EURO NCAP MOBILE PROGRESSIVE DEFORMABLE BARRIER TESTING

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ABSTRACT

The European New Car Assessment Programme (Euro NCAP) implemented an updated Adult Occupant Protection assessment in 2020. This saw the adoption of the Mobile Progressive Deformable Barrier (MPDB) frontal impact test and the use of the THOR anthropometric test device. The procedure was developed by the Frontal Impact Working Group (FIWG) supported by Euro NCAP and its members, alongside representatives from both the European Automobile Manufacturers Association (ACEA) and the European Association of Automotive Suppliers (CLEPA). This paper summarises the implementation of this new procedure and the work of the FIWG over the last five years.

Data from official Euro NCAP testing has been analysed to provide an overview of results from the first three years of MPDB assessments. Euro NCAP is the first consumer rating programme in the world to include an assessment of a vehicle’s compatibility. The assessment is based upon three measured parameters: standard deviation (SD) of the post-test barrier face deformation, the Occupant Load Criterion (OLC) of the MPDB trolley, and whether or not the barrier face has been crushed beyond a designated limit. The performance of the THOR dummy and its impact on vehicle ratings has also been examined. In particular, the assessment of chest and abdomen compression, iliac crest loading, and acetabulum loading were considered as they have never been included in previous assessments.

An investigation of the MPDB tests found that it is not uncommon for the diagonal belt to slide from the shoulder clavicle towards the neck of the THOR dummy. The effect of this belt movement has been investigated and improvements to the dummy hardware have been considered. As the THOR dummy is also able to measure rotational movement of the head, the group implemented a two-step approach to evaluate brain injury criteria. The first step analysed signal-based criteria culminating in the adoption of DAMAGE for assessment in 2023 ratings, another world first. The group is also reviewing existing advanced brain injury criteria that utilise FE based brain models for adoption in 2026.

The test data analysis was based on the results of Euro NCAP official tests; there was no access to manufacturers’ in-house or preliminary Euro NCAP test data. Therefore, this paper does not address any repeatability or reproducibility issues. The current assessment of THOR chest compression uses the maximum peak resultant displacement of the four thoracic ribs (Rmax). The intention is to adopt a more sophisticated chest criterion in future assessments which will be performed alongside an evaluation of THOR certification data.

Euro NCAP has evaluated the implementation of a new frontal impact test in a consumer rating programme and is the first such programme to utilise the THOR ATD, advanced injury criteria and a vehicle compatibility assessment. Further developments in the assessment are being considered and will be incorporated into the vehicle rating scheme in 2026.

INTRODUCTION

The MPDB frontal impact test was introduced by Euro NCAP in 2020 as part of a package of measures to provide more demanding crash test requirements. At the same time, the test speed of the AE-MDB side impact test was increased from 50km/h to 60km/h, and the mass of the barrier increased from 1300kg to 1400kg [1]. Finally, there was the addition of a Farside occupant assessment [2] and Rescue & Extrication assessments, as part of Adult Occupant Protection (AOP) part of the five-star rating programme.

The early work of the FIWG was first published at the 25th ESV conference [3]. These investigations formed the foundation for the MPDB test and assessment protocols along with supporting technical bulletins that were first published in 2018. Euro NCAP protocols and technical bulletins can be found on the Euro NCAP website (www.euroncap.com/en/for-engineers/protocols/).

This paper reviews the outcomes of the first three years of the updated Euro NCAP AOP assessment and focusses on the trends observed in the application of the MPDB test. With the adoption of the THOR 50th male dummy and compatibility assessment, the FIWG has investigated how the test equipment and barrier face measurement procedures might be improved, as part of its consideration of future developments.

The official Euro NCAP MPDB test data available for the analyses in this report is based on 81 MPDB tests performed from 1st January 2020 up to and including results published in October 2022. For comparison, data from 83 official Offset Deformable Barrier (ODB) tests (2018-2019), the predecessor of the MPDB test in Euro NCAP, has also been analysed to examine the impact on vehicle ratings due to the new adult occupant assessment.

THE MPDB FRONTAL IMPACT TEST

The MPDB frontal impact test replaced the ODB test for all Euro NCAP assessments published from the 1st January 2020. The test is a 50% overlap, moving car to moving barrier test with both crash partners travelling at 50km/h. A THOR 50th percentile male dummy and a Hybrid III 50th percentile male dummy are placed on the driver's and passenger's seats respectively. The 2nd row outboard rear seats are occupied by a Q6 child dummy, seated behind the driver, and a Q10 behind the passenger, the results of which are used to assess child occupant protection (COP). Details of the tests and corresponding assessment can be found in the Euro NCAP MPDB Testing Protocol [4] and the AOP Assessment Protocol [5]. See Figure 1.

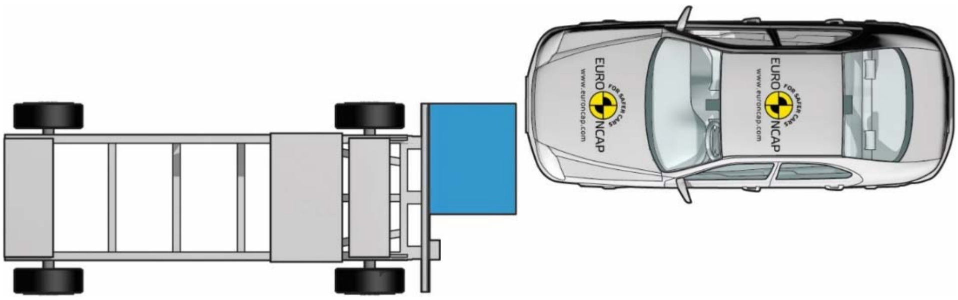


Figure 1: MPDB test configuration

It is important to note that in 2020 there were changes not only to the Adult Occupant Protection (AOP) box, but also to the Child Occupant Protection (COP) and Safety Assist (SA) boxes. This paper only examines the influence of replacing the 40% overlap, ODB frontal impact test with the MPDB test. Within the AOP box, the relative weight of the ODB and MPDB tests was unchanged and so, therefore, the weight of that box in the overall rating scheme. Scoring of other areas within the AOP assessment changed with the additional of farside occupant safety and rescue and extrication. A comparison of scoring within the AOP box is summarised in Table 1.

	2018-2019		2020-2022	
	Frontal ODB	**8.000**	Frontal MPDB	**8.000**
	Frontal FW	**8.000**	Frontal FW	**8.000**
	Side MDB	**8.000**	Side MDB	**6.000**
	Side Pole	**8.000**	Side Pole	**6.000**
	-	**-**	Farside	**4.000**
	Whiplash	**2.000**	Whiplash	**4.000**
	AEB City	**4.000**	Rescue	**2.000**
Total Score	38.000		38.000	

Table 1: Adult Occupant Assessment scoring

Both sets of data from ODB (2018-2019) and MPDB tests (2020-2022) are similarly sized in terms of the number of vehicles; 83 vs 81 respectively. Partner models utilising the same ODB and MPDB test results have been excluded from this assessment to avoid duplication of data. The distribution of vehicles throughout the Euro NCAP vehicle categories is similar for both samples, with small family car and small off-road being the most popular categories, followed by large off-road. The number of vehicles included in the Supermini category has halved over the last 10 years. It is important to note that vehicle category is not a good measure against which to compare results as these categories are self-declared by the vehicle manufacturers and lack a clear definition, but it is mentioned here to offer an overview of the vehicle types included in this assessment.

Approximately half of the vehicles tested in 2020-2022 were either full electric or hybrid powered, which is doubling the number of that vehicle type tested in 2018-2019. The variation of unladen kerb weight between the two sets of data was quite small, but it is acknowledged that vehicle mass continues to rise, even more so with the proliferation of Hybrid and Electric vehicles in the market. Vehicle mass is discussed further in the section of this paper that considers future work.

Having noted the composition of vehicles within the two data sets, the next step was to review the highest level of Euro NCAP results, which is the overall star rating. A comparison of the number of vehicles scoring 0 to 5 stars shows the proportion of vehicle star ratings has remained largely unchanged with the updates to the AOP assessment. Most vehicles scored either four or five stars in both data sets, see Figure 2.

