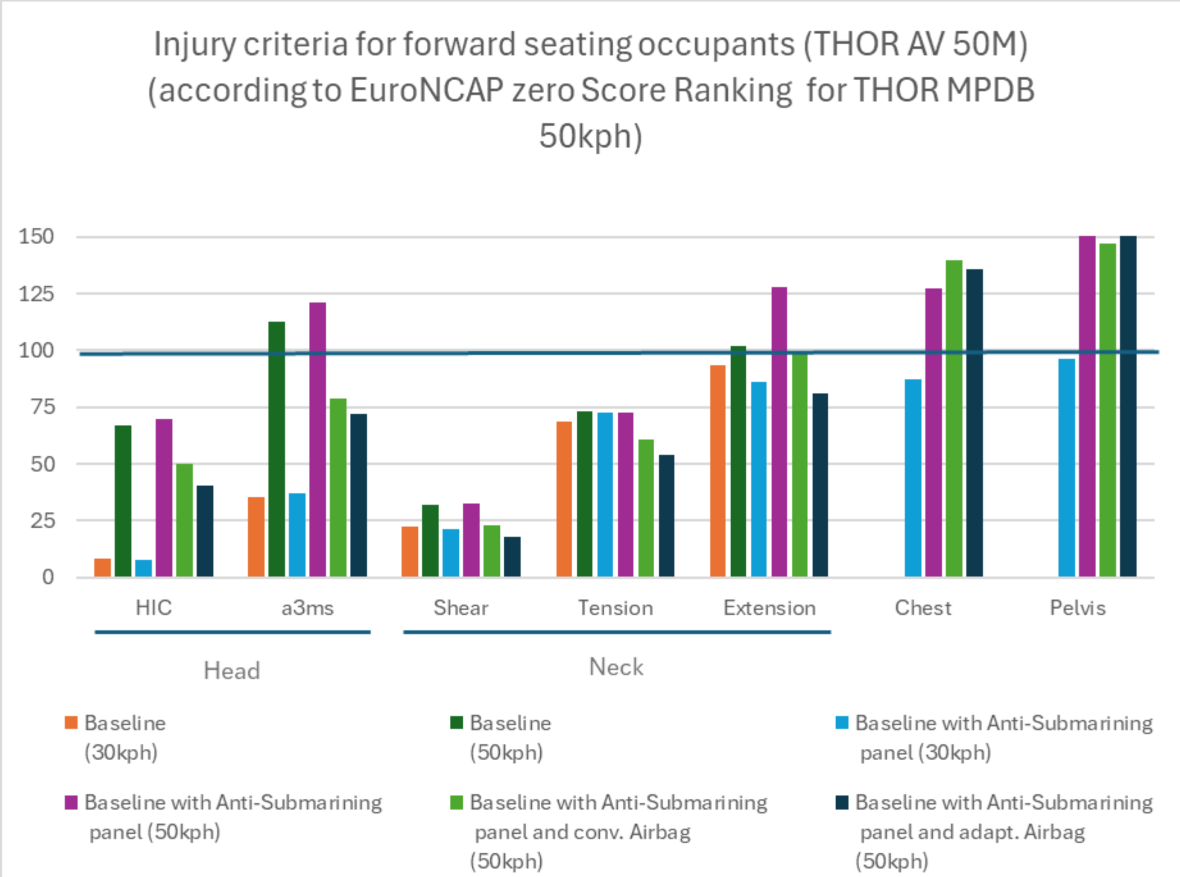

Figure 41. Represents results of the THOR AV 50M (UC1.2) FFRW

A similar outcome is presented with the 5th percentile female occupant, THOR AV 05F, under the same crash pulse. Figure 42 presents the results using the 5th percentile female occupant.

