D4.2 ARCHITECTURE OF PASSIVE SAFETY SYSTEMS

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Executive summary

The overall objective of work package 4 is to increase occupant safety in future automated vehicles (AVs) when exposed to critical situations defined in work package 2. This will be achieved by an occupant protection system including sensing (occupant monitoring system), actuation (restraint system) and a logic (control algorithm), all with the purpose to make new seating positions inside the vehicle safe.

This technical report aims to describe the system concept definition methodology and the resulting system layouts completed in Task 4.2 of the SAFE-UP Project. In work package 4, Task 4.2 represents the second step in the evolution to increase occupant safety in new seating positions, building on the first step, the use case definition carried out in Task 4.1.

The primary objective of Task 4.2 is to define the system concept, which consists of *the system requirements* (system prerequisites, use cases and human body model (HBM) assessment criteria), *the system layout* (the sensors and the actuators that together are needed to fulfil the system requirements) and *the activation logic* (how the actuators work together and should be activated to meet the system requirements).

Four different systems were identified and described, each with a specific aim:

- System 1: “State-of-the-art”. This system only includes in-crash sensing for restraint activation and no occupant monitoring system nor pre-crash sensing. The restraint system consists of a seat belt with B-pillar mounted belt guide, equipped with pre-tensioner and single-stage load limiter in the shoulder belt, driver and knee airbags. System 1 will be evaluated in a traditional vehicle, in manual mode, i.e. with HBM representing a driver in the driver’s seat exposed to peri-urban crash scenarios, car to car Head-on and Intersection crashes and car to heavy goods vehicle (HGV) Head-on crashes (use case 1 in Task 4.1). Results from this system will be used as a reference for the other systems.

- System 2: “Adaptive actuators”. This system is an advancement from the “state-of-the-art” system both in terms of sensing and actuators. Pre-crash sensors and occupant monitoring system are added that make it possible to activate an electrical pre-tensioner in the seat belt before the crash occurs and activating the seat belt pre-tensioners and airbags at T0. Moreover, the in-crash actuator includes a more advanced seat belt with a dual stage load limiter in the shoulder belt and additional pre-tensioner and load limiter function in the lap belt and driver airbag with adaptive ventilation. System 2 will be evaluated in a Level 3 type vehicle in automated mode with occupants of various sizes in a rearward moved seat and reclined backrest (use case 2 in task 4.1). The vehicle is exposed to the same crash scenarios as system 1.

- System 3: “Pre-crash actuators”. This system builds on system 2 by adding pre-crash functions (i) possibility to move the seat in longitudinal direction and rotate the backrest from a potential reclined position to upright. Both actions with the purpose to bring the occupant to an upright position within reach of the frontal restraint system (driver and knee airbag). (ii) possibility to activate the airbags before the crash occurs. This system will be evaluated for the same use case as system 2.

- System 4: “New interior”. In contrast to the other three systems this system is targeting a level 4/5 type vehicle with the occupants in a face-2- face seating configuration (use case 3 in Task 4.1). Besides that, this system will not include frontal airbags, the system will have the same functionality as system 3 with additional functionality in the seat, a seat track load limiter. Different from the previous systems, this system will be evaluated in highway crash scenarios with rear-end impacts from cars and HGV.

Keywords: activation logic, occupant monitoring system, occupant restraint system, system requirement, system layout

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List of abbreviations

Abbreviation	Meaning
AIS	Abbreviated Injury Scale
AEB	Autonomous Emergency Braking
ASIS	Anterior Superior Iliac Spine
ATD	Anthropomorphic Test Device
AV	Automated Vehicles
BrIC	Brain Injury Criterion
CSDM	Cumulative Strain Damage Measure
C2C	Car-to-car crash
C2HGV	Car-to-Heavy Goods Vehicle crash
HBM	Human Body Model
HIC	Head Injury Criterion
HGV	Heavy Goods Vehicle
HMI	Human-Machine Interface
L	Automation level according to SAE, ranging from 0, not automation to 5, full automation
OMS	Occupant Monitoring System
PMHS	Post Mortem Human Subject
VRU	Vulnerable road user
WP	Work Package

1. Introduction and Objectives

1.1 Introduction

Automated vehicles (AV) will have a big impact on vehicle safety. On the one hand, AV will still be involved in collisions in the foreseeable future, since mixed traffic with non-automated traffic participants will prevail for a rather long time. On the other hand, vehicle manufacturers will have to cope with increasing variability of occupant positions within novel vehicle interiors. The challenge to build safe passenger vehicles in the future can only be covered through a more holistic approach. The characteristics of occupant restraint systems, the accident situation and corresponding requirement elicitation will require a more stringent coupling to a real-time capable activation than before.

Current state-of-the-art vehicle crashworthiness must comply with legal requirements addressing a selected number of crash configurations in the European Union being either pure frontal (ECE R94 and R137) or pure lateral (ECE R95 and R135) including mainly a mid-size male Anthropomorphic Test Device (ATD). Besides the legal regulation crash configurations, consumer rating focus on a wider range of crash configurations assessing both pre-crash and in-crash occupant protection. As an example, Euro NCAP currently evaluates four aspects of crashworthiness [1]:

1. Adult Occupant Protection (for the driver and passenger).
2. Child Occupant Protection (for the rear seat).
3. Vulnerable Road User (VRU) Protection.
4. Safety Assist, which evaluates driver assistance and crash avoidance technologies.

To improve occupant protection even more, a possible next step would be to include restraint robustness for a diverse population, new seating positions and to allow for integrated safety functions including pre-crash activation of in-crash actuators and occupant monitoring for adaptation of the actuators in the evaluation methods [2].

The introduction of seat belts, airbags and advanced front vehicle structures in passenger vehicles has led to large injury reductions in the past [3][4]. However, the variations in occupant sizes, shape, gender and postures challenge the functionality of the restraint systems. In frontal impacts, occupant age, gender (being female), BMI, vehicle age, and delta-v were all found to be positively associated with increased injury risk [5]. It is important to secure a good belt geometry before and during the whole crash event for everyone, meaning that the belt is positioned to restrain the “high load resistance areas” of the body; the pelvis, shoulder/clavicle and chest during the whole crash event [6][7]. Two examples are given for potential failure modes of the lap belt engagement of the pelvis [8]:

1. The belt is worn in such a way that it loads directly on the flexible abdomen instead of on the robust pelvis bone.
2. The lap belt is correctly positioned, but when the occupant is displaced forward, the lap belt slides over the iliac wings and compresses the abdomen, also called submarining.

The position of the seat belt on the occupant depends on both the design geometry but also on the care taken by the user in placing it correctly. However, do the users know that the lap belt should restrain the pelvis? Most public awareness campaigns have generally focused on seat belt use rather than encouraging adults to improve seat belt fit with belt placement [9].

Besides a good belt geometry for everyone, it is important to eliminate any slack in the lap belt and shoulder belt by pre-tensioning the seat belt and designing for good support from the seat. Poorly restricted pelvis and chest is potentially injurious, with submarining and/or sliding out of the shoulder belt as consequences [10][11][12][13]. Today's 3-point seat belt systems are designed and verified to eliminate these risks for specific conditions and anthropometries, but to fully address the needs of a more and more diverse population might require further work.

When drivers become passengers in automated vehicles, they will have the potential for a wider range of seating positions and postures [14]. However, the level of automation [15] might affect the selected posture and seating position. A level 3 (L3) vehicle (a vehicle where the driver can safely take the attention away from the road but needs to be ready to take back the control) will give some increased flexibility; while, with level 4 (L4) and level 5 (L5) vehicles, where the driver is not required to do any driving task at all, full flexibility in seating position is expected. This increased seat position flexibility is represented by examples of seats that can be moved more rearward than current seats, creating more room for the legs, to be reclined fully, or tilted to provide more relaxed conditions for sleep or relaxation [16][17][18][19].

Even today, awaiting the future with more comfortable seating positions, drivers and occupants might not be seated in the poses tested in legal requirements [14][20][21], see Figure 1. Human seated positions may vary voluntarily due to their selected activity or involuntarily due to emergency intervention (braking or steering) by the AV when trying to avoid a potential crash.

Figure 1. Examples of voluntarily selected occupant postures in a vehicle front seat.

Current state-of-the-art frontal restraint systems, a 3-point seat belt with B-pillar mounted belt guide; driver airbag in the steering wheel; knee bolster/airbag in the instrument panel as shown in Figure 2, cannot necessarily be expected to provide equal protection in the new more comfortable seating positions, Figure 2 [22][23].

A reclined backrest and a tilted seat pan forms a relaxed position optimal for sleeping [19] expected to be available in the future, but associated with three clearly defined challenges: firstly, the reclined posture with posterior rotated pelvis increases the risk of submarining; secondly, reclined upper body and absence of a knee bolster that support the lower body increase spine and pelvis forces; and thirdly, absence of head restraining airbags may increase the risk for high head accelerations and neck extensions [24].

Submarining in reclined occupant posture can be prevented with engineering solutions [25], but if submarining is avoided and the lower body is properly restrained, it is expected that the lumbar spine compression forces will increase due to body kinematics, i.e. upper body pitches forward and lower body is restricted by the lap belt [26][27].

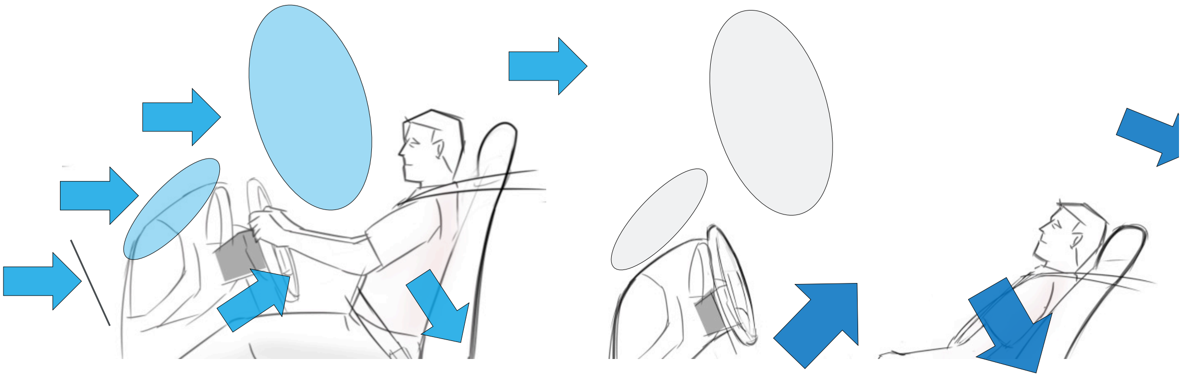


Figure 2. Left: State-of-the-art restraint system. Right: reclined and rearward position occupant

Integrated safety, (here defined as the combination of pre-crash occupant monitoring and environmental sensing, pre-crash actuators as well as in-crash sensing and actuators) with the purpose to identify crash characteristics and based on this adjust the occupant restraint system for optimal protection, have been studied extensively. One example of such strategy is to bring the occupant into a position where the frontal protection system can protect the occupant best before the crash occurs (e.g. rotating the seat [28][29] or rotating the backrest to upright [30]. Another example of such strategy is to optimize airbag deployment timing for expected crash severities [31].

