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Pedestrian Human Model Certification

Crash Protection

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PREFACE

During the test preparation, vehicle manufacturers are encouraged to liaise with the laboratory and to check that they are satisfied with the way cars are set up for testing. Where a manufacturer feels that a particular item should be altered, they should ask the laboratory staff to make any necessary changes. Manufacturers are forbidden from making changes to any parameter that will influence the test, such as dummy positioning, vehicle setting, laboratory environment etc.

It is the responsibility of the test laboratory to ensure that any requested changes satisfy the requirements of Euro NCAP. Where a disagreement exists between the laboratory and manufacturer, the Euro NCAP secretariat should be informed immediately to pass final judgment. Where the laboratory staff suspect that a manufacturer has interfered with any of the set up, the manufacturer's representative should be warned that they are not allowed to do so themselves. They should also be informed that if another incident occurs, they will be asked to leave the test site.

Where there is a recurrence of the problem, the manufacturer's representative will be told to leave the test site and the Secretary General should be immediately informed. Any such incident may be reported by the Secretary General to the manufacturer and the person concerned may not be allowed to attend further Euro NCAP tests.

DISCLAIMER: Euro NCAP has taken all reasonable care to ensure that the information published in this protocol is accurate and reflects the technical decisions taken by the organisation. In the unlikely event that this protocol contains a typographical error or any other inaccuracy, Euro NCAP reserves the right to make corrections and determine the assessment and subsequent result of the affected requirement(s).

CONTENTS

1 INTRODUCTION

The Vulnerable Road User Test Protocol requires that the vehicle manufacturer provides Euro NCAP with detailed information relevant to the deployment of the active pedestrian protection system, if available. Based on the evidence provided by the vehicle manufacturer, the Secretariat will decide whether the vehicle qualifies for subsystem testing in either the deployed or undeployed position or if dynamic tests are required.

A combination of physical testing and numerical Human Body Model (HBM) simulations is required to demonstrate the suitability of the sensing system for the range of pedestrian sizes; the timing of system deployment; and the bonnet deflection due to body loading.

Only CAE simulation results, generated with HBMs that meet the certification requirements laid down in this document, will be accepted by Euro NCAP. HBM compliance must be demonstrated by the vehicle manufacturer in accordance with the procedure in this document. If HBM compliance can't be demonstrated, the active bonnet will be tested undeployed.

Throughout this document, the following definitions are used:

- A Human Body Model (HBM) is understood as a virtual geometric and mechanical representation of the human body. The geometry of the model should result in dimensions, masses and moments of inertia per body parts in agreement with standard anthropometry databases. It has to consider the complex human anatomy and consist of a full skeleton composed of all bones (except for the feet, hands, face and ear where simplifications are allowed) and soft tissue. All the bones should be articulated in a realistic manner enabling a biofidelic range of motion for all joints.
- More simplified human models, referred to as humanoid models, may lack detail to improve calculation time and are not consisting of a full skeleton and use simplified modelling approaches. In all parts of the protocol without special specification for humanoid models, a consistent procedure as for HBMs should be applied for humanoid models.
- Certification simulations: A computer simulation providing evidence that the specific human body model is comparable with other models and shows consistent results – in particular referring to body kinematics and Head Impact Time.
- Active bonnet simulation: A computer simulation for the assessment of deployable systems as specified in the Euro NCAP Pedestrian Testing Protocol.
- Generic Vehicle (GV) Models are generic replications of current car fronts and are provided in all FE codes. The car fronts were developed for kinematic comparisons only and should not be used for evaluations of injury metrics as they do not meet the UN Regulation No. 127.

1.1 General requirements

The pedestrian human model that is certified is the exact same model used for final active bonnet simulations. This applies to:

- Version of the human body model;
- Node-Position of every single node of the human body model;
- If applicable:
    - identical initial element stresses/strains;
    - identical initial contact penetrations/contact forces;

- Identical material cards (including fracture mode), contact cards, control cards and constraints.
- The time step used for simulations.

Furthermore, it is important that all simulations (certification and active bonnet) are performed with *consistent settings*. This applies to:

- Solver-Version;
- Solver-Platform (parallelisation);
- Solver-Precision (Single, Double Precision);
- Number of CPUs/ nodes used (on cluster/computer);
- Time-step settings (relating to initial and dynamic mass scaling);
- Contact settings (between Human Body Model and Vehicle);
- Control settings which are affecting the pedestrian model.

Ideally, HBM certification and active bonnet simulations shall be performed on the same computer system and with the same number of CPUs. If the cluster architecture does not allow simulations to be performed with either a consistent number of CPUs or on the same platform, evidence must be provided showing that the results are reproducible and comparable. This must be done by providing results of the FCR and SUV load case at 40 kph using varying CPU numbers and platforms.

1.2 Output requirements

HBM certification data is to be submitted in the *prescribed format*. The complete output dossier must be send to the Euro NCAP Secretariat at the earliest possible moment but latest together with active bonnet simulation result. Fully completed Excel templates must be submitted using the latest versions of the documents provided by Euro NCAP[1]. Furthermore, videos of the animated results have to be provided for each loadcase. The Secretariat reserves the right to reject data that are not provided in the correct format, are provided incomplete or not on time.

The following files are requested for each certification:

- Videos of the animated simulation results should be submitted (from t=0 to H) including timestamp for each submitted simulation. The videos should be named according to the loadcase and should be named according to cell C1 in the respective excel sheet where the data was filled in (e.g. FCR_50kph_AM50).
- Excel File with impactor simulation results (GV only):
    1. GV_Check.xlsx
- Excel File specifying the applied models and environment:
    2. Documentation.xlsx
- Excel Files with HBM-GV simulation results:
    3. FCR_AM50.xlsx
    4. FCR_6yo.xlsx
    5. RDS_AM50.xlsx
    6. RDS_6yo.xlsx
    7. SUV_AM50.xlsx
    8. SUV_6yo.xlsx

[1] Excel and PowerPoint templates can be downloaded as part of the certification pack via the download link available from https://www.euroncap.com/en/for-engineers/supporting-information/

9. SUV_AF05.xlsx

All requested data should be filled into the yellow fields in the templates provided - they **must not be renamed!** Do not forget to include the total mass of your setup and to check if automatic H detection was applicable.

If automatic detection of H is not applicable, check your animations and fill in the comment cell to comment how you derived H and why the peak acceleration occurs earlier than the contact between head and vehicle. **If no explanation is provided, a switch from H_auto to H_manual is not accepted!**

2 BACKGROUND

The Pedestrian HBM certification procedure was developed within the CoHerent project (Methodology for Comparison of Human Body Models for pedestrian simulations) at Graz University of Technology (Klug et al. 2017, Klug et al. 2019). The certification procedure should ensure that human body models have comparable and reproducible results. For this reason, the procedure is aimed to be:

- Independent of FE solver used (procedure applicable in all defined FE codes);
- Independent of human body model (reference points applicable for all HBM);
- Reproducible (accurately defined boundary conditions);
- In accordance with boundary conditions of Pedestrian Test Protocol;

In the HBM certification procedure, the kinematics of one model is compared against the response of known, validated, consistent state-of-the-art models in pedestrian impacts against generic vehicle models at speeds ranging from 30 to 50 kph. To that extent, four generic vehicle models are prescribed, representing the following categories:

- Family Cars (FC)
- Multi-Purpose Vehicles and Superminis (MPV)2
- Roadsters (RDS)
- Sports Utility Vehicles (SUV)

The vehicle models provide a representative and up-to-date vehicle shape for the selected vehicle categories, median structural response upon pedestrian impact in terms of force- deflection characteristics and are modelled to be robust and transferable to all considered explicit FE codes considered. The generic vehicle models required to certify the human body models are offered in the four most relevant explicit FE solvers on the market[3]:

- LS-Dyna by LSTC;
- VSP by ESI;
- Radioss by Altair;

The detailed modelling approach to the development of the generic vehicle models is summarised in APPENDIX D.

[2] Simulations against the generic MPV model are not requested anymore from 2022 onwards. It has been decided to remove them from the certification simulations to reduce the efforts. The shape of the MPV model lays in between the FCR and SUV and is therefore covered already.

[3] The procedure provides detailed guidelines for each of these four codes. If a vehicle manufacturer opts for another FE code, evidence needs to be provided, that modelling is consistent with the modelling guidelines outlined in this document. Available models can be downloaded from the website.

3 PEDESTRIAN HBM CERTIFICATION PROCEDURE

3.1 Generic vehicle robustness check

To avoid any issues with upcoming or outdated solver versions, the generic vehicle models have to be checked ahead of the HBM certification simulations. Therefore, four impactor simulations with the provided simulation setups have to be performed at the vehicle centreline (ID 1, 3, 5 and 7).

A rigid cylindrical impactor with a total mass of 5.95 kg should be propelled against the generic vehicle front at four different specified impact locations. Force (calculated from the impactor acceleration) and displacements of the impactor simulations have to be provided and compared to the reference responses of the respective code (see APPENDIX C) for each vehicle geometry, using the provided template.

The history (resultant deflection and resultant acceleration) of the node with ID 10000 should be used. The full simulation setup for the impactor simulations including the specification of the impact points is available in LS-Dyna, VPS and Radioss on the Euro NCAP website. The latest release of this setup should be used and the release date should be provided within the documentation template.

If any issues with the GV models are identified, they should be reported to the responsible code house first, before contacting Euro NCAP (contact details can be found in the header of the simulation files).

3.2 Certification Simulations

3.2.1 HBM Pre-processing

Shoes

The HBM shall be fitted a pair of shoes – with a sole thickness (at the heels) between 20 and 30 mm at the heel. The pair of shoes can consist of a sole only. In the latter case, the sole has to be tied – without failure – to the foot. The pair or shoes for the mid-sized male pedestrian shall not weight more than 1.300 g[4]. The total mass of the HBM specified in tables 1-2 shall be compared to the HBM without shoes.

Output Parameters

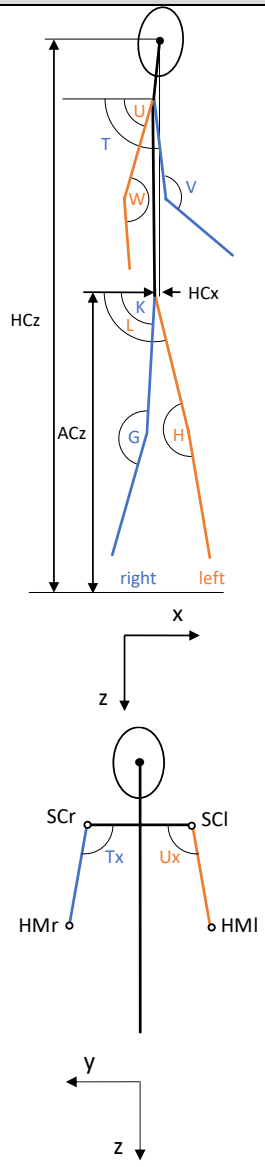
The HBM must be equipped with “sensors” and other output definitions, which allow tracking the trajectories of selected body parts. The centre specifies the centre of all nodes; i.e. the node with averaged coordinates. The “sensors” have to be located at the locations specified in APPENDIX B and constrained to the surrounding structures such that the movement of the surrounding nodes is averaged and applied to the sensor node. The corresponding keywords are also specified in APPENDIX B.

[4] A pair of shoes used with the 50th HIII dummy weights 1.300 g.

Positioning

The car manufacture has the freedom to choose a positioning tool. Positioning can be achieved through pre-simulation (pulling/pushing the limbs to the desired position) or re-meshing/morphing. The target posture of the AM50 model are specified within Table 1. The joint angles of the legs are based on SAE J2782 and the arm posture is based on a natural posture[5].

Table 1 Initial Posture AM50

Abbrev.	Measure	Ref. Value	Tolerance (+/-)	Angle Definition
Px	Heel to heel distance Longitudinal	310 mm	5.0%	
Py	Heel to heel distance lateral	185 mm	15.0%	
ACz[6]	Height of AC relative to the ground level	949 mm	1.2%	
K	Right Upper Leg Angle (around Y w.r.t. horizontal)	89°	3°	
L	Left Upper Leg Angle (around Y w.r.t. the horizontal)	106°	5°	
G	Right Knee flexion Angle (Y)	164°	3°	
H	Left Knee flexion Angle (Y)	175°	5°	
Ty	Right Upper Arm Angle (Y w.r.t. horizontal)	98°	3°	
Uy	Left Upper Arm Angle (Y w.r.t. horizontal)	70°	3°	
Tx	Right Upper Arm Angle (X w.r.t. horizontal)	100°	10°	
Ux	Left Upper Arm Angle (X w.r.t. horizontal)	100°	10°	
V	Right Elbow flexion Angle	140°	5°	
W	Left Elbow flexion Angle Left	160°	10°	
HCx	x-Position of HC relative to AC	44 mm	15 mm	
HCz[7]	Height of HC relative to the ground level	1686 mm	0.8%	
M	Total mass (without shoes)	76.7 kg	+10% /-5%	

[5] Referring to 50% Position described in Untaroiu et al. (2009) (based on Perry (1992)).
[6] The tolerance for ACz was adjusted to be aligned with the updated corridors at t0 (938-960 mm)
[7] The tolerance HCz was adjusted to be aligned with the updated corridors at t0 (1673-1699 mm)

The angles should be measured using the reference axis as defined in APPENDIX A. A reference skeleton is available within the certification pack on the Euro NCAP website and should be used for qualitative comparison of the initial position of the AM50 model. A screenshot showing an overlay of the HBM and the reference skeleton should be added in the documentation of the HBM shared with Euro NCAP. The reference point AC should be aligned between the actual model and the reference skeleton. The initial posture of the other sizes of the pedestrian models should be in line with the AM50 model (in terms of orientation of the body parts). The reference measures for the other sizes of models are listed in Table 2.

Note: Results of a sensitivity study (Klug et al. 2017) indicate that the arm posture has remarkable influence on Head Impact Time. The best correlation between two models was achieved when models were positioned as close as possible. Therefore, the posture of the HBM should match the target posture as close as possible.

Table 2 Reference Posture of other pedestrian sizes.

Abbrev.	Unit	Reference	Tolerance	Reference	Reference	Tolerance
		6YO	6YO	AF05	AM95	AF05 & AM95
Px	mm	199	5.0%	243	340	5.0%
Py	mm	152	15.0%	164	265	15.0%
ACz	mm	613	1.3%	831	1043	2.0%
K	°	89°	3°	89°	89°	3°
L	°	106°	5°	106°	106°	5°
G	°	164°	3°	164°	164°	3°
H	°	175°	5°	175°	175°	5°
Ty	°	98°	3°	98°	98°	3°
Uy	°	70°	3°	70°	70°	3°
Tx	°	100°	10°	100°	100°	10°
Ux	°	100°	10°	100°	100°	10°
V	°	140°	5°	140°	140°	5°
W	°	160°	10°	160°	160°	10°
HCx	mm	6.5	15 mm	27	16	15 mm
HCz	mm	1100	1%	1468	1836	1.0%
M	kg	22.8	1.5%	46.9	102.6	+10% /-5%

The right side of the HBM is defined as the struck side. The z-direction is defined as the vertical axis, positive in inferior direction. The local HBM x-axis is the frontal axis, facing anterior. The angle of the shoes is not given as reference measure as the sensitivity study did not show a significant influence on the kinematics. Anyway, the initial posture should aim for a natural walking posture. The shoe sole angle can be varied to get as close as possible to the target height of AC. Both shoe soles should ideally contact the ground – if ACz can't be achieved with ground contact, a z-offset of the model is permitted.

None of the limbs, i.e. arms/legs shall be artificially connected, tied or constrained to each other (e.g. wrists tied)[8] The HBM should be exposed to a vertical acceleration field constituting the gravitational loading, both, in certification and assessment simulation.

Note: A sensitivity study showed a neglectable difference in terms of kinematics when pre-simulations were carried out until the ground contact force was equal to the HBM weight force. Therefore, pre-simulations are not obligatory, but allowed.

3.2.2 Impact simulations

The HBM must be impacted by all vehicles at three different impact velocities (30 kph, 40 kph and 50 kph). The simulation time must be higher than the expected Head Impact Time. The HBM should be positioned as close to the vehicle as possible (check initial penetrations especially for SUV).

