Safe Small Electric Vehicles through Advanced Simulation Methodologies

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Definition of requirements for consistent safety analysis for pedestrian protection in SEVs

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EXECUTIVE SUMMARY

WP3 of SafeEV deals with an advanced simulation methodology for integrated pedestrian / occupant safety in small electric vehicles (SEVs). This report is part of Task 3.2 of work package 3 and concerns the development of an advanced simulation methodology for consistent safety analysis for pedestrian protection for SEVs. Task 3.2 runs in parallel with Task 3.3 which deals with the corresponding development of a simulation methodology, but for occupant protection only. The objective of the D3.2 report is as an initial definition of requirements for consistent safety analysis for pedestrian protection in SEVs. These requirements are interpreted as the necessary steps to develop a so called "seamless tool chain" in order to virtually assess and optimise pedestrian safety. The main aspects covered by this report are the following:

- test conditions and body regions to be evaluated (Chapter 2)
- simulation tools to be used by the different partners (Chapter 3)
- a brief look back to the EC funded project IMVITER (IMplementation of VIrtual TEsting in safety Regulations) in order to provide an exemplary process and protocols which could enable type approval through virtual testing (Chapter 4)
- description of the necessary steps and tools needed to develop a "seamless tool chain" for pedestrian safety (Chapter 5) consisting of:
  - agreement on how to evaluate injury risk using human body models (HBMs)
  - comparison of a HBM vs. a pedestrian accident compliant (PAC)
  - code dependence in the application of Finite Element (FE) HBMs
  - utilisation of an advanced ground model to evaluate the secondary impact
  - comparison of acceleration sensor signals derived from pedestrian impactor and HBM contact against the vehicle

The reporting of Task 3.2 will be completed by three future reports. Report D3.4 will make a comparison of the simulations with the models running under different FE codes for identical load cases. Thereafter, report D3.5 will describe the resulting methodology for the virtual tool chain for pedestrian safety simulation. This will include an analysis of the robustness of the virtually gained results by slightly varying the defined load cases. Finally report D3.7 will summarise the final definition of the relevant load cases and appropriate criteria for injury risk evaluation using HBMs as a result of a separate Task 3.4 in WP3. Hence report D3.7 finally closes Tasks 3.2 to 3.4 and WP3 itself.

APPROVAL STATUS

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REVISION TABLE		
Document version	**Date**	**Modified sections - Details**

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Glossary

ADVANCE	Advanced Model Development and Validation for the Improved Analysis of Costs and Impacts of Mitigation Policies
APROSYS	Advancec PROtection SYStems
CORA	CORrelation and Analysis
ECE	Economic Commission for Europe
EU	European Union
Euro NCAP	European New Car Assessment Programme
FEM	Finite Element Method
GCM	Generic Car Model
GUI	Graphical User Interface
HBM	Human Body Model
H-Point	Hip point
IKA	Institut für Kraftfahrzeuge RWTH Aachen University
IRA	Injury Risk Assessment tool developed by UNISTRA
IMVITER	IMplementation of VIrtual TEsting in safety Regulations
LS-DYNA	Finite element method solver provided by Livermore Software Technology Corporation
LSTC	Livermore Software Technology Corporation
NCAC	National Crash Analysis Center
NCAP	New Car Assessment Programme
NHTSA	National Highway Traffic Safety Administration
PAC	Pedestrian Accident Compliant dummy developed by Chalmers and Autoliv Research Sweden
PAC FE	FE model of the PAC developed by Altair and CRF
PAM-CRASH	Explicit crash solver which is included in VPS and is provided by ESI group
PDB	Partnership for Dummy Technology and Biomechanics
REVM	Reference Electric Vehicle Model
SafeEV	Safe small Electric Vehicles through advanced simulation methodologies
SEVs	Small Electric Vehicles
SUFEHM	Strasbourg University Finite Element Head Model
SUFE-HN-Model	Strasbourg University Finite Element Head-Neck Model

THUMS	Total Human Model for Safety provided by Toyota Motor Corporation and Toyota Central R&D Labs. Inc.
UNECE	United Nations Economic Commission for Europe
US	United States of America
VPS	Virtual Performance Solution (VPS) is a global solution for Virtual Product Engineering having its origins in PAM-CRASH and is provided by ESI group
VRU	Vulnerable Road User
VT	Virtual Testing
V&V	Verification & Validation
YOC	Years Old Child

1 Introduction

The objective of this D3.2 report is defined as an initial “definition of requirements for consistent safety analysis for pedestrian protection in SEVs” within WP 3 of the SafeEV project. The mentioned requirements are interpreted as the necessary steps to establish a so called “seamless tool chain”. This “seamless tool chain” is intended to be a big step forward towards a virtual assessment and finally virtual certification of SEVs in terms of occupant protection and pedestrian safety.

After having completed a detailed analysis regarding future accident scenarios in WP1 of this project, followed by the specification of test conditions as well as the provision of an overview of injury criteria for occupant and vulnerable road user assessment and protection in WP2 (see D2 [2]), WP3 is about the development of the necessary simulation tools for the assessment of the proposed test cases. For the assessment of pedestrian safety, current and widely used impactors as well as the pedestrian dummy PAC and two HBMs, will be utilised in the work packages WP3 and WP4 of this project. The two reference vehicle models (REVM1 and REVM2) which represent future SEVs are to be used for the analysis and are described in the D3.1 report [3]. The impactors, dummy and HBMs to be used by the partners involved in Task 3.2 are described in detail in Chapter 3 of this report. Since the secondary impact will be simulated as well, a special ground model will be used. This model is also described in detail in Chapter 3.4.2.

The virtual tool chain implies the utilisation of validated models, either of the two vehicle models as well as dummies, impactors and HBMs. However, T3.2 and T3.3 will not reinvent the wheel for this obligatory process which of course is part of the complete tool chain. Therefore, the EU-project IMVITER [10], which defined in detail a process for the relevant validation requirements for numerical tools, is used as reference. A summary of the IMVITER project is included in Chapter 4 of this report.

The main part of T3.2 will be the simulation of a reduced but representative number of the proposed test conditions while applying appropriate injury criteria derived from the overview in D2 [2]. However, in terms of the application of the HBMs, further investigations and agreements on the criteria are necessary between the partners. Appropriate tools which are ready to be used exist with reservations for the head model only (see Chapter 3.6). As already mentioned in D2 [2], neither “injury predictors” nor “corresponding thresholds” are commonly agreed or accepted. Hence, the future work in T3.2 will also contain a proposal for applying criteria for the assessment by using HBMs.

Another important sub-task in T3.2 will be the comparison of the application of the same HBM while running with different solvers (THUMS-D under LS-DYNA vs. THUMS under VPS). Moreover, this comparison will be summarised in a separate future report D3.4.

Further on, after having completed the simulation matrix which is shown in Chapter 2 of this report, the simulation results will be reviewed and the results will be reported in a further report of Task 3.2 in D3.5. The outcome of this review which is to be performed in a separate Task 3.4 may result in a confirmation of the proposed test conditions and applied criteria, but may also result in a revision of these, based on new findings. The outcome of this final Task

3.4 in WP3 will result in the final report D3.7 summarising test conditions and criteria for pedestrian and occupant safety for SEVs.

Analogue simulations for occupant safety are to be done in T3.3 and are reported in the analogous reports D3.3 [9] and D3.6. The final report D3.7 mentioned above will contain both occupant and pedestrian test conditions and criteria.

2 Definition of test (accident) conditions and criteria that will be simulated

The test or assumed future accident conditions which will be simulated in T3.2 were already roughly defined in Chapter 3.3 of D2 [2]. The relevant pedestrian impact locations as well as speed ranges and the different percentiles are shown in Figure 1 for both a "conventional design" (as far as wheel positions are concerned) and an outstanding wheels design. These new test scenarios are based on the outcome of the studies conducted under WP1 and are reported in D1.1 [1]. The test scenario for pedestrian assessment which is suggested in D2 is completely different from that one for the current M1 regulations. The impactors as well as the test conditions for these current regulations are described in detail in D2 of this project [2]. In SafeEV a complete virtual tool chain will be developed for SEVs using a complete dummy like the FE PAC or the HBM THUMS variants. Hence, the whole kinematic of the pedestrian impact is taken into account rather than concentrating on impact tests with single impactors.

	Speed Range:	Size:
3 Orange	V1, V2	A, B, C, D
2 Green	V1, V2	A, C
2 Red	V1	A, B, C, D

Proposal 2

~36 Sim.

A= 6yO
B= 5%
C= 50%
D= 95%

V1=25-30km/h
V2=45-50km/h

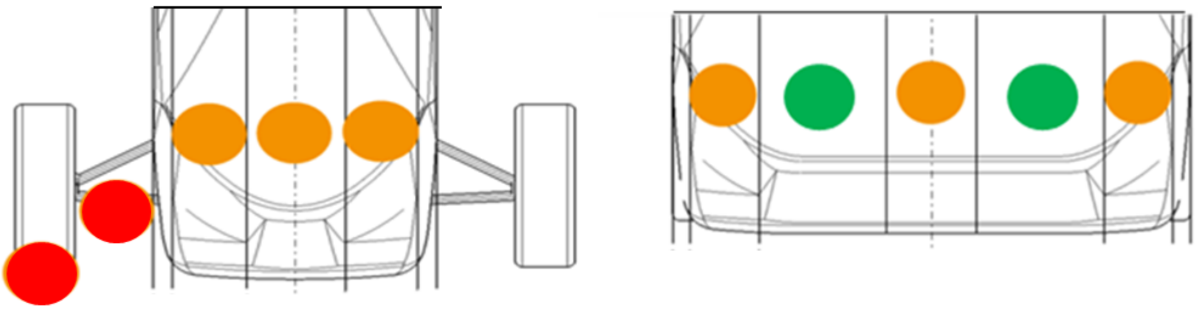


Figure 1. Final proposal for pedestrian impact locations and the simulation effort. [2]

The final proposal coming from D2 suggests about 36 simulation runs [2]. Based on this test matrix a reasonable number of selected impact conditions to be run in T3.2 for further evaluation of more specific test conditions have been chosen. As far as the different percentiles are concerned, it has to be mentioned that not all of these models are available for dummy and HBM simulation. For the FE PAC which will be used by CRF, there is the 50^{th}% male available only. As far as the THUMS models are concerned, Daimler AG will run two model sizes as there are the 50^{th}% male and its scaled derivative which is a 6 years old child model. At Volkswagen AG, only the 50^{th}% male will be used.

2.1 Definition of the test matrix

In Figure 2 the final T3.2 simulation matrix overview is shown. It provides an outline overview of the models – vehicle models as well as dummy models and HBMs – that will be used by the different partners (fields marked yellow). Furthermore it shows dependencies between certain partner’s contribution and the relevant model information and simulation results to be shared (see arrows in Figure 2). The detailed description of the HBM, dummy or impactor models each partner is using can be found in Chapter 3 of this report.

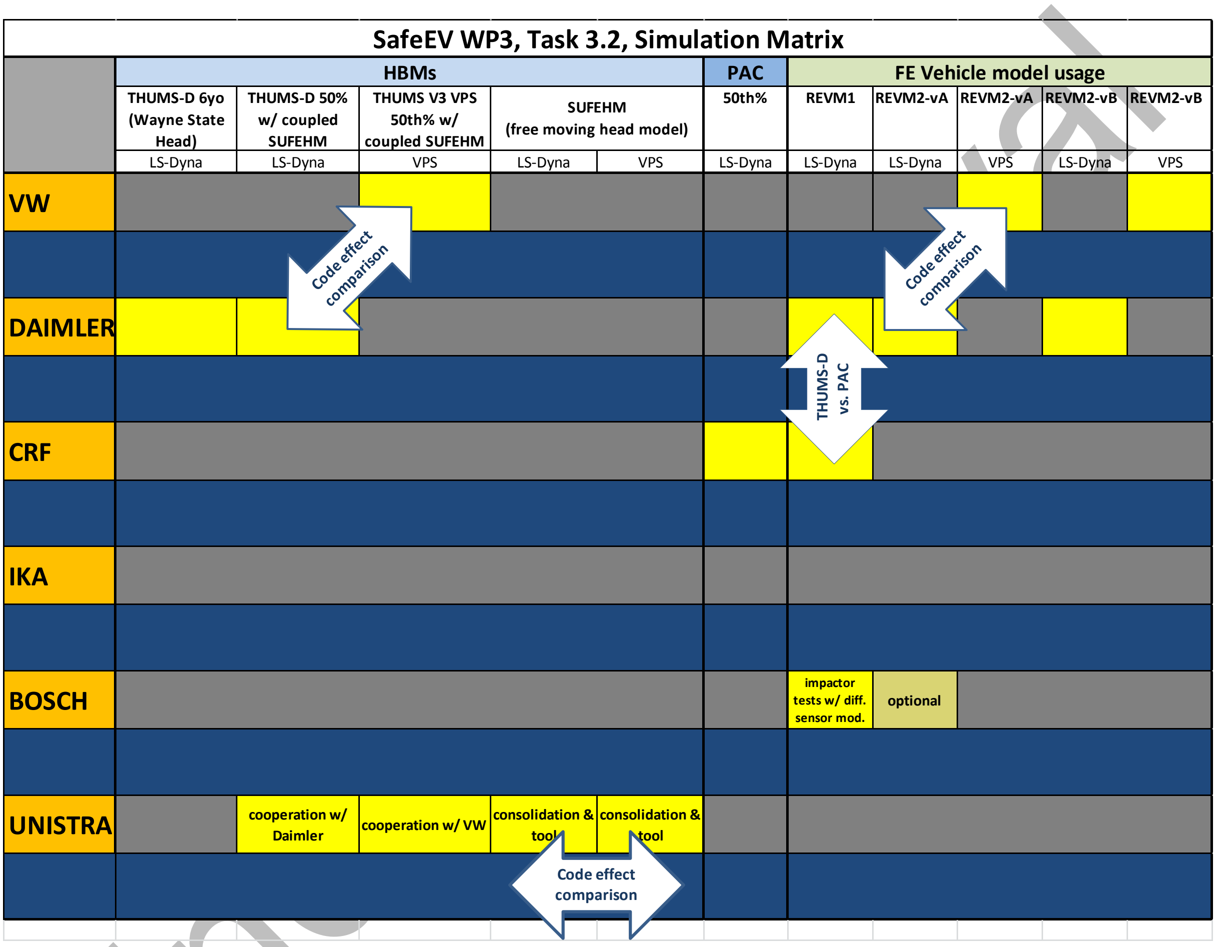


Figure 2. Task 3.2 Simulation matrix overview

While CRF, Daimler AG and Volkswagen AG will perform full vehicle simulations including the FE PAC dummy or HBM respectively (Figure 3), the other partners will support the simulation and evaluation with their tools. Hence, UNISTRA will cooperate with Daimler AG and Volkswagen AG with respect to the SUFEHM and SUFE-HN (Daimler AG only). Ika will support with its FE ground model(s). Both of the mentioned tools are described in detail in Chapter 3 of this deliverable. Bosch will be using a generic leg impactor model as described in Chapter 3.5 of this report in order to test various sensor configurations. Additionally Bosch will get virtual sensor data from the PAC and HBM impact simulation as well.

	WP3 - Task 3.2, Simulation Matrix														
		Pedestrian at 20 % (veh. width) nearside *REVM1, REVM2 - var. 1 and var. 2*							Pedestrian Middle Position *REVM1, REVM2 - var. 1*						
	Partners	Low velocity	High velocity	Var. 1 (robustness)	Var. 2 (robustness)	Var. 3 (robustness)	Var. 4 (robustness)	incl. 2nd impact	Low velocity	High velocity	Var. 1 (robustness)	Var. 2 (robustness)	Var. 3 (robustness)	Var. 4 (robustness)	incl. 2nd impact?
1	**VW** REVM2 only (var. 1 & 2)	25 kph	40 kph	Veh. braking / Veh. not braking	Position y+/- 10 mm	HBM rotation +/- 2°	45 kph (robustness)	X	25 kph (braking)	40 kph (braking)	optional tbd	Position y+/- 10 mm	THUMS rotation +/- 2°	45 kph (robustness)	X
2	**Daimler** REVM1+ REVM2 (var. 1 & 2)	25 kph	40 kph	Veh. braking / Veh. not braking	6yo child (kinem. 1st impact)	optional HBM rotation +/- 2°			25 kph (braking)	40 kph (braking)	32 kph (braking) 2nd impact analysis	2 - 3 ground surface var. 2nd impact	6yo child (kinem. 1st impact)		X
3	**CRF** REVM1 only	25 kph	40 kph						25 kph (breking)	40 kph (breking)					

Figure 3. Task 3.2 simulation matrix with detailed test description

In order to further define the test set-up for the usage of either FE PAC dummy or THUMS as shown in Figure 1 it is necessary to agree on a posture of the pedestrian models. Figure 4 is showing the agreed walking posture with a THUMS model including some reference points. The posture is in line with the requirements provided by Euro NCAP pedestrian testing protocol [8].

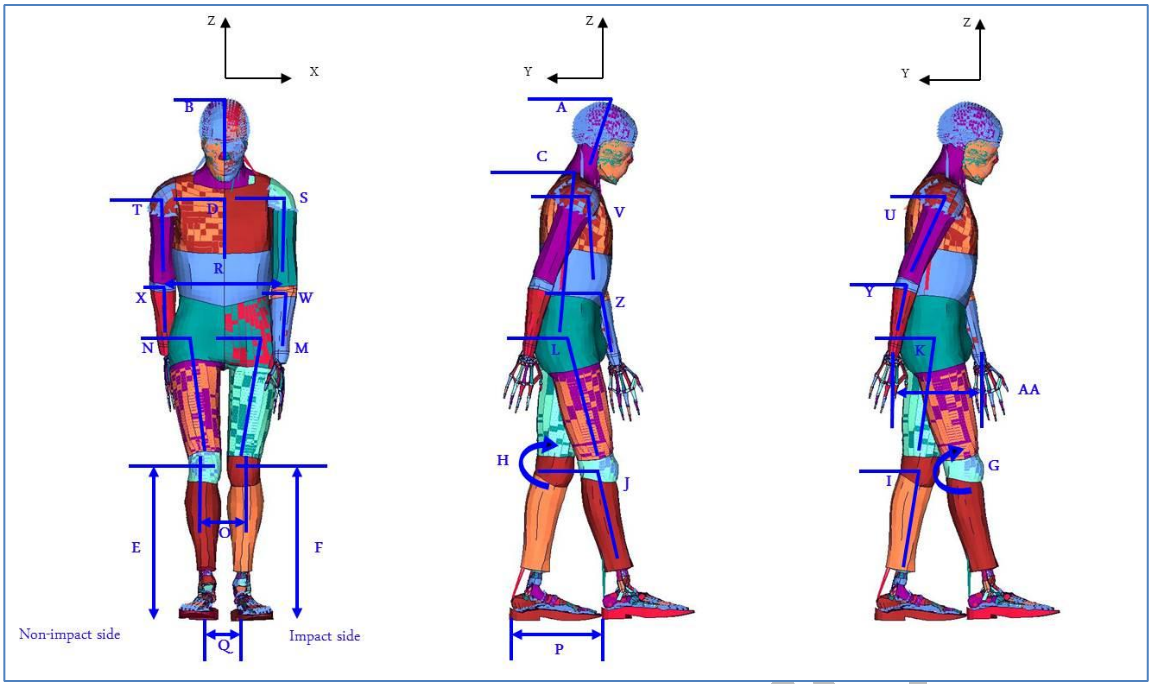


Figure 4. Definition of the walking posture for the HBMs demonstrated on a THUMS [11]

Further on, a more precise description of the initial positions for the pedestrian simulations has to be defined. The impact locations that are shown in Figure 1 are showing target points for head impact zones on the vehicles. In Figure 5 two initial positions of the pedestrian are shown. These initial positions are expected to generate head impacts within the area defined in D2. This first definition of the pedestrian's initial position will be further evaluated during the simulations conducted in T3.2. In order to define a clear reference to position the pedestrian models, the H-Point (on left leg) has been proposed as the relevant reference point.

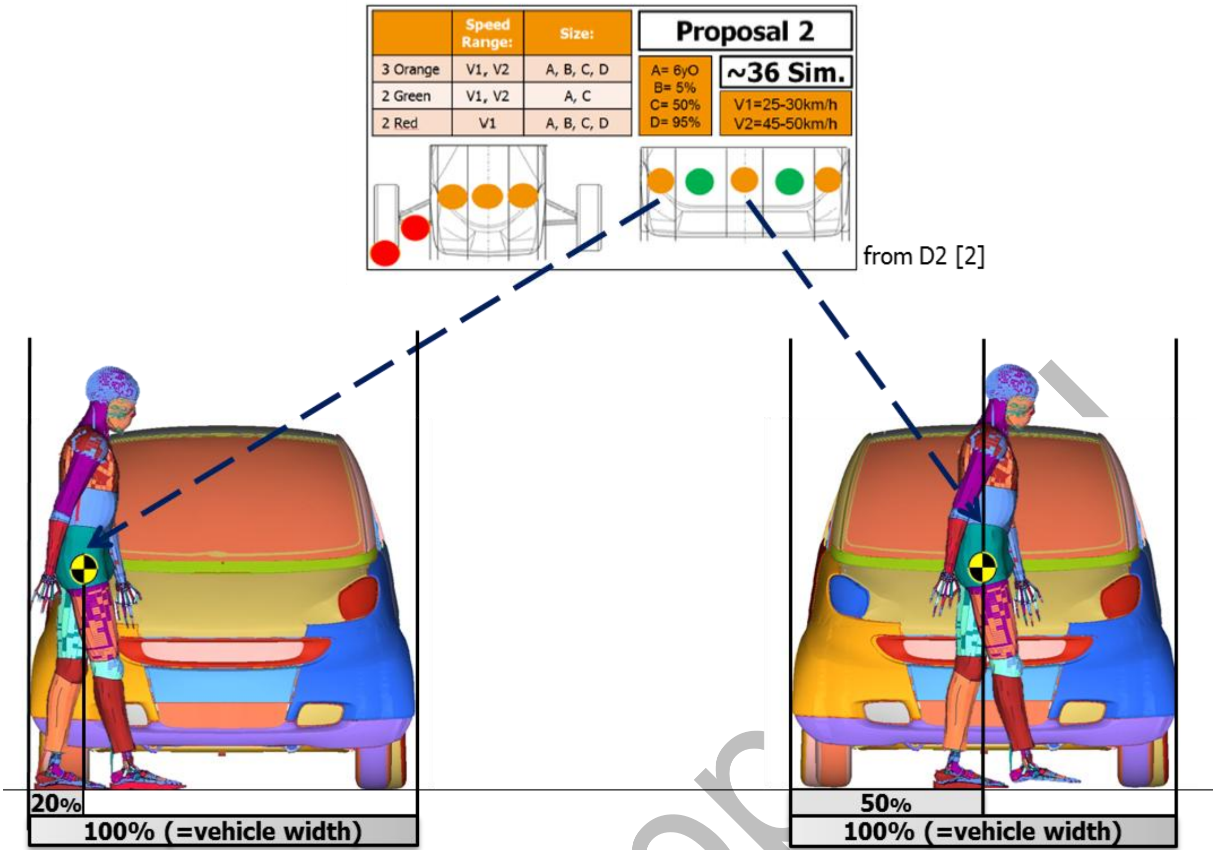


Figure 5. Initial pedestrian model position based on "Proposal 2" [2], demonstrated for the conventional vehicle design with THUMS-D in step position; left picture shows the "20% near side" position, right picture shows the mid position

2.2 Definition of evaluation criteria

In order to evaluate the performance of the impactors, dummy and HBMs to be used as described above the definitions of injury criteria is mandatory. Injury criteria have been widely discussed in detail in D2 [2].