1.2 Objectives and descriptions

One overall objective of the SAFE-UP project is to proactively address the novel safety challenges of the future road mobility environment through the development of tools and innovative safety methods that lead to remarkable improvements in road transport safety [32]. More specifically, as already described in the introduction, for work package (WP) 4 the objective is to increase occupant safety in future automated vehicles (AVs), by addressing a larger variation of occupant sizes in new seating positions. This will be achieved by adapting the occupant restraint system functionality based on input from an occupant monitoring system (OMS). The new proposed system(s) can both address different occupant seating positions and occupant sizes in that new actuators are included and how these are activated (both pre-crash and in-crash) applying an integrated safety approach. This overall WP4 objective is addressed in five different tasks, each with its own key activity:

Task 4.1 - Specify occupant safety use cases: The aim of this task is to identify the most relevant occupant safety use cases based on crash configurations delivered by WP 2 and a literature study defining new seating positions.

Task 4.2 - System concept definition: The aim of this task is to design the overall occupant protection system considering the sensing part (occupant monitoring system), the actuator part (restraint system) and the logic part (control algorithm) needed to protect occupants in new seating positions.

Task 4.3 - Optimization of system concept for different seating configurations: The aim of this task is to clarify the potential benefit of the combination of an occupant monitoring system and an advanced restraint system (defined in task 4.2) for new seating positions (defined in task 4.1) by occupant simulations using human body models (HBM).

Task 4.4 - Algorithm development: The aim of this task is to investigate how a real time algorithm capable of identifying the position and posture of the occupant can be set-up to timely activate and adapt the occupant restraint system to improve the occupants’ protection.

Task 4.5 - Integration in demo: The aim of this task is to materialize and verify the investigations done in the previous tasks in a prototype, a mock-up vehicle called Demo 1, in which the occupant monitoring system will be evaluated. The occupant restraint system will be evaluated in parallel both virtually (using human body models) and physically (in mechanical sled test using Anthropomorphic test device (ATD).

2. Description of Work

The task to define the system concept was separated into three specific areas that together define the system concept. First, the system requirements that describe the system operational functionality and limitations, second, the system layout that describes the sensors and actuators that together form the system and, third, the activation logic that describes how the actuators in the system should be activated in a specific situation to fulfil the system requirements. Each area is outlined in this report but will be verified in Task 4.3, see Figure 3.

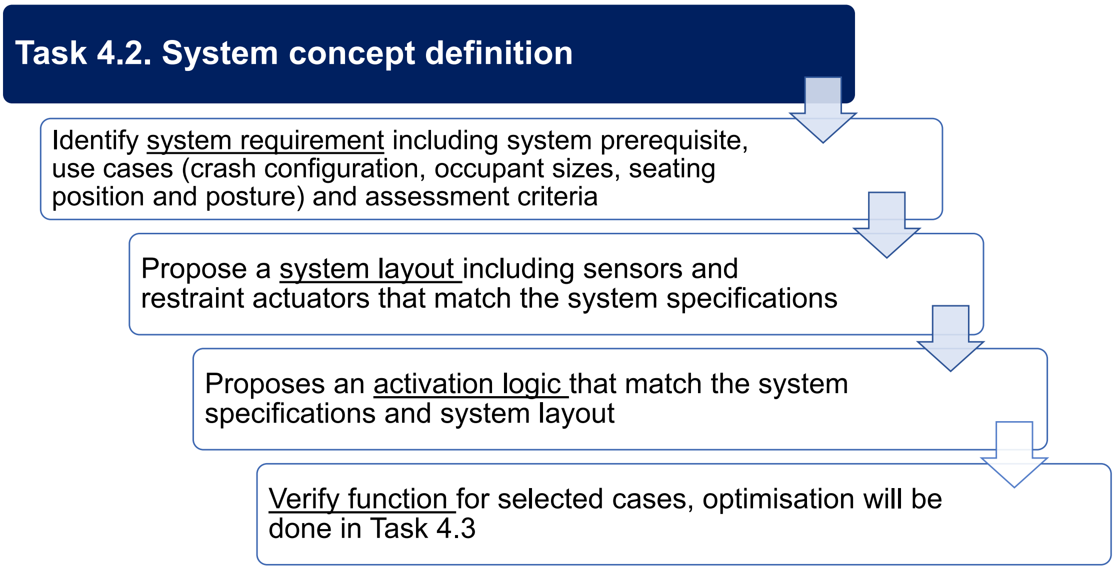


Figure 3. Task 4.2 sub-tasks to identify the system concept

2.1 System requirements

The system requirements were built up by the system prerequisites, that set the assumptions under which the system will work, the use cases in which the system shall be evaluated and the assessment criteria under which the system will be judged.

2.1.1 System prerequisites

System prerequisites are needed to set the boundaries for the system, describing what is included and excluded in the system and what can be characterised as optional. However, listing a system function in the system prerequisites does not necessarily mean that it will be addressed or verified within the SAFE-UP project, rather that it is assumed to have full functionality in a possible future system. Five prerequisites were identified:

1. The occupant monitoring system (OMS) provides information *during the travel and during the pre-crash intervention (if existing) but not during the crash*. This is assumed due to limitation in frame rate to acquire data from multiple occupants by using multiple 2D and 3D depth cameras [33].
2. The OMS have the capacity to output the status of the occupant (e.g. position, posture and alertness) and the compartment (e.g. seat position and objects) to the pre-and in-crash actuator control unit. Potentially, it could be possible to take “static data” of the

occupant (meaning data that does not change during the travel) like weight, height, age and gender from another source than the OMS (e.g. a human-machine interface (HMI) input). Potentially also seat position could be retrieved from another source, e.g. seat sensors. Therefore, the *OMS will primarily focus on delivering "dynamic data" (meaning data that changes during the travel)* describing the status of the occupant:

   a. Occupant posture (including head, chest, pelvis and upper and lower extremities).
   b. Occupant level of alertness (for example if the occupant is sleeping or not can have an effect of how the restraint system shall be activated). This can potentially be investigated using active and passive HBM in Task 4.3.
   c. Seat position including longitudinal position, backrest angle and rotation around z-axis and how the occupant wears the seat belt.

3. By connecting the OMS output with a human-machine interface (HMI), several critical situations are assumed to be addressed before the crash occurs, making it possible to exclude those from the use cases:
   a. The seat belt is assumed to be on. If the seat belt is not on, the HMI will ensure that it is.
   b. Seat belt fit will be addressed by the HMI by warning for improper wearing of the seat belt and improving seat belt wearing.
   c. In the case of dangerous objects that can potentially degrade the protection from the occupant restraint system or directly induce a risk for an injury, two types of situations are assumed to be prevented by HMI prompts and user action:
      i. Level 3 vehicles (traditional seating): objects between occupant and a potentially inflating airbag
      ii. Level 4/5 vehicles (face-to-face seating): object that can impact the occupant seated in the opposite seat.
4. Occupant protection will be evaluated for *occupant sizes in the interval of 50 kg – 125 kg and for heights between 1.50 m – 1.90 m*. Therefore, smaller children using child restraints are excluded, motivated by the following arguments:
   a. Evaluation of child restraints was by definition not included in the SAFE-UP project since the simulation model development (i.e. HBM for children) is not advanced enough.
   b. The volunteer testing would be limited as including children will put stronger requirements on data usage and storage according to GDPR.
5. When pre-crash sensors is in use *the crash configurations (impact point, impact angle, delta velocity and crash opponent) are assumed to be known before the crash occurs*, i.e. before T0, see Figure 4, making it possible to optimise the activation of the occupant restraint system for each unique crash. For example, this will make it possible to activate pre-crash functions like electrical pre-tensioner in the seat belt and position the seat by electrical drives.

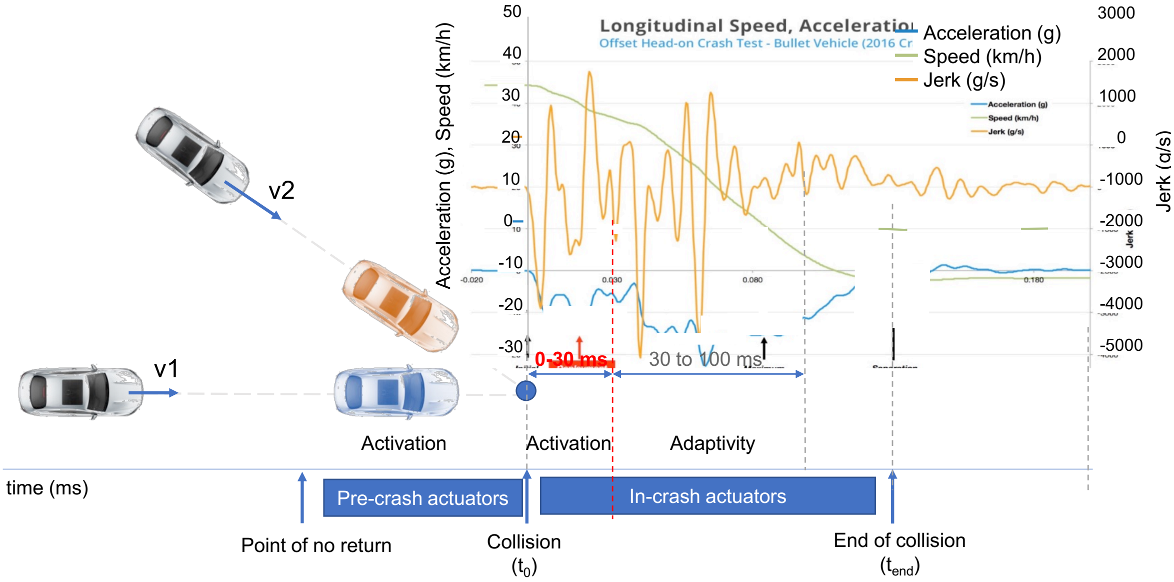
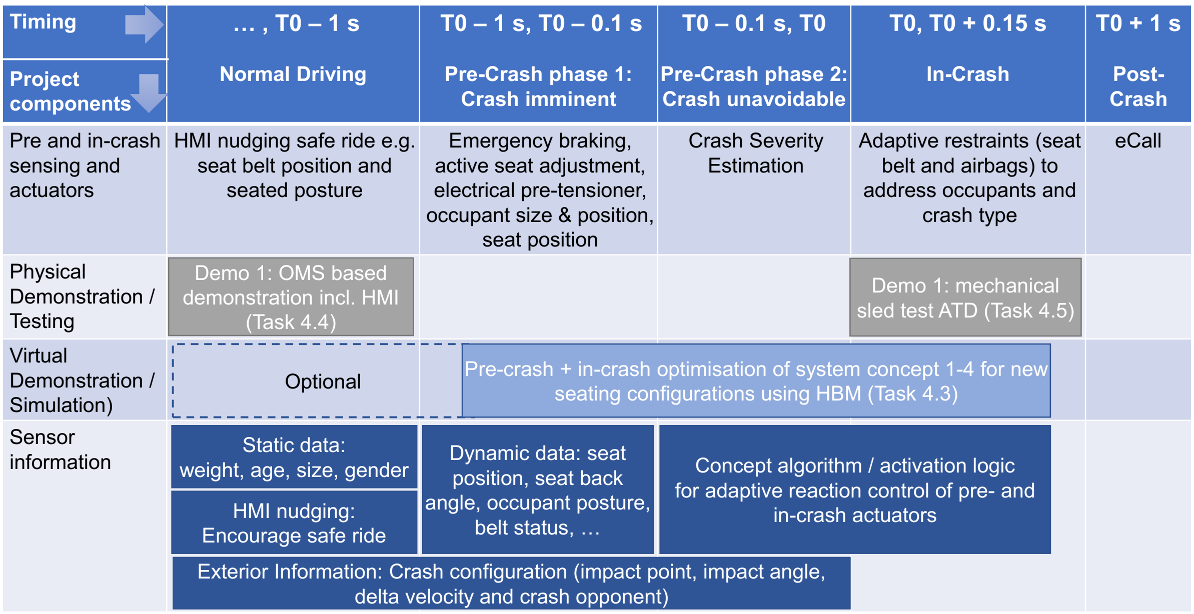


Figure 4. The pre-crash sensors are assumed to give information about impact point, impact angle, relative velocity, crash opponent before the crash occurs.

