INJURY MITIGATION IN SUV-TO-PEDESTRIAN IMPACTS

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ABSTRACT

In passenger car-to-pedestrian impacts head and leg injuries account for the largest number of severe injuries (AIS 3+). US data from 2005 confirmed this but when studying LTV (Light Truck Vehicle) type of vehicles; thorax injuries replaced leg injuries at 2nd place for AIS 3+ injuries. For passenger cars the hood edge contributed to very few injuries, while in the LTV vehicles it was the main contributor for both lower extremity as well as thorax injuries. It is likely that the lower extremity injuries mainly consist of pelvic injuries, and that the hood edge (also called bonnet leading edge or BLE) of large Sport Utility Vehicles (SUV) produce more thorax injuries while lower SUV hood edges produce more pelvic injuries.

The recent development of pre-crash sensors has opened up new possibilities for pedestrian protection. Reversible solutions can be used as well as airbags in the very front of the car, where time is too short when using a bumper contact sensor.

In this study a bonnet leading edge airbag was developed to mitigate pelvis and thorax injuries for an SUV. The airbag was designed using mathematical simulations with the goal to decrease the upper legform requirements below the threshold levels of EuroNCAP. A physical prototype was produced which was tested and further developed using side impact dummies at a test speed of 40 km/h where pelvic and thoracic loadings were in focus. To do this a dummy test method was developed based on field data. The field data showed that the injury pattern of car occupants in near-side crashes is similar to that of pedestrians impacted by SUVs.

In simulations the BLE airbag proved able to pass the tough EuroNCAP requirements with the upper legform impactor. In full-scale tests the airbag decreased the risk of chest and pelvis injuries considerably, with the largest reductions in the chest and abdomen area.

INTRODUCTION

The upper legform test has been discussed and criticized during many years. The test method was developed as part of EEVC Working Group 10 (EEVC 1994) during the 80's and early 90's, when cars were box-shaped and caused rather many pelvis and femur injuries. Today's passenger cars are considerably more stream-lined and the EEVC working group 17 showed in their report a large decrease of these injuries from 1980 to 1990 cars (EEVC 1998). Therefore when the EU pedestrian directive (2003/102/EC) was finally enforced 2005, this test had been changed to a "monitoring test". A monitoring test means that a test is performed and the data is recorded and saved for the future, but no requirement is set. This is a way for regulators to keep track of the car fleet if it becomes more aggressive in this area of the car.

However, in the USA the Sports Utility Vehicle (SUV) has become very popular and now makes up around 50% of the total sales (Summers et al 2003). This car type has a more box-shaped front and it is also significantly higher in the front than today's passenger cars. Lefler and Gabler (2004) reported that the fatality risk is increased with more than 2.5 times for SUVs compared to cars. Head injuries are the most frequent cause of severe injury for LTVs, as well as for cars. According to Longhitano et al (2005-1), chest injuries are in 2nd place for AIS3+ injuries for the so called Light Trucks and Vans (LTV). For passenger cars lower extremity injuries take the 2nd place

In a second study, Longhitano et al (2005-2) reports that the most common torso AIS 3+ injury locations in SUV impacts are ribcage at 23% and lung at 21%, followed by aorta at 11%. For AÌS 4+ injuries, ribcage still leads, now shared with aorta, at 23 %. Spleen follows at 14%.

Longhitano et al (2005-1) also studied the car impact location. The most frequent AIS 3+ torso injury causing part of the LTV was the hood edge with the hood in second place.

The pedestrian test methods consist of sub-system test methods or pedestrian dummy tests. The sub-system test methods include legform, upper legform and headform test methods. The upper legform is developed to mitigate femur or pelvis injuries for passenger cars.

The dummy test method standard (SAE 2006) is limited in measuring requirements in the chest and abdomen region. Only chest acceleration is required, while chest displacement is recommended. For abdomen there is no requirement or recommendation.

The Polar II dummy was developed for pedestrian impacts (Akiyama et al 2001), with a focus in the development on leg impact, dummy kinematics and head impact. It has measuring capabilities for chest deflection with a so called “Crux” unit in one point. Okamoto et al (2001) performed crash tests with the Polar II and a utility vehicle, but the height of the bonnet leading edge was such that the BLE impact was concentrated in the pelvis region. No risk curves have been published for chest loading of a pedestrian dummy.

A pedestrian impact typically occurs when the pedestrian crosses a street. Field data shows that the pedestrian is impacted in the side in more than 2/3 of all pedestrian impacts (Kam et al 2005, Chidester and Isenberg 2001, Okamoto et al 2000, Otte 1989, Ashton 1975). The average impact velocity for severely injured (AIS 3+) pedestrians is 40 km/h (IHRA 2003). It is the impact speed on which all pedestrian test methods are based.

The aim of this study is to develop a bonnet leading edge airbag which can mitigate not only pelvis and femur injuries, but also thorax injuries, depending on the height of the car and the pedestrian.

