

## Structural Optimisation in Vehicle Development for the current Euro NCAP side crash protocol: how to minimise the structural changes due to the current barrier stiffness and geometry

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**Abstract** The current Euro NCAP side impact protocol introduces the dummy WorldSID 50th percentile, which exhibits a much more complex performance than the EuroSID-II; and AE-MDB barrier, which causes new loading patterns in the structure.

The aim of this study is to identify the key differences between the past and current Euro NCAP protocols and propose countermeasures to achieve the new requirements using a mid-sized previously designed vehicle. Outcomes from a possible Euro NCAP increase in crash speed from 50 km/h to 60 km/h were also evaluated. Finite Element Method (FEM) tools were used, including validated and correlated models with experimental full car tests.

With the current protocol, the most critical anatomical area observed in this research was the pelvis. The countermeasures proposed and evaluated to decrease the load on this area were:

- sill and B-pillar redesign;
- stiffness reduction of the door panel;
- door beam optimisation;

After the application of the structural countermeasures, the sacroiliac force decreased by 24.9% and the pubic force decreased by 32.5%. Furthermore, similar results were obtained in the 60 km/h test. This countermeasure describes a potential strategy to enhance occupant protection in mid-sized cars without increasing the cost or weight of the vehicle.

**Keywords** AE-MDB, crashworthiness, Euro NCAP, side crash, WorldSID 50th, FEM.

### I. INTRODUCTION

Side and oblique collisions account for approximately 16 and 41% of all traffic collisions [1]. Side impacts involving US passenger cars accounted for 33.4% of all fatalities and 28.1% of all injuries on American roads (reference based on the Traffic Safety Facts 2000–2009, published by NHTSA, a compilation of Fatality Analysis Reporting System (FARS) and General Estimates System (GES) data). In previous epidemiologic research, side impact was found to be twice as likely as frontal impact to be fatal [2].

The current European regulatory side-impact test procedure (ECE R-95) has been evaluated by several studies to assess whether it is representative of the actual car fleet in Europe. The main conclusion reached by these studies was that the past test method may not reflect the real vehicle fleet and real-life traffic conditions [3]. Thus, the European Enhanced Vehicle-safety Committee (EEVC) Working Group 13 (WG13) has coordinated studies to improve the applicability of the side-impact test procedure (ECE R-95) to the present European fleet.

The Advanced European Mobile Deformable Barrier (AE-MDB), which is more representative of the European vehicle fleet, was developed to enhance the ECE R-95. The AE-MDB presents a higher stiffness, increased weight and enlarged width compared to the MDB. This last one was used by Euro NCAP between 1997 and 2014. The AE-MDB weighs 1,300 kg, which is 350 kg heavier than the MDB. The AE-MDB is also 200 mm wider than the MDB and includes a 45 degree chamfer on the edges. Although the barriers have the same height, the initial ground clearance is 50 mm higher in the AE-MDB. Both barriers are composed of six blocks of varying stiffness; the AE-MDB has stiffer blocks in the side-low part of the barriers [3]. All these facts demonstrate that the AE-MDB has been developed to better represent the current vehicle frontal face. The midplane of the MDB is aligned to the vehicle's R-point, whereas the AE-MDB is aligned 250 mm rearwards. This position was designed to represent a "moving car to moving car" side impact.

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Euro NCAP examines and modifies its protocols to encourage the automotive industry to improve cars and therefore increase occupant safety. Thus, Euro NCAP has included the AE-MDB barrier in the side-impact protocols since 2015. In addition, the past crash test dummy for side-impact protocols, European Side Impact Dummy EuroSID-II 50th percentile, has been replaced by the WorldSID 50th. The overall biofidelity rating for the WorldSID 50th has increased substantially compared to the EuroSID-II [4].

Even though the barrier has changed, the velocity used in the present protocols is still below that found in the majority of real-life fatal crashes [5]. Thus, the present speed of 50 km/h for the AE-MDB should be increased by about 15 km/h to be more representative of real-life crashes [6]. It is for this reason that the Korean New Car Assessment Program (KNCAP) side protocols use the AE-MDB barrier with a higher speed (55 km/h) [7]. With that in mind, the countermeasures presented in this paper were also assessed at 60 km/h, in addition to the protocol velocity of 50 km/h.

The introduction of the side-impact protocols by Euro NCAP poses a challenge to the automotive industry. This study details the implications for a 2012, five-star-rated vehicle when the present side-impact protocol is applied to it and also proposes some countermeasures to improve occupant safety in order to achieve the Euro NCAP 2015 requirements.

### **Description of different countermeasures**

As a first part of this project, a biomechanical study was carried out to evaluate the most critical dummy values in a side-impact crash when using the barrier AE-MDB. It was obtained that the pelvis area (pubic and sacroiliac forces) exceeded its upper performance limit for both barrier velocities (50 km/h and 60 km/h). The pelvis was the only body region to go beyond its upper performance limit in AE-MDB 50 km/h. Therefore, the countermeasures were focused on reducing pubic force, pelvis acceleration and sacroiliac force. Moreover, countermeasures were tested with AE-MDB 60 km/h in order to show their validity in more severe conditions.

The first countermeasure was **the elimination of the pelvic energy-absorbing element**. Since the introduction of dummy WorldSID 50th, some doubts have arisen regarding the usefulness of this element with the new pelvis and new lumbar spine.

The second countermeasure was **the orientation change in door beam**. The new orientation was almost horizontal in order to increase the stiffness in door lower parts.

The third countermeasure was **the sill and B-Pillar redesign**. These parts were redesigned to improve their behaviour in side impact with taller cars, which are represented by the AE-MDB barrier.

## **II. METHODS**

All the values, results and countermeasures of this study were based on finite element methods (FEM). One mid-size car, weighing 1,401 kg and awarded five stars by the Euro NCAP test 2012, was used as the reference vehicle. This real car was additionally crashed using the Euro NCAP 2015 side-impact protocol in order to correlate and validate the FE model.

The reference FE model used in this study was comprised of a total of 2,411,672 shell and solid elements, having an average mesh size of 7–10 mm. A cluster of SEAT, S.A was used to compute model simulations using Pam-Crash 2011. The current SEAT, S.A cluster is comprised of several Intel® Xeon® CPU E5-2670 @ 2.60 GHz 32 nodes, with 16 cores running on a Red Hat Enterprise Linux operating system, making a total of 512 cores with 64 GB Memory RAM. A controlled time step of 0.8  $\mu$ s was imposed, the model was tested using up to 16 CPUs and computational times were recorded. The materials used by the model are from the Volkswagen material database.

