

# **DEVELOPMENT AND EVALUATION OF A THORAX INJURY PREDICTION TOOL (TIPT) AND POSSIBILITIES FOR INCORPORATION WITHIN IMPROVED TEST AND ASSESSMENT PROCEDURES – RESULTS FROM SENIORS**

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## **ABSTRACT**

Test and assessment procedures for passive pedestrian protection of passenger cars are in place for many years within world-wide regulations as well as consumer test programmes. Nevertheless, recent accident investigations show a stagnation of pedestrian fatality numbers on European roads alongside increasing injury severities for older road users. The EU-funded SENIORS (Safety ENhancing Innovations for Older Road userS) project developed and evaluated a thorax injury prediction tool (TIPT) for later incorporation within test and assessment procedures.

Accident data indicates an increasing portion of AIS2 and AIS3+ thoracic injuries of older pedestrians and cyclists which are currently not assessed in any test procedure for vulnerable road users. Therefore, SENIORS focused on the development of a test tool predicting the risk of rib fractures of vulnerable road users (VRU). While injury risk functions were reanalyzed, human body model (HBM) simulations against categorized generic vehicle frontends served as input for the definition of test setups and corresponding impact parameters. TIPT component tests against a generic frontend and an actual vehicle were used for the evaluation of the technical feasibility.

The TIPT component tests shows the general feasibility of a test procedure for the assessment of thoracic injuries, with good repeatability and reproducibility of kinematics and results. Impact parameters such as the inclination angles of the thorax, angles of the velocity vector and impact speeds well replicate the parameters gained from the HBM simulations. The proposed markup and assessment scheme offers the possibility of a homogeneous evaluation of the protection potential of vehicle frontends while maintaining justifiable testing efforts. During evaluation testing, the proposed requirements were entirely met.

The developed prototype of TIPT and launching system offer impact angles and speeds as suggested by HBM simulations. However, since thorax impacts during pedestrian accidents do not occur perpendicularly to the vehicle surface in most cases, the TIPT built-in linear potentiometers do not acquire the true resultant intrusions on the ribcage and thus, TIPT rib deflections do not reflect the actual human injury risk. However; for the impact forward to the bonnet leading edge, the TIPT seems applicable without further modifications.

The test and assessment procedures using the TIPT offer for the first time the possibility of replicating the kinematics of a pedestrian thorax with a component test. The developed assessment scheme gives a first indication

on how the risk for thoracic injuries could be implemented within the Euro NCAP Box 3 assessment. Future development of the TIPT may focus on implementing a rib cage that can deflect in all axes in a humanlike way.

## INTRODUCTION

Test and assessment procedures for passive pedestrian protection which are based on developments by the European Enhanced Vehicle-safety Committee (EEVC, 2002) have been introduced more than a decade ago within and harmonized to a large extent between world-wide regulations such as UN-GTR9 (2009) and consumer test programmes like Euro NCAP (2018). Despite continued improvements to passive vehicle safety of passenger cars, latest accident investigations resulted in a stagnation of pedestrian fatality numbers on European roads (European Commission, 2017), facing the risk of not meeting the European Union’s goal of halving the number of road fatalities by the year 2020. The EC-funded research project SENIORS under the HORIZON 2020 framework programme developed modified pedestrian test and assessment procedures and impactors with the aim to improve passive pedestrian safety. In-depth accident studies investigated the injury severity of the mostly affected body regions of vulnerable road users (VRU) to figure out relevant fields of action. Current pedestrian impactors were analyzed regarding their ability to address recent accident scenarios and remaining open gaps were closed describing new impactor concepts. Paired simulations with human body models (HBM) and impactor models against generic test rigs were performed to generate correlations that could be used for thoracic injury criteria. Finally, a test tool for predicting thoracic injuries was prototyped and tested according to modified test and assessment procedures.

## ACCIDENT STUDIES AND INJURY PATTERNS

A recent in-depth investigation of road accidents in Germany showed the injury severity of different VRU body regions subsequent to collisions with passenger cars. Besides the consistent relevance of severe pedestrian head and leg injuries in collisions with passenger cars registered between 1995 and 2005 and between 2006 and 2013 respectively, i.e. before and after implementation of pedestrian safety legislation, two body regions were in the focus of interest in accidents with type-approved passenger cars. The first was the pelvis area with 14.9 percent of all AIS2+ injuries and 23.3 percent of all AIS3+ injuries. The second body region, with an increased percentage of severe injuries was the thorax, having 17.2 percent of all AIS2+ injuries and 26.7 percent of all AIS3+ injuries. Therefore, in terms of AIS3+ pedestrian injuries, the thorax was the most relevant body region followed by the head, pelvis and lower extremities (Zander et al., 2015). A similar trend could be observed for bicyclists. Here, the relevance of head and leg injuries was nearly unchanged in terms of AIS2+ injuries. For AIS3+ injuries, a slight decrease was observed. Similar to the pedestrians, the thorax area demonstrated an increased relevance regarding AIS2+ as well as AIS3+ injuries. Altogether, focusing on AIS3+ injuries, lower extremities were the most relevant body region (34.1 percent), followed by the thorax (31.7 percent) and the head (17.1 percent). Also for AIS2+ injuries, these body regions remained the mostly affected ones.

SENIORS aimed to consider the safety needs in particular of older road users. Based on German and Swedish collision data from GIDAS and STRADA as reported by Wisch et al. (2017), the percentages of AIS1, AIS2, and AIS3+ injuries to the different body regions of the age groups 25-64 and 65+ are displayed in Figure 1 exemplarily for pedestrians in collisions with passenger cars:

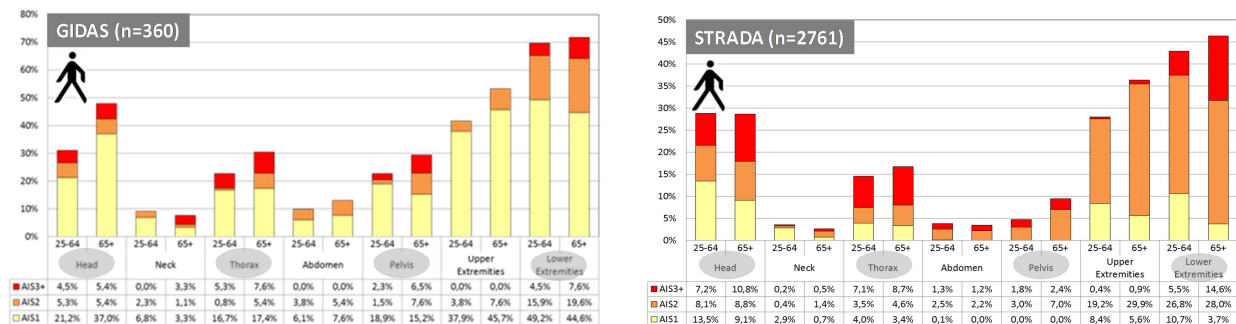


Figure 1. Percentages of injury severities for the different pedestrian body regions within GIDAS and STRADA. Each column adds up to 100 percent by adding all percentages from AIS0 to AIS9. (Wisch et al., 2017).

Both databases agree regarding the mostly affected body regions for pedestrians and cyclists and their particular relevance for the elderly. Regarding the pedestrian injury levels, head, thorax, pelvis and lower extremities are the most relevant body regions with the highest portions of AIS2 and AIS3+ injuries, with the elderly suffering more frequently from severe injuries than younger pedestrians.