METHOD

Simulations

To save development time and costs, a finite element (FE) simulation model was used to determine the basic characteristics of the bonnet leading edge airbag. A Ford Explorer MY 1997 FE model was downloaded from the NCAC website (NCAC 2006). NCAC is a collaborative effort between National Highway Traffic Safety Administration (NHTSA), Federal Highway Administration (FHWA) and George Washington University. An FE upper legform model was used as impactor (Ove Arup upper legform model V3). The setup can be seen in Figure 1.

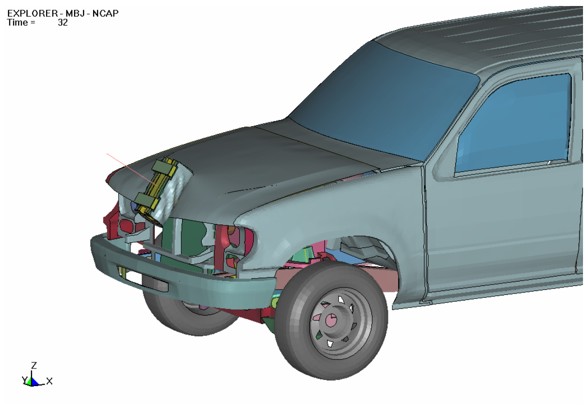

Figure 1. SUV and upper legform FE model.

The upper legform is currently used in EuroNCAP and the test specifications were taken from there. To determine impactor angle and mass and test impact speed, geometric measurements are taken from the car regarding bonnet leading edge height and bumper lead. For the vehicle in this study, specifications gave a test speed of 40 km/h, impactor mass of 11.4 kg, and an impact angle of 27 degrees.

To decrease calculation times in the FE model, the car model was reduced in such a way that parts, that were not believed to influence the pedestrian impact, were removed. Comparative simulations were then performed with the original and the reduced model. They showed almost identical results.(See the graph for upper legform force in Appendix Figure 9.) Bending moment showed very similar results.

When studying the upper legform force and bending moment it was found that the model gave rather low values. When comparing with a real vehicle it was found that the lock latch was missing in the model. It is a rather stiff and heavy part just designed for locking the hood/bonnet. Geometric measurements were taken from the real vehicle and introduced into the model. To find the right stiffness EuroNCAP data was used. In EuroNCAP, tested vehicles in the “large offroader” category in average had an upper legform force of 9.2 kN and a bending moment of 577 Nm, while “small off-roaders” had 8.6 kN and 535 Nm. It was also decided to include an “overload” case which reflected the highest values found in EuroNCAP tested “large off-roaders”. The chosen new reference model resulted in an upper legform force of 9.6 kN and a bending moment of 560 Nm, while the overload model resulted in a force of 15.5 kN, and a bending moment of 980 Nm. This is shown in Appendix Figure 10 and Figure 11.

Next step was to introduce an airbag. The airbag was tuned to give resulting force and bending moment below the EuroNCAP requirements for the upper legform. The EuroNCAP higher level requirements are 300 Nm in bending moment and 5 kN in force. This is estimated to correspond to a risk of 18-20% for pelvis and femur fracture. The prototype airbag can be seen in Figure 2.

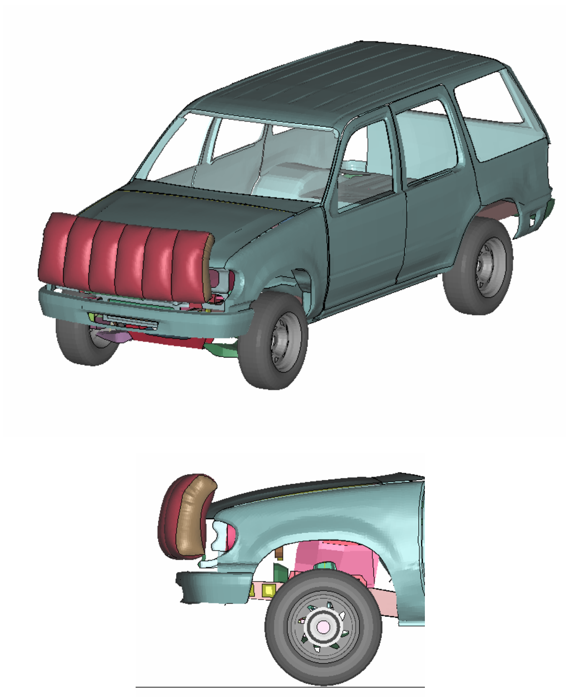

Figure 2. Bonnet leading edge (BLE) airbag.

Field data

A field data study of side impacts was performed, to compare with the Longhitano data of chest injuries for pedestrian to SUV impacts. NASS data from 1994-2005 was studied. In total 208 crashes were studied, where the occupant was hit from the near-side with an impact direction between 2-4 o'clock or 8-10 o'clock. Age of the occupant was between 19 and 50 years old, all younger and older were excluded. In total 208 occupants were included, where the impact vehicle was in 84 cases a passenger car and in 124 cases a LTV. AIS 3+ chest and abdomen injuries were selected for study. In total 386 injuries were included. This makes it comparable to Longhitano's data for pedestrians. The analysis was done both for unweighted and truncated weighted data. The truncation was done to give less importance to cases with very high weight factors. The truncation was set so that 98% of the cases kept its weight factor, while the weight factor was reduced to a certain limit for those cases above the limit. For the truncated weighted data the 208 crashes corresponded to 5602 car impacts and 7781 LTV impacts.