While for the impactors being currently used for pedestrian protection assessment the relevant injury criteria as well as thresholds are well defined, this is not the case for the HBMs or the THUMS.

As far as the FE PAC model is concerned the following measurements are available as output and can be used for the assessment. The PAC dummy output is comparable with the corresponding existing dummy output parameters. Therefore, the application of the existing injury criteria and thresholds can be used for the following outputs:

- head acceleration and HIC
- lateral chest deflection
- hip force
- total knee force
- knee shear and bending

For the SUFEHM and SUFE-HN an injury risk assessment as well as an assessment tool is already available. It is described in Chapter 3.6 in detail. However, there are some restrictions as far as its ability under VPS code is concerned. For the SUFEHM running under VPS a simplified skull criterion has to be used and the neck model of UNISTRA is not yet available under VPS at all. That implies, that for the coupled THUMS with SUFEHM or SUFE-HN model the head or head and neck assessment respectively is possible. For all other body regions injury criteria and assessment parameter still have to be discussed and agreed on in T3.2 by all partners. Hence, a catalogue showing body regions, body part injury risk criteria and evaluation method is due to be developed in the course of this task. An overview of currently discussed injury criteria to be used with HBMs is given in D2 Chapter 5.1 [2]. In SafeEV, it is the intention to, beside a head injury assessment, also to include the following body regions into the evaluation:

- neck
- chest
- abdomen
- pelvis
- lower leg

Relevant criteria can be derived from appropriate test data from literature. However, the ability to robustly predict injury risks with the used HBMs of this project need to be evaluated as well.

3 Status of current simulation tools to be used on partner level in WP3.2

The FE models that will be used for the simulations to be done in T3.2 are described in this chapter. The vehicle models REVM1 and REVM2 have already been described in detail in D3.1 [3]. Hence their description will not be repeated here. However, there are two exceptions with respect to the REVM2. Firstly, there is to mention the modifications of REVM2 as far as the “electrification” of the vehicle are concerned, i.e. the replacement of the powertrain, and the implementation a restraint system. These modifications are not relevant for the pedestrian impact simulation and are described in more detail in D3.3 [9]. Secondly, REVM2 model was translated from LS-DYNA into VPS for Volkswagen AG by ESI GmbH as part of their contribution to SafeEV (by subcontract). First comparisons between both models using simple load cases with almost rigid impactors within the (for pedestrian impact) relevant areas of the vehicle front have shown a good comparability of both virtual models. A more detailed description will be part of D3.4 of which the main objective is to report on the principal comparability of HBMs in different codes.

3.1 Status of current simulation tools to be used in T3.2 by Volkswagen

3.1.1 Model description (THUMS VPS)

The THUMS (Total Human Model for Safety), developed by Toyota Motor Corporation and Toyota Central R&D Labs [4]), version 3.0, pedestrian model, will be used by Volkswagen for the simulative work to be performed from Task 3.2 onwards. The THUMS model Version 3.0 (strictly speaking version 3.0-080225) was the basis for the translation of the original THUMS into VPS. The translation was performed by ESI group. The objective during the translation process was to keep the translated model as close as possible to its origin (in LS-DYNA code) and to use as close as possible correlating definitions in VPS, without changing for instance material parameters, connection definitions or element types and geometry. In order to evaluate the success of the whole translation, the original model as well as the translated THUMS were impacted by the Dodge Neon FE model which is a public vehicle model provided by NCAC [6] in LS-DYNA code. An appropriate translation of that vehicle into VPS is available at Volkswagen. The overall kinematic behavior was compared between the original and the translated model. Figure 6 is showing a sequence of the THUMS kinematics for both cases [5]. The translation of the original THUMS was further improved until a “good” comparison between both models could be observed. While the overall kinematic behavior is looking quite similar by now, also the head impact time (being an important parameter) is occurring at the same moment in time. Onwards from then THUMS running under VPS was used at Volkswagen and Audi AG in simulating different pedestrian load cases. In order to overcome upcoming issues within single load cases (error terminations etc.) the improvement of the model is still an ongoing process and mainly focuses on simulation robustness. Nevertheless, within Task T3.2 the status of the model will be frozen. The parameters which will affect deformation, stress levels or element deletion were kept to the values of the original THUMS under LS-DYNA. This point is important in order to allow a reasonable result comparison in this and following tasks, in particular with respect to the results delivered by Daimler who will perform the same load cases using THUMS-D.

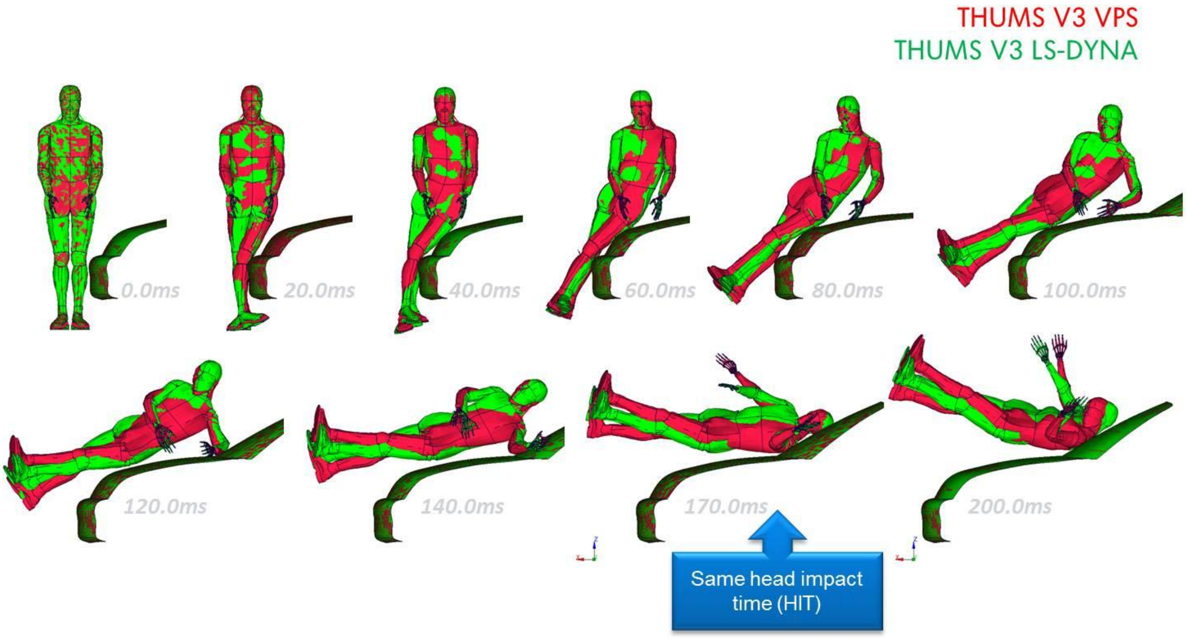


Figure 6. Comparison of LS-DYNA and VPS version of THUMS in a 40 km/h impact against a rigid front of Dodge Neon [6] model [5]

In order to accomplish an assessment with the THUMS which is planned in Task 3.2 (and following tasks) a more detailed evaluation and validation of the model will have to be done beforehand. Especially, to allow assessing body regions or segments by using appropriate injury criteria as described in Chapter 2 of this deliverable, a validation of the model against tests - on a component as well as on a body region level - available from literature will have to be conducted in advance.

3.1.1.1 Model posture change

The THUMS VPS model has been brought from its original posture into a step position by simulation. This new position (Figure 7) is based on certain definitions, as there is to mention the so called heel to heel distance which is defined in the Euro NCAP pedestrian protocol [8].

Figure 7. THUMS, brought into a step position

3.1.2 THUMS VPS and SUFEHM coupling

Further on, the model has been coupled recently with the SUFEHM head model. Therefore, the original THUMS head was removed completely and was replaced by the SUFEHM. The flesh around the neck which builds the connection between upper torso and head has been re-meshed to fit the SUFEHM head. The bar elements which connect the head to the rest of the body were kept and re-connected to the SUFEHM. The material and element types for the re-meshed flesh around the neck was not changed compared to the original modelling. The same applies to the bar elements connecting to the head. The intention is to use this coupled model in T3.2 and the following tasks. However, the test phase and validation of the coupled model is not finished and has yet to be described in the following D3.5 report. Figure 8 shows the coupled model.

In order to assess the head injury risk the IRA tool of UNISTRA will be used to analyse the impact to the SUFEHM head during initial and second impact. However, in contrast to the tool used within a LS-DYNA environment, no precise risk evaluation for the skull fracture is possible under VPS. The risk of skull fracture will be analysed based on a simple contact force evaluation until the more enhanced skull model for the SUFEHM together with an extended IRA tool for the SUFEHM is available within the VPS environment. The intention is to have this enhancement available by the end of T3.2, i.e. to be ready for usage in WP4 of this project. Figure 9 shows the IRA GUI for VPS.

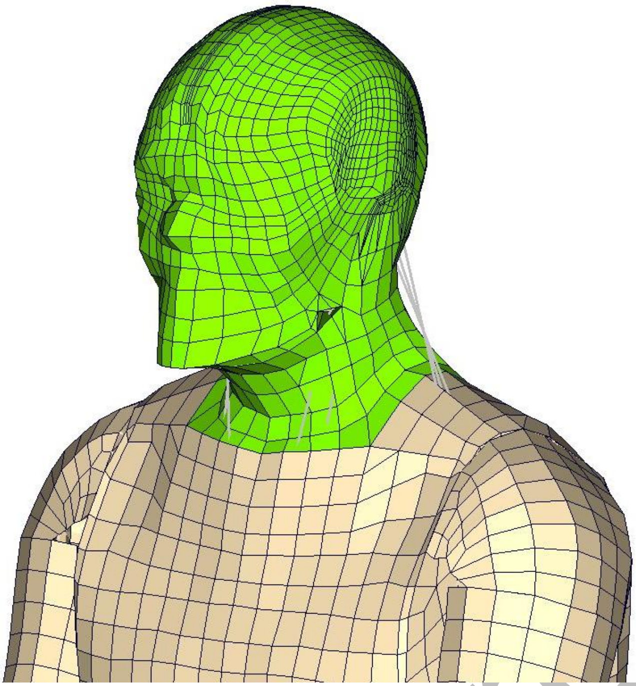


Figure 8. Coupled THUMS and SUFEHM

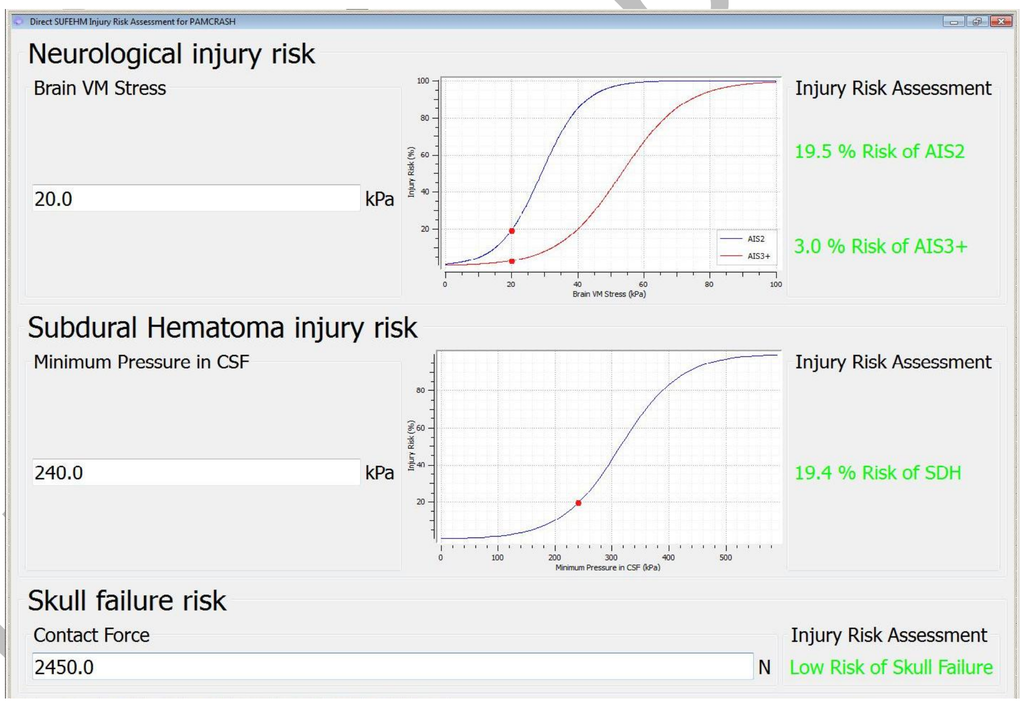


Figure 9. IRA (Injury Risk Assessment) tool for VPS from Strasbourg University

3.2 Status of current simulation tools to be used in T3.2 by Daimler AG

3.2.1 Daimler FE Pedestrian Model

THUMS (Total Human Model for Safety) is a virtual human Finite Element model developed by Toyota Motor Corporation and Toyota Central R&D Labs. Its 50% male version 3 was the basis for the currently in-house usage of Daimler AG and so also now for the projected application within SafeEV Task 3.2.

Especially numerical stability was improved by revision of the FE-mesh and contact definitions. Henceforth this improved respectively updated THUMS version is called THUMS-D.

Figure 10 shows the original and improved THUMS pedestrian models. Coarse meshes in lower extremities including pelvis of THUMS were refined as shown in Figure 10(b) and mesh continuity was established between bones and soft tissues in the regions of pelvis, upper and lower extremities. Many existing contact definitions were removed and new contacts were introduced in order to ensure realistic contact interaction between different body segments. Introduction of new contacts also improved numerical stability of the THUMS model.

(a) **(b)** **(c)**

Figure 10. (a) Original THUMS Model (b) Remeshed Body Parts (c) Improved THUMS-D model

The **anthropometry** of THUMS-D has been compared with the specifications recommended by SAE [12]. Table 1 and Table 2 in the Appendix A provide different dimensions and mass of THUMS-D body segments, respectively. It is seen that the body dimensions and mass distribution of THUMS-D are well within the dimensions recommended by SAE.

The **validation** of THUMS-D FE human body model was done in 2 steps. First, different **body segments** which play a significant role in pedestrian kinematics have been validated for responses under impactor tests. The validated body segments are thorax, abdomen, pelvis, tibia, shoulder, knee, femur, tibia and head. Second, body trajectories and global kinematics are validated by comparing the response of THUMS-D model with the SAE corridors and cadaver responses.

Table 3 in the Appendix A shows details of tests which were simulated with THUMS-D model in order to validate individual body segment response (also in comparison with former used multi body model).
For the impactor tests conducted for different body parts, response of the THUMS-D model shows good conformity with the cadaver response. At component level tests, impact response of the THUMS-D knee and shoulder is stiffer than the cadaver response (see Appendix A).

3.2.1.1 Validation of Full Body Kinematics

The car-pedestrian impact simulations were conducted to validate full body kinematics of THUMS-D model. Global kinematics, body trajectories and head impact location were used as main comparison parameters for evaluation as these parameters influence the vehicle design and safety measures for pedestrian protection. The kinematics of the THUMS-D pedestrian model is validated by:

- Comparing the body segment trajectories with SAE specified kinematic corridors SAE-J2782 [12].
- Comparing the global kinematics and body segment trajectories with cadaver responses [13].

3.2.1.1.1 SAE Test for Body Segment Trajectories

The vehicle used in the cadaver tests was a mid sized car. The SAE document SAE-J2782 [12] specifies the vehicle make and model to remove the test variability but also clearly suggests using alternative vehicles if they can be shown to lead to same results. A number of available car models were studied and the car model used in simulation was selected because of its closeness to centre-line profile of the car used in tests. The comparison of centerline profiles are shown in the appendix.

3.2.1.1.2 Results

The Figure 11 and Figure 12 show that the trajectories of head centre of gravity, upper spine and mid thorax are well within the corridors. The pelvis trajectory is slightly out of corridor which is mainly because of the difference in the hood edge geometry of the simulation car model and test car (see Appendix A – SAE Test “a”). It is clearly seen that the profile of THUMS-D pelvis trajectory closely resembles the hood edge geometry. The hood edge of the simulation car acts as a pivot point about which the whole body rotates leading to the jump observed in the pelvis trajectory.

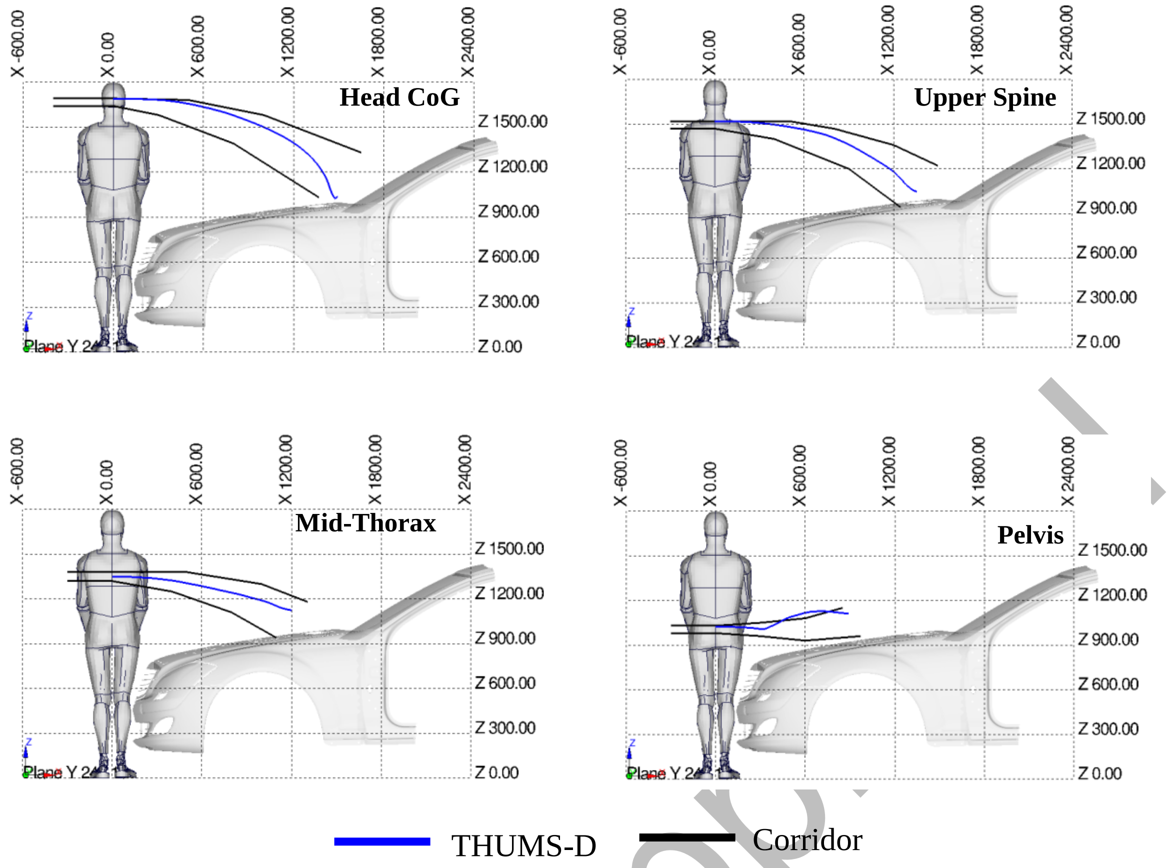


Figure 11. Body Trajectories for THUMS-D

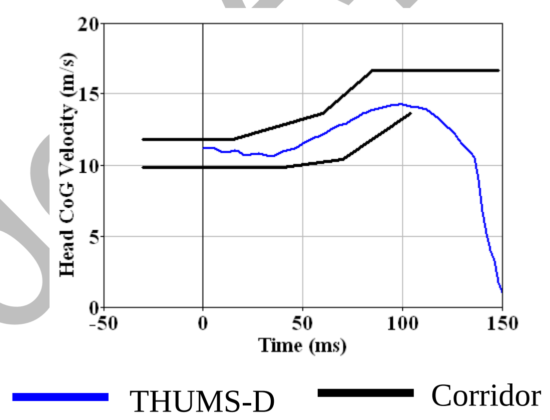


Figure 12. THUMS-D Head Centre of Gravity Profile

3.2.1.1.3 Simulation of Ishikawa Cadaver Tests

Ten cadaver-car impact tests conducted by Ishikawa et al. [13] have been simulated with THUMS-D pedestrian human body model. The stiffness of the simulation car was modified to match the stiffness of the car used in cadaver tests. The comparison between cadaver test car and simulation car for vehicle geometry and stiffness is shown in the appendix. The cadavers were positioned in walking position with the impact-side leg positioned forwards. Table 1 gives details of bumper height, hood - edge height, impact velocity of the test car and cadaver anthropometry. *For simulation, THUMS-D model was scaled to match anthropometry of the cadavers used in experiments.*

Table 1. PMHS Test Conditions (Source: Ishikawa et. al. [13])

Test Number	Vehicle Impact Speed (kmph)	Bumper Height (mm)	Hood-Edge Height (mm)	Age/Sex of Cadaver	Cadaver Mass (kg)	Cadaver Height (mm)
Test-1	25	380	730	54/M	75	1800
Test-2	25	380	730	74/M	56	1670
Test-3	32	380	730	48/M	62	1700
Test-4	32	380	730	58/M	85	1850
Test-5	32	380	730	17/M	90	1920
Test-6	32	380	730	52/M	65	1780
Test-7	32	440	730	59/M	88	1840
Test-8	32	440	730	53/M	89	1800
Test-9	39	390	720	68/M	88	1750
Test-10	40	390	720	36/F	54	1660

3.2.1.1.4 Results

The full body kinematics of the THUMS-D model has been evaluated by comparing its response parameters to the cadaver results. The parameters considered are:

- Global Kinematics
- Body segment Trajectories (Head centre of gravity, pelvis, knee and foot)
- Head Impact Location

The global kinematics of THUMS-D pedestrian model shows good agreement with the cadaver response (Figure 13 and Figure 13). The THUMS-D torso shows realistic rotation compared to MADYMO and is very close to cadaver response for tests 1, 6 (Figure 13) and 9 (Figure 14). The global kinematics indicates that the validity of THUMS-D model is good for both low and high speed impacts.The trajectories of THUMS-D body segments (head, pelvis, knee and foot) for all 10 tests have been compared with cadaver response and they show good correlation with cadaver trajectories (see Appendix A). The pelvis trajectory which did not have 100 % compliance with SAE corridors (Figure 11) shows very good concurrence with cadaver response. In some of the cases like test 9 and 10, the leg trajectories show 100% similarity with cadaver response thereby indicating the significant influence of vehicle geometry and stiffness on leg kinematics.