An overview of how all system prerequisites come together is shown in Figure 5. The horizontal axis represents the time, i.e. from standing and normal driving situations to the crash at T0 and after that in the post-crash phase (not treated in detail in SAFE-UP). An interesting feature is that the pre-crash phase is subdivided into two phases, one where the crash is imminent but avoidable and another one, where the crash is unavoidable. Data acquisition of dynamic data by the OMS is expected to work in the normal driving phase up to the pre-crash phase 1, when the crash is imminent. The vertical axis shows the project components from the possible system reaction through the physical and virtual demonstration capabilities to the required sensor information.



Timing **Project components**	**… , T0 – 1 s** **Normal Driving**	**T0 – 1 s, T0 – 0.1 s** **Pre-Crash phase 1: Crash imminent**	**T0 – 0.1 s, T0** **Pre-Crash phase 2: Crash unavoidable**	**T0, T0 + 0.15 s** **In-Crash**	**T0 + 1 s** **Post-Crash**
Pre and in-crash sensing and actuators	HMI nudging safe ride e.g. seat belt position and seated posture	Emergency braking, active seat adjustment, electrical pre-tensioner, occupant size & position, seat position	Crash Severity Estimation	Adaptive restraints (seat belt and airbags) to address occupants and crash type	eCall
Physical Demonstration / Testing	Demo 1: OMS based demonstration incl. HMI (Task 4.4)			Demo 1: mechanical sled test ATD (Task 4.5)	
Virtual Demonstration / Simulation)	Optional	Pre-crash + in-crash optimisation of system concept 1-4 for new seating configurations using HBM (Task 4.3)			
Sensor information	Static data: weight, age, size, gender HMI nudging: Encourage safe ride Exterior Information: Crash configuration (impact point, impact angle, delta velocity and crash opponent)	Dynamic data: seat position, seat back angle, occupant posture, belt status, …	Concept algorithm / activation logic for adaptive reaction control of pre- and in-crash actuators		

Figure 5. Overview of all system prerequisites.

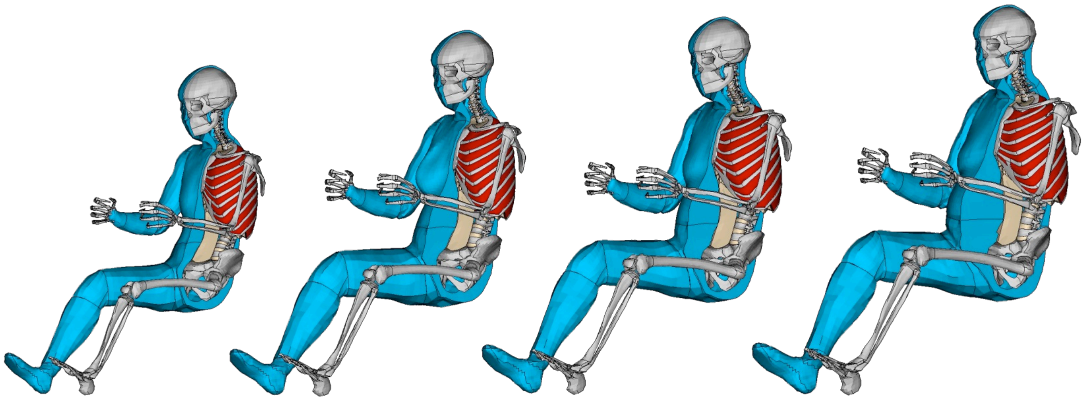
The first part of SAFE-UP Demo 1 (hardware-based) considers a demonstration of the OMS in a mock-up vehicle (Task 4.4), see Figure 5. The second part of Demo 1 is carried out using a virtual setup and human body models (HBM), showcasing the different system layouts and the benefits that can be reached in terms of increased occupant safety in new occupant seating positions by the SAFE-UP occupant protection system (Task 4.3), Figure 5. Additionally, the system 2 “adaptive actuators”, see section 2.2, will be showcased using physical sled tests with ATD as complement to the HBM simulations (Task 4.5), see Figure 5.

Creating a safe riding experience also if passengers are not obeying expected standards, like correct belting, upright seating, etc. implies an HMI interaction. Including safety systems for every occupant configuration (leaning to the side, wearing the belt wrong etc.) might not be feasible, thus in SAFE-UP we will consider nudging actions. In general, nudging represents a method of influencing people's behaviour without resorting to prohibitions and rules [34]. It is assumed that it is possible to guide the occupant (nudging) to a safer seating position by dedicated HMI interaction (e.g. speech, visual within the display, belt vibration) [9].

2.1.2 Use case parameters

Use cases describe in what conditions the system should operate, i.e. its operational design domain (ODD) [35], including where the vehicle will drive and in what position the occupant can be seated. Three different ODDs / use cases were identified in Task 4.1, consisting of vehicle type, crash configuration, seat position and seating position. These were further developed in Task 4.2 by adding the parameters human variation and occupant posture.

Human variation includes different genders, shapes, sizes and ages. Therefore, it is important to define how a diverse population of vehicle occupants should be represented. One approach is to ask oneself: which occupants are at greatest risk of injury in today’s vehicles? An answer was found in a Swedish Licentiate thesis aiming to “*define and create a population of HBMs, through morphing, that represent the injury risks of a diverse population of adult occupants in current and future vehicle crashes”* [36]. Based on a literature review in chapter 3.1, page 6, it is concluded that[36] “*Accident statistics reveals that females, obese and elderly are vulnerable occupants*.” Therefore, four different human sizes, see Figure 6, were selected, all with its specific purpose. Firstly, a small female, because females are at higher risk, and low weight and height may challenge the restraint system. Second and third, a mid-sized female and male, to be able to compare differences between genders. Forth, a large obese male, because obese are at higher risk and the large weight and size may challenge the restraint system. In addition to these four sizes, two different ages, 45 years and 65 years of age were selected for the use case parameter matrix to quantify potential additional safety needs of the elderly.



Small Female (1.50 m, 50 kg) | Mid-sized Female (1.66 m, 69 kg) | Mid-sized Male (1.80 m, 86 kg) | Large/Obese male (1.90 m, 125 kg)

Figure 6. Example of the SAFER HBM morphed to different human shapes

To select relevant occupant seated postures, one main source was used that describes how passengers are seated during the ride: in [14], a novel video-based system was used to estimate front-passenger seat position, backrest angle, seat belt status and seated posture. Two parameters that were judged to have the largest influence on how well the seat belt can restraint the occupants were selected from this study: occupant upper body position (leaning to the left or the right) – which will affect how the shoulder belt interacts with the occupant - and leg position (feet on the floor, leg crossed, foot and seat, etc.), that will affect how the lap belt interacts with the occupant, see Figure 7.

Figure 7. Self-selected occupant postures

By this, each use case will consist of vehicle type and crash scenario(s), seat position(s) and occupant seated postures and human variation, see Table 1 below.

Vehicle type and crash scenarios: Task 4.1 identified three different vehicle types for the three different use cases. A level 3 vehicle in manual mode, a level 3 vehicle in automated mode and a level 4/5 vehicle. In terms of crash configuration, the L3 vehicles are exposed to crash scenarios in rural conditions with another passenger vehicle (car-to-car – C2C) in Head-On and Intersection crash configurations and with a heavy goods vehicle (HGV), (car-to-HGV – C2HGV) in a Head-On crash configuration. The L4/L5 vehicles are exposed to C2C and C2HGV Rear-End crash configuration on highways (Task 4.1). Additionally, the crash configuration can include either pre-braking, evasive steering, or no intervention at all.

Seat position(s) and occupant seated posture: Task 4.1 identified seat configurations in terms of either forward facing or rearward facing seats in vehicle longitudinal direction, backrest angle, seat pan angle and seat rotation. Additionally, Task 4.2 has added two types of occupant seated postures describing the position of the upper body and the legs, see examples in Figure 7. The level 3 vehicle interior considers an evolutionary development of today's vehicle interior in that it incorporates larger flexibility in terms of seat longitudinal position and recline of the backrest, still with driver and passenger seats looking forward, while the L4/L5 vehicle has a face-2-face interior, i.e. seats facing each other.

Human variation, occupant size(s), gender, and age: Task 4.1 did not include the human variation in the use case description. Task 4.2 identified occupant size, gender and age as important parameters describing the human variation. Those parameters have been added to the use case parameter matrix in Task 4.2.

The final SAFE-UP use case parameter matrix with its variation is then built up from the described areas, see Table 1. If all parameters would be addressed for each vehicle type, this would account for almost 1 million variations. Therefore, when addressing the different use case parameters by the different system layouts in later work (Task 4.3) a selection needs to be made based on what research question is supposed to be addressed. Examples of such research questions could be for a given system as follows:

- "What are the limitations of a given seat belt geometry to protect occupants seated in a rearward seat position when varying upper body and leg position?"
- "Is there an increased risk of thorax, lumbar spine and pelvis injuries for occupants of different sizes and gender seated in a rearward and reclined seating position compared to occupants seated in a traditional upright seating position?".
- "How well can an occupant seated in a relaxed seating position (backrest at 60° and seat pan at 35° [19]) be protected by the different systems compared to an upright occupant in the state-of-the-art system?". (For description of the different systems, see chapter 2.2.1 - 2.2.4.)

Table 1: Use case parameter matrix

Vehicle type and crash configuration			Seat position and occupant seated posture							Human variation	
Vehicle type	Pre-crash intervention	Crash type	Seat position	Longitudinal seat position	Back rest angle	Seat pan angle	Seat rotation (z)	Seated postures		Size and gender	Age
								Upper body	Leg position		
L3 manual	No	C2C Head-on	Forward facing	Forward	25°	15°	0°	Nominal	Feet on floor	Small female	45 yr
L3 automated	Braking	C2C Intersection	Rearward facing	Mid	35°	25°	15°	Leaning right	Cross legs left up	Mid-size female	65 yr
L4/5	Steering	C2C Rear-end		Rear	45°	35°	30°	Leaning left	Cross legs right up	Mid-size male	
		C2HGV Head-on		Rear +	60°			Leaning forward	Foot on seat left	Large/obese male	
		C2HGV Rear-end							Foot on seat right		
									Feet on seat		
									Yoga		
In total 2 903 040 variations possible (3x3x5x2x4x4x3x3x4x7x4x2)											

2.1.3 Human body model assessment criteria

The anthropometric test devices (ATDs) used in current vehicle safety regulations and consumer ratings are neither developed nor validated for any seated position other than upright postures. Human body models (HBMs) have the potential to enable biofidelic predictions for omni-directional loading of the body in a crash [36]. The models have been validated for a wide range of applications, including reclined seating [37]. Therefore, HBMs are used to assess occupant protection systems in the SAFE-UP project. However, there are no standards that define the HBMs as there are for ATDs. The anthropometries, the level of detail, etc. vary between different HBMs. In addition, there is no standard for postprocessing the output from the models, such as how to predict injury risk. There is no agreed certification protocol for HBMs today. Different HBMs can predict both kinematics and injury risk, such as submarining and prediction of forces and moments differently [38]. Also, despite replicating human anatomy, HBMs do not necessarily predict human responses outside their validation regime [38].

Despite the limitations described above, a recommendation of HBM evaluation criteria is done see **Error! Reference source not found.** with the goal to focus on the most frequent severe injuries in passenger vehicles (including those leading to long term consequences) [32]. The use of fewer evaluation criteria rather than many will enable aligning and interpreting output from different HBMs.