Also injuries to bicyclists show the highest injury levels for the head, the thorax and the lower extremities being the key affected body regions for both age groups.

The data shows the thorax currently representing a higher percentage of severe injuries for both groups of vulnerable road users. Meanwhile, the importance of head and lower extremity injuries remains in most cases at the same level as before. Furthermore, injury severities of the elderly especially in the described body regions are higher than for the age group 25-64 years. It thus can be concluded, that the main focus in the revision and further development of impactors and test procedures needs to be settled to the head, the thorax and the lower extremities.

## METHODOLOGY

At this point in time, no component test procedures related to the assessment of thoracic injuries of VRU are in use. Fredriksson et al. (2007) reported about sled tests with the EUROSID 2 (ES2) dummy as external surrogate concluding good measurement capabilities for the chest and abdomen area. Based on these findings, the torso of the ES2 model was uncoupled for subsequent use as an injury prediction tool during pedestrian component tests. In a next step, simulations with the uncoupled ES2 torso, named thorax injury prediction tool (TIPT), were performed according to impact conditions previously defined by HBM simulations. Finally, tool revision and fine tuning were done towards improving the correlation between TIPT and HBM kinematics and loadings. For validation, physical component tests were carried out under various test setups with a prototyped TIPT against a generic vehicle front end as well as an actual vehicle model.

The general workflow for the development of the TIPT is illustrated in Figure 2:

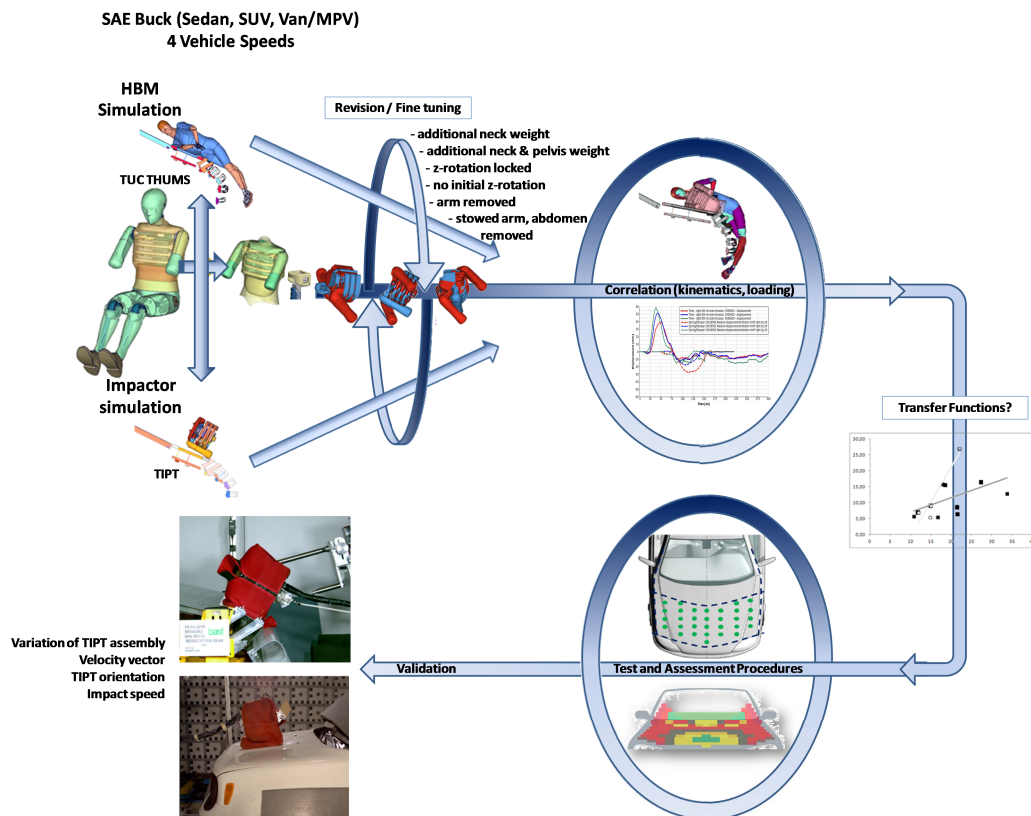
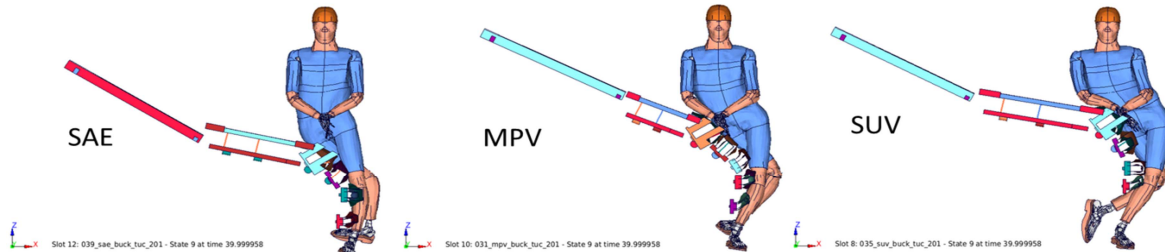


Figure 2. Workflow describing the development of TIPT and its test and assessment procedures.

## HUMAN BODY MODEL SIMULATIONS

First input for correlation studies to be carried out were HBM simulations with the Total Human Model for Safety of the THUMS User Community (THUMS TUC) against a vehicle buck of the Society of Automotive Engineers (SAE Buck – Pipkorn et al., 2012) and two derivatives, SUV and MPV, at vehicle speeds of 20km/h, 30km/h, 40km/h and 50km/h, see Figure 3:



**Figure 3. THUMS TUC simulations against SAE, MPV and SUV buck.**

THUMS TUC V2.01 was positioned in the stance according to SAE (2010) and impacted on its right side, i.e. rear leg impacted first. HBM tracking points that were recorded during simulations were head centre of gravity (CoG), neck (C1 and C7), thorax (T1 and T12), and pelvis. Rib 4, 6 and 8 lateral deflections were also recorded with implemented spring elements.

The present study was focusing on the thorax loadings, only. The thorax impact velocity relative to the car depended on both, Buck velocity and geometry. The SAE Buck impacted THUMS lower on the legs compared to the remaining two Buck geometries and gave the highest thorax rotational velocity. In all 30km/h load cases the left arm got trapped between the thorax and the bonnet, causing higher rib deflections. The highest deflection on the impact side was measured for the 30km/h MPV load case. On the non-impact side (left) the deflection increased with the impact velocity and seemed not to be affected by the impact location.

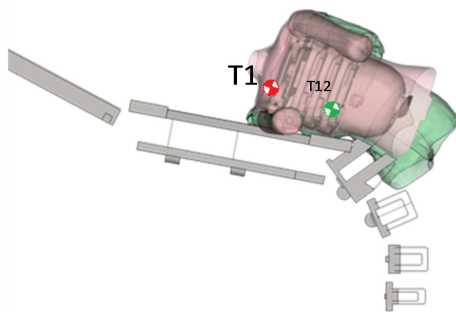
Subsequent simulations with TIPT used the thorax orientations and speeds of THUMS for each load case.