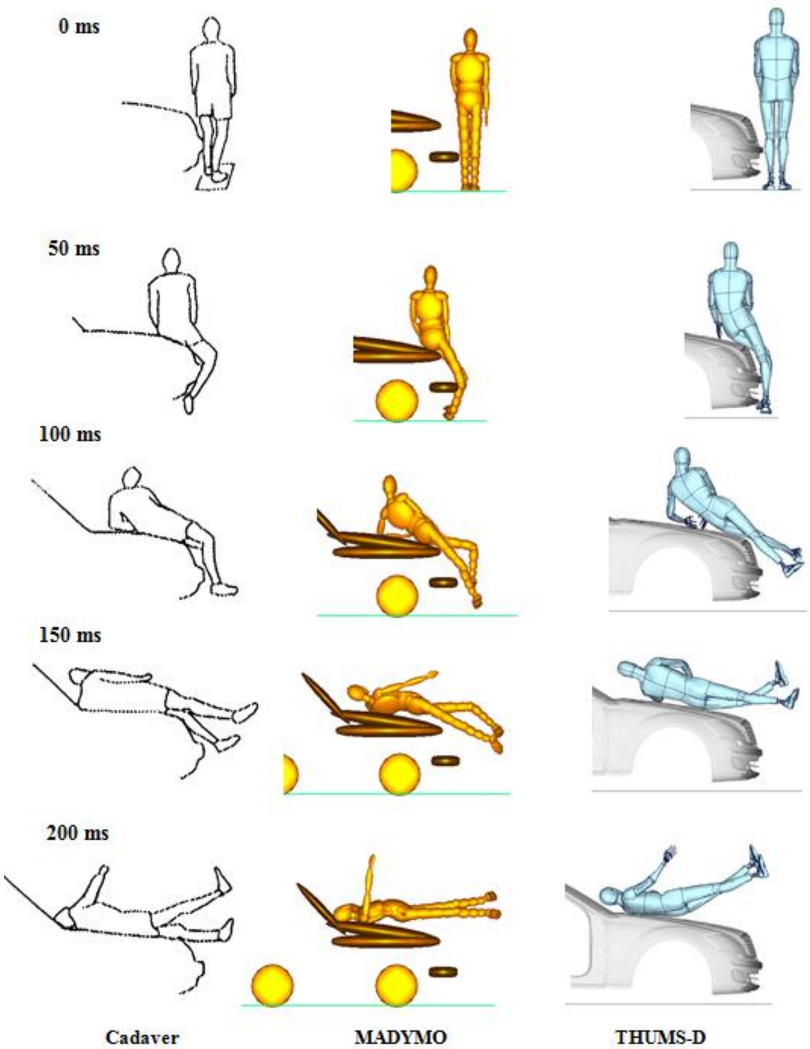


Figure 13. Comparison (exemplary) of global kinematics between cadaver test, Madymo Sim. and THUMS-D. (Ishikawa Test “No 6”).

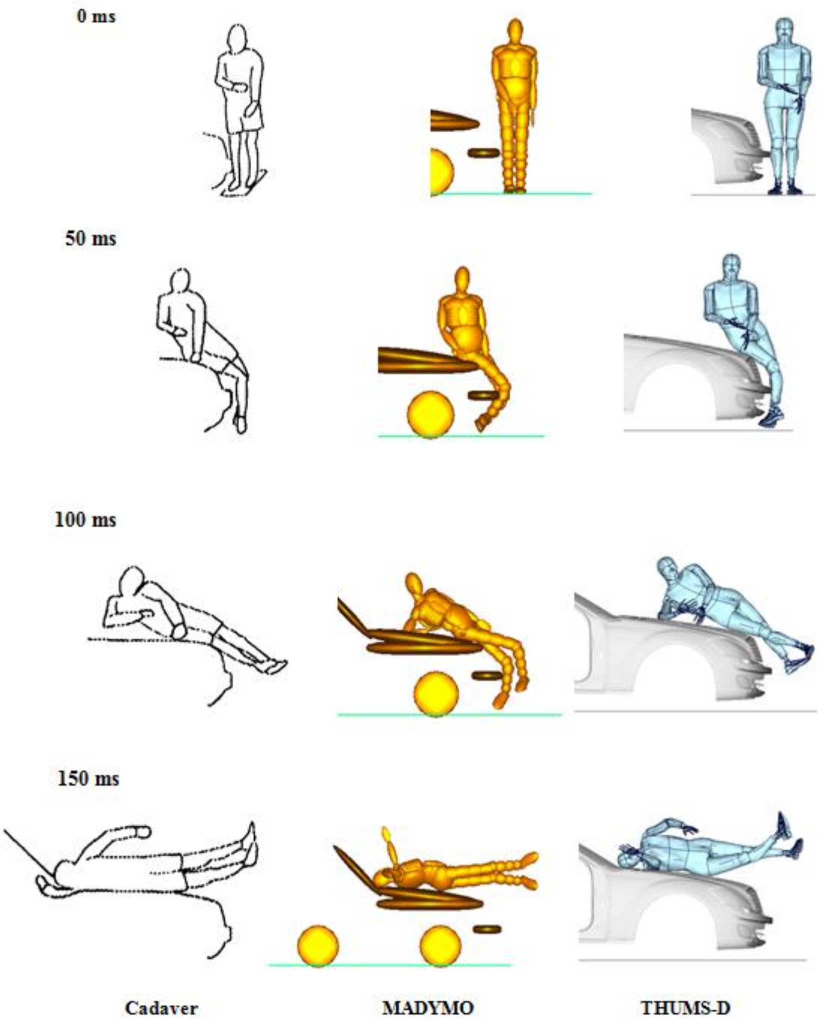


Figure 14. Comparison (exemplary) of global kinematics between cadaver test, Madymo Sim. and THUMS-D. (Ishikawa Test “No 9”).

Finally from the validation results it can be concluded that the improved THUMS-D pedestrian human body model shows acceptable biofidelity in terms of impact response at body segment level and full body kinematics. The demonstrated biofidelity qualifies THUMS-D as a reliable numerical tool that can be used for full body simulations in the vehicle development process for pedestrian safety.

3.2.1.2 Different Pedestrian Sizes

The validated 50th % male pedestrian model is also scaled to different pedestrian sizes such as 6 year old child, 5th % small female and 95th % large male (Figure 15). The height and mass of the different pedestrian sizes are shown in Table 2.

The 6YChild model will also be used in the course of SafeEV Task 3.2.

Table 2. Anthropometry of Different Pedestrian Sizes

	Total Height (mm)	Total Mass (kg)	Head Mass (kg)
95th % Male	1903	101	5.1
50th % Male	1789	76.6	4.92
5% Female	1545	44.8	3.67
6Y child	1201	23.4	3.5

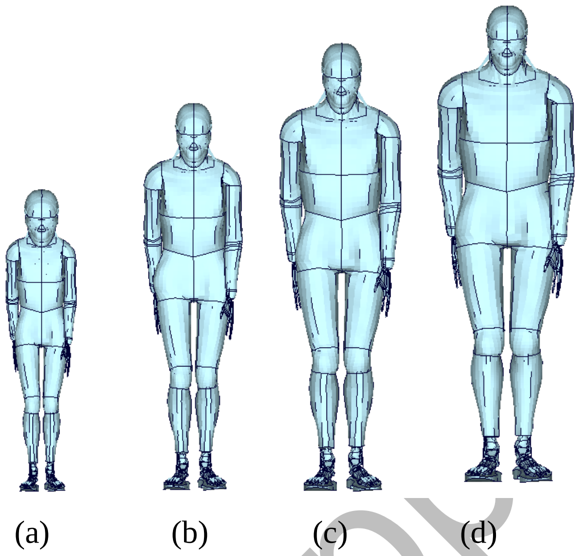


Figure 15. Pedestrian Sizes: (a) 6Y Child (b) 5 % Female (c) 50 % Male (d) 95% Male

3.2.2 THUMS-D & SUFEHM coupling

The coupling of the SUFEHM head with the THUMS-D model has been done manually by using a FE pre-processor. The original head of the THUMS-D models has been replaced completely. The mesh of the THUMS-D neck has been changed in the connection area between the SUFEHM head and the THUMS-D neck. The connection methods are the same like in the original THUMS model. Between head and neck elements the same nodes are shared. The mesh is continuously without any tied contacts or boundary conditions. The Figure 16 shows the new generated head-neck complex.

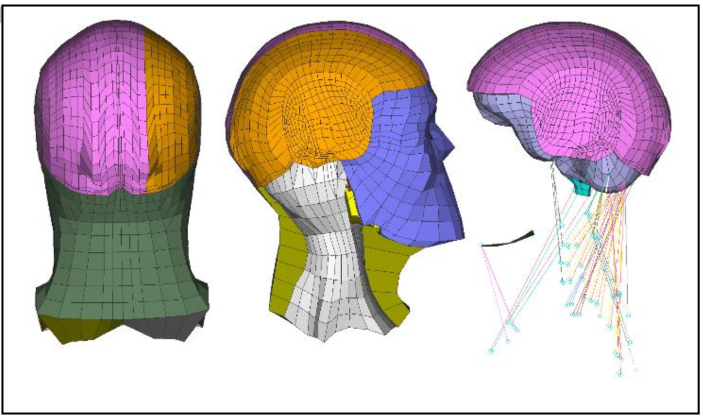


Figure 16. Head neck complex with SUFEHM head and modified THUMS-D neck.

The Validation of the new head-neck complex has been done against the volunteer tests of Ewing et al. [14, 15]. The results show a good fit for the linear accelerations and linear displacements of the head centre of gravity for all three impact directions.

The coupling and validation is also described in detail and already published in [7].

3.2.2.1 SUFEHM post-processing

With the application of THUMS-D and SUFEHM a post-processing tool respectively interface will be used in the course of the project. This SUFEHM Post Process interface has been developed under Python. In order to use this interface easily it has been developed to permit an inexperienced user to assess automatically the head injury risks calculated with the SUFEHM Model in terms of percentage for three different injury mechanisms i.e. neurological injuries, subdural hematoma and skull fracture.

The next Figure 17 and Figure 18 illustrate the results respectively output of the tool. The effective use of this post processing interface will be shown in more detail with the application of the model in Task 3.2.

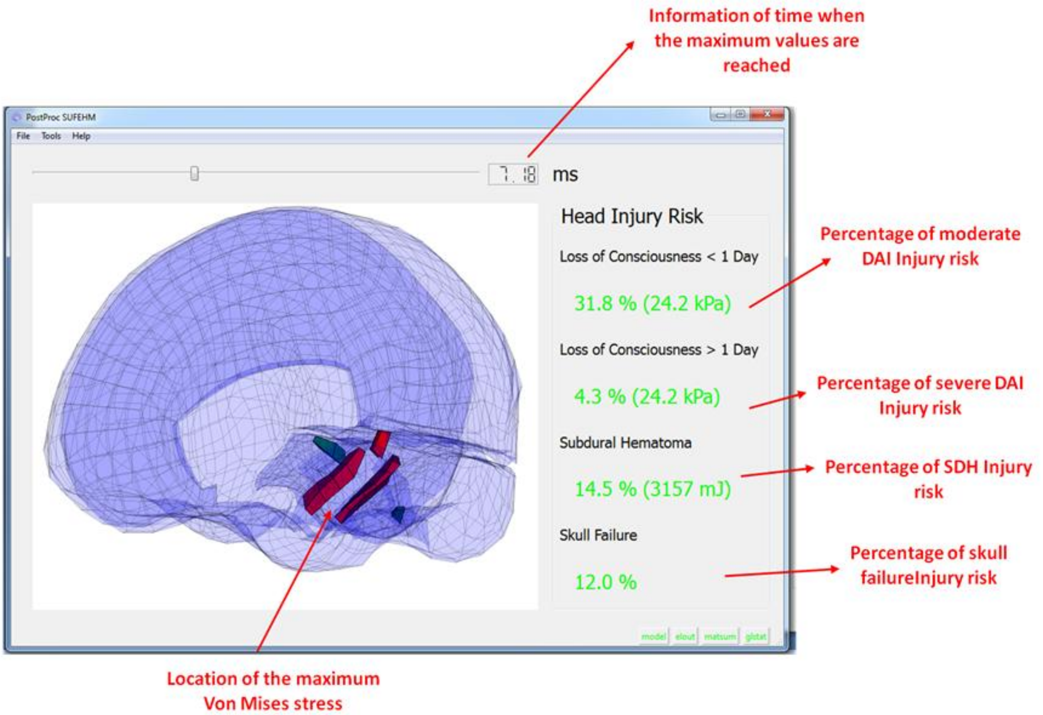


Figure 17. Illustration of the SUFEHM Post Process showing results in terms of percentage risks.

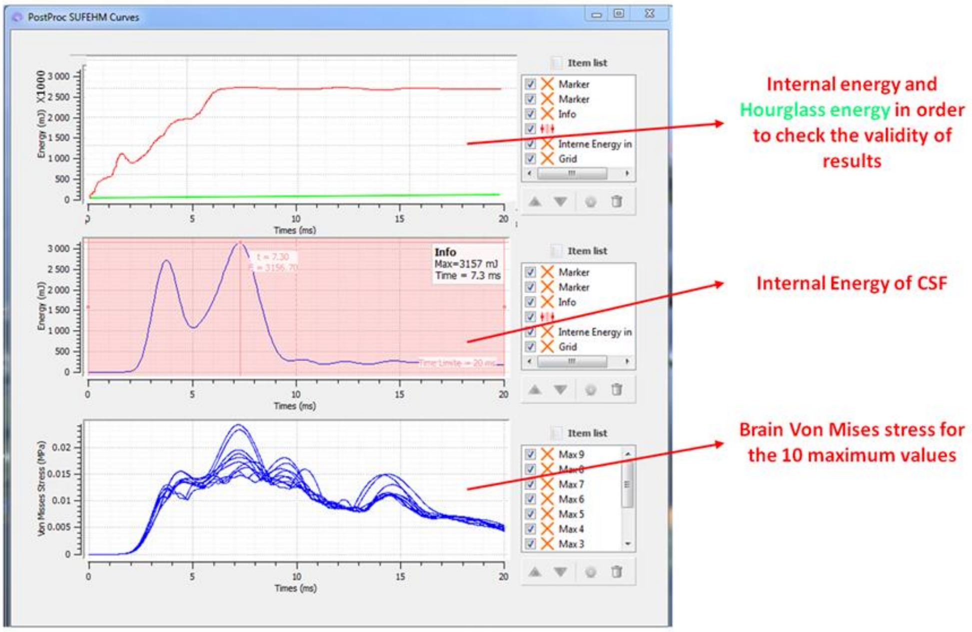


Figure 18. Illustration of results obtained with SUFEHM Post Process in terms of curves.

3.3 Status of current simulation tools to be used in T3.2 by CRF

3.3.1 Pedestrian Accident Compliant dummy (PAC) - Purpose of model

PAC (Pedestrian Accident Compliant) is a particular physical standing pedestrian dummy developed by CHALMERS and AUTOLIV Research Sweden in the past [16].

It's built by properly assembling different parts of different existing dummies:

- ✓ head and neck from EuroSID
- ✓ thorax from US-SID
- ✓ Hybrid III standing position pelvis and lower limbs
- ✓ modified knees in order to incorporate the EEVC WG17 lower legform (bending) characteristics

This physical dummy has been used in the past to study the whole response of a standing pedestrian during impact tests against cars, especially in presence of activated protection device like pop-up bonnets. Within T3.2, the numerical model of this dummy will be used in order to compare its results w.r.t. the ones obtained from HBM (Human Body Model, more precisely the THUMS), in the same reference impact conditions, with the aim to obtain an improved PAC standing pedestrian FE dummy model version, to be used within the virtual testing procedures for SEV-to-pedestrian impact analysis.

3.3.2 Model description

The current PAC FE model was built by CRF and Altair in the past, by assembling existing validated parts of other available FE dummy models and by "interpreting" the possible way to realize their connections, on the basis of a published technical paper [16] describing this experimental tool; no detailed drawings of the modifications implemented on the real dummy were in fact available.

Figure 19 shows this model together with its physical counterpart.

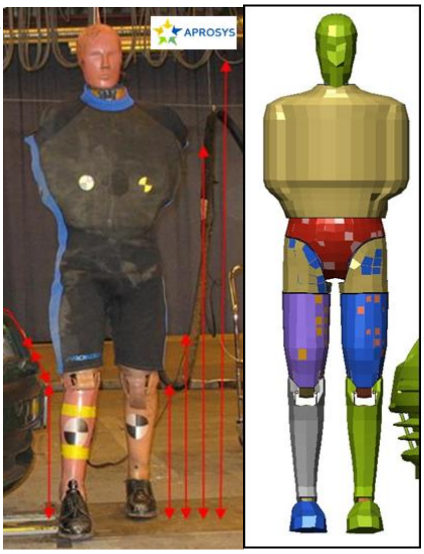


Figure 19. PAC dummy: experimental and numerical model

The outputs that PAC numerical dummy can provide are listed below and shown in Figure 20 the next figure, too:

- ✓ deformations,
- ✓ head acceleration and HIC,
- ✓ lateral chest deflection,
- ✓ hip force,
- ✓ total knee force,
- ✓ knee shear,
- ✓ knee bending.

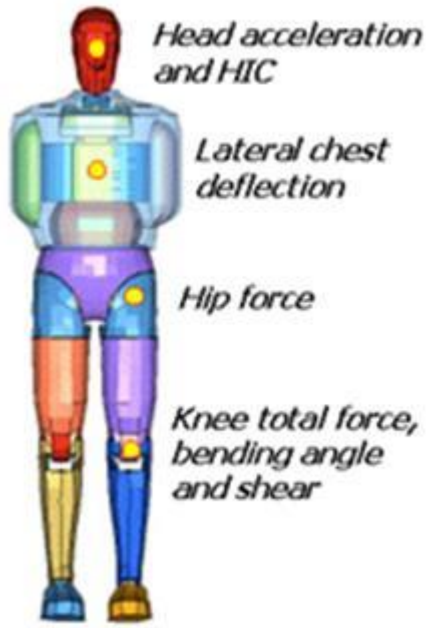


Figure 20. Overview of available output from PAC numerical dummy

In the FE PAC dummy model, a similar mechanism like the one used on TRL legform impactor model [62] was implemented on the knee; the physical PAC uses instead a mechanism for the knee that is different from the TRL knee joint assembly, i.e. a tube having a bending characteristic like the one prescribed for the impactor deformable knee elements (as a result, knee shear displacement is not available as an output on the physical dummy, while this is the case for the FE model).

3.3.3 Validation

PAC model was used as research tool within the past EC Integrated Project APROSYS. During the activities of the Sub Project 3 Pedestrian Accidents, the numerical model was subjected only to a first step towards a global validation w.r.t. its physical counterpart. To this purpose, two physical test performed by CHALMERS (together with AUTOLIV Research Sweden) and involving a used-production passenger car Fiat Punto second series, built in year

2000 were performed (two impact speeds, 20 and 40 km/h, walking posture and impact on vehicle centerline) [17].

Figure 21. PAC dummy: experimental and numerical model comparison done within APROSYS project

This activity led to the conclusion that the numerical behaviour of PAC model seems already quite good in its dynamics and response shape, if the way in which the model has been built is taken into consideration. The main behavioural differences between numerical and physical dummy were in fact due to the assumption made in generating the numerical model (as the already mentioned knee-joint).

The PAC dummy was also extensively used within another APROSYS Sub Project, the SP2 Heavy Truck Accidents, where the pedestrian-to-heavy truck collisions were studied towards the identification/definition of an Aggressivity Index for trucks [18]. Figure 22 shows this type of simulations.

Figure 22. PAC dummy: numerical simulations of pedestrian-to-truck collisions done within APROSYS project

3.3.4 Conclusions on status of model

The output that can be obtained (and that have been obtained in APROSYS) through the use of this FE model (as it is) can be considered already realistic as the usefulness and validity of this model in its current version, as research tool, was confirmed by the activity performed in the above mentioned APROSYS SP3 Pedestrian Accident task. The activity with this model planned within T3.2 will permit to evaluate the potential of the use of the PAC dummy model within the tool chain for SEVs, thanks to the direct comparison with the THUMS model. Improvements to PAC model are expected as a result of this comparison, too.

3.4 Status of current simulation tools to be used in T3.2 by IKA

Within the work of Task 3.2 in SafeEV ika will conduct head impact simulations using adult and child head forms in LS-DYNA. Furthermore ika will develop a FE model of an asphalt street in order to evaluate the injury risk of secondary impacts. The current status of the models will be described in the following chapter.

3.4.1 Child and Adult Head Form

Impactors modeling lower and upper leg as well as 6 years old child and adult head are being used in the current development process of pedestrian friendly solutions for vehicle body components. These impactors are available in hardware and virtual environment. In legislative vehicle evaluation processes mainly hardware impactors are being considered. One aim of SafeEV is to show the future benefit of using virtual full human body models. Vehicle evaluation processes only based on virtual human body models will be a final step and might not be feasible in the short term. Large simulation run times and the missing possibility to evaluate the complete vehicle front will promote hybrid approaches using virtual impactor models in the meantime. Thus, ika will consider the usage of virtual head forms.

Ika will use a licensed version of the head forms. The outside geometry as well as the geometrical set-up of the models are shown in Figure 23. Both head forms have a diameter of 165 mm. The mass of the adult head form is 4.5 kg and the mass of the child head form is 3.5 kg. Both models are based on the Japan Head Forms described in [19].

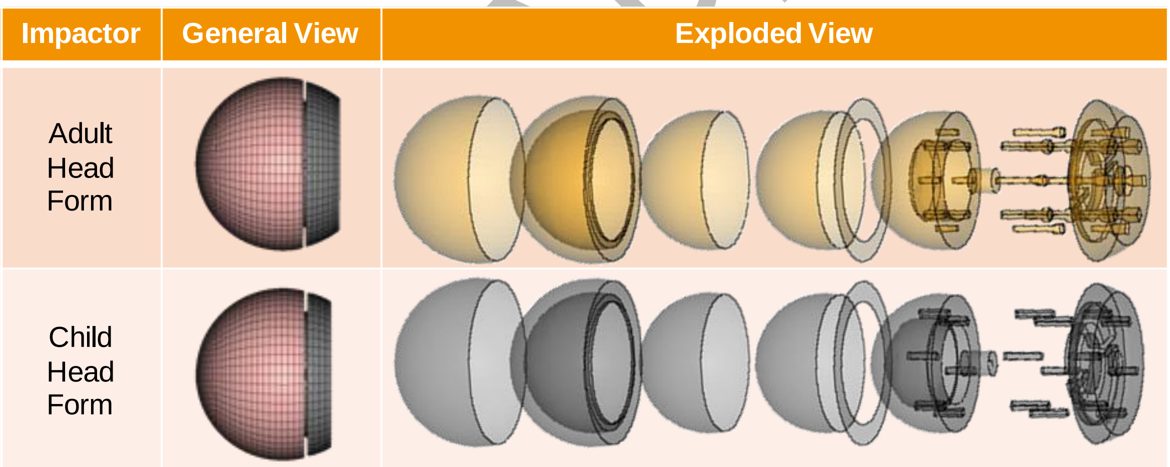


Figure 23. General and exploded view of pedestrian head form impactors

The validation and development of the head form models was conducted by LASSO. According information for the validation process could be taken from the manual [19] and is shown in Figure 24. For describing the contact parameters LASSO suggests to use *CONTACT_AUTOMATIC_SINGLE_SURFACE including friction values for a contact on the vehicle bonnet. The user has to implement the impactor velocity, the impactor position as well as the gravitational forces. Any suggestion regarding the preferred LS-DYNA Release is not included in the manual.

