Head Injury Risk Assessment in Pedestrian Impacts on Small Electric Vehicles using Coupled SUFEHM-THUMS Human Body Models Running in Different Crash Codes

Pronoy Ghosh, Christian Mayer, Caroline Deck, Nicolas Bourdet, Frank Meyer, Remy Willinger, Henry Bensler, Jens Weber

Abstract This research addresses the assessment of head injury risks in pedestrian impacts in different codes. The methodology discussed identifies some key building blocks necessary for virtual assessment. These key building blocks form the basis for assessing head injuries in event of pedestrian collision using a validated head model developed at the University of Strasbourg in LS-DYNA and VPS.

The collision scenario considered for the study is a 40 km/h, no braking mid-position configuration. The small electric vehicle and Human Body Models used in the study were validated separately in both codes. The human body models used is similar but *not completely identical*. The comparability between the two Human Body Models concerning full body kinematics and related values for the Head Impact Time and the forces are quite good with a difference of just 3 ms. The models also showed good comparability for skull fracture risk and diffuse axonal injury; however differences were observed for the prediction of subdural haematoma.

The simulation results indicated that the two Human Body Models and the Strasbourg University FE Head Model models under LS-DYNA and VPS deliver comparable results respectively, predict quite comparable injury risks and show almost similar full body kinematics and head impact time. This is the basis for developing a *harmonised* Human Body Model yielding reproducible and comparable results in multiple codes with a valid injury risk prediction.

Keywords brain injury, electric vehicle, harmonisation, human body model, pedestrian protection.

I. INTRODUCTION

The prognosis of future mobility on urban roads by 2025 shows a significant market share for L7e class electric vehicles [1]. These vehicles, which have a Gross Vehicle Weight (GVW) less than 600 kg, are expected to show distinctive design differences compared to traditional cars (e.g. minimal bonnets, vertical windscreens, outboard wheels). These new or alternative designs would pose varied challenges for pedestrian during a collision. Therefore a project funded by the European Commission within the 7th Framework- Programme, with the title "*Safe Small Electric Vehicles through Advanced Simulation Methodologies"* (SafeEV) was envisaged and aimed to define advanced test scenarios and evaluation criteria for pedestrians relevant to these Small Electric Vehicles (SEVs) based on future accident scenarios. Within the framework of this project, a seamless toolchain, for evaluation and development, was also foreseen. Its applicability was verified for virtual testing by instituting SEV development and evaluation using this methodology during the course of the EU Project.

The development of a reliable and universal tool chain requires simulations and models generated under different codes to deliver comparable results concerning dedicated criteria – in this case injury risk prediction. Currently no widely accepted criteria or quality measure exists to evaluate the comparability of results which are generated by harmonised or translated models in different codes. In this study, a head injury risk assessment tool based on the Strasbourg University FE Head Model (SUFEHM) coupled to the Total Human Model for Safety models, THUMS-D (LS DYNA, used by Daimler) and THUMS V3 (VPS (ESI Group, Paris, France), used by Volkswagen AG) was evaluated from the perspective of code comparability.

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The objective of this study was to investigate the comparability and injury risk prediction of identical FE models (Human Body Model (HBM), Reference Electric Vehicle Model (REVM)) running with different solvers for pedestrian safety applications. The work was based on test conditions which were defined within the SafeEV Project for pedestrian collision scenarios foreseen to be relevant in urban areas by 2025. The impact simulations were conducted at different speeds for two positions, 20% offset and middle position. A detailed FE model of a SEV was used within these simulations. The SUFEHM was independently developed for the LS-DYNA code [2] before it was further reported and validated for different codes to predict skull fractures, subdural haematoma and brain injury risks. In the context of this study, the SUFEHM was coupled to two different pedestrian models (THUMS-D (LS DYNA) and THUMS V3 (VPS and results were compared for the two crash codes. A post-processing tool for the head Injury Risk Assessment (IRA tool) was also developed to assess the three different head injury risks predicted by SUFEHM automatically. The comparison between results from VPS and LS DYNA was done for a 40 km/h no braking collision scenario for the pedestrian in the mid-position.

II. METHODS

Virtual Evaluation

The method employed in this study for virtual evaluation is illustrated in Figure 11 below. The methodology can produce correct results, if a structured model validation approach is adopted. This is a pre-requisite for any virtual assessment. The present study meets all the stages identified in this procedure. Moreover, the configuration of the overall model settings used in application cases should match with the settings used within the validation procedure of the individual sub-models. If this cannot be guaranteed (due to different general settings as default within a company or an organisation), the effect of this deviation, i.e. its sensitivity to the results, has to be analysed before any assessment is done.

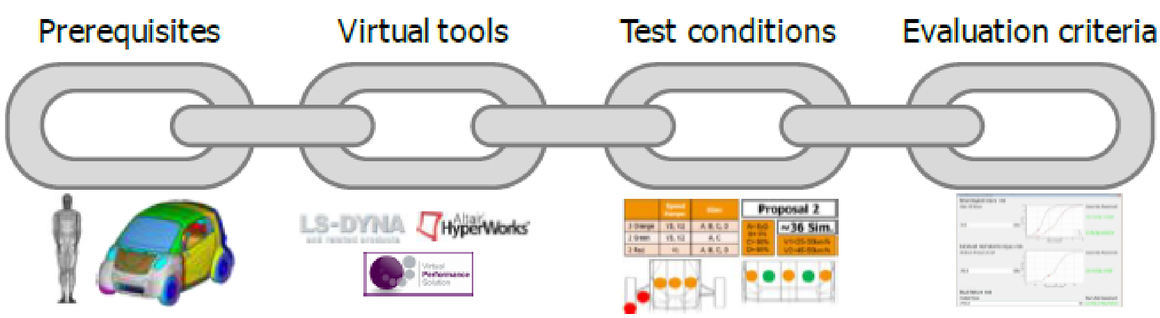


Fig. 1. Key building blocks required for virtual assessment.

1. Pre-requisites & Virtual Tools

Vehicle Model – Description of the Generic Reference FE Vehicle Model

The generic vehicle model used shall represent a future SEV design and is shown in Figure 2. The vehicle considered for this study is a small electric vehicle developed in the EU Project Safe EV. The origin of this model was only available in LS-DYNA and has been converted to VPS during the course of the SafeEV project. In order to ensure comparable behaviour of both vehicle models, i.e. in LS-DYNA vs. VPS crash code, simple impactor load cases using a rigid head and leg were simulated. Figure 3 shows two examples of a head as well as of a leg impactor load case together with the derived output, for instance impactor acceleration. Overall a good comparability between both vehicle models could be demonstrated while applying simple impactor load cases, so that the influence due to the vehicle model (LS-DYNA vs. translation into VPS) was minimised.

