Title: Influence of Different Parameters of Vehicle and Pedestrian on Chest Kinematics Using Human Body Model (HBM)

Chinmoy, Pal
Shigeru, Hirayama
Nissan Motor Company Ltd,
Japan
Pratap Naidu, Vallabhaneni
Vimalathithan, Kulothungan
Renault Nissan Technology Business Centre India,
India

Paper Number 23-0290

ABSTRACT

In Japan from 2000 to 2019, the number of motor vehicle occupant fatalities decreased significantly. Pedestrian road user type contributes to 37% of total traffic fatalities, the highest compared to other road user types since 2009. In pedestrian accidents, Head and chest body regions account for 51% and 40%, covering about 91% of the total AIS4+ injuries, respectively. So, head and chest protection are important elements for reducing pedestrian fatalities. At present, there are test procedures for head and lower extremities injury protection, but no test procedure exists for pedestrian chest protection. BAST has proposed a specific thorax injury prediction tool (TIPT) developed from side impact dummy ES-2. Based on their proposal, an adult chest impactor will be impacted by several predefined impact grid points covering a range from a child's lower rib height (WAD: 770mm) to a 95th-%ile male's upper rib height (WAD:1540mm). Injury criteria for TIPT were based on injury risk curves of 45 to 67 year-old adults. In this paper, the influence of different parameters of vehicles and pedestrians on chest injury using human body models (HBM) and TIPT modules are studied in detail. It can be concluded that (a) similar to the existing head injury evaluation impactors, child and adult TIPT impactors need to be different since the biomechanical characteristics are different (b) based on human body models' CAE simulation with the target generic vehicles models (GVM), the chest impact velocity is considerably lower than those recommended values of BASt and (c) it has been observed that BLE height, bumper lead upper, hood angle are the significant parameters for the chest impact velocity.

INTRODUCTION

Societies of advanced countries are aging demographically. Based on serious injury comparison among different body regions for the age group 25-64 and >65 year-old categories, the thorax body region ranks 3rd for the age group 25-64 and ranks 2nd for the age group >65 [Wisch et al., 2017]. Presently pedestrian regulations do not consider chest protection. Project SENIORS (Safety ENhanced Innovations for Older Road userS) aims to improve the safe mobility of the elderly and overweight persons, using an integrated approach that covers the main modes of transport.

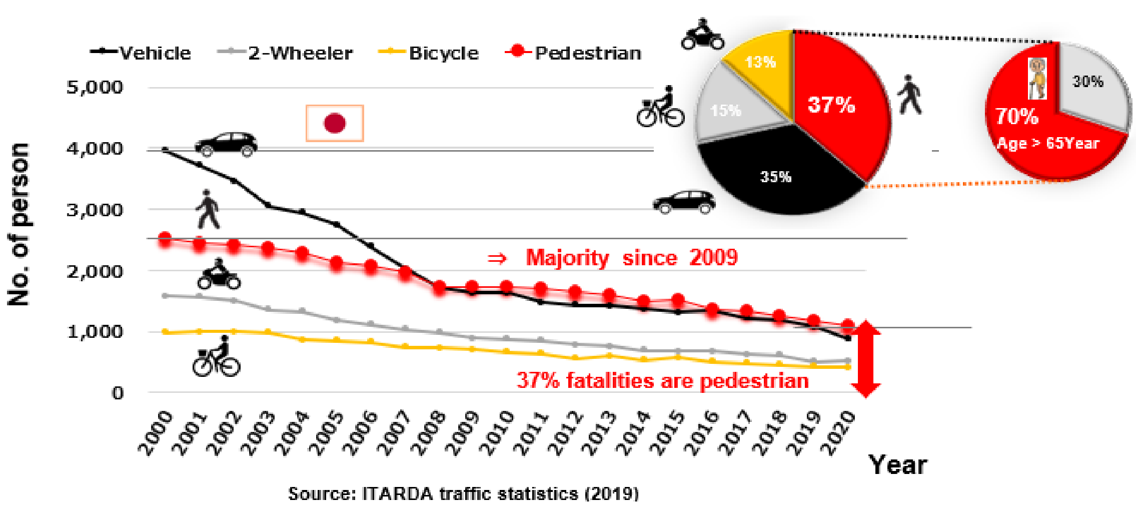

Figure 1. No. of fatalities based on the Japanese traffic accident database ITARDA, 2000-2020

According to International Transport Forum Report for Japan, pedestrians account for 37% of traffic fatalities in Japan for the year 2020. The road fatality rate per 100000 population for different age groups shows the risk for 65-74 & >75 year-old age groups is high compared to other age groups. Within 65-74 & >75 year-old age groups road fatality rate for different road user categories shows, pedestrian accidents account for a major share as shown in Figure 1.

The mission of BAST, a German organization for the Federal Highway Research Institute, is to improve the safety, environmental compatibility, economic efficiency, and performance of roads. It does Testing, certification, approval, and recognition activities in the field of road traffic. BAST's research activities have a considerable influence on EU-Regulation/ Euro-NCAP. BAST proposed a test tool for predicting thoracic injuries and assessment procedures as they did previously for bicyclist's head protection which was later included in EuroNCAP Roadmap 2021-2025. They have extracted the chest module from a side impact dummy EUROSID-2(ES-2), which has good capability in measuring chest injuries for side impact conditions. ES-2 dummy chest module was converted into an impactor TIPT (Thorax Injury Prediction Tool) which was designed to launch against the vehicle at the designed speed and angle. The test area was marked on the vehicle from WAD 770mm (height of lowermost rib of 6 year-old) to WAD 1540mm (height of uppermost rib of 95th-%ile male). Based on the half of the height of 160mm and width of 276mm of the chest module, evaluation impact points are marked with a pitch/interval of 80mm and 133.5mm as shown in Figure A1. Impact angle and velocity vary with the type of vehicle as shown in Figure 2 below and in Figure 4 of the method section. Scores are proposed based on the serious injury risk parameters for 45 year-old and 67 year-old PHMS test data. Nothing is mentioned about the child's chest injury criteria.