A segment-based contact should be defined between the vehicle and the outer surface of the HBM. The static and dynamic coefficient of friction between the car and the HBM[9] should be set to 0.3.

The Head COG of the HBM must be positioned in line with the vehicle centreline (y=0 in the global coordinate system).

The mass scaling and timestep settings should be chosen such that they can be also used for the assessment simulations. The process for deriving the timestep is shown in Figure 1.

[8] Most of the PMHS tests were conducted with tied wrists to gain better reproducibility. But in real world crashes, the arms will be unconstrained, which is why it was chosen to prescribe a more realistic arm position.

[9] A sensitivity study (Klug et al. (2017)) showed that the coefficient of friction between HBM and car has a remarkable effect on trajectories and Head Impact Time and was therefore set to 0.3 which is accordance with several studies (e.g. Crocetta et al. (2015), Mizuno and Ishikawa (2001); Simms and Wood (2006)).

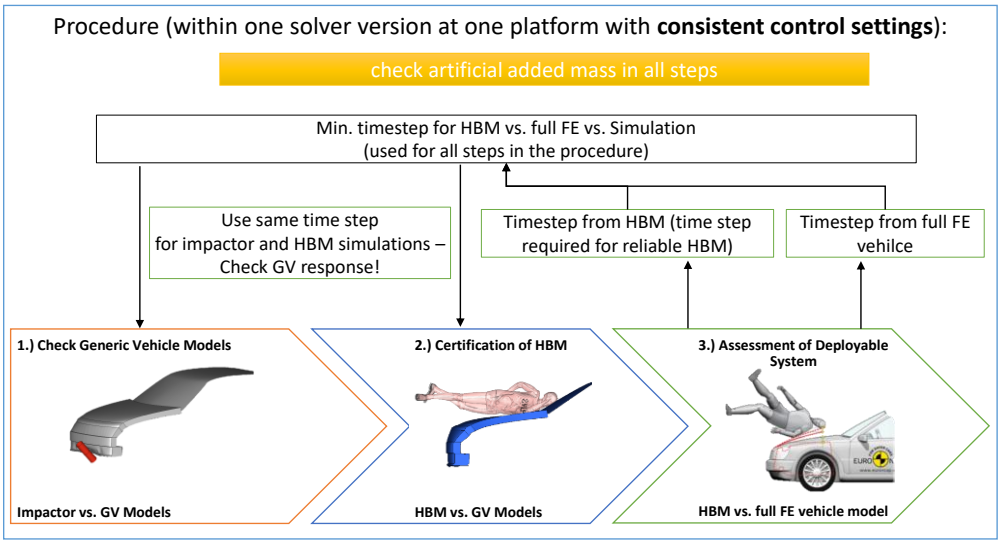


Figure 1: Process for defining timestep settings

Note: The activation of fracture mode led to marginal changes of the monitored results. Therefore, it is open to the user to use HBMs with or without element elimination, as long as they show consistent results and no numerical instabilities. However, the same settings have to be applied for all steps. If fracture mode is activated, it should be checked if fracture locations are plausible.

3.2.3 Post-processing

The following outputs are required:

- x and z coordinate history of tracking points in the global coordinate system.
- x displacement of vehicle COG in the global coordinate system.
- Resultant and z acceleration of HC.
- Contact forces (total contact force between vehicle and HBM and contact force per interface layer and body part as specified in the template).
- Hourglass, contact and internal energies.
- Animations.

The time interval between the outputs has to be 0.1 ms for all outputs except animations where 1 ms is sufficient. No filtering needs to be applied. The output curves should be included in the postprocessing template for the respective vehicle categories. Figure 2 shows the functionality of the postprocessing template.

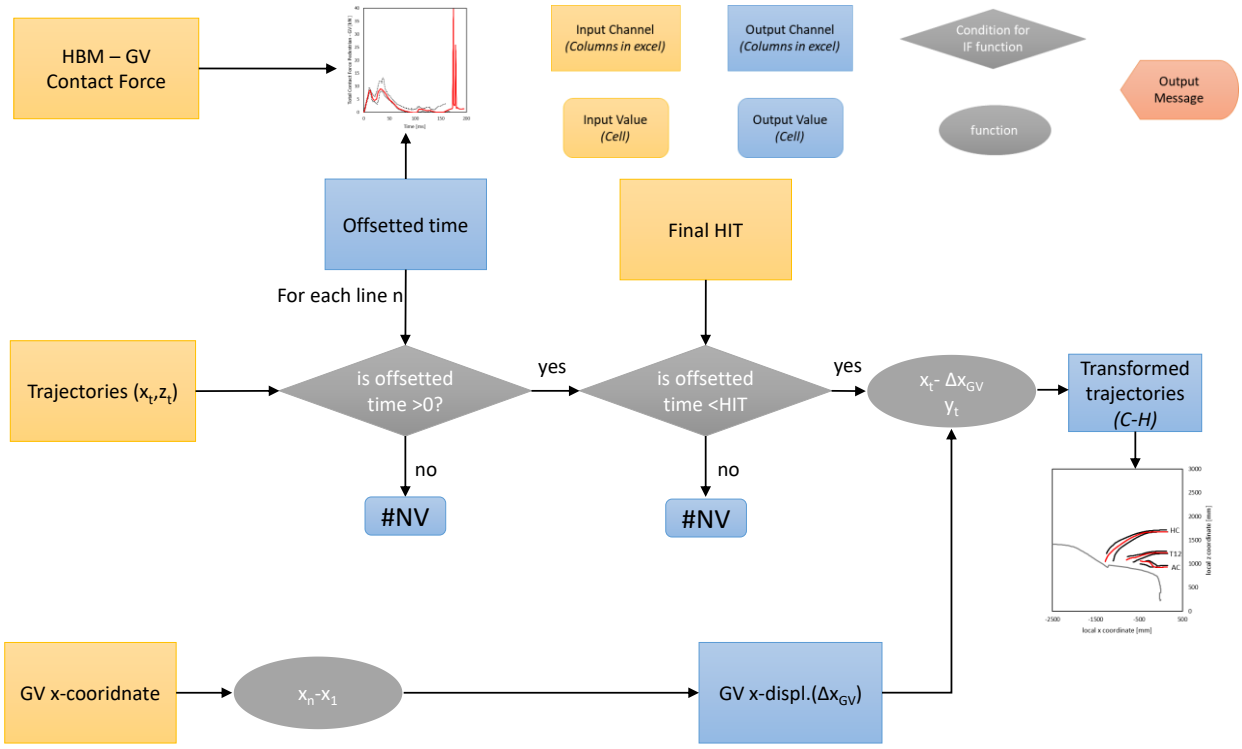


Figure 2: Flowchart of postprocessing template

3.2.4 Quality checks

All checks and quality criteria[10] defined within the postprocessing template must be met:

- FE surfaces getting in contact do not cross each other.
- Surfaces getting in contact do not get trapped one in the other (no sticky nodes).
- Contact force (between HBM and vehicle) is zero at simulation start.
- Total energy (HBM + vehicle) remains constant within a 15% tolerance.
- Total hourglass energy (HBM + vehicle) ≤ 10% of the total energy.
- Contact energy at the simulation start ≤ 1% of the total energy.
- Artificial energy (contact energy and hourglass energy) ≤ 15% of the total energy.
- Artificial mass increase ≤ 3%.

The hourglass energy and added mass of the HBM is specifically checked for monitoring only. Thresholds will be defined for the next version of this procedure.

3.2.5 Calculation of Head Impact Time

The Head Impact Time (***HIT***) is defined as the time from the first increase of the bumper contact force (***C***) until the first increase of the contact force between head and generic vehicle (***H***) like shown in Figure 3. Figure 4 describes the process of deriving ***HIT***.

[10] Quality criteria were chosen based on the recommendations from the IMVITER project (FP7- 2007 SST – 218688 - D4.3).

H is defined as the time where the contact force starts to increase (first time where contact force is not zero anymore) and automatically derived in the provided template. If this is not clearly identifiable, the resultant and z acceleration of the head COG should be used additionally. If the upper extremities are stuck between the head and the vehicle and avoid that the head is contacting the vehicle, the contact between head and upper extremities should be disabled to enable a clear determination of H. The respective simulations have to be rerun with the disabled contact. For the determination of ***C,*** a first contact between upper extremities and bumper should be ignored.

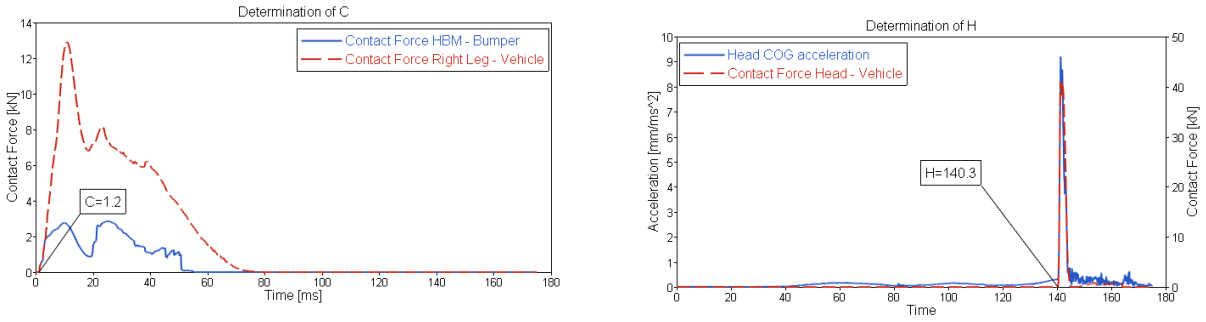


Figure 3: Example for calculation of HIT=H-C

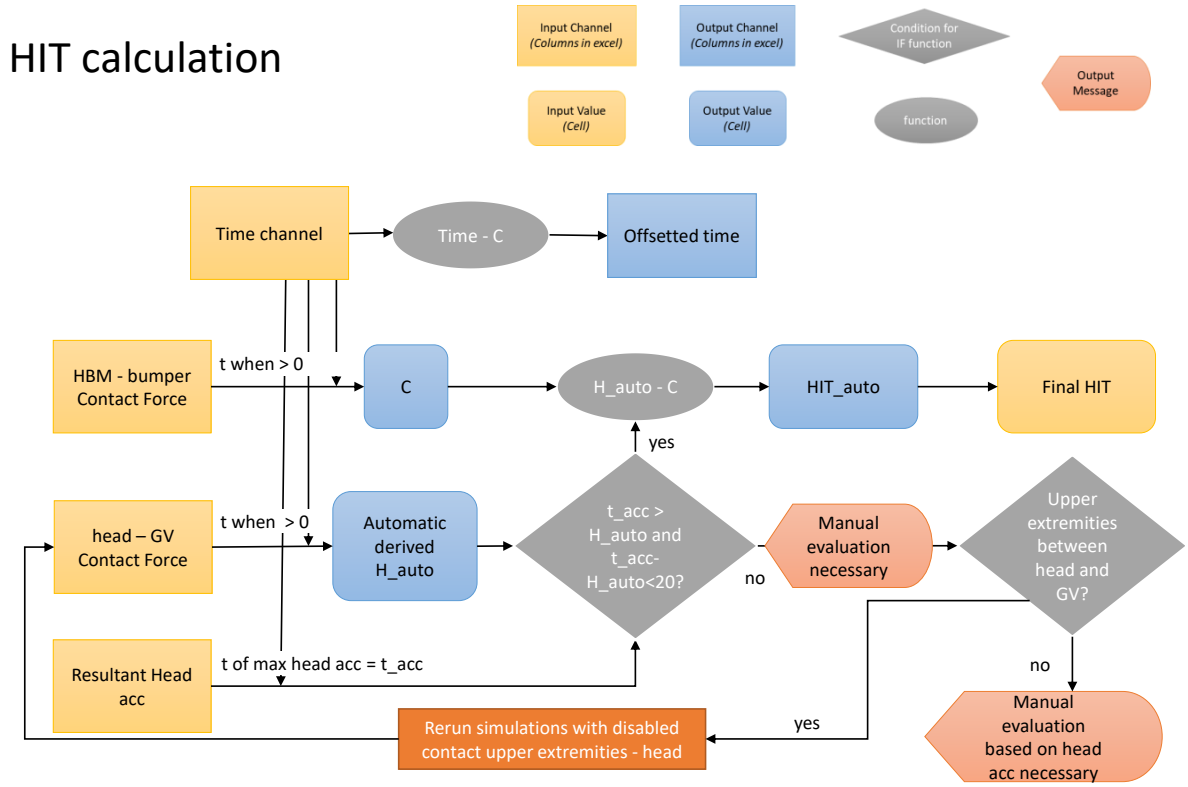


Figure 4: Flowchart describing determination of HIT

3.2.6 Calculation of trajectories

Trajectories of HC, T12 and AC should be provided and compared with the corridors. Node histories are trimmed from ***C*** to ***H*** automatically in the postprocessing template. The x displacement of the vehicle COG is subtracted from the x coordinate of every tracking point to get the transformed x coordinate. The z coordinate is plotted over the transformed x coordinate.

3.2.7 Evaluation of contact forces

The total contact force between vehicle and HBM should be compared with the provided corridors. Furthermore, all contact forces specified in the postprocessing templates have to be provided. The time of the contact curves must be offset with ***C*** *(Note: explained within section 3.2.5)* so that they start at the first increase of bumper contact force. This is done automatically within the excel template. A first contact between vehicle and upper extremities of the HBM is disregarded. Therefore, the contact forces between bumper and lower extremities and torso are requested in the template. Contact forces are monitored only.

3.3 Corridors for AM50 pedestrian size

Trajectories should be compared with the proposed corridors for all nine simulations (FCR, RDS and SUV). Contact forces will be monitored only. The difference to the reference HIT and the derived HIT has to be within the defined reference values[11].

The corridors for HC, T12 and AC, which should be met are shown in the following figures[12]. In the templates the contact force is also compared to the reference simulations for monitoring. The procedure with which the corridors were derived is described in Klug et al. (2019). Results were updated based on the latest results based on latest model versions in 2021.

[11] Reference values are based on the mean value +/- 2 standard deviations from the 13 reference simulations selected within the CoHerent Phase 4 project.
[12] The corridors represent the mean value +/- 2 standard deviations from the 13 reference simulations

3.3.1 Corridors for family car

Figures 5a-c show the corridors for the impact with the generic Family car model at 30, 40 and 50 kph respectively.