Skeletal injuries (ribcage) placed first for both target vehicles and both weight methods, between 32.6 to 40.7% in near-side data as well as for the pedestrians. Lungs placed second in all cases with values between 23.3 to 27.3%. In third place it was quite close between arteries/veins, spleen and liver in all cases. The unweighted near-side data is compared below with the pedestrian injury data for cars in Figure 3 and the LTV comparison is shown in Figure 4. Although the two databases do not use identical terminology it is quite similar so general comparisons are possible.

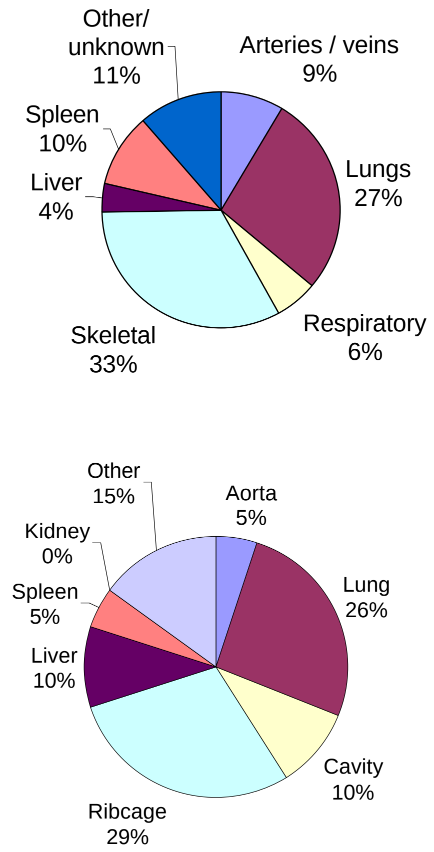

Figure 3. Chest/abdomen AIS3+ injury distribution for near-side car occupants (top) compared to pedestrians (bottom) (Longhitano et al 2005-2), both impacted by <u>cars</u>.

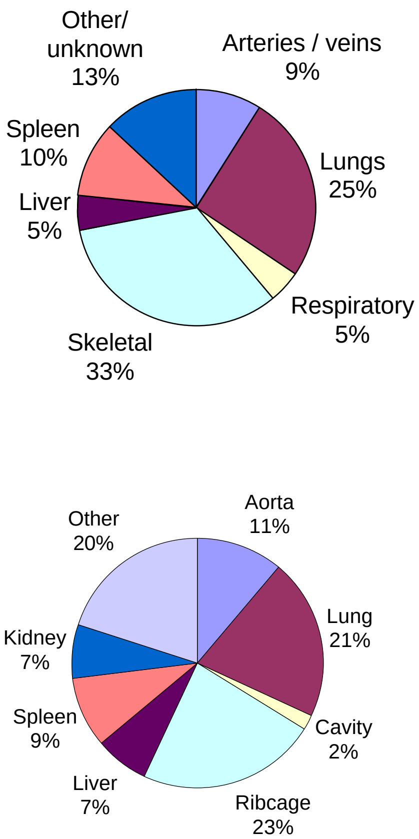

Figure 4. Chest/abdomen AIS3+ injury distribution for near-side car occupants (top) compared to pedestrians (bottom) (Longhitano et al 2005-2), both impacted by LTVs.

Full-scale crash tests

No test method exists to evaluate pedestrian chest injuries in impacts with high front-end cars. The standard pedestrian dummy test method has a limited measuring capability in the chest region, and with a high front end car the risk of running over the dummy will largely increase. The chest contact with SUVs occur early in the event, when not much upper body bending has occurred. Therefore it was believed relevant to use side impact dummies for this test method.

Sled – A physical airbag was designed according with the mathematical BLE airbag. The BLE bag was mounted to a car buck of a Ford Explorer, 1997 model year. The car buck was cut behind the A-pillars and was mounted on a sled. In front of the car buck a low friction bench was placed. This bench was adjustable to different heights. The dummy was placed on the bench approximately 500 mm from the car front. The sled pulse was chosen so that the sled had come to a full stop when the dummy first impacted the car. In this way it was possible to simulate a car impact to dummy at 40 km/h impact speed, all done on a sled but still a full-scale test. This eliminated the risk of the car driving over the dummy after first impact.

The hood edge height of the Ford Explorer 1997 was measured to 1017 mm above the ground, and the bench was adjusted so that the different percentile dummies would impact at the correct height corresponding to its respective body height. The test setup with the adjustable bench is shown in Figure 5, and in the left part of Figure 6 and Figure 7 the test vehicle is shown with the two percentile pedestrians.

It was also found that a 2006 model year Ford Explorer was considerably higher with a BLE height of 1168 mm. Since only the 1997 model year was available as test vehicle this was simulated by lifting the 1997 model car buck to match the BLE height of the 2006 model Ford Explorer. This could also be seen as an attempt to include a larger part of the SUV fleet. As a result, the test series consisted of four different impact heights.