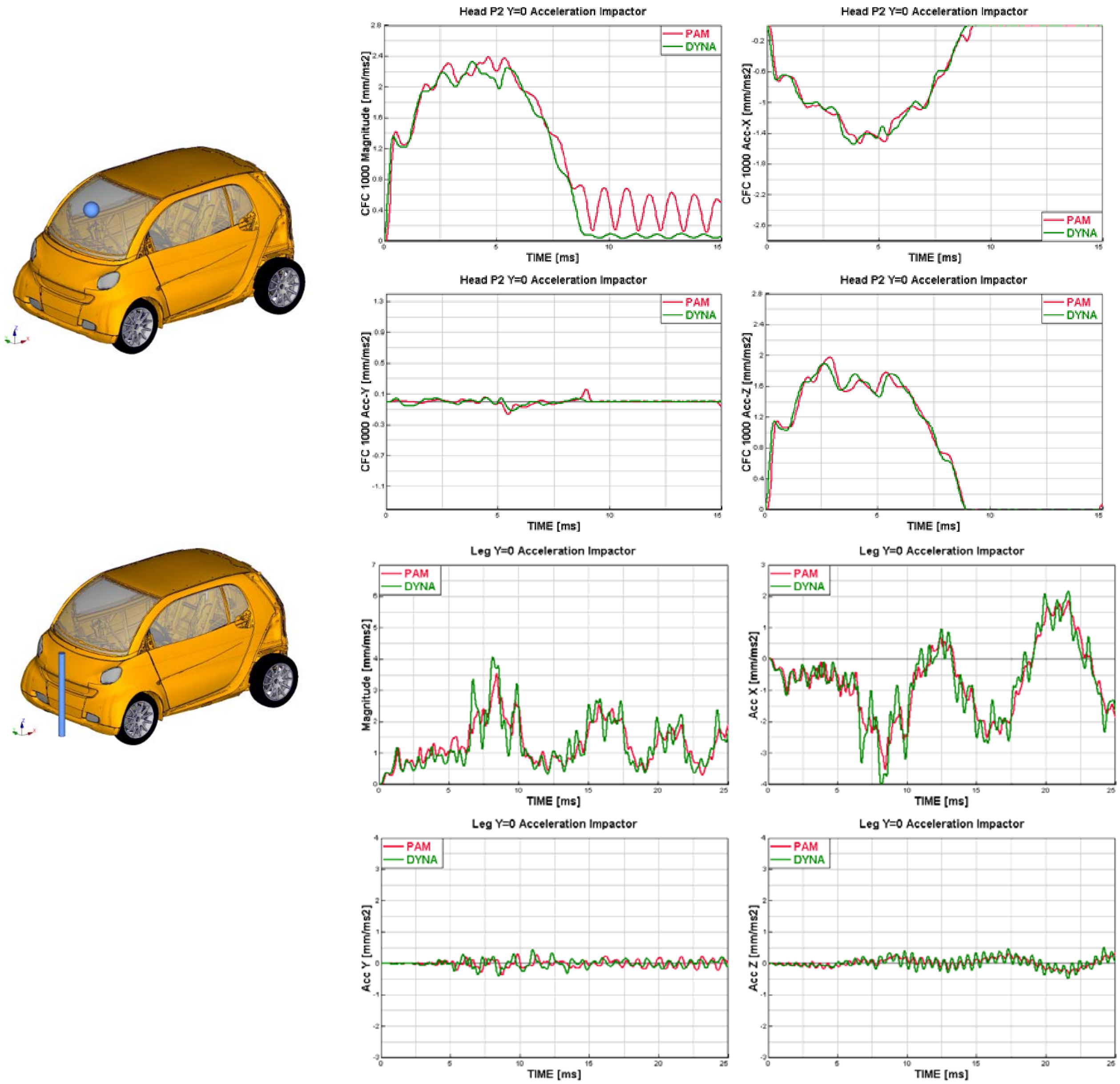


Fig. 2. Impactor load cases using rigid head (top) and leg (bottom) to check for comparability of vehicle front and windscreen stiffness [5].

FE Human Body Models

The current study utilised two different FE Human Body Models (HBMs): (1) HBM of Daimler (THUMS-D pedestrian with SUFEHM) and (2) HBM of VW (THUMS-VW pedestrian with SUFEHM). A brief description of both models is provided below.

> THUMS-D (LS-DYNA) – This model is based on THUMS V 3.0 with several updates / re-mesh to improve simulation robustness published in the "*Implementation of Virtual Testing In Safety Regulations"* (IMVITER) report. The model was then validated and the results of the same were published in IMVITER report [6].

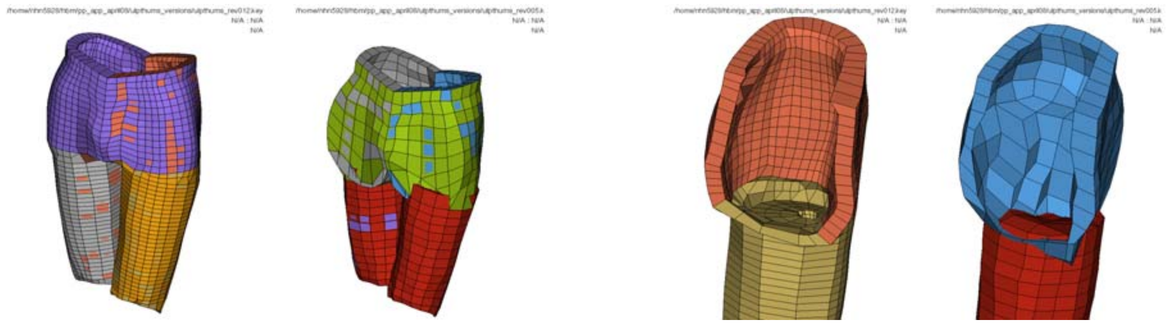


Figure 3: Re-mesh and model improvement of THUMS-D – Buttock and Thigh connectivity and re-mesh. (Left is modified version & Right is original version)

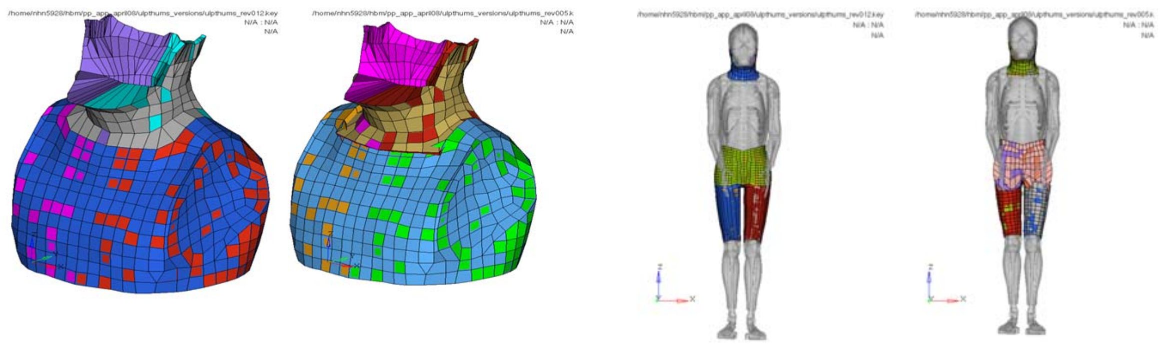


Figure 4: Re-mesh and model improvement of THUMS-D – Left > Neck area connectivity and intersection (left modified version – right original version) – Right > Overview modified body regions.