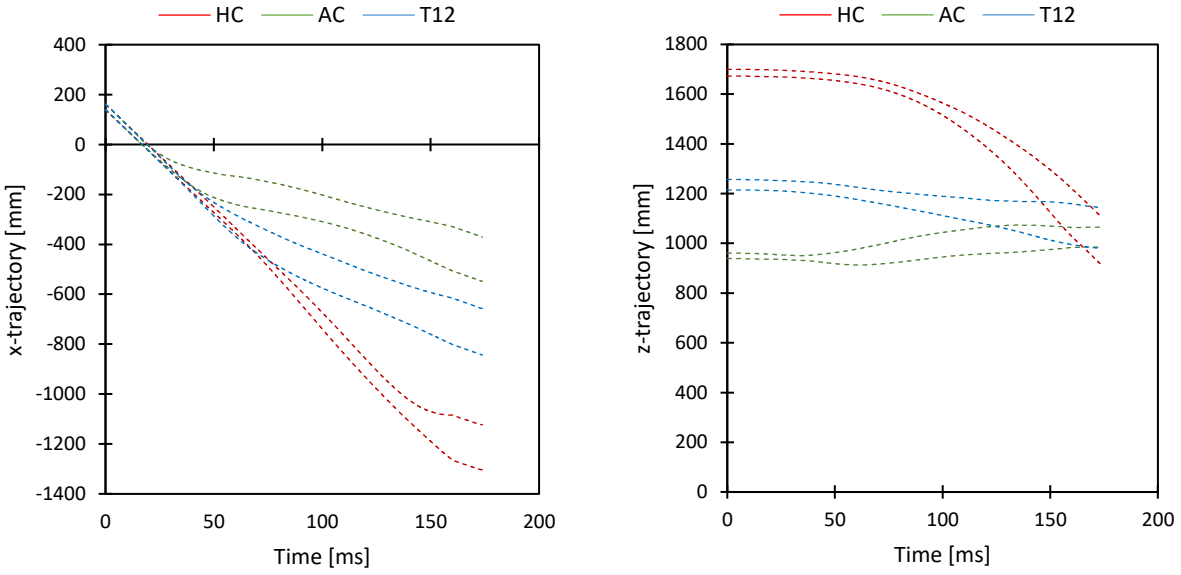


Figure 5a: FCR, 30 kph– Reference HIT = 152-197 ms

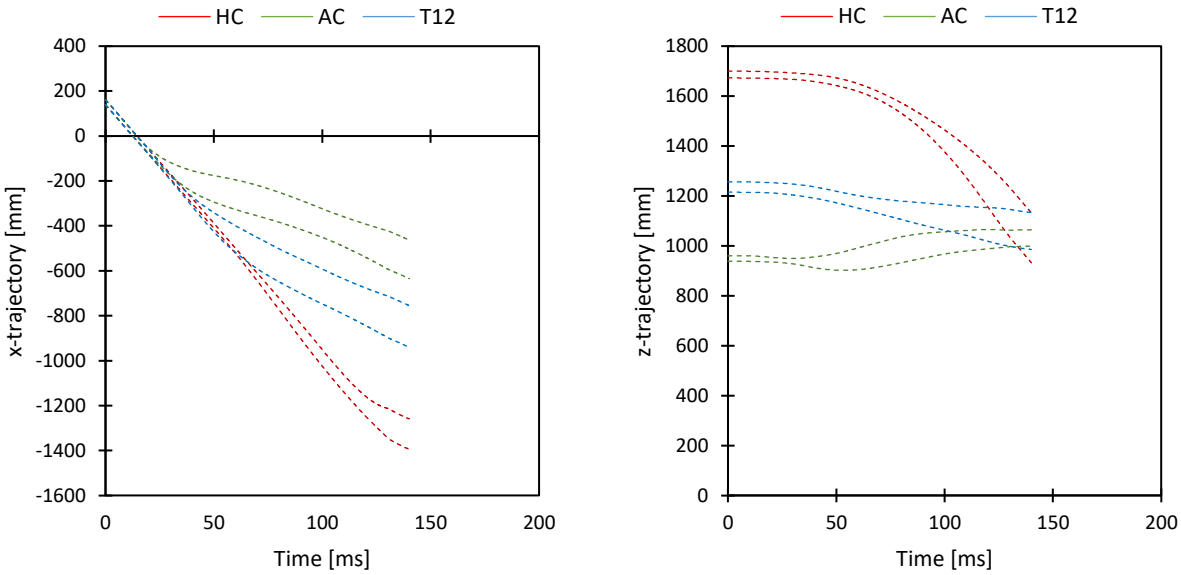


Figure 5b: FCR, 40 kph – Reference HIT = 127-150 ms

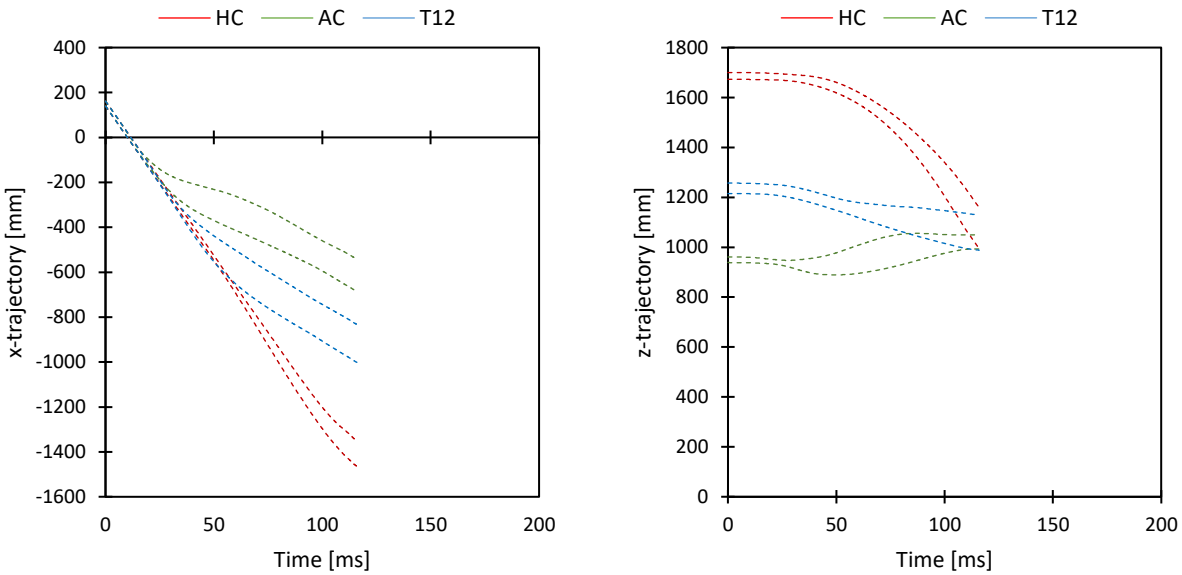


Figure 5c: FCR, 50 kph – Reference HIT= 107-121 ms

3.3.2 Corridors for roadster

Figures 6a-c show the corridors for the impact with the generic roadster model at 30, 40 and 50 kph respectively.

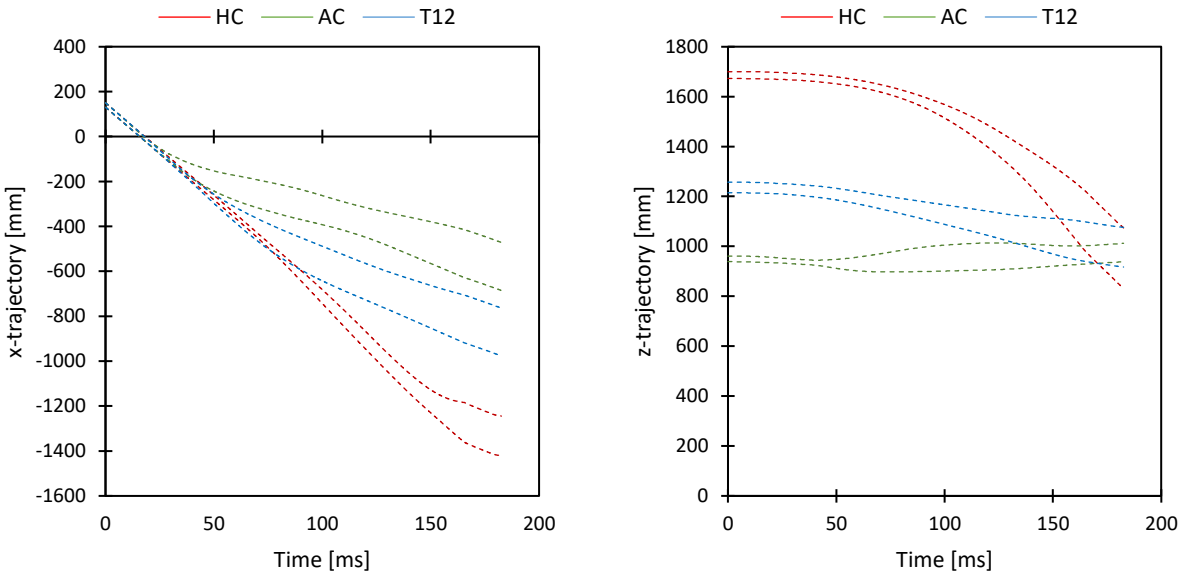


Figure 6a: RDS, 30 kph – Reference HIT = 163-199 ms

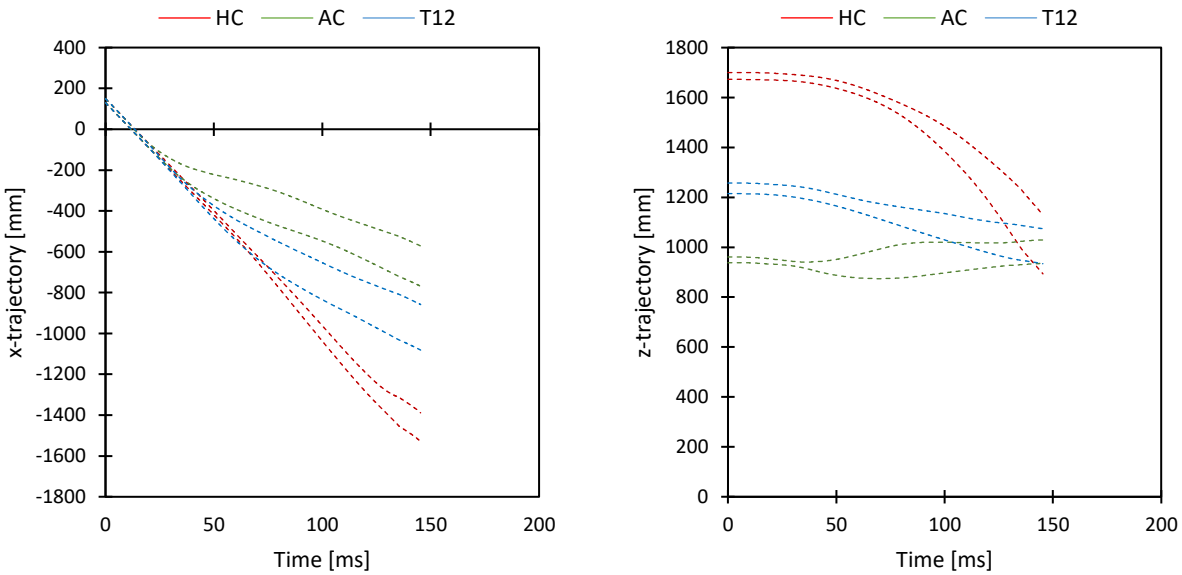


Figure 6b: RDS, 40 kph – Reference HIT =133-156 ms

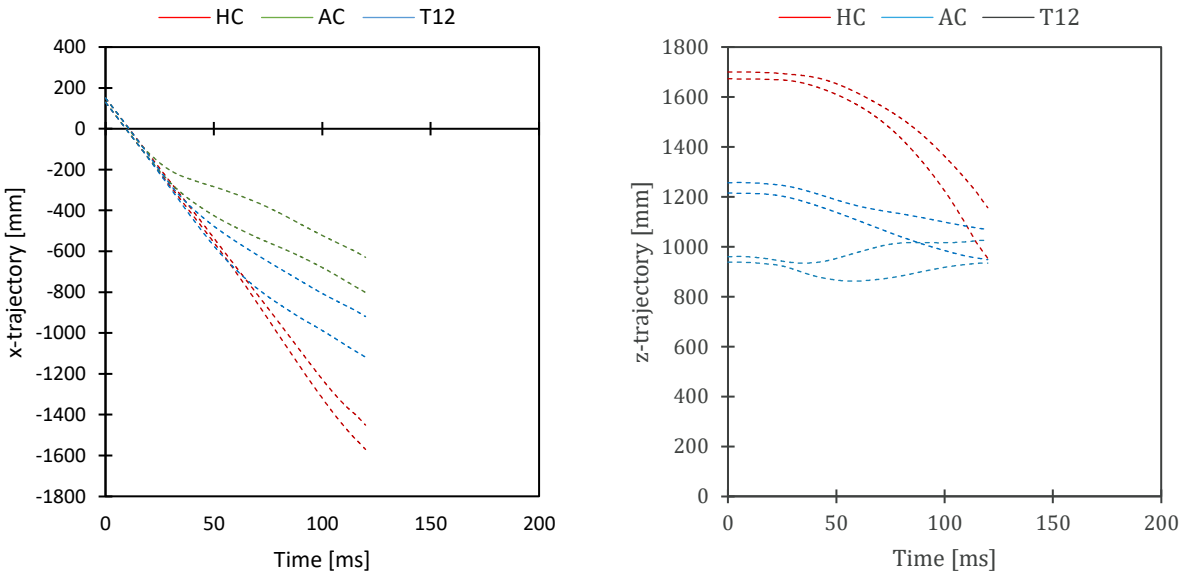


Figure 6c: RDS, 50 kph – Reference HIT =112-127 ms

3.3.3 Corridors for SUV

Figures 7a-c show the corridors for the generic SUV model at 30, 40 and 50 kph respectively.