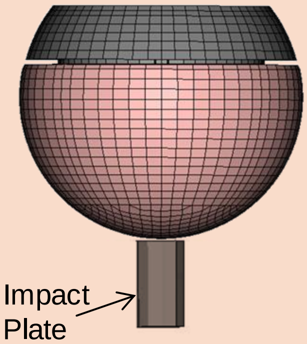
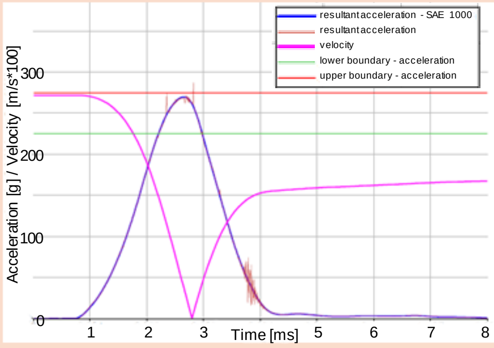
Validation Criteria	Validation Set-Up	Validation Results
Drop Height: 376 mm Acceleration: Upper Limit: 275 g Lower Limit: 225 g		

Figure 24. Validation of pedestrian adult head form model [19]

Due to the advanced progress and the extensive application of the head forms further updates for the following work are not intended at this stage of the project.

3.4.2 Asphalt Model

Since over 30 % of both non-minor and fatal pedestrian injuries in vehicle-pedestrian collisions were attributed to ground contact [20], the secondary impact plays a major role in protection of Vulnerable Road Users and thus has to be considered. In order to evaluate the injury risks resulting of the secondary impact, a virtual model of the road which could be implemented in the simulation has to be developed.

Today's roads are mainly constructed in a three-layer approach [21]. The so-called base layer, which is usually made of treated materials, is at the bottom (see Figure 25). It provides the pavement with the mechanical strength to withstand the loads due to traffic. In the middle is the binder layer that connects the upper surface layer with the base layer in shear direction. Being exposed to the effects of traffic and climate, the surface layer must resist traffic wear and protect the lower structural layers [22]. Since the surface layer in urban areas and rural roads is mainly made of asphalt (compare Figure 26), it is sufficient to consider an asphalt road in first place.

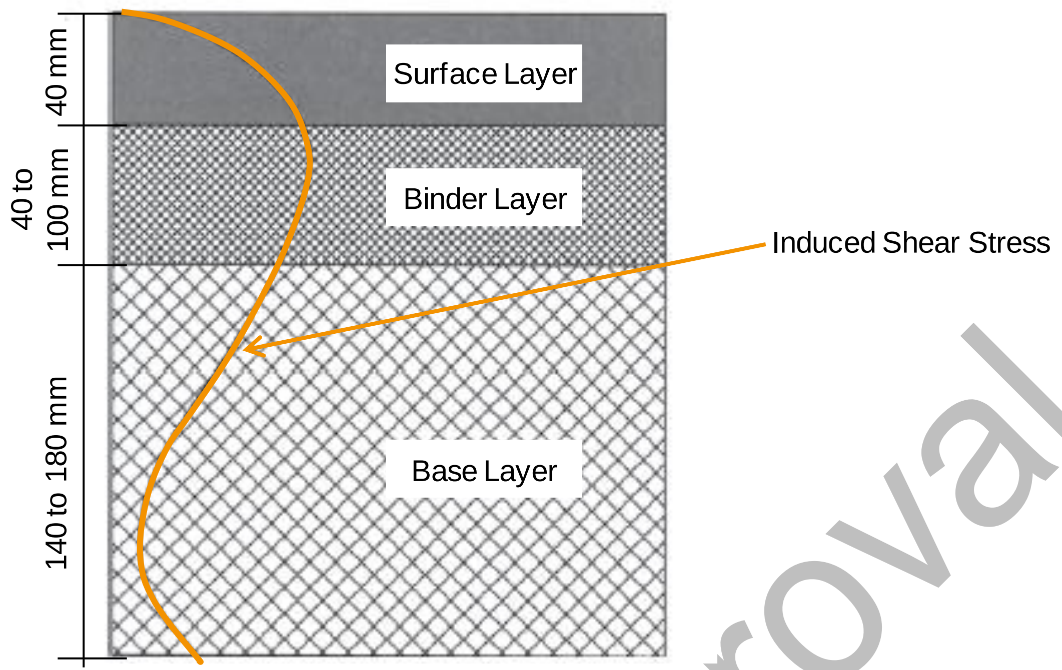


Figure 25. Typical Road Structure and Included Shear Stress [21]

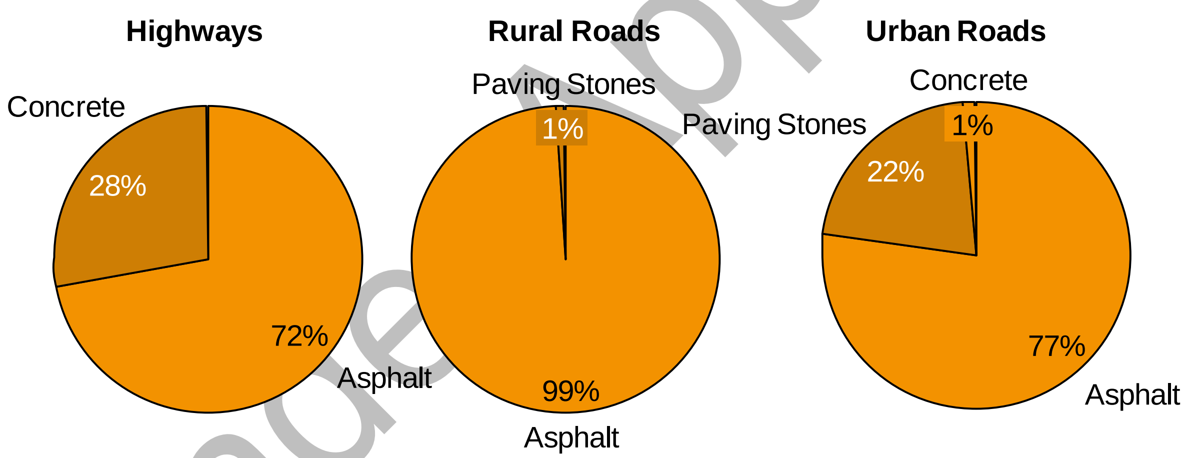


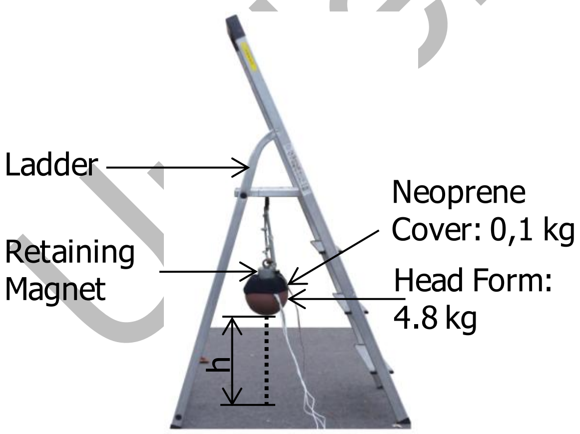
Figure 26. Percentage of Road Surface Constructions in Germany in 1999 [21]

Asphalt is a naturally occurring, but mostly artificially produced mixture of bitumen and minerals [21]. The mixture depends on their usage (layer and additional requirements). Due to the mixture with bitumen, which shows thermoplastic behaviour, the mechanical values of asphalt also depend of the temperature (compare Figure 27). Young modulus and viscosity decrease with increasing temperature. The values for friction included in Figure 27 were measured in slide experiments with dummies wearing different clothes as described in [23].

Parameter	Value	Dependency	Source
Young Modulus	1,000 (30°C) to 14,000 (-10°C) MPa	f=(Temperature, Mixture)	[24, 25]
Density	1,875 to 2,600 kg/m³	f=(Mixture)	[26, 21]
Poisson's Ratio	0.25 (30°C) to 0.45 (-10°C)	f=(Temperature)	[24, 25]
Friction (Leather or Goretex on dry Asphalt)	0.51 to 0.58	f=(Contact-Partner)	[23]
Friction (Leather or Goretex on wet Asphalt)	0.47 to 0.51	f=(Contact-Partner)	[23]

Figure 27. Mechanical Characteristics of Asphalt

For the validation of the ground model to be developed, drop tests with an adult head form are conducted. Due to availability reasons an adult head impactor with a mass of 4.8 kg is used for experimental and numerical analysis. This adult head form was former used within the EEVC regulation. Due to the harmonization process within the development of the Global Technical Regulation No. 9 this impactor was replaced with the 4.5 kg head form discussed in Chapter 3.4.1. In order to conduct the test on different road positions a variable drop mechanism consisting of a ladder, a retaining magnet and a head form equipped with three one-axial accelerometers are built (see Figure 28). The neoprene cover shall protect the aluminium parts of the impactor from damage. Impacts from several drop heights as well as on different asphalt positions are observed.



Ground-Position	Height		
	37 cm	78 cm	183 cm
Position 1	3	3	3
Position 2	3	-	-

Figure 28. Set-Up of Drop Tests (left) and Test Matrix (right)

The determined test data is very homogeneous. As shown in Figure 29 no significant difference between the impacts on different asphalt could be observed within the relevant acceleration signals. The acceleration increases as expected with increasing drop height or increasing impact velocity respectively.

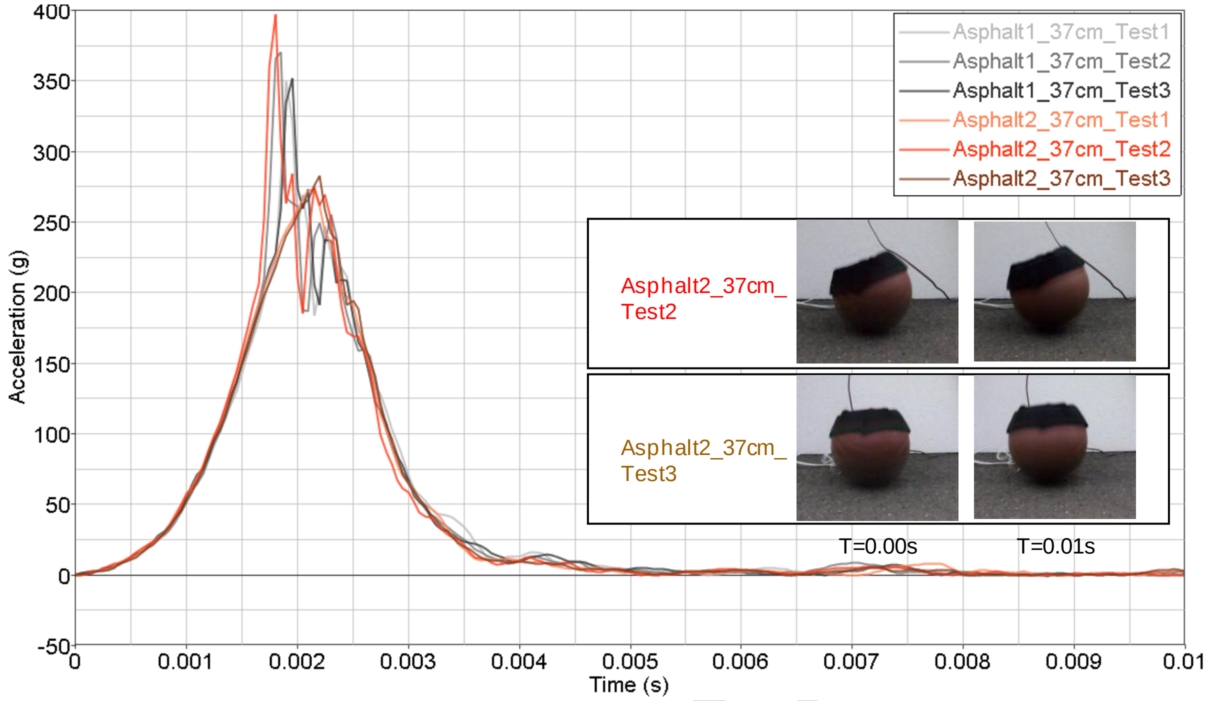
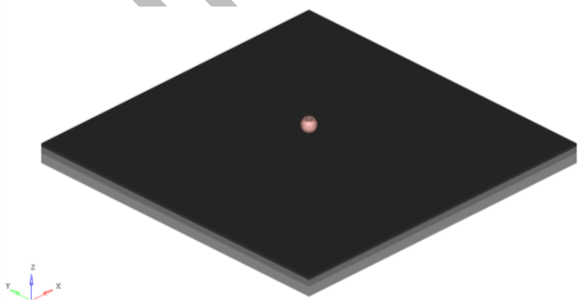


Figure 29. Acceleration Signal for Drop Tests on Two Different Asphalts

As a starting point, a FE model of the asphalt ground was developed. The model, which is shown in Figure 30, consists of solid hexaeder elements with an edge length of 35 mm. Similar to a typical road structure (compare Figure 25) the model consists of a surface, a binder and a base layer. The thickness of the surface layer is 35 mm, of the binder layer 70 mm and 105 mm for the base layer. The total length and width of the asphalt model is 3.5 m. The material characteristics are modelled with an elastic behaviour (*MAT_ELASTIC). The corresponding values are shown in Figure 30. It is assumed, that the lower surface of the base layer will not experience any translational movement and thus is fixed in the global coordinate system. For the friction value within the contact definition a value of 0.5 is chosen based on [23].



Para-meter	Value (Literature)	Value (Model)
Young Modulus [MPa]	1,000 (30°C) to 14,000 (-10°C)	14,000
Density [kg/m³]	1,875 to 2,600	2,600
Poisson's Ratio [1]	0.25 (30°C) to 0.45 (-10°C)	0.28

Figure 30. Model Set-Up of Ground Model (left) and Used Material Data (right)

When comparing the test and simulation results (see Figure 31), it could be observed, that the simulation data shows an overall smoother acceleration signal. Good similarities could be observed for the slope of the acceleration signals during the first contact phase. The area below the curve is smaller for the test results for a drop height of 37 cm and 78 cm and larger for a 183 cm. Further work for investigating the differences between test and simulation results will be conducted in Task 3.2 of the SafeEV project.

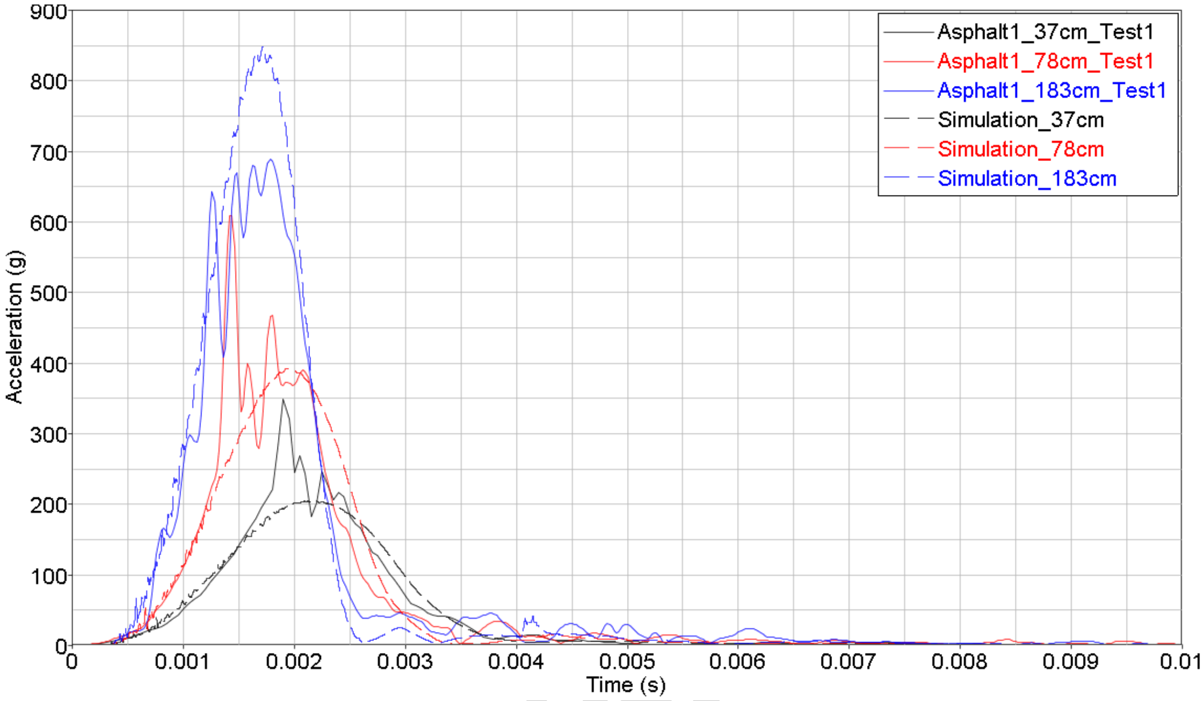


Figure 31. Comparison of Test and Simulation Results of the Head Form Drop Test on Asphalt

With regard to the definition of requirements for consistent safety analysis for pedestrian protection in Small Electric Vehicles, further attention shall be paid in the definition of validation corridors, contact characteristics especially in terms of interface with the Human Body Models as well as adequate post processing standards. It shall be defined if an injury resulting of the secondary impact can be assigned to the evaluated vehicle. Furthermore, it shall be defined how to position the asphalt model with respect to the vehicle and the pedestrian.

3.5 Status of current simulation tools to be used in T3.2 by Bosch

In WP3 Bosch will use the SafeEV reference electric vehicle models (REVMs), freely available reversed engineered LS-DYNA vehicle models by NCAC and freely available LSTC pedestrian impactor models.

3.5.1 Purpose of model

Our long term purpose of the usage of freely available reversed engineered LS-DYNA vehicle models by NCAC is to include appropriate sensor models and analyze crash signals (acceleration signals) through LS-DYNA crash simulations. In T3.2 we will primarily use REVM#1 by CRF and REVM#2 based on a reversed engineering model of TECOSIM. More information on and status of these models can be found in Chapter 3 of D3.3 [9] as well as in D3.1 [3]. Description of the standard vehicle models used for our internal tools chain are based on NCAC's model and are also described in Chapter 3 of D3.3 [9]. In the following we will focus on the pedestrian impactors by LSTC used as generic impactor models for a generic sensor evaluation.

3.5.2 Model description

LSTCs physical model of a Pedestrian Impactor according to Jensen et al [27] describes an impactor model along the lines of European Commission Regulation (EC) No 631/2009, where all the testing requirements are defined. According validation simulations were performed using LS-DYNA version 971 R4.2.1. In Jensen et al [27] the calibration requirements of the legform impactor, specified by the regulation are compared with results obtained with the FE model. Finally, it is shown that the FE model demonstrates good agreement with the calibration specifications.

Figure 32 exemplarily shows some impressions of LSTCs model. The legform model consists of 47409 nodes, 33664 solid, 2960 thin shell and two beam elements totaling 29 parts. Furthermore the model is divided into a Femur (upper leg) and Tibia (lower leg) part. Both parts are surrounded by a single foam layer covered by a neoprene skin. For accuracy and computational expense reasons mostly brick elements with rigid material properties are used. The foam layer, the outer skin, the leaf spring and the ligaments are modeled as deformable parts.

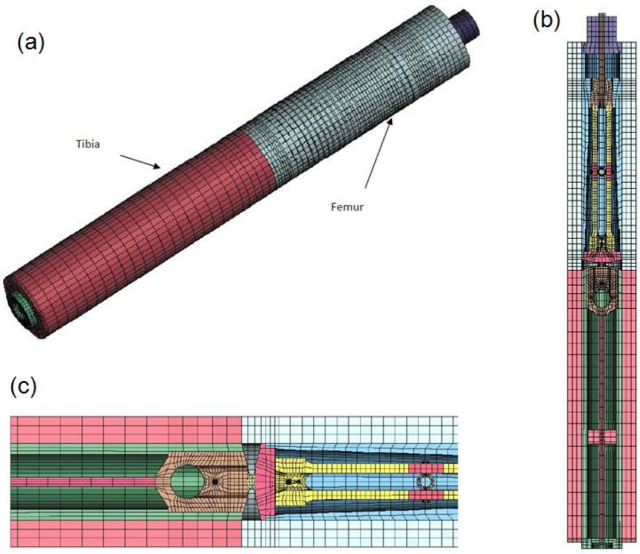


Figure 32. Picture from Jensen et al [27]: LSTC legform model (a), cut through symmetry plane (b), detail of knee area (c)

3.5.3 Validation tests

A calibration has been carried out by Jensen et al [27] according the requirements defined by the regulation. The following three test cases were used:

Static bending test: Lower leg part fixed while upper leg part is connected to a 2 meter metal tube. A horizontal normal force is applied at the outer end of the tube inducing a bending between the upper and lower leg part. The applied force over the bending angle is measured. (Figure 33 (left))

Static shear test: Same setup, but outer end of tube connected to the femur is constrained. The horizontal normal force is applied 5 cm from the center of the knee joint and the knee shear displacement is tracked. (Figure 33 (right))

Dynamic test: Legform model impacted by a certification test impactor (mass = 9 kg, impact velocity = 7.5m/s). The tibia acceleration, the bending angle and the shearing displacement are measured.

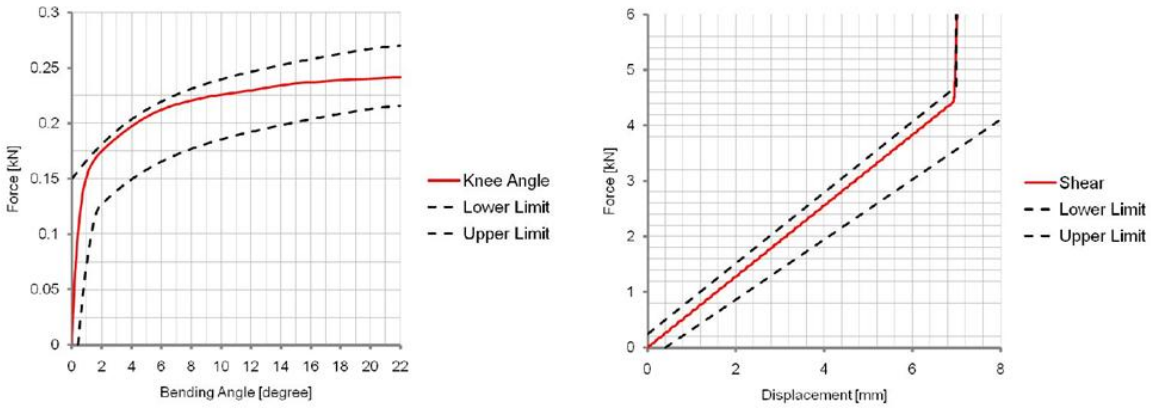


Figure 33. Picture from Jensen et al [27]: Results of the static bending test (left), Results of the static shear test (right)

3.5.4 Conclusions on status of model

The "generic" pedestrian impactor described above is steadily improved by LSTC. Actual revision is 100813_v2.3.