Otte et al. (2017) [39] identified AIS3+ injuries to German passenger vehicles occupants to most often involve the thorax, followed by injuries to the lower extremities and the head. Similarly, Klinich et al. (2016) [40] found AIS3+ injured US passenger vehicle occupants to be most often injured in the thorax body region. It was also found that the share of occupants sustaining AIS3+ injuries to the thorax and spine increased in recent years, while the share of occupants sustaining AIS3+ injuries to the upper and lower extremities has decreased. Finally, Pipkorn et al. (2020) [41], investigating AIS2+ injuries of US passenger vehicle occupants looking at details beyond body regions, identified concussion, rib and pelvis fractures as priorities for occupant protection. Therefore, the safety evaluation in SAFE-UP is suggested to focus on the risk of at least moderate head and brain injury, rib fractures and pelvis fractures.

In addition, reclined seating adds new challenges; in particular, submarining needs to be evaluated. Post-mortem human subject (PMHS) testing has shown which types of injuries are expected when submarining can be prevented, namely injures to ribs, the pelvis and the lumbar spine [27]. Therefore, it is also recommended to address submarining and at least moderate (AIS2+) injuries to the lumbar spine.

A final challenge is a seating position far away from the steering wheel, when the occupant is potentially out of reach for the driver airbag, with potential high tension for the neck. Therefore, the last suggested injury evaluation concerns neck injury in tension.

Table 2: Recommended HBM assessment criteria

Body region	Injury	Proposed evaluation
Head	Concussion / Rotational based brain injury.	Risk of concussion based on the peak value of the first principal Green-Lagrange (G-L) strain of the brain tissue (AIS 2) [42][43]. Monitor brain injury criteria (BrIC) based on cumulative strain damage measure (CSDM, AIS 2) [44].
Head	Skull fracture / translational brain injury.	Head injury criterion (HIC15, AIS 2) [45].
Neck	Tension injury.	Pass/fail at 3 kN in any vertebra [46].
Thorax	Rib fracture.	Risk for two or more fractured ribs (AIS2+) based on rib strain [47].
Spine	Lumbar spine compression fracture.	Fracture risk of any lumbar spine vertebra: 10% risk for 3.0 kN compression force and 50% risk for 4.5 kN compression force [48]. Alternatively, a pass/fail at 4.5 kN in any vertebra.
Pelvis	Iliac wing fracture.	Resultant force on anterior superior iliac spine (ASIS) left and right side (from belt loading) with a pass/fail criterion at 4 kN [37] or a lap belt load not exceeding 5 kN [49][50].
Submarining	Subsequent abdomen injuries.	As per Euro NCAP (drop in lap belt forces and visual inspection) [51].

The optimization of the occupant restraint system should aim at minimizing the overall risk of severe injury, assuming independence of injuries by body region. Where risk cannot be numerically evaluated, measurements shall be below the pass/fail criterion. The assessment can also include an overall evaluation of occupant kinematics assessing risk for hard contact and interaction with the belt (slipping off shoulder) and seat headrest.

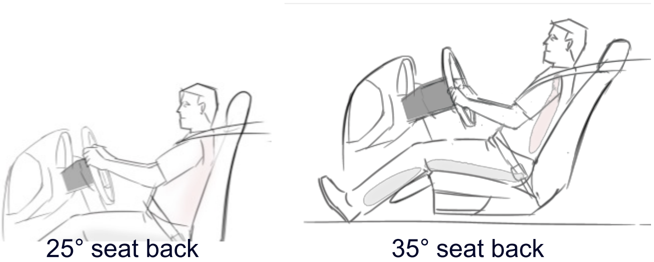
2.2 System layout and activation logic

The system layout describes the different sensors and actuators that together form the occupant protection system. Four different system layouts with increasing complexity were defined. This will make it possible to address more and more advanced situations (use case variations) and/or vehicle types.

The systems consist of pre-crash and in-crash actuators that can be activated individually based on pre-crash and in-crash sensor output with the target to address each unique situation. Each of the three main use case areas, vehicle type and crash scenario(s), seat position(s) and occupant seated posture(s), and human variation opens up for millions of combinations that should be addressed. Therefore, the functionality of each actuator and how it should be activated to achieve good occupant kinematics (avoid hard contacts and belt slipping-off shoulder or pelvis) and minimising the restrain load applied to each individual occupant by using available space (adaptive seat belt load limit force and airbag pressure) will be given on a generic level. The target is to minimize injury risk using the assessment criteria described in section 2.1.3.

2.2.1 System 1 “State-of-the-art”

The “State-of-the-art” system only includes in-crash sensing for restraint activation and no occupant monitoring system nor pre-crash sensing. System 1 will be evaluated in a traditional vehicle, in manual mode, i.e. with a driver in the driver’s seat in a nominal seating position and a slightly reclined seating position (use case 1 in Task 4.1), see Figure 8. The vehicle will be exposed to three different types of crash configurations: C2C Head-on, C2C Intersection, C2HGV Head-on. Additionally, a pre-crash brake or steering pulse can be added. Results from this set-up will be used as reference when assessing the results from the other systems that will address more complex use cases [52].



Normal driving

25° seat back
15° seat pan

Reclined driving

35° seat back
15° seat pan

Figure 8. Seating positions for the “state-of-the-art” restraint system.

Pre-crash sensors: This system does not include any pre-crash sensors.

Pre-crash actuators: This system does not include any pre-crash actuators.

In-crash sensors: The in-crash sensors consist of accelerometers to sense the crash in longitudinal and lateral direction, microcontrollers that compute and make decisions (also called restraint system algorithm) and special activation units that send the triggering current to the actuators, see Figure 9. The restraint algorithm takes decisions on:

- **Activation or no activation:** to activate or not activate an actuator driven by the need for additional restraint for a given vehicle acceleration signal.
- **When to activate**: when to activate the actuator is driven by the time needed for the actuators to come in place (e.g. it takes approximately 30 ms for a driver airbag to inflate) and the time in the crash when the actuator needs to be fully functional. A general guideline to set the triggering time for the airbag is the so-called 5” 30 ms rule [53]. This rule is based on the assumption that an unbelted occupant moves 5 inches (127 mm) before the airbag is fully deployed and that full airbag deployment takes 30 ms. This calculation is dependent on the crash severity, and in a crash where the occupant moves 5 inches in 40 ms, the airbag firing time requirement then equals 40 ms – 30 ms= 10 ms. In high severity crashes, i.e. where the occupant moves 5 inches in shorter time the rule has its limitation and a constant activation time of the airbag has to be used instead.

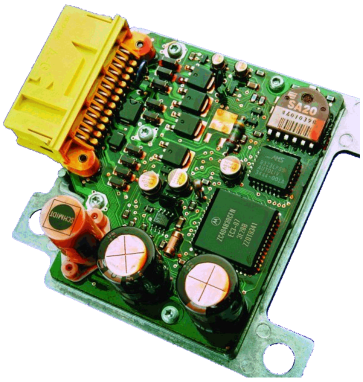


Figure 9. Example of a control unit for airbag activation.

The in-crash sensor might also include sensors for checking if the occupant is belted or not and if there is presence of a child restraint. Since unbelted status and child restraint are not included in the project, those sensors are not further described.

In-crash actuators: The in-crash actuators in this system consist of a 3-point seat belt with B-pillar mounted belt guide. The shoulder belt retractor is equipped with pyrotechnical pre-tensioning of 2 kN, single stage load limiter to reduce the force that acts on the thorax. Moreover the seat belt tongue is equipped with a crash locking tongue and the end-bracket is equipped with a pyrotechnical lap belt pre-tensioner of 2 kN, see Figure 10. When the belt is loaded by the occupant in a frontal crash, the crash locking tongue mitigates webbing transfer from shoulder belt to the lap belt, thereby providing a higher force in the lap belt portion compared to the shoulder belt portion which is load limited by the retractor. A low force in the shoulder belt reduces the risk of rib fractures [54]. Moreover, the steering wheel is equipped with a stroking steering column and a driver airbag, while the instrument panel is equipped with a knee airbag, Figure 11. However, the implementation of a knee airbag is optional and can be replaced with a stiff knee bolster to simplify the modelling work in Task 4.3.

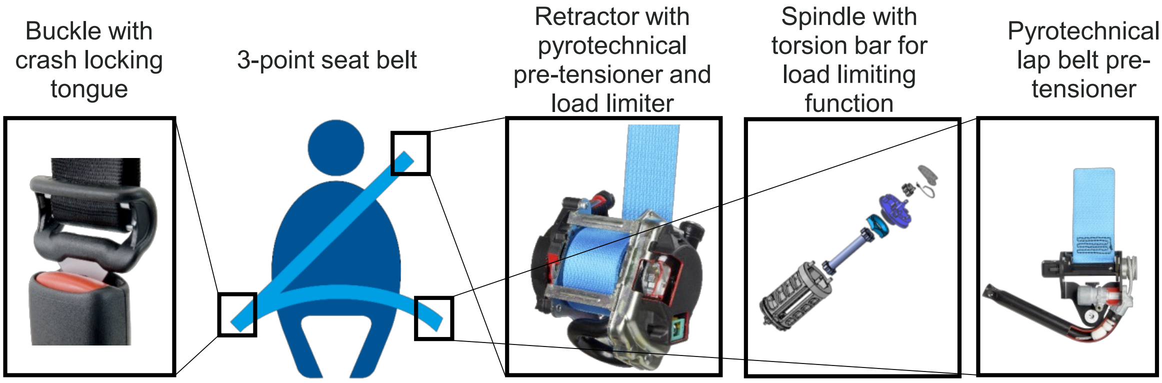


Figure 10. 3-point belt with buckle, crash locking tongue, shoulder belt retractor and lap belt pre-tensioner.

Figure 11. 3 Frontal airbags in steering wheel and instrument panel.

Functionality and activation times: Schematic functionality description of the belt forces vs. time for shoulder belt retractors with and without pyrotechnical pre-tensioner and single stage load limiter is shown in Figure 12. To couple the occupant to the seat, the seat belt pre-tensioner should be activated as early as possible. However, since the first part of the passenger vehicle front structure is soft, due to pedestrian safety and repairability requirements, the acceleration generated in the centre of the vehicle is delayed. (To keep repair cost down, so-called crash boxes are used, those have to be "softer" than the structure behind and easy to replace.) Thus, the activation of the belt pre-tensioner is normally set to 8 ms after first impact (T0). Potentially, an earlier activation can be realised for the C2HGV Head-on crash configuration due to the expected higher acceleration signal.