> THUMS-VW (VPS) – This model is based on and translated from THUMS V 3.0; including some minor updates to the mesh to improve stability (i.e. re-meshed soft tissue of the shoulder area); parameters which will affect deformation, stress levels were kept to the values of the original THUMS under LS-DYNA in Figure 17.

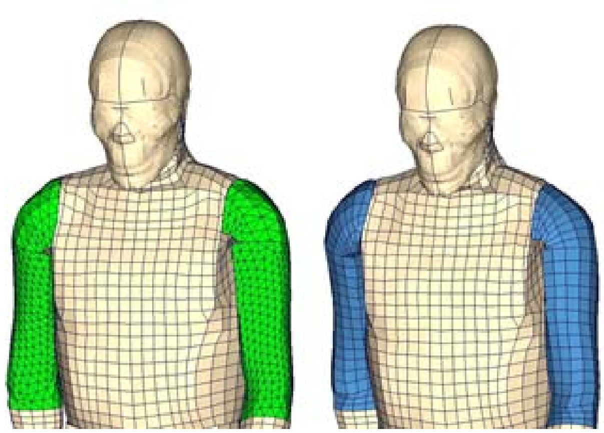


Figure 5: Re-mesh and model improvement of THUMS-VW – Arm and shoulder region re-meshed (left modified version – right original version)

These two THUMS models are therefore not identical (except for the SUFEHM coupled to both of them), but can be described as similar as being based on the same source HBM: THUMS V 3.0. Therefore the coupled HBMs are expected to deliver comparable results at least in terms of overall kinematics and head injury risk prediction.

Nevertheless, also these two THUMS models should deliver comparable results regarding injury risk prediction, also injury patterns and load levels should show the same trend. Therefore, further work was conducted with inception of SUFEHM in the two different HBMs, THUMS-D (LS-DYNA) and THUMS-VW (VPS) where the aspect of injury risk analysis is addressed.

<u>HBM Posture - Description of the applied Pedestrian Posture for the HBMs</u>

In order to further define the test set-up for the usage of full pedestrian models it was necessary to agree on a specific posture. Figure 6 is showing a walking posture definition used in [6] based on the THUMS-D model including some reference measurements. The posture is also in line with the requirements as defined within the Euro NCAP pedestrian testing protocol [4]. Both models utilised within this study meet requirements of posture definition to the maximum achievable extent. Therefore, also with respect to the pedestrian posture of the HBMs a similar, however not identical, posture was achieved in the project. This was checked by using some tracking points (also refer to Fig. 8) which were also used for the demonstration of the HBMs kinematic post-processing, but not yet by a complete set of reference points based on anatomical landmarks.

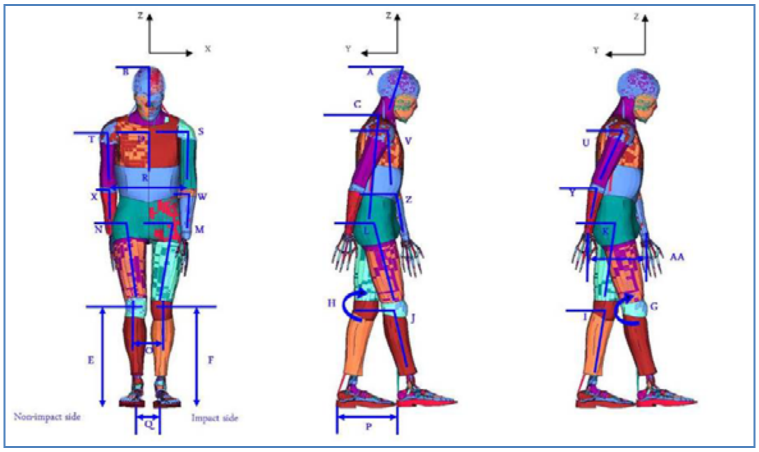


Fig 6. Pedestrian posture description used as basis for the positioning of the HBMs in this analysis [6].

Head Model – SUFEHM in LS-DYNA and VPS

The first step of conducting a risk assessment study in the two different codes, LS-DYNA and VPS requires the tool to be validated for both of the codes. This section focusses on model validation and extraction of head injury criteria related to the SUFEHM in these two codes. The model has been validated against existing experimental head impact data available in the literature in terms of brain pressure, brain deformation and skull fracture under VPS code as it was already validated under LS-DYNA [2]. The model was validated using extensive real world head trauma simulation in order to derive model based head injury criteria for three different injury mechanisms, neurological injuries, subdural hematomas and skull fracture under both codes [2]. The model development is explained in the following section and the details pertaining to injury criterion are discussed in the section related to evaluation criteria.

Skull model under LS-DYNA and VPS codes:

The SUFEHM, which is a 50th percentile FE model of the adult human head, developed under Radioss software [7] and transferred to LS-DYNA [2][8], is considered in the present study. The SUFEHM presents a continuous mesh that is made up with 13,208 elements, including 1,797 shell elements utilised to compose the skull. The geometry of the inner and outer surfaces of the skull was digitised from a human adult male skull to ensure anatomical accuracy.

The current skull was modelled by a three layered composite shell representing the inner table, the diploe and the external table of human cranial bone. Under LS-DYNA platform, INTEGRATION_SHELL card has been implemented in order to define the three skull layers with the following thicknesses (2 mm for each cortical layer and 3 mm for diploe). The material model 55 which is available in LS-DYNA named as MAT_ENHANCED COMPOSITE_DAMAGE was used to represent the material behaviour of skull bones. This material has three failure criteria for four different types of in plane damage mechanism based on Tsai and Wu criterion [9] which is an operationally simple strength criterion for anisotropic materials developed from a scalar function of two strength tensors. The parameters for the composite material model for the skull are identified from various in vitro experimental data reported in the literature. For the elastic material properties like Young's modulus and Poisson's ratio, parameters remain the same as for the initial model [2][8]. For the different strength tensors like longitudinal / transverse tensile and compressive strength and shear strengths, a range of values were acquired from in vitro experimental tests conducted by [10][11]. The skull mechanical parameters implemented under LS-DYNA have been extensively validated against experimental data in [12] and are represented in Table I.