Figure 5. Sled setup with dummy on bench and car buck.

Figure 6. Ford Explorer 1997 model (left) and 2006 model (right), and pedestrian scaled to 5th percentile female.

Figure 7. Ford Explorer 1997 model (left) and 2006 model (right), and pedestrian scaled to 50th percentile male.

It was decided to exclude all dummy loading that came from contact with the bumper.

Dummy – Two dummies were chosen due to their good measuring capabilities in the chest area, the SIDIIs 5th percentile female and the EuroSIDII 50th percentile male. The dummies differ slightly in instrumentation but in common they had head, T1, T12, pelvis and rib acceleration, rib displacement and forces in neck and pubic symphysis. Injury parameters used in the study were viscous criterion (VC), chest compression, abdomen and pelvis force.

The idea of the tests was to simulate impact with a standing pedestrian but with a seated dummy. Because these dummies are seated the hip point (H-point) height above the ground for a standing situation is not given. This was determined with Madymo to 813 mm for the 5th percentile and 936 mm for the 50th percentile. These values were used for the dummies in the study.

In the “high SUV” test the 5% dummy the dummy pelvis impacted the bumper. In all other tests the pelvis contact was above the bumper. It was decided to exclude dummy loading that came from contact with the bumper.

Film – Three high speed digital cameras were used, filming at 1000 fps from the top, side and from the side with an angle.

Impact conditions – All tests were run at 40 km/h. The dummy was impacted on the right hand side with the torso in a vertical position and the thighs in a horizontal position. The arms were placed in a 35 degree position from the vertical.

Test plan – Seven tests were planned and performed according to the test plan in Table 1. Due to lack of replacement parts, a reference test for the 5th percentile impacting the SUV with high BLE was not possible to perform.

Table 1. Test plan for full-scale tests

SUV height	Dummy	Bag
Low	5% female	Bag
		Ref
	50% male	Bag
		Ref
High	5% female	Bag
	50% male	Bag
		Ref

Injury criteria and risk curves

No injury criteria exist for a pedestrian chest impact. Due to the similar nature of the impact and the input from field data, a survey of the injury criteria for side impact for car occupants was performed.

The SID-IIs is a 5th percentile dummy. Injury criteria values are shown below from three sources using the SID-IIs: 1) a technical working group for side airbag out-of-position testing (a joint project of Alliance, AIAM, AORC and IIHS), 2) Insurance Institute of Highway Safety (IIHS) side impact test program and 3) a proposed FMVSS 214 upgrade in Table 2.

Table 2. Injury criteria and IARV for SID-IIs

SID-IIs				
	TWG SIDIIs	IIHS SIDIIs		FMVSS 214 proposed
		Good	Accept	
Chest VC	NA	1.0	1.2	NA
Chest D (mm)	34	34	42	NA
Abdomen F (kN)	NA	NA	NA	NA
Pelvis Acetab f	NA	4.0	4.8	NA
Pelvis Iliac F (kN)	NA	4.0	4.8	NA
Pelvis Acet + Iliac F (kN)	NA	5.1	6.1	5.1

Injury criteria thresholds for the EU regulatory test using EuroSID-1, as well as EuroNCAP tests using EuroSID-2 and a proposal for FMVSS 214 are shown in Table 3.

Table 3. Injury criteria and IARV for EuroSID2-re

ES-2re				
	EU*	Euro NCAP		FMVSS 214 proposed
		High	Low	
Chest VC	1.0	0.32	1.0	NA
Chest D (mm)	42	22	42	35-44
Abdomen F (kN)	2.5	1.0	2.5	2.4-2.8
Pelvis Pubic F (kN)	6.0	3.0	6.0	6.0
*EU requirements for EuroSID-1				

In a NHTSA NPRM, injury risk curves for the side impact dummies SID-IIs and ES-2re are presented. Injury risk curves for SID-IIs and EuroSID2-re were developed using cadaver sled test data and corresponding sled tests with the two dummies (Kuppa 2004 and Kuppa et al 2003). For the SID-IIs, risk curves were developed for thoracic and abdominal rib deflection, and a pelvic force which adds the measurements of acetabular and iliac force. For the EuroSIDII risk curves were developed for thoracic rib deflection, abdomen force and pubic symphysis force.

ISO developed thoracic injury risk curves for AIS3+ injuries using the Eurosid-1 (ISO 2005). Since no risk curves for VC, and the dummies used in this study, could be found in literature; it was decided to use the risk curves for Eurosid-1.

RESULTS

Simulations

The two significantly different hood edge stiffness cases resulted in very similar output values with the airbag (see Appendix Figure 12 and Figure 13). The force value is slightly above the EuroNCAP requirement while the bending moment value is well below the required level.