This study was carried out to identify the key differences between the past and the current Euro NCAP protocols for side impact. In addition, a new test was incorporated to broaden the scope of the present study. This test has the same characteristics of the current protocols, but with the barrier velocity increased to 60 km/h. In order to reduce the variables, the WorldSID 50th dummy was placed in the driver position in all three tests performed, thus the only difference between the past and present protocol was the barrier.

The reference FEM crash was the Euro NCAP side-impact test procedure with the dummy WorldSID 50th in the driver position and the simulated barrier was the MDB, aligned in the vehicle's R-point at a speed of 50 km/h. This reference model was created from the original FE model, which was used during the development of the vehicle. The original FE model was correlated with a different crash test.

The reference FE model incorporates curtain and thorax airbags, manufactured by KSS and TRW. The firing time of these airbags and the seatbelt were defined at 7 ms after the initial contact, per laboratory crash observations.

After the reference FE model was created, the other two models were developed. In the AE-MDB 50 test the barrier used was the AE-MDB, aligned with a point 250 mm rearward from the vehicle’s R-point. The WorldSID 50th dummy was positioned in the driver position.

This model was correlated with the additional real crash test. The dummy and the barrier were new variables introduced regarding the original and correlated model to create the AE-MDB 50 test. The barrier’s FE model was the 4.01 version from the Volkswagen database and the dummy’s FE model was the 2.5 version from ESI Germany. The barrier had already been correlated by the manufacturer, thus the correlation efforts were focused on the biomechanical values of the dummy and its kinematics. To achieve this objective, the contacts between the dummy and its environment were modified in number, type and friction. Significant emphasis was placed on seatbelt, airbags and seat foam.

Figure 1 shows the results from the correlation of the AE-MDB 50 test. Some discrepancies are detected in the rib deflection, especially in the chest area. They present a similar tendency, however, which allows for predictions. On the other hand, values of the lower part of the dummy (T12, pelvis, pubis and sacroiliac), which are the main focus of this study, present an accurate correlation.

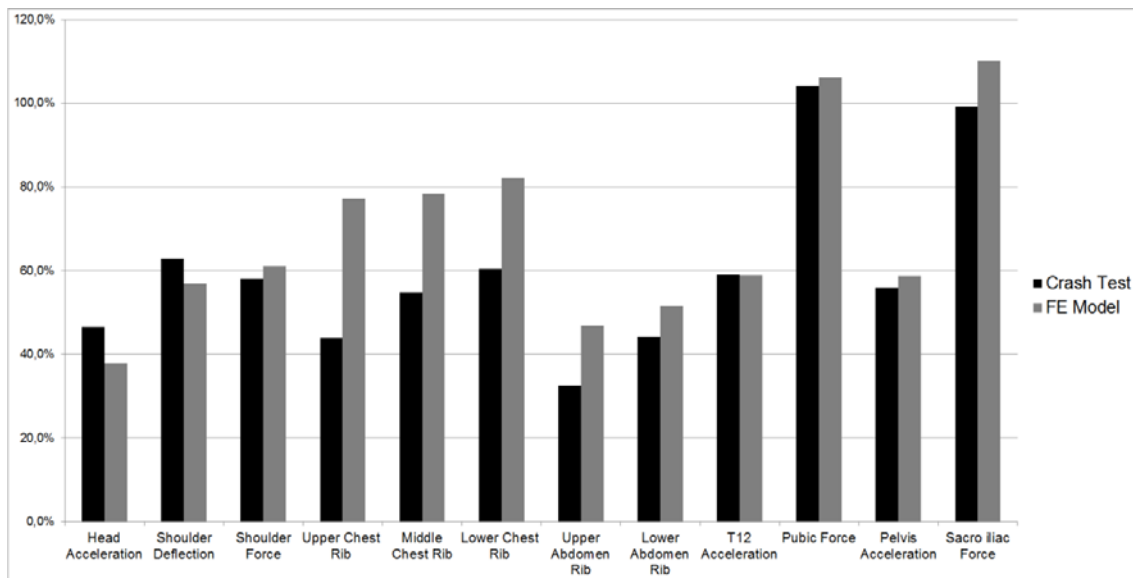


Fig. 1. Crash test – FE Model correlation max. values.

Additionally, a second simulation with the AE-MDB was run at a collision speed of 60 km/h. This test was included in order to explore the behaviour of the countermeasures in the event of facing a more challenging protocol. Table I summarises these different simulated models, and additional information could be found at Appendix 1.

A structural and biomechanical study was made using the three models. The study was carried out to assess the differences between the past and current protocol. Subsequently, different countermeasures were simulated individually in the AE-MDB 50 and in the AE-MDB 60 to assess their benefits. Finally, all countermeasures were included simultaneously in both AE-MDB models to evaluate their compatibility.

TABLE I  
SIMULATION-TEST MATRIX

	Reference		
Simulations	Model	Model AE-MDB(50)	Model AE-MDB(60)
Barrier	MDB	AE-MDB	AE-MDB
Dummy FR	WS	WS	WS
Speed Barrier	50 km/h	50 km/h	60 km/h

**Elimination of the pelvic energy-absorbing element**

Common strategies introduce an energy-absorbing element located in the low-rear end of the front door panel, increasing the stiffness of the panel (Fig. 2). The goals of this element are to dissipate energy and to modify the EuroSID-II kinematics to move the dummy away from the door panel and thereby reduce the applied loads. Since the introduction of the WorldSID 50th, especially its lumbar spine, the biofidelity of this element has been under assessment. Thus, the energy-absorbing element was eliminated in order to evaluate its influence on the dummy results.

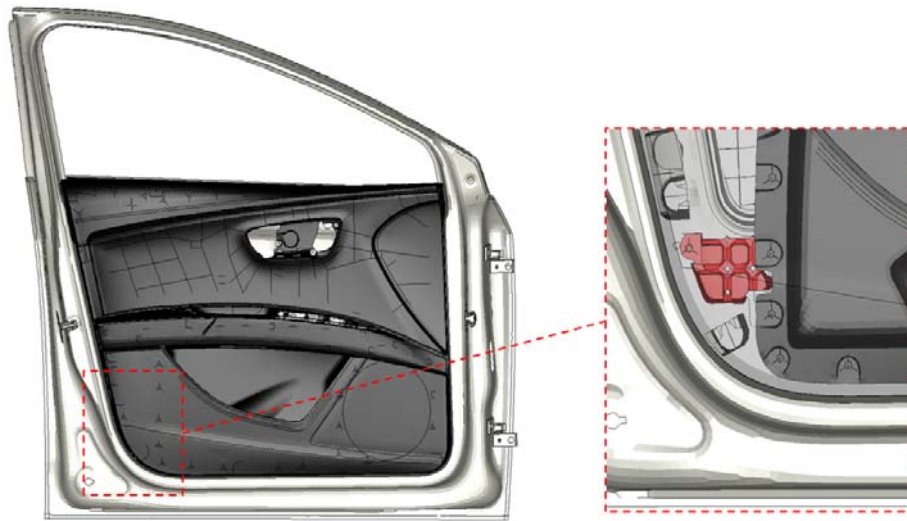


Fig. 2. Energy-absorbing element location.