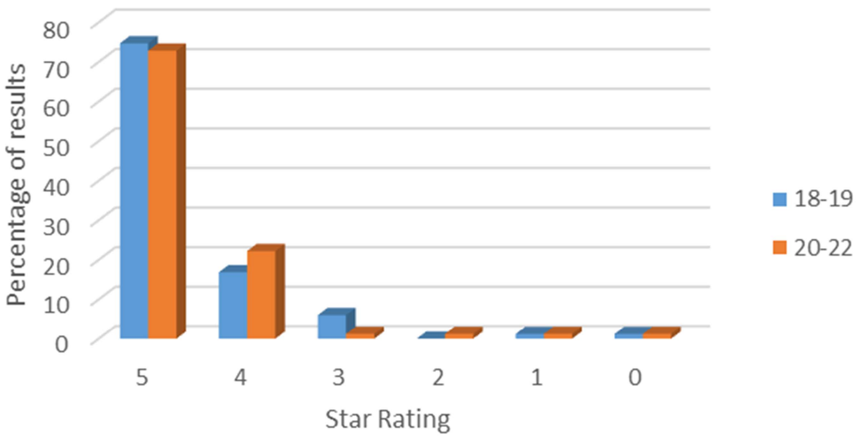


Figure 2: Distribution of vehicle star ratings in the sample sets.

Overall MPDB Test Results

On average, the updated assessments resulted in an AOP score reduction of approximately 2 points out of a possible 38 (~5%) but, as mentioned previously, this was not enough to affect the star rating. Although both sets of data show most vehicles above the 80% threshold required for five stars, the ODB data shows there are more lighter vehicles (<1500kg) achieving four stars. See Figure 3. This reduction is also visible in the individual scores for the ODB and MPDB tests. One vehicle scored zero points in the MPDB test, this was due to a high driver's chest compression of 62mm. In the MPDB test, the chest is determined a 'critical' body region along with the head and neck. Where the caping limit for any of these criteria is exceeded, the total MPDB test score is automatically set to zero.

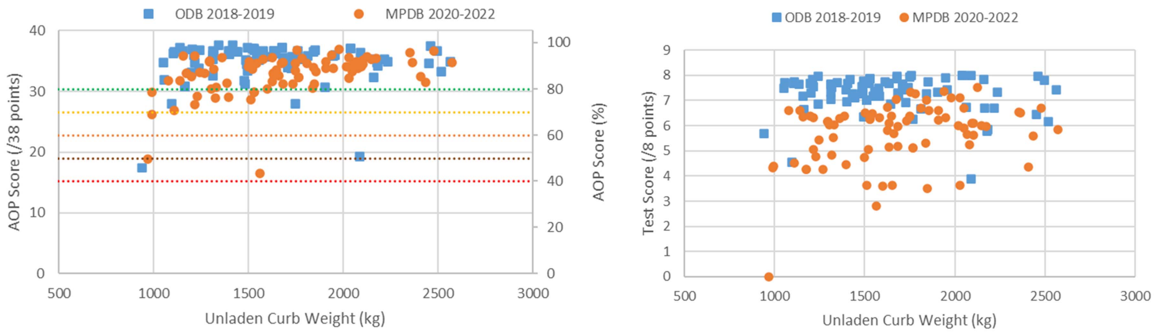


Figure 3: AOP Score breakdown, total (left) and for the offset test (right)

Driver and Passenger Results

To further illustrate the differences between the ODB and MPDB procedures, the body region data was examined more closely. The scoring for each of the body regions is shown in Figure 4.

Driver

Head – It has been the case for many years now that the driver's head is mostly awarded full points in Euro NCAP ratings. No drivers were penalised in the data sets based on biomechanical criteria (skull fracture risk, HIC & 3ms exceedance) and in only a handful of cases was the head penalised for 'bottoming out' the airbag. Accident research undertaken by ADAC [6] indicates that head injuries are still a common cause of death and serious injury, but the frequency of skull fractures is relatively low. This suggests that, while the low risk of skull fracture shown in Euro NCAP tests is in line with real world occurrence, injury mechanisms for brain injury are now more prominent and should be addressed. Accident studies from the US [7] have shown that, in newer vehicle models, there is a trend toward a reduction in the likelihood of AIS 4+ brain injury, but an increased risk of lower severity brain injures (AIS 2+ and AIS 2-3).

Chest – The test data shows lower chest scores with the MPDB test and THOR dummy compared to the ODB test and Hybrid III; roughly 1 point less on average. For THOR, the chest assessment is based on the value of Rmax, the maximum resultant chest displacement. For Hybrid III, was based on the worst performer between chest potentiometer displacement and viscous criterion (V*C) and, in all cases, chest displacement was the worst performing parameter. The shoulder belt load penalty that is applied when the peak load exceeds 6.0kN, was not incurred by and of the cars in the datasets.

Knee, femur and pelvis – The Euro NCAP femur compression limit remained unchanged at 3.8kN with the adoption of the THOR dummy. The results were similar between the two datasets, but in the MPDB test eight vehicles were penalised for either femur load or knee slider displacement, with a maximum compression of over 14kN. In the ODB tests, no vehicles exceeded the 3.8kN femur compression limit. Acetabulum compression was also included in the assessment from 2020, and in almost all cases the load was below the higher performance limit (HPL) of 3.28kN.

Lower leg – The data from the MPDB tests shows a wider spread of results than in the ODB tests. It is worth noting that the THOR dummy is equipped with the same tibias and feet as those of the Hybrid III, suggesting that this is more a test difference rather than a dummy difference. This was also seen during the development phase of the MPDB procedure conducted in 2018. Anecdotal evidence from Euro NCAP inspectors, who examine the vehicles after the official tests, suggests that with the introduction of the MPDB test more vehicles are suffering greater levels of footwell intrusion in the MPDB test.

Passenger

There appears to be little difference between the ODB and MPDB results for the passenger dummies. However, scores for the lower region leg appear to be slightly worse in the MPDB test. The cause for this is not completely understood and but it has been observed in vehicles across the mass range. It could be a result of the different pulse and/or the lower amount of vehicle rotation observed in MPDB test compared to ODB impacts.

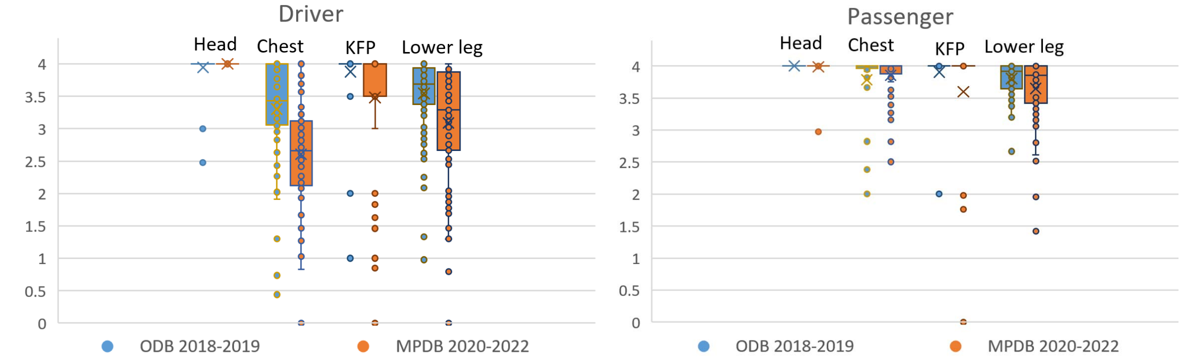


Figure 4: Driver and passenger body region scores (max 4 points per body region)

Compatibility Assessment

The Euro NCAP compatibility modifier was first applied to ratings in 2020 in combination with the MPDB test. It is an assessment that uses the trolley deceleration (Occupant Load Criterion, OLC) and post-test barrier deformation measurements (homogeneity) to evaluate a vehicle's crash compatibility. This assessment is described in more detail in Euro NCAP Technical Bulletin TB 027 and is applied as an increasing penalty when compatibility worsens. See Figure 5.

For 2020 to 2022 assessments, the maximum penalty was -4 points to be deducted from the MPDB test score (max 16 points). It is treated as a penalty, rather than a reward, because a reward system would give an initial perspective of all vehicles offering poor compatibility unless proven otherwise. A malus system was considered to be a fairer approach to apply to all vehicles.

Of the 81 official Euro NCAP MPDB tests performed to date, there has only been one vehicle that was not penalised for compatibility. This was a supermini with an unladen kerb mass of 990kg and a test mass of 1237kg. It is encouraging to see that more than half of the vehicles assessed were penalised by 1.5 points or less, and even vehicles weighing >2000kg have performed well in this assessment, which was not the case during the development of this test procedure. The average penalty across all vehicles was -1.83 points.