## FE IMPACTOR SIMULATIONS

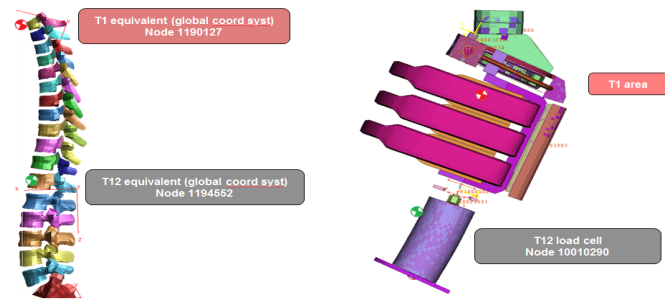
Finite element (FE) simulations with TIPT were carried out against identical setups and load cases, i.e. using the thorax orientations and speeds of THUMS for each load case, compare Figure 4.

### Setup and Evaluation Method

The TIPT readings used for comparison with the HBM results were rib deflection, spine acceleration and tracking points. To match HBM with TIPT anatomy for the tracking points, T1 and T12 were used, as illustrated in Figure 5.



**Figure 4. Comparative simulations with THUMS and TIPT.**



**Figure 5. HBM and TIPT points used for tracking and speed matching.**

For comparable results between HBM and TIPT simulations the impactor was propelled at angles, speeds and arm positions identical to those of the HBM at the time of head impact. While the HBM simulations were carried out with the Buck impacting the stationary HBM, the TIPT FE model was propelled against the stationary Buck.

### HBM vs. TIPT Correlation

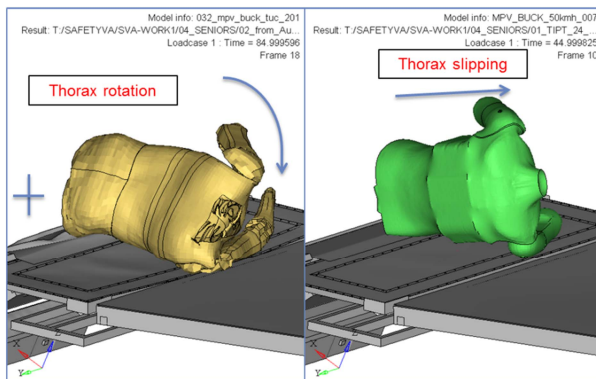
Altogether, seven test setups within five simulation loops with TIPT against the SAE Buck and its derivatives SUV and Van/MPV at impact speeds between 20 and 50km/h were carried out, see Table 1:

**Table 1.**  
**Overview of simulations with TIPT**

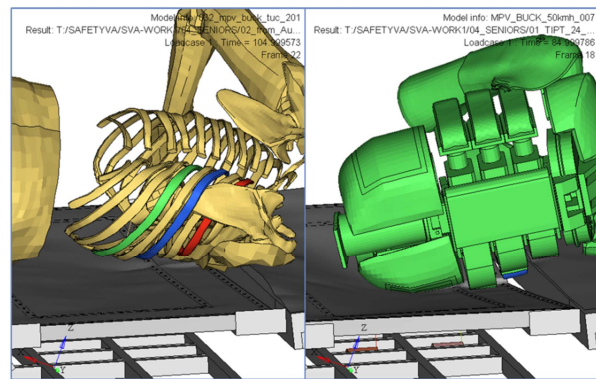
Loop	Description	Generic Frontends	Vehicle Speed
1	Baseline	Sedan, SUV, Van/MPV	20/30/40/50 km/h
2a	additional neck weight	Sedan, SUV, Van/MPV	20/30/40/50 km/h
2b	as loop2a but with additional pelvis weight	Sedan, SUV, Van/MPV	20/30/40/50 km/h
3	z-rotation locked	Sedan, SUV, Van/MPV	20/30/40/50 km/h
3r1	no initial z-rotation	Sedan, SUV, Van/MPV	20/30/40/50 km/h
4	w/o interaction arm vs. vehicle	Sedan, SUV, Van/MPV	20/30/40/50 km/h
5	as loop3r1 but with stowed arm w/o abdomen	SUV, Van/MPV	30/40 km/h

TIPT baseline simulations using the conditions derived from THUMS TUC simulations (loop1) showed the very low sensitivity of all three ribs of the ES2 ribset during low speed tests, while simulations at higher impact speeds resulted in higher deflections. These observations were underlined looking at the ribwise maximum TIPT displacement vs. the maximum THUMS rib intrusion. The best maximum correlation over all impact speeds and vehicle shapes was found for the 4th rib. On the other hand, when focusing on higher impact speeds ( $\geq 40\text{km/h}$ ) and under consideration of the maximum rib displacement over all ribs as injury assessment criterion, the coefficient of determination could be improved, compare Figure 8.

The impact condition of TIPT was assumed as the major reason for the altogether low correlation of maximum output values. Using the test setup of the baseline loop, the TIPT simulations were therefore amongst other things replicated neglecting the initial impactor rotation around the local z-axis (loop3r1). Here, at initial position, the TIPT was kept in a yz-plane parallel to the xz-plane of the impacted vehicle, being the plane in which rib displacement is measured with the ES2 dummy. While the correlation of readings was good to acceptable for lower impact speeds, the TIPT overpredicted the rib deflections at higher speeds in most cases. One of the reasons could be due to the different impact locations of THUMS ribs compared to those of TIPT, as demonstrated in Figure 6 and Figure 7.



**Figure 6. THUMS vs. TIPT kinematics on MPV SAE Buck 50 km/h simulation – rotation vs. translation.**



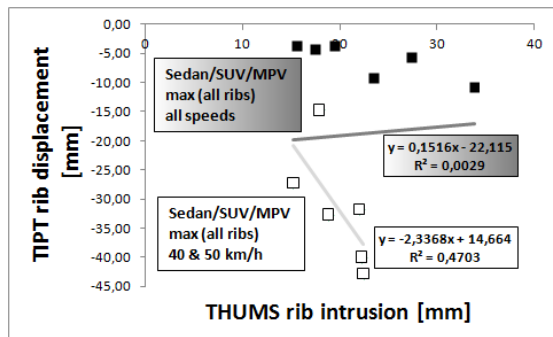
**Figure 7. THUMS vs. TIPT impact point on MPV SAE Buck 50 km/h simulation – different impact locations.**

During simulations at 50km/h with the Van/MPV Buck, a remarkably different thorax kinematics in the impact event (rotation with THUMS and translational sliding with TIPT) was found as the main cause of the different impact locations of the ribs. In this load case, the upper and middle TIPT rib deflection were influenced by the lower part of the windshield while the ribs didn't get in contact at all with the windshield during the THUMS simulation. Altogether, the global coefficient of determination for TIPT maximum rib deflection with THUMS maximum rib intrusion remained almost unchanged.

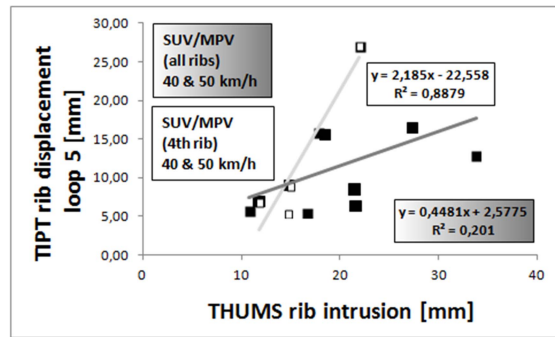
A fourth simulation loop was carried out, starting from the TIPT position neglecting the initial rotation around the z-axis and excluding the arm of the impactor from contact with SAE buck models. Intention was to determine the effect of arm interaction on peak rib deflection, showing a general overestimation of the peak loadings with TIPT. In some cases the interaction between TIPT ribs and SAE buck models were characterized by a high load on the ribs in the 'neck-pelvis' direction. The fourth simulation loop didn't show any considerable improvement. An increment of TIPT rib sensitivity at lower velocities was confirmed. There was however no further improvement of the coefficient of determination neither under consideration of the maximum deflection over all the ribs nor accounting for each rib separately.