TABLE I
SKULL MECHANICAL PARAMETERS UNDER LS-DYNA CODE FOR THE SUFEHM

Mechanical Parameters	Cortical Bone	Diploe Bone
Mass density (Kg/m^3)	1900	1500
Young's modulus (MPa)	15000	4665
Poisson's ratio	0.21	0.05
Longitudinal and transverse compressive strength (MPa)	132	24.8
Longitudinal and transverse Tensile strength (MPa)	90	34.8

The skull model in the VPS platform was implemented as composite ply card (PLY) which defines the three skull layers with the following thicknesses (2 mm for cortical layers and 3 mm for diploe). The classical material parameters along with damage criteria were implemented in this card for each layer. The damage mechanism is based on Tsai and Wu criteria, a criterion which is an operationally simple strength criterion for anisotropic materials developed from a scalar function of two strength tensors as used under LS-DYNA software. Then these three plies were combined and thickness was assigned under 131-MULTILAYER-ORTHOTROPIC-BI-PHASE card which is a material model for a multilayered orthotropic shell. The mechanical properties implemented under PAM-CRASH/VPS are listed in Table II.

TABLE II
SKULL MECHANICAL PARAMETER UNDER PAM-CRASH CODE FOR SUFEHM SKULL MODEL

Mechanical Parameters	Cortical Bone	Diploe Bone
Mass density (kg/m^3)	1900	1500
Young's Modulus (MPa)	15000	4665
Poisson's ratio	0.21	0.05
Initial yield stress (MPa)	90	28
Hardening law multiplier	0.23	1.5
Hardening law exponent	0.1	0.5
Tensile strength in direction 1,2and 3 (MPa)	90	34.8
Compressive strength in direction 1,2 and 3 (MPa)	132	24.8
Shear strength (MPa)	145	24.8

The data for skull model validation was collected from the experiments conducted on PMHS in collaboration with the Medical College of Wisconsin. Seventeen specimens were isolated at the level of the occipital condyles. The scalp was included in the preparation. The instrumentation for biomechanical data acquisition consisted of tri-axial accelerometers at the vertex, anterior and posterior regions of cranium, and a nine accelerometer package was attached to the skull at the contra-lateral site of impact using screws [13].

The test matrix consists of a total of 86 drop tests from 17 PMHS specimens. Repeated drop tests were conducted on the same specimen with successively increasing input energies (increasing drop heights) to the specimen until fracture. The SUFEHM with updated constitutive law for skull bone was used to simulate the whole set of cadaver tests under LS-DYNA and VPS codes. The simulations for all the tests were conducted and the contact force time history between skull and pad was calculated in order to validate simulations in regards to experiments under the two codes (LS-DYNA and VPS). More details related to this skull validation step can be found in [12] where the whole procedure is conducted under LS-DYNA code. The resultant contact force between SUFEHM and padded surface during simulations for all the cadaver tests was extracted and plotted with the experimental resultant force curves. The results are filtered at SAE 1000 Hz as for the experiments. Figure 5 shows an example of results obtained with LS-DYNA and VPS codes showing the comparison of simulation contact force with mean experimental contact force (obtained by averaging the upper and lower corridor) for 40D flat padding at 6.47m/s. The deviation of the peak value of the simulation curve from the peak of mean experimental curve was calculated for all cases and for the two codes. The average discrepancy in peak values was less than 3 %. The correlation coefficient between the simulation and mean experimental curve was also calculated for all cases. The average value is 0.99.

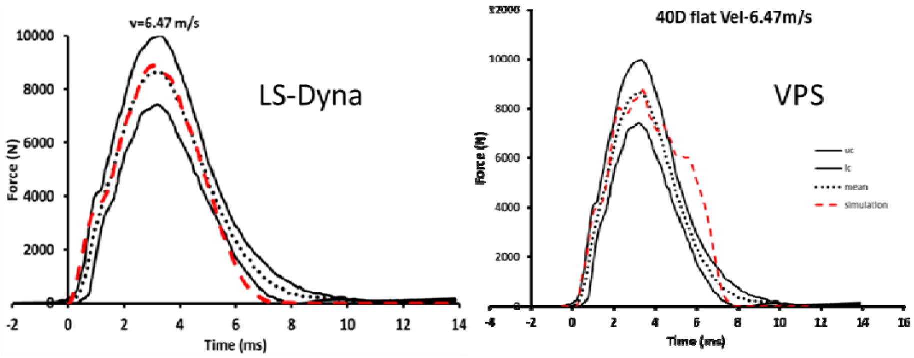


Fig. 7. Example of results obtained in terms of force vs time for a case with 40D flat impactor with impact velocity 6.47 m/s under LS-DYNA and VPS codes.

2. Test Conditions - Impact Configuration applied in the EU funded project SafeEV

Within the EU funded project SafeEV a number of relevant impact positions to assess pedestrian safety of future SEVs by the utilisation of full HBMs were proposed [3]. Figure 8 shows an overview of proposed pedestrian impact locations on one of the proposed vehicle designs while taking different vehicle speeds as well as relevant pedestrian sizes into account. However, in this study, mainly dealing with the comparison of results between the two crash codes, LS-DYNA and VPS, the focus will be on the *mid position* - i.e. alignment of H-point and vehicle's y=0. Also, this study was reduced to the application of a 50th %ile male HBM, impacted with a speed of 40 km/h.

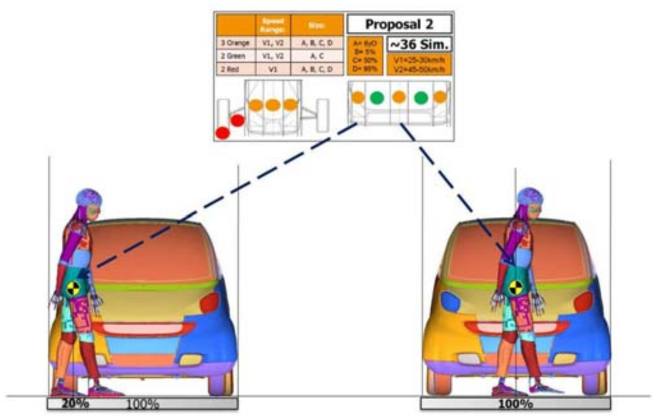


Fig. 8. Pedestrian impact conditions used in the EU-funded project SafeEV [3][20], demonstrated on the utilised generic vehicle model together with THUMS-D in a step position; left picture shows the *20% near side* position, right picture shows the *mid position.*

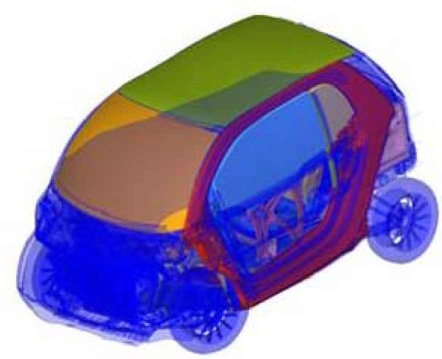


Fig. 9. Safe EV vehicle model developed in LS DYNA.