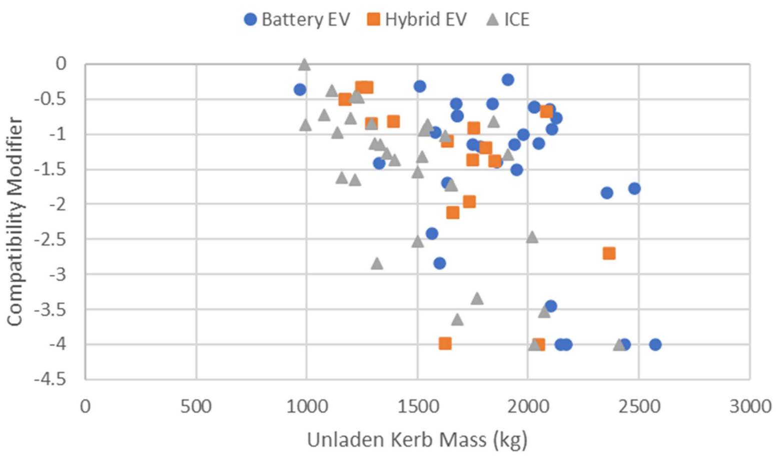


Figure 5: Compatibility modifier 2020-2022

The data contains another supermini with a similar kerb mass (993kg), which was penalised by -0.87 points, mostly due to high standard deviation (112mm). This shows that although small cars offer a lower OLC, it is still necessary to ensure that front structures are designed to be homogeneous, and less aggressive to their crash partner. Many, far heavier vehicles, had designs offering lower standard deviation. The modifier limits for OLC were based upon test data from the FIWG testing programmes as well as the understanding that the lighter test vehicles will impart the lowest OLC on the trolley. Only one vehicle, weighing 2070kg, exceeded the 40g limit for OLC. The spread of OLC values is greatest between kerb masses of 1500kg to 2200kg. The data also shows that mass seems to be the driving factor, but not the only one. This is indicated by higher and lower values for SD and OLC within the same vehicle mass. When devising the compatibility modifier, Euro NCAP did not anticipate OLC values above 40g, but based on the recent data, this range still fits around most of the vehicle population. See Figure 6.

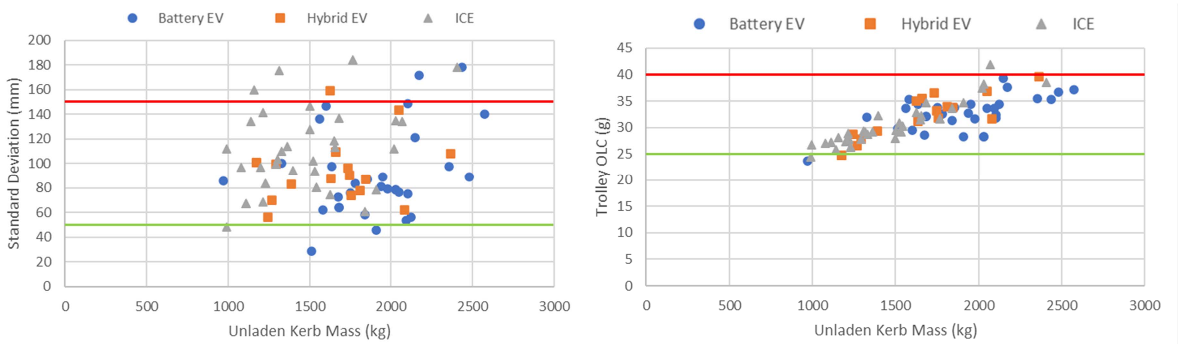
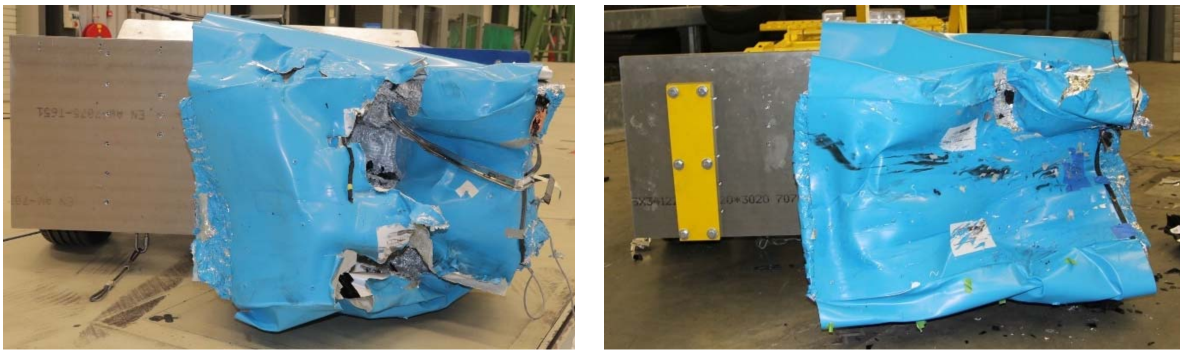


Figure 6: Compatibility assessments 2020-2022

The final component of the compatibility assessment is an additional penalty that is applied when bottoming out of the barrier face occurs. This is defined as barrier deformation in the defined assessment zone of 630mm or more. 14 vehicles bottomed out the barrier face, the lightest of which had a kerb weight of 1316kg. In half of the bottoming out cases the kerb weight was over 2000kg. See Figure 7.



Kerb mass: 2173kg Deformation SD: 172mm Bottoming out: Yes	Kerb mass: 2480kg Deformation SD: 89mm Bottoming out: No

Figure 7: MPDB face deformation, with (left) and without (right) bottoming out.

During the development of the MPDB test procedure, Euro NCAP investigated the variation in the outcome of the compatibility assessment caused by the use of MPDB faces produced by different suppliers. Test data from five comparative tests, using three different MPDB suppliers, was analysed in line with the compatibility assessment. It should be noted that the same specification of test vehicle (test mass 1350kg) was used in all tests, but this vehicle was not engineered to meet any vehicle compatibility measures.

The results of the five tests are shown in Table 2. Both the vehicle pulses and trolley OLC pulses compared well and resulted in a 5g difference in trolley OLC. The variation in standard deviation was 21mm, resulting in a spread in compatibility assessment of 0.7 points. The vehicle bottomed out the barrier face in all tests.

	Barrier supplier				
	A	**A**	**B**	**B**	**C**
Test index	1	2	3	4	5
Trolley OLC (g)	24.5	26.6	29.6	29.4	28.6
SD (mm)	158	148	137	139	147
Bottoming out	Yes	Yes	Yes	Yes	Yes
Compatibility assessment	**2.0**	**2.3**	**2.7**	**2.7**	**2.7**

Table 2: Compatibility assessment results, comparison of barrier suppliers.

It should be noted that there were differences in the structural performance of the test vehicles, particularly regarding the failure of the bumper beam. In some cases, the bumper beam broke, whereas in others it did not. Also, in some cases, the bumper beam remained attached to the lower rails, and in others it did not. Given these differences, the subsequent difference in compatibility assessment between the barrier faces was deemed acceptable.

Figure 8: Comparative test MPDB face deformation

In addition to the reduced vehicle rotation observed in MPDB tests, another notable difference to that of the ODB test is the vehicle pulse. ODB tests typically offer a back-loaded pulse with a much longer duration. The MPDB pulse is of a shorter duration and like that of the rigid wall full width test. See Figure 9. The averaging of pulses hides the differences in acceleration levels between vehicles of different weight, so the MPDB pulses of the lightest (1349kg) and heaviest (2676kg) vehicles are also provided. It should be noted that a smaller data set of MPDB pulses was used to produce this data.

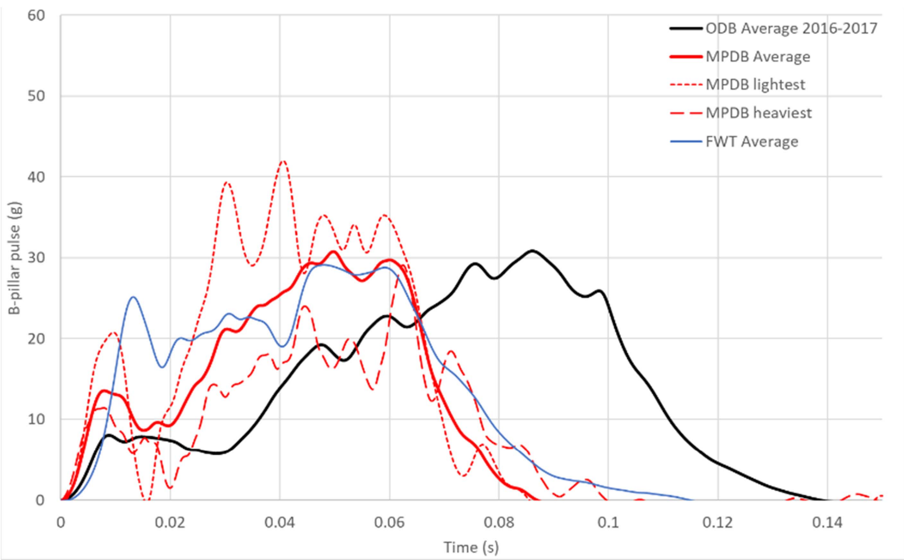


Figure 9: Euro NCAP Test pulse comparisons

MPDB Test Observations - Belt Slippage

With the adoption of THOR dummy, Euro NCAP observed that in some tests the diagonal section of the driver's seat belt slid from the shoulder into the gap between the neck and shoulder pad. This could allow the belt to directly load the spine box rather than the rib cage, see Figure 10. This phenomenon can only be identified with the use of onboard cameras. Although it is not always possible to see the belt to shoulder interaction, where it could be seen on the high-speed film, the belt slips into the neck gap in approximately 1/3rd of cases.