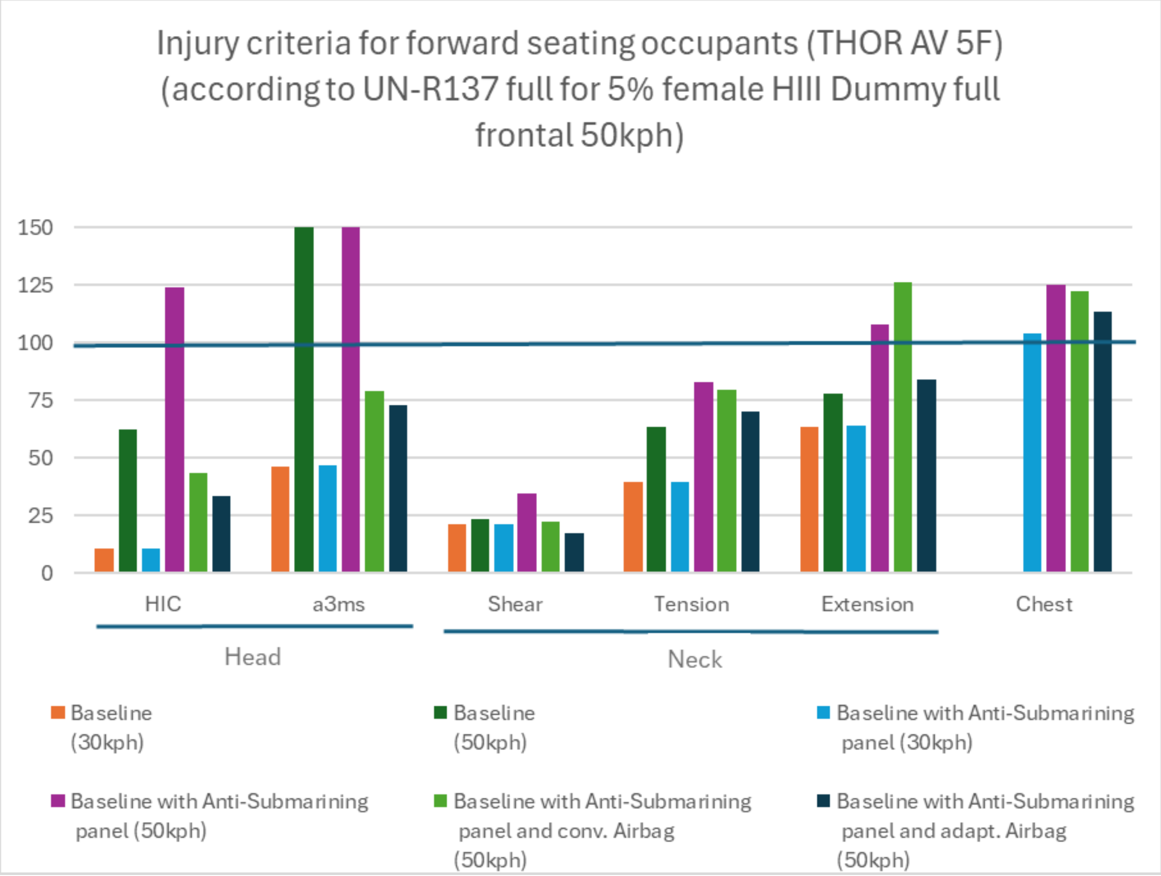

Figure 42. Represents the Results of the THOR AV 05F (UC1.2) FFRW

For the 5th percentile woman, very similar behavior between the baseline and simulations with integrated airbags can be seen. The baseline variant shows significant submarining, resulting in excessive loads in the lower half of the body. Consequently, these loads are not depicted in the figure. Incorporating an anti-submarining plate has resulted in a substantial reduction in submarining.

Consequently, the head load is notably higher in comparison with built-in airbags.

While the tension forces and neck extension increase with the installation of the airbag, this is due to the occupant's interaction with the airbag, designed during development to adapt to both the 50-percentile man and the 50-percentile woman.

The version with the adaptive airbag, in particular, demonstrates the advantage of an airbag that can adapt to the occupant's body through inflation and deflation. The strain on the neck and chest has been visibly reduced.

The THOR AV 50M study described that the belt substantially influences chest compression and pelvic loads. In this configuration, the high crash pulse, in conjunction with the absence of energy-reducing load paths, results in elevated loads in these regions.

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Rearward Facing Occupancy (UC 1.1)

For the rearward facing occupants, simulations have been done with the THOR AV 50M and the THOR AV 5F for 30 and 50 kph, occupants in an upright position. The results are shown in Figure 43. For backwards seating occupants no injury criteria are defined for occupants in high speed impacts. Therefore, the method of evaluation follows that described earlier in this chapter.