Further boundary conditions for the simulation of the impact were defined as follows:

- Struck leg is facing backwards
- Vehicle is not braking
- Friction values of 0.3 between shoes and ground was defined in line with the Euro NCAP protocol [4]

3. Evaluation Criteria - SUFEHM criteria for LS-DYNA & VPS

Finally the different head injury criteria have been consolidated via the simulation of a minimum 125 real world head trauma cases as reported in [12]. In order to ensure an easy use of the model, a SUFEHM dedicated Injury Risk Assessment tool (IRA-tool) has been developed. This post-processing tool facilitates automatic analysis and risk assessment while avoiding any influence by the end-user. The SUFEHM under LS-DYNA and VPS codes has been updated in terms of skull mechanical properties and validated against experimental data. Further, head injury criteria have been consolidated in terms of percentage risks of skull fracture, DAI (AIS 2+) and SDH under LS-DYNA and VPS computation codes. Table III summarize the values of the injury parameters for a 50% risk for the three types of head injury (DAI (AIS2+)), Skull failure and SDH) under LS-DYNA and VPS codes. These updated head injury criteria have been implemented into IRA-tool for both LS-DYNA and VPS codes. The IRA tools have been transferred to DYNAMORE and are available for automatic post processing of SUFEHM simulations and head injury risk assessment.

TABLE III
SUMMARY OF 50% RISK VALUES CALCULATED WITH THE SUFEHM FOR THE THREE TYPES OF HEAD INJURY (DAI(AIS2+), SKULL FAILURE AND SDH) UNDER LS-DYNA AND VPS CODES

	Ls-Dyna	VPS	Type of injuries
Brain Von Mises stress [kPa]	37	42	DAI (AIS2+)
Skull internal energy [mJ]	439	1750	Skull fracture
CSF internal energy [mJ]	4950		SDH
CSF minimum pressure [kPa]		312	

After computation of a head impact under LS-DYNA and VPS, the comparison of results was initially done in terms of percentage of risk. However, in the critical loading range, this percentage changes rapidly with a small change of injury parameter that leads to difficulties in code comparison. Therefore the following recommendation is made in order to end up with a more realistic code comparison. Following the modelling of a head impact it is suggested to express the results quantitatively for each injury mechanism (SKF, SDH, DAI) by giving the value of the computed injury parameter and to add a qualitative evaluation of the risk in terms of no risk (NR-under 10%), risk (R- 10 to 90%) and high risk (HR- over 90%) to this value. The following tables give the threshold values of the injury parameter for this NR/R/HR distinction for the three injury mechanisms, for LS-DYNA (Table IV) and for VPS (Table V). Alternatively NR-R-SR could be expressed in Green-Yellow-Red.

TABLE IV
INJURY PARAMETER THRESHOLDS FOR QUALITATIVE EVALUATION OF RISK FOR LS-DYNA

Injury Mechanism	Injury Parameter	NR (under 10%)	R (10 to 90 %)	SR (over 90%)
DAI	Shearing Von Mises (kPa)	under 11	11 to 62	over 62
SDH	Strain Energy (mJ)	under 2750	2750 to 7150	over 7150
SKF	Strain Energy (mJ)	under 130	130 to 755	over 750

4.

TABLE V
INJURY PARAMETER THRESHOLDS FOR QUALITATIVE EVALUATION OF RISK FOR VPS

Injury Mechanism	Injury Parameter	NR (under 10%)	R (10 to 90 %)	SR (over 90%)
DAI	Shearing Von Mises (kPa)	under 25	25 to 59	over 59
SDH	Strain Energy (mJ)	under 200	200 to 430	over 430
SKF	Strain Energy (mJ)	under 1010	1010 to 2480	over 2480

III. RESULTS

Full Body Level Assessment of the SUFEHM in LS-DYNA and VPS

This section focusses on comparison of THUMS-D (LS-DYNA) and THUMS-VW (VPS) on full body level. The collision scenario considered for this study is 40 km/h, no braking and pedestrian contact in mid position of the vehicle. The whole-body kinematics has been compared based on the defined and harmonised tracking points (Figure 10) and also the motion sequences in 10 ms time-steps are depicted in Figure 11. The Head Impact Time (HIT) – as a relevant parameter for the development and assessment of safety systems like deployable bonnets, airbags, etc. was taken as a main value for the comparison. The impact area and deformation of the vehicle has also been plotted for comparison. Contact forces for the tibia, pelvis, shoulder and head have been plotted over time for both models (Figure 15 in Appendix).

In a second step, the simulation results of the two models were also compared concerning their head injury risk prediction. Thoracic deflection and plastic strains of the ribs were also evaluated for both models for establishing the differences in loading patterns of both the models. The contact forces for tibia and femur as well as their plastic strains were also utilised for comparing the loading patterns in both models.

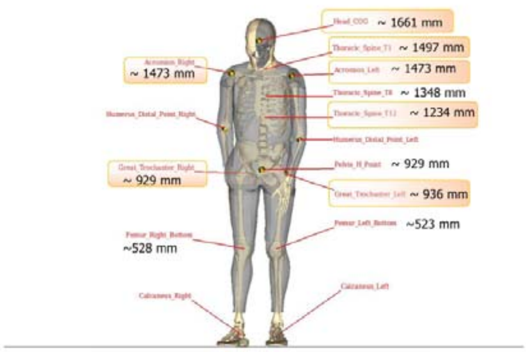


Fig. 10. Figure with tracking points (as defined by the THUMS User Community (TUC)) and z heights measured on THUMS-VPS