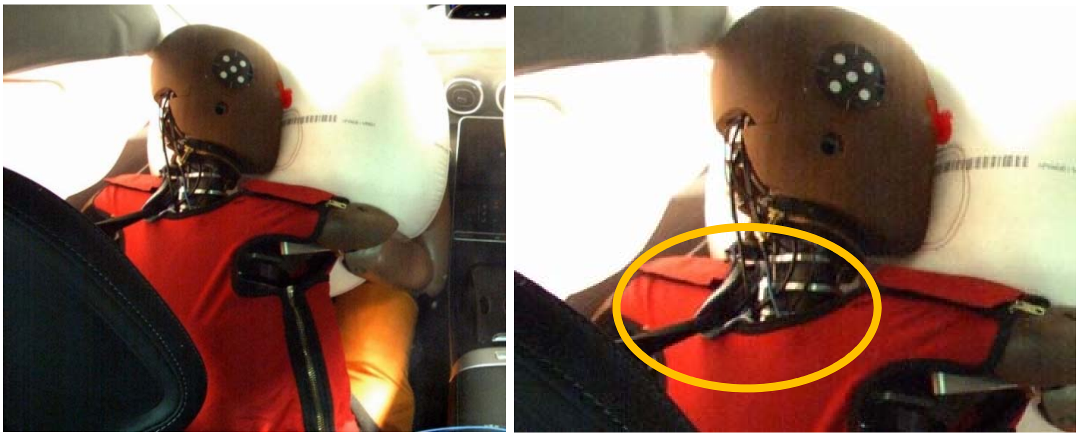


Figure 10: THOR diagonal belt slippage

Belt slippage is a dummy artifact and not biofdelic behaviour, possibly leading to un-instrumented load paths. When reviewing the cases where the belt slips off, there did not appear to be a common trend in the timing between the belt slippage and peak Rmax value. In some cases, the belt slipped before peak Rmax, and in others this occurred after peak Rmax. In some cases the belt slippage was visible in the dummy outputs and in others it was not. At this stage the influence of belt slippage on Rmax is not well understood and further investigations into this phenomenon will be performed. With the planned introduction of a more advanced chest criterium, consistent belt behaviour will be critical for the correct assessment of chest injury risk.

Updated shoulder pads have been produced by two dummy suppliers to prevent the belt from moving into the neck gap. At the time of writing, there was very little data available on the efficacy of these shoulder pads [22]. The FIWG took the decision to permit the use of modified shoulder pads where the vehicle manufacturer believes that belt slippage will occur. This issue will continue to be examined alongside the anticipated introduction of an improved chest assessment criterion.

THOR Dummy

The THOR dummy has been available in various guises for over 20 years and Euro NCAP was the first consumer rating scheme globally to adopt the dummy. A series of comparative sled tests and full scale MPDB to car tests were used to compare the results of THOR dummies produced by two different manufacturers. A generic sled rig was used with an airbag, pretensioner and load limiter. The dummy outputs compared well and was subsequently used to approve a second THOR dummy manufacturer for use in Euro NCAP testing.

By now, there are many of these dummies available worldwide and the FIWG decided that certification data should be reviewed to see the status of dummies in use in the field. A programme of work will be undertaken to collect whole dummy certification data from as many sources as possible and collated for review. This will include a comparison with the latest NHTSA proposed qualification procedures for the dummy.

Collecting such a large amount of data from different institutions is a demanding task and it was necessary to standardise the certification data to allow direct comparison. The Partnership for Dummy Technology and Biomechanics (PDB) developed a procedure to achieve this [8] confirming ISO codes, sign conventions and post processing steps to be taken. Due to the sensitivity of sharing in-house certification data, data will be anonymised before comparison. This work has only just begun, and no data has yet been collected, but it is hoped that the first review can be performed in the first half of 2023.

Figure 11: THOR dummy comparison tests

Chest Certification

The current THOR certification corridors adopted by Euro NCAP are detailed in Euro NCAP TB 026. This document was compiled to limit the difficulties that laboratories encountered in meeting the Z deflection certification requirements. The corridors were based on data from over 700 certification tests performed between 2018-2019 and were designed to fit the global population of dummies globally. The dummy response characteristics were examined, and it was found that a rhombic corridor was required to better represent the relationship between X and Z displacement during certification. Subsequently, peak resultant displacement (Dres) and Z/X ratio were adopted with a 7% variation limit.

Further investigations into the chest certification process are being undertaken within ISO WG5 (ATD). A modified test is under consideration that uses a trapezoidal impactor and an impact location that is 15mm higher, which aims to offer more realistic loading of the chest during certification, based on full scale test behaviour. At the time of writing, testing was still ongoing and no vehicle-based results have yet been made available. This will be considered by the group in future with the aim of reducing the variability of THOR chest results.

UPDATES TO THE MPDB TEST 2023

Compatibility Modifier

It was initially Euro NCAP's intention to have a -8 point maximum penalty beginning in 2020. However, this was reduced to a -4pt maximum for the introductory years 2020-2022 to allow more time for compatible designs to enter the market and limit the size of the penalty while this happens. In 2023, the compatibility modifier will be increased to -8 points. Several vehicles have proven that their concept of compatibility can be effective in real life and demonstrate this in the MPDB test. Compatible frontal structures can be implemented in all vehicles, but it is acknowledged that time and money is required before they become commonplace in the vehicle fleet. To continue to drive the development of compatible vehicles, an increased penalty is needed in the future to avoid slow or even no development in compatible frontal structure design.

Brain Injury - Incorporation of DAMAGE criterion 2023-2024

With the adoption of the THOR driver dummy in the MPDB test, Euro NCAP decided that simply evaluating the skull fracture risk of the driver's head was insufficient and that more should be done to address head injuries. It was decided that a criterion would be adopted to evaluate the risk of sustaining a mild traumatic brain injury risk (AIS2 moderate concussion). A number of well known, kinematically based criteria were considered including BrIC [9], UBrIC [10], DAMAGE [11], HAIC [12] and CIBIC [13]. The kinematic criteria were compared to the FE brain injury models from KTH [14] and SUFEHM [15]. When comparing the risk calculated by the kinematic criteria versus Maximum Principal Strain (MPS100) from the KTH model, DAMAGE and CIBIC appeared to have the best correlation in frontal impacts. This has also been seen with WorldSID in far side impacts, but the correlation was lower. Kinematic criteria that consider rotation only, such as UBrIC and DAMAGE, may have some limitations when it comes to evaluating the translation kinematics. It is noted that the different FE brain injury models, such as THUMS [16], GHBM [17], KTH and SUFEHM have different brain shear modulus making the rotational effects more important for those models with a lower shear modulus. Furthermore, the different brain injury risks were based on different head trauma databases that contain different types of injury, which may also influence results.