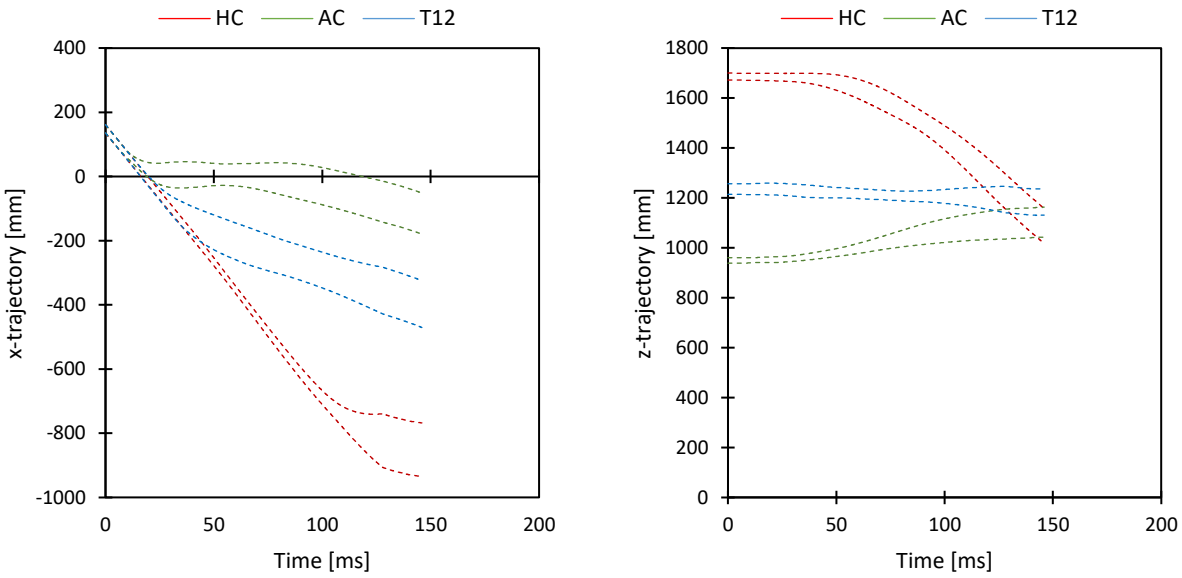


Figure 7a: SUV, 30 kph – Reference HIT = 127-144 ms

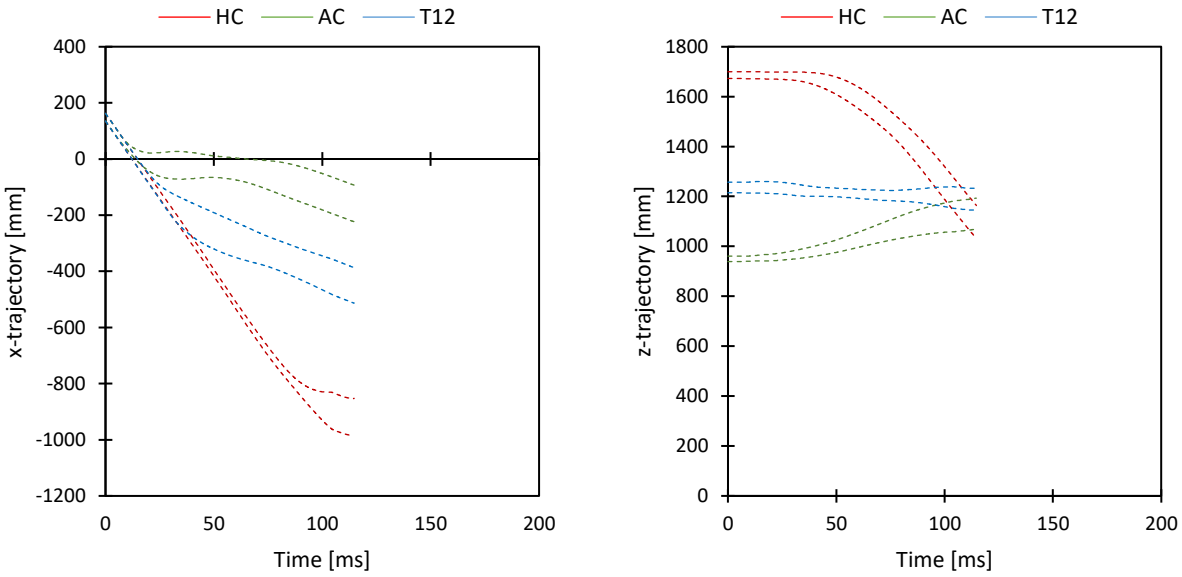


Figure 7b: SUV, 40 kph – Reference HIT = 101-116 ms

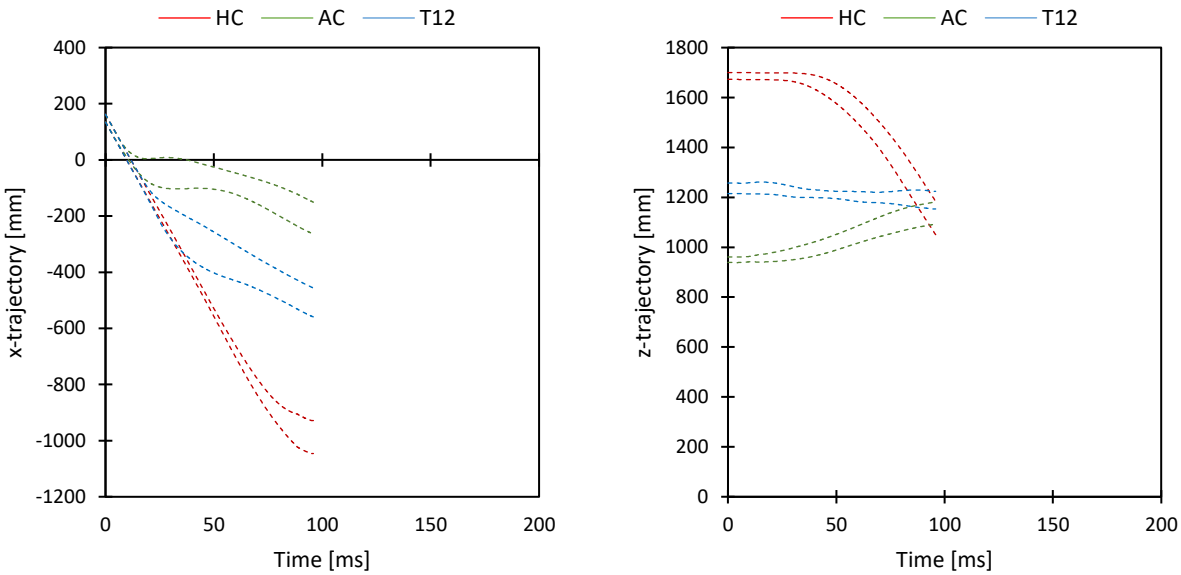


Figure 7c: SUV, 50 kph – Reference HIT = 86-99 ms

3.4 Corridors for 6YO pedestrian size

Trajectories should be compared with the proposed corridors for all nine simulations using the FCR, SUV and RDS GV models at all three impact speeds. Contact forces will be monitored only. The difference to the reference HIT and the derived HIT has to be within the interval given as reference (±2 standard deviations to the mean value which was derived from results submitted within phase 5 of the CoHerent project).

The graphs show the corridors for HC, T12 and AC, which should be met.

3.4.1 Corridors for family car

Figures 8a-c show the corridors for the generic FCR model at 30, 40 and 50 kph respectively.

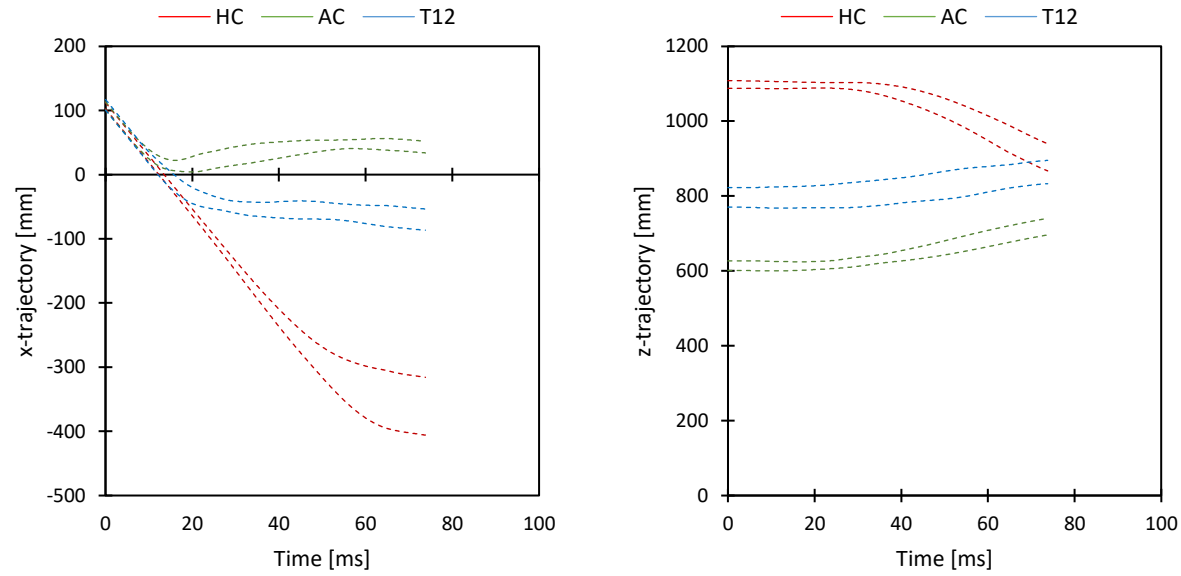


Figure 8a: Family car, 30 kph– Reference HIT = 60-78 ms

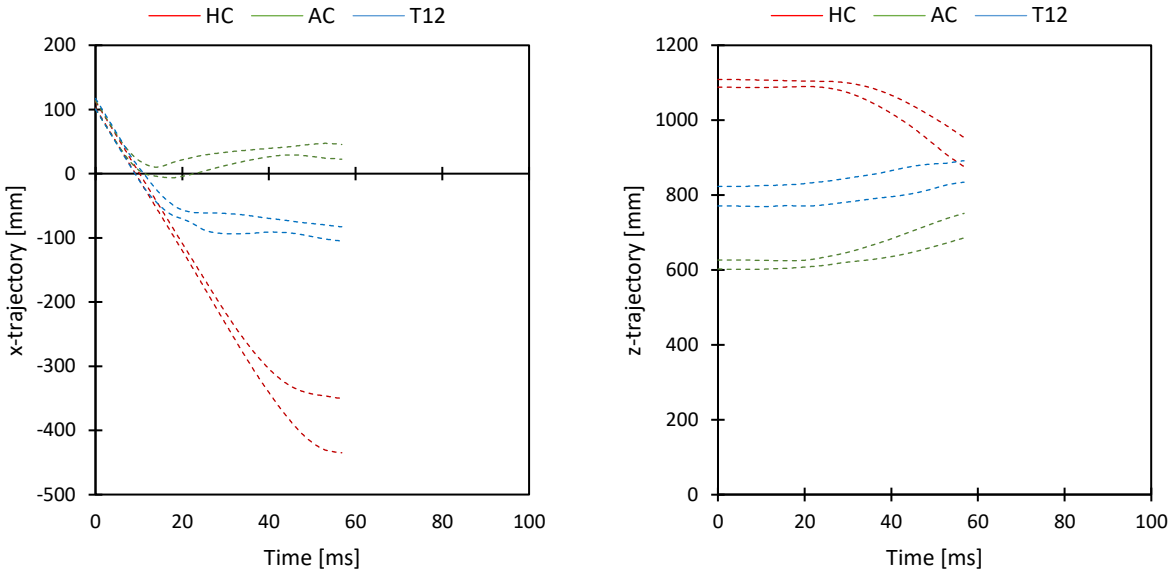


Figure 8b: Family car, 40 kph – Reference HIT = 49-60 ms

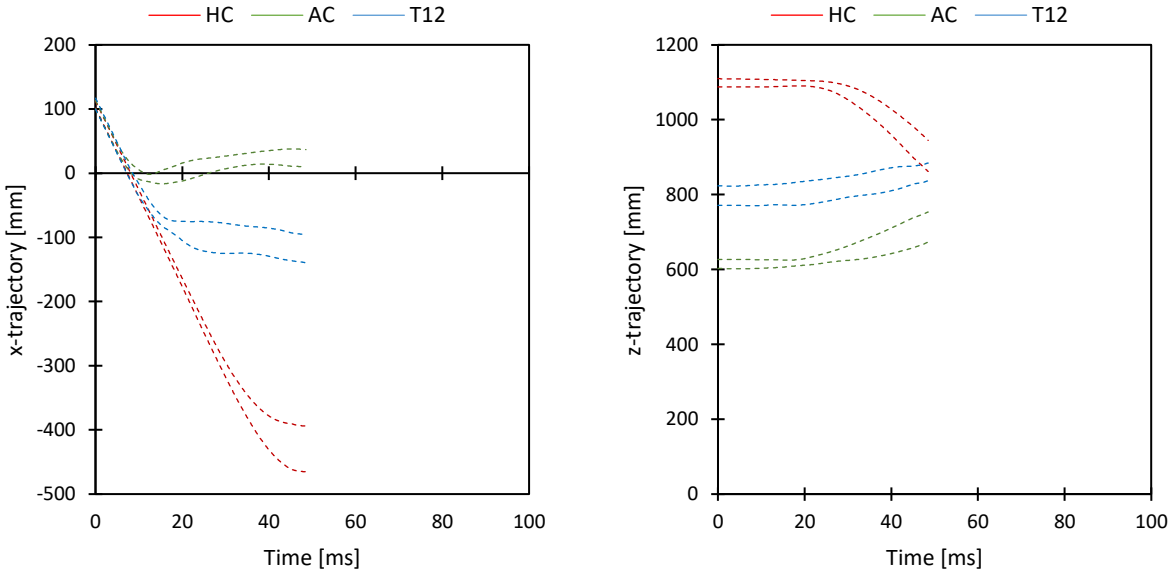


Figure 8c: Family car, 50 kph – Reference HIT= 43-49 ms

3.4.2 Corridors for roadster

Figures 9a-c show the corridors for the generic RDS model at 30, 40 and 50 kph respectively.

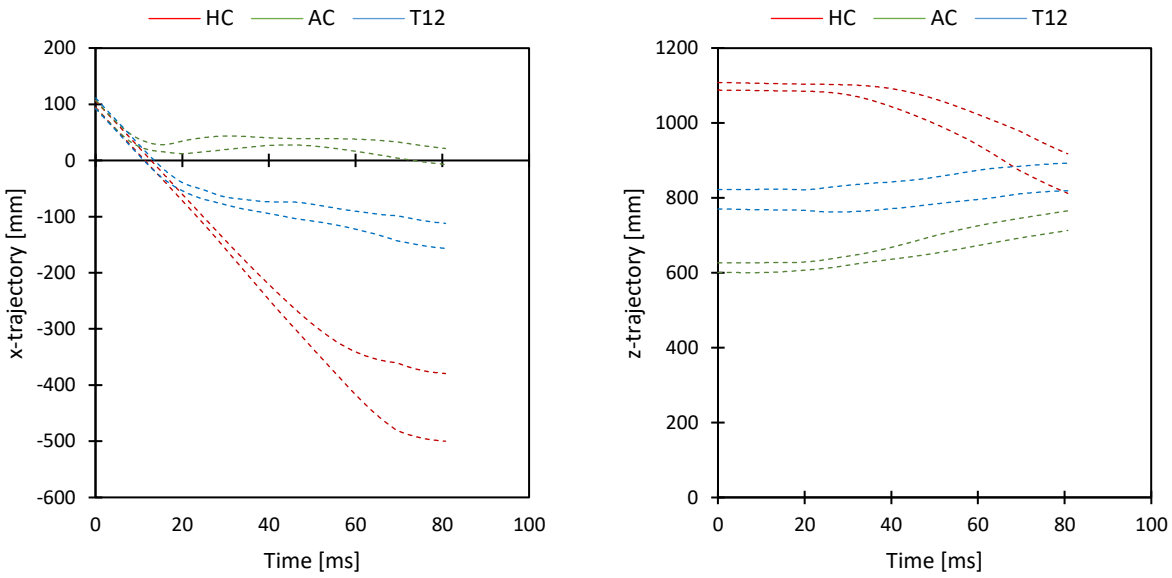


Figure 9a: RDS, 30 kph– Reference HIT = 66-80 ms

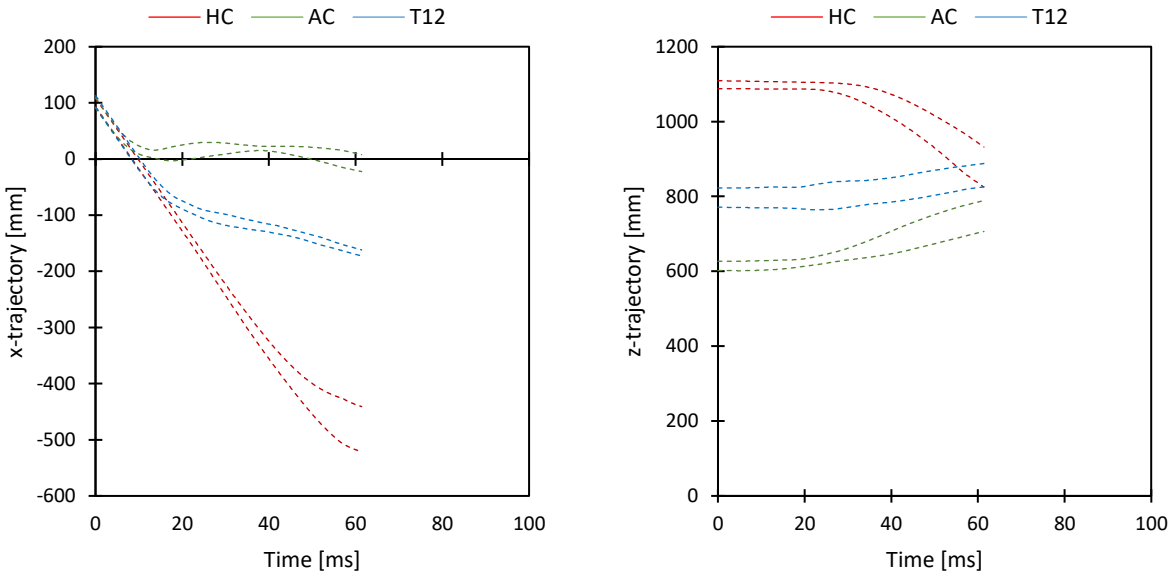


Figure 9b: RDS, 40 kph – Reference HIT = 53-61 ms

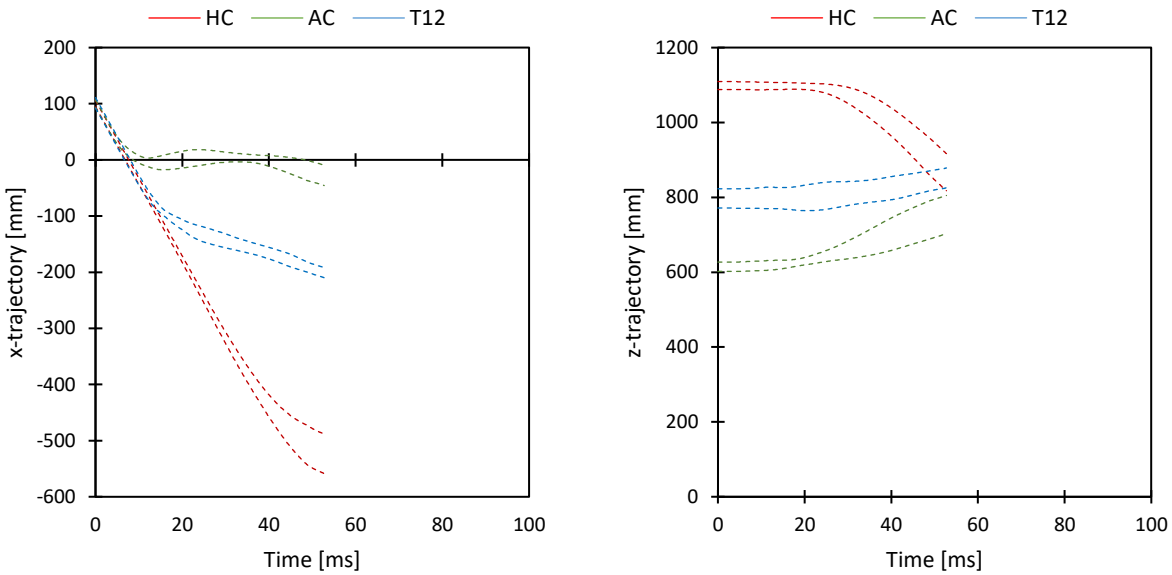


Figure 9c: RDS, 50 kph – Reference HIT= 45-52 ms

3.4.3 Corridors for SUV

Figures 10a-c show the corridors for the generic SUV model at 30, 40 and 50 kph respectively.