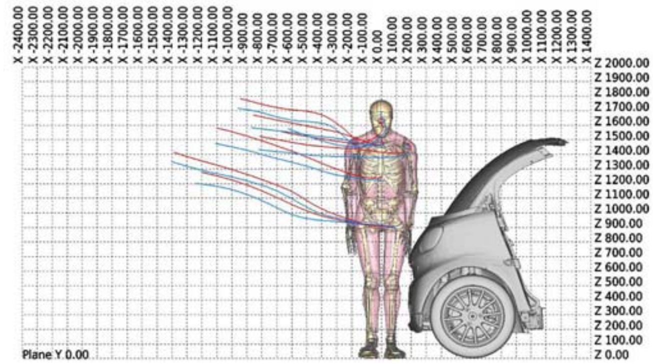


Fig. 11. Overlay full body kinematics (tracking points) THUMS-D (body surface) and THUMS-VW (skeleton)

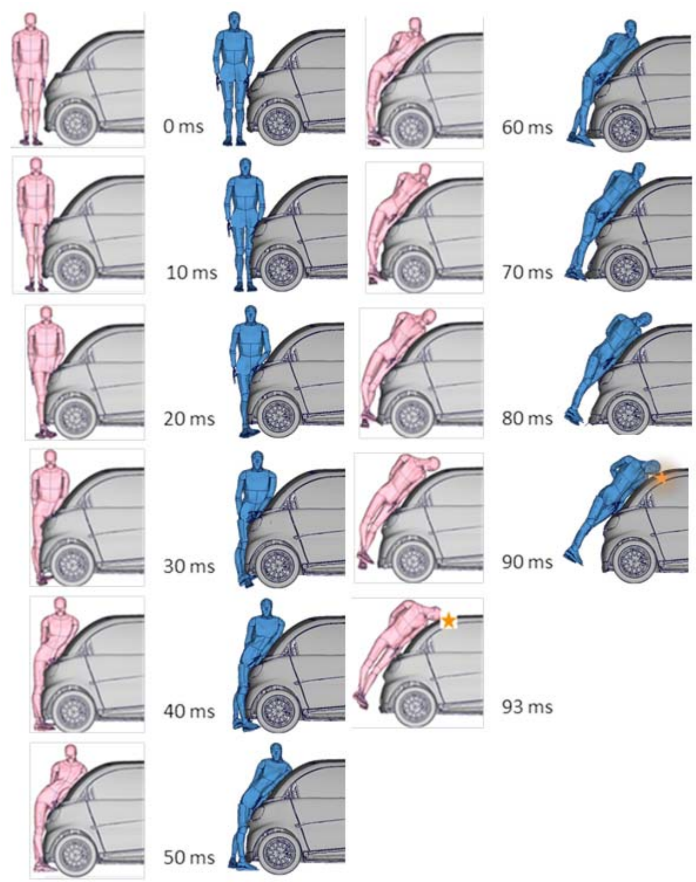
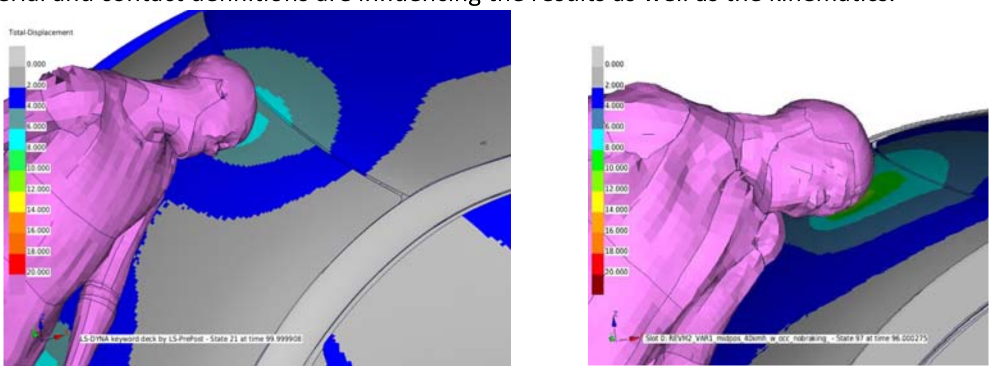


Fig. 12**.** Kinematic sequence and HIT (Head Impact Time).Left (magenta): THUMS-D, right (blue): THUMS-VW. Load case: Generic SEV; pedestrian in mid position; 40 km/h; no braking.

Comparability between the two THUMS models concerning full body kinematics and related values for HIT and forces are good. Especially the difference of 3 ms for the HIT, which is also a relevant value within the current Euro NCAP pedestrian test protocol [4], suggests good comparability of the models whenever kinematic issues are addressed. Also overall kinematics and head contact location on the vehicle (windscreen) show a good comparability (Figure 12) although only similar HBMs were used in this comparison as described above. However, when comparing the results from contact forces or, for instance, the head position at the time of impact/contact (Figure 13) some deviations were observed. Figure 14 illustrates the variation of resultant contact forces for the head over time. Moreover, the head contact force varies from 4.2 kN to 5.2 kN which may lead to a different head injury risk based on strain energy between both models. It looks like, that this results from the pelvis and thigh contact respectively and that the contact induces some rotation around the longitudinal axis of THUMS-D – see Figure 13. This might be due to the fact that the major differences of the two models are in the thigh, pelvis and shoulder region. Higher upper leg and pelvis contact forces of the THUMS-D model indicates that to this body region more energy is transferred whereas THUMS-VW shows higher contact force values in the lower leg, shoulder and finally the head contact – see Figure 15 & Table VI.

Due to the fact that the two models differ in some body regions, respectively material definition (as already mentioned), some discrepancies could be expected. Finally the values for the lower body parts on full body level differ within the same range as some results from the body region level respectively from the validation cases [16]. It should be also kept in mind, that now the interaction with the vehicle front and therefore also different material and contact definitions are influencing the results as well as the kinematics.



THUMS-D THUMS-VW

Fig.13. Contact force plot and deformation on vehicle.
Left: THUMS-D – maximum deformation of 8 mm (windscreen); Right: THUMS-VW – maximum deformation of 14.5 mm (windscreen).

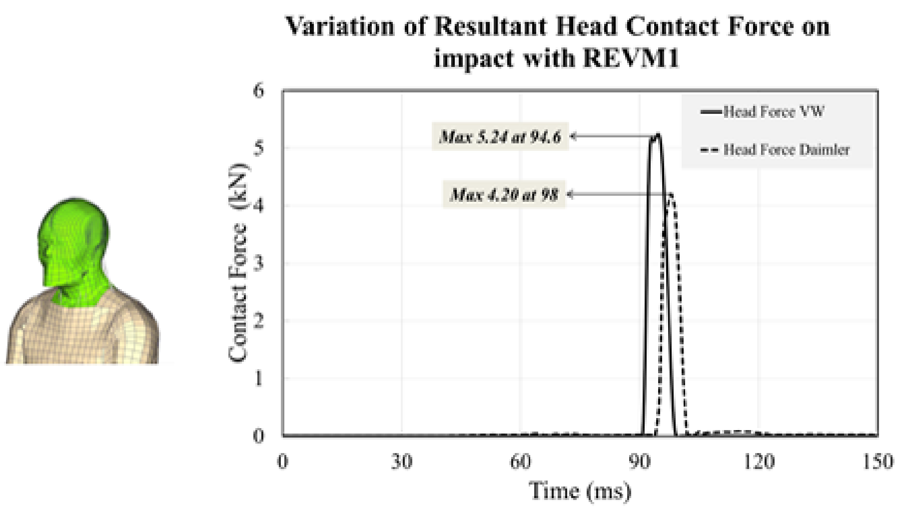


Fig. 14. Head contact force variation with time.