A final simulation loop5 was carried out, using a revised TIPT FE model with stowed arm on the struck side and without abdomen, pelvis and without arm on the non-struck side, reducing the TIPT mass from 32.85kg to 22.15kg. These modifications aimed at increased feasibility and higher repeatability for subsequent physical testing. Using this TIPT configuration, the load cases at 30 and 40km/h on SUV and Van/MPV Buck models were replicated. Impactor positions and velocities were identical to those used in loop3r1.

Compared to loop3r1, loop5 showed lower rib deflections and a more uniform distribution of the peak rib deflections. The time histories for THUMS TUC and TIPT rib deflection were however hardly comparable. A correlation study using loop 5 simulations resulted in a reasonable coefficient of determination with THUMS, especially for the 4<sup>th</sup> rib, with a good linear correlation, see Figure 9:



**Figure 8. Correlation of THUMS maximum rib intrusion vs. TIPT maximum rib deflection at all and at higher impact speeds, loop 1.**



**Figure 9. Correlation of THUMS maximum rib intrusion vs. TIPT maximum rib deflection for all and for the uppermost rib at higher impact speeds, loop 5.**

In an effectiveness study of side airbags, Hayashi et al. (2006) investigated the responses between THUMS and ES2. While THUMS showed higher rib deflections in the lower parts, ES2 showed considerable deflections in the upper segments.

Altogether, the predominant discrepancy between THUMS and TIPT besides the different TIPT impact kinematics is represented by a rib extension phase of the HBM before the thorax impact against SAE Buck models, during all simulations. It was not possible to catch this phenomenon with the TIPT; thus the conditions of THUMS and TIPT ribs, immediately before the impact against all SAE Buck derivatives were very different in high velocity load cases.

### FE Simulations on actual Vehicle

Subsequent to the finalization of the TIPT model and test setup, further simulations were carried out on an actual SUV representative. Four simulations using loop5 setup were performed with TIPT impact points located in different areas of the bonnet. Three additional simulations were conducted against the grille area of the vehicle in order to replicate a possible impact between a high front-end vehicle and a small stature pedestrian.

The impact locations were positioned on the intersections of four different wrap around distance lines (WAD) with the longitudinal vertical vehicle centreplane and with two longitudinal vertical planes at a distance of 133.5mm (half

of the impactor width) inwards the side reference lines (SRL - contact line of a 700 mm straight edge inclined by 45° inwards on both sides of the car). The impact locations were aimed at with the TIPT reference point, defined by the intersection of the middle rib plane with the yz-plane passing through the shoulder reference point and the centre rib. The TIPT was then rotated and aligned on the WAD along the direction of the velocity vector. The simulations against the SUV bonnet resulted in very low levels of rib deflection ( $\leq 11$  mm) and spine acceleration ( $< 10g$ ). During the simulations against the grille, the perpendicular orientation and different kinematics of TIPT led to significantly higher rib deflections (17.8-55.3mm) and spine accelerations (29.5–54.4g).

## TIPT DESIGN AND PROTOTYPING

As test tool, the ribcage of the ES2 was used as standalone TIPT. Simulations concluded to add the ES2 arm in stowed position on the impact side. This was realized using a TIPT suit with fixed sleeve, compare Figure 10. A pusher device was designed for attachment to the pedestrian test stand, with the possibility of adjustment of the impact angle within the launcher to the values defined according to the test procedures, see Figure 11:



Figure 10. Final TIPT prototype.

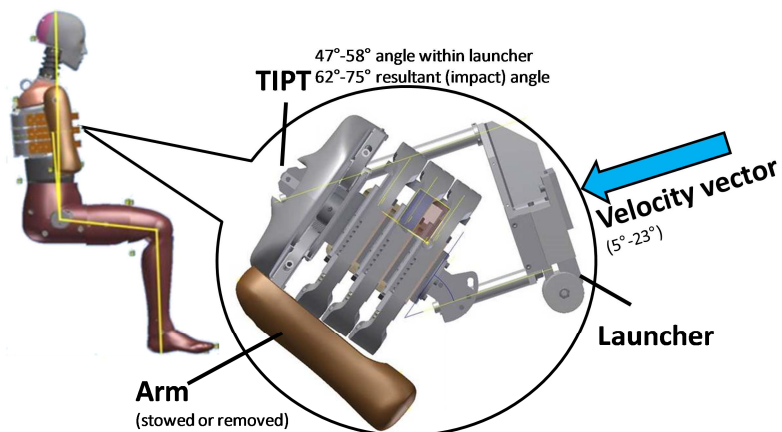


Figure 11. TIPT setup and launching device.

## TEST PROCEDURES

### Anthropometric Data

For an assessment of the VRU protection potential of passenger cars related to thoracic injuries, information on the human and dummy anthropometry as well as the kinematics of impact is needed.

In principle, the entire vehicle front can contain potentially injury causing parts affecting the human thorax during an accident. The test and assessment area for the thorax however further depends on the vehicle height, human anthropometry and the dimensions of the impactor to be used. Figure 12 summarises the most relevant human data for the 5th female, the 50th male, the 95th male (DIN, 2005) and the thorax-related proportions derived from the human body models THUMSv4 and the family of MAThematical DYnamic MOdels (MADYMO). Based on anthropometric data, the test area should be described by WADs coinciding with the height of the lowermost rib of the six year old child (6YO) and the height of the uppermost rib of the 95<sup>th</sup> adult male. Under consideration of THUMS 50th, the area would then be described by WAD 1192 and WAD1485. Taking into account the MADYMO family (6YO–95<sup>th</sup>), the test area would be limited by WAD770 and WAD1540.

Since the TIPT is derived from the ribcage of the ES2 (between WAD1156 and 1316), the test area needs to be verified against all locations on the vehicle front that can potentially be impacted by the ES2. Figure 13 shows the dimensions including the theoretical standing height of the ES2 dummy. From these measurements, the potential impact area of the ES2 ribcage can be approximated between WAD 1156 and 1316. The entire ribcage is thus covered by the impact area described by the anthropometric data as shown in Figure 12.

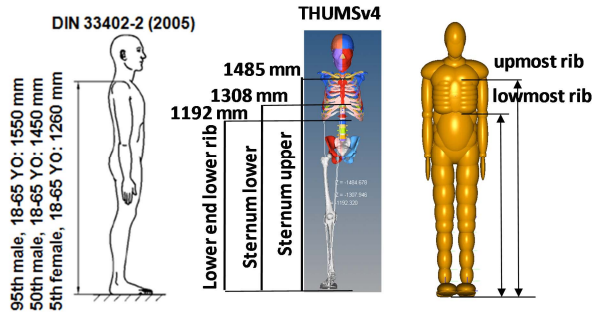


Figure 12. Anthropometric data: human, THUMSv4 (50<sup>th</sup>) and MADYMO.