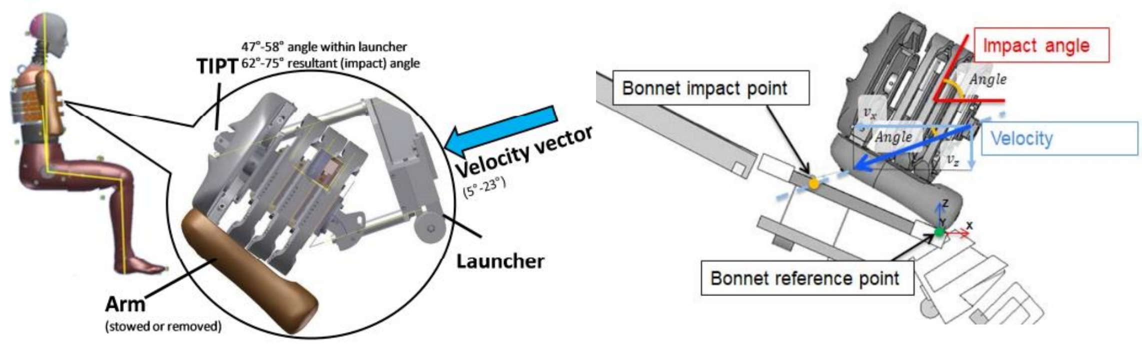

Figure 2. ES-II dummy chest-based TIPT module and a typical testing procedure (Oliver 2019)

This paper focuses on the following topics (i) to survey the chest injury characteristics of children and adults based on past published literature, (ii) to study the chest impact testing conditions using GHBMC pedestrian human model simulations against generic vehicles models (GVM), and (iii) to estimate the most influential front-end vehicle profile parameters contributing to a chest injury and impact conditions.

LITERATURE SURVEY

Children suffer fewer rib fractures and less blunt cardiac injury, but more lung contusions. Children's thoracic injuries are more often associated with head injuries and less often with spine injuries than those observed in adults. Notably, the majority of pediatric deaths were secondary to traumatic brain injury rather than thoracic injury. There was a significantly lower mortality rate in the pediatric group (16.7% v. 27.8%; p=0.037), despite Injury Severity Score ISS values in the two groups being similar [Skinner, 2015]. Osteopenic changes and co-existent underlying disease may also play a significant role in this process [Bass, 1990]. The overall outcome of child pedestrian casualties appears to be relatively constant across the pediatric stature range. However, pedestrian height seems to affect the frequency of injury to individual body regions, including the thorax and lower extremities. This suggests that vehicle safety designers need to account for the difference in injury patterns between adult and pediatric pedestrian casualties [Ivarsson, et al., 2007]. Based on Japan Trauma Data Bank 2004-12, the percentage of MAIS2+ thorax injuries in pedestrians of age 0-14 year-old children (M:16.3%, F:14.0%) are comparatively less than those of adults above 15 years (M:24.7%, F:22.6%) [Ito, et, al., 2015]. Due to the lower incidence of rib fractures, as mentioned in a number of past published literature[Ziegler1994], the patients in the pediatric age group need alternative criteria to identify patients with major chest injuries. The main focus of the present study is to identify the rationality of the chest protection proposal as recommended by BAST for adult pedestrian populations only.

METHOD

TIPT CAE Model Development

As per BAST recommendation, the CAE TIPT module was developed from an ES-2 dummy with a mass of 22.2kg as shown in Figure 3. ES-2 is already an authorized dummy for evaluating the side impact performance of existing vehicles. The mode of the impact of the pedestrian's chest is somewhat like that of a pure lateral impact for an occupant inside a car. Hence, there is an underlying basic assumption that the TIPT is expected to perform well in evaluating pedestrian chest injuries when impacted with the front end of a car also.

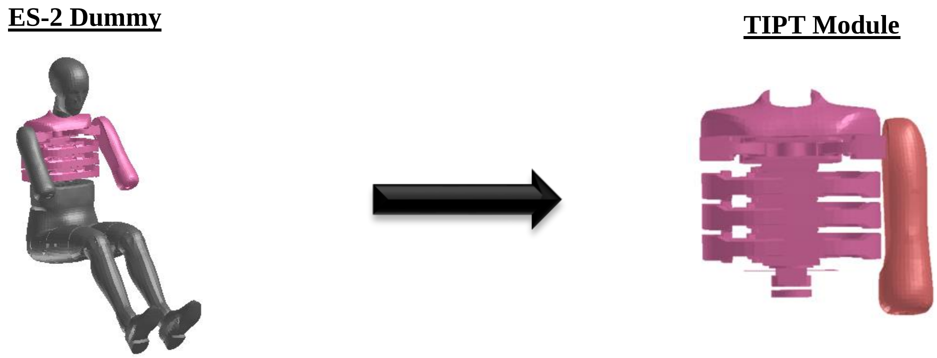

Figure 3. TIPT CAE module derived from ES-II dummy

TIPT impact conditions with vehicles (BASt proposal)

BAST recommended impact locations for chest protection, ranging from 6 year-old(YO) children to 95th-%ile male adult pedestrians as shown in Figure A1. Testing conditions such as orientation, impact speed, and impact angle vary for different types of vehicle categories based on BLE height and front-end profiles. Scoring for each impact location is decided based on the amount of maximum rib deflection. A five-level scoring method was recommended based on the injury risk curves of 67-YO & 45-YO as shown in Figure 4. A separate impactor was not proposed for child chest protection. Rather the same scoring system as adult injury risk conditions is indicated for evaluation in child impact zones near WAD>770mm with the TIPT chest module of 22kg mass.

TIPT	Vehicle	FCV BLE<835	SUV BLE>836	MPV/ VAN
FRD of BLR-RL*	Impact Angle (deg)	15(75)	20(70)	28(62)
	Velocity Angle(deg)	19	23	5
	Impact speed(kph)	27	15	21
FRD to BLR-RL*	Impact Angle (deg)	90		
	Velocity Angle(deg)	0		
	Impact speed(kph)	40		
* Bonnet Leading Edge Reference Line				

Color	Max deflection (mm)	Injury Risk	Score
Green	<28	5% of AIS3 **(67YO)**	1
yellow	28 - 35	20% of AIS3 (45YO)	0.75
orange	35 -40	30% of AIS3 (45YO)	0.5
brown	40-44	40% of AIS3 (45YO)	0.25
Red	>44	50% of AIS3 (45YO)	0

Figure 4. TIPT Evaluation proposed by BAST and injury score criteria

Pedestrian evaluation condition with different vehicle types

The present study used Generic Vehicle Models (GVMs) for standard vehicle categories (Family Car, SUV & MPV). In line with real-world pedestrian safety evaluation methodology as proposed by Euro-NCAP, CAE models of HBMs (GHBMC, AM50, AF05 & AM95) as mentioned in "Euro-NCAP Technical Bulletin TB 024" was chosen for this study. Refer to Figure 5 and Euro-NCAP technical bulletin [TB-024, 2022].