**Change in orientation of the door beam**

To improve the door performance when subjected to AE-MDB loads, the door beam was rotated to increase the stiffness of the lower part of the door (Fig. 3). From this optimisation, the door beam is connected almost horizontally at the lower hinge of the door, increasing its stiffness.

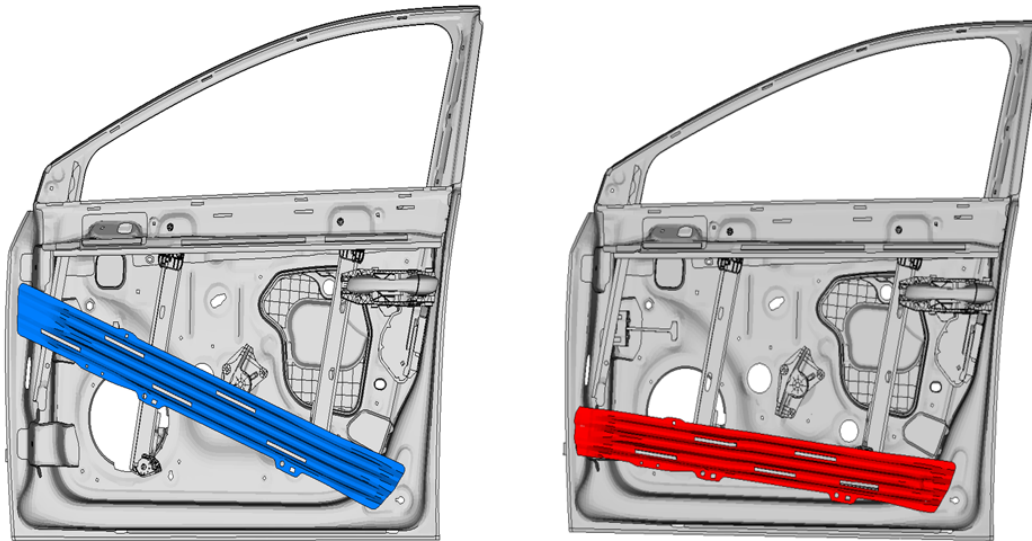


Fig. 3. Present door beam position (*left*); optimised door beam position (*right*).

### Sill and B-Pillar redesign

In a side crash, two of the most important parts responsible for good structural behaviour are the sill and the B-pillar. They function to dissipate energy and transfer load throughout the bodywork.

The energy and mechanical loads endured by both the sill and the B-pillar were increased when the AE-MDB was adopted. Therefore, three geometry modifications were evaluated: a belt retractor reinforcement lengthening to join the sill upper and lower parts; a reduction of sill section to introduce the B-pillar base; and a redesign of the B-pillar base to adapt it to a new sill section. (The detail of this redesign is described in Fig. 4.)

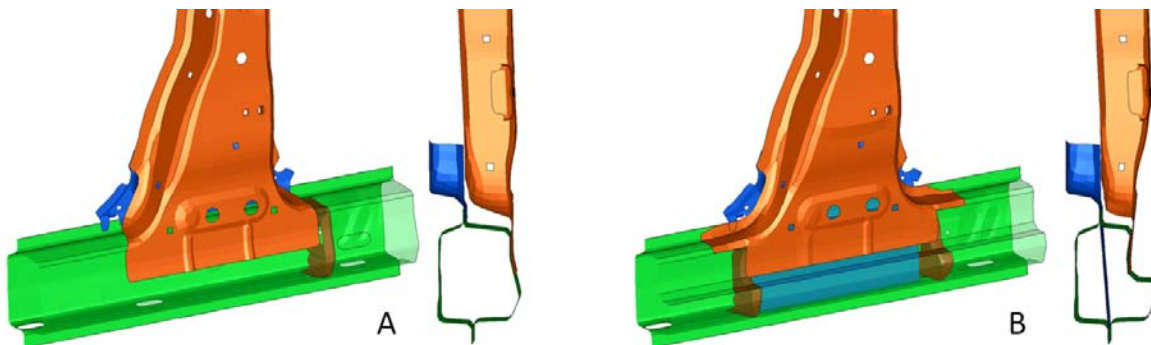


Fig. 4. Sill and B-pillar base. (A) Original, and (B) countermeasure.

### Biomechanical assessment

The biomechanical values were expressed as a percentage of the different upper performance limits in order to assess and compare them. The limits shown in Table II summarise the Euro NCAP upper performance limits. Additional values that are not considered by Euro NCAP, such as sacroiliac force, were included in this research to better understand the dummy's performance.

TABLE II  
BIOMECHANICAL VALUES LIMITS

Results	Unit	Lower limit
HIC 15	-	500
Peak resultant head acc.	[g]	72
Shoulder force	[N]	3000
Shoulder rib deflection	[mm]	70
Thoracic rib deflection	[mm]	28
Abdomen rib deflection	[mm]	47
Pubic force	[N]	1700
Sacroiliac force (not Euro NCAP limit)	[N]	3000
Lower spine acceleration	[g]	75
Pelvis acceleration	[g]	100

III. RESULTS

**Reference situation - Vehicle deformation**

The outer deformations of the vehicle side at three heights for the three FE simulations are presented in Fig. 5 so as to compare their intrusions. The R-point was chosen as the grid's reference to represent the intrusion contours. Initial ground clearance was 50 mm higher in the AE-MDB impact condition, which resulted in less energy being distributed throughout the bodywork (Fig. 5). The vehicle's final deformation at the R-point was similar between MDB and AE-MDB 50. The maximum intrusion for the MDB test was located at the R-point due to the barrier being aligned at this point and higher stiffness of the middle-block. On the other hand, the AE-MDB geometry and its rearward alignment produced a different intrusion profile. In this case the maximum intrusion was located in the middle of both doors instead of being located at the R-point.

At the pelvic height, the relative intrusion was larger with the AE-MDB than with the MDB, due to the higher stiffness of the low-blocks in the AE-MDB face. This type of intrusion may be associated with more severe injuries in the pelvis. Therefore, the AE-MDB test procedure was more severe than the MDB, producing higher intrusions due to both weight increase and higher stiffness face. Additionally, intrusion profiles from simulated results at 60 km/h at three different height levels can be seen in Fig. 5.