Validated simulation models are very helpful in carrying out crash signal analysis and propagation studies. Furthermore these studies help to derive guidelines for the usage of FEM models in view of the creation and representation of crash signals, cf. Kärner et al [28]. In order to save time and money car manufacturers include purely simulated sensors signals in very early stages of the development process. In T3.2 we will use REVM1 and REVM2 as reference vehicle model. The status of these models is reported in Chapter 3 of Deliverable D3.3 [9].

3.6 Status of current simulation tools to be used in T3.2 by UNISTRA

3.6.1 50th percentile head model

3.6.1.1 Purpose of the model

In this section a state of the art FE head model will be presented, namely the Strasbourg University Finite Element Head Model (SUFEHM). After a description of the model, its validation as well as the related head injury criteria will be synthesis.

3.6.1.2 Description of the model

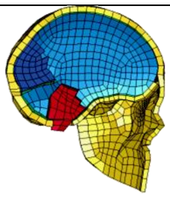
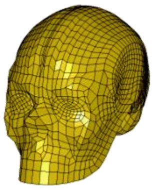
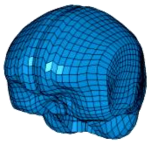
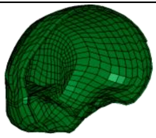
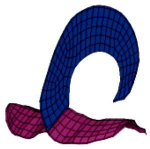
A FE model of the 50th percentile adult human head, developed at the University of Strasbourg by Kang et al. [35] under RADIOSS platform and transferred to LS-DYNA (Deck and Willinger [29,30]) and to VPS was called The Strasbourg University Finite Element Head Model (SUFEHM). The main anatomical features includes the scalp, the brain, the brainstem and the cerebrospinal fluid (CSF) represented by brick elements and the skull, the face and two membranes (the falx and the tentorium) modeled with shell elements as shown in Table 3. The SUFEHM presents a continuous mesh that is made up with 13,208 elements (10,395 brick elements and 2,813 shell elements), including 1,797 shell elements utilized to compose the skull and 5,320 brick elements for brain. The total mass of the head model is 4.7 kg which is equivalent to the mass of a 50th percentile adult human head. The geometry of the inner and outer surfaces of the skull was digitized from a human adult male skull to ensure anatomical accuracy. Isotropic, homogeneous and elastic mechanical constitutive material models were applied to each of the SUFEHM parts except for the brain, for which viscoelasticity was assumed. The skull was modeled by a three layered composite shell. The mechanical properties of all parts of SUFEHM head model except the skull are reported in Table 3.

The mechanical parameters of the material which models the subarachnoid space has been derived from experimental and numerical head modal analysis. A linear visco-elastic and isotropic law is affected to the whole brain. This law was described by Herrmann and Peterson [34] in terms of relaxation shear modulus as defined in equation below.

$$G(t) = G_\infty + \left(G_0 - G_\infty\right)e^{-\beta t}$$

where G_0, G_∞ and β represent the short-time modulus, the long-time modulus and the decay constant respectively. Parameters were identified from experimental data on human brain tissue, i.e. *in vitro* results proposed by Shuck and Advani [40] as well as *in vivo* based values from Magnetic Resonance Elastography (MRE) published by Kruse et al. [36], with following values: $G_0 = 49.10^3$ Pa, $G_\infty = 1.62.10^4$ Pa, $\beta = 145\ s^{-1}$.

Table 3. Detailed SUFEHM model with mechanical properties [35, 29]

 Parts	 Face	 Scalp	 Brain	 Brain stem	 CSF	 Falx and Tentorium
Density [kg/m^3]	2500	1000	1040	1040	1040	1140
Young's modulus [MPa]	5000	16.7	Viscoelastic		0.012	31.5
Poisson's ratio	0.23	0.42			0.49	0.45
Element type	Shell	Brick	Brick	Brick	Brick	Shell
Shell thickness [m]	1x10^{-2}	-	-	-	-	Falx=1x10^{-3} Tentorium= 2x10^{-3}

3.6.1.3 Model Validation

The SUFEHM developed by Kang et al. [35] was validated under RADIOSS code against intracranial pressure data from Nahum's experiments. The intracranial response was recorded at 5 locations and compared with the experimental results. A good agreement was found for both impact force and head acceleration curves when compared with experimental data. Also the pressure data at five locations were match very well with less than 7% deviation of peak pressure from experimental peak pressure values. This head model was validated under RADIOSS code against intracranial pressure data of Trosseille et al. [41] experiments. Five tests from Trosseille's experiments were replicated and a reasonable agreement was observed between simulation and experimental pressure and acceleration curves. In the context of APROSYS SP5 investigations have been completed to try and determine a suitable state-of-the-art numerical head model with which to develop numerical based head injury criteria and to identify the principle head injury mechanisms. The choice of models evaluated was partly based on the willingness of the developer of each head model to provide predictions of intra-cerebral pressure, skull deformation and rupture and brain skull displacement for six impact conditions, detailed in published PMHS impact tests (Nahum et al. [37], Trosseille et al. [41], Yoganandan et al. [58], Hardy et al. [32]). SUFEHM model was one of the "state of the art" model. A comparison of the SUFEHM results under RADIOSS code with the other existing FE head model were published by Deck and Willinger in 2009 [31].

The previous FEHM (Kang et al. [35]) was transferred to LS-DYNA software by Deck and Willinger [29]. All the material properties are the same as the previous model. This model was validated against intracranial pressure data from Nahum et al. [37]. An experimental test by Yoganandan et al. [58] was used to validate the FEHM to predict skull fracture. In both the validations a good agreement was found between simulation and experimental data.

Sahoo et al. [39] proposed a validation of this head model under LS-DYNA in terms of brain strain against experimental data published by Hardy et al. [32, 33]. Finally the skull behaviour was validated by Sahoo et al. [38] by reproducing 15 PHMS data. The composite material model which takes in account the skull fracture was used to simulate tests conducted at various velocities for three different boundary conditions using different specimens. The skull was modelled by a three layered composite shell representing the inner table, the diploe and the external table of human cranial bone. Force–time histories instead of peak forces were obtained from tests for each case and used for the validation process. Results indicate that the FE model force outputs in the time domain matched very well with all tests and all conditions. In addition, Fracture patterns predicted by the FE model were also in agreement with experimental outcomes

3.6.1.4 Head Injury criteria

Deck and Willinger [29, 30] developed improved head injury criteria based on reconstruction of 68 accident cases (6 Motorsport accidents, 22 American football players, 11 motorcyclists and 29 pedestrian cases) in RADIOSS software. Statistical regression analysis was then carried out on the head loading parameters from the accidents, such as the peak linear and rotational acceleration of the head, and predictions from the head model, such as the Von Mises stress or strain and pressure in the brain, in order to determine which of the investigated parameters provided the most accurate metrics for the injuries sustained in the real world head trauma under consideration. The proposed tolerance limits for 50% injury risk for different injury are listed below in Table 4. Results showed that, the new improved criterion was able to predict the head injury with a much better accuracy than HIC.

Table 4. The proposed tolerance limit for 50% injury risk for different injury under RADIOSS

Injury predictors	Mild DAI	Severe DAI	SDH	Skull fracture
Brain Von Mises strain (%)	25	35	-------	--------
Brain First principal strain (%)	31	40	-------	--------
Brain Von Mises stress (kPa)	26	33	------	---------
Minimum of CSF pressure (kPa)	---------	---------	-135	---------
Skull strain energy (mJ)	---------	---------		865

Deck et al. [30] reconstructed 58 accident cases (11 motorcycle cases, 20 American football cases and 28 pedestrian cases) to develop the head injury criteria in LS-DYNA platform. The proposed tolerance limits for 50% injury risk for different injury are listed below in Table 5 under LS-DYNA and in Table 6 under VPS (PAM-CRASH). In all the cases the injury predict by the new improved criteria was better than HIC.

Table 5. The proposed tolerance limit for 50% injury risk for different injury under LS-DYNA

Injury predictors	Mild DAI	Severe DAI	SDH
Brain Von Mises strain (%)	30	57	-------
Brain First principal strain (%)	33	67	-------
Brain Von Mises stress (kPa)	28	53	------
Minimum of CSF pressure (kPa)	---------	---------	-290
CSFstrain energy (mJ)	---------	---------	4950

Table 6. The proposed tolerance limit for 50% injury risk for different injury under VPS (PAM-CRASH)

Injury predictors	Mild DAI	Severe DAI	SDH
Brain Von Mises stress (kPa)	29	53	------
Minimum of CSF pressure (kPa)	---------	---------	-315

More recently Sahoo et al. [39] proposed a tolerance limit related to this model in terms of skull fracture. The authors have demonstrated that a 50% risk of skull fracture is obtained for skull strain energy about 544 mJ. This was based on a validation process for skull behaviour on 15 PHMS data.

3.6.1.5 Conclusion on status of the model

SUFEHM human head model available under three different codes (PAM-CRASH, RADIOSS and LS-DYNA) is a state of the art head model, validated against all existing data available in the literature in terms of brain pressure, brain strain and skull fracture. This full validated model was used for the reconstruction of a number of real world head trauma in order to derive advanced head injury criteria for three different injury mechanisms, i.e. neurological injuries, subdural hematomas and skull fracture. These advanced model based head injury criteria have been extensively published and discussed in the context of different standardisation bodies such as ISO-WG6, EEVC-WG12, CEN TC 158-WG11 and ASTM (see references in Chapter 3.6.1.6). Moreover post process software has been developed in order for an end user to automatically extract the percentage head injury risks easily.

3.6.1.6 References

SUFEHM related presentation at standard bodies:

- Strasbourg University Head Injury Criteria , *San Diego, October 2003 (ISO-doc N° 594)*
- HIC injury prediction capability versus Strasbourg criteria, *Nashville, October 2004 (Idoc N° 611)*
- HIC injury prediction capability vs Strasbourg criteria and SIMON, *Paris, June 2005 (doc N° 620)*
- State of the art head FE models and guidelines for validation, *Seoul, May 2007 (doc N° 680 & 681)*
- Improved Model Based Head Injury Criteria, *Madrid, January 2008 , EEVC WG 12 meeting*
- Improved Model Based Head Injury Criteria, ISO, WG6 ,*Paris, May 2009*
- Code and Model dependence of model based head injury criteria, *Stuttgart, June 2009 (EEVC-WG 12)*
- Towards new head protection standards, *Saint Louis, MO, USA, May 2010 (ASTM meeting)*
- *Model based Head Injury Criteria : Code, Model and Age Dependence, Paris June 2011, ISO WG6*
- New bicycle helmets test procedure, Milan October 2012, CEN TC158 WG11

3.6.2 6 YOC head FE model

The 6 Y.O.C. (Years Old Child) head model is based on the adult head geometry. In fact, the 6 Y.O.C. head can be considered as the scale down of the adult (Irwin and Mertz [59]). Therefore the characteristic dimensions were based on the size of children in the United States. Concerning the Head the scale factor was established at 0.914.

Figure 34 summarizes the external dimension of the Head segment (Irwin and Mertz [59]) and Table 7 recapitulates the 6YOC FE Head Model dimension.

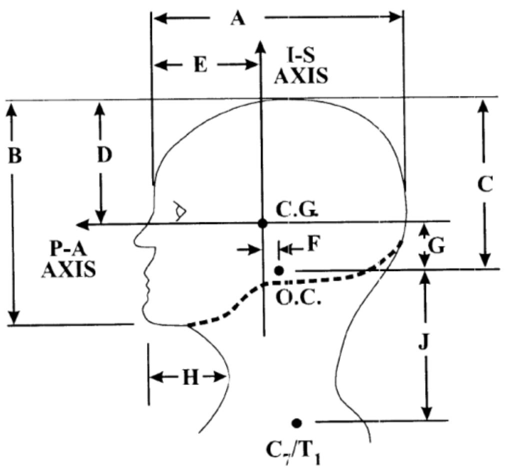


Figure 34. Pertinent Head and Neck Dimensions describe by Irwin and Mertz [59].

Table 7. Comparative Head Dimensions for the 50th 6 YOC (Irwin and Mertz [59]) and Head FE Model.

Description	*CHILD 50th 6 YOC (mm)*	*6 YOC FE Model (mm)*
A	**180**	**177**
B	**182**	**185**
C	**127**	**138**
D	**87**	**83**
E	**76**	**87**
F	**16**	**11**
G	**40**	**51**

Table 8 summarizes head mechanical properties used under LS-DYNA for the 6YOC.

Concerning the skull mechanical properties a composite law was implemented in order to define inner and outer tables as well as diploe layer, with a Young modulus set to 6.6 GPa (Irwin an Mertz [59]). The others biomechanical parts are supposed to have similar mechanical properties as the adult model. Finally the Head mass was calculated at 3.200 Kg. General evolution of skull elastic modulus as a function of age is recalled at Figure 35.

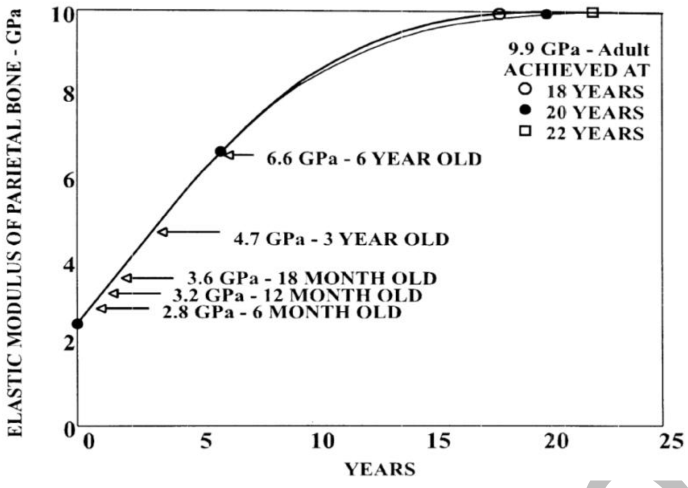


Figure 35. Elastic Bending Modulus of parietal skull bone as a function of age.

Table 8. Mechanical properties and element characteristics of the SUFEHM 6 YOC Head FE model.

Part	Material property	Material parameter	Value	Shell thickness [mm]
Scalp	Elastic	Density	1.0E+03 Kg.m^{-3}	/
		Young modulus	1.67E+01 MPa	
		Poisson's ratio	0.42	
Brain	Viscous Elastic	Density	1040 Kg.m^{-3}	/
		Bulk modulus	1.125E+03 MPa	
		Short shear mod.	4.9E-02 MPa	
		Long shear mod.	1.62E-02 MPa	
		Decay constant	145 s^{-1}	
CSF	Elastic	Density	1040 Kg.m^{-3}	/
		Young modulus	0.12E-01 MPa	
		Poisson's ratio	0.49	
Falx	Elastic	Density	1140 Kg.m^{-3}	1.0
		Young modulus	3.15E+01 MPa	
		Poisson's ratio	0.45	
Tentorium	Elastic	Density	1140 Kg.m^{-3}	2.0
		Young modulus	3.15E+01 MPa	
		Poisson's ratio	0.45	

Concerning the validation of this 6YOC FE head model, no experiments are available in the literature in order to validate this model. Concerning the head injury criteria similar thresholds as for the adult are proposed.

3.6.3 50th percentile neck model

3.6.3.1 Description of the model

The Strasbourg University Finite element Neck model was developed by Meyer et al. [49]. The neck geometry is based on a living human subject of average size and close to 50th percentile male: [Height: 1.72 m, weight: 72 Kg, age: 33 years]. From a modeling point of view, millimetric scan sections of the subject have been taken. These scanner sections then underwent grey level processing in order to extract the bone part of the cervical column and of the skull. A rough tria mesh in STL format was then constructed. This file was then imported under the Hypermesh meshing software so that the cervical vertebrae have been completely meshed.

The cervical vertebrae were modelled using shell elements, the intervertebral discs with bricks elements, the ligaments using spring elements. As far as the lower cervical spine is concerned, the authors have distinguished five types of ligaments: The anterior longitudinal ligament (ALL), the posterior longitudinal ligament (PLL), the flavum ligament (FL), the interspinal ligament (ISL) and finally the capsular ligaments (CL). For the upper cervical spine, we have modelled the posterior common ligament (C2-C0; C2-C1; C1-C0), the atloidien-axoidien anterior ligament, the transverse ligament, the yellow ligament (C2-C1), the transverse axoid ligament, the anterior occipito-atloid ligament, the alar ligament, the posterior occipito-atloidien ligament, capsular ligament C2-C1, capsular ligament Head-C1, membrane tectaria, the median occipito-odontoid ligament as well as the lateral occipito-atloidien ligament as illustrated in Figure 36

The finite element model of the neck system thus defined consists of 498 spring elements, 4308 shell elements, and 947 brick elements (Figure 37).

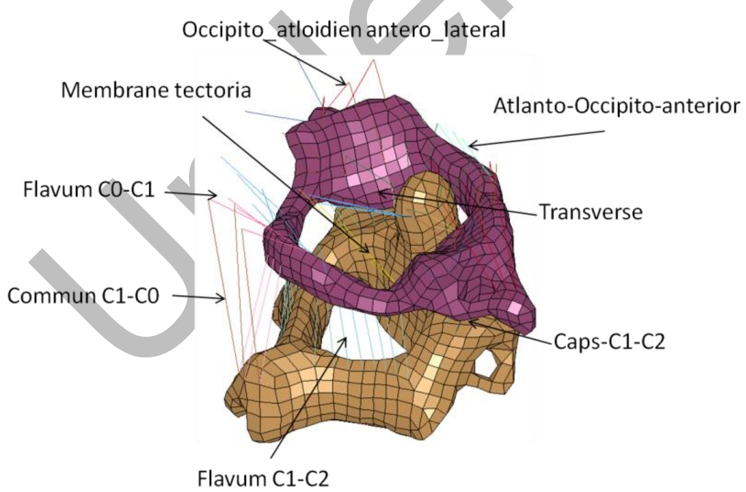


Figure 36. Upper ligamentary system FEM

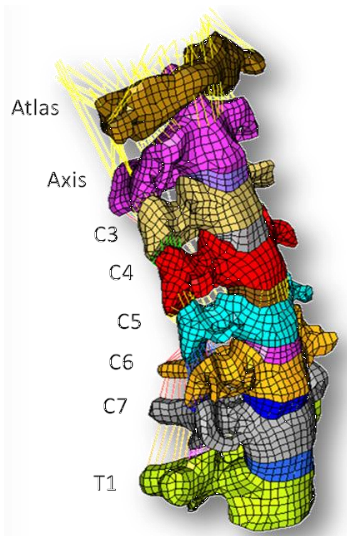


Figure 37. Cervical spine FEM

3.6.3.2 Mechanical properties

The ligaments were modelled using non-linear spring elements with a damping coefficient of η=900 Nm/s (De Jager et al. [45], η=300Nm/s, Dauvilliers et al. [69], η=2000Nm/s). To define the behaviour laws of each ligament in both the lower and upper cervical spines, we referred to two complementary studies by Chazal et al. [44] and Yoganandan et al. [53, 54]. The Chazal et al. study [44] highlights the non-linear viscoelastic behaviour of ligaments whereas Yoganandan et al. [53, 54] gives information on their failure properties.
Concerning the intervertebral disks the hypothesis of a homogeneous linear elastic isotropic material was considered with a Young modulus of 100 MPa and a Poisson's ratio of 0.3. These values are situated between the extreme values related in the literature which represents a global behaviour of this structure (Kleinberger [61], Dauvilliers et al. [60]).

The cervical vertebrae were declared as rigid bodies. The mechanical characteristics in terms of mass and inertias are taken from the work of Deng et al. [46]. Finally for the muscles a viscoelastic law has been implemented based on the Chawla et al. [43] study. Mechanical properties are listed in Table 9.

Table 9. Mechanical properties of the Strasbourg University Finite Element Neck Model

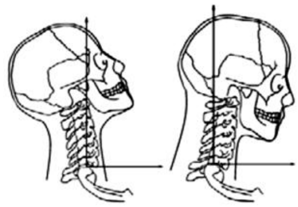
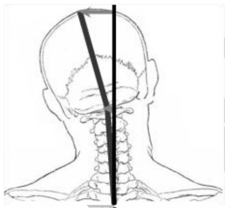
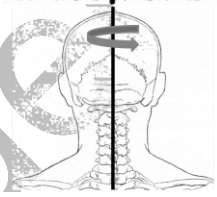
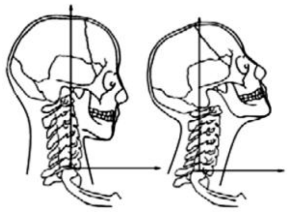
Part	Material property	Material parameter	Value	Element type
Intervertebral discs	Elastic	Density	1100 Kg.m^{-}	Solid
		Young modulus	100 Mpa	
		Poisson's ratio	0.3	
Muscle Posterior	Viscous Elastic	Density	1100 Kg.m^{-3}	Solid
		Bulk modulus	2500 Mpa	
		Short shear mod.	0.115 Mpa	
		Long shear mod.	0.086 Mpa	
		Decay constant	100 s^{-1}	
Muscle Anterior	Elastic	Density	1100 Kg.m^{-3}	Solid
		Bulk modulus	2500 Mpa	
		Short shear mod.	0.0395 Mpa	
		Long shear mod.	0.00295Mpa	
		Decay constant	100 s^{-1}	

3.6.3.3 Model validation

A time domain validation of the Strasbourg University Head-Neck Model (SUFE-HN-Model) was proposed by Meyer et al. [49] under LS-DYNA and it has been carried out in comparison to the N.B.D.L tests [15] under front, oblique and lateral impacts. This time analysis permitted to validate the model in accordance with the classic validation procedures systematically chosen in the literature. Finally temporal validation was completed by simulating Ono et *al*. [52] experience in order to evaluate the relative cervical motion under rear impact.

Furthermore SUFE-HN is validated in the frequency domain. In past studies, Bourdet et *al*. [42] and Meyer et *al*. [49] showed that a validation in the time domain is not sufficient to reproduce the dynamic behavior of the neck. In fact, a great amount of responses may exist in a given corridor. And these responses do not correspond to a same mechanical behavior. More recently, Gunzel et *al*. [48] produced an extend of the head/neck system characterization in the frontal and horizontal plane. Two kinds of experimental devices were therefore realized. The first one is the same than the one used by Bourdet et *al*. [42] and the second one consists in a rotational solicitation of the thorax. The results obtained thanks to the FEM of the head/neck system are summarized in the Table 10.

Table 10. Results of experimental test and simulation in terms of natural frequencies

Mode	Mode -Illustration	Average Volunteer Natural frequency	Head-Neck FEM Natural frequency
Flexion-Extension		1.68±0.2 Hz	2.8 Hz
Inclination		1.7±0.2 Hz	2.6 Hz
Axial rotation		3.2±0.3 Hz	3.4 Hz
S-Shape		8.8±0.5 Hz	11 Hz
Lateral retraction		9.5±1.4 Hz	9.6 Hz

3.6.3.4 Injury criteria

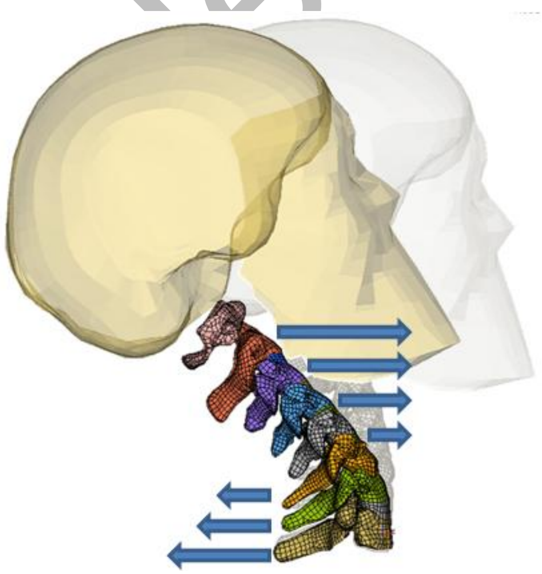
A real world rear impact accident database including crash pulses of 86 accidents was considered for the computation of the 3D acceleration at T1 level for each victim by Meyer et al. [50]. This step was used with a previously published car seat and human torso multibody models. The extracted T1 kinematics was finally considered as the input of FE simulation of the head and neck response.