Full-scale crash tests

The thoracic, abdomen and pelvis injury values were evaluated. The injury values used were Viscous Criterion (VC), Chest Compression and pelvis force. For the ES-2, abdominal force also was evaluated. The SIDII-s 5th percentile female dummy has three thoracic ribs and two abdominal ribs, and the maximum VC and compression values were taken for the thoracic respectively the abdomen ribs. These values were calculated into an injury risk value using risk curves. (See Table 4) In the same way the risk values were calculated for the EuroSID-II 50th percentile tests. (See Table 5)

Highest chest values were found for the 5th percentile female impacting the low SUV, while abdominal force had the highest value in the 50th percentile "high SUV" test. When using both VC and chest compression as criteria there was a risk greater than 90% of an AIS3+ injury. These values were reduced considerably with the airbag. The maximum value was then chest compression at 46%. All risk values, except for the risk values already below 1%, decreased considerably with the airbag. The "5%F/high SUV" test was not possible to compare to a reference test, but it had risk values in line with the "5%/low SUV" bag test.

Table 4. Chest/abdomen injury risk values from the SID-IIs (5%-F) crash tests

		VC		Compression	
		Th Ribs	Abd Ribs	Th Ribs	Abd Ribs
		Risk* AIS3+	Risk* AIS3+	Risk AIS3+	Risk AIS4+
Low SUV	Bag	23%	8%	46%	0.6%
	Ref	99%	77%	91%	0.7%
High	Bag	30%	6%	30%	0.1%

*Note. VC risk values taken from risk curves for Eurosid-1.

Table 5. Chest/abdomen injury risk values from the ES-2 (50% M) crash tests

		VC*	Compression	Abdomen Force addition
		Risk* AIS3+	Risk AIS3+	Risk AIS3+
Low SUV	Bag	1%	12%	1.3%
	Ref	28%	31%	3.7%
High SUV	Bag	29%	33%	3.4%
	Ref	66%	57%	99%

*Note. VC risk values taken from risk curves for Eurosid-1.

Pelvic injury risks were rather low already in the reference tests, with a maximum risk value of 11% in the "50%M/low SUV" reference test. The pelvis then hits at the height of the hood edge. This value was reduced to 1.7% risk of pelvic injury with the airbag. See Table 6 and Table 7.

Table 6. Pelvic injury risk values from the 5%F crash tests

		Iliac +Acet F
		Risk AIS2+
Low SUV	Bag	2.7%
	Ref	4.2%
High	Bag	N/A

Table 7. Pelvic injury risk values from the 50%M crash tests

		Pubic symph. F
		RiskAIS3+
Low SUV	Bag	1.7%
	Ref	10.6%
High SUV	Bag	0.6%
	Ref	0.7%

The maximum AIS3+ risk values for each test were selected, taken from the body part showing the largest risk in each test configuration. See Table 8. Most values come from thoracic rib compression. For the "50%M/high SUV" reference test, abdomen force resulted in the highest risk of injury. For the "5%F/low SUV" reference test the highest risk value was found in the chest region using the VC criterion. But since the risk values, using the VC criterion, were based on Eurosid-1 this value was put into parenthesis.

Table 8. Maximum risk values in each test (different body parts)

			Max risk value	Body part
			Risk AIS3+	
5% F	**Low SUV**	Bag	46%	Thor.
		Ref	91% (*99%)	Thor.
	High SUV	Bag	30%	Thor.
		Ref	N/A	Thor.
50% M	**Low SUV**	Bag	12%	Thor.
		Ref	31%	Thor.
	High SUV	Bag	33%	Thor.
		Ref	99%	Abd.

* Value in parenthesis from using VC criterion (based on ES-1 risk curve)

DISCUSSION

In the simulations two significantly different BLE stiffnesses were used to cover a range of vehicles. However, it was found as a result almost identical upper legform loadings when adding the airbag. This is indicating that the airbag design is not so sensitive to bonnet leading edge stiffness, making it easier to design it for different SUVs.

When studying the risk values from the tests it can be seen that the highest risk values for each test configuration is found at the body part that is situated at the height of the hood edge in the impact. This indicates that the presented test method reflects the injuries found in the field, where chest injures can be linked to high bonnet leading edge heights.

The so-called "high SUV" tests were introduced to try to study the influence of a higher bonnet leading edge on the pedestrian torso loading. Since a test vehicle with this bonnet leading edge height was not available, this was simulated by lifting the car buck to match the hood edge height of the higher SUV. This means that the bumper of the SUV will be positioned higher than it would have been on the higher SUV. Therefore it was considered relevant to exclude dummy loadings that resulted from bumper contact.

The test configuration used in this study with side impact dummies leads to an impact in a seated position. It is likely not to influence the thorax and abdomen impact with the car front, but in the pelvis impact it is possible that the load is spread over a larger area of pelvis and femur instead of the pelvis only. Therefore it is likely that the pelvic forces should be somewhat higher with a standing dummy.

In three test configurations both tests with and without the BLE airbag were performed. In these three test configurations risk reductions can be calculated, using the different criteria (see Figure 8). The risk was reduced in the identified critical injurious loadings between 42 and 97% with the BLE airbag. The three loadings with lower risk reduction have already very low risk values without the airbag. These specific risk values are all below 4% injury risk in the reference tests.