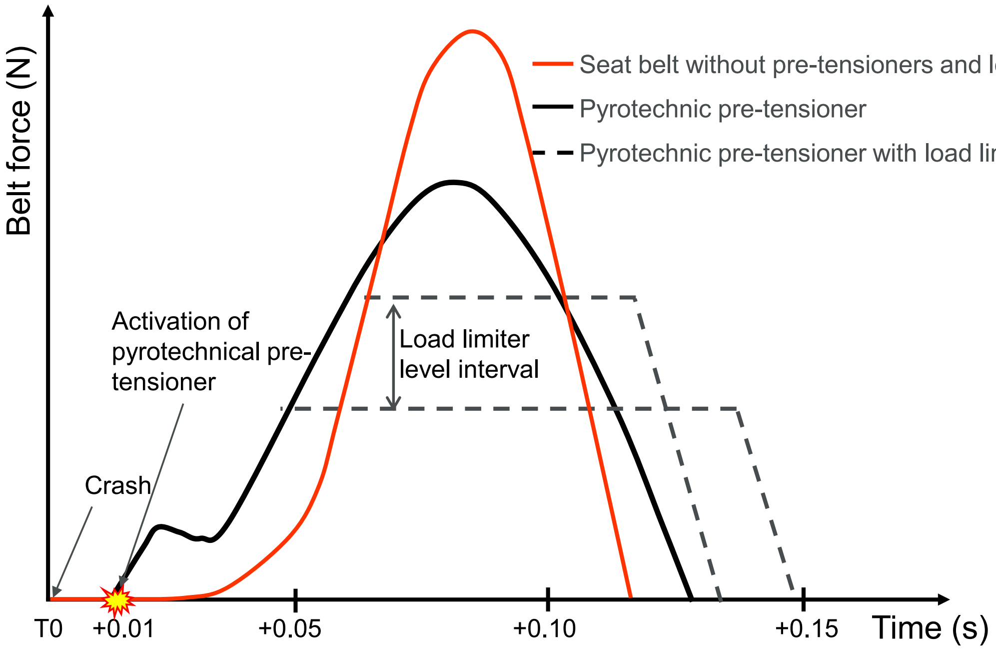


Figure 12. Schematic description of belt forces vs. time for shoulder belt retractors with and without pyrotechnical pre-tensioner and single stage load limiter.

The shoulder belt load limiter has a fixed single-stage level that can be set to values between 3 - 5 kN depending on what torsion bar is selected. (Shoulder belt force shall not exceed 6 kN [51].) The driver and knee airbag should be activated at 10 ms in the C2C Head-on crash configuration and potentially later in the C2C Intersection crash configuration and slightly earlier in the C2HGV Head-On crash configuration, see the earlier described 5'' 30 ms activation rule. The pressure levels in the driver airbag and the knee airbag can be adjusted based on what size of inflator is used. State-of-the-art pressure levels is between 15 – 30 kPa for the driver airbag and between 70 – 130 kPa for the knee airbag. Additionally, the driver airbag is equipped with a ventilation hole whose diameter can be chosen in the interval of 20 – 70 mm. The steering column can stroke 100 mm at a fixed force level that can be set to any value between 3 – 10 kN.

In this report ranges are given for all actuators, see Table 3. Exact values will then be selected and verified in Task 4.3: Optimisation of system concept.

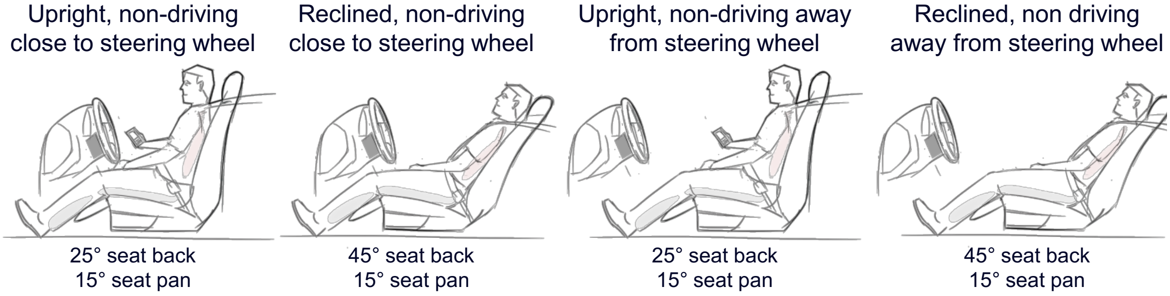
Table 3: Functionality and activation times for System 1 “State-of-the-art”

Actuator	Activation time (relative to T0)	Optimisation parameter 1	Optimisation parameter 2
Shoulder belt pre-tensioner	8 ms	Crash pulse	N/A
Shoulder belt load limiter	N/A	Single stage force level 3 – 5 kN	N/A
Driver airbag	10 ms	Pressure level to be chosen in the interval 15 – 30 kPa	One size ventilation hole ø 20 mm – 70 mm
Knee airbag	10 ms	Pressure level to be chosen in the interval 70 – 130 kPa	N/A
Steering column	N/A	Single stage force level 3 – 10 kN	Single stage stroke distance 100 mm

2.2.2 System 2 “Adaptive actuators”

The “adaptive actuators” system is a conceptual advancement from the “state-of-the-art” system by that the occupant monitoring system and pre-crash sensors are added, making it possible to activate an electrical pre-tensioner in the seat belt and adapt the restraint system to the occupant’s seat position and size. The in-crash actuator includes a more advanced seat belt with an adaptive dual stage load limiter in the shoulder belt and additional double pre-tensioning and load limiter function in the lap belt and dual volume driver airbag with adaptive ventilation.

This system layout was created with a five- to ten-year readiness perspective and will be evaluated in a level 3 vehicle in automated mode with different occupant sizes in the driver’s seat (non-driving). The occupants are either in upright or reclined seating position close to or away from the steering wheel representing use case 2 in Task 4.1, see Figure 13. The same crash configurations as for the “state-of-the-art” system will be used, i.e C2C Head-on, C2C Intersection, C2HGV Head-on, possibly considering a pre-crash brake or steering pulse.


Upright, non-driving close to steering wheel
25° seat back
15° seat pan

Reclined, non-driving close to steering wheel
45° seat back
15° seat pan

Upright, non-driving away from steering wheel
25° seat back
15° seat pan

Reclined, non driving away from steering wheel
45° seat back
15° seat pan

Figure 13. Examples of seating positions for a level 3 vehicle in automated mode.

Pre-crash sensors: Advanced sensor system consisting of several radar and camera sensors that give information about the crash configurations (impact point, impact angle, delta velocity and crash opponent) before the crash occurs, i.e. before T0, see Figure 4. Additionally, an occupant monitoring system (OMS) is added consisting of a set of time-of-flight and infrared cameras and a computer for acquisition and processing. The OMS gives detailed information about the occupant (e.g. posture and stature) and compartment (e.g. seat position) before T0. Because the OMS is a central part of the deliverable, its functionality is described in detail in chapter 2.5.

Pre-crash actuators: This system consists of a seat belt with an electrical pre-tensioner of 200 N - 1000 N force (where 200 N represents the “state-of-the-art") that can be activated before T0, see Figure 14.

In-crash sensors: Same as for system 1 “state-of-the-art”.

In-crash actuators: Conceptual seat belt, see Figure 14 with seat integrated shoulder belt retractor with pyrotechnical pre-tensioning of 2 kN and adaptive dual stage load limiter, see Figure 15, [55]. Additionally, the seat belt tongue is equipped with a crash locking tongue , the lap belt is equipped with double pre-tensioning of 2 kN with the target to reduce risk of submarining [25][26][50] and load limiter functionality in both buckle and end bracket to reduce the force to the pelvis [37][49][50]. The steering wheel includes a stroking steering column and a dual volume driver airbag with adapting vent, making it possible to adapt the pressure in the airbag. Finally, a knee airbag is included in the instrument panel, see Figure 16.

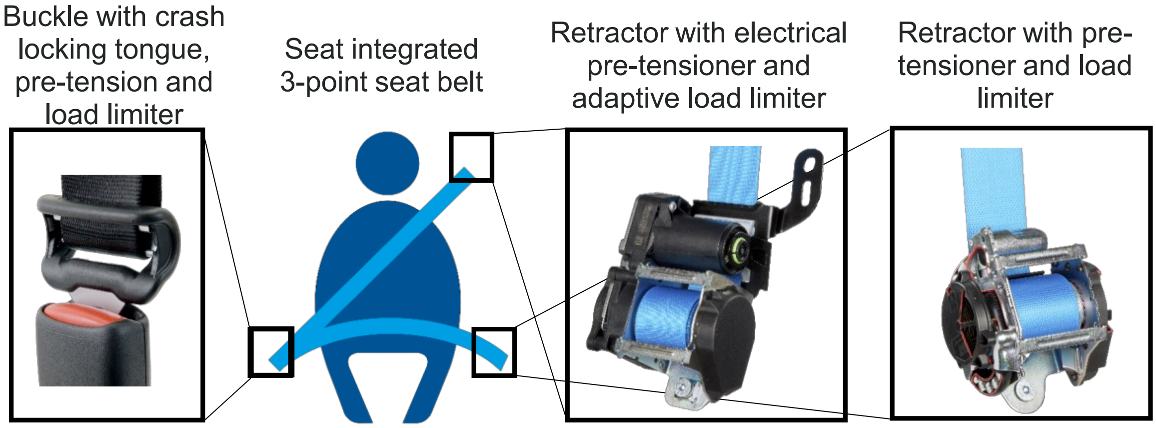


Figure 14. Conceptual seat integrated 3-point belt with crash locking tongue, shoulder belt retractor with electrical pre-tensioner and lap belt retractor.

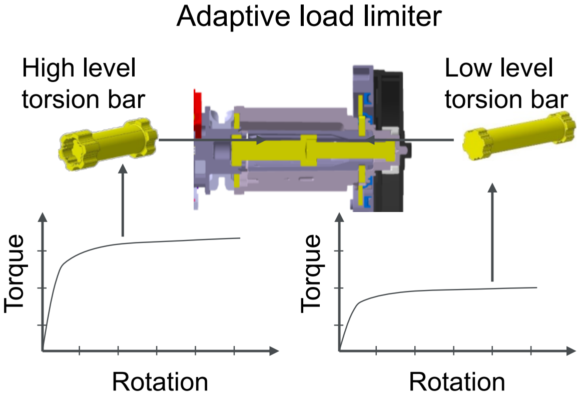


Figure 15. Function description of a retractor with adaptive load limiter

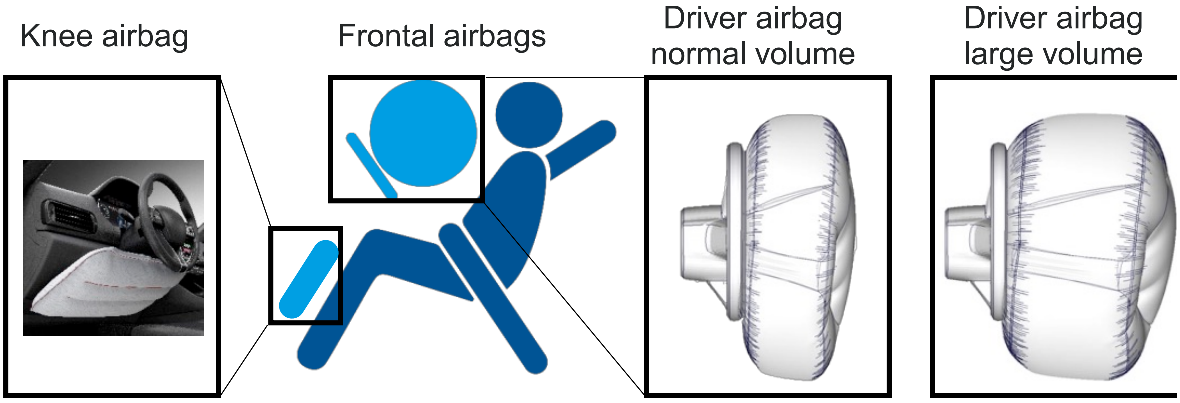


Figure 16. Advanced frontal airbag including a dual size driver airbag in the steering wheel.

Functionality and activation times: Schematic description of the belt forces vs time for shoulder belt retractors with electrical pre-tensioner and pyrotechnical pre-tensioner and single or dual stage adaptive load limiter is shown in Figure 17.