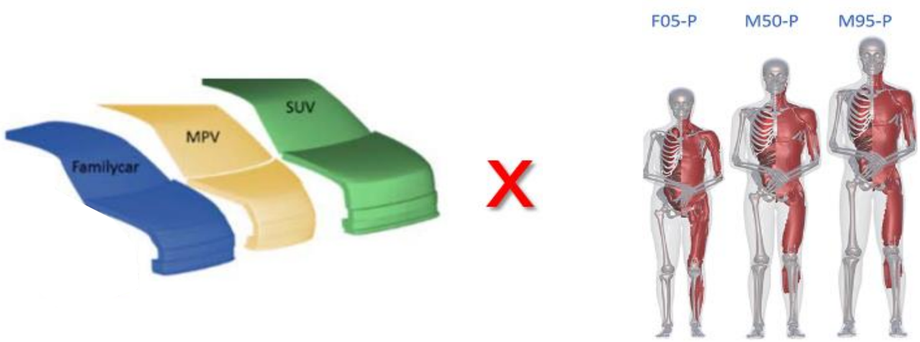

Figure 5 GVMs and different pedestrian human body models (GHBMC, AM50, AF05 & AM95).

RESULTS

HBM interaction with GVM

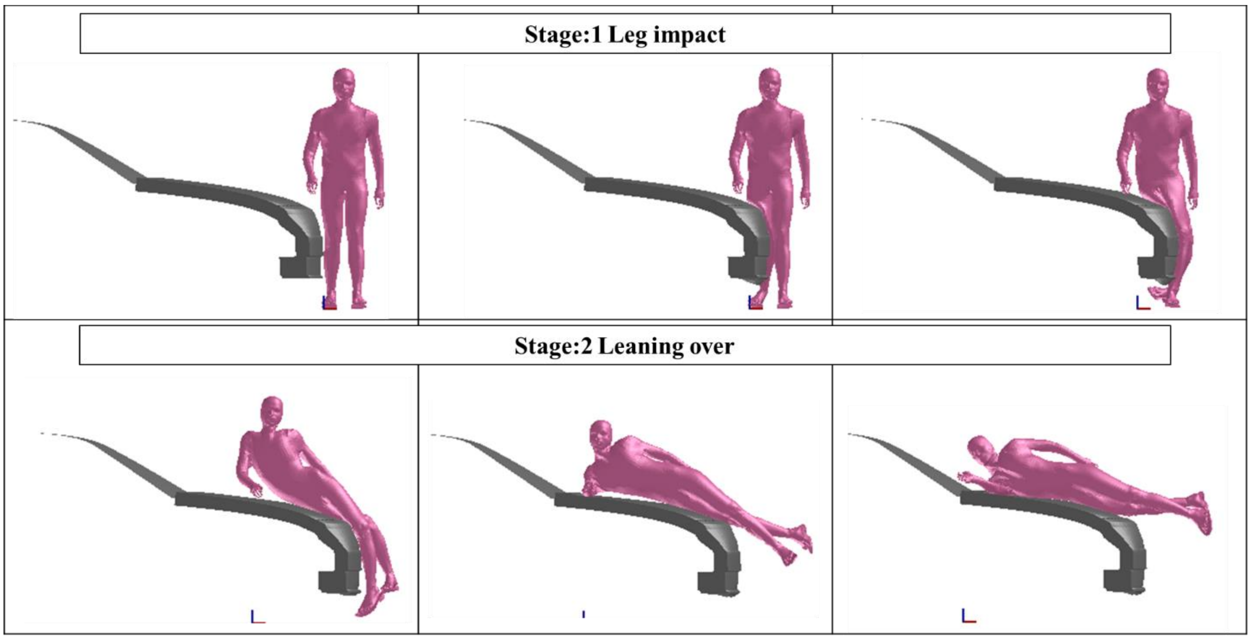

Figure 6 Evaluation of a typical SUV at the hood region with TIPT "with-arm & without arm" condition

This study simulated the different vehicle categories of GVM with different sizes (AM95, AM50 & AF05) of human body models (HBMs) at 40kph as shown in Figure 6. There are two stages of pedestrian-vehicle interaction; i) at first, the vehicle impacts the pedestrian's legs and causes injuries to leg bones (femur, tibia, fibula, etc.) and if the velocity is more, then the second stage will start ii) pedestrian slips and slides over the vehicle, which cause injuries to arms, chest, and head. At 40kph impact, AF05, AM50 & AM95 HBMs were impacted against different GVMs and the chest velocity is monitored at the time of contact between the vehicle and chest skin as shown in Table 1. The study reveals that

a) Chest impact velocity for a small family car (FCV) category is high, followed by MPV and SUV categories, It shows a similar trend recommended with BASt.
b) However, chest impact velocities identified are lower than those of BASt recommendations

Table 1: Chest impact velocity for FCV, SUV and MPV/VAN at 40kph impact speed

Chest impact velocity (kph)			
Category	**FCV**	**SUV**	**MPV/VAN**
BAST (Recommendation)	27	15	21
AM95	21.6	14.4	19.1
AM50	17.8	10. 1	14.4
AF05	18	6.1	11.9

Based on this limited case of the simulation studies, the proposed BAST impact velocities are high in all vehicle categories compared to the present simulation results which are tabulated in Table 1.

Effect of vehicle front-end profile

To understand the effect of different dimensional parameters of a vehicle's front-end profile (refer to Figure A2-1) on pedestrians' chest impact velocity on the hood, the morphing technique is used in this present study. Morph volume-based method was used to develop a series of new front-end profiles created from the original base vehicle. The front-end profile dimensions, such as BLE height, hood angle, bumper profile heights at different locations, etc., are some of the top influential parameters having a higher degree of sensitivity with respect to the chest impact velocity of AM50 HBM. Among all geometric parameters, the position of the BLE with respect to the pedestrian's CG location, which is located near the sacrum of the pedestrian, is the most influential parameter (relative sensitivity of 72%) in determining the kinematics of the chest as shown in the sensitivity chart of Figure A2-1. As the BLE height increases to a level of 120% of the BLE of the reference vehicle (BLE:100%, chest velocity:100%, as shown by the red dot of Figure A2-2), the CG of the pedestrian will be almost equal to the BLE height. The gradient of chest impact velocity becomes flat as highlighted by the blue segment in Figure A2-2.