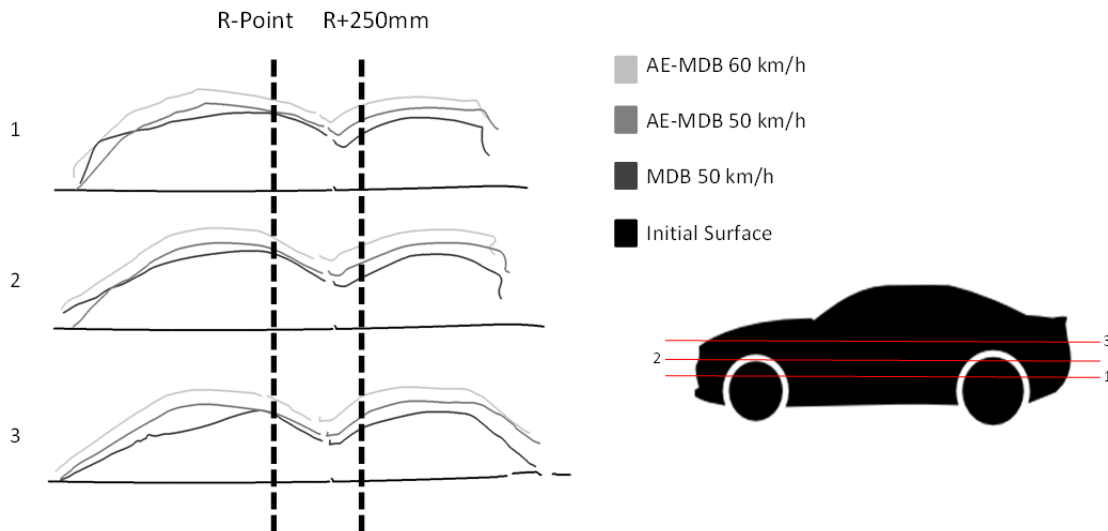


Fig. 5. Intrusion Profile measured at the vehicle exterior structure.

### Reference situation - Driver dummy injury criteria

Focusing on the driver dummy for the MDB test (Fig. 6), all injury criteria values for the car (without design optimisation) were below 90% of their limits. On the other hand, in the AE-MDB test at 50 km/h, the pubic and sacroiliac forces were above the limits (Fig. 6), this values increased by 38.6% and 25.8% respectively comparing to the MDB test. Results for the AE-MDB 60 km/h test indicate that the thorax rib deflections also became critical (Fig. 6). Pertaining to head, shoulder and abdomen, injury values of both MDB and AE-MDB 50 were below the limit value (60%). For chest injury, the lower rib presented the worst biomechanical values of all three tests. In the AE-MDB 60 km/h test, however, the chest rib deflection values were above the limits because the side airbag bottomed out. This effect was mainly caused by an increase in the impact speed. The AE-MDB shape increased the door and B-pillar intrusion velocity, specifically at the pelvis height. Consequently, the inner part of the vehicle impacted the pelvis at higher velocity, thus producing increased injury values. This high intrusion velocity also reduced the deployment airbag space, which caused difficulties in the mitigation of impact energy by the side airbag.

It should be noted that only the pelvis injury values reached the limits in AE-MDB 50 km/h. Therefore, the countermeasures were focused on reducing these values: the pubic force, the pelvis acceleration and the sacroiliac force. Moreover, those countermeasures were tested with AE-MDB at 60 km/h in order to show their validity under more severe conditions. Since the aim of the countermeasures was to reduce the pelvic injury values in the AE-MDB tests, it was necessary to cope with three aspects: the higher intrusion velocity of the vehicle side; the increased stiffness of the low side barrier face; and the door panel stiffness at the impact location with the occupant.

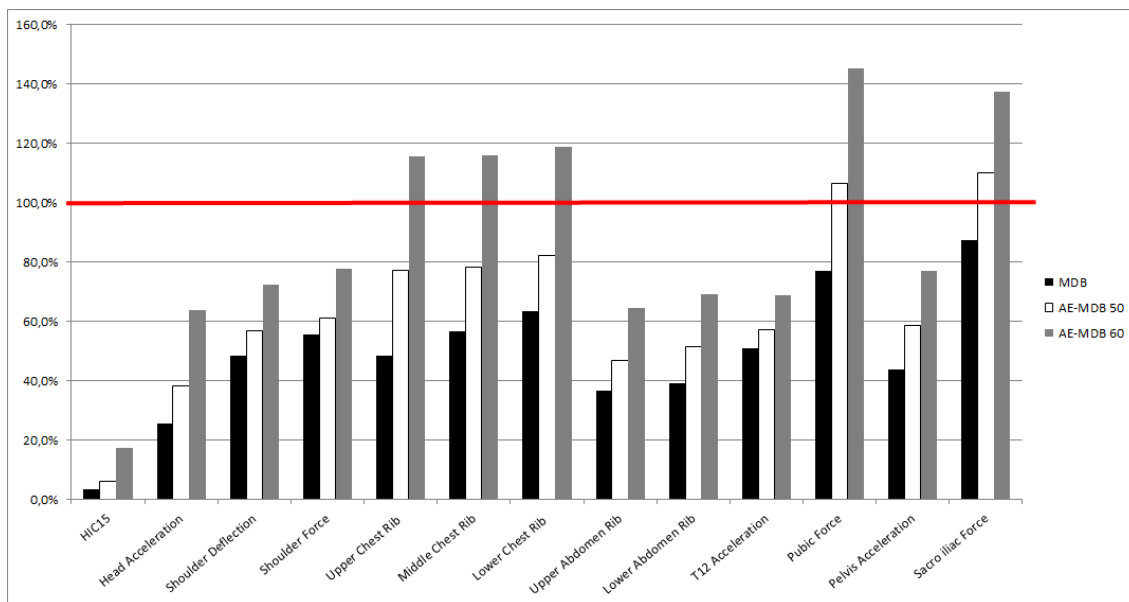


Fig. 6. Injury values in the three different tests.

### Performance of countermeasures

#### Elimination of the pelvic energy-absorbing element

The elimination of the pelvic energy-absorbing element in the AE-MDB 50 km/h test reduced pelvis injury values, especially in pubic force (Fig. 7A). The decreased stiffness in the contact location between the pelvis and the door panel lowers the force received by the pelvis. Due to the decreased stiffness, the pelvis acceleration and the sacroiliac force values were reduced by 12.1% and 5.4%, respectively. Meanwhile, the pubic force value was reduced by 21.5%, placing its value well below the limit. The rest of the values remained similar. All injury values, except for the sacroiliac force, were calculated to be below the limit by at least 15% of the criteria.