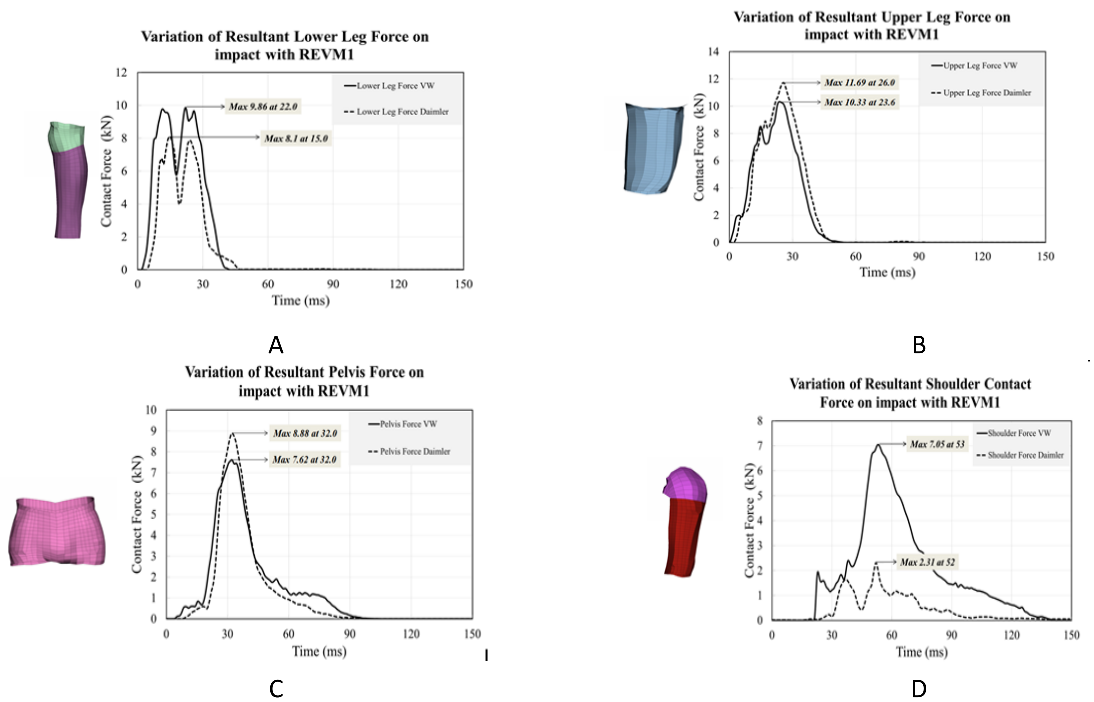


Fig.4. Lower leg- (left & right), upper leg-, pelvis -, shoulder - & head contact force plotted over time.

TABLE VI
PEAK CONTACT FORCES OBSERVED BETWEEN BOTH MODELS in kN

Body Region	Peak Contact Force (LS-DYNA)	Peak Contact Force (VPS)	Difference
Lower Leg	8.1	9.86	-1.76
Upper Leg	11.69	10.33	1.33
Pelvis	8.88	7.62	1.26
Shoulder	2.31	7.05	-4.74
Head	4.2	5.24	-1.04

	DAI AIS 2+ Risk	SDH Risk	Skull Fracture Risk
THUMS-D/SUFEHM (LS-DYNA)	79% (R)	8.6% (NR)	4.1% (NR)
THUMS-VW/SUFEHM (VPS)	99.5% (HR)	69.2% (R)	2.1% (NR)

Legend

NR	***no risk***
R	***risk***
HR	***high risk***

Fig.16. Comparison of head injury risks derived from the SUFEHM IRA tool using VPS and LS-DYNA HBMs.

IV. Discussion

The most important body region concerning injury risk prediction within pedestrian safety applications is unquestionable the head. This body segment and model part was even more in focus due to the fact that SUFEHM and the related post-processing tool (IRA), implemented now in the two codes, represent a complete virtual method for injury risk assessment as well as a complete tool chain. It should be mentioned that for this study improved skull modelling was implemented into the SUFEHM. However the brain constitutive law considered is linear visco-elastic as reported by, when advanced anisotropic hyper-viscoelastic brain modelling which enable the computation of axon elongation have recently been published [15]. The reason for applying a simplified brain modelling approach in this study was to implement existing model based head injury criteria into an industrial context even if research is progressing in this field. This approach permits to demonstrate the feasibility of the application of human body modelling in an industrial context, under different FE platforms in order to progress towards Virtual Testing. Both models, the SUFEHM on THUMS-D and THUMS-VW, predict almost the same *high risk* for an AIS2+ brain injury (DAI-AIS2+) as illustrated in Figures 16. *No risk* of subdural hematoma (SDH) is predicted by SUFEHM with THUMS-D whereas SUFEHM with THUMS-VW shows a *risk* level for a SDH.

For the injury mechanism related to skull fracture both models are showing quite comparable injury risk on a *no risk* level. The discrepancy concerning injury risk prediction for SDH could be explained by the fact that the head orientation at the time of impact differ between the two simulations. Also the head contact force shows some difference. This is due to the slightly different full body kinematics as already discussed before. So, some divergence concerning risk prediction via both the SUFEHM and post-processing tools was to be expected. Both models also show comparable injury risk for the thorax as well as predicted number of fractured ribs (applying *plastic strain* as an injury indicator, whereas 3% was set as critical value for cortical bone fracture based on [14]). Whereas THUMS-D predicts *no risk* for a tibia fracture THUMS-VW shows plastic strain slightly above 3% and therefore indicates a probability of tibia fracture. Nevertheless, it should be mentioned, that also THUMS-D plastic strain values are close to the critical value given by [14]. Comparability of both models concerning injury risk prediction for the femur is questionable due to the fact that the THUMS-D femur lies outside an acceptable validation corridor. Nevertheless, both models showed low or *no risk* level for a bone fracture. So the (bending) load on the femur bone might be low in this specific load case as well as with this car design. When looking on the quite comparable results of the contact forces as well, it seems that the soft tissues have a kind of damping effect on this bone characteristic.