DISCUSSION

Effect of impact velocity

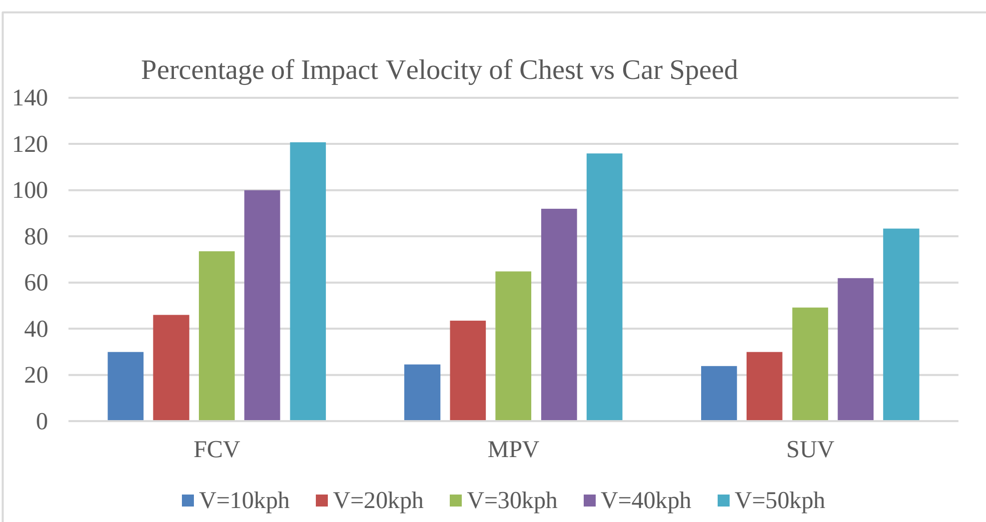

Figure 7. Impact velocity influence on chest velocity (normalized with FCV, V40kph as 100%)

Encompassing a wider range of real-world traffic accidents, the AM50 human model was impacted against different GVMs at different velocities ranging from 20 to 50 kph (Figure 7). Chest impact velocity is positively correlated with impact velocity. Linear relationships exist between chest impact velocities and the corresponding impact velocities for different GVM. Irrespective of the initial impact velocity of the car, the chest impact velocity for sedan/small (FCV) cars is higher compared to those of other types of GVM. As the height of the bonnet leading edge (BLE) increases, the overlap portion and the initial contact area of the lower part of the pedestrian with the vehicle front end will be increased. As a result, the vehicle will exert more horizontal force to throw or push the pedestrian forward further. Consequently, there will be more forward translational movement causing a delay in the start of the rotational movement of the upper part of the pedestrian. Hence, the impact velocity of the chest just before it touches the hood will be significantly reduced.

Effect of walking speed

In general, walking speed significantly decreases as age increases. Walking speed decreases slightly each year as one gets older. This averages out to a difference of 1.2 minutes slower for every kilometer at age 60 than at age 20. However, the walking speed changes over time, with smaller velocities in the first, and larger velocities in the second half of the crossing time at the intersection [Asano, 2017]. The AM50 human model was impacted against different GVMs at 40kph impact velocity and a walking speed of 3.5kph and 5kph. Pedestrian walking speed has less influence on chest impact velocity, as the lateral walking speed component near an intersection is much less than the impact

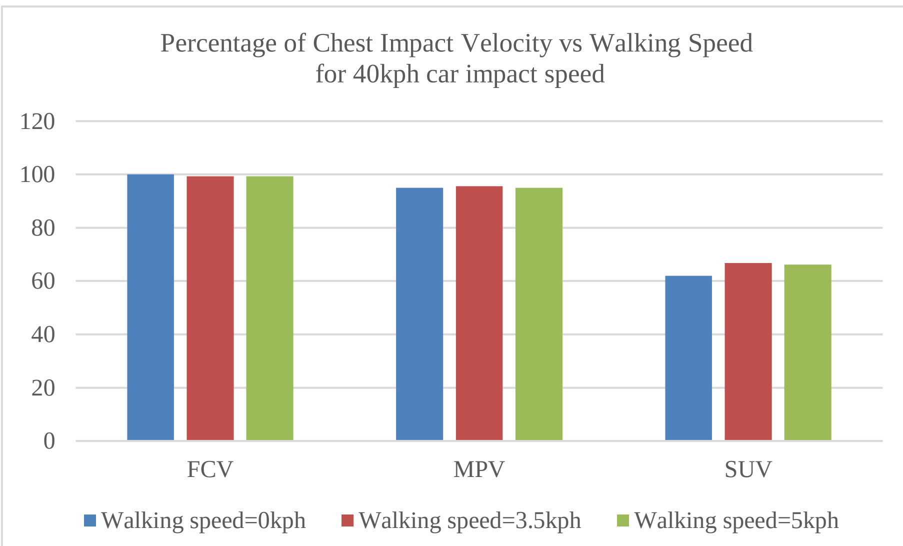

Figure 8. Influence of walking speed on chest impact velocity (normalized by FCV, AM50 walking speed 0kph)

velocity of the vehicle (refer to Figure 8). However, the situation will be different, in the case of bicyclists who travel at a relatively higher speed of an average of 15 kph than a pedestrian. Refer to the paper by Pal, et al. [Pal, 2020] for a detailed study of bicyclist kinematics which shows the effect of the speed of the bicycle.

Pediatric injury protection

The thoracic cage of a child is more elastic and flexible than that of an adult. Age-related bone diseases like osteoarthritis, osteoporosis, osteomalacia, and osteopenia are very less likely in children compared to adults and the elderly >65 year-old population. Children have significantly lower mortality than adults, despite having similar Injury Severity Scores, ISS. Compliance of the pediatric thorax is much greater than that of the adult thorax, because of the pliability of the cartilage and bony structure. With the same level of mortality, ISS=15 for adults is equivalent to ISS=25 for children [Skinner 2015, Brown 2017].

Based on human body models (Figure A3), the approximate child chest mass is 5-7 kg (height =178 mm, width =195 mm, depth = 111mm) and it is quite different from TIPT characteristics (mass=22.2kg, height =272 mm, width = 302mm, depth = 268mm). TIPT was derived from an adult side impact dummy with 22.2kg mass and injury criteria based on 67-year-old and 45-year-old populations (Figure 4). It may be a debatable issue whether such an adult dummy-based TIPT chest module can be used for predicting pediatric chest injury accurately.