In the AE-MDB 60 km/h test, the variation of the injury values was quite similar to that obtained in the 50 km/h test, as shown in Fig.7B. The pelvis injury values were reduced significantly and the rest of the injury values did not experience significant variation. The main decrease in injury value was produced in pubis; the value was lowered by 25%, placing it near its limit. The velocity of the impact in this test was higher and, consequently, the injury values were higher as well. Therefore, the padding elimination in this test obtained greater reduction in the injury values.

The elimination of a pelvic energy-absorbing element in both tests caused a reduction in pelvis injury values without any significant increase in the other injury values.

#### **Results of door beam optimisation**

The results of the door beam countermeasure showed that the pubic force value was reduced in both tests. In the AE-MDB 50 km/h test the pubic force was reduced by 8.6%, while in the 60 km/h test the value was decreased by 8.7%. This reduction in pelvis force resulted from the stiffness increase in the lower-side parts of the door, which decreased the intrusion velocity of the door panel. Implementing the door beam countermeasure caused the pubic force value to be below the limit in the AE-MDB 50 km/h test.

All other injury values in the AE-MDB 50 km/h test did not obtain a significant variation (less than  $\pm 5\%$ ). Conversely, in the AE-MDB 60 km/h test all injury values did not result in any significant variation, with the exception of the shoulder force. The 13.0% shoulder force value reduction was produced by a change in dummy kinematics throughout the test.

#### **Results of Sill and B-Pillar redesign**

The redesign of the sill and the B-pillar resulted in a controlled bending behaviour. More energy was dissipated in these tests, causing a reduction in the low side intrusion velocities. Due to the difference in energy dissipation, all lower extremity injury values were reduced with the introduction of this countermeasure, with the exception of the T12 measurements in the 60 km/h test.

In the AE-MDB 50 km/h test, all three pelvis values decreased. Pubic force decreased by 11.9%, pelvis acceleration decreased by 22.8%, and sacroiliac force decreased by 21.2%. In the test, the B-pillar impacts against the seat through belt retractor reinforcement, which produces contact between the seat structure and the rear part of the pelvis. The large reduction of the sacroiliac injury value was caused by the decrease in B-pillar intrusion velocity. This decreased velocity also caused all injury values in this test to remain below the limits.

Examining the chest and abdomen injury values, whole rib intrusion values were reduced due to a better side airbag deployment. However, head and shoulder injury values increased, but none of these injury values was found to be above 80% of the injury limit. Thus, the introduction of this countermeasure significantly enhanced the dummy protection in the AE-MDB 50 km/h test.

The trend of decreasing injury values was similar when comparing the AE-MDB 50 km/h and the 60 km/h tests, with the only exception being the T12 acceleration. The reductions of other injury values were increased when compared to the AE-MDB 50 km/h test; the pubic and sacroiliac force decreased by 14.9% and 20.2%, respectively, and all chest intrusion obtained was more greatly reduced. For example, the lower chest rib value decreased by 16.0%. In the 50 km/h test, the head and shoulder injury values increased, but did not exceed, the injury limits. Hence, sill and B-Pillar redesign countermeasure also provides an improvement of the dummy safety in the AE-MDB 60 km/h test.



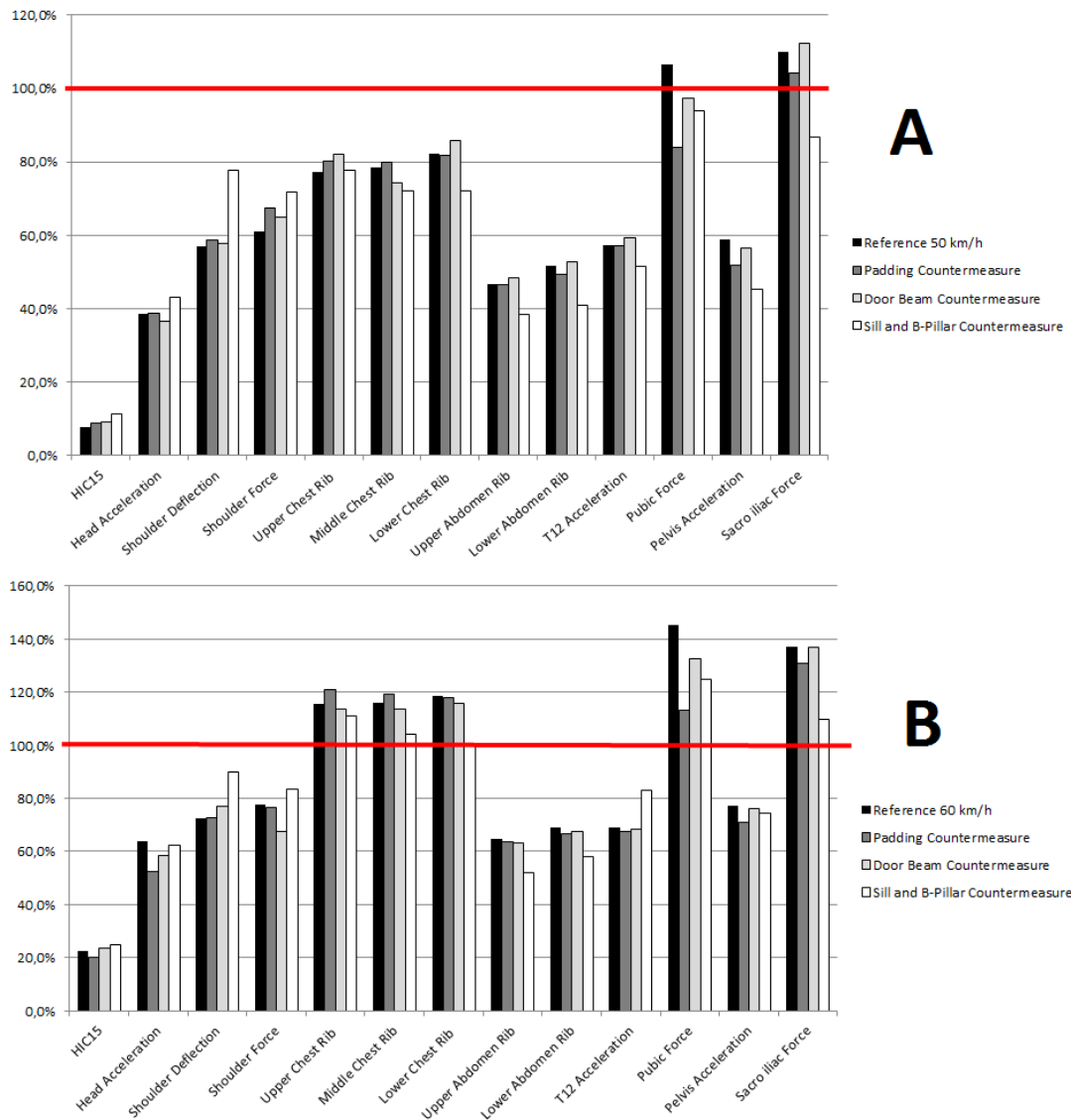


Fig. 7. Injury values in the (A) AE-MDB 50 km/h test and in the (B) AE-MDB 60 km/h test with the different countermeasures.