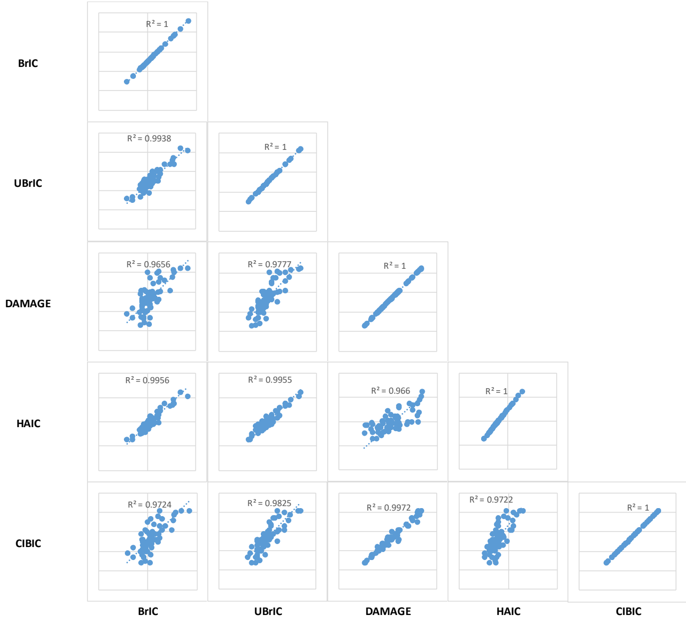


Figure 12: Brain injury metric correlations

Calculation of the Diffuse Axonal Multi-Axis General Evaluation (DAMAGE) criterion is defined in the THOR dummy technical report ISO TR 19222. This was chosen by Euro NCAP as an interim brain injury metric until a more advanced assessment could be implemented. The time window for calculation of the DAMAGE criterion is limited to exclude secondary head contacts with the vehicle interior and is detailed in Euro NCAP Technical Bulletin TB 035. This criterion will be evaluated during the loading and early rebound phases of the impact over a maximum period from T0 up to 200ms. The time window will be reduced to less than 200ms if, during rebound, a secondary head impact results in an external neck force drop below 500N.

The DAMAGE criterion is incorporated into the driver's head assessment as a modifier applied after the assessment of the biomechanical criteria. A maximum score of four points is available for the head. Where DAMAGE reaches a value of 0.47 and above, a -2 point penalty will be applied; for values between 0.47 and 0.42, the penalty will be -1 point; and values below 0.42 will not be penalised. These values were chosen to penalise the worst performers. Although it was acknowledged that the supporting injury risk curves were sufficiently reliable to use a sliding scale risk assessment, due to the limited application of DAMAGE in vehicular testing this was rejected for the initial implementation of the criterion.

A more limited set of official test data (n=67 vehicles) was evaluated for DAMAGE. Only two vehicles exceeded the HPL of 0.42, and none exceeded 0.47. Six different vehicles exceeded 0.40 with masses ranging from 1175kg to 2103kg. The distribution of the data suggests that lighter vehicles are not more susceptible than heavier ones. See Figure 13.

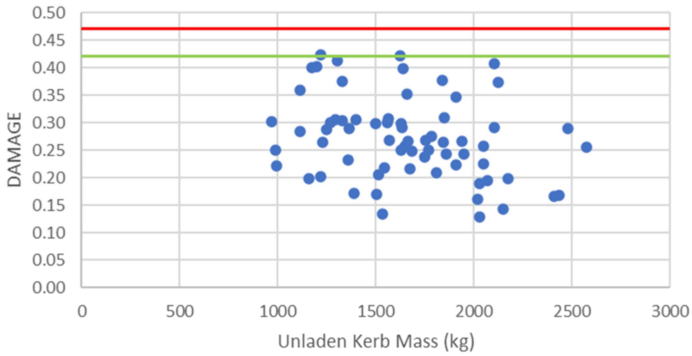


Figure 13: DAMAGE values, MPDB tests 2020-2022

Taking a closer look at the vehicles with a DAMAGE value of ≥0.42, it was found that the rotational velocity about the Z axis was the controlling parameter in the calculation. Both vehicles had angular velocities >1500 rad/s in the loading phase of the impact.

FUTURE EURO NCAP UPDATES

Euro NCAP Roadmap 2030

In November 2022, Euro NCAP published its roadmap detailing the strategic goals for the period up to 2030 [21]. The current rating scheme will be replaced in 2026 with a system identifying four phases of a vehicle accident: safe driving, crash avoidance, crash protection and post-crash safety. All crash testing will be included under the crash protection assessments, and the tests themselves will also be updated to address the differing levels of protection being offered to different occupant demographics. This is most notably the case for drivers of different statures and ages as vehicle restraint systems are primarily designed to protect the mid-sized male occupants.

The MPDB test will be updated to include the THOR 50th male in the driver's seat and a 5th female on the front passenger's seat, most likely to start with the Hybrid III followed by the THOR type of dummy. The rear seats will continue to be occupied by the Q6 and Q10 dummies but will be assessed using improved biomechanical criteria and limits. The test parameters will also be reviewed to represent the increasing mass of the European passenger car fleet as well as considering crash severities seen more closely in the real world.

Barrier Mass

In the Euro NCAP protocols, the mass of both the MPDB and AE-MDB trolleys is currently 1400kg. Of the assessments performed by Euro NCAP in 2018 & 2019, the average unladen kerb mass of the test vehicles was 1604kg. Comparing this to the 2020-2022 data, there has been no major change in recent years as the average kerb mass was 1693kg. However, when looking back to older Euro NCAP test vehicles, average vehicle mass has increased over the last 10 years. The average kerb mass of the vehicles assessed by Euro NCAP between 2009-2011 was 1416kg (similar sample size). The distribution of these masses for the later vehicles was toward the heavier side of the distribution. Based on this data, it would already seem that there is justification to increase the mass of the MPDB trolley to be more representative of the average vehicle.

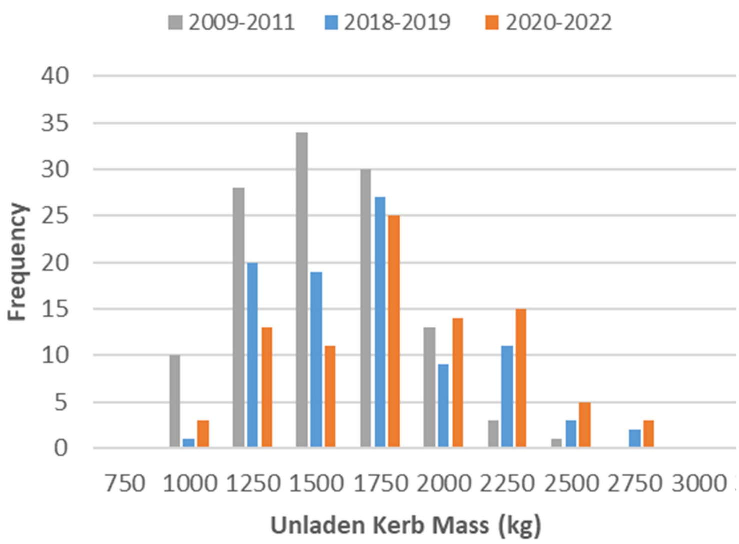
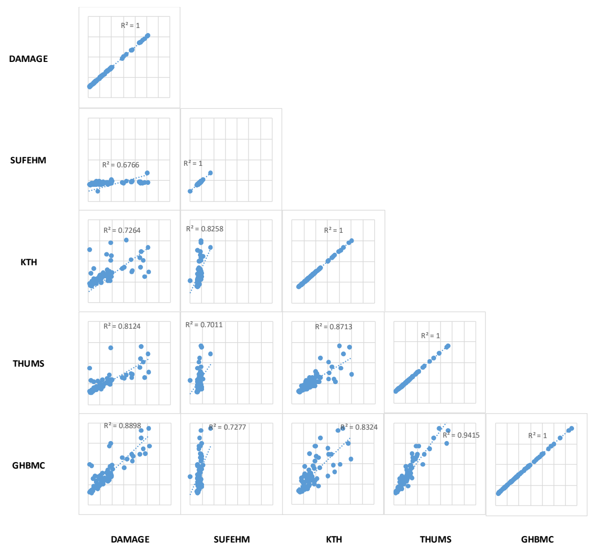


Figure 14: Unladen kerb mass distribution

Advanced Brain Injury Assessment

Euro NCAP is currently reviewing advanced brain injury metrics for future introduction that will allow a more representative measurements of brain injury risk. This is expected to replace DAMAGE in 2026 and will use a sliding scale assessment instead of the pass/fail limits. A comparison of brain injury criteria in full vehicle crash tests was reported in several previous publications e.g. [18]. To compare the outputs of possible candidate criteria, including those based on FE models, the THOR head output signals of more than 60 full-vehicle MPDB crash tests conducted between 2020 and 2022 were evaluated. The criteria values and AIS2 risk are shown in Appendix I. Figure 15 shows the correlation of the AIS2 risk of the different criteria.



	DAMAGE	SUFEHM	KTH	THUMS	GHBMC
DAMAGE	1.00				
SUFEHM	0.52	1.00			
KTH	0.58	0.54	1.00		
THUMS	0.74	0.44	0.80	1.00	
GHBMC	0.85	0.48	0.72	0.92	1.00

Figure 15: AIS2 (+) brain injury risk and parameter correlations

On reviewing the correlations between the injury risks from the different criteria, five correlations were statistically significant (>0.70). In some cases, the predicted risk for DAMAGE, KTH and GHBMC were high at over 50%. As the injury risk curves for DAMAGE, THUMS and GHBMC were generated using the same brain injury databases, therefore a good correlation could be expected.