TIPT evaluation with or without arm

The arm and shoulder will play an important role in rib deflection. In most real-world scenarios, a pedestrian's arm and shoulder will influence the level of chest injury. As a rational approach, the TIPT module should be evaluated with arms for more accurate chest injury estimation. From Figure 9, it is evident that the pedestrian arm interacts with the vehicle before the chest impact. From Figure 10, it is also evident that the 'TIPT with arm' rotation behavior is different from TIPT 'without arm'.

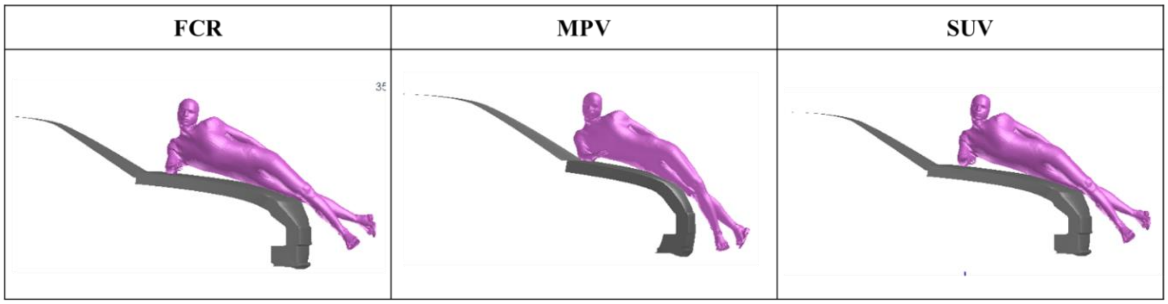

Figure 9. Typical arm interaction just before chest impact with the hood for different GVMs

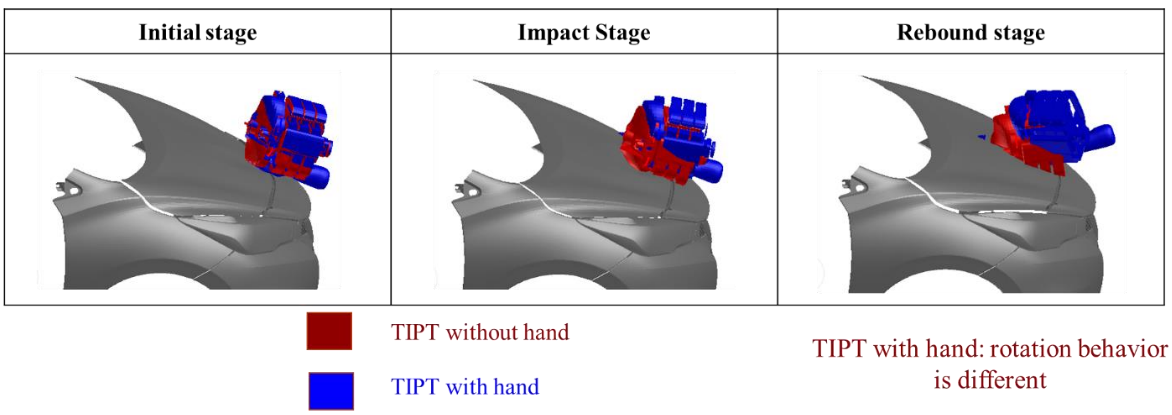

Figure 10. TIPT kinematic impact behavior with-arm and without-arm after hood contact

Effect of TIPT arm angle

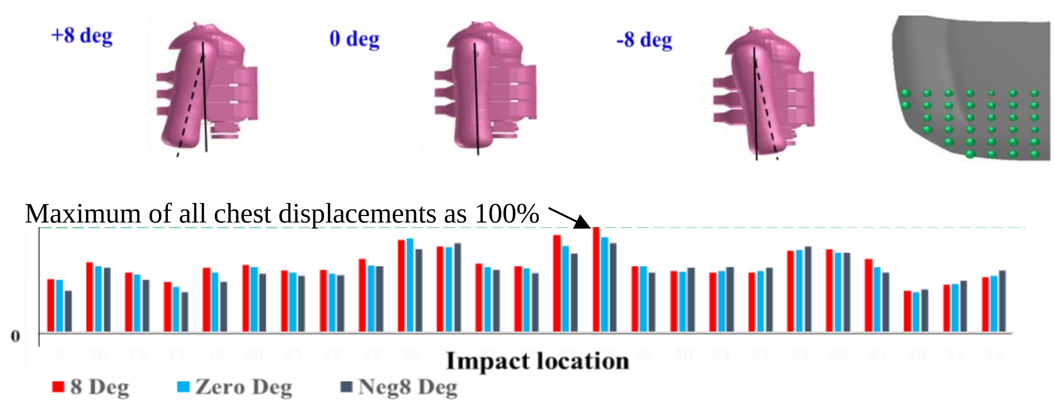

Figure 11. Arm angle influence on TIPT displacement for a typical SUV vehicle hood based on BAST test evaluation procedure at different locations as marked green on the hood.

TIPT with 3 different arm angle positions (-8 deg, 0 deg, +8deg) were impacted against the typical SUV vehicle as shown in Figure 11. Irrespective of TIPT arm angle positions, rib deflection for all impact locations will vary in the order of 12% for TIPT arm angle variations -8 deg. to +8 deg with respect to its corresponding values at 0 deg. vertical arm position. Hence, the arm angle is not a significant influential parameter for TIPT chest displacement.

Effect of vehicle speed on impact chest-spine angle before impact

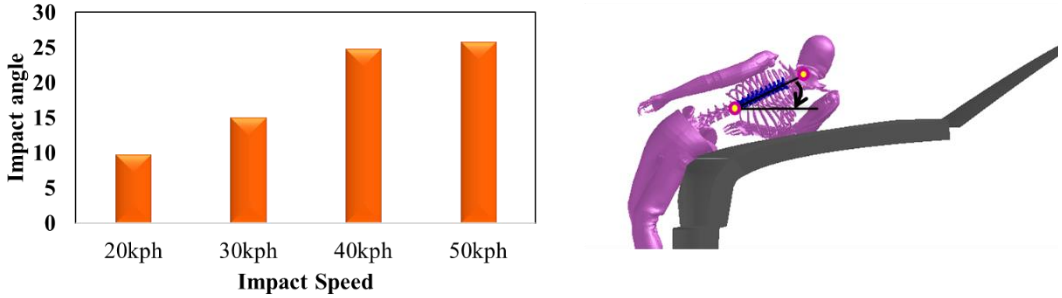

Figure 12. Variation of chest-spine angle for AM50 HBM impacted with SUV GVM with different speeds.