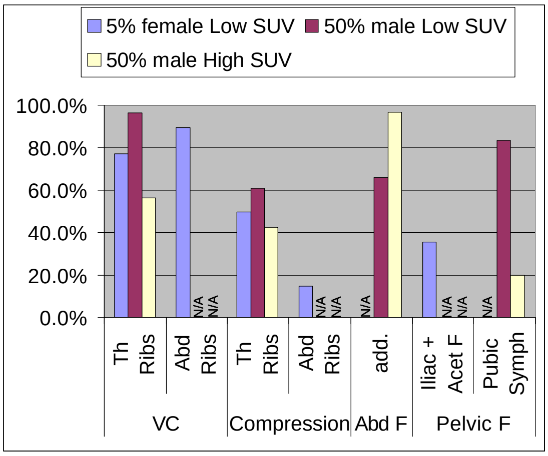

Figure 8. Risk reduction with the BLE airbag for different injury values.

From earlier full-scale tests it has been found that the head impact speed of a pedestrian dummy was decreased with a car with less stiff hood edge compared to a car with a stiffer bonnet leading edge. Therefore as a next step, the BLE airbag effect of reducing head impact speed of a pedestrian dummy could be studied.

CONCLUSIONS

A new test method, for evaluation of pedestrian impacts to the bonnet leading edge of high front end cars, such as SUVs, has been developed in this study. The front design of SUVs leads to an early impact to the torso of pedestrians with not much upper body bending. This lead to the conclusion that side impact dummies could be used for this evaluation. The benefit of using side impact dummies is the good measurement capabilities for the chest and abdomen area. The field data showed a similar injury distribution in near-side car occupant injuries and pedestrian injuries which led to the conclusion that side impact injury criteria and injury risk curves could be used.

An airbag system was developed to mitigate injuries caused by the pedestrian impact to the bonnet leading edge of SUVs. The initial design was developed using finite element simulations. In simulations the airbag proved able to pass the tough EuroNCAP requirements with the upper legform impactor. In full-scale tests the airbag decreased the risk of chest and pelvis injuries considerably, with the largest reductions in the chest and abdomen area. For example the chest compression was reduced more than 40% with the airbag in all test configurations. The airbag system seems to be a good candidate to mitigate torso injuries in a pedestrian-to-SUV impact.

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APPENDIX

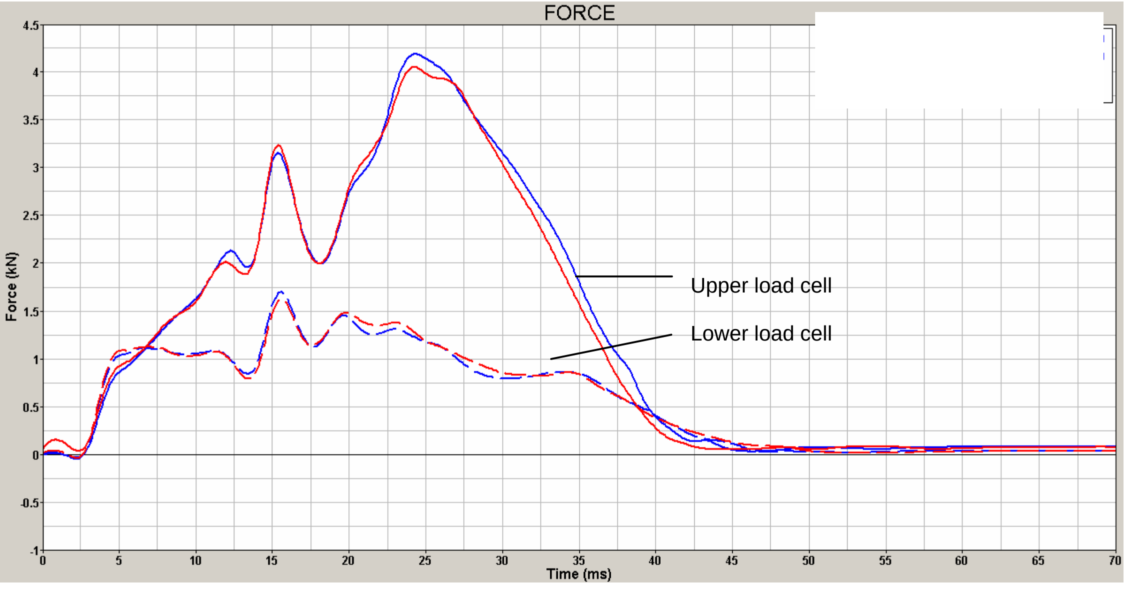

Figure 9. Comparison of original and reduced model, upper legform forces.