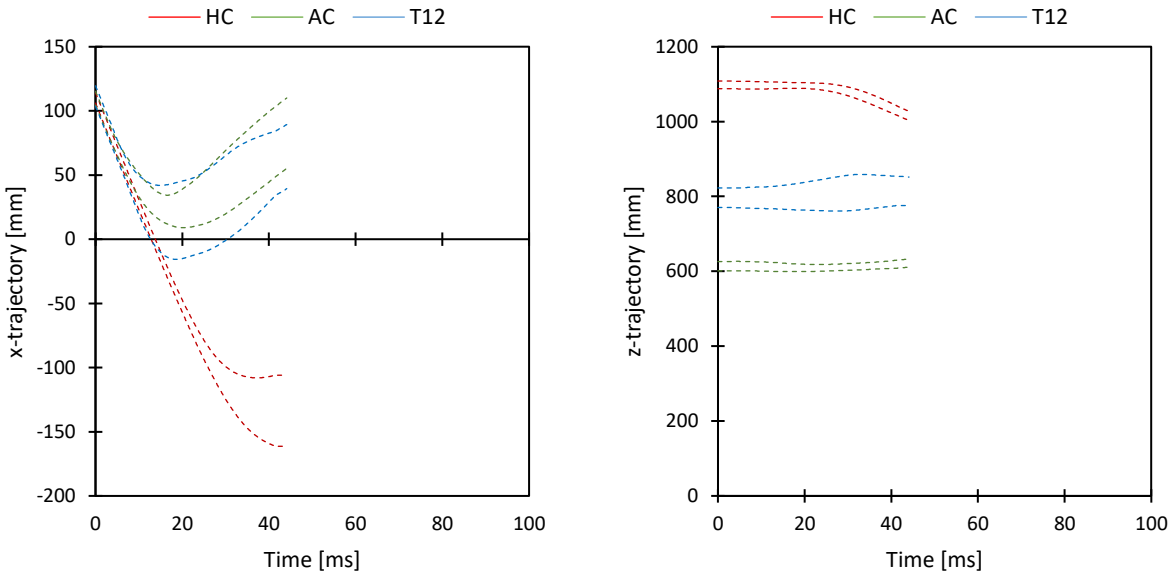


Figure 10a: SUV, 30 kph– Reference HIT = 35-50 ms

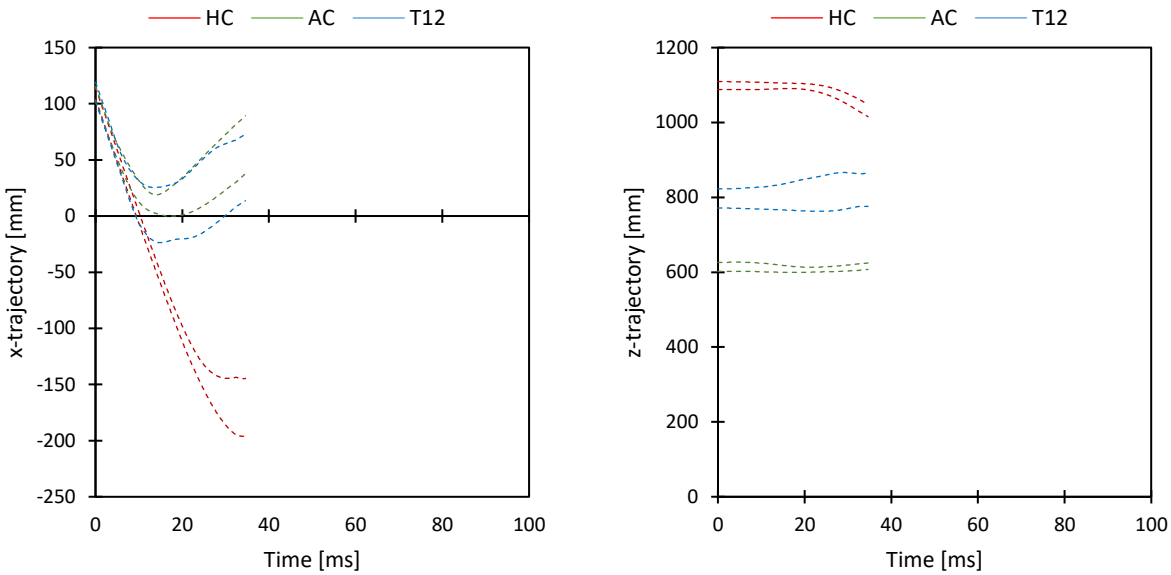


Figure 10b: SUV, 40 kph – Reference HIT = 28-38 ms

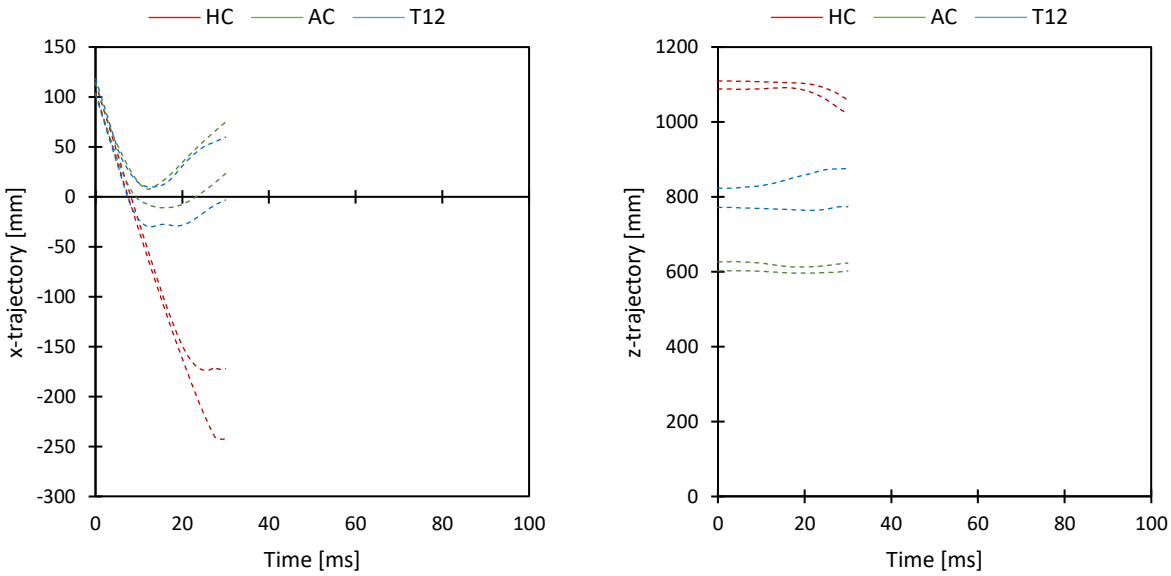


Figure 10c: SUV, 50 kph – Reference HIT= 19-34 ms

3.5 Corridors for AF05 pedestrian size

Figures 11a-c show the corridors for the generic SUV model at 30, 40 and 50 kph respectively for the AF05 models.

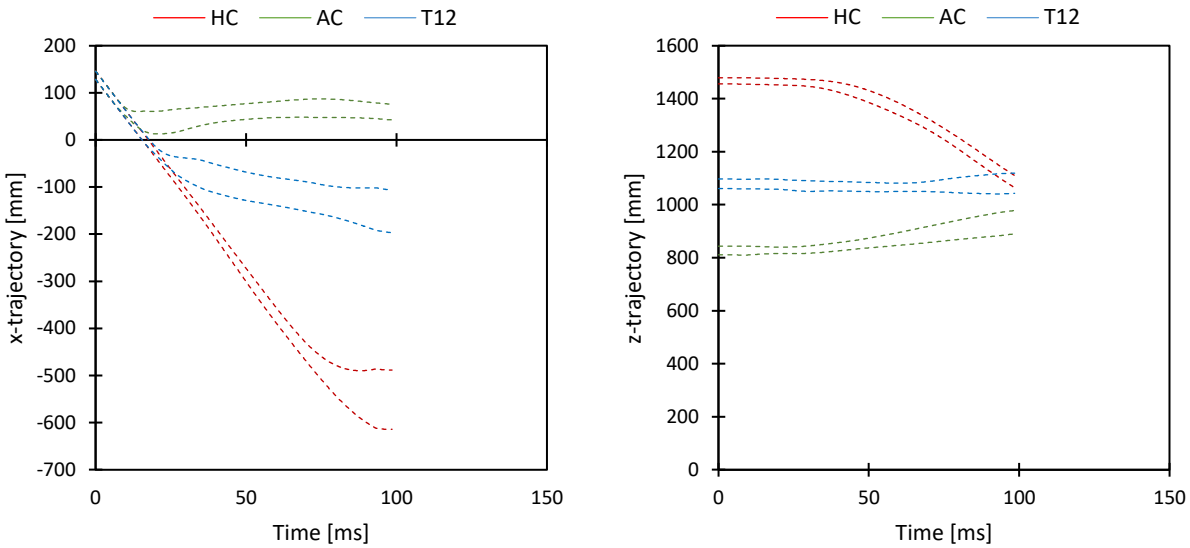


Figure 11a: SUV, 30 kph– Reference HIT = 90-102 ms

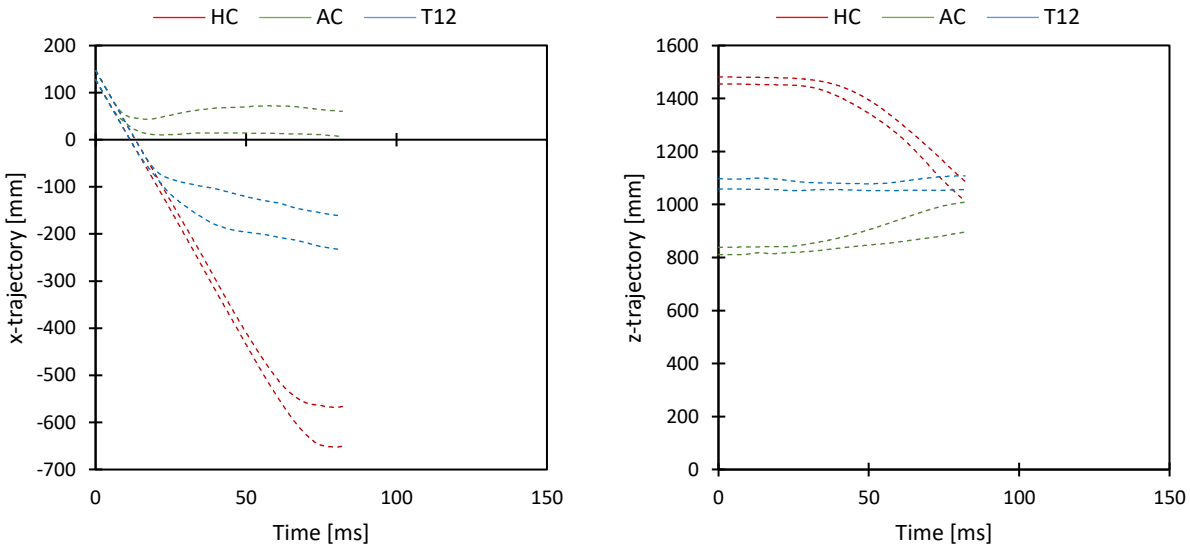


Figure 11b: SUV, 40 kph – Reference HIT = 69-82 ms

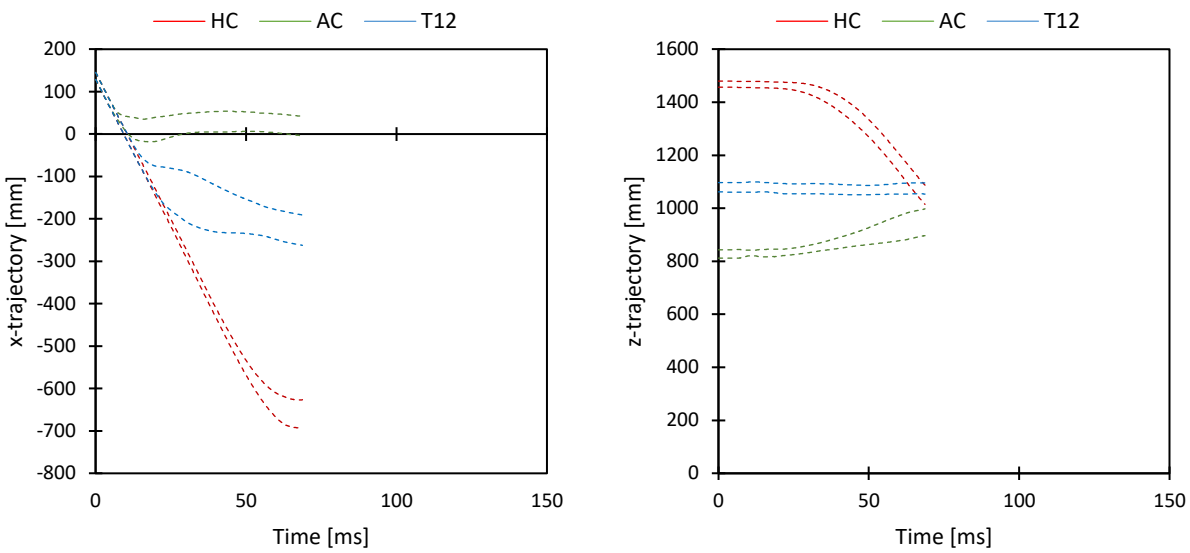


Figure 11c: SUV, 50 kph – Reference HIT= 59-70 ms

3.6 Requirements for AM95 Pedestrian Size

For the AM95 model, no specific corridors have been developed and no certification simulations have to be performed. It qualifies automatically when the AM50 model passes the certification as long as it meets the required initial posture defined in Table 2 (on page 9) as well as the general requirements in Section 1.1.

3.7 Compliance of the Trajectories

Within the postprocessing template, the actual trajectories of HC, T12 and AC are compared every 0.1 ms with the minimum and maximum z and x values derived from the simulations with consistent models.

Note: As the major aim of the procedure is to make the location of the head and other body parts comparable at a specific time, it was decided to consider the timing for the trajectories instead of evaluating z as a function of x only.

The compliance check works automatically within the excel template and max. deviation of the location of the sensor of the actual model to the inner corridor as well as the total duration in which the trajectories of the model are outside the corridor per sensor location for the x and z coordinate respectively is shown.

The certified models should aim to stay inside the 2 standard deviation corridors for the whole impact duration from the reference line (leading to the judgement “OK” in the template). A maximum deviation of **one more standard deviation** to the corridor is tolerated (leading to the judgement “within tolerance” in the templates).