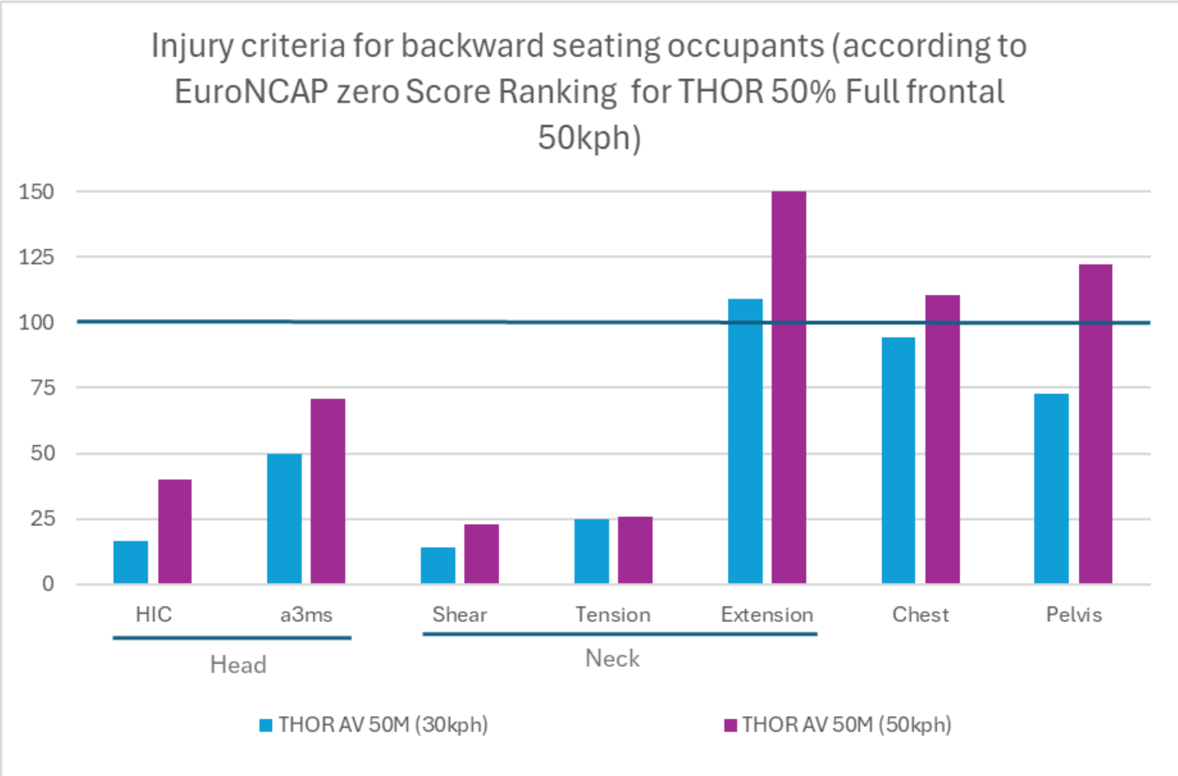

Figure 43. Represents the results of THOR AV 50M (UC1.1) FFRW

The results show high values for the neck extension, but also comparatively high head acceleration. The resulting high HIC-Value are a result of the contact between the head and the headrest in the first milliseconds of the crash pulse. The chest and pelvic loading could be attributed to the vertical excursion of the occupant from the seat with hard and sustained contact with the restraining belt as it is activated. The factors will be investigated in T2.4 as part of the refinement verification tasks.