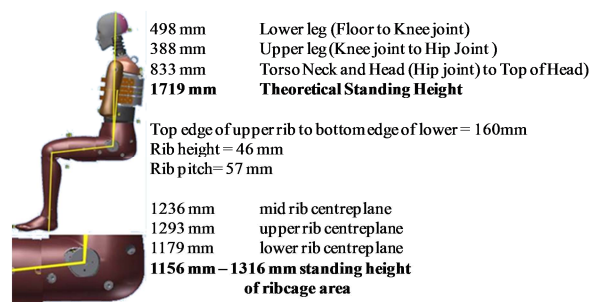


Figure 13. Dimensions and theoretical standing height of ribcage area of ES2 dummy.

### Vehicle Markup

The test area for TIPT that needs to cover the aforementioned aspects is thus defined by:

- WAD770 (height of lowermost rib of 6YO)
- WAD1540 (height of uppermost rib of 95th)
- SRLs.

All impact points are aimed at with the intersection of the TIPT mid rib and vertical rib centreplanes (see Figure 14). Furthermore, all impact points are located within the test area and

- 80mm rearward of WAD770 (=WAD850)
- 80mm forward of WAD1540 (=WAD1460)
- 133.5mm laterally inwards the SRLs.

A grid with a resolution of 133.5mm\*80mm derived from the dimensions of the ES2 ribcage (compare Figure 14) is marked on the vehicle, starting with the intersection of y0 with WAD850, marking a grid point every 80mm in rearward wrap around direction until WAD1460. Starting from each y0 intersection with the particular WAD, it is moved laterally rightwards (leftwards) and a grid point is marked every 133.5mm until 133.5mm laterally inwards the SRL, see Figure 15:

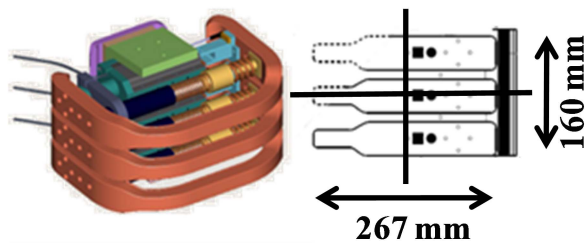


Figure 14. ES2 ribcage dimensions.

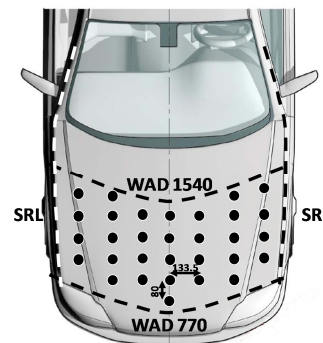


Figure 15. TIPT test area and vehicle markup.

### Test Parameters

TIPT impact speeds and angles have been determined during the FE simulations of THUMS TUC against the SAE Buck and its derivatives. It has been found that thorax speed and impact angle mainly depend on the geometry of the vehicle front. Thus, the TIPT speeds and angles derived from the HBM simulations mainly depend on the vehicle to be tested. The categorization of vehicles should in principle follow the method developed by the International Harmonized Research Activity Pedestrian Safety Working Group IHRA (Mizuno, 2005).

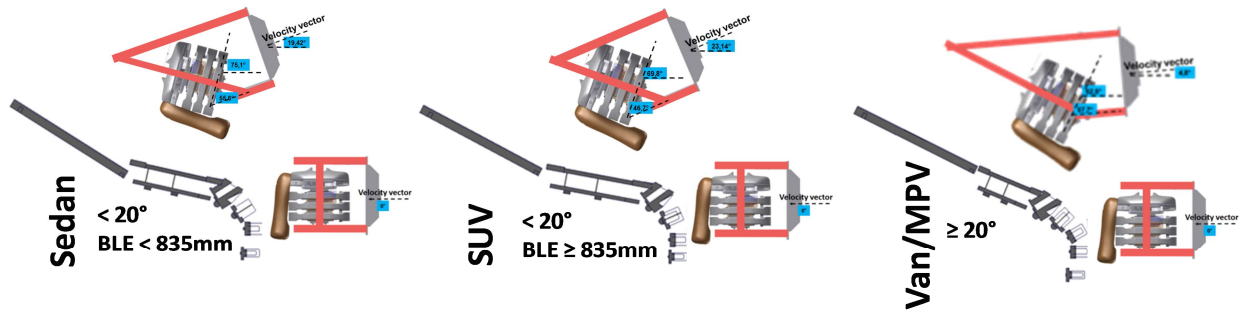
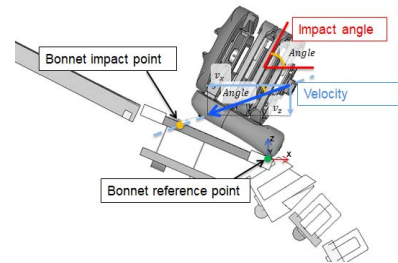


Subsequent, the TIPT impact speeds, impact angles and angles of the velocity vectors derived from the corresponding parameters of the thorax during THUMS TUC simulations were defined as outlined in Table 2 and illustrated in Figure 16:

**Table 2.**  
**Impact parameters for TIPT component tests**

	Vehicle category	Sedan	SUV	Van / MPV
Rwd to BLE-RL*	TIPT impact angle	15 ° (75°)	20° (70°)	28 ° (62°)
	Angle of velocity	19°	23°	5°
	TIPT impact speed	27 km/h	15 km/h	21 km/h
Fwd to BLE-RL*	TIPT impact angle	90° (0°)		
	Angle of velocity	0°		
	TIPT impact speed	40 km/h		

\*: Bonnet Leading Edge Reference Line



**Figure 16. Illustration of impact parameters for TIPT component tests.**

These angles, due to the kinematics of the human thorax during the impact, differ from each other, i.e. that also the angle of the velocity vector in the component test is not perpendicular to the TIPT.

## ASSESSMENT

### Derivation of Impactor Thresholds

Until 2014, the ES2 dummy was used as a car occupant surrogate in the Euro NCAP lateral impact tests. Limits for the lateral chest compression were used as assessment indicator for 45YO and 67YO car occupants suffering AIS3 injuries. While the upper performance limit for maximum rib deflection in both crash modes was set to a value of 28mm, representing a 5% AIS3 injury risk for the 67YO, the lower performance limit and, in terms of the side impact with the mobile deformable barrier, the capping limit, were defined at 50mm, indicating a 30% AIS3 injury risk for the 45YO. The capping limit for the pole side impact was defined at 55mm, representing a 50% risk of the 45YO for suffering AIS3 injuries (Euro NCAP, 2014).

Lowne et al. (n.d.) developed risk curves for suffering AIS2+, AIS3+ and AIS4+ thoracic injuries as functions of peak rib deflections out of PMHS tests and normalized the results to a 45YO and to the production prototype EuroSID injury parameters. The presented injury risk functions were based on four series of PMHS tests performed in the 1970's and 1980's, using AIS injury coding. The same injury risk functions still form the basis of the UN Regulation 95 (UNECE, 2014) thorax performance requirement and thus were used in the SENIORS project.

In accordance with findings from the accident data analysis, SENIORS focused on AIS3+ injuries. Following the 5 color scheme being applied in the Euro NCAP VRU assessment (Euro NCAP, 2018-2), the TIPT total score is calculated from threshold values for maximum rib deflection.