APPENDIX A REFERENCE SYSTEMS

Global Coordinate System

The global coordinate system is defined as shown in Figure A.2:

- X direction is the driving direction of the vehicle (longitudinal axis) and X=0 at the foremost point of the vehicle at t=0
- Y direction is the vehicle lateral axis with Y=0 at the vehicle centreline
- Z direction is parallel to the vehicle height axis facing upwards. Z=0 at the ground level

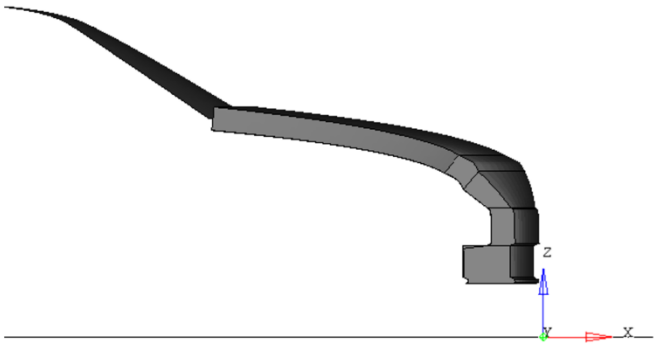


Figure A.2: Global Coordinate System

Note: All generic vehicle models are already positioned correctly – no transformation of the vehicle is needed

HBM Reference Axis

The HBM reference coordinate system is defined as: The local HBM x-axis is the sagittal axis, facing anterior. The y-axis is the defined as the frontal axis and the z-direction is defined as the vertical axis, facing in inferior direction.

The reference axis for the skeleton are based on the recommendations of the international society of biomechanics (ISB) using anatomic landmarks (Wu et al. 2002)[13]. All axis describing the initial posture with the corresponding landmarks are shown in Figure A.2 (small capital r stands for right and l for left side of the body)

For humanoid models the connection of the joint centres shall be used instead of the axis. After that they should be overlaid with at least one HBM in reference posture or the IP free skeleton to fine adjust the position until the outer surface of the models are as close as possible.

[13] Wu et al. (2005), Wu and Cavanagh (1995); Wu et al. (2002)

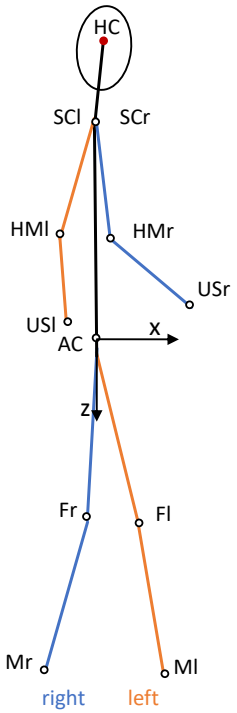


Figure A.2: HBM Reference Axis for angle definitions

- The **Upper Leg Angle** is defined as the angle around Y between the femur reference axis and the horizontal.
- The femur reference axis is defined as the connection between the centre of the nodes of the acetabulum and the midpoint (**F**) between Epicondylus femoralis medialis (FEM) and Epicondylus femoralis lateralis (FEL). If FEM and FEL are not clearly identifiable the approach shown in Figure A.3 can be used[14]:
    - The femur has to be positioned such that the lateral and medial epicondyle are overlaying as much as possible. A section cut normal to the view plan should be created. Create a circle from the contour of femoral condyle. The midpoint of the circle can be used as reference for FEM and FEL which should be placed with an offset normal to the view plane. Turn the femoral bone 90 degrees around and identify the most lateral and the most medial point in line with the centre of the circle created at the previous step.

[14] Based on Churchill et al. (1998)

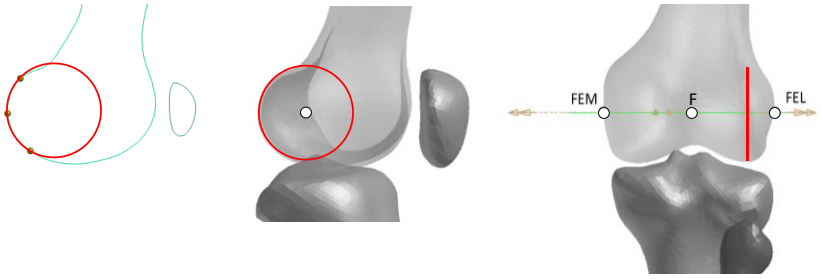


Figure A.3: Construction of FEL and FEM

- The **Knee Flexion Angle** should be measured between the femur reference axis and the connection between the midpoint of the femoral epicondyles and the inter-malleolar point (**M**) located midway between the tip of the medial malleolus (MM) and tip of the lateral malleolus (LM).

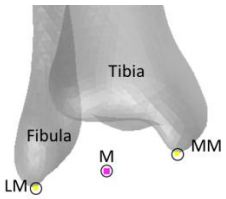


Figure A.4: The right inter-malleolar point (MR) located midway between MM and LM

- The **Upper Arm Angle** is defined as angle around the Y axis between the horizontal plane and the humerus reference axis. **The humerus reference** axis is defined as the connection between the midpoint (**SC**) of AA (the most laterodorsal point of the Angulus Acromialis) and PC (the most ventral point of processus coracoideus) and the midpoint (**HM**) of EL (the most caudal-lateral point on lateral epicondyle) and EM (the most caudal-medial point on medial epicondyle).

- The **Elbow Flexion Angle** is defined as angle between the humerus reference axis and the connection between the midpoint of EM and EL and the most caudal-medial point on the ulnar styloid (**US**).

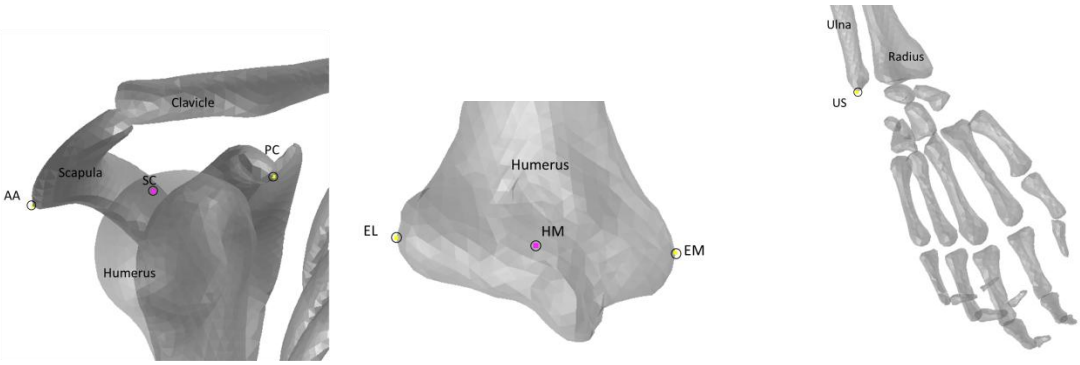


Figure A.5: Anatomic Landmarks of upper extremities

- The **Heel to Heel** distance is defined as the distance between the centre of all nodes of the right and the left calcaneus. If this can’t be determined the distance between the most posterior node of the left heel to the most posterior node of the right heel of the shoe sole.

APPENDIX B HUMAN BODY MODEL OUTPUT

Sensors must be located at several locations – some are for monitoring purposes only:

Centre of gravity of the head (hereafter called **HC**) (all parts of skull, scalp, face, brain, intracranial space, scalp) connected to all nodes of inner cranium (at least 100 nodes)

- Centre of all nodes of vertebral body of C1 (hereafter called **C1**); connected to all nodes of C1 (Figure B.1) for monitoring only

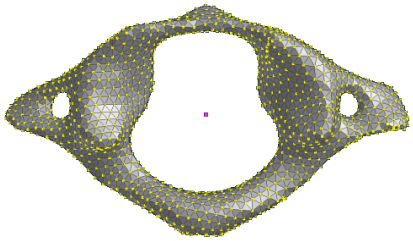


Figure B.1: Centre of C1

For the analysis of the kinematics of the spine, the centre of the vertebral bodies is used like shown in Figure B.2.

- Centre of all nodes of vertebral body C7 (hereafter called **C7**); connected to all nodes of vertebral body of C7 – for monitoring only
- Centre of all nodes of vertebral body of T8 (hereafter called **T8**), connected to all nodes of vertebral body of T8 – for monitoring only
- Centre of all nodes of vertebral body of T12 (hereafter called **T12**), connected to all nodes of vertebral body of T12

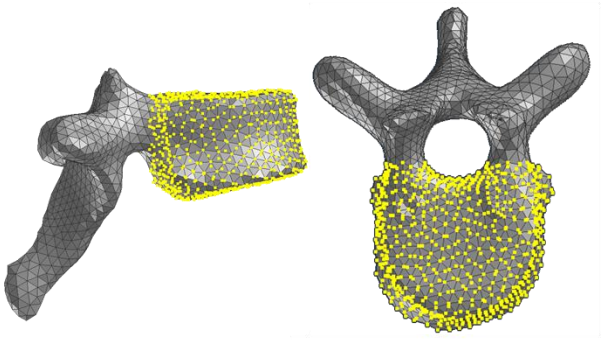


Figure B.2: Definition of Vertebral Body

- Instead of the H-Point which comes from physical crash test dummies, the centre of the right and left acetabulum centres (hereafter called **AC**) is used: Determine at first the centre of all nodes within the concave surface: select the sharp edge where the bone changes curvature as boundary and select all nodes inside like shown in Figure B.3. This has to be done at the left and the right side of the Acetabulum. The midpoint of the left and right acetabulum centre is AC and should be connected to all nodes of the right and left acetabulum.

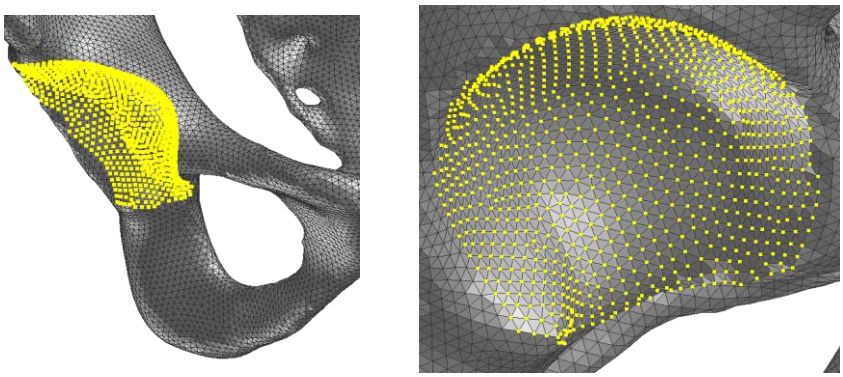


Figure B.3: Definition of Acetabulum Centre

- Midpoint of lateral and medial femoral epicondyle (for monitoring purposes) for right (hereafter called **Fr**) and left femoral epicondyle (hereafter called **Fl**) – It should be connected to its surrounding nodes (all nodes of the elements around FEM and FEL on the femur) – for monitoring only
- Inter-malleolar point right (hereafter called **Mr**) and left (hereafter called **Ml**) - It should be connected to its surrounding nodes (all nodes of the elements around MM and LM of the tibia and fibula like shown in Figure A.2) – for monitoring only

For Humanoid Models at least AC, HC and C7 have to be identifiable. The other nodes can be positioned with respect to these nodes according to Table B.1.

The sensors must be defined such, that outputs are returned in the global coordinate system, with the x-direction parallel to the vehicle longitudinal axis in driving direction and the z-direction parallel to the vehicle height axis facing upwards. The sensor shall be connected to the bony structure (cortical and trabecular bone) to the nodes which were used for the definition of the centre. The node output shall be achieved through an interpolation constrained.[15] With these interpolation constraints, the motion of a single slave (dependent or reference) node depends on the motion of a set of master (independent) nodes. For all codes it is advisable that only the translational components of the master nodes (e.g. IDOF=123) are used to calculate the motion of the slave nodes (e.g. DDOF=123456)[16]. All master nodes shall be assigned the same weighting factor (mostly the default anyways). Automatic adjustments of weighting factors (e.g. in Radioss) shall be disabled. It is recommended that the slave (dependent or reference) node is not used in any other constrained definitions (e.g. a nodal rigid body). The user is advised to make sure, that the dependent node is massless and no external forces act on the dependent node.

[15] Rational: An interpolation constrained already provides a pre-filtering of output signals and prevents excessive noise. It makes data post-processing straightforward and almost obsolete. By contrast to a nodal rigid body, the interpolation constraint does not rigidify the master nodes, to which the slave node (sensor node) is attached (Approach described in Golman et al. (2015).)

[16] Unless the master nodes are all collinear or the master set consists of two nodes only, which seems both very unlikely in the present application

Table B.1 Reference position of sensors

Long Name	Abbreviation	Reference Position (with respect to global CSYS)		
		x	y	z
Head Centre of Gravity	HC	170	0	1679
Centre of all nodes of vertebral body of C1	C1	170	33	1618
Centre of all nodes of vertebral body C7	C7	170	38	1508
Centre of all nodes of vertebral body of T8	T8	170	78	1340
Centre of all nodes of vertebral body of T12	T12	170	78	1234
Centre of the right and left Acetabulum centres	AC	170	44	944
Midpoint of lateral and medial femoral epicondyle	Fr	84	66	500
	Fl	254	-57	511
Inter-malleolar point right and left	Mr	75	187	100
	Ml	259	-131	101

Table B.2 Slave node interpolation Keywords

Code	Keyword	Recommended Parameters
LS-DYNA	*CONSTRAINED_INTERPOLATE	DDOF=123456, CIDD=0, ITYP=1, IDOF=123, TWGHTi=RWHGTi=0
VPS	OTMCO_/	DOFCOD=111000, IMETH=0, IELM=1, ITYP=0, RADIUS=0, WTFAC=1
RADIOSS	/RBE3	I_MODIF=2 or 3, WTi=1, TRAROT_REFi=111111, TRAROT_Mi=111000

APPENDIX C CORRIDORS FOR GVM

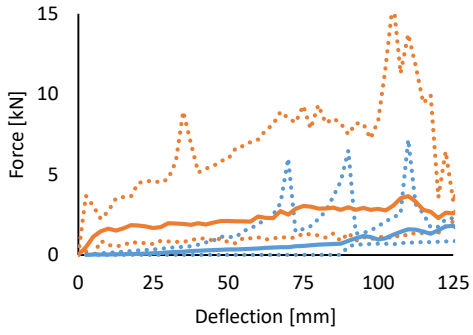
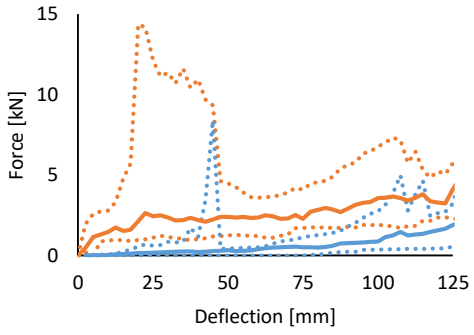
Impactor response corridors

The structural impact response upon impact is aimed to lie within pre-defined corridors. These corridors, shown in Table C.3 were established by propelling a close-to-rigid cylindrical impactor against selected full-FE numerical models[17]. The impactors were propelled against eight locations on the spoiler, bumper, bonnet lead and bonnet once at the vehicle centreline and once at the y location of the bumper corner width (definition according to Euro NCAP pedestrian protocol v8.2: "The Corner of Bumper is the point of contact of the vehicle with a vertical plane which makes an angle of 60° with the vertical longitudinal plane of the car and is tangential to the outer surface of the bumper").

In total 11 vehicle models from 5 different car manufacturers were used for deriving the stiffness corridors[18]. As there were only marginal differences of the median stiffness's for differing vehicle categories, they were summarised. So the corridors can be used for all vehicle categories. Nevertheless, it has to be considered, that roadsters showed less clearance at the bonnet impacts. Four vehicle models with pop up bonnets were impacted too. For the impact at the centreline, the median of the max. deflection was comparable to the other vehicle, but for the impact in y-offset direction, a significant higher value for the median of the maximum deflection was observed.