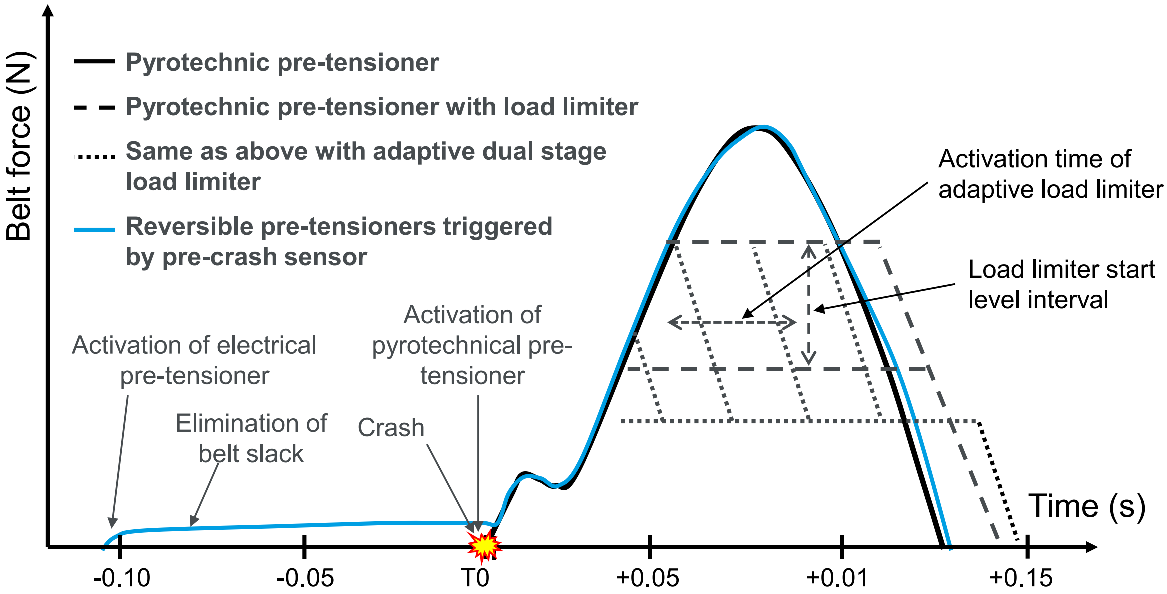


Figure 17. Schematic description of belt force vs. time for shoulder belt retractors with electrical and pyrotechnical pre-tensioner and single or dual stage adaptive load limiter.

Activation of the electrical pre-tensioner in the seat belt should start at latest when the autonomous emergency brake (AEB) is activated to keep the occupant in position during braking. Additionally, because of the pre-crash sensing, it is possible to activate the seat belt pre-tensioner and airbag at T0. However, the driver airbag and knee airbag activation time will depend on the occupant position at T0. If the occupant is out of reach of the airbags, they will not be activated or potentially activated at a later time. This system has features that can be adapted to occupant size and position. As an example, it is recommended to activate a lower seat belt load limiter force for the smaller occupant to reduce the forces from the seat belt to the thorax and thereby reduce the risk of thorax injuries. As another example it is recommended to avoid activating the lap belt load limiter for the large obese occupant to avoid too far excursion. Moreover, the dual sized airbag with a larger size should be activated when the occupant is in the reclined and/or rearward seating position. For the different occupant postures, no generic recommendation can be given. Detailed selections have to be done in task 4.3 where exact values of all parameters will be defined for the selected use cases, see Table 4.

Table 4: Functionality and activation times for System 2 "Adaptive actuators"

Actuator	Activation time (relative to T0)	Optimisation parameter 1	Optimisation parameter 2
Shoulder belt pre-tensioner (pre-crash)	Same time as AEB	Force level 200 – 1000 N	N/A
Shoulder belt pre-tensioner (in-crash)	0 ms	N/A	N/A
Lap belt pre-tensioner (in-crash)	0 + 8 ms	N/A	N/A
Buckle pre-tensioner (in-crash)	0 ms	N/A	N/A
Shoulder belt load limiter force level	N/A	First force level between 3 – 5 kN	Second force level between 2 – 4 kN
Shoulder belt adaptive	0 ms – not activated	Crash pulse	Occupant size and position
Lap belt load limiter (end bracket side)	Between 0 ms – not activated	Single stage force level 4 – 6 kN	Occupant size and position
Lap belt load limiter (buckle-side)	Between 0 ms – not activated	Single stage force level 5 – 8 kN	Occupant size and position
Driver airbag	0 ms or later	Pressure level between 15 – 30 kPa	Dimension and timing of adaptive vent
Driver airbag adaptive vent	0 ms – not activated	Crash pulse	Occupant size and position
Knee airbag	0 ms or later	Pressure level between 70 – 130 kPa	N/A
Steering column	N/A	Single stage force level 3 – 10 kN	Single stage stroke distance 100 mm

2.2.3 System 3 “Pre-crash actuators”

The “pre-crash actuators” system is a conceptual advancement from the “Adaptive actuators” system by that additional pre-crash actuators are added beside the electrical pre-tensioner in the seat belt. In this system the airbag can inflate before the crash occurs and the seat are equipped with electrical drives that make it possible to move the seat in longitudinal direction towards the frontal airbags and rotate the backrest to upright position. (This protection principle can potentially be carried over from the OSCCAR project D2.4).

This system layout was created with a ten- to fifteen-year readiness perspective and will be evaluated for the same use cases as system 2 (see Figure 13 above).

Pre-crash sensors: Same as for system 2, “adaptive actuators”.

Pre-crash actuators: Same restraints as in system 2, but with additional protection principle that the seat can move in longitudinal direction 150 mm in 300 ms or the backrest can be rotated by 20° in 300 ms [29][30], both with the purpose to bring the occupant to an upright position within reach of the driver and knee airbag**.**

In-crash sensors: Same as for system 1 “State-of-the-art” (which also is used in system 2).

In-crash actuators: Same as for system 2 (see Figures 14-16 above).

Functionality and activation times: Additional to system 2, activation of the electrical drives of the seat should start 300 ms before T0 with the purpose to bring the occupant back to a nominal position in the cases of a reclined or a rearward seat position [30]. Based on what seat position can be reached with the pre-crash moved seat, the restraint system should be activated accordingly. This needs to be further investigated in Task 4.3. The driver airbag and knee airbag activation time will depend on the occupant position at T0. If the occupant is out of reach of the airbags, they will not be activated or potentially activated at a later time, see Table 5.

Table 5: Functionality and activation times for System 3 “Pre-crash actuators”

Actuator	Activation time (relative to T0)	Optimisation parameter 1	Optimisation parameter 2
Shoulder belt pre-tensioner (pre-crash)	Same time as AEB	Force level 200 – 1000 N	N/A
Shoulder belt pre-tensioner (in-crash)	0 ms	N/A	N/A
Lap belt pre-tensioner (in-crash)	0 + 8 ms	N/A	N/A
Buckle pre-tensioner (in-crash)	0 ms	N/A	N/A
Shoulder belt load limiter force level	N/A	First force level between 3 – 5 kN	Second force level between 2 – 4 kN
Shoulder belt adaptive	0 ms – not activated	Crash pulse	Occupant size and position
Lap belt load limiter (end bracket side)	Between 0 ms – not activated	Single stage force level 4 – 6 kN	Occupant size and position
Lap belt load limiter (buckle-side)	Between 0 ms – not activated	Single stage force level 5 – 8 kN	Occupant size and position

Driver airbag	-100 ms, or later	Pressure level between 15 – 30 kPa	Dimension and timing of adaptive vent
Driver airbag adaptive vent	0 ms – not activated	Crash pulse	Occupant size and position
Knee airbag	-100 ms or later	Pressure level between 70 – 130 kPa	N/A
Steering column	N/A	Single stage force level 3 – 10 kN	Single stage stroke distance 100 mm
Backrest rotation (y-axis)	- 300 ms	Δ 20° in 300 ms	Backrest position
Seat longitudinal position (x-direction)	- 300 ms	Δ150 mm in 300 ms	Seat position

2.2.4 System 4 “New interior”

The “New interior” system is different to the other 3 systems as this system is targeting a level 4/5 type vehicle with the occupants in a face-2-face configuration (use case 3 in Task 4.1, see Figure 18). Because of the vehicle type, the system will not include frontal airbags nor an instrument panel. Besides not having frontal airbags, system 4 will have the same functionality as system 3 with one additional pre-crash functionality: pre-crash rotation of the seat (z-axis), and one additional in-crash functionality: seat track load limiter. (These two protection principles can potentially be carried over from the OSCCAR project D2.4).

This system layout was created with a ten- to fifteen-year readiness perspective. In contrast to the previous system, this system will be evaluated for occupants traveling in various rearward facing positions (Figure 18) in highway crash scenarios with rear-end impacts from cars and HGVs. The reason for focusing on the occupant traveling rearward is the more complex seat belt loading compared to the forward-facing seat and that more HBM validations are needed for high severity rear end crashes [24][56][57].

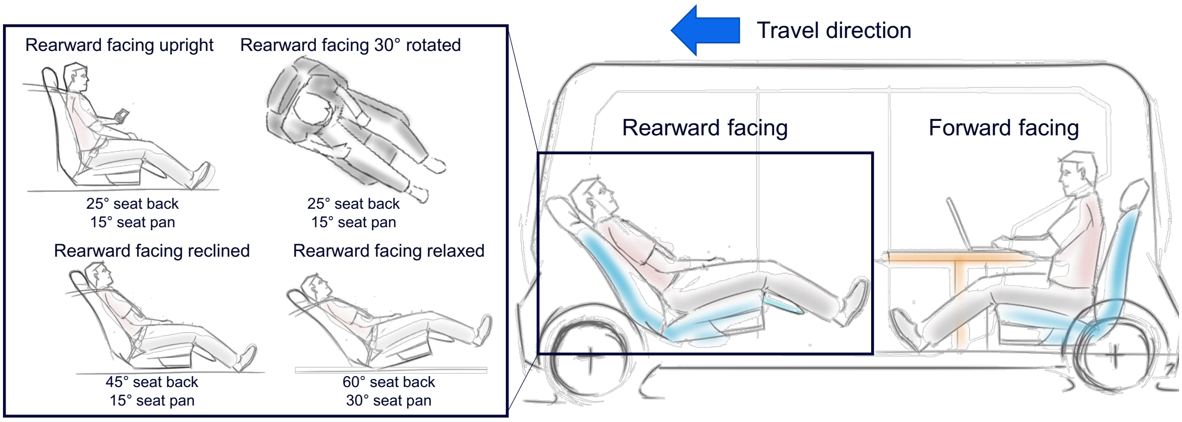


Figure 18. Vehicle layout and seating positions for L4/5 vehicle.

Pre-crash sensors: Same as for systems 2 and 3.

Pre-crash actuators: Same restraints as in system 3, but with additional protection principle that the seat can rotate around the z-axis [29] with the purpose to bring the occupant back to a nominal position, as proposed in the OSCCAR project.

In-crash sensors: Same as for System 1 “State-of-the-art” (which also is used in Systems 2 and 3).

In-crash actuators: Same as for System 3, except for removing the driver and knee airbags and with the additional protection principle that the seat can move under energy absorption, representing a so-called seat track load limiter (virtually investigated in the OSCCAR project, [37] and further evaluated in mechanical test [58], see Figure 19). If the seat track load limiter protection principle is used instead of or in combination with the pre-crash moved seat, a baseline activation time at T0+30 ms is recommended. However, the seat position, the occupant weight, and the crash severity should be considered in Task 4.3 when setting the activation strategy. Thereby an earlier or a later activation time might be beneficial [58], see Table 6.