A number of intra cervical local and global parameters were considered as candidate parameters for neck injury criteria by investigating the correlation of the different metrics with the occurrence of injury.

Main conclusion of this extensive real world rear impact accidents simulations and statistical analysis is that none of the existing criteria or more local parameters (such as facet distortion) presents an acceptable correlation level. However when a more global (or cumulative) parameter is considered, such as the summation of the shearing displacement at each level, an acceptable regression parameter was observed and it was possible to derive a tentative injury risk curve for whiplash injury based on this metric.

This criterion can be seen as the sum of the displacements of the cervical bodies along a horizontal direction (Figure 38). Depending on the intensity of the impact and on the cervical spine body level, this displacement can follow the direction of the impact or its opposite direction. To take these different displacements into account it is necessary to work with the absolute value of the displacement at each level and then to sum the displacements. The histogram in Figure 39 illustrates the correlation between the candidate mechanical parameter proposed (Shearing at each cervical level) computed with the Head-Neck FE model.

Figure 40 gives neck injury risk curves obtained for WAD 1, WAD2 and WAD3 with the Strasbourg University Finite element neck model under rear impact conditions.



$$\sum_{i=1}^{7} |C_i - C_{i+1}| dx$$

With C8=T1

Figure 38. Illustration of the shearing in the cervical spine produce by a rear impact.

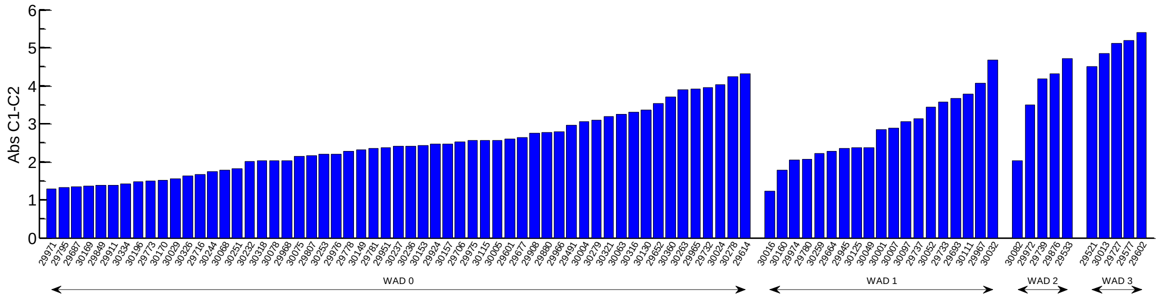


Figure 39. Representation of the mechanical parameter propose as a metric for neck injury criterion (sum of the shearing displacement at each level) versus Whiplash Associated Disorder.

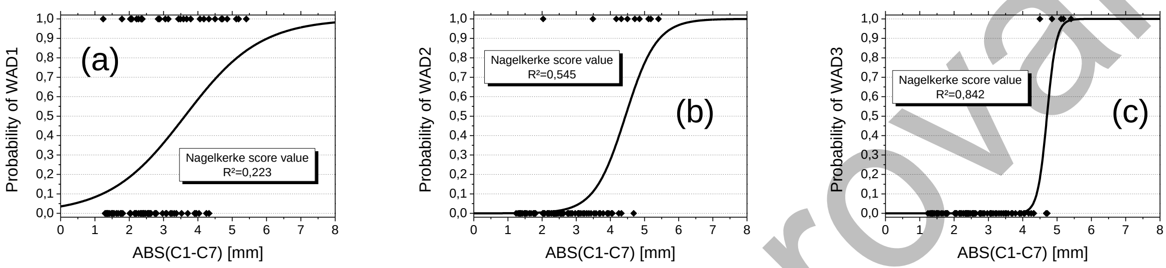


Figure 40. Risk curves of the injury criteria proposed for the WAD 1(a), WAD 2 (b) and WAD 3 (c). R^2 WAD1 = 0.223; R^2 WAD2= 0.545; R^2 WAD3= 0.842

3.6.3.5 Conclusion on status of model

The Strasbourg University FE neck model was coupled with the SUFEHM model (Figure 41) and validated in the time and modal domains (Meyer et al. [50]). The results obtained for the numerical modal analysis of the Strasbourg University head-neck model were presented. For this model the five natural neck natural frequencies are adequately reproduced and this demonstrates that the Strasbourg model reproduces realistically the retraction phenomenon. This SUFE-HN-Model was used to derive neck injury criteria (Meyer et al. [50]) by reconstructed 86 real world rear impact accident cases.

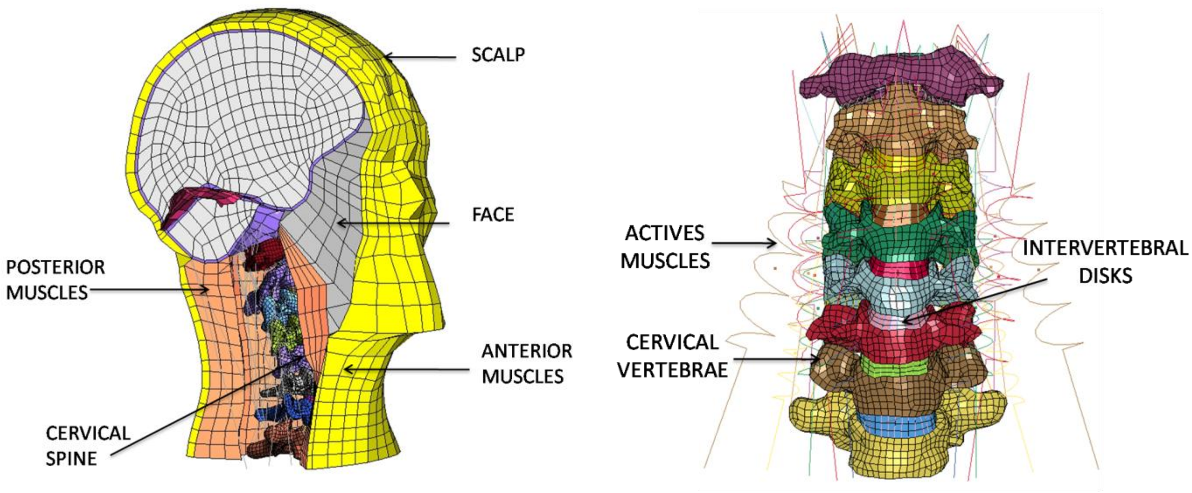


Figure 41. Cross section of the Strasbourg University human Head-Neck system FE model

4 Code of best practice regarding virtual testing – Recommendations from IMVITER

The following description of the code of best practice regarding virtual testing is also included in the Deliverable D3.3, since it was considered strongly and equally relevant for both of the Tasks 3.2 and 3.3.

IMVITER was also an EU FP 7 research project (2009-2012) with the key objective to implement Virtual Testing (VT) in existing type approval procedures, and particularly in safety related regulatory acts, by consolidation of advanced VT technologies.

Virtual Testing was therefore defined as the assessment of any kind of requirement imposed on a physical part or system, which is conventionally accomplished through some kind of test, but performed using a numerical model instead. Thus VT inherently replaces real (hardware) tests by simulation models and test results by simulation predictions.

In general IMVITER continued a long term process which is expected to lead step by step to a complete "electronic certification".
The strategic and political background was laid down in the CARS 21 High Level Group 2 (a High level group set up by the Commission in 2005 to chart the way towards sustainable development of a competitive European automotive industry) recommendations concerning the implementation of VT as a way to improve the European automotive sector competitiveness [55]. In the following years the European Commission has taken the necessary steps to accomplish this objective and offers now with the dedicated regulations No. 371/2010 and update of the EC Whole Vehicle Type Approval Directive (ECWVTA) 2007/46/EC and its corresponding annexes the principal and practical implementation of VT.

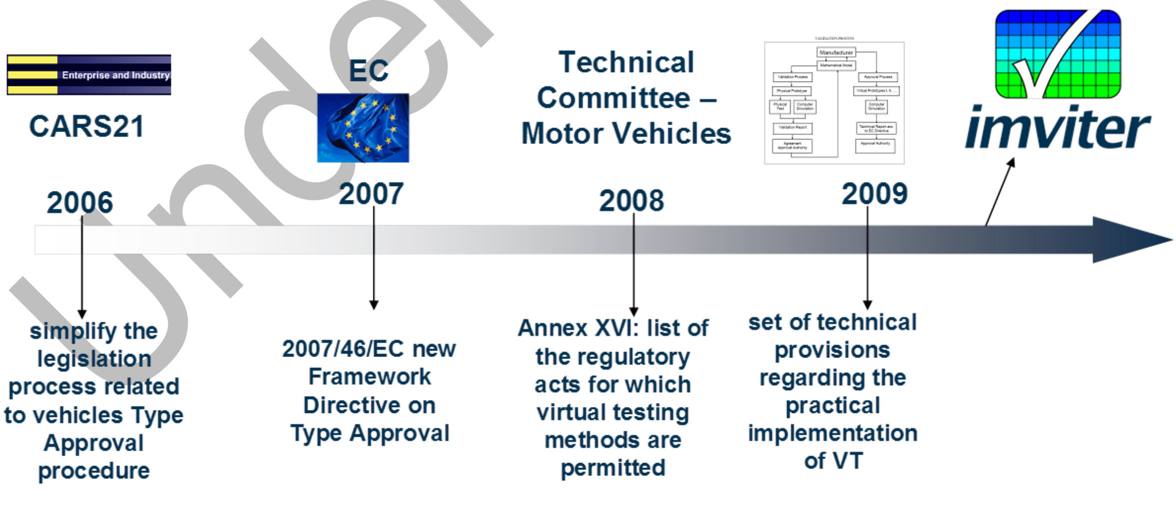


Figure 42. Strategic and political context of IMVITER and steps in the implementation of VT in safety regulations [10]

The methodological and technological history and basis of IMVITER was also worked out in previous EC projects such as VITES, ADVANCE and APROSYS.

The main objective and projected tasks of IMVITER are listed in the following overview. Objectives which are now also relevant for the virtual SafeEV tool chain and assessment are marked in italics.

- Identify current physical tests under specific type approval regulatory acts that could be candidates for replacement by VT, based on technical, economical and institutional aspects.
- *Development of VT implementation procedures, fully substituting RT in particular regulatory acts, and/or combined with RT (e.g. pedestrian protection legislation).*
- *Development of simulation models validation criteria independent of software platform or performing organization.*
- *Investigate the introduction of stochastic methods, reliability analysis and robustness optimisation in the VT framework.*
- Enhancement of the accuracy and reliability of type approval requirements assessment, due to the ability to better check points of interest via VT.
- Reduction in costs and number of real tests. The car market demands more and more niche products leading to high increase in number of models and car components which have to be type approved.
- Define procedures for VT including validation of virtual test devices. Analyse the feasibility and potential of these procedures.
- *Investigate the possibility to transfer the process of VT to assess new advanced safety systems (active and pre-crash safety systems).*

Beside methodological aspects also the practical implementation and fundamental feasibility of VT was analysed and discussed by the selection and definition of 4 pilot cases.
It should be mentioned, that one of the pilot cases focused on the safety area of pedestrian protection, which has been identified as one of the fields with greatest advantages and potentials for VT implementation and which has also now an exceptionally important role within the assessment clusters of SafeEV.
Based on the experience of all the stakeholders who have taken part to IMVITER, it can be asserted that numerical simulation is highly predictive for the assessment of pedestrian protection safety requirements. Moreover, studies carried out in previous EC projects such as APROSYS concluded also that the implementation of VT in type approval with regards to pedestrian protection directives, could not only lead to tangible benefits in terms of injury reduction, but also in terms of cost reduction in vehicle design.
In the following paragraph the three main outcomes of IMVITER, which are now could be seen as also relevant for the methodological background of SafeEV, are compiled and summarised:

- VT implementation approaches, described as detailed flowcharts (Figure 43)

- VT methods, describing V&V (Verification & Validation) requirements as well as validation metrics and criteria (as an example for each pilot case)
- V&V templates, which serve as reference documents that help to exchange essential information between involved actors

A **generic VT type approval implementation process**, divided in **three sequential phases**, was agreed by carmakers, regulatory bodies and the rest of partners. It follows fundamentally the flowchart annexed in Commission Regulation (EU) No 371/2010 as already named above, but includes a more detailed description of the steps to follow in its execution.

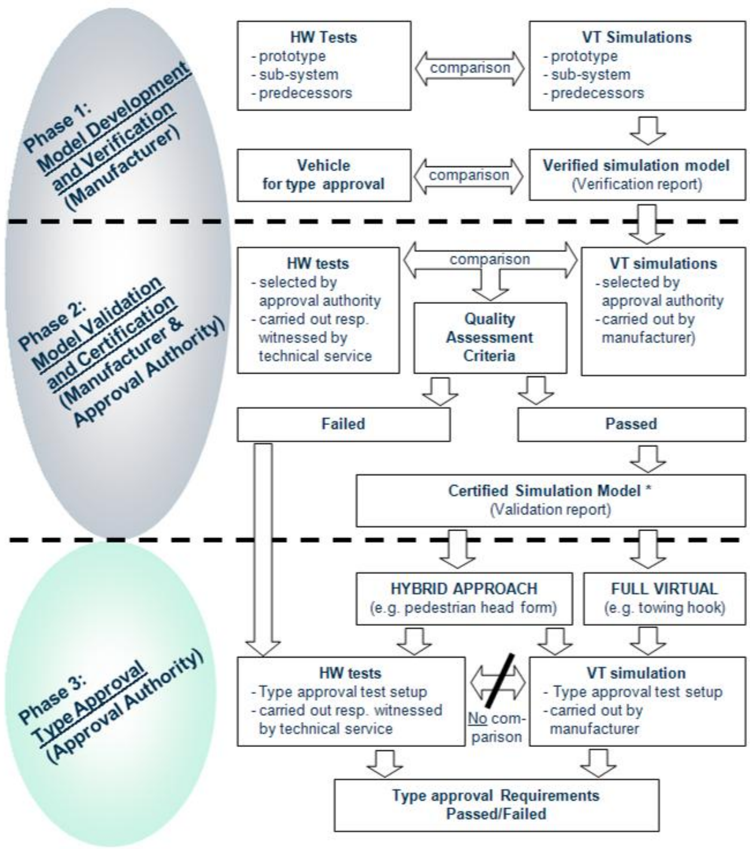


Figure 43. General IMVITER VT implementation flowchart [10]

Phase 1 indicates the regular and routine use of numerical methods and virtual models within a development process of a manufacturer. Nevertheless, if a virtual model will be used later within a type approval procedure the process starts with verification and documentation on this level. *Phase 2* is characterised by interaction of Approval Authority respectively a Technical Service and the manufacturer. At the end of this phase a *Certified* Simulation Model and a related V&V report allows finally its application within Phase 3 or the Type Approval in the true sense.

It could be stated, that most of the SafeEV activities are currently addressing *Phase 1* and partially *Phase 2*.

A key aspect in the implementation of VT is the assessment of simulation models predictability. Finally VT methods shall provide for the same level of confidence as physical tests, as is stated in the Framework Directive. For that reason **the Verification and Validation (V&V) methodology** as described in ASME V&V 10-2006 Guide for Verification and Validation in Computational Solid Mechanics was adapted to the particular needs of the IMVITER project.
The ASME V&V 10-2006 has been established as the reference document providing guidelines for assessing the credibility of computational solid mechanic models and is based on its following key principles:

- Verification must precede validation, i.e. before assessing model predictability for physical phenomena, *code and calculation correctness from a mathematic perspective* must be assured.
- The need for validation experiments and the associated accuracy requirements for computational model predictions are based on *the intended use of the model* > In IMVITER and now also SafeEV, the vehicle safety evaluation in a new assessment process and/or type-approval scenario.
- Validation of a complex system should be pursued in a *hierarchical fashion from the component level to the system level*; the higher the complexity the more branchy the tree.
- Validation is specific to a particular computational model for a particular intended use. Each pilot case and system level will need dedicated validation requirements.
- Simulation results and experimental data must have an *assessment of uncertainty* to be meaningful.

It is important to note that verification and validation activities have nothing to do with calibration: "Calibration is the process of adjusting numerical or physical modelling parameters, components, or aspects of the computational model for the purpose of implementing a computational model or improving agreement with experimental data". Calibration of physical parameters in a simulation is an activity normally performed during model building (> Phase 1) and always before any verification or validation.
As stated above, as a part of a Validation Assessment, comparisons between simulation results and experiment results (measurements) are performed. Based on these comparisons, assessments are made about the applicability of the simulation capability for making predictive simulations of a similar nature.

A **metrics, to quantitative assessment of these results** is then the next key point within the process [3]. From the initial set of pre-selected metrics (for more information, please refer to IMVITER deliverable D2.1 – Evaluation criteria to choose VT methods [3]), some of them specially correlated well to a, so called, SMEs' (Subject Matter Expert) assessments. Nevertheless, only a few of them fully discriminated between validated & not validated cases in the same way the experts do, and therefore they are preferred. In conclusion and finally just exemplary, for the European regulation on pedestrian protection (head) and as it would be also a pilot application within the course of SafeEV, these metrics and threshold values would be proposed for model validation with regard to resultant acceleration signal:

- CORA cross correlation V* (progression component) ≥ 0.430
- with parameters INT_MIN = 0.80, K_V = 55
- ADVISER SGM phase (phase component) ≥ 0.920
- OSRS Reliability index ≥ 0.846

Validation metrics used in the IMVITER project are the ones deemed most appropriate by the time being, according to the status of the art. However in the future **IMVITER strongly recommend the use of internationally recognised validation metrics, and in particular validation metrics and procedures specified by *the ISO group on Virtual Testing*.**

As also a part of the VT process implementation, a set of **V&V report templates** for the tools and vehicles, were presented. These templates specify which information is to be provided by the carmaker to the Technical Service during a type approval based on VT. Therefore these documents also offer a standardised format to include all the before mentioned evaluation and specification of the numerical models. It can be considered as an equivalent test report now for simulation results, although with specific contents that are totally new in the type approval framework.
Figure 44 shows some examples from IMVITER pilotcase "pedestrian". The templates will be made available also for exemplary use within SafeEV (see Appendix A - Crash Barrier description of D3.3 [9]).

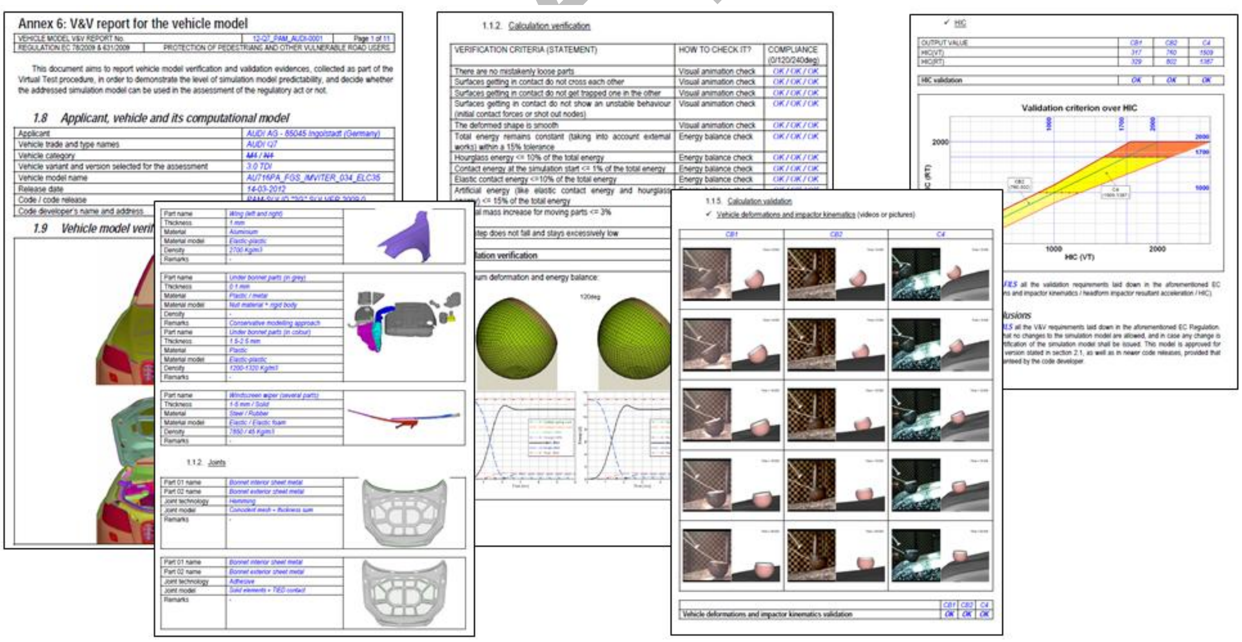


Figure 44. Example for IMVITER V&V (Validation & Verification) report templates - to be used within proposed VT procedure (Figure 43) – Report has to be provided on the one hand for the vehicle or component model and on the other hand also for assessment tools and its criteria [57].

In the last phase of IMVITER for some chosen safety systems related to pedestrian safety such as the Brake Assist (BAS) and pedestrian detection systems, advanced simulation methods and tools (HBM & SUFEHM) were applied to investigate the potential of VT to evaluate also integrated safety systems in the future - this approach is now continued with the SafeEV objectives.

Finally the main focus of IMVITER project was the implementation of Virtual Testing (VT) in existing type approval procedures, and particularly in safety related regulatory acts, by consolidation of advanced VT technologies – a consistent application of all results and methods within the course of SafeEV will not be possible due to the generic character of most of the models. Nevertheless, the basic IMVITER method and code of best practice will be adopted by SafeEV and will be also now even further developed with the application and use of advanced tools and criteria.

5 What will be developed within T3.2 to complete the tool chain

As it is the objective to develop an "advanced simulation methodology for consistent safety analysis for pedestrian protection for SEVs" within Task 3.2 additional development work has to be performed. The focus will be put on the selection of appropriate criteria for injury risk prediction for the HBMs, the analysis of full kinematics until ground contact including the utilisation of an advanced model for the ground, the comparison of similar HBMs running under different codes and the comparison of FE HBMs vs. the FE PAC. The latter two will play an important role as far as reliability of the virtual approach is concerned.