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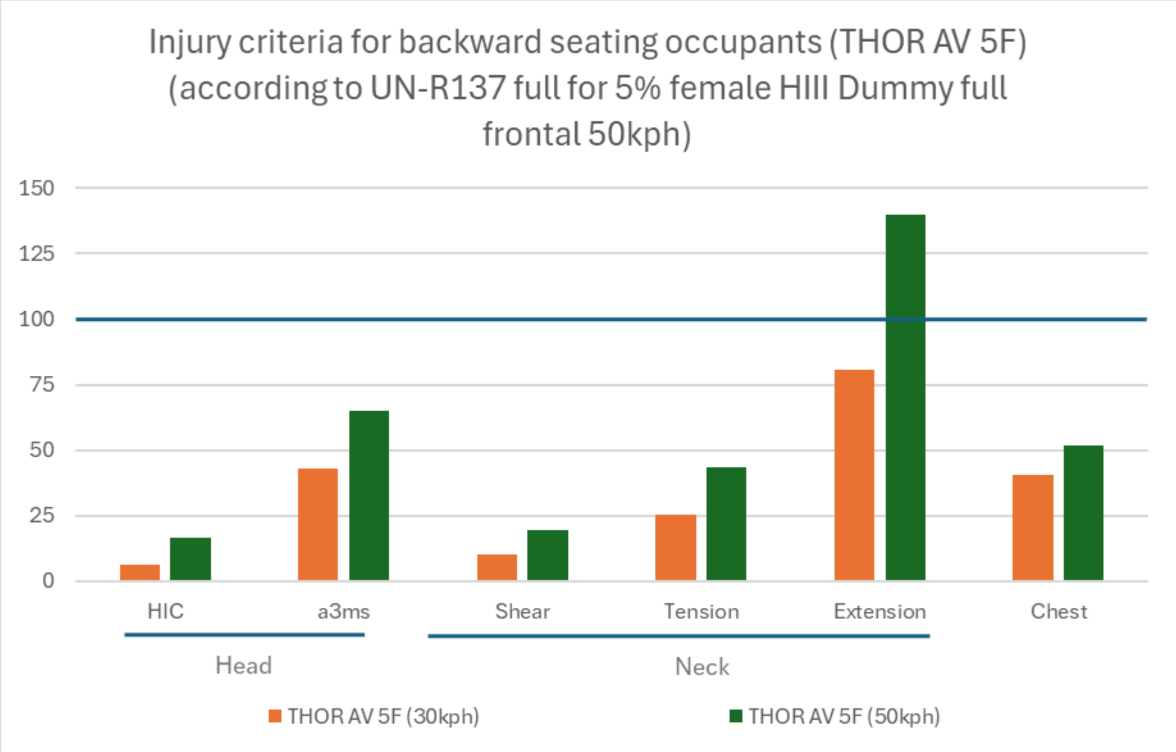

Figure 44. Represents the Results of the THOR AV 05F (UC1.1) FFRW

The 5th percentile occupant exhibits similarly high loads of neck extension, however the HIC value is lower, attributed to the lessened contact between the head and headrest upon upwards excursion. In comparison, the chest compression is significantly less. This could be an indication that the reduced mass of the occupant reduces the force to the chest region throughout belt pre-tensioning and loading. The pelvis is not shown in Figure 44 as there are no critical values in accordance to UN R137 with the Hybrid-III 05 ATD.

Out-of-Position (OoP) Occupancy (UC 1.4)

Occupant positions from this study focus upon the reclined position for restraint system development. As part of the UC1.4, forward and rearward facing occupants are considered.

Figure 45 shows the results for the backward and forward seating occupant (THOR AV 50M 45°) at 30 and 50 kph. Submarining and slippage of the seatbelt over the pelvis leads to high injuries in the abdominal region, resulting in mass increase and stability issues of the simulation. Therefore, the injuries could not be measured for the 50 kph forward facing, reclined THOR AV 45° 50M. Due to the issues previously outlined concerning the forward seating reclined THOR AV 45° 50M (at 50kph), the results are unavailable, and the following figure may be misinterpreted.

Specifically, a substantial load on the neck, or more precisely, elevated neck moments, is evident. This phenomenon can be attributed to the initial impact of the head on the head restraint, followed by the subsequent rebound of the occupant. The reduction in occupant mobility in a reclined posture leads to an overall decrease in body inertia, resulting in forward movement of the head. This phenomenon is known as "high neck strain."

Notably, the illustration employed a single maximum value from the four IR-TRACCs to represent the rib load, a choice that may have contributed to the observed discrepancy between the chest loads at 30 and 50 kph. However, caution should be exercised when interpreting the chest loads for occupants sitting backward, as research has not fully elucidated the underlying mechanisms.