Table 6: Functionality and activation times for System 4 “New interior”

Actuator	Activation time (relative to T0)	Optimisation parameter 1	Optimisation parameter 2
Shoulder belt pre-tensioner (pre-crash)	Same time as AEB	Force level 200 – 1000 N	N/A
Shoulder belt pre-tensioner (in-crash)	0 ms	N/A	N/A
Lap belt pre-tensioner (in-crash)	0 + 8 ms	N/A	N/A
Buckle pre-tensioner (in-crash)	0 ms	N/A	N/A
Shoulder belt load limiter force level	N/A	First force level between 3 – 5 kN	Second force level between 2 – 4 kN
Shoulder belt adaptive	0 ms – not activated	Crash pulse	Occupant size and position
Lap belt load limiter (end bracket side)	Between 0 ms – not activated	Single stage force level 4 – 6 kN	Occupant size and position
Lap belt load limiter (buckle-side)	Between 0 ms – not activated	Single stage force level 5 – 8 kN	Occupant size and position
Backrest rotation (y-axis)	- 300 ms	Δ 20° in 300 ms	Backrest position
Seat longitudinal position (x-direction)	- 300 ms	Δ150 mm in 300 ms	Seat position
Seat rotation (z)	- 300 ms	Δ 20° in 300 ms	Seat position
Seat track load limiter	30 ms	Start at 20 kN – 30 kN at 0.25 m stroke (70 kg seat)	Seat position, crash severity, occupant size

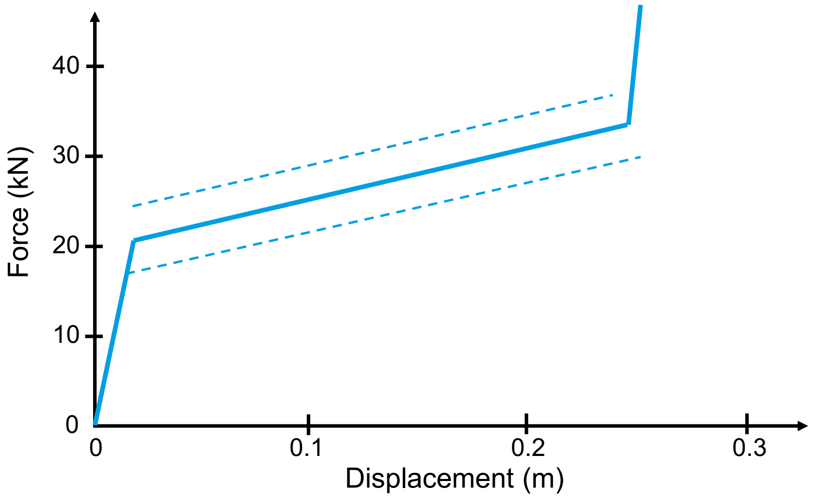


Figure 19. Conceptual seat track load limiter force-displacement characteristics for a 70 kg seat

2.2.5 Description of the Occupant Monitoring System (OMS)

The occupant monitoring system is composed of multiple submodules, as illustrated in Figure 20, that process the acquired data from multiple sensors (cameras) to generate as output the required information about the occupants. This information will be used by the HMI (secure safer seating position) and the occupant protection system (in case of a crash to activate the actuators in an optimal way).

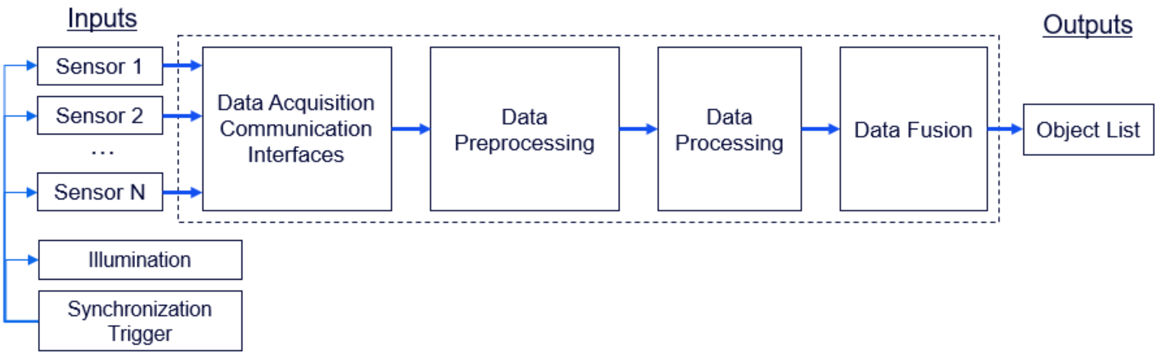


Figure 20. Occupant Monitoring System: Architecture

A detailed description of the different submodules that together form the OMS are listed as follows:

Sensors: the chosen sensors for the OMS are the image-based ones, because they provide image data with rich information and high resolution if compared to other technologies (e.g., RADAR, ultrasonic, pressure sensors). The main sensors for the system are cameras that can capture monocular images with depth information (e.g., time-of-flight cameras), which allows the use of deterministic algorithms (i.e. occupancy detection only with depth information / point clouds) in contrast to the state-of-the-art methods for 3D human pose estimation that are based on deep neural networks [59][60]. As complementary sensors, Infrared (IR) cameras equipped with large field-of-view lenses (i.e., fisheye models) will be combined to the time-of-flight cameras to improve the detection performance in specific tasks (e.g., different colour clothes and materials) and overcome problems with occlusions.

The main requirements for the cameras are the (1) minimum acquisition frame rate and (2) sensor field-of-view. The acquisition frame rate is a factor that influences the overall system performance. For an off-the-shelf time-of-flight camera the data frame rate recommendation is 25 Hz to perform 3D object reconstruction. Higher frame rates are possible, however, the acquired data will not be optimal (more noise or invalid depth data) [33].

Figure 21 illustrates the field-of-view of two time-of-flight cameras to be used. One camera captures data from the occupants in front row seats and a second camera from the occupants on the rear row seats. To increase the robustness of the detection system for the desired use cases, two additional IR cameras will be installed, one in the front and the other in the back, to generate redundant and complementary data. The minimum diagonal field-of-view for a sensor is 100 degrees, which can capture enough data of the occupant's body when placed at a distance of 0.9 meters. Figure 22 shows the planned structure of the cameras' placement inside of the vehicle. The accurate position will be defined upon the availability of the demo vehicle and it will be based on tests to minimize possible occlusions and avoiding the standard location of restraint systems (e.g., airbag deployment regions).

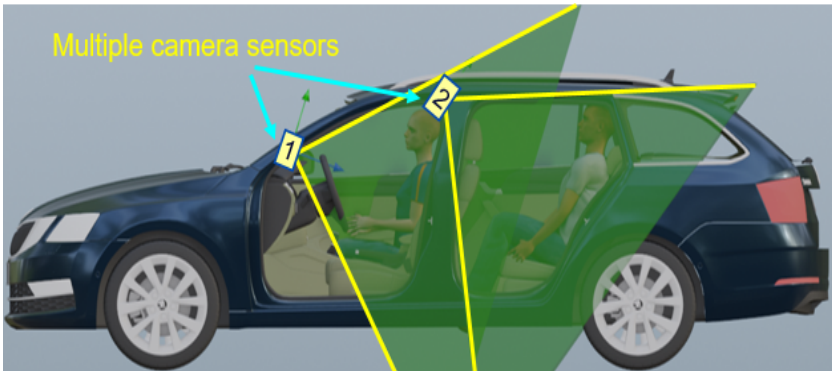


Figure 21. Placement of cameras inside of the vehicle, side view

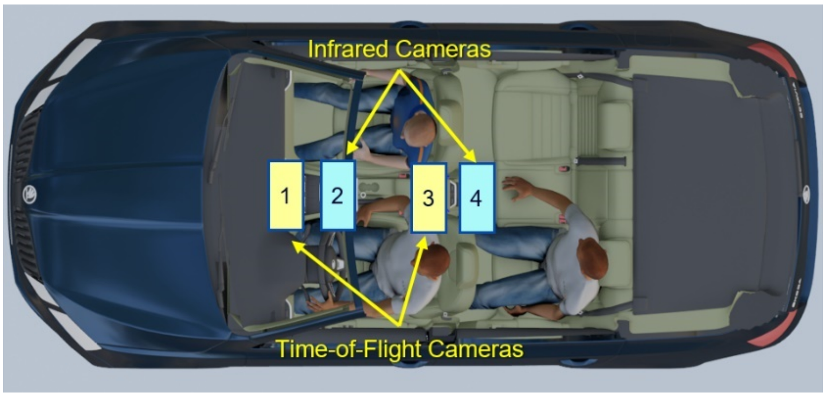


Figure 22. Placement of cameras inside of the vehicle, top view

Illumination: to improve the robustness of the system according to variations in ambient lighting the use of active illumination is recommended, i.e., infrared lights that are not in the range of the spectrum human visible light, which do not cause any perturbations to the occupants. The main requirement for the cameras is that the image sensors must support the IR range. The infrared light from time-of-flight cameras will be used as main illumination source.

Synchronization mechanisms: as the sensors are composed of different systems, e.g., each camera has its own firmware and frequency clock, a synchronization mechanism is required to capture data frames at the same time in order to provide a reference time for data fusion purposes. Other requirements arise for active illumination and multiple time-of-flights cameras in the same scene: the cameras must be synchronized with the active illumination sources to avoid light flicker on the captured images. In the case of time-of-flight cameras, as it is based on the emission of IR light and on time-of-flight principle, it is necessary to acquire data in different time slots to avoid interferences that increase noise or cause invalid measurements. The synchronization mechanism will be generated by an external triggering equipment using the general-purpose input/output (GPIO) port from the camera sources.

Data acquisition and processing hardware: as multiple cameras are required, the acquisition system needs to provide communication interfaces: dedicated host controllers for USB (Universal Serial Bus) 3 and/or Gigabit Ethernet, to control external devices (e.g., external synchronization trigger) and to receive data from sensors (i.e., seat longitudinal position and inclination angle).

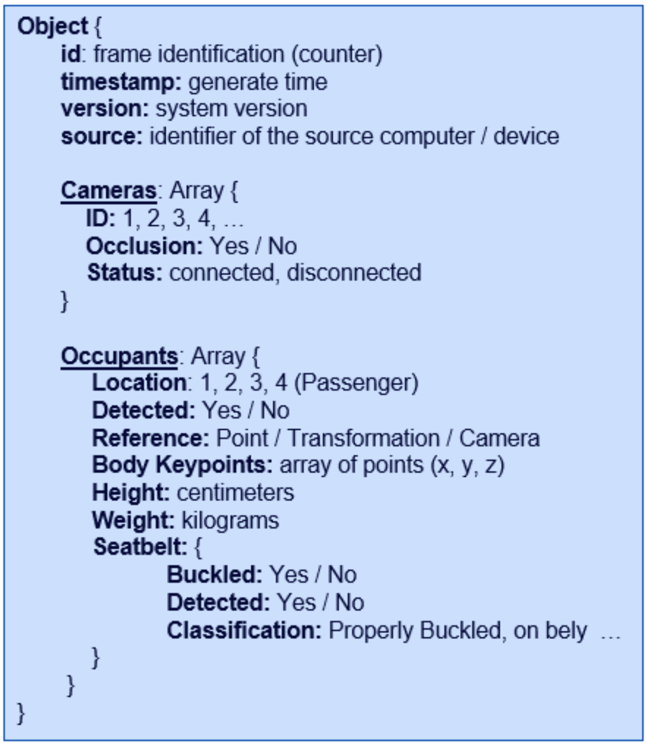
Due to the power consumption of the OMS, additional direct current (DC) battery pack equipment must also be installed in the vehicle capable of delivering at least 900 Watts and must be automatically recharged by the vehicle in order to guarantee the continuous operation of the system.