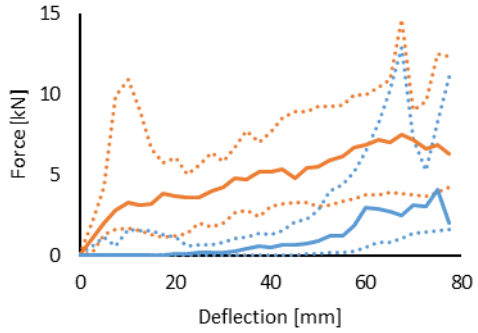
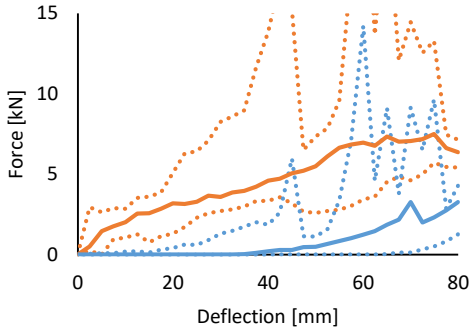
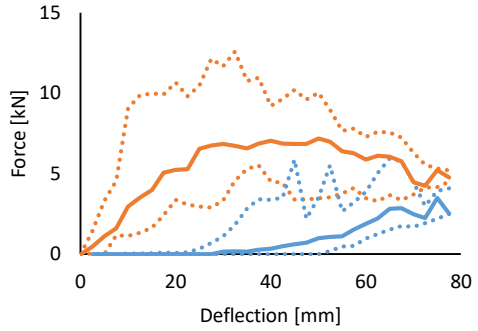
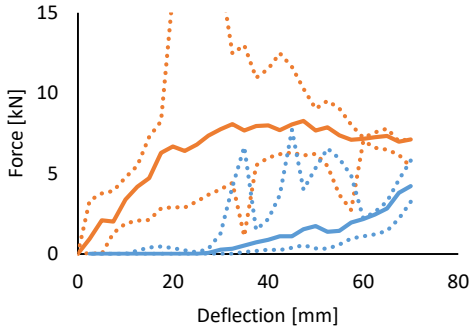
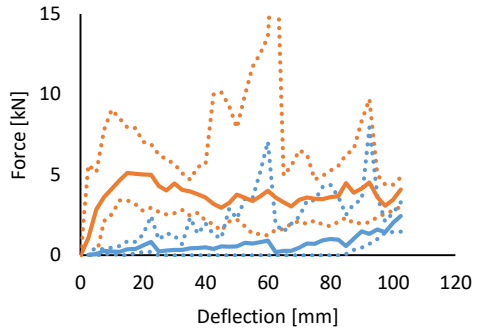
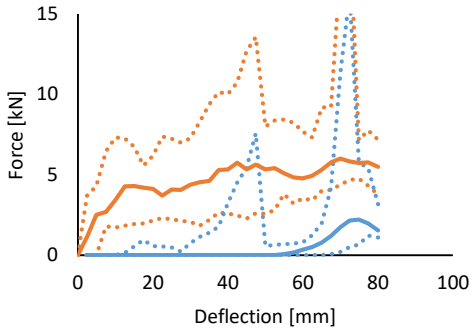
Table C.3:

Stiffness Corridors derived from Simulations with full FE vehicle models

Centreline	At Bumper Corner Width
Median Loading, Median Unloading	Min / Max Loading, Min / Max Unloading
	
Spoiler: Median of max. deflection: 117.5 mm	Spoiler: Median of max. deflection: 115.7 mm

[17] The full-FE models were either provided by OEMs to the Vehicle Safety Institute at Graz University of Technology or the OEM conducted the impactor simulations in-house, providing the results for analysis.

[18] (Klug et al., 2017)

Centreline Median Loading — Median Unloading	At Bumper Corner Width Min / Max Loading ····· Min / Max Unloading
	
Bumper: Median of max. deflection: 70.0 mm	Bumper: Median of max. deflection: 70.7 mm
	
BLE: Median of max. deflection: 68.7 mm	BLE: Median of max. deflection: 57.3 mm
	
Bonnet: Median of max. deflection (all): 91.8 mm Roadster only: 63.6 mm wo Roadster: 92.7 mm with active bonnet: 88.54 mm	Bonnet: Median of max. deflection (all): 75.8 mm Roadster only: 61.3 mm wo Roadster: 76.2 mm with active bonnet: 102.0 mm

Response of Generic Vehicle Models

When checking the result of the generic vehicle models with the provided simulation setup the force deflection curves should be close to the response of the corresponding reference GV model.

The comparison should be done within the provided template. The following tables show the response of the GV models R3 and the corridors used for the GV check.

Table C.4: Optimised stiffness of generic Family car model compared to stiffness corridors

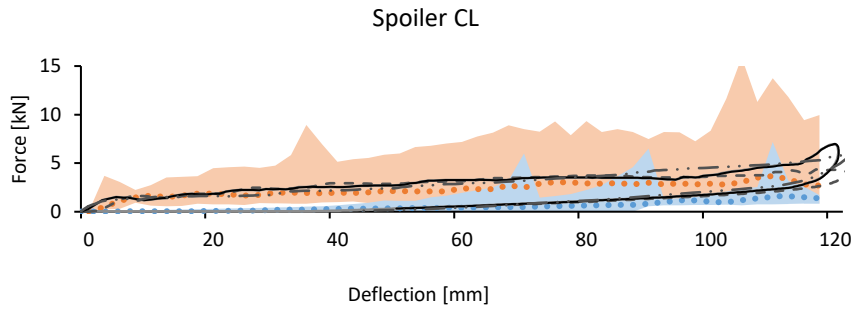
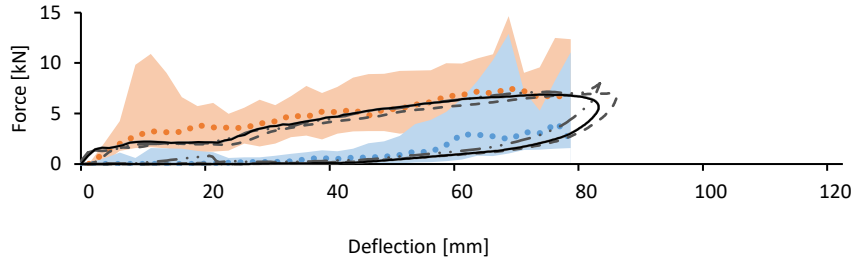
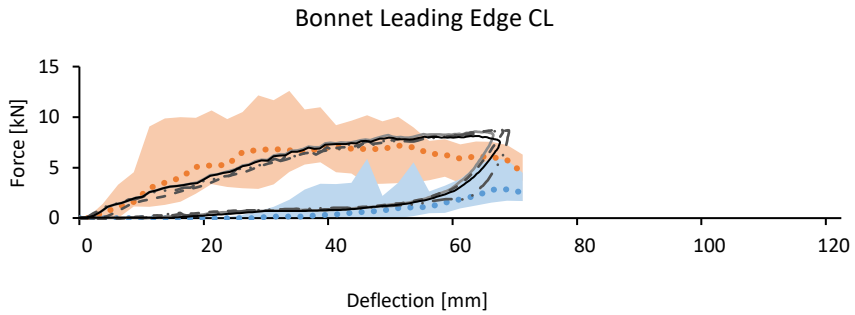
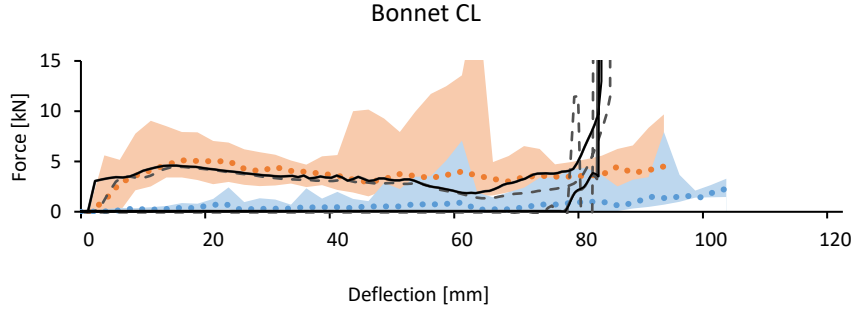
	Familiycar
	Corridor Loading, Corridor Unloading, Median Unloading, Median Loading, GV LS-DYNA
Spoiler	
Bumper	
Bonnet Leading Edge	
Bonnet	

Table C.3: Response of generic Roadster model compared to stiffness corridors

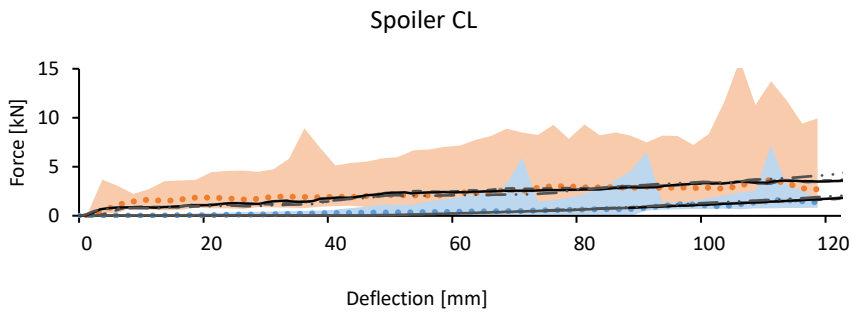
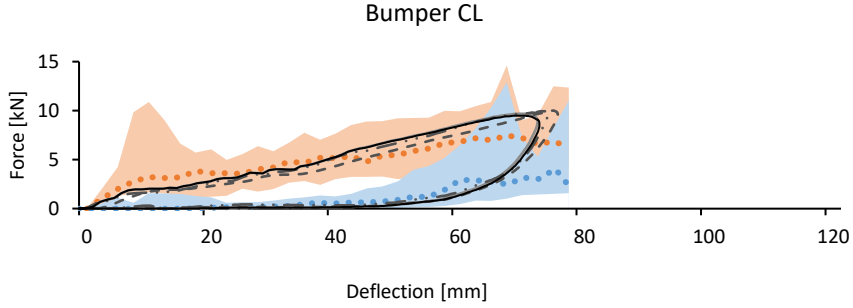
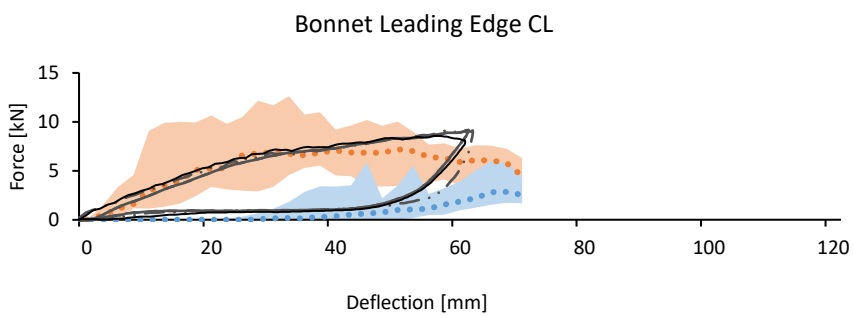
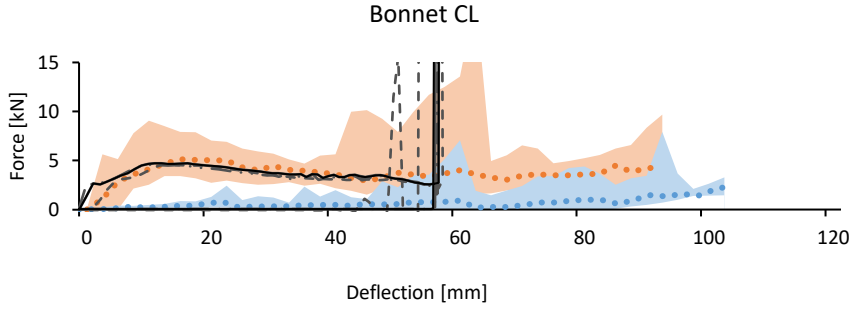
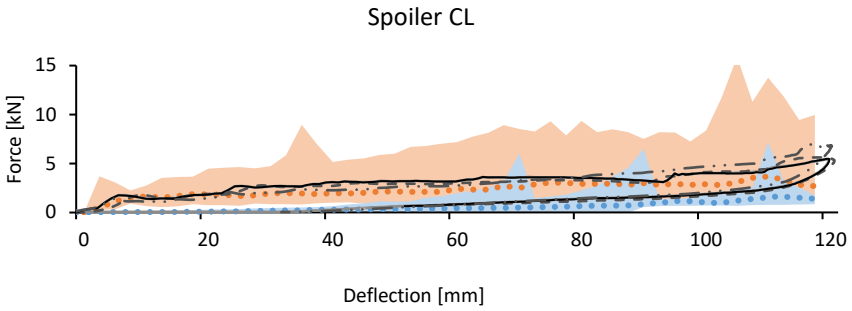
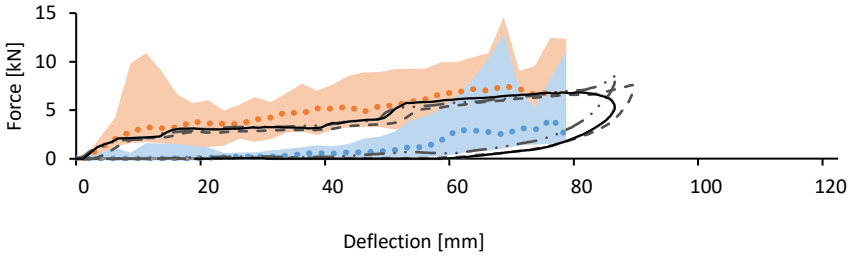
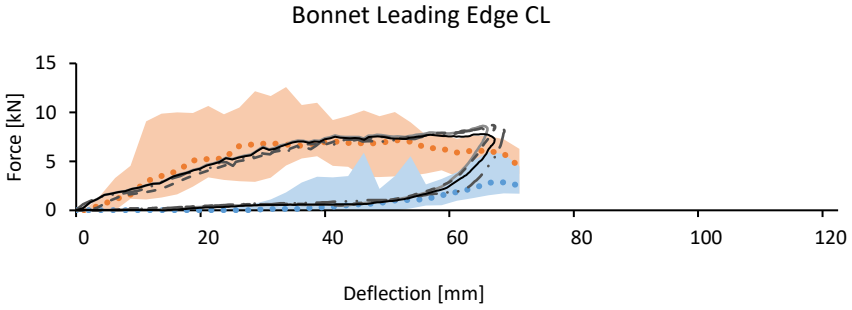
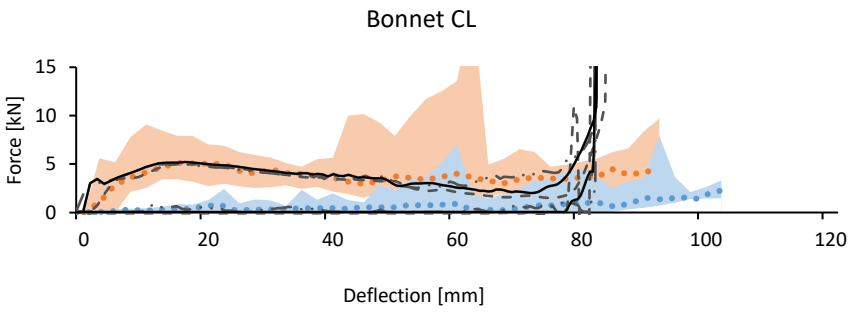
	Raodster
	Corridor Loading · Corridor Unloading · Median Unloading · Median Loading · GV LS-DYNA
Spoiler	
Bumper	
Bonnet Leading Edge	
Bonnet	

Table C.4: Response of generic SUV model compared to stiffness corridors

	SUV
	Corridor Loading · Corridor Unloading · Median Unloading · Median Loading · GV LS-DYNA
Spoiler	
Bumper	
Bonnet Leading Edge	
Bonnet	

APPENDIX D MODELLING OF GENERIC VEHICLE MODELS

In this Appendix, the modelling of the Generic Vehicle (GV) is described in larger detail. This is done for two reasons. First, the modelling approach shall be openly visible and understandable to the users. Second, the approach shall be implementable to other FE solvers than those considered in this protocol, e.g. if the vehicle OEM wishes to use another FE code not discussed here. The description refers to revision 1.0 of the generic vehicle models.

The generic vehicle shall:

- Provide a representative and up-to-date vehicle shape for selected vehicle categories.
- Provide a realistic structural response upon pedestrian impact in terms of force deflection characteristics
- Employ simple and clear modelling techniques, which are
    - Robust,
    - Repeatable,
    - Convertible, i.e. implementable to any FE code.
- Use consistent modelling techniques for all major explicit FE codes.