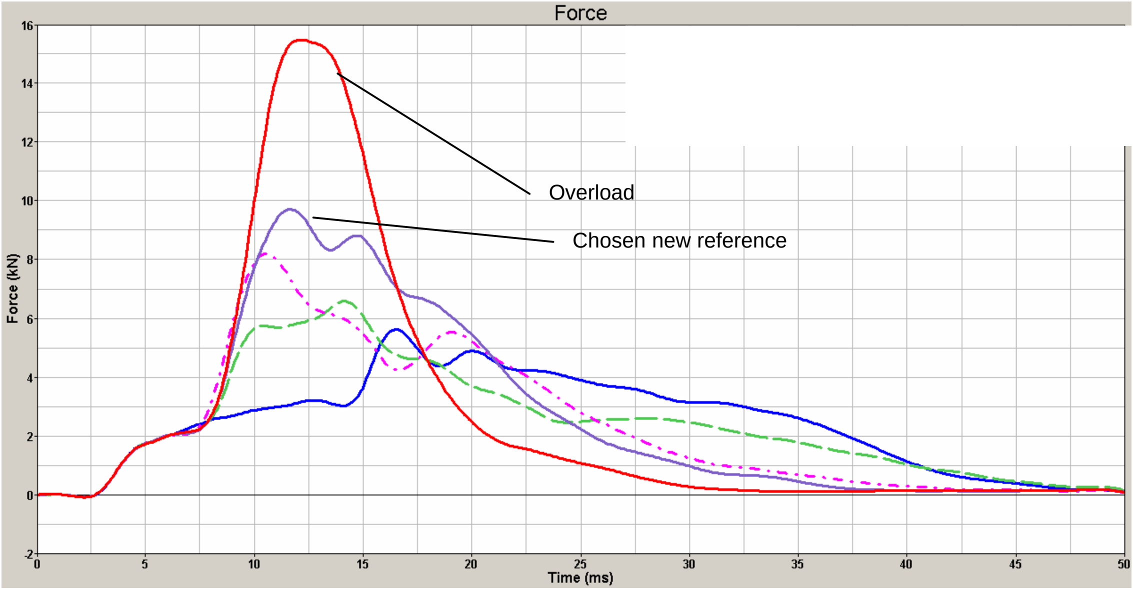

Figure 10. Determination of BLE stiffness in car model, upper legform force.

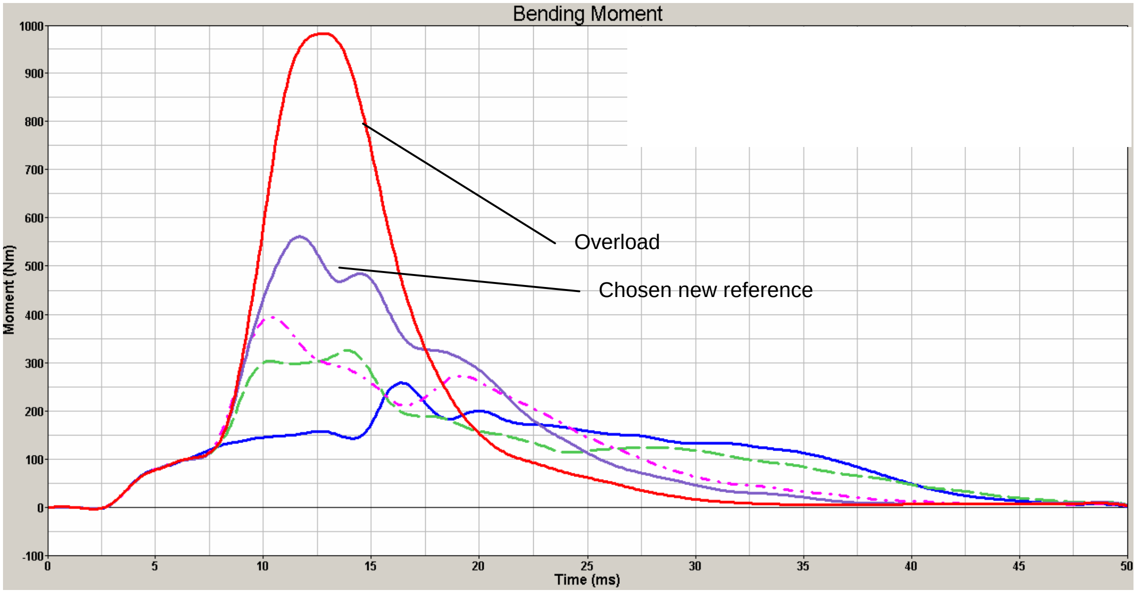

Figure 11. Determination of BLE stiffness in car model, upper legform bending moment.