For multiple data source acquisition and real-time processing capacity, multiple processes need to run in parallel. For that, a multi-core central processing unit (CPU) computer with a clock frequency of at least is 2.0 GHz, 32 GB of random-access memory (RAM), Graphical Processing Unit (GPU) with at least 8GB of memory to perform inference of deep neural networks and computer vision processing algorithms is required.

Data pre-processing: each sensor captures raw data frames in a format that is defined by the respective manufacturers, which can vary according to the camera technology or model. At first, it is therefore required to parse the raw data frames to a format compatible with the occupant monitoring system. In the second step, pre-processing techniques are applied used to improve the monocular image quality (e.g., noise filtering, histogram equalization). For depth information and point clouds captured by sensors located in different positions, translation and rotation transformations will be applied to map the data to a common reference. In addition, as the 3D spatial information accuracy is important, a correction transformation based on calibration parameters will also be applied in this step.

Data processing and Data fusion: the main function of the occupant monitoring system is the real-time detection of spatial information of all vehicle occupants via computer vision: position and posture regarding a specific reference point or geometrical linear transformation. For that, the information extracted from both of the cameras will be used by the pose algorithm to detect with accuracy the position of the occupants inside of the vehicle. The algorithms needed will be determined in Task 4.4.

Output data format: the output of the system is an object list, as illustrated in Figure 23, which contains information about the system function and the occupants' detections. This data will be transmitted from the OMS to other sources via connection sockets using Transmission Control Protocol (TCP/IP). Additional information can also be added to the object list for system diagnostics (data log and debug) and performance analysis.



```
Object {
      id: frame identification (counter)
      timestamp: generate time
      version: system version
      source: identifier of the source computer / device

      Cameras: Array {
         ID: 1, 2, 3, 4, …
         Occlusion: Yes / No
         Status: connected, disconnected
      }

      Occupants: Array {
          Location: 1, 2, 3, 4 (Passenger)
          Detected: Yes / No
          Reference: Point / Transformation / Camera
          Body Keypoints: array of points (x, y, z)
          Height: centimeters
          Weight: kilograms
          Seatbelt: {
                   Buckled: Yes / No
                   Detected: Yes / No
                   Classification: Properly Buckled, on bely  …
          }
       }
}
```

Figure 23. Example of the output object list format

Sensor calibration: one factor that influences the accuracy of the detection system is the calibration of the sensors. The calibration focuses on finding two types of parameters: (1) extrinsic parameters, which are composed of the position (location and rotation) regarding a reference coordinate system (vehicle coordinates); and (2) the intrinsic parameters that refer to the image sensor and lens model [61][62].

The intrinsic camera parameters will be calibrated only once outside of the vehicle, and the extrinsic parameters must be calibrated when the cameras are placed in the vehicle. Due to the vehicle movement and other factors (vibration, temperature, etc.), the cameras may have small deviations in their position. Therefore, it is recommended to perform a periodic calibration while the detection system is operating to ensure the system's accuracy.

Data collection: data is needed to develop the detection system, perform evaluation, calibrate, and select the optimal placement of sensors. For that, test cases were defined focusing the same seated postures (Figure 7) and seat variations (longitudinal position and inclination angle).

The main metric to evaluate the acquisition system is the percentage of visible occupant body key points for the captured data in all test cases. Accuracy, Precision, and Recall [63] are used to measure the performance of the classification methods. And, to measure the error of the detected key points in the 3D space, the selected metric is Mean per Joint Position Error (MPJPE) [59].

To perform the data collection, specific software is required. It should be based on multi-process and multi-threading architecture to support multiple data sources and should be able to configure device parameters (exposure time, gain control, image resolution), to visualize and store the collected data in real-time.

To compute the metrics and evaluate the system, the collected data must be cleaned and labelled; specific software and libraries in Python 3 will be used to handle data from multiple data sources and generate labels in 2D image space and 3D space manually. Due to the huge amount of time required to manually label 3D data, different approaches will be applied to generate label information automatically: (i) pre-trained models for 2D detection and segmentation can be used with 2D images to map the occupants on captured point clouds, and (ii) the 3D depth information and the knowledge of the vehicle space can be used to extract and generate semantic segmentation information on the 2D images.

To validate the system, a mock-up vehicle will be built to test the sensors in different positions and also different seat configurations.

3. Dissemination and Exploitation

This report identifies new challenges and technologies to address these challenges; therefore, this information will be used as input for future rating programmes (such as Euro NCAP) when assessing vehicle occupant protection.

The deliverable reports D4.1 and D4.2 both aims to provide the foundation for occupant protection in future vehicles by identifying future critical scenarios (crashes) and new seating positions for Level 3 and Level 4/5 vehicles. As such they are both important documents and will be made public via the SAFE-UP website. Additionally, especially the four system layouts, i.e. "*State-of-the-art*", "*Adaptive actuators*", "*Pre-crash actuators*" and "*New interior*", see Figure 24, is planned to be disseminated via the website and in a future SAFE-UP newsletter.

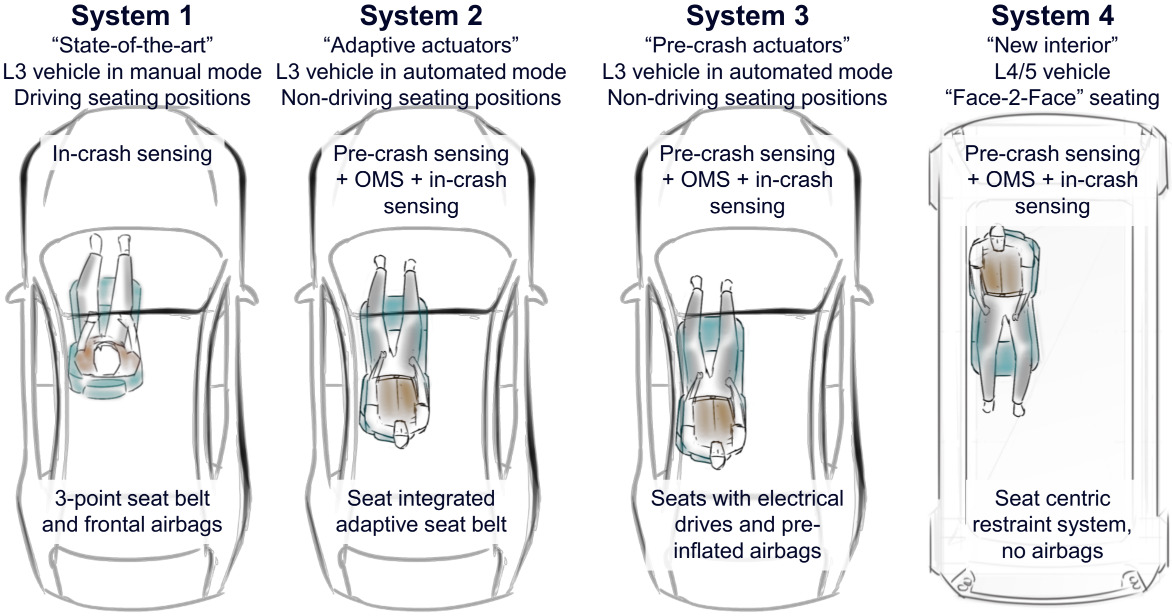


Figure 24. Overview of the four identified system layouts.

In terms of exploitation, the work done in task 4.2 will be an important building block enabling new seating positions and increasing the robustness of the occupant protection system by giving examples of how the system requirements and system layout can look like when developing occupant restraint systems for future vehicles.

4. Summary and Outlook

4.1 Summary

Starting from a set of system requirements including relevant system prerequisites, defined use cases as well as assessment criteria, four different occupant protection systems have been identified. They are characterized by increasing complexity in terms of pre- and in-crash sensors and actuators but also by an increasing time of technical readiness perspective, all with the purpose to make it possible to address more and more advanced situations (use case variations) and/or vehicle types.

System 1 “State-of-the-art” is representing current occupant protection systems and has its functional window in a limited number of seating positions and flexibility options, i.e. the seat needs to be close to the steering wheel and in upright position. Results from this system will be used as a reference when judging on the functionality of the other systems defined through more advanced restraint systems as well as new seating positions (L3 interior in systems 2 and 3) and seat configurations (L4/5 interior in system 4).

System 2 “Adaptive actuators” is a conceptual system with a five- to ten-year readiness perspective. It adds functionality to (a) activate seat belt pre-tensioner before the crash started, (b) early activation of seat belt pre-tensioner and airbag, i.e. at T0 and (c) increases the functionality of the seat belt by integration into the seat, enabling good belt fit also in reclined backrest and rearward positioned seat. Moreover, the system adds (d) adaptive features to the seat belt and the airbag to address variation of occupant size, (e) pre-tensioner in the lap belt to address increased risk of submarining in reclined seating positions and (f) lap belt load limiter to address increased belt force and thereby increased risk of pelvis fracture in rearward positioned seat, i.e. when the occupant is out of reach of the knee bolster. This system is evaluated in an L3 vehicle in automated mode.

System 3: “Pre-crash actuators” is adding functionality to the seat by introducing electrical drives enabling a re-positioning of the seat (longitudinal movement and recline position) before the crash starts and pre-crash activations of the airbags. This system has a longer time perspective with ten-to fifteen-year readiness and is evaluated in an L3 vehicle in automated mode.

System 4 “New interior” is an occupant protection system for a new type of interior, i.e. occupant facing each other in a face-2-face configuration. To reduce the load to the occupant a seat track load limiter concept is introduced. Also, this system has the ten-to fifteen-year readiness perspective and is evaluated in an L4/5 vehicle in automated mode.

Additional to the definition and characterization of the four SAFE-UP occupant protection systems, use case parameters have been identified that need to be addressed to guarantee safe seating, including vehicle type, crash configuration, seat position, occupant seated posture and human variations. Systems 1-3 address C2C Head-on, C2C Intersection, and/or C2HGV Head-on scenarios, possibly considering a pre-crash brake or steering pulse, while System 4 will be evaluated for occupants traveling in various rearward facing positions in highway crash scenarios with rear-end impacts from cars and HGV. The most relevant use case parameters will be selected within a subset of these general scenarios. Moreover, a limited number of injury prediction criteria for HBMs are introduced that can be used to address the most frequent severe injuries and expected new types of injuries in the new seating positions.

4.2 Outlook

The following SAFE-UP WP4 Task 4.3 “Optimization of system concept for different seating configurations” has the aim to clarify the potential and benefit of the combination of an occupant monitoring system and an advanced restraint system for future seating positions. This will be done with the starting point of what has been identified in this deliverable in terms of system layouts, use case variation and injury predictors.

Due to the high number of variations in use case parameters and number of (sub)systems it is foreseen that Task 4.3 will work with the starting point of specific research questions. These will address one specific system and several use case parameters or two or more systems and fewer use case parameters. The target will be to show the benefit of the combination of the occupant monitoring system and advanced restraint systems. One example of such a research question is to understand the limitations to protect an occupant in different occupant postures of the upper body and leg position within the different vehicles types and system contents. Understanding the limitations of the restraint system helps to identify situations where an HMI could effectively support by nudging the occupant into a safer position.

In Task 4.4 “Algorithm development” the focus is on the development of an algorithm for the occupant monitoring system and an algorithm for activation and adapting the restraint system actuators. Both tasks will consider the requirements and design of the occupant monitoring system, possible actuators in the restraint systems and the new seated positions according to the new interior designs suggested in this document.

Finally, the demonstration of the systems and their benefits in Task 4.4 and 4.5 is closely aligned with SAFE-UP WP5. The first part considers mainly the OMS in the hardware-based SAFE-UP Demo 1. The second part of the demonstration is carried out by using the outcome of Task 4.3 which builds upon the four occupant restraint systems defined in this deliverable.

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