The original GV models were developed in LS-DYNA. They were translated by the code houses to the other FE codes (Altair Engineering France translated models to RADIOSS, 3DPLM Software Solutions Limited to ABAQUS and ESI group to VPS).

The generic vehicle is separated into the following areas (acronyms in brackets):

- Spoiler (spl)
- Bumper (bmp)
- Grill (grl)
- Bonnet Lead (ble)
- Bonnet (bnt)
- Rigid Structure (rst)

A consistent approach for all codes was pursued. It was assumed that the structural response under the loads of a pedestrian impact can be modelled through an outer shell surface, the interface layer, (for modelling the vehicles fascia) and a generic foam, the foam layer, resting on a rigid skeletal vehicle structure, the bottom layer. The compaction layer emulates hard structures and works as an end stop, as a contact with the interface layer is defined. The foam shall replicate a variety of unknown base structures, like for example rips, collapsible cones, buckling structures and foams, i.e. structures which absorb energy. Figure D.1 shows the layers which make up the Generic Vehicle Model.

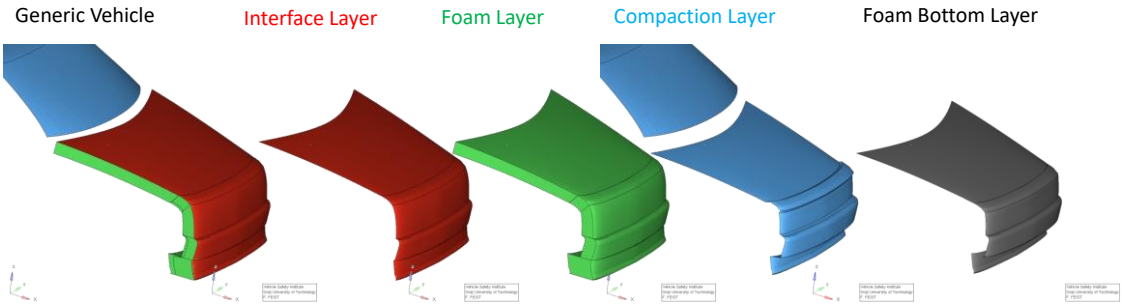


Figure D.1: Components of the Generic Vehicle Model

The foam layer features:

- Piecewise-linear behaviour (elasticity, yielding, compaction-initialisation, full-compaction);
- Definable energy absorption;
- Negligible expansion upon compression (i.e. a Poisson's ratio of 0);
- No strain rate dependency: It is assumed that interface layer's inertial effects are more important for the impact response behaviour than material induced strain-rate effects.

The parameters T1, T2, T3, E1, and E2 describe the structural behaviour of the foam layers (compare Table D.1). T4, the compaction stiffness is assumed to be 3 GPa (the young's modulus of polystyrene). Compaction strain is assumed to be 95%. The approach is summarised in Figure D.

The density of all parts except the bonnet is defines with the parameter RO. For the bonnet, the density of the foam had to be decreased to avoid too soft behaviour because of inertia effects and is defined with the parameter *RObnt*.

The outer surface of the foam is covered by an interface layer, which

- provides a realistic mass of the contact interface and thus inertial effects upon impact,
- structural mechanical characteristics (Young's modulus, Tangential modulus, yield stress).

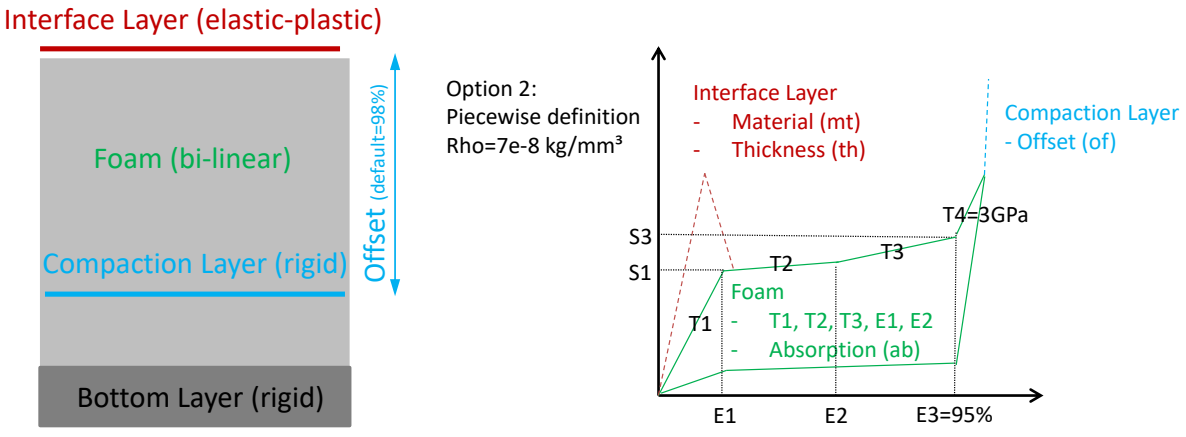


Figure D.2: Structural impact response model (SIRM)

To calibrate the structural impact response model (SIRM) the following parameters are assigned to each area (see Table D.1). The name of the parameter is formed by the contact area acronym and the parameter acronym, e.g. splth is the thickness of the interface layer at the spoiler.

Table D.1 Structural Impact Response Calibration Parameters

Layer	Abbrev.	Description
Interface	MT TH	Material type (integer) (selection of predefined materials: Null, Steel, Plastic) Thickness of Layer (real)
Foam	T1 T2 T3 S1 S2 AB	Primary Stiffness (real) Secondary Stiffness (real) Tertiary Stiffness (real) (Yield) Strain at transition between primary and secondary stiffness (real) Transition Stiffness between yield and compaction stiffness (real) Energy Absorption (real)
Compa-ction	OF[19]	Offset between interface and compaction layer (can be thought as thickness of foam layer) (real)

To summarise, the impact response is governed by eight parameters per contact area. The windshield and all vehicle parts lying behind the windshield are assumed rigid, as these parts play no role for the head impact kinematics. The first three letters of every parameter refer to the contact area (e.g. bmpTH = thickness of bumper interface layer).

Geometry

Vehicle geometries were parameterised based on outer shapes provided by car manufactures or pictures with vehicle dimensions (pictures were scaled according to vehicle length and height). The whole vehicle front is described with 120 parameters. The vehicle midsection consists of 10 Bézier curves shown in Figure D.3. Start- and endpoint and corresponding slope of the tangents are defined for every curve (Figure D.4).

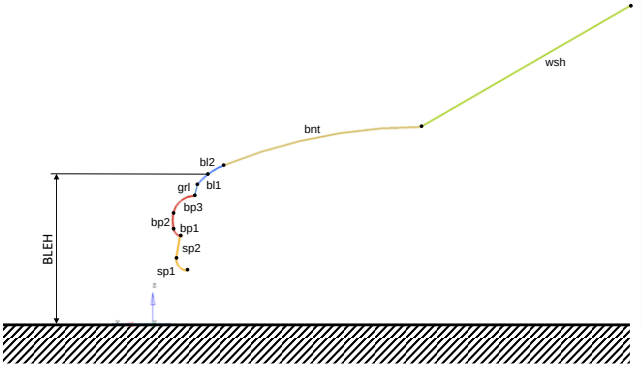


Figure D.3: Bézier curves defining the vehicle midsection

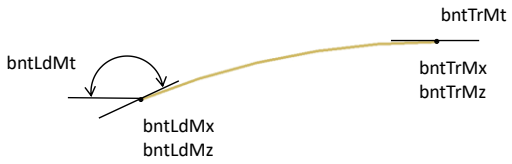


Figure D.4 Definition of single curve

Median Values of the parameters describing the vehicle geometry were derived and median geometry was created based on median geometric parameters.

[19] It is important to understand that the true thickness of the foam and thus the stiffness of the foam is not affected by the parameter 'OF'. The motivation to do so is to keep SIRM calibration parameters decoupled (else the foam stiffness would be a function of thickness and density).

Note: Difference in height between provided pictures and 3D geometry models of vehicles in Euro NCAP position were observed (due to differing loading conditions). Therefore, vehicle geometries where only pictures were provided were offset in z direction. The mean z offset of vehicles where 3D models in Euro NCAP position and pictures were available was determined therefore (max. 32 mm).

Figure D.3 shows the midsection of the generated generic median vehicle geometries (red dashed line) compared to the discretised vehicle geometries from current European cars.

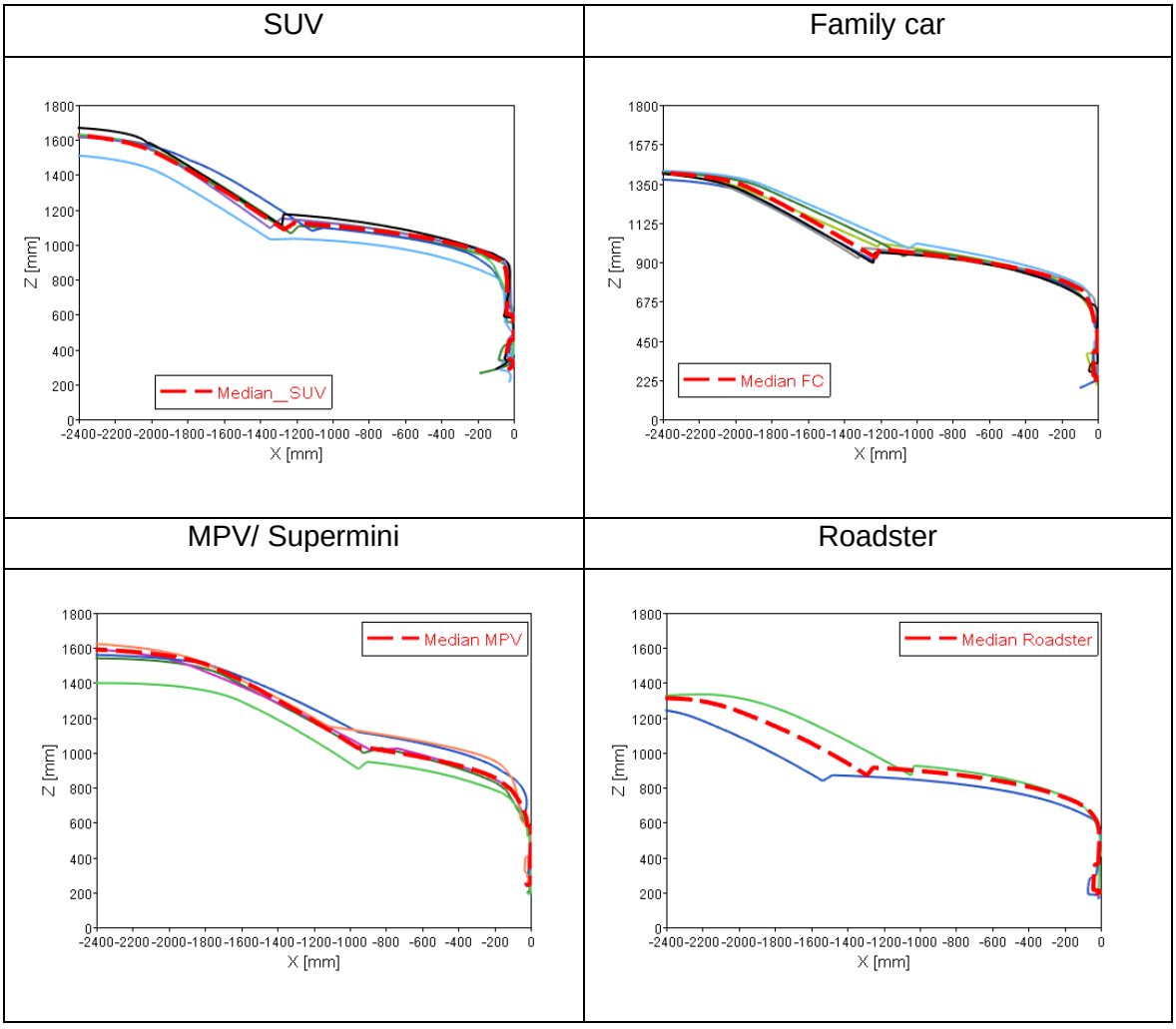


Figure D.3: Median Geometries for every vehicle category

Discretisation

The vehicle shape is discretised using 4 node shell and 8 node solid elements only. Average element size is 12mm. The following parts of the interface layer share nodes: Spoiler, Bumper, Grill and Bonnet Lead. At the transition between bonnet leading edge and bonnet, coincident nodes were not merged.

The coincident nodes at the edges of the various parts of the compaction layer are merged. This means that the compaction layer surface is continuous.

None of the foam layer nodes are merged (except for the nodes shared at the interface and bottom layer: E.g. the coincident nodes between the grill foam layer and the bonnet lead foam layer).

The 'Foam Bottom Layer' is assigned a rigid material. All rigid materials are merged with the vehicle COG rigid body using e.g. *CONSTRAINED_RIGID_BODIES in LS-Dyna, in such a way that the pre-defined mass (and inertia) is not altered (e.g. IFLAG=0 in LS-Dyna).

All foam layers have a thickness of 100 mm, except for the spoiler, which is 200 mm thick. The foam layer is created through extrusion: The spoiler and bumper nodes are extruded along the x-axis. The bonnet lead is created through extrusion along a vector enclosing 50 deg with the horizontal x-axis. The bonnets rearmost edge is extruded along the normal to the bonnets rearmost surface. The other foam elements are extruded such to fill up the gaps between bumper and bonnet lead, as well as bonnet lead and rearmost bonnet edge (see Figure D.4).

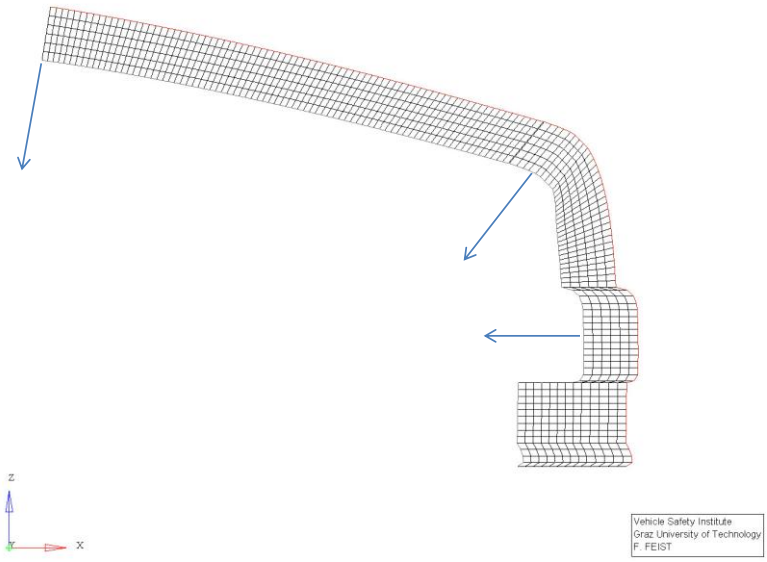


Figure D.4: Discretisation of foam layer: The three dragging vectors

Boundary Conditions

The vehicle is assigned the median mass as established for each vehicle category. The median mass consists of the median kerb weight of the vehicle and the additional mass of 150 kg for driver and front passenger as specified in the Euro NCAP pedestrian testing protocol. The

vehicle's moments of inertia remain unconsidered, though. The vehicle has only one degree of freedom, which is the x-direction in the vehicle coordinate system.[20]

Table D.2 Median Mass per Vehicle Category

Vehicle Category	Median Kerb Weight [kg]	Median Total Mass [kg]
SUV	1625	1775
Familycar	1540	1690
MPV	1440.5	1590.5
Roadster	1312.5	1462.5

ID-Ranges

The generic vehicle uses the ID ranges 1.000.000 to 9.900.999. The leading number is also indicating the sub-section of the generic vehicle (1…spoiler, 2…bumper, 3…grill, 4…bonnet lead, 5…bonnet, 9…remainder). ID range 9.900.000 to 9.900.999 is for items (e.g. materials, sets, hourglass models) which are used by multiple sub-sections (see pre-defined materials).

[20] The boundary conditions were selected to be consistent with experimental crash and PMHS tests. Complex consideration of the vehicle suspension system remains unconsidered for reasons of simplicity. Hence only one vehicle DoF is released.

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