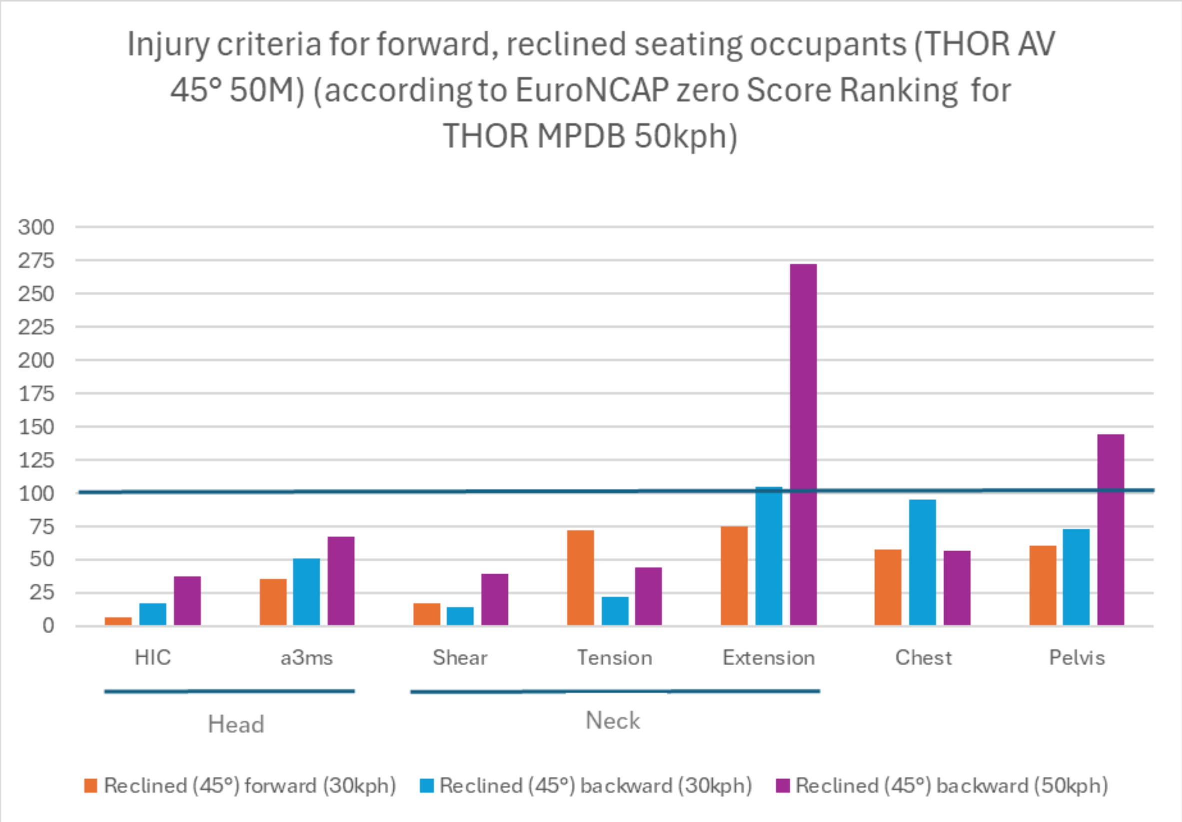

Figure 45. Represents results in reclined positions of THOR AV 50M (UC1.4) FFRW

Figure 46 represents the results of the THOR AV 5F for forward and backward seating, reclined occupant.

In the case of the 5th percentile woman, an increase in loads between 30 and 50 kph is observed for both the forward—and rearward-facing occupants. A pronounced neck moment is also evident for rear-seated occupants at 50 kph. The underlying reasons for these observations are analogous to those observed in the 50th percentile male subject.

It should be noted that, given the absence of load limits for the pelvis area, the corresponding measured values are not displayed in the subsequent figure. However, given the occupant's forward movement and the absence of a lower load path for energy absorption, a high pelvis load is anticipated, which must exceed the limit values.