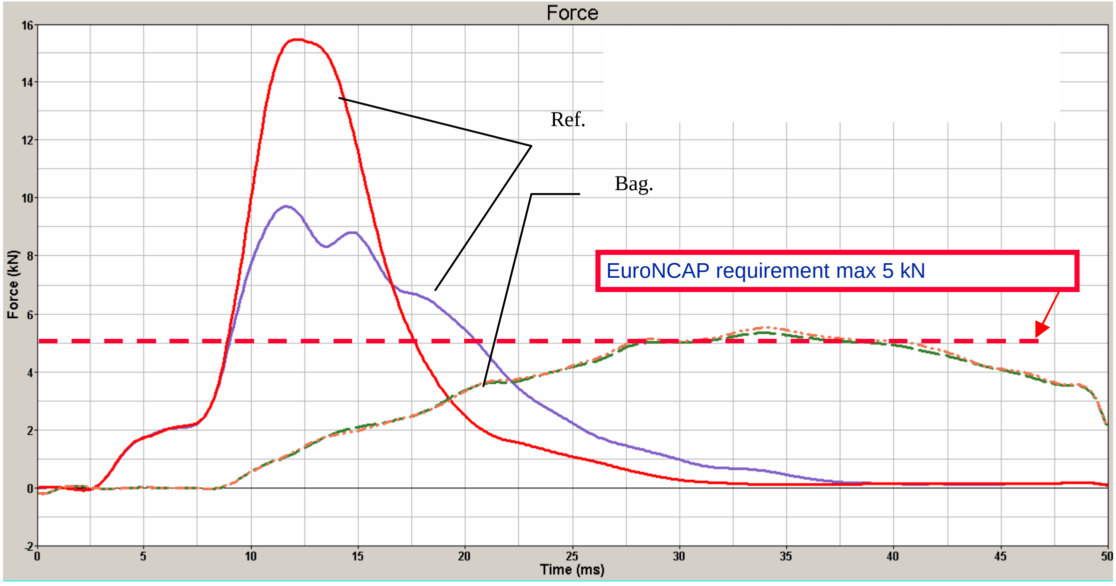

Figure 12. Upper legform force with and without BLE airbag. EuroNCAP threshold in dashed red.

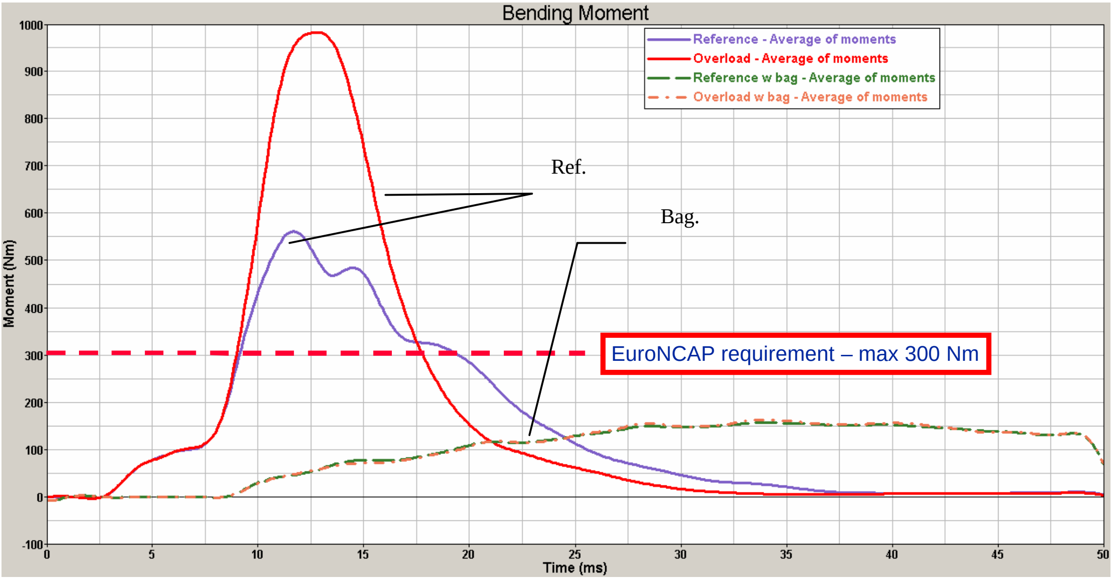

Figure 13. Upper legform bending moment with and without BLE airbag. EuroNCAP threshold in dashed red.

The injury IARV values from all tests are listed in Table 9. They are compared to the IIHS side impact threshold levels for the tests using the SIDII-s dummy (5th percentilen female), and EuroNCAP side impact threshold levels when using the EuroSID-II dummy (50th percentile male).

Table 9. Test data from all tests with colour marking and threshold limits using IIHS and EuroNCAP protocols

				VC		Compression		Abdomen	Pelvis	
				Th Ribs	Abd Ribs	Th Ribs	Abd Ribs	Force addition	Iliac + Acet F	Pubic Symph F
	Vehicle	Bag?	Dummy	m/s	m/s	mm	mm	kN	kN	kN
5%F	Low SUV	Bag	SID-IIs	0.38	0.18	36.50	29.00	N/A	2.72	N/A
		Ref	SID-IIs	1.76	0.78	52.80	30.20	N/A	3.17	N/A
	High SUV	Bag	SID-IIs	0.44	0.13	32.00	17.80	N/A	5.49	N/A
	IIHS "Good" limit			1	1	34			5.1	
	IIHS "Accept" limit			1.2	1.2	42			6.1	
50%M	Low SUV	Bag	ES-2	0.01	N/A	2.6	N/A	0.80	N/A	3.24
		Ref	ES-2	0.32	N/A	27.1	N/A	1.31	N/A	4.97
	High SUV	Bag	ES-2	0.33	N/A	28.4	N/A	1.26	N/A	2.22
		Ref	ES-2	0.70	N/A	49.0	N/A	6.18	N/A	2.42
	EuroNCAP higher limit			0.32		22		1		3
	EuroNCAP lower limit			1		42		2.5		6