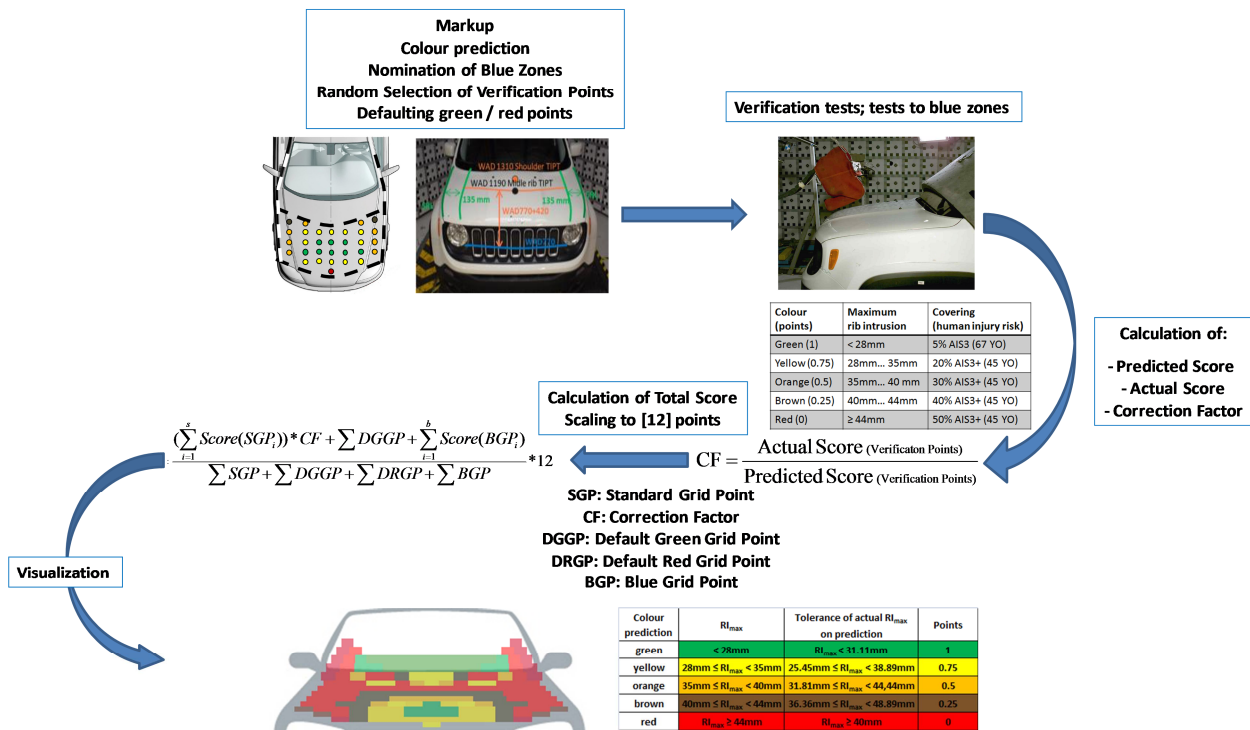
## Test Synthesis

Prior to testing, a prediction of grid point results is to be given by the vehicle manufacturer for the performance in terms of maximum rib deflection, to be indicated with the colors green – yellow – orange – brown – red, compare Table 3:

**Table 3.**  
**TIPT thresholds (maximum rib deflection)**

Colour (points)	Maximum rib deflection	Covering (human injury risk)
Green (1)	< 28mm	5% AIS3 (67 YO)
Yellow (0.75)	28mm... 35mm	20% AIS3+ (45 YO)
Orange (0.5)	35mm... 40 mm	30% AIS3+ (45 YO)
Brown (0.25)	40mm... 44mm	40% AIS3+ (45 YO)
Red (0)	≥ 44mm	50% AIS3+ (45 YO)

Random test point selection is to be done according to the headform test procedure of Euro NCAP (2018). Following the approach for the upper legform impactor assessment, the maximum rib deflection for each TIPT impact location is taken into account. As for the headform test, a grid approach is also followed for the TIPT impact procedure. For consistency with the current assessment procedures, the total amount of points is calculated by scaling the total grid point score to the maximum number of achievable points for this subsystem test. Visualisation of results is done likewise to the headform procedure. The flowchart of TIPT testing and assessment is illustrated in Figure 17:



**Figure 17.** TIPT testing and assessment flowchart.

## Scenario for Euro NCAP Box 3 Rating

The Euro NCAP Pedestrian Test and Assessment Procedures currently include the child and adult headform, the upper legform and the FlexPLI with a weighting of 66 ⅔ vs. 16 ⅔ vs. 16 ⅔ percent (Euro NCAP, 2018-2). Recent studies of injuries suffered by pedestrians and bicyclists for all age groups and focused on the elderly (65+) during collisions with passenger cars in Germany confirm a change in injury patterns in the last years. Here, depending on where the focus is set, different scenarios for balancing the nowadays most relevant body regions head, thorax and lower extremities (including femur, knee and tibia) are possible. In light of a considerable number of AIS3+ injuries to the mentioned body regions within the GIDAS database it is suggested to equally balance the three body regions in a first step, allocating a maximum of 12 points to each the head, the thorax and the lower extremities (introducing the FlexPLI with upper body mass) within Euro NCAP Box 3. This, in the end, would result in scaling the thorax test synthesis to the maximum of 12 points.

Altogether, if the weighting for AEB Pedestrian and Cyclist systems remained unchanged after 2019, the Box 3 rating scheme would result in a point distribution as summarised in Table 4:

**Table 4.**  
**Possible scenario for Box 3 weighting, in-Box balancing and overall balancing of pedestrian safety performance in Euro NCAP after introduction of the TIPT test procedures**

Test Procedure / Year	Score	2016-2017		2018-2019		2022		Score	Test Procedure / Year
<b>Headform</b>	24	24	57,1%	24	50,0%	12	25,0%	12	<b>Headform</b>
<b>Upper Legform</b>	6	6	14,3%	6	12,5%	12	25,0%	12	<b>TIPT</b>
<b>Lower Legform</b>	6	6	14,3%	6	12,5%	12	25,0%	12	<b>FlexPLI-UBM</b>
<b>AEB Pedestrian</b>	6	6	14,3%	6	12,5%	6	12,5%	6	<b>AEB Pedestrian</b>
<b>AEB Cyclists</b>	6			6	12,5%	6	12,5%	6	<b>AEB Cyclists</b>
<b>Total</b>		42	100,0%	48	100,0%	48	100,0%		<b>Total</b>
<b>Total passive</b>		36	85,7%	36	75,0%	36	75,0%		<b>Total passive</b>
<b>5 star threshold (Balancing)</b>		25,2	60%	28,8	60%	28,8	60%		<b>5 star threshold (Balancing)</b>
<b>4 star threshold (Balancing)</b>		21	50%	24	50%	24	50%		<b>4 star threshold (Balancing)</b>
<b>Min. passive for AEB inclusion</b>		22	61,1%	22	61,1%	22	61,1%		<b>Min. passive for AEB inclusion</b>

## TIPT TESTING

Taking into account all HBM and TIPT simulations, loops3r1 and 5 were considered as reflecting the most realistic as well as most feasible impact conditions for physical testing. Therefore, it was decided to initially use these setups and TIPT geometries for the experimental test programme.

Several tests were performed against the SAE Buck and its derivatives and against one actual SUV front-end. For comparison, two tests were carried out as full scale tests with the Sedan Buck against the ES2 pedestrian dummy with first impact at vehicle centerline. All further tests were performed as pedestrian component tests, using TIPT. The major goal was to check the applicability of the defined draft test procedures alongside the sensitivity of the test tool, to investigate the correlation between FE simulation and physical testing and to study the impactor behaviour at the lateral borderlines of the test area.