**Results of the simultaneously applied countermeasures**

A model was built to determine the potential of different countermeasures and the effect of the different vehicle and occupant interactions (Fig. 8). Focusing on the AE-MDB 50 km/h test, all values remained below the established injury limit, with a safety margin of 17%.

The pelvis was the location where the largest reduction occurred. Initially, the sacroiliac force achieved 110% of its limit and the pubic force achieved 104% of its limit. However, after the global countermeasure the injury values were 82.7% of the limit for the sacroiliac force and 71.9% of the limit of the pubic force.

From analysis of the rib deflections, the calculated abdomen injury values decreased by 16% and 20%, and the middle and the lower chest values decreased by 5%. However, the upper chest increased by 2.5%. Conversely, both the shoulder and the head injury values increased with the implementation of the global countermeasure. None of them exceeded 75% of their limit injury value, however. Higher injury metrics were caused by energy transference from the lower to the upper part of the dummy, because there was a load reduction in the pelvis for this test.

Overall, the trend of decreased injury measures in the AE-MDB 60 km/h test was similar to the 50 km/h test. T12 acceleration value was the only injury value to behave differently: it increased for the sill and B-pillar countermeasure. The highest decrease in injury value was observed in the pubic force, which decreased by 35.1%. Abdominal rib injury metrics decreased by the same amount in both tests. However, the decrease in

chest lower rib value was greater in the AE-MDB 60 km/h test, which approached the rib injury limit. The remaining two chest values were above the injury limit due to their initial high values. Head and shoulder injury calculations increased, similar to the 50 km/h test, with the shoulder elongation reaching the highest likelihood of injury and the injury metric reaching 88.9% of its limit.

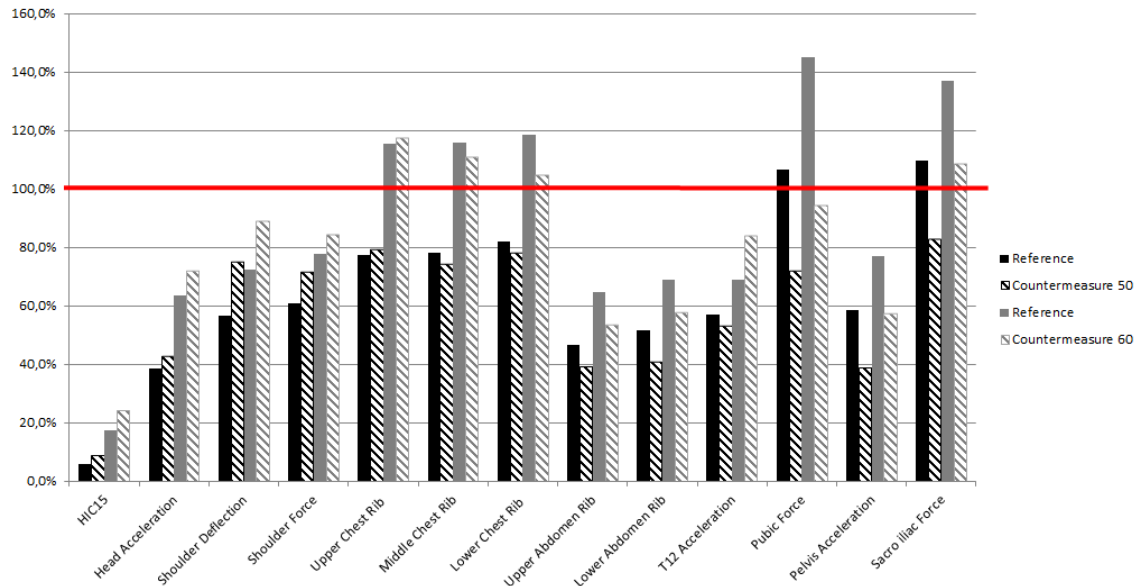


Fig. 8. Injury values in the (A) AE-MDB 50 km/h test and in the (B) AE-MDB 60 km/h test, with the countermeasures applied simultaneously.

#### IV. DISCUSSION

The use of the AE-MDB increased the intrusion velocity compared to that of the MDB, i.e. it caused higher deformation of the vehicle side. This increased deformation has been previously reported throughout literature [8-10] and has been associated with more severe injuries [6]. With the new stiffness distribution, this increased deformation was more obvious in the side-lower parts of the vehicle, which were further from the symmetric axis of the barrier. Due to this fact, there is a decrease in the deployment time of the restraint systems. This decrease in deployment time of restraint systems means that these restraint systems will likely need to be more precisely developed.

All these structural changes resulted in changes in the biomechanical injury values calculated from the AE-MDB 50 km/h test. The injuries that increased the most, or were placed closer to their respective injury limits are: thorax rib elongation; the pubic force; and the sacroiliac force. The increase in rib deflections was caused by higher intrusion velocity, which caused a subsequent reduction airbag deployment volume. This decreased airbag deployment volume increases the pressure of the airbag, which likely increases injury measurements. The increase in the pubic force injury value was caused by higher stiffness of the barrier causing a larger intrusion value and thus producing a more severe impact against the pelvis. Although the sacroiliac force value is currently not assessed in the Euro NCAP side-impact protocol, it should be taken into account to better understand the distribution of forces for the occupant. Their values result from the impact between the belt retractor reinforcement and the seat, and from the impact of the seat structure against the rear part of pelvis.

Additionally, previous studies [6] have shown that the 60 km/h test produces greater deformations than the 50 km/h test in all areas of the vehicle structure. The highest risk injury values are the rib chest deflection and the forces in pubis and sacroiliac joint, as in the other test, but with higher values. In this test, the violating values are the same as in the AE-MDB 50 km/h test and the three chest rib deflections.

The goal of the countermeasures is to decrease the pelvis force injury values so that they remain below the injury thresholds in the 50 km/h test. In addition, the countermeasures were tested in a 60 km/h test in order to verify their functionality in higher velocity impacts.