There was a large spread of risk between the criteria with GHBMC predicting the highest risk of injury at 65%, see Figure 16. Except for SUFEHM, the other criteria give a maximum risk of 46-54%. SUFEHM offered a maximum risk of 17%. Two of the criteria, SUFEHM and GHBMC gave maximums for the same vehicle. No further analyses were available at the time of writing. The next steps will be to identify several individual cases from the Euro NCAP data to review in more detail. These cases will be chosen based upon the high spread of risk between different criteria, and where multiple criteria highlight a high risk.

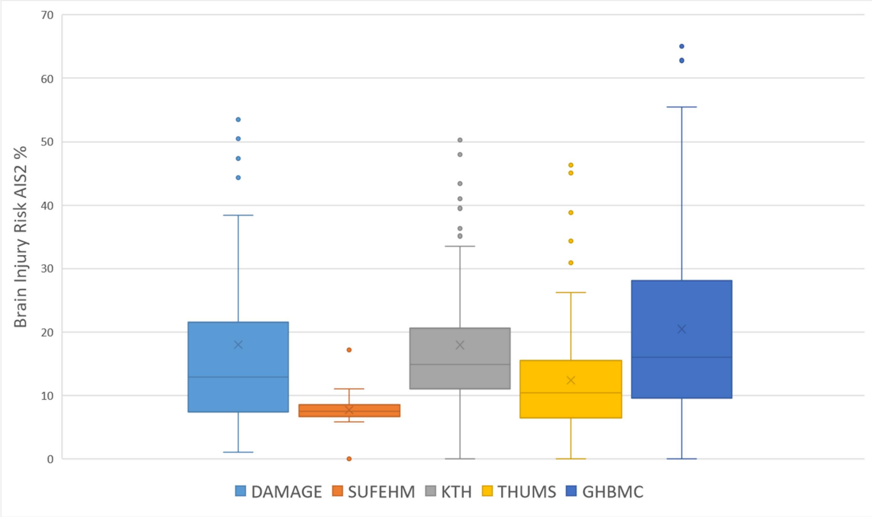


Figure 16: Brain injury risk spread

To support the decision of which criterion is most suitable to predict brain injury in an occupant safety assessment, accident reconstruction using Human Body Models (HBMs) could be a complementary addition. However, few studies were done so far regarding brain injury of car occupants. Therefore, accidents where the driver suffered brain injury were selected from an in-depth accident database and reconstructed using an HBM. The objective of this was to support the identification of an appropriate predictor for brain injury caused by motor vehicle accidents.

The methodology and computational studies for the accident reconstruction followed several steps. In the first step, accident cases were extracted from the German In-Depth Accident Study (GIDAS) database. In the second step, the vehicle model and occupant model were selected based on the accident data. For the vehicle model in this study, a midsize sedan car published on NHTSA website *1 was used. Regarding the occupant model, THUMS (version 4.02) was used and resized based on the target occupant size. The seating position was estimated by the hip point location of a typically sized occupant *2. In the third step, the reconstruction based on the above information was conducted while considering each of the brain injury predictors. These predictors were calculated based on six DOF acceleration of the centre of gravity of the THUMS head. In the fourth and final step, the validity of the reconstruction results was confirmed in terms of the vehicle rebound direction, the vehicle deformation level, the location of injury and the part responsible for the head injury. Once the results were validated, the injury risk probability predicted by each injury risk function of the predictors for the ATD were compared as well as the one calculated by the brain strain of THUMS.

Three cases were selected and reconstructed. In the following section, the reconstruction of the first case is described in detail. For the second and third case limited details are provided in Appendix II. Figure 17 shows the sketch of the first accident including the vehicles' movement paths. Vehicle A was a midsize sedan with a collision speed determined to be 10 km/h. Vehicle B was a midsize wagon with a collision speed of 70 km/h. The relative angle between both cars was 121°. In this accident, the driver of Vehicle A suffered from an AIS2 brain injury due to impact with the B-pillar. The injuries sustained by the driver are listed in Table 3. The simulation set-up is shown in Figure 18. Each accident simulation was set based on the prescribed accident data and the THUMS HBM was installed as shown in Figure 19.

*1NHTSA website, https://www.nhtsa.gov/crash-simulation-vehicle-models.
*2Autograph website, http://www.autograph.de/index.php?id=30

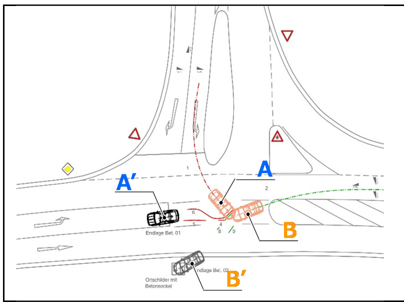


Figure 17: Accident sketch

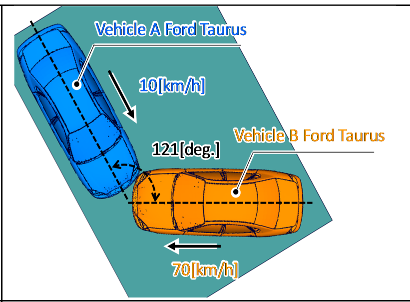


Figure 18: Simulation model set-up

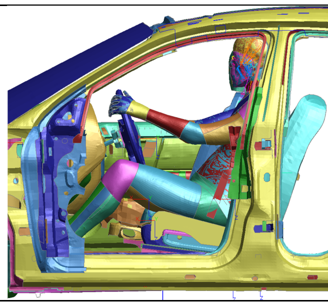


Figure 19: THUMS seating position

No.	Regions	AIS 2008	Diagnosis	Trauma causes
1	Chest	1	Contusion	Seat belt
2	Head	1	Scalp laceration	B-pillar
3	Cervical spine	1	Whiplash	Body motion
4	Head	2	Lost consciousness	B-pillar
5	Stomach	1	Contusion	Seat belt

Table 3: Injuries to driver of vehicle A

To confirm whether results are suitable to evaluate brain injury predictors, some points were used to judge the validity of the reconstruction result. The rebound direction of Vehicle A was similar to that extrapolated from the accident's (Figure 17). The initial driving direction of Vehicle B is shown in Figure 20, and both vehicles came to a stop facing away from each other. The vehicle deformation level was almost the same as that observed in the accident's as judged by the post-crash pictures, the deformation level in GIDAS data and the results of the reconstruction. An example of the comparison between the post-crash picture is shown in Figure 21. With regard to the driver's kinematics of Vehicle A, the head injury location and the head contact part described in the GIDAS data were reproduced as shown in Figure 22.

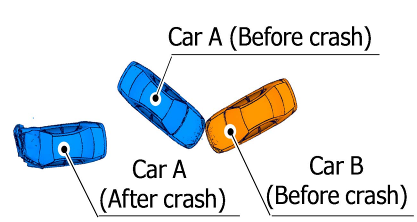
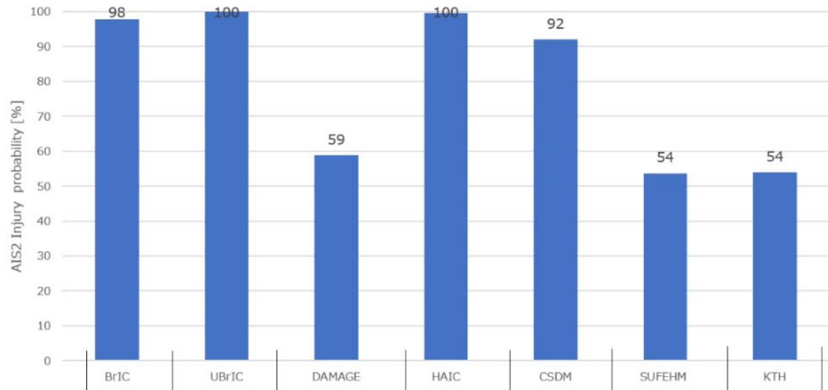


Figure 20: The rebound direction of Vehicle A.