An overview of all tests with TIPT is given in Table 5. Altogether, 24 tests with the TIPT were performed. For each of the vehicle categories represented by the SAE Buck, baseline TIPT tests were carried out, following the standard test configuration used in the TIPT simulations. At a later stage, several parameters were changed to investigate the test tool performance and sensitivity. Moreover, TIPT tests following the defined test protocol were performed against an actual SUV representative.

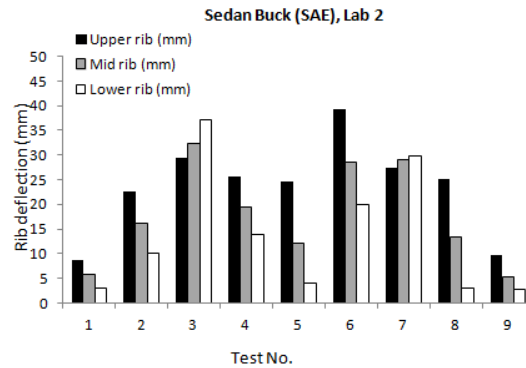
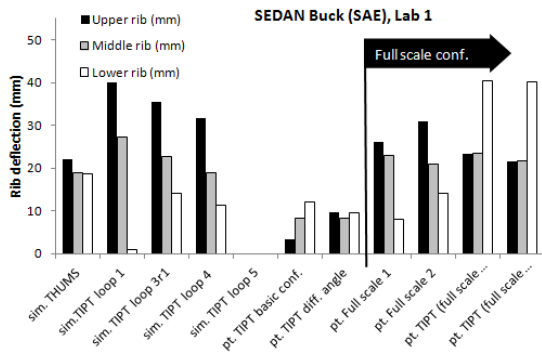
**Table 5.**  
**Test matrix for experimental tests with the TIPT**

Surrogate/ Vehicle	TIPT			
	y0 according to draft test procedure	Full scale test configuration repeat (2)	impact angle variation; steeper angle of the velocity vector	
SAE Buck (Sedan)	y0 vs. bonnet according to draft test procedure	y0 vs. bonnet variation of TIPT assembly, aiming point, velocity vector, TIPT angle, impact speed (6)	y0 vs. BLE variation of aiming point (2)	
SAE Buck (SUV)	y0 according to draft test procedure	y0 sensitivity / bottoming out	y0 sensitivity / light bottoming out with reinforced structure	
SAE Buck (Van/MPV)	y0 according to draft test procedure	y0 increased impact speed		
Actual SUV	y0 – WAD 1190 (3)	+SRL - 133.5 WAD 1330	y0 – WAD 1330	y0 – WAD 1010

The impact speed, angle of the velocity vector and TIPT inclination angle were determined according to Table 2. Impact points on the actual SUV were the aiming points of the TIPT velocity vector intersecting the shoulder reference point.

**Sedan Buck**

The peak rib deflections during simulations with HBM and TIPT and experimental tests with ES2 pedestrian dummy and TIPT against the Sedan Buck are depicted in Figure 18 and Figure 19:



**Figure 18. Peak rib deflections during simulations (sim.) with HBM and TIPT and experimental tests (pt.) with ES2 pedestrian dummy and TIPT – Sedan Buck, Lab 1.**

**Figure 19. Peak rib deflections during experimental tests (pt.) with TIPT – Sedan Buck, Lab 2.**

**Lab 1** While TIPT tests according to the test specifications and with modified impact angle showed very low peak deflections, those replicating the ES2 full scale test configuration resulted in higher loadings, in particular for the lower rib. This is contrary to the ES2 tests where the highest deflections were obtained by the upper rib. Altogether, neither the simulations nor the full scale dummy tests could be properly reflected by the tests with TIPT. Also the full scale pedestrian dummy test results were not comparable to the HBM simulations with THUMS TUC.

**Lab 2** Subsequent to a repetition of the baseline test with TIPT against the centre of the bonnet of the Sedan Buck, several modifications to the TIPT and the test and impact parameters were done in order to study the influence on the test results and vehicle safety performance.

All tests following the baseline test were carried out without the arm to more directly load the TIPT ribcage. Additionally, a rubber layer between ribcage and jacket was added to more equally distribute the loading on the entire ribcage. As from test 3 onwards the shoulder was removed from the TIPT to avoid interaction during the impact, once again bringing more severe loadings into the ribcage. Most tests were carried out against the center of the bonnet; only during two tests (no. 3 and no. 7) the TIPT impacted the centre of the bonnet leading edge (BLE). For all except the first two tests against the bonnet, a structure was installed underneath the bonnet at different distances, causing bottoming out of TIPT. Regarding the impact parameters, six tests followed the draft test procedure (see Figure 20), thereof one with reduced impact speed (no. 9). During the tests against the BLE (compare **Error! Reference source not found.**), a most possible upright position of TIPT in the launcher was chosen to follow a more realistic impact scenario in that area.

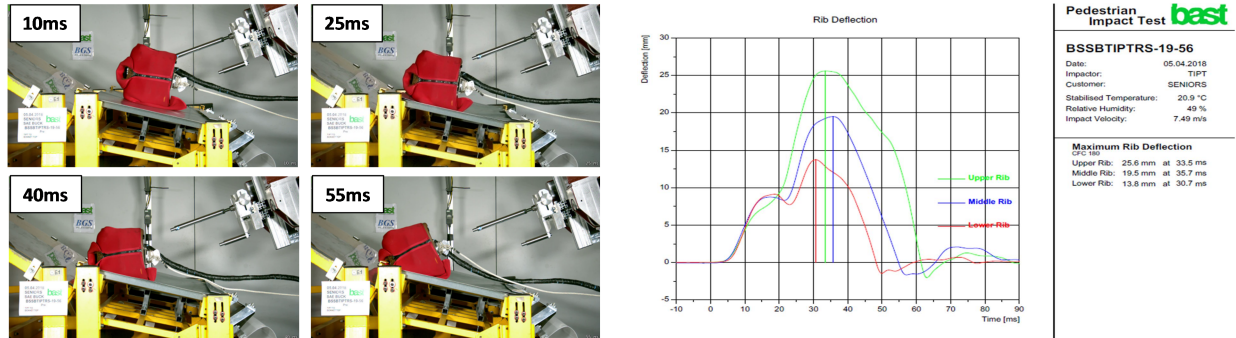


Figure 20. TIPT to bonnet test.

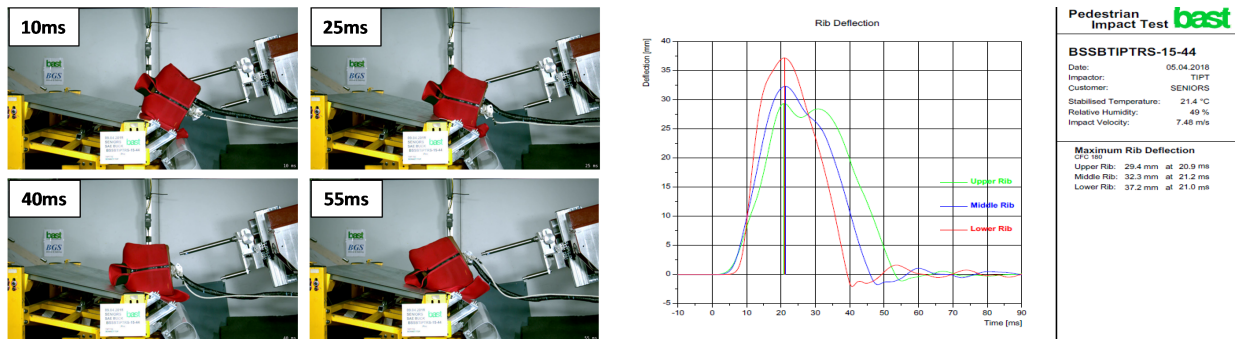


Figure 21. TIPT to BLE test.