V. Conclusions

Finally it can be stated, that the two THUMS and SUFEHM models under LS-DYNA and VPS deliver comparable results and predict quite comparable injury risks and show almost similar full body kinematics and head impact time. Definitely, given the similarity of the models and yet the differences in the injury risks predicted (Fig 11), the risk predictions of these finite element model are highly code and model dependent. The risk for three different types of head injuries could be quantified based on model dependent injury parameters. This could be achieved using the SUFEHM together with the related post-processing IRA tool for both crash codes and therefore is demonstrating a complete tool chain. However, on a component and validation level, some differences were observed between the two THUMS models in the pelvis and the thigh region. This was due to mesh updates in case of THUMS-D which influenced the pedestrian kinematics. Finally, this study underlined the need for *harmonised* HBMs which can reproduce comparable results in different crash codes.

VI. Acknowledgement

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VII. References

[1] Svensson., M., D'Addetta, G., Carlsson, A., Edwald, C., Luttenberger, P., Mayer, C., Strandroth, J., Tomasch,E., Gutsche,A., Wismans, J. (2014) Future Accident Scenarios involving Small Electric Vehicles. *Proceedings of IRCOBI Conference*, Germany.

[2] Deck, C., Willinger, R. (2008) Improved head injury criteria based on head FE model. *International Journal of Crashworthiness*, 2008a, 13(6): 667–678.

[3] Wismans, J., Davidsson, J., Carlsson, A., Mayer, C., Luttenberger, P., D'Adetta, G., Hinc, M., Dux, E., Nuss, F., Willinger, R. (2013) Report on test conditions and evaluation criteria for occupant and vulnerable road user protection of small electric vehicles, *Deliverable D2 of Reports of SafeEV Project, Grant Agreement No. 314265*, Austria.

[4] EuroNCAP. "*Pedestrian Testing Protocol Version 8.0*" Internet: [www.euroncap.com], June 2014 [November 2015].

[5] Mayer, C., Ghosh, P., Weber, J., Willinger, R., Deck, C. (2015) Principal comparability of HBM & REVM in different codes, *Deliverable 3.4 of Reports of SafeEV Project, Grant Agreement No. 314265*, Austria.

[6] IMVITER EU-project, Project report: D6.1 Analysis of new simulation technologies for pedestrian safety. Potential of VT to fully substitute RT for this purpose; FP7 – 2007 – SST – 218688; www.imviter.com.

[7] Kang, H., Willinger, R., Diaw, B., Chinn, B. (1997) Validation of a 3D human head model and replication of head impact in motorcycle accident by finite element modeling. *Proc. 41th Stapp Car Crash Conf.*, *Society of Automotive Engineers*, USA.

[8] Deck, C., Willinger, R. (2009) Head injury prediction tool for predictive systems optimization. *Proc. of the 7th European LS-DYNA Conference*, Austria.

[9] Tsai, S., and Wu, E. A general theory of strength for anisotropic materials. *Journal of Composite Materials*, 1971, 5 (1): 58-80.
[10]Wood, J. Dynamic response of human cranial bone. *Journal of Biomechanics,* 1971, 4(1), 1–12.
[11]McElhaney, J., Fogle, J., Melvin, J., Haynes, R., Roberts, V., Alem, N. Mechanical properties of cranial bone. *Journal of Biomechanics*, 1970, 3(5): 495-511.
[12] Sahoo, D., Deck, C., Yoganandan, N., Willinger, R. Anisotropic composite human skull model and skull fracture validation against temporo-parietal skull fracture. *Journal of the Mechanical Behavior of Biomedical Materials*, 2013, 28, 340-353.
[13] Yoganandan, N., Zhang, J., Pintar, F., King, L. Lightweight low-profile nine-accelerometer package to obtain head angular accelerations in short-duration impacts. *Journal of Biomechanics*, 2006, 39:1347-1354.
[14]Burstein, A., Reilly, D., Martens, M. Aging of bone tissue: mechanical properties. *J. Bone Joint Surg. Am.*, 1976, 58 (1), 82–86.
[15]Sahoo, D., Deck, C., Willinger, R. (2015) Axons train as brain injury predictor based on real-world head trauma simulations. *Proceedings of IRCOBI Conference*, France.

VIII. APPENDIX

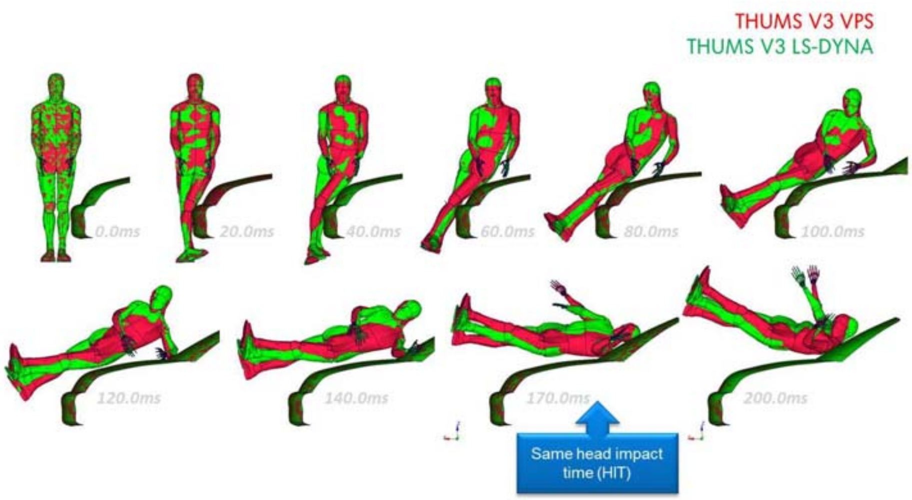

Fig. 57. Comparison of LS-DYNA and VPS version of THUMS V3.0 in a 40 km/h impact against a rigid front of a Dodge Neon model.

Erratum

IRC-16-66

Head Injury Risk Assessment in Pedestrian Impacts on Small Electric Vehicles using Coupled SUFEHM-THUMS Human Body Models Running in Different Crash Codes

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Table V to be corrected to:

TABLE V
INJURY PARAMETER THRESHOLDS FOR QUALITATIVE EVALUATION OF RISK FOR VPS

Injury Mechanism	Injury Parameter	NR (under 10%)	R (10 to 90 %)	SR (over 90%)
DAI	Shearing Von Mises (kPa)	under 25	25 to 59	over 59
SDH	Pressure (kPa)	under 200	200 to 430	over 430
SKF	Strain Energy (mJ)	under 1010	1010 to 2480	over 2480