Figure 12 shows the variation of the chest-spine angle of AM50 HBM impacted with an FCV GVM for different vehicle speeds of initial impact. There is a positive increasing linear relationship between the chest-spine impact angle of HBM AM50 and vehicle impact speed. However, above 40kph vehicle speed, the gradient of change of chest-spine angle is decreased. The values of TIPT impact angles (refer Figure 4, FCV:15deg., SUV: 20 deg. and MPV:28deg.) as proposed by BAST [Oliver, 2019] are slightly different from the respective GVM-based simulations results of chest-spine angles (FCV:16.7deg., SUV: 25deg. and MPV:18.5deg.). As shown in Figure A4, the kinematics of the upper extremity above the pelvis undergoes three stages, i) initial state ii) intermediate hand interaction state and iii) final chest interaction state. However, at a high speed of 50kph impact, there will be no distinct separation between the intermediate hand interaction state and final chest interaction state. Due to the higher inertia effect at 50kph, the leaning/deformation patterns of the spine and head are different when compared with those of the 20kph kinematics. As a result, the chest impact angle is high for a 50kph impact.

Considerations for future evaluations

In the future, in regulations and NCAP evaluation procedures, if such test procedures are necessary to be introduced to ensure better chest injury protection to address the issue of increasing elderly pedestrian population using existing dummy chest modules, one needs to keep in mind the following point also.
A detailed accident data analysis is necessary to identify the actual benefits of new evaluation procedures [Henrik Liers, 2009] and to establish relevant detailed test procedures with a sufficient level of confidence related to repeatability and reproducibility. Further, detailed basic research is necessary before it is to be implemented in actual vehicle safety performance evaluations in the future to include findings from real-world accident data and associated effectiveness studies in the development of passive safety measures, legislation tests, or ratings like NCAP.
Based on the outcome of ongoing European HBM4VT WG activity and the trend of roadmaps of Euro-NCAP, from 2026 onwards, the NCAP evaluations will have more focus on using digital virtual testing procedures. Hence, it may be a more rational approach to incorporate the present TIPT based pedestrian chest injury evaluation procedure within the above framework.

CONCLUSION

To check the impact velocity conditions of TIPT test procedures as mentioned by BASt in the 2019 ESV paper, Euro-NCAP recommended GVMs and detail GHBMC HBMs are used in the present study to check the impact velocity conditions of TIPT test procedures as mentioned by BASt in the 2019 ESV paper, It is observed that, the chest impact velocities are lower than those proposed by BASt.

Chest impact velocity for a family small car (FCV) is highest, followed by MPV and SUV. The height of the BLE of a vehicle will be inversely proportional to the chest impact velocity of the thorax on the hood. Based on the present sensitivity study of vehicle front-end profile parameters, it is more appropriate to define the impact speed of TIPT more precisely as a function of the height of the BLE of the vehicle under consideration instead of defining it approximately by a broad category definition of the vehicles.

Unlike a faster bicyclist's travel speed, a slower pedestrian walking speed will have negligible influence on chest impact velocity.

Based on accidents in real-world scenarios, TIPT with arms should be considered for chest injury evaluation. Arms will interact with the thorax before hitting the hood as observed in all simulations of the present study. A detailed TIPT model is developed to check the kinematics of TIPT in "with arm" and "without arm" impact conditions. However, the position or angle of arm has marginal effect.

However, for child chest protection evaluation criteria, a separate impactor should be considered to represent not only the chest geometry (size, shape, etc.) but also, appropriate chest injury criteria which are very different from those of adults [Brown, 2017].

REFERENCES

Wisch M., Vukovic E., Schäfer R., Hynd D., et al., (2017). "Road traffic accidents involving the elderly and obese people in Europe including investigation of the risk of injury and disabilities." SENIORS Deliverable D 1.2.

Wisch M., Zander O., Vukovic E., Schäfer R., Hynd D., Fiorentino A., et al., (2017), "Road traffic crashes in Europe involving older car occupants, older pedestrians or cyclists in crashes with passenger cars – results from SENIORS." Paper no. 17-0398 of 25th ESV conference proceedings, Detroit, 2017.

Ito, et al, (2015), "Analysis of pedestrian and bicycle rider injury occurrence using JTDB", Journal of the Japanese Council of Traffic Science Vol.15 No.2 2015.

D L Skinner, et al., (2015) "Severe blunt thoracic trauma: Differences between adults and children in a level I trauma center", South Africa Medical Journal 2015;105(1):47-51.

Joshua B. Brown, et al., (2017), "The value of the Injury Severity Score in pediatric trauma: Time for a new definition of severe injury?", Journal Trauma Acute Care Surgery. 2017 June; 82(6):995–1001. doi:10.1097/TA. 0000000000001440.

Lowne R., Janssen E. "Thorax injury probability estimation using production prototype EUROSID." ISO/TC22/SC12/WG6 document N302.

European New Car Assessment Programme 2018-2. "Assessment Protocol – Pedestrian Protection Version 9.0.4" Euro NCAP, September 2018. www.euroncap.com.

Oliver Zander, Marcus Wisch, et al., (2019), "Development and Evaluation of A Thorax Injury Prediction Tool (TIPT) and Possibilities for Incorporation Within Improved Test and Assessment Procedures – Results From Seniors", paper no. 19-0014, 26th ESV conference proceedings,

Ziegler DW, Agarwal N.N. (1994), "The morbidity and mortality of rib fractures", J Trauma 1994;37(6):975–979.

RB, Bass SM, Morris JA, MacKenzie E., (1990), "Three or more rib fractures as an indicator for transfer to a level I center: A population-based study", J Trauma 1990;30(6):689–694.

"Pedestrian Human Model Certification Euro-NCAP pedestrian TB024", https://cdn.euroncap.com/media/66108/tb-024-pedestrian-human-model-certification-v301.pdf.

Chinmoy Pal, et al., (2020), “Comparison of Head Kinematics of Bicyclist in Car-to-Bicycle Impact”, paper number 2020-01-093, SAE 2020 World Congress.

B. Johan Ivarsson and Jeff R. Crandall, (2006), Influence of Age-Related Stature on the Frequency of Body Region Injury and Overall Injury Severity in Child Pedestrian Casualties, Traffic Injury Prevention, 7:290–298, 2006.