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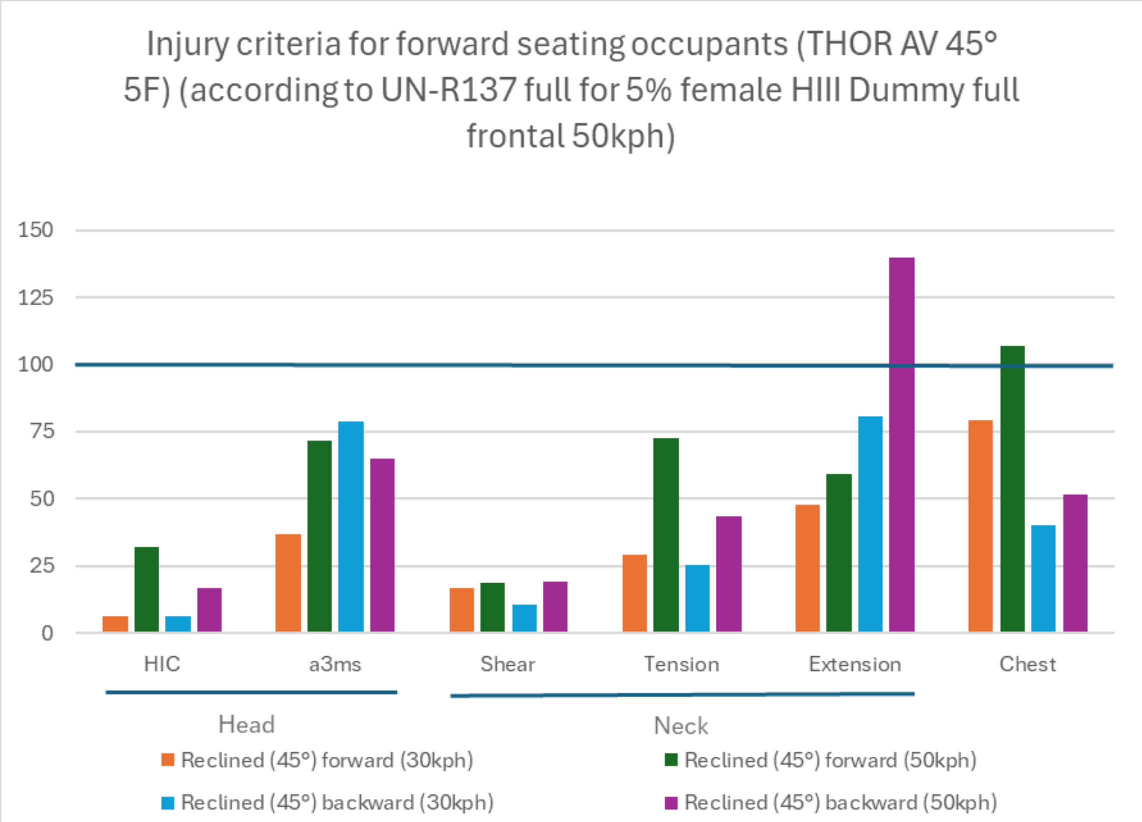

Figure 46. Represents results in reclined positions of THOR AV 05F (UC1.4) FFRW

7. Conclusions

In the comprehensive D2.3 document, the methodology for developing the passive safety systems has been presented. The initial background and constraints informed decisions in the structural development, OLC targets and restraint system design and improvements.

It is evidenced through section 6 that significant improvements have been made in improving the crashworthiness of a vehicle from identification of critical aspects and constraints only present in a HAV, to testing multiple solutions and developing upon specific technologies with consideration of varying occupant anthropometries, including those with a physical disability that is especially demanding on the restraint system. As part of D2.3, the open-source disabled variant of the VIVA+ 50F HBM will be uploaded to Zenodo of Aware2All.

The framework for the respective systems is also presented. The structure external to the occupant cabin utilizes automated solutions for the vehicle model reduction, ideally suited for the optimization process to be enacted. The optimization framework has been enhanced to permit a large array of variables, with consideration to manufacturing and material constraints, and additional targets and constraints of the HAV crash response to improve the general safety of the occupants.

Rigorous investigations and adaptations of restraint systems to assess feasibility of designs, as well as crucial systems to be deployed, have been highlighted. The adaptive airbag, for example, provided evidence of reducing the injury risk of the upper regions of the occupants in comparison to a conventional airbag and a system without an airbag. Submarining has been initially addressed through implementation of anti-submarining panel and the requirements for further safety components have been identified.

It has been shown that improving the passive safety of the HAV is a complex task. For instance, effectively absorbing the kinetic energy of a severe crash pulse in a reduced energy absorbing region while ensuring no intrusions to the occupant cabin to protect contact of the rearward facing seats has a trade-off that induces high accelerations to the occupant compartment. A similar trade-off is observable with the restraint system in which the risk of injury to a particular region of the occupant, often increases the risk of injury to another region. For this reason, it is important to note that the technology development in T2.3 will be continued in T2.4 to verify and refine the solutions adopted for the use cases to address the trade-off effect that is observed. The solutions will be assessed within WP5 of Aware2All.