In another test (no. 6), the steepest possible velocity vector was chosen to achieve the highest possible lateral loadings to the ribs, taking into account the limitations of ES2. Test 5 was a repetition of test 4.

Altogether, comparatively low rib deflections (all below 40mm) were measured during all tests against the Sedan Buck, thereof the majority below the tentative upper performance limit to a green assessment (28mm). As expected, the highest rib deflections were achieved during the test against the center of the bonnet with the steepest possible velocity vector, and during the two tests against the centre of the BLE. The mentioned impact configurations resulted in highest possible lateral loadings, following the properties of the ES2 ribcage where potentiometers allow for a proper acquisition of deflections in a linear direction, only.

The repeatability of test results was not satisfactory in particular for the mid rib with a range of 7.3mm and the lower rib with a range of 9.8mm.

Interestingly, lab-to-lab variability was extraordinary high for the baseline test. While in lab 1 the deflection of the lower rib was highest and the deflection of the upper rib lowest, the opposite tendency was observed in lab 2; however, all measured rib deflections in those two tests were far below the borderline to green assessment according to the draft assessment procedures.

In the vast majority of tests, regardless of the rib location aiming at the impact point, rib deflections were highest for the upper rib and lowest for the lower rib. Only the tests against the BLE resulted in maximum deflections in the lower rib and minimum deflections in the upper rib.

The application of the rubber layer between ribcage and jacket did not result in a more equal distribution of rib deflections. On the other hand, significantly higher rib deflections were observed in all tests subsequent to the removal of the impacting arm.

Testing without the arm contributed to a reduced TIPT rotation around the z-axis.

### SUV Buck and actual SUV

The peak rib deflections during simulations with THUMS TUC and TIPT (both against the SUV Buck only) and experimental tests with TIPT against the SUV Buck and the actual SUV are shown in Figure 22.

Both, TIPT tests against the SUV Buck as well as the actual SUV resulted in rib deflections significantly below the proposed threshold values. The loadings obtained during THUMS TUC as well as TIPT simulations could not be replicated during physical testing. TIPT results cannot be directly related to real life injury risk of a pedestrian during a vehicle accident.

### Van/MPV Buck

The same observation was made during simulations with HBM and TIPT and experimental tests with TIPT against the Van/MPV Buck, as illustrated in Figure 23. Peak rib deflections during the tests were very low and not comparable to the loadings measured during the simulations.

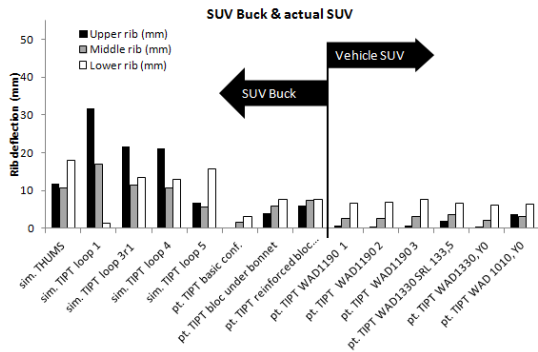


Figure 22. Peak rib deflections during simulations (sim.) with HBM and TIPT (SUV Buck) and experimental tests (pt.) with TIPT (SUV Buck, actual SUV).

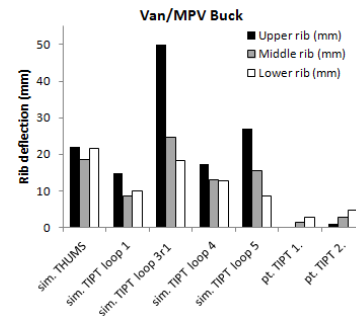


Figure 23. Peak rib deflections during simulations (sim.) with HBM and TIPT and experimental tests (pt.) with TIPT – Van/MPV Buck.

## DISCUSSION

The reported simulations related to the assessment of thoracic injuries show the basically good approach of using the isolated ribcage of the ES2 dummy during component tests. However, several limitations need to be considered. First, the ES2 dummy was designed as vehicle occupant for the assessment of lateral impacts. HBM simulations show the kinematics of the human thorax in many cases differing from this load case, with oblique thorax angle and the velocity vector not perpendicular to the thorax. The capacity of capturing oblique loadings with the available instrumentation is limited. THUMS rib extension before the impact, rotational elements in THUMS kinematics and translational movement of the TIPT furthermore result in different impact locations and loadings. Thus, besides the diverging time histories of THUMS intrusions and TIPT rib deflections, also the quantitative correlations are unsatisfactory in most cases. When using a TIPT based on the ES2 ribcage, establishing impactor limits should rather be based on injury criteria for the ES2.

## CONCLUSIONS

Collision investigations stress the change in injury patterns for pedestrians and cyclists with respect to all age groups. These converted safety requirements underline the need for revised test and assessment procedures towards a further improved VRU protection of passenger cars. From the reported changes, new requirements for external

road users were derived. Regarding the thorax area, a new test tool and new test procedures address, in principle, these requirements.

Based on a review and evaluation of the current test and assessment procedures, updates, incorporating the new test tool TIPT, were proposed together with the corresponding biomechanical limits.

Tests with the TIPT showed the feasibility of the assessment of thoracic injury risks of vulnerable road users, using for the first time a component test procedure, with acceptable repeatability and reproducibility of kinematics and test results. It needs however to be taken into account that the impact conditions such as thorax inclination angle and angle of the velocity vector differ from those in the lateral impact with ES2 dummy where the TIPT is derived from. The linear potentiometers of the ribcage do not acquire the actual rib deflections unless perpendicularly loaded.

Modifications of the load transducers would thus be needed for the TIPT component test rearward of the BLE. Future development of the TIPT may need to focus on developing a rib cage that can deflect in all axes in a humanlike way, and on developing an injury metric that takes account of these multi-axes deflections. By way of comparison, the THOR frontal impact ATD displays large y- and z-axis deflections, even though the primary loading is in the x-axis. Current THOR injury criteria also make use of the resultant deflection, not just the x-axis deflection, and it is likely that similar improvements in biofidelity and injury criteria would be of benefit for future development of the TIPT. For the impact forward to the BLE however the TIPT seems applicable without further modifications.

A straight launcher was designed and manufactured to test the TIPT at the end of the project when the need to launch directly in line with the deflection sensors was identified. The fixture was designed so that the effect of the linear rib sensors could be assessed. This is because the TIPT tested in the project was launched at simulated angles that did not directly load the sensors in their direction of measurement. This was considered the main reason for the lower than expected deflections seen in physical testing. FE analysis had shown higher deflections so it could have been a friction problem with the hardware not seeing expected results. Therefore, further testing with the TIPT will help to establish the sensitivity of the sensors and to better understand the requirements for an improved test tool.

A set of new test and assessment procedures for the thorax led to a draft rating scheme for Box 3 of Euro NCAP. Impactor thresholds were derived from studies of impact biomechanics alongside correlation studies between impactor and HBM simulations. A synthesis of the particular assessment was proposed as an example of VRU overall rating within Euro NCAP. However, despite of first promising results, several significant modifications will be necessary prior to implementation within consumer or regulatory test procedures.

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