HBM4VT (2022), https://projectvirtual.eu/2022/10/31/virtual-testing-with-human-body-models-global-initiatives/

Henrik Liers, (2009), “Benefit Estimation of the EURONCAP Pedestrian Rating Concerning Real World Pedestrian Safety”, Paper 09-0387 ESV2009.

M. Iryo-Asano et.al. (2017), “Modeling pedestrian crossing speed profiles considering speed change behavior for the safety assessment of signalized intersections,” Accident Analysis & Prevention, vol. 108, pp. 332–342, 11 2017

NOMENCLATURES

ADAS: Advanced Driver-Assistance Systems
AM95, AM50 & AF05: Male 95%ile, Male 50%ile, Female 05%ile population
BLE: Bonnet Leading Edge,
BLR-RL: Bonnet Leading Edge Reference Line
EUROSID-2(ES-2): European Side Impact Dummy
GVM: Generic Vehicle Model
HBM: Human Body Model
HBM4VT: Human Body Model for Virtual Testing
ISS: Injury Severity Score
TIPT: Thorax Injury Prediction Tool,
WAD: Warp Around Distance

APPENDIX

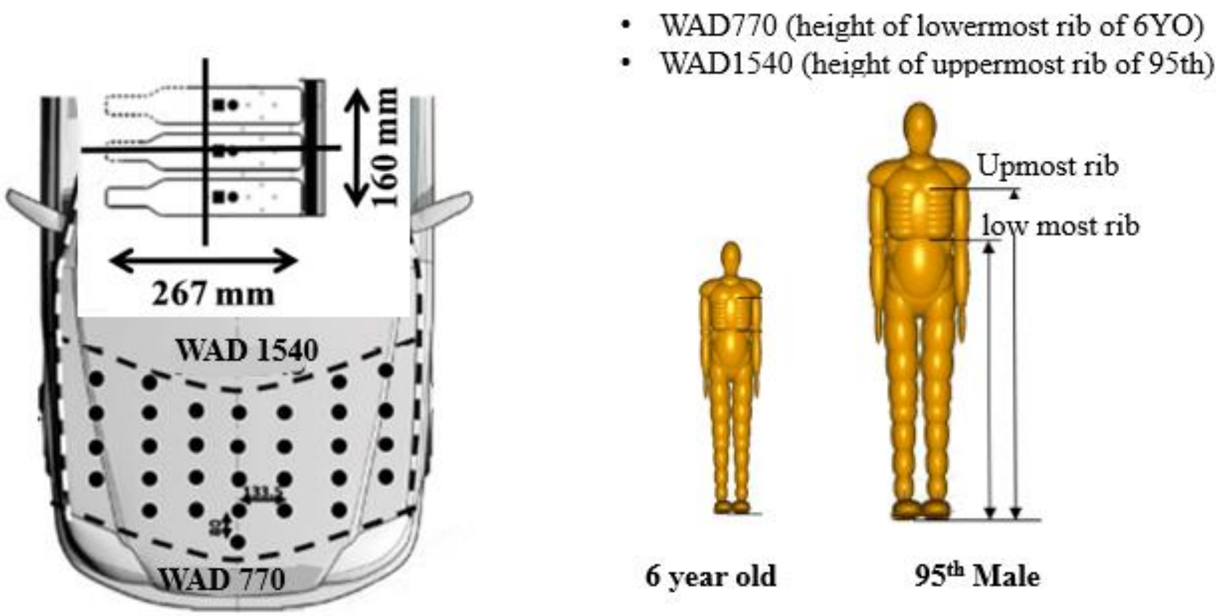

Figure A1. TIPT evaluation Grid map locations with all impact target locations at the intersection of the TIPT middle rib and vertical rib center planes (Oliver, 2019)

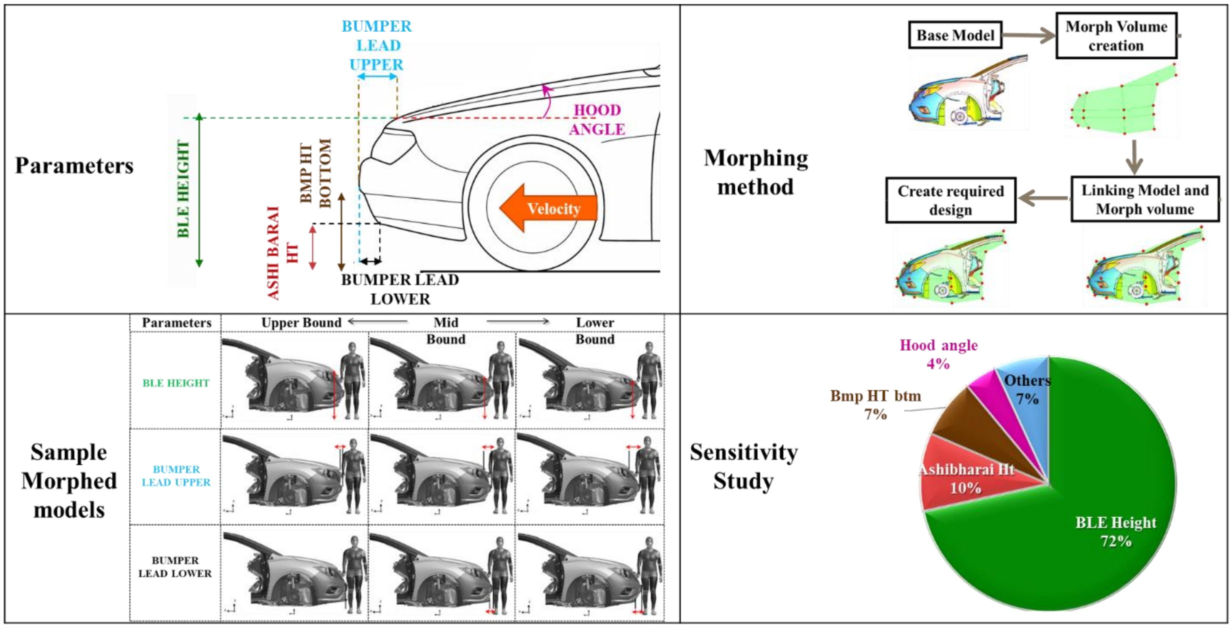

Figure A2-1. Morphing parameters, morphing method, morphed models and sensitivity chart of influential parameters for HBM AM50 chest velocity.