Figure 21: The comparison of vehicle apperance

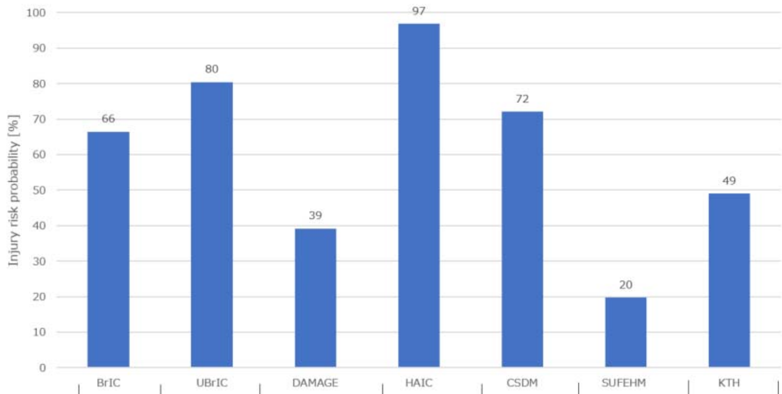
Figure 22: The injured position

Figure 23 to Figure 25 show the AIS2 of brain injury predicted by different injury metrics. In all considered cases the occupant suffered AIS2 injury. Thus, the candidate criterion should predict a high risk of AIS2+ injury. However, it is difficult to assess the correct prediction capability of the different criteria based on only three accident cases, especially at car modelling level. Therefore, it is proposed to add additional cases for evaluation before drawing any further conclusions. It would also be beneficial to add AIS0 brain injury accident reconstruction cases for reference with car occupants that suffered AIS2+ injury of other body regions but did not sustain any brain injury. In summary, the method of HBM based reconstruction of in-depth car occupant cases is considered the right approach to further selection of the most suitable brain injury criterion. However, more accident cases and improved car models are need.



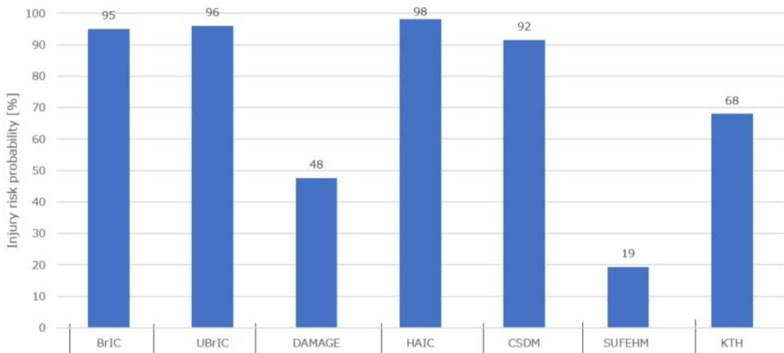
	BrIC	UBrIC	DAMAGE	HAIC	CSDM	SUFEHM	KTH
Injury value	1.21	0.77	0.45	122	29	38 kPa	0.55

Figure 23: AIS2 brain injury probability for accident reconstruction case 1



	BrIC	UBrIC	DAMAGE	HAIC	CSDM	SUFEHM	KTH
Injury value	0.86	0.51	0.38	97	11,4	20 kPa	0,46

Figure 24: AIS2 brain injury probability for accident reconstruction case 2



	BrIC	UBrIC	DAMAGE	HAIC	CSDM	SUFEHM	KTH
Injury value	1.12	0.6	0.41	103	28	20 kPa	0. 36

Figure 25: AIS2 brain injury probability for accident reconstruction case 3

Chest Assessment

The assessment of chest injury risk has been based on displacement and V*C since the first Euro NCAP tests were performed in 1996. With the adoption of THOR Rmax, the maximum peak resultant displacement of the four chest displacement transducers, has been used alongside a peak belt load limit of 6kN. Accident data suggests a strong correlation between belt load and thoracic injury risk and the thorax is one of the most critical areas involved in deaths and serious injuries.

The FIWG has been reviewing alternative chest assessment criteria - TIC and PCA [19, 20], but data is currently limited and further evaluations need to be performed. The first step in this process will be for the group to review the THOR certification test data and await the outcome of the modified certification test procedure.

Another criterion investigated was DEQ-NSFR. The Euro NCAP test data shows that DEQ-NSFR correlates strongly to both chest Rmax and diagonal belt load, see Figure 26. DEQ-NSFR uses a combination of Rmax and peak diagonal belt force (0.33*Rmax + 6*USBF). A comparison of vehicle rankings based on Rmax and DEQ-NSFR values (mm) resulted in a coefficient of concordance of 0.85.

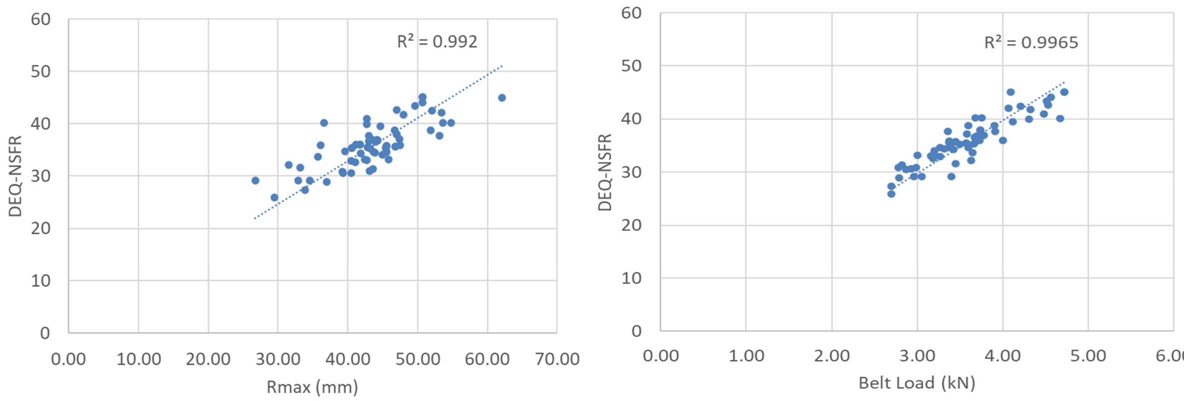


Figure 26: Correlation of THOR chest Rmax, Diagonal belt load and DEQ-NSFR

Concerns have been raised regarding the reliability of belt load data, as well as difficulties in the calibration of sensors. Euro NCAP requires seatbelt load cells to follow the calibration procedure developed by ISO (TS 17242:2014) to help prevent issues with belt load measurements. Currently, Euro NCAP limits the use of diagonal belt load assessments to simple pass/fail criteria rather than incorporating these loads into a sliding scale assessment. With the chest being still one of the most injured body regions further investigations in a more advanced chest assessment need to be done, based on the work to reduce scattering of the individual THOR dummies.

CONCLUSIONS

The development of the Euro NCAP Mobile Progressive Deformable Barrier frontal impact test began in 2015 and the test procedure was applied to vehicle ratings in 2020. Although this test has not led to reductions in star ratings, this new test procedure gives more stringent requirements for vehicle restraint systems while also providing a measure against which a vehicle's compatibility can be evaluated. This could be seen in more advanced restraint systems with new pre-tensioning systems and different belt load limitations. The increased weight in the AOP rating of the compatibility assessment is expected to provide sufficient encouragement for vehicle manufacturers to improve the level of vehicle compatibility from what it currently is today.

With the adoption of DAMAGE, Euro NCAP will offer an improved head injury assessment compared to what is currently done. For the thorax, further investigations will be performed using other chest criteria that do not correlate to Rmax to see if they provide additional information. The database used to develop the Rmax criterion was limited and would benefit from the incorporation of distributed airbag load cases, which could also show the benefit of advanced multi-point deflection criteria like PCA or TIC. The FIWG will continue to review THOR certification data in order to drive improvements in procedures and corridors, this will be done using a collaborative approach to data sharing and analysis. The need for modified shoulder pads will be examined, but data on the efficacy of these it awaited.

In future, the MPDB test will be complemented with an advanced brain injury assessment and a more stringent assessment of vehicle compatibility. With increasing vehicle masses, the severity of the MPDB test will be reviewed to ensure that the trolley mass is representative of the vehicle fleet and that the test severity is representative of crashes occurring on the road.

Looking further ahead, the FIWG will focus on implementing the next safety priorities identified in the Euro NCAP roadmap for 2030 [21]. Vehicle safety has improved significantly over the last 20 years. The tests that are being introduced will help to protect all aspects of the population (age, gender, anthropometry etc). However, some areas are now being highlighted where there are additional risks to certain parts of the population. Equality in crash safety is important to all, and this extends well beyond gender and applies to many other human characteristics, including age. Representation for all humans is important, but we need to understand what factors are overrepresented in crashes – such as the elderly, obese, large males and small females. It is important to examine accident data and PMHS research to try an understand the reasons behind this additional risk. For example, is this due to belt fit, femur to facia interaction etc.