5.1 Injury risk evaluation using HBMs

Based on the overview of injury criteria derived from WP2 Chapter 5.1 [2] the body regions as mentioned under Chapter 2 of this report will be assessed by the use of either the THUMS or the FE PAC. Further on, especially as far as the THUMS is concerned, the criteria to be used will be discussed and defined in the course of Task 3.2 (and Task 3.3) and reported in D3.5 (and D3.6 for the occupant accordingly). In addition, a minimum level of required validation of each body region to be used for the assessment will be defined. Furthermore, for each body region reasonable injury criteria will be defined and evaluated during the simulations. Then, a sanity check of the applicability of these criteria is needed. If necessary, possible enhancements of the model(s) will be proposed. However, the model enhancement might not fall into SafeEV project, but has to be performed separately. For the time being, a criteria or body region might not be completely assessed or even not assessed at all.

Current regulatory and public domain pedestrian testing protocols for M1 class vehicles focus on the three body regions head, upper and lower leg which are assessed using impactors. However, the application of HBMs offers the possibility to have a more detailed look on injury mechanisms while taking into account realistic kinematics of the impacting pedestrian. Hence, the application of HBMs in Task 3.2 leads to an appropriate consideration of the unique vehicle front end design of future SEVs for each load case.

As far as the injury risk assessment is concerned, at least for the head this task is to be consolidated with the application of the SUFEHM and its evaluation tool IRA (Injury Risk Assessment). Main focus of UNISTRA therefore is to consolidate head injury criteria for adults (50^{th} percentile male and 5^{th} percentile female) based on an extended head trauma database under both LS-DYNA and VPS. Specific SUFEHM post-processing tools for these codes will also be developed. As far as possible, if further accidents are available, injury criteria will also be proposed for the 6 years old child head model. In order to ensure realistic results under both FE codes a number of basic head impacts will be simulated under LS-DYNA and VPS for comparison purposes. However the 6YOC will not be considered by VW under VPS code. Finally UNISTRA will assist Daimler AG and Volkswagen for complete pedestrian versus car impact simulations including secondary impact. While the THUMS-D couple to the SUFEHM is already in use at Daimler AG, the coupled model under VPS is just to start its application.

5.2 THUMS and FE PAC

The comparison of the injury risk assessment provided by THUMS-D model of Daimler AG and the FE PAC of CRF is another important analysis. In order to be able to perform this comparison not only with respect to the overall kinematics, injury criteria in the THUMS-D analogue to the PAC need to be defined as far as possible.

Following a second independent path Bosch carries out LS-DYNA simulations with pedestrian impactors in combination with REVM1. The results are used to define and roughly review the pedestrian safety sensor systems of the SEVs, e.g. focussing on acceleration based sensor systems. A plausibility check is done by comparing HBM and PAC simulations results to the impactor test results. Thus, we are able to evaluate the reliability of the virtual approach with regard to state of the art sensor layout of SEVs.

5.3 THUMS running under different crash codes

Within T3.2 a number of similar load cases will be run under either LS-DYNA as well as VPS. Both, the vehicle model REVM2 as well as the THUMS model is available in both codes whereas both original models were generated under LS-DYNA. When it comes to the comparison of the simulation results, mainly as far as injury patterns and load levels (e.g. stresses, plastic strains, etc.) are concerned, the results are expected to point in the same direction. In terms of a reliable tool chain it is mandatory that the models – vehicle models as well as HBM models – deliver comparable results regarding the injury risk prediction. It is clear that no identical values for instance for a ligament stress can be derived from two simulations under two different codes, however the results should not be contradicting. The mentioned comparison will be undertaken in the terms of this task and the outcome will be reported in a separate deliverable D3.4.

5.4 Ground model

In Task 3.2 a certain number of simulations will be run including the secondary impact, i.e. the contact between the pedestrian head and the ground (see Chapter 2 of this report). Instead of just modelling the ground as a rigid surface, ika will provide a ground model which will be representative for a typical road (see Chapter 3.4 of this report). At UNISTRA some second impacts on the ground were done with the SUFEHM model by using a ground FEM. The ground model is composed of two layers made of solid elements. The first one consists of an 80 mm thickness of layer with a MAT24 _PIECEWISE_LINEAR_PLASTICITY mechanical law (under LS-DYNA). The second one with a 40 mm thickness of layer is called concrete and is modelled as elastic law. The element size is 10 mm for both the layers and mechanical parameters are given in Table 11.

Table 11. UNISTRA ground mechanical parameters

Layers	Mass density [Kg/m^3]	Young's Modulus (MPa)	Poisson's ratio	Yield Stress [MPa]
First	1,600	5,400	0.35	500
Second	1,600	9,300	0.35	----------------

Both models will be used and further evaluated in Task 3.2.

5.5 Activities in Task 3.2

In order to provide a short overview of the upcoming tasks in T3.2, sub-tasks, responsibilities and according execution date are listed in Table 12.

Table 12. Overview of the main sub-tasks in T3.2 by the partners.

Task 3.2 activities	Responsible	Project month
To discuss and agree on methods for injury risk evaluation using HBM THUMS within the SafeEV project (together with Task 3.3).	Chalmers, Daimler, ika, UNISTRA, TU Graz, Volkswagen	M18
To consolidate head injury criteria and to compare SUFEHM response under specific impact conditions computed with LS-DYNA and VPS To compute severe head impact i.e. second impact	UNISTRA, Daimler, VW	M18
To report on the simulation results using simple impactors against REVM2 with the solvers LS-DYNA and VPS	Volkswagen	M19
Simulation of Pedestrian-Vehicle (REVM2) impact scenarios using THUMSD 50^{th} male . Focus on robustness, kinematics and comparability of HBM / Full body simulations in different crash codes.	Daimler, Volkswagen	M19
To define a FEM modelling approach for the ground in order to evaluate the injury risk during a ground impact in a necessary detail level	ika	M20
To compare results of PAC standing pedestrian dummy model w.r.t. THUMS-D human pedestrian model ones, in the same reference impact conditions against REVM1, with identification and implementation of eventual improvement actions for the PAC model.	CRF	M20
Simulation of Pedestrian-Vehicle impact scenarios with THUMSD 6Y & 50^{th} male with Univ. Strasbourg head as described in the test matrix. Further development of post processing tool and method for the head.	Daimler, UNISTRA	M21
To translate ika's FEM ground modelling approach into VPS code	Volkswagen	M21
LS-DYNA simulations with pedestrian impactors in combination with REVM1 to define and review pedestrian safety sensor systems of the SEVs.	Bosch	M21
Simulation of Pedestrian-Vehicle secondary impact configuration – discussion of post processing and injury risk estimation within a virtual assessment procedure.	Daimler, Volkswagen	M22
Plausibility check by comparing HBM and PAC simulations results (by other partners) to impactor test results to evaluate reliability of virtual approach with regard to state of the art sensor layout of SEVs	Bosch	M23
Final definition of relevant load cases and criteria to assess injury risk	All Task 3.2 partners	M23

6 Discussion and Conclusions

The objective of Task 3.2 is the development of an advanced simulation methodology for consistent safety analysis for pedestrian protection for SEVs. Therefore a “seamless tool chain” will be developed to enable a virtual assessment of pedestrian safety for future small electric vehicles. This report summarises the requirements for this tool chain.

The definition of the test matrix with load cases derived from the outcome of the first two work packages of SafeEV, WP1 [1] and WP2 [2] is presented in Chapter 2. Test condition definitions in D2 for pedestrian protection has not yet been described in detail, since they are based on generic SEV shapes using multi body simulations. In Task 3.2, FE models including vehicle models as well as dummy or HBMs respectively, will be utilised. Based on the findings in D2 as far as relevant head impact locations are concerned, a more detailed initial position for the pedestrian, including posture, has been defined in Chapter 2. However, further simulation work will be required to define the boundary conditions of appropriate load cases more precisely. Additionally, Chapter 2.1 provides an overview of the simulation work to be conducted by each partner and it shows the dependencies between their results. Finally, Chapter 2.2 provides a rough overview of the body regions which are intended for evaluation and assessment. The agreement on how to evaluate the injury risk of different body regions as far as HBMs are concerned is still open and has yet to be agreed upon in the next steps of Task 3.2. The same applies to a validation catalogue for the HBMs, at least for the body regions which will be assessed.

In Chapter 3, all relevant models used by the different partners are described in detail. The description of the SafeEV Reference Electric Vehicle Models (REVMs) was already part of D3.1 [3]. Different versions of the THUMS V3 will be used and will have to run in different solvers. The outcome will be compared and reported later in this project in a separate deliverable.

Chapter 4, which is identical with the according section in D3.3 [9], summarises the SafeEV relevant content of the EU project IMVITER. For a virtual certification of SEVs, which is also the aim of SafeEV, the usage of validated vehicle models as well as validated impactors, dummies and HBMs is required. One focus of the IMVITER project was the definition of necessary steps of an appropriate process for validation of the virtual tools. “Verification & Validation (V&V)” templates are reviewed in Chapter 4 which define the requirements for validation and serve as “reference documents that help to exchange essential information between involved actors” are presented in Chapter 4.

Finally, Chapter 5 summarises the new developments of Task 3.2. The new main developments are:

- definition of required validation of HBM body region used for an assessment
- definition of injury risk predictors for the application of HBMs
- assessment of further body regions beyond head and leg while taking into account future SEVs vehicle design

- assessment and comparison of a dummy like pedestrian model (PAC) vs. a HBM
- assessment and comparison of a similar HBM, but running in different codes
- inclusion of the secondary impact using advanced ground models
- assessment of pedestrian safety sensor systems in the virtual tool chain

There will, however, be some limitations corresponding to the above new developments in Task 3.2. One important limitation is the missing validation of the vehicle models, since no physical tests are available to assess their prediction accuracy. The models have not undergone a regular serial development procedure with validation by a comparison to tests of their physical counterparts. Nevertheless, engineering judgement by the involved partners was applied to finalise these models in the best positive way. This is acceptable for this project as it is mainly about the development of the virtual tool chain itself. However, in order to virtually certify a SEV, a physical (impactor) test in terms of a V&V process is absolutely necessary. This was already shown in the IMVITER project.

Furthermore, there are no broadly agreed definitions of injury risks for HBMs available. Injury risk evaluation is up to the HBM user and there are no tools available for an automatic evaluation of these models in terms of an injury risk assessment. In SafeEV, suggestions for different body regions as mentioned in Chapter 2.2 will be given. These focus mainly on qualified criteria on a tissue level. An exception from this is the injury risk assessment as far as the head is concerned. Using the SUFEHM with the IRA tool, an injury risk assessment can be immediately calculated after the impact simulation.

Another limitation is due to the current limited availability of appropriate body size models. This is the case for either the dummy, where only a 50th% male is available, or the HBMs, where only a 50th% male and a 6 years old child model are currently available.

Despite the mentioned limitation, the outcome of Task 3.2 is expected to be a big step forward for either the evaluation of SEV's pedestrian safety using HBMs with according criteria, discussed between and proposed by the different partners and towards a future virtual certification for the SEVs.

List of Tables

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Acknowledgements

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Appendix A

Body Dimensions	SAE Dimensions (mm)	THUMS-D (mm)
Bottom of shoes to top of head	1787 ± 15	1789
Bottom of shoes to the Upper spine/lower neck joint	1525 ± 15	1500
Bottom of shoes to the center of the shoulder/arm rotation joint	1459 ± 20	1438
Bottom of shoes to center of rotation of the elbow	1139 ± 20	1120
Bottom of shoes to center of rotation of the hip socket	970 ± 15	1067
Bottom of shoes to center of rotation of wrist	881 ± 20	978
Bottom of shoes to Knee center	522 ± 15	509
Bottom of shoes to center of rotation of ankle	103 ± 5	111

Table 1: Dimensions of Whole Body Segments THUMS-D

Body Segment	SAE mass (kg)	THUMS-D mass (kg)
Head	4.25 ± .45	4.9
Neck	1.05 ± 0.2	1.22
Thorax	22.6 ± 4.5	25.33
Upper Extremities (2)	Arms: 3.5 ± 0.6 Forearms: 4 ± 0.6	6.29
Pelvis	13.5 ± 2	8.4
Thighs (2)	18.4 ± 3	18.12
Legs (2)	7.5 ± 1.1	8.98
Shoes	Per shoe mass : 0.5 kg ± 0.2 kg	0.72
Total Mass	79 kg ± 5 kg incl. Instrumentation	76

Table 2: Mass of Body Segments THUMS-D

Body Segment	Test	Impact Direction	Impactor Mass (kg)	Impactor Velocity (m/s)	Measured Output	Source
Thorax	1	Oblique	23.4	4.3	FD	Viano (1989)
	2	Oblique	23.4	6.7	FD	"
	3	Oblique	23.4	9.5	FD	"
	4	Lateral	12	5.76	FD	Talantikite (1998)
	5	Lateral	16	5.9	FD	"
	6	Lateral	12	8.34	FD	"
	7	Lateral	16	7.09	FD	"
	8	Frontal	23.4	4.27	FD	SAE
Abdomen	9	Oblique	23.4	4.3	FD	Viano(1989)
	10	Oblique	23.4	6.7	FD	"
	11	Oblique	23.4	9.5	FD	"
Pelvis	12	Lateral	23.4	4.3	FD	"
	13	Lateral	23.4	9.5	FD	"
Tibia	14	Lateral- Medial	32	4.2/3.7	BM	Nyquist (1985)
	15	Anterior- Posterior	32	3.5/3.2	BM	"
Shoulder	16	Lateral	23.4	4.5	FT	ISO
Knee	17	Lateral-Shearing	6.25	5.55/11.11	FT	Kajzer (1999)
	18	Lateral- Bending	6.25	5.55/11.11	FT	"
Femur	19	Anterior- Posterior	NA	Quasistatic	FD	
Head	20	376 mm Drop Test	NA	2.71	H. CoG AT	Yaguchi
	21	200 mm Drop Test	NA	1.98	H. CoG AT	WSU/ISO
	22	1200 mm Drop Test	NA	4.85	H. CoG AT	APR/ISO

FD - Force vs. Displacement Curve

BM – Bending Moment

AT – Acceleration vs. Time

WSU – Wayne State University Tests

APR - Association Peugeot Renault

Table 3 : Impactor Tests for Body Segments – THUMS-D

Thorax Tests

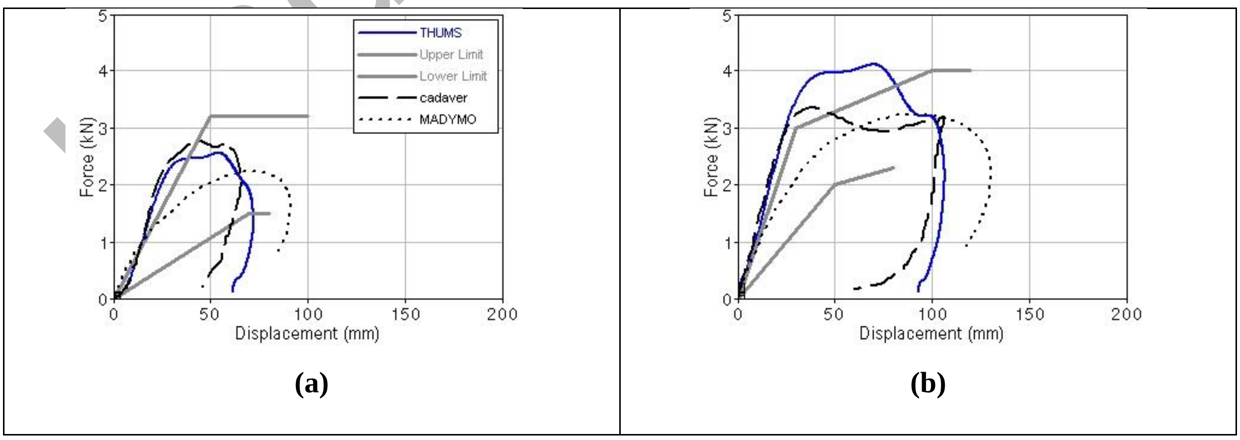


Figure 1: Force- Displacement curves for oblique Thorax tests with impactor mass 23.4 kg

(a) Impactor Velocity 4.3 m/s, (b) Impactor Velocity 6.7 m/s.

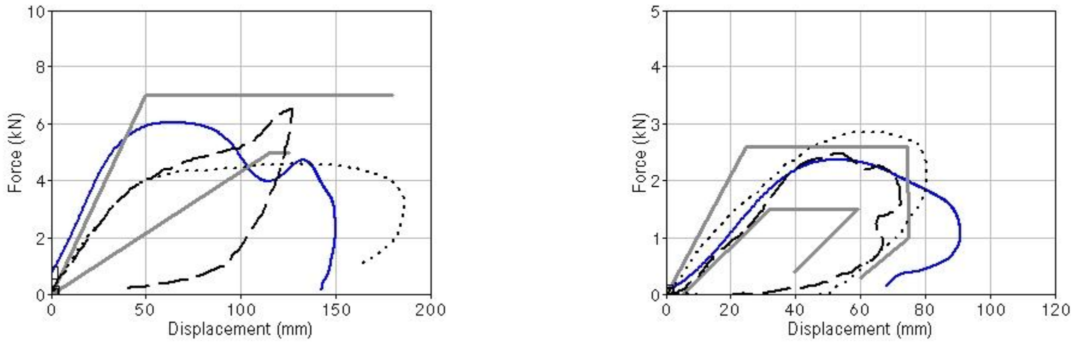


Figure 2: Force - Displacement response (a) Oblique Thorax test with Impactor mass 23.4 kg and Impactor velocity 9.5 m/s. (b) Lateral Thorax test with Impactor mass 12 kg and velocity 5.76 m/s.

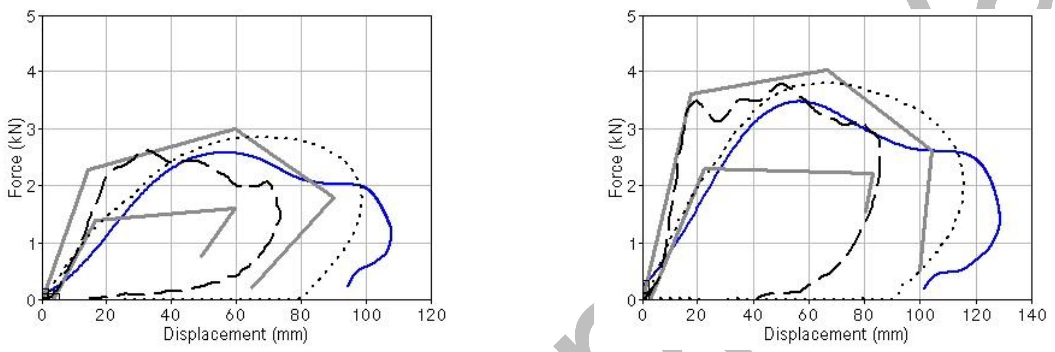


Figure 3: Force - Displacement response for Lateral Thorax tests (a) Impactor mass 16 kg and velocity 5.9m/s, (b) Impactor mass 12 kg and velocity 8.34 m/s.

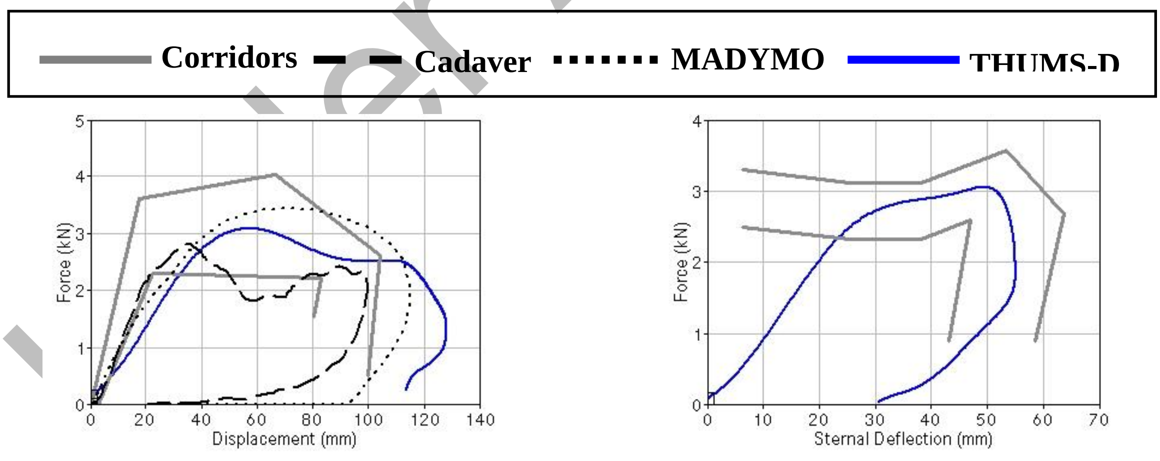
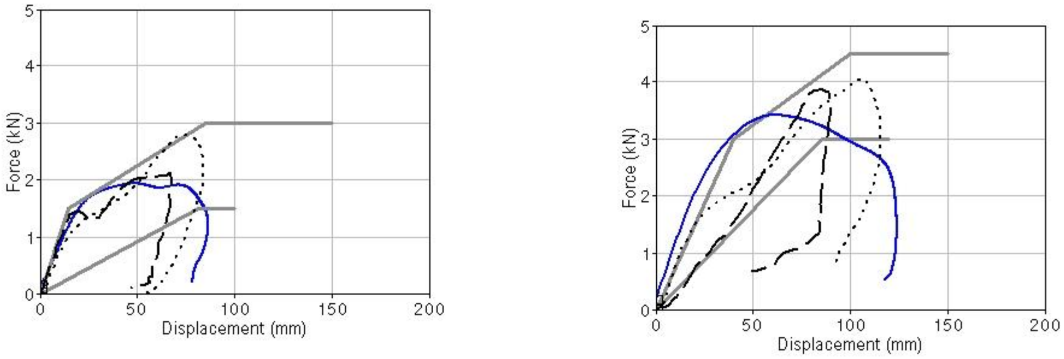


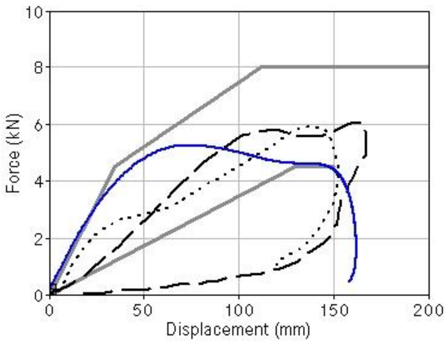
Figure 4: Force - Displacement Response (a) Lateral Thorax test with Impactor mass 16 kg and velocity 7.09 m/s. (b) Frontal Thorax test with Impactor mass 23.4 kg and Impactor velocity 4.3 m/s.

Abdomen Tests



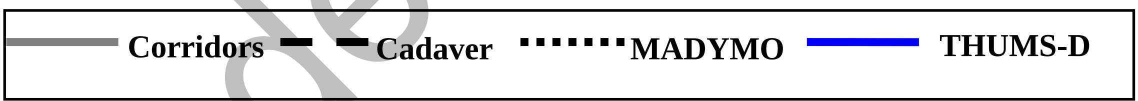
(a) **(b)**

Figure 5: Force - Displacement Response for Oblique Abdomen tests with Impactor mass 23.4 kg (a) Impactor Velocity 4.3 m/s. (b) Impactor Velocity 6.7 m/s.