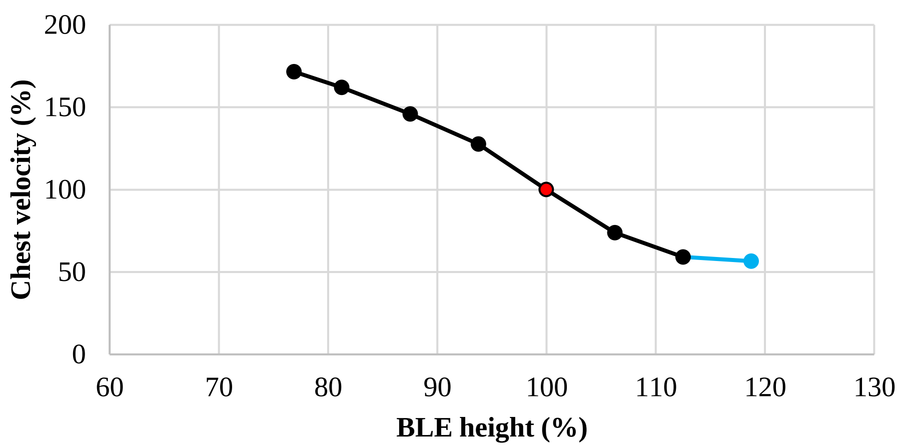

Figure A2-2. Sensitivity of chest impact velocity w.r.t BLE height of the original vehicle (100% as reference).

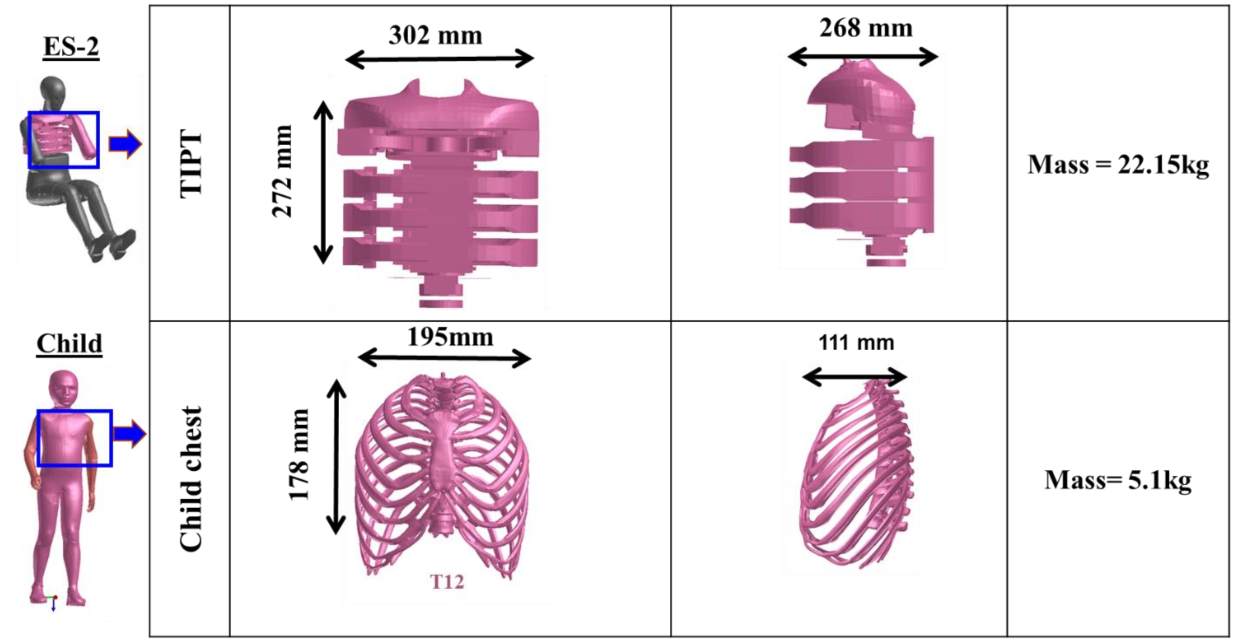

Figure A3. Comparison of chest size (TIPT vs Child)

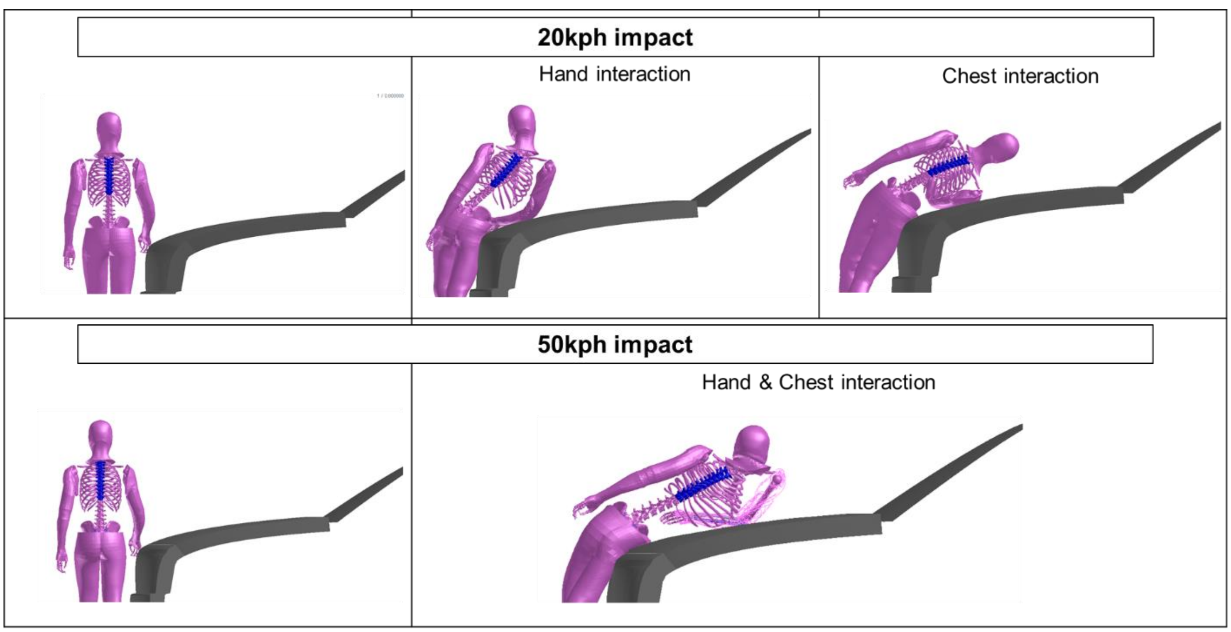

Figure A4. Impact velocity influence in chest spine angle