Euro NCAP is already testing with crash dummies of different types and stature in frontal impacts, and other assessment areas also consider different occupant statures (e.g. side impacts). However, not all dummies used by Euro NCAP can be considered state-of-the art, and Euro NCAP will adopt the latest generation THOR 5th percentile female in addition to the current THOR 50th percentile male dummy. Both dummies will be used as driver and front passenger respectively in a revised low severity full-width barrier test, applying criteria and injury limits that promote restraints that better protect elderly occupants.

Adoption of more sophisticated, next generation test dummies poses challenges that have already been encountered with the THOR 50th male. The issues regarding thorax certification and belt slippage must be solved before the smaller female THOR 5th female is introduced. Also, biomechanical criteria, especially for chest injury risk assessment of different populations such as the small female, will be needed.

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Appendix I

Unladen Kerb Mass kg	DAMAGE AIS2%	SUFEHM AIS2+ %	KTH AIS2%	THUMS AIS2+ %	GHBMC AIS2+ %
970	19	8	15	13	21
990	10	7	14	11	19
993	7	8	8	7	14
1111	33	9	50	19	35
1111	15	8	36	12	22
1158	4	7	23	12	8
1175	45	8	24	34	55
1199	45	9	39	46	63
1216	5	7	13	6	7
1217	51	8	20	21	48
1230	12	7	15	9	13
1246	16	9	22	12	15
1270	19	7	11	10	28
1294	20	7	18	13	19
1305	48	8	15	16	40
1328	19	9	48	45	50
1330	37	9	20	16	33
1356	8	8	13	7	6
1362	16	7	17	16	16
1389	3	7	11	4	5
1397	19	8	31	14	18
1500	18	8	20	19	48
1503	3	6	6	2	4
1513	5	8	11	5	7
1531	1	7	9	3	3
1544	6	6	12	No data	No data
1560	18	No data	17	10	17
1563	20	11	35	14	29
1570	13	8	15	10	14
1625	51	17	43	39	65
1626	10	9	16	9	15
1627	18	8	17	11	14
1633	17	6	11	12	20
1636	44	9	34	26	40
1649	11	6	13	7	16
1660	31	8	24	16	26
1664	12	8	18	8	13
1675	6	7	10	5	9
1682	10	6	13	8	15
1748	8	No data	12	13	18
1755	13	9	19	7	10
1767	10	7	14	6	10
1782	14	No data	16	10	17

1810	5	7	10	7	18
1840	38	9	21	20	38
1842	12	8	16	14	21
1847	20	10	19	14	25
1857	9	10	15	6	10
1910	29	9	23	16	36
1910	7	9	13	4	8
1940	13	7	15	9	12
1950	9	7	14	6	8
2020	2	7	6	3	4
2029	4	6	8	3	4
2030	1	6	41	25	29
2050	11	6	10	8	11
2050	7	7	11	7	12
2070	4	7	8	5	16
2103	47	7	30	31	45
2105	17	7	14	11	24
2125	37	9	31	20	39
2149	1	6	6	2	3
2173	5	7	9	4	7
2408	3	6	18	14	28
2435	3	6	7	2	2
2480	17	8	20	11	13
2573	11	8	9	5	13
Count	**67**				

	Unladen Kerb Mass	**DAMAGE**	**SUFEHM**	**KTH**	**THUMS**	**GHBMC**
Maximum	2573	51	17	50	46	65
Minimum	970	1	6	6	2	2

Appendix II

Details of accident reconstruction cases 2 and 3 for brain injury criteria evaluation.

Case 2

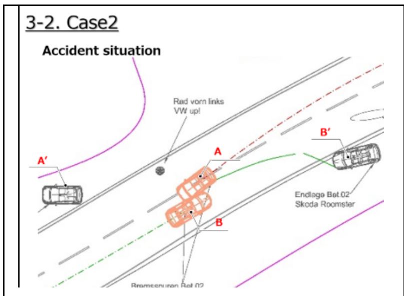

Figure 27: Accident sketch

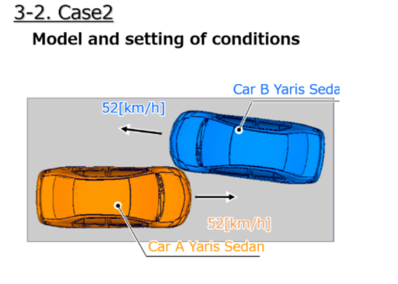

Figure 28: Simulation model set-up

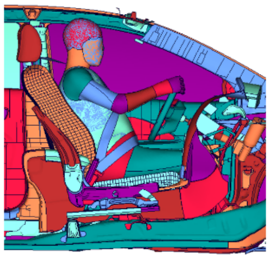

Figure 29: THUMS seating position

No.	Regions	AIS 2008	Diagnosis	Trauma causes
1	Chest	1	Contusion	Seat Belt
2	Head	1	Scalp laceration	B-Pillar
3	Cervical spine	1	Whiplash	Body motion
4	Head	2	Lost consciousness	B-Pillar
5	Stomach	1	Contusion	Seat Belt

Table 4: Injuries to driver of vehicle A

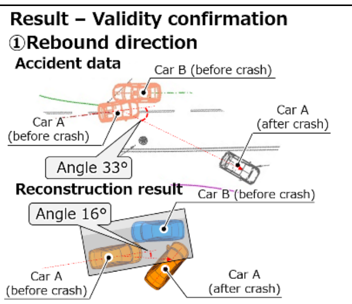

Figure 30 Rebound direction compared to accident data different. Steering and pedal operation might have possibly affected the direction.

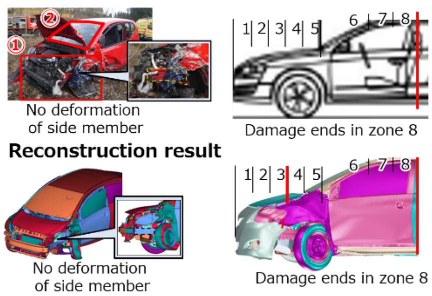

Figure 31: The comparison of vehicle deformation

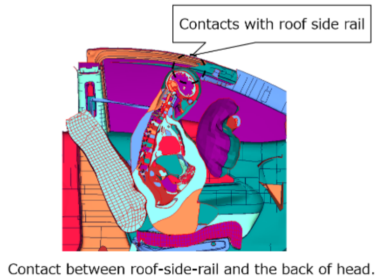

Figure 32: Injured position. Difference between simulation result and accident documentation

Case 3

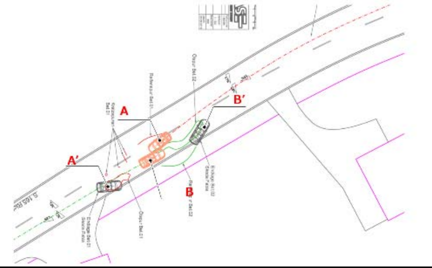

Figure 33: Accident sketch

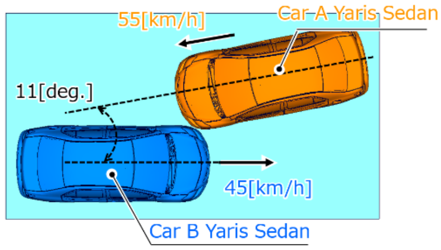

Figure 34: Simulation model set-up

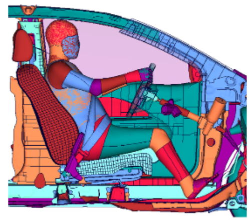

Figure 35: THUMS seating position

No.	Regions	AIS 2008	Diagnosis	Trauma causes
1	Head	2	Concussion	Body motion
2	Head	1	Scalp laceration	B-pillar
2	Head	1	Scalp laceration	Unknown
3	Head	1	Scalp laceration	Unknown
4	Upper extremity	1	Abrasion	Unknown

Table 5: Injuries to driver of vehicle A

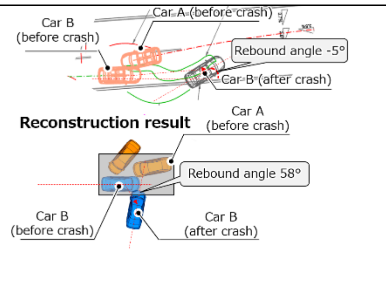

Figure 36: Rebound direction compared to accident data different. Steering and pedal operation might have possibly affected the direction.

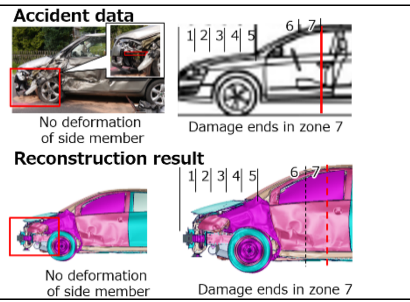

Figure 37: Comparison of vehicle deformations

Figure 38: Injured position