The first countermeasure was the elimination of the pelvic energy-absorbing element. In the previous Euro NCAP barrier test, the EuroSID-II pelvis contacts with energy-absorbing element at the outset of the crash. Due to the high stiffness of the energy-absorbing element, the pelvis moves away from the door panel. This movement is transmitted from the pelvis to the upper part of the dummy through the lumbar spine, reducing thorax and abdomen loads. Similar kinetics are not reproduced with the WorldSID 50th dummy because of geometric and stiffness differences in its lumbar spine.

The lumbar spine has a significant influence on the global kinematics of the dummies. The WorldSID 50th lumbar spine has a lower stiffness than the EuroSID-II [11]. Also, the current protocol assigns the WorldSID 50th dummy a lower injury limit value at the pelvis area. As a result of protocol changes in injury values and the different energy distribution in the new protocol, the benefit of the padding with the WorldSID 50th has been reduced. The presence of the energy-absorbing element was not that important in this loading condition.

The introduction of the AE-MDB with higher mass, different geometry and a higher stiffness in side-low part has created the need to increase the stiffness in the side-low part of the vehicle. Several elements are present in the structure that absorb and distribute the energy in side impacts, one being the door beam. Therefore, the door beam was optimised by modifying the location of the joints and the orientation of the beam. This countermeasure was focused on reducing the intrusion velocity of the door, thus increasing the stiffness at the lower part of the door, so the beam cushions the impact between the door panel and the dummy.

Lastly, the sill section and the B-pillar base were redesigned in order to reduce bending and torsional behaviour. These phenomena are induced by the higher energy involved in the crash and the new barrier's geometry. Specifically, the increase of 50 mm in the initial ground clearance makes the initial contact between the vehicle and the barrier to be located over the sill. Initially, the sill and B-pillar were designed to perform properly in bending against the MDB. Due to this different loading distribution, the sill section was lost quickly, decreasing both the energy dissipation and the load distribution throughout the bodywork. The proposed sill design optimises the behaviour of the sill, enhancing the effectiveness of the structure and reducing the intrusion velocities.

These three countermeasures were included in a global one to test them simultaneously. All the calculated injury values of the abdomen and the pelvis in both tests, with the exception of T12 acceleration in the 60 km/h test, were reduced with the introduction of the global countermeasure. Thus, all the biomechanical values in the 50 km/h test were below the injury limit.

The use of the global countermeasure reduced the pubic force value by 33% in both tests, placing it below the injury limit. The reductions were caused by the elimination of the padding. Sacroiliac force was the other value in the 50 km/h test that was placed below the injury limit when the global countermeasure was applied. It decreased by 24.9%, due to the lowered intrusion velocity of belt retractor reinforcement. Conversely, in the 60 km/h test, the sacroiliac injury value was reduced by the same percentage as in the other test, although this was not enough to be below the injury limit. The last pelvis acceleration obtained reductions of 25% in both tests. These reductions were caused by the first and third countermeasure (the pelvic energy-absorbing element and the sill/B-pillar effect).

The abdomen rib elongation injury metrics decreased between 16% and 21% in both tests, which placed the values further from the injury limits. Decrease in this injury metric was caused by the reduction of the intrusion speed in the B-pillar lower part, which resulted in a larger volume for airbag deployment. However, the thorax rib elongation injury metric did not decrease in the 50 km/h test, and decreased by only 11.9% in the 60 km/h test.

Initially, and without countermeasures, when the pelvis impacted against the door panel, the upper torso of the dummy moved away from the door panel. The dummy kinematics changed due to the introduction of the countermeasures, which reduced the severity of the impact between the pelvis and the vehicle interior. However, all of the head and shoulder injury values increased. In the AE-MDB 50 km/h test, the shoulder elongation injury value increases the most, up to 75.1% of its injury limit. In the 60 km/h test the shoulder injury value increased up to 88.9% of its injury limit. These injury value increases were caused because the shoulder was not covered by the airbag, so there was no energy-absorbing element between the shoulder and the vehicle interior.

To reduce shoulder injury values, an airbag adapted to the new impact requirements should be implemented. This airbag should cover the WorldSID 50th shoulder in order to avoid direct impact against rigid elements

inside the vehicle. Also, these kinds of airbag would increase the dummy retention and, as a consequence, probably further decrease the thorax ribs deflection.

The global countermeasure obtained an improvement of occupant safety in the AE-MDB 50 km/h test, with all of the injury value metrics remaining below the threshold of injury. This was achieved without increasing the weight of the car, unlike other studies [8][9], and without using pre-crash countermeasures [12]. Moreover, despite being beyond the scope of this study, the global countermeasure was tested in oblique pole test obtaining none relevant changes.

## V. CONCLUSIONS

With the introduction of the AE-MDB and the WorldSID 50th, Euro NCAP has made a step forward in terms of safety standards. The tests are now more representative of the field not only regarding the impact severity but also the human behaviour. This test has a strong impact in mid-sized cars in terms of pelvis loading, leading the pubic and sacroiliac forces to increase by 38.6% and 25.8%, respectively, setting them over the accepted injury limits.

This paper shows that it is manageable to meet the current Euro NCAP requirements with a safety margin of over 15%, and that it is also possible to reach a good protection level at higher speed through vehicle structure optimisation. Following introduction of the proposed structural countermeasures, the sacroiliac pubic force decreased by 24.9% and the pubic force decreased by 32.5% in the AE-MDB 50 km/h test. Furthermore, similar results were obtained in the 60 km/h test.

Another important conclusion is that safety strategies, based on less biofidelic dummies such as the EuroSID-II, must be reviewed as they may be not that effective on the current testing scenario. Utilising objects such as the pelvic energy-absorbing element should be minimised since this study showed these elements to be counterproductive in terms of biomechanical values. Removing the energy-absorbing elements, the pubic force decreased by 21.5%, the pelvis acceleration by 12.1% and the sacroiliac force by 5.4%.

This paper describes a potential strategy to enhance occupant protection in mid-sized cars without increasing the cost or weight of the vehicle. The proposed individual and combined countermeasures have proved to provide effective safety over the current Euro NCAP standards.

## VI. ACKNOWLEDGEMENT

The authors would like to thank Alexander Mait, Lee Gabler, Carolyn Roberts and Gareth Howells for their efforts in editing this article.