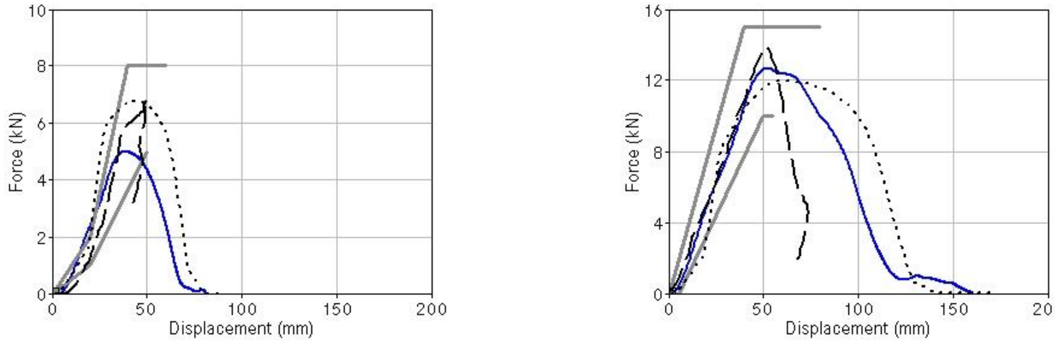


(a)

Figure 6: Force - Displacement Response with Impactor mass 23.4 kg (a) Oblique Abdomen test with Impactor Velocity 9.3 m/s.



Pelvis Tests



(a) **(b)**

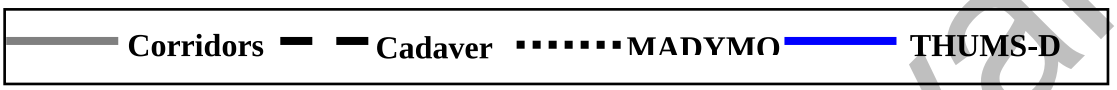
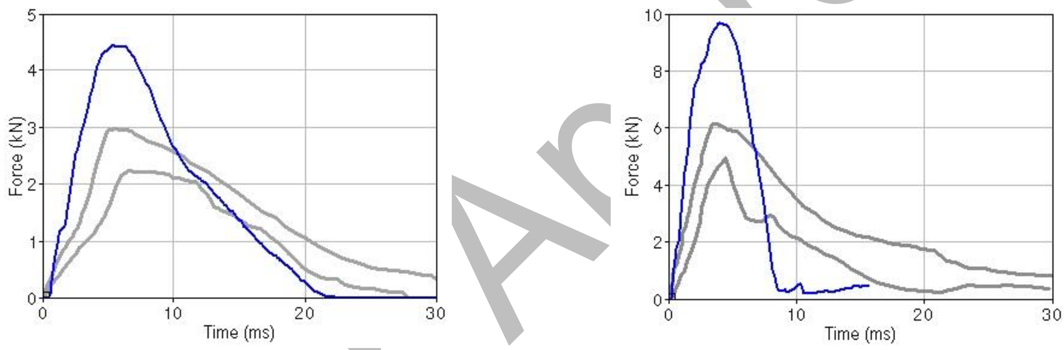


Figure 7: Force - Displacement Response for Lateral Pelvis tests with Impactor mass 23.4 kg (a) Impactor Velocity 4.3 m/s, (b) Impactor Velocity 9.5 m/s.

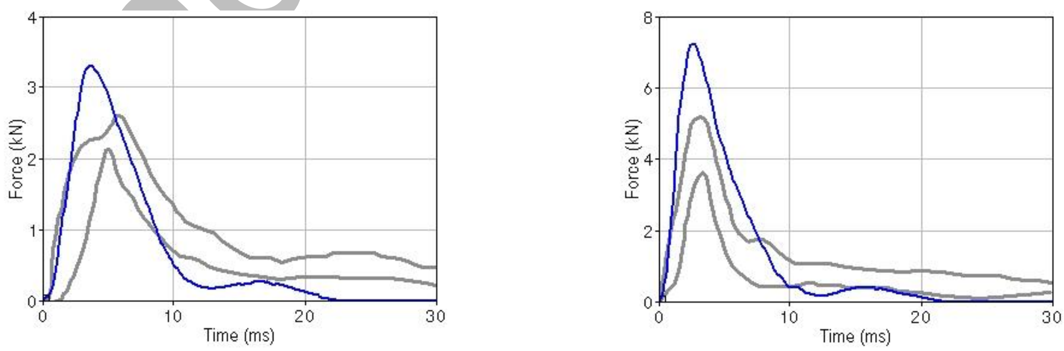
Knee Shear Tests



(a) **(b)**

Figure 8: Force - Time History for Knee shear tests (a) Impact speed 20kmph (b) Impact speed 40kmph

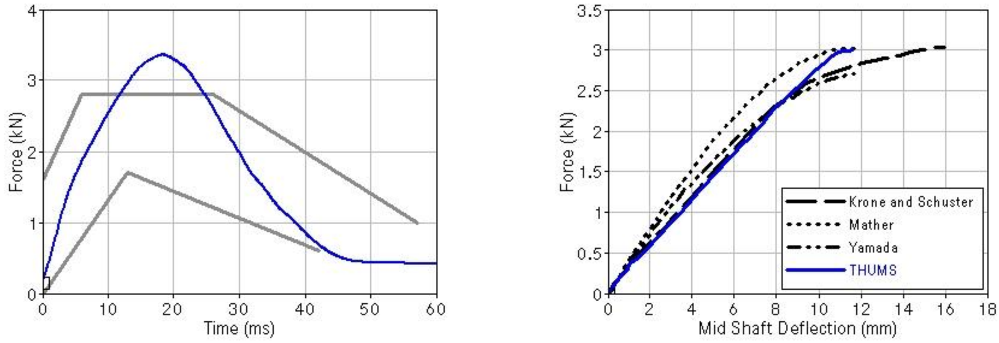
Knee Bending Tests



(a) **(b)**

Figure 91: Force - Time History for Knee bending tests (a) Impact speed 20kmph (b) Impact speed 40kmph.

Shoulder and Femur Tests



(a)

Figure 10: Force - Displacement Response (a) Impactor mass 23.4 kg and Impactor Velocity 4.5 m/s (b) Quasi-static bending test for femur.

Tibia Bending Tests

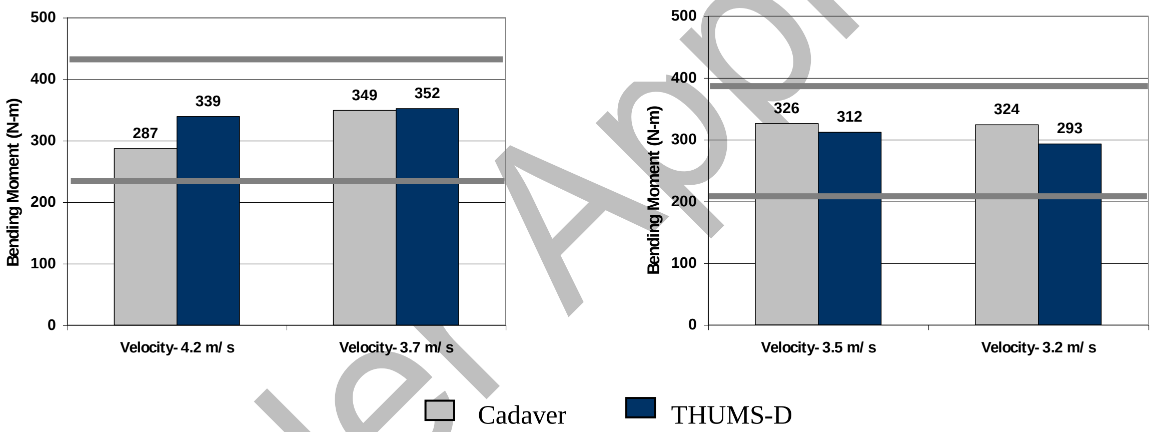
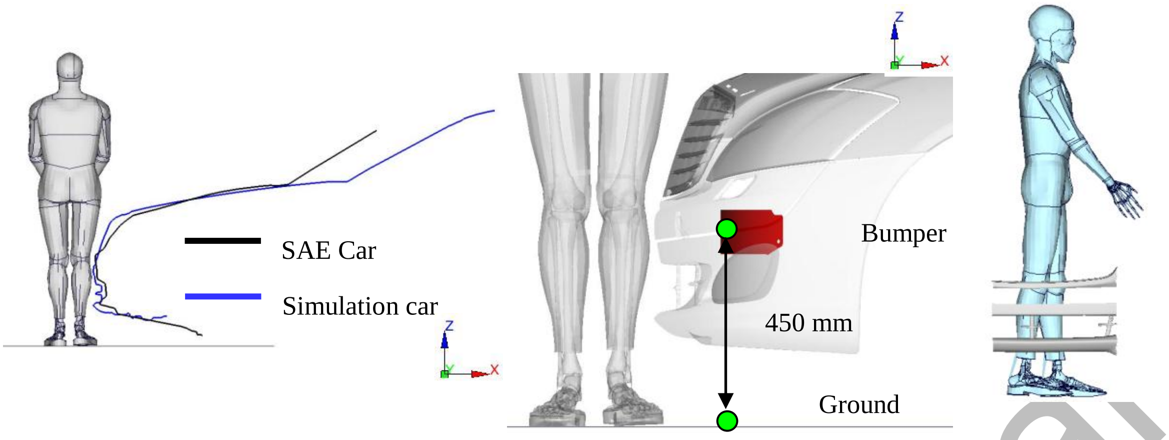


Figure 11: Tibia Bending Moments (a) Lateral - Medial direction (b) Anterior- Posterior direction

SAE Test for Body Segment Trajectories



(a) (b) (c)

Figure 12: (a) Simulation and cadaver test cars profile (b) Pedestrian and Vehicle Positioning (c) Pedestrian Impact - side Leg Position

The vehicle considered for the simulation with THUMS-D pedestrian model has a mass of 1180 kg and the impact speed is 40 Kph without braking. The bumper height is set such that the mid-point of the structural bumper beam is at a height of 450 mm above the ground plane (b). The posture of the pedestrian is such that the impact side leg is positioned backwards (c).

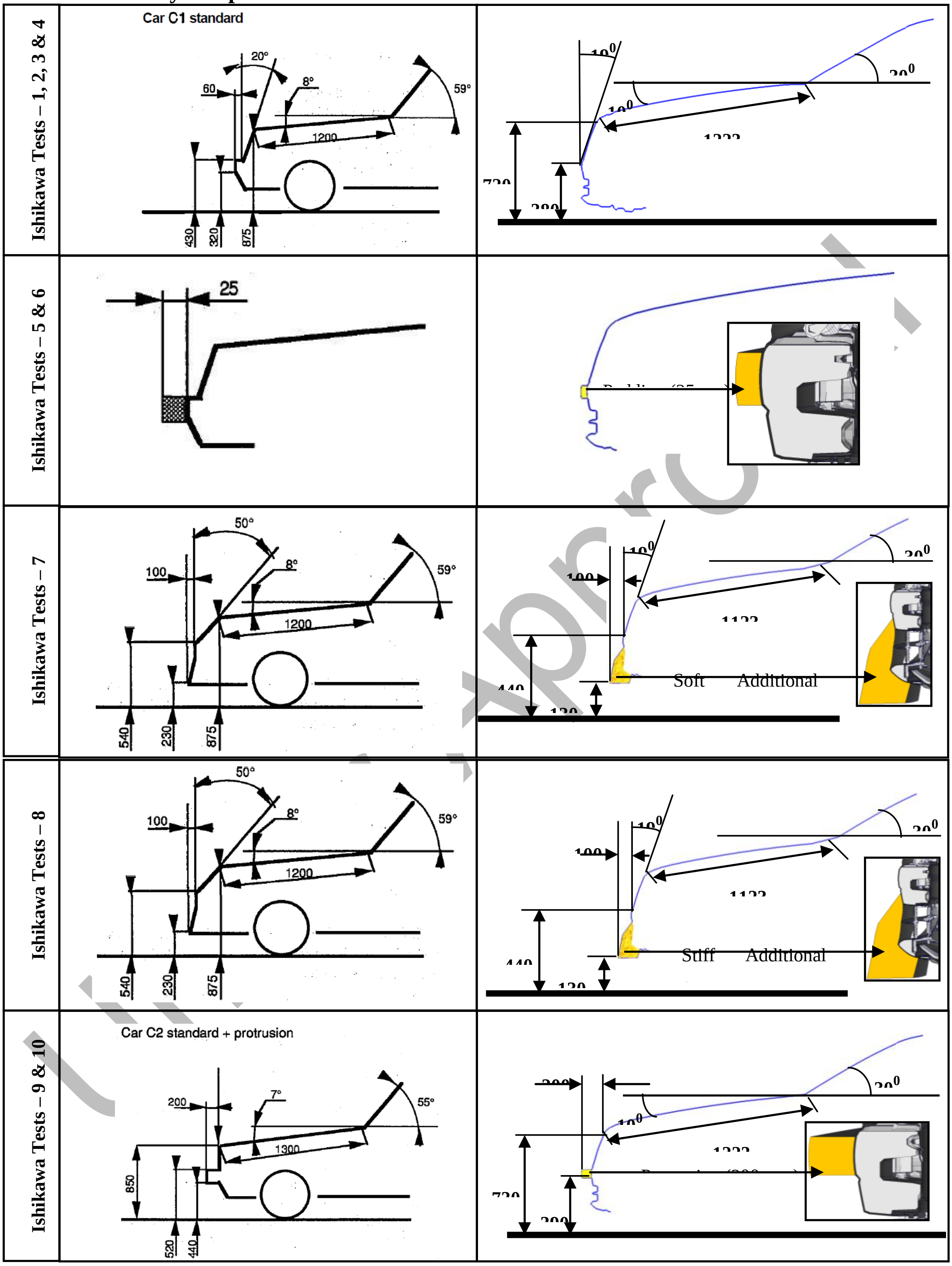
Test Condition	SAE Recommendation	Simulation with THUMS-D
Vehicle mass (kg)	1175 ± 25	1180 kg
Vehicle Impact Velocity (kmph)	40	40
Bumper Height from ground (mm)	450 ± 10	450
Pedestrian	The wrists of the pedestrian dummy are tightly bound with a stiff material.	The wrists of the THUMS-D model are tightly bound using Nodal Rigid bodies.

Table 4: Impact Conditions for test and simulation

Measurement Point	SAE Recommendation	Simulation with THUMS-D
Upper Spine Trajectory measurement point from ground (mm)	1525 ± 5	1521
Mid thorax trajectory measurement point from ground (mm)	1375 ± 5	1347
Pelvis trajectory measurement point from ground (mm)	1025 ± 5	1022

Table 5: Measurement Points for evaluation of Body Trajectories

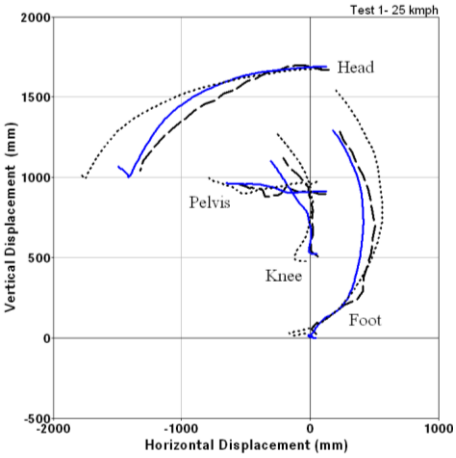
Vehicle Geometry comparison between Cadaver test car and Simulation car



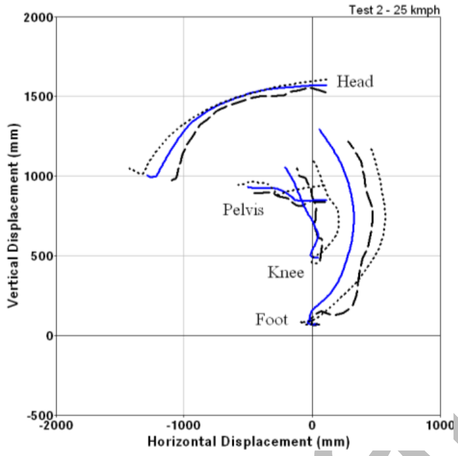
Cadaver Test car Simulation Car

Figure 13: Vehicle Geometry Comparison between cadaver test car and simulation car

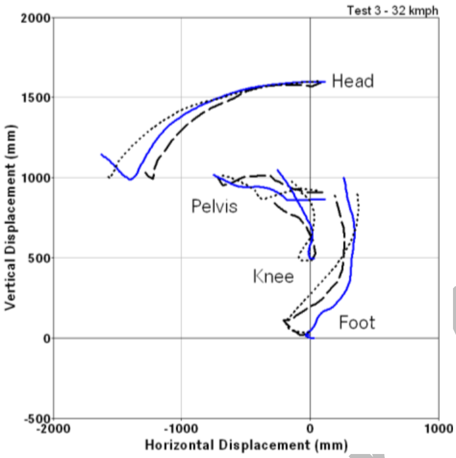
Body Trajectories – Ishikawa Cadaver Tests



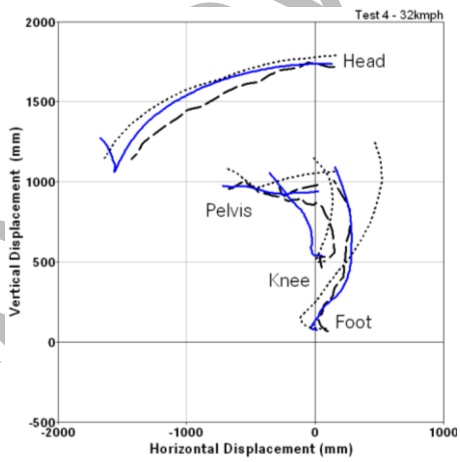
(a) T1 – 25 kmph



(b) T2 - 25 kmph

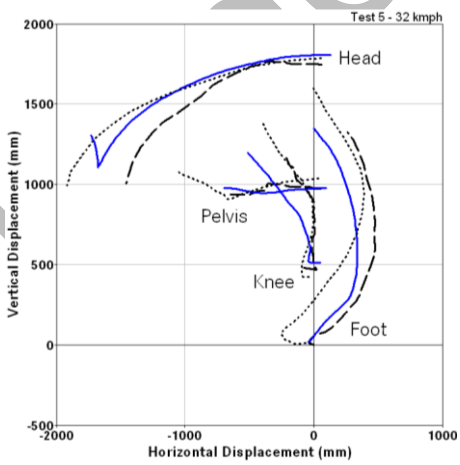


(c) T3 - 32 kmph

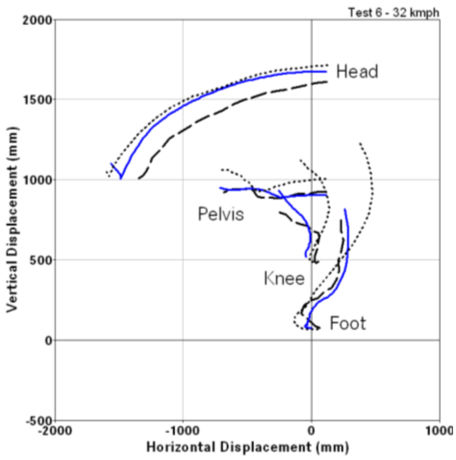


(d) T4 - 32 kmph

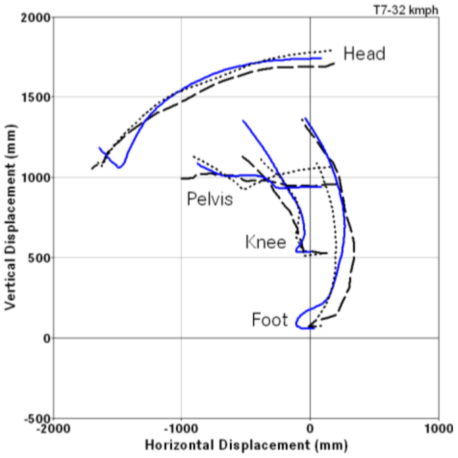
Corridors — Cadaver ······ MADYMO — THUMS-D



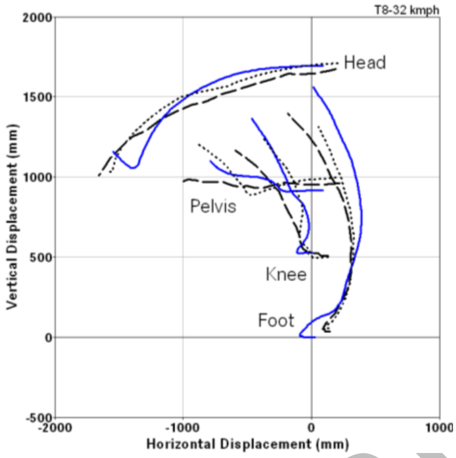
(e) T5 - 32 kmph



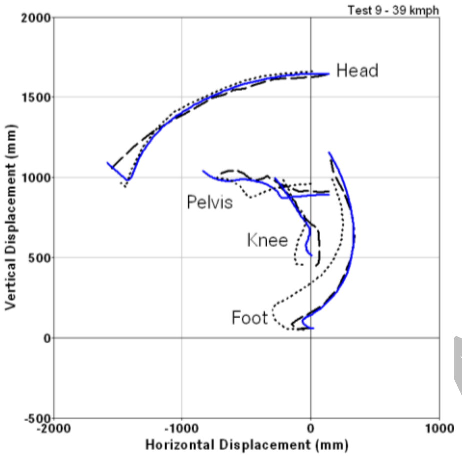
(f) T6 - 32 kmph



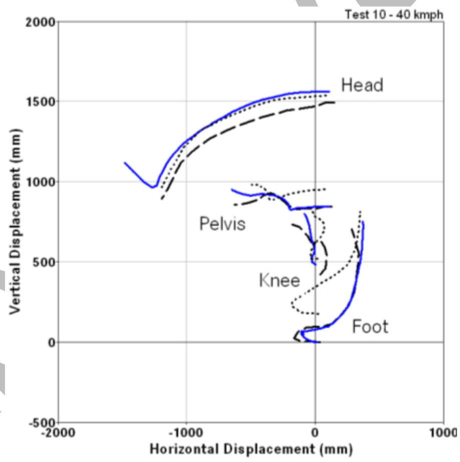
(g) T7 - 32 kmph



(h) T8 - 32 kmph



(i) T9 – 39 kmph



(j) T10 - 40 kmph

Cadaver	**MADYMO**	**THUMS-D**

Figure 14: Comparison of Body Trajectories between cadaver, MADYMO and THUMS-D

The numbers in the Table 6 indicate the percentage of closeness between the head impact location predicted by THUMS-D model and head impact locations observed in cadaver tests. The head impact location is well predicted by THUMS-D model with 8 out of 10 cases having an average objective rating of more than 90%. The objective rating is done in the same way as it was done for MADYMO models (Jack van Hoof, 2003) using the following relation:

$$ObjectiveRating = \left(1 - \left|\frac{Experiment - Simulation}{Experiment}\right|\right) * 100\%$$

Ishikawa Tests	THUMS-D		
	Head X Impact Position	**Head Z Impact Position**	**Average**
Test - 1	94.4	97.7	96.0
Test - 2	86.0	98.6	92.3
Test - 3	89.3	97.3	93.3
Test - 4	91.7	95.2	93.4
Test - 5	88.7	81.9	85.3
Test - 6	90.8	98.8	94.8
Test - 7	85.4	96.8	91.1
Test - 8	81.5	92.9	87.2
Test - 9	88.8	97.4	93.1
Test - 10	97.3	89.5	93.4
Average	89.4	94.6	

Table 6: Head Impact Location