## VII. REFERENCES

- [1] Dirección general de tráfico. *Anuario estadístico de accidentes 2011*. Available at: [[http://www.dgt.es/Galerias/seguridad-vial/estadisticas-e-indicadores/publicaciones/anuario-estadistico-de-accidentes/anuario\\_estadistico017.pdf](http://www.dgt.es/Galerias/seguridad-vial/estadisticas-e-indicadores/publicaciones/anuario-estadistico-de-accidentes/anuario_estadistico017.pdf)] Accessed: 1 July 2014.
- [2] Bédard, M., Guyatt, G.H., Stones, M.J., Hirdes, J.P. (2002) The independent contribution of driver, crash, and vehicle characteristics to driver fatalities, *Accident Analysis & Prevention*, **34**(6) pp. 717–27
- [3] Ellway, J. D., van Ratingen, M. *et al.* (2013) The advanced European mobile deformable barrier specification for use in EuroNCAP side impact testing. *NHTSA*.
- [4] Scherer, R., Bortenschlager, K. *et al.* *WORLDSID production dummy biomechanical responses. 21st International Technical Conference on the Enhanced Safety of Vehicles Conference (ESV)*, 2009, Stuttgart, Germany.
- [5] Thomas, P., Wg, E. *et al.* *Priorities for Enhanced Side Impact Protection in Regulation 95 Compliant Cars. 21st International Technical Conference on the Enhanced Safety of Vehicles Conference (ESV)*, 2009, Stuttgart, Germany.

- [6] Edwards, M., Hynd, D., Carroll, J., Thompson, A. Side Impact Safety: assessment of high speed Advanced European Mobile Deformable Barrier (AE-MDB) test and WORLDSID with 'RibEye'. *22nd International Technical Conference on the Enhanced Safety of Vehicles (ESV)*, 2011, Washington, D.C.
- [7] Lim, J., Chang, H., Kim, G., Lee, J. A consideration on the AE-MDB for the side impact test in KNCAP. *23rd International Technical Conference on the Enhanced Safety of Vehicles (ESV)*, 2013, Seoul, Republic of Korea.
- [8] Roussarie, M., Zeitouni, R., Adalian, C. Enhancement of side impact protection using an improved test procedure. *20th International Technical Conference on the Enhanced Safety of Vehicles Conference (ESV)*, 2007, in Lyon, France.
- [9] Bumjin, K., Hyunwoo, K., Dongho, P. Research on the AE-MDB CAE analysis for the improved Euroncap side impact test procedure. *23rd International Technical Conference on the Enhanced Safety of Vehicles (ESV)*, 2013, Seoul, Republic of Korea.
- [10] Sangwook, S., Doohyeok, S., Jinkyu, M. The study of Side Structure Optimization of the SUV for New Side NCAP tests. *23rd International Technical Conference on the Enhanced Safety of Vehicles (ESV)*, 2013, Seoul, Republic of Korea.
- [11] ESI-Group. (2012) *WorldSID 50th User's Manual*.
- [12] Luzon-Narro, J., Arregui-Dalmases, C. *et al.* (2014) Innovative passive and active countermeasures for near side crash safety. *Int J Crashworthiness*, **19**(3): pp.209–21.

VIII. APPENDIX 1

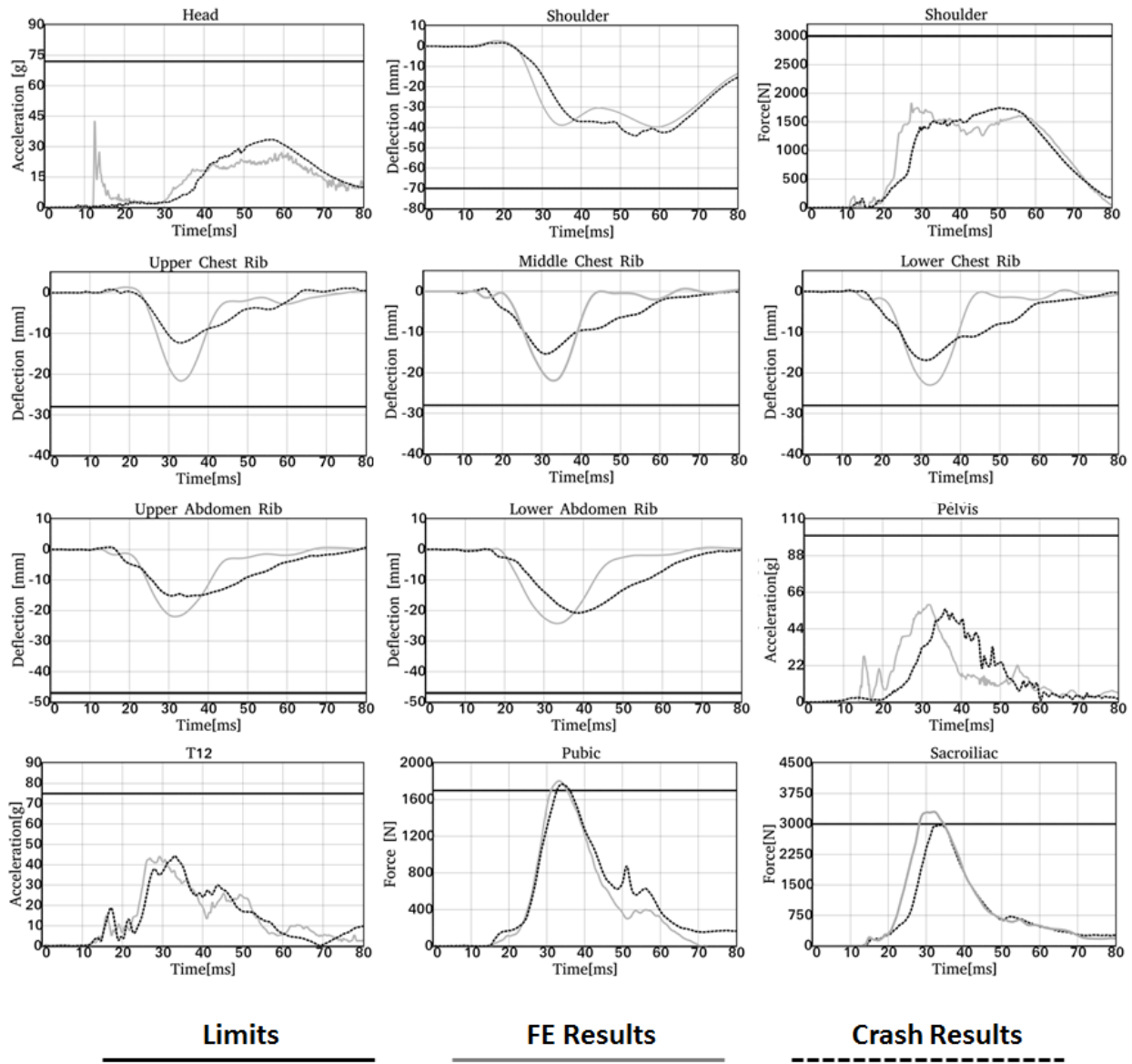


Fig. A1. Correlation curves.