THE BENEFITS OF DOUBLE PRETENSION IN DECREASING KNEES & LOWER LEGS INJURIES IN FRONTAL IMPACTS

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INTRODUCTION

European official data from the European Road Safety Observatory (ERSO, www.erso.com) shows that Road traffic accidents in 2004 in the Member States of the European Union lead to about 47.000 fatalities and more than 1.8 million people injured. Coming back to the data in France provided by ONISR (Observatoire National Interministériel de la Sécurité Routière) in 2004, 5232 fatalities and 17435 seriously injured people have been observed. 3186 persons died in passenger cars. Frontal impacts represent 47% of killed and 69% of seriously injured people in passenger cars. The distribution is 1290 fatalities in front seats and 143 fatalities in rear seats. Recent progress in passive safety, coming from both regulation enforcement and consumers ratings allowed to solve most of the lethal issues in frontal impact which were :

- Intrusion (steering wheel, firewall, footwell,…), which decreased with well-designed absorbing structure
- Head contact with steering wheel, avoided with frontal airbags
- Chest injuries, reduced with seat belt load limiters.

The aim of this paper is to review the evolution of lower legs injuries throughout the last vehicles generations to find out the benefits of advanced restraints systems such like double pretension.

The first part of this paper is dedicated to an explanation of the Renault double pretension system, adopted on most of the line-up. Test data using Renault's current procedure will show the effectiveness of that technical solution compared to a single pretension restraint system. The effectiveness will be shown not only for current 50th percentile occupant usually used in regulation and ratings, but also 5th and 95th percentile occupants.

The second part is a review of real accident data provided by the LAB. Injury data have been collected on vehicles fitted with a double pretension and compared with those of the rest of the fleet, in order to estimate the effectiveness of double pretension.

1° DOUBLE PRETENSION RESTAINT SYSTEM

1-1°) Description of the different restraint systems

The main purpose of pretensionning is to optimize the occupant coupling with the seat, and to reduce his relative speed with that of the structure. Buckle or retractor pretensioners are already well-known to yield a good occupant chest coupling with the seat. Firing the pretensioner once the impact is detected leads to a retractor pull-in or a downward movement of the buckle, allowing to remove all the gaps in the belt as well as to maintain the occupant chest and pelvis as close as possible to the seat.

In addition to that single pretension, a second pretensioner can be fitted to increase the occupant pelvis coupling with the seat and then limit the pelvis forward displacement. Figures 1&2 show an example of pelvis pretensioner before and after deployment.

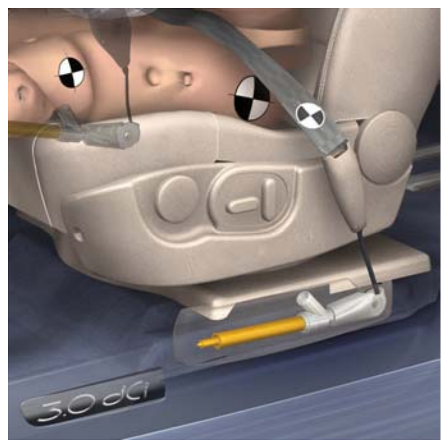

Figure 1 : pelvis pretensioner before test

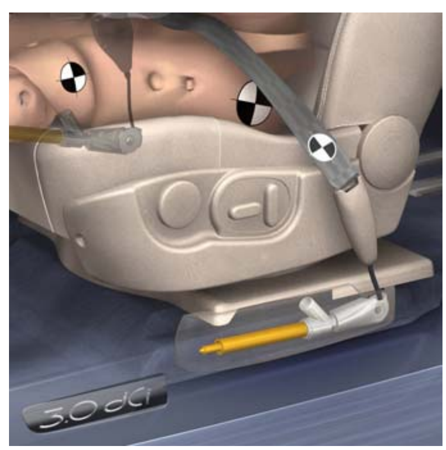

Figure 2 : pelvis pretensioner deployed

Some specific car designs prevent from being able to fit a second pretensioner on the outer side of the front seat. It is the case, for example, with 3 door or convertible cars, for which the front seats need to be moved forward to allow rear passengers to ingress. In that case, there is generally a sliding outer seat belt anchorage, and no pretensionner can be fitted. To reach the same performance level, a deployable cushion, named Pelvis Restraint Cushion, can be fitted in the front seat base. It consists of an inflatable metal box located just below the occupant thighs. The deployment of such a device reduces the pelvis forward movement in the same manner as the pelvis pretensioner. Figures 3 & 4 show a seat base cushion before and after deployment. Picture 5 shows the deformation of the seat base deployable cushion after its interaction with the occupant's pelvis.

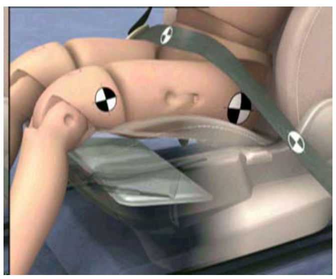

Figure 3 : Pelvis Restraint Cushion at rest

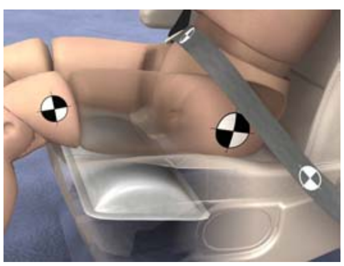

Figure 4 : Pelvis Restraint Cushion deployed, before interaction with occupant

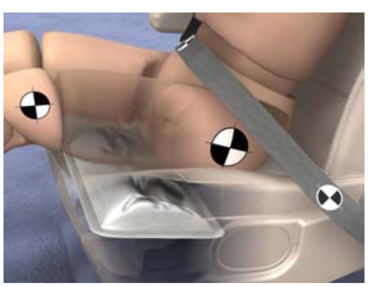

Figure 5 : Pelvis Restraint Cushion deployed, after interaction with occupant

1-2°) Assessment of the performance through a full lap frontal impact

1-2-1°) Test setup

The performance of a restraint system can be assessed through the following test configuration :
Full lap test on a rigid wall. The test features are given below :

- Velocity : 56km/h
- Offset : 100%
- No deformable barrier to really assess the restraint system performance
- Instrumented HIII dummy

This test configuration can be performed either through a full scale test or a sled test. The following test campaign has been performed using a High-G sled test where the input pulse is that of the car obtained when tested against a rigid wall at 56km/h. The setup contains seats and belt systems with the actual geometry. The belt is equipped with a pyrotechnic retractor for the single pretension configuration and a pyrotechnic retractor + lap belt pretensioner in case of double pretension configuration. Since the purpose is to assess lower leg performance, the airbag is not present and to reduce the chest forward movement without airbag, a 6kN load limiter is fitted instead of the 4kN usually present in the Renault cars.

The table below summarizes the different tests presented in this paper :

Configuration / Setup	Restraint system	Dummy size		
Full lap test 56km/h	Single pretension	5^{th} percentile	50^{th} percentile	95^{th} percentile
	Double pretension	5^{th} percentile	50^{th} percentile	95^{th} percentile

The figures 6&7&8 present the setup of configuration 2 with the 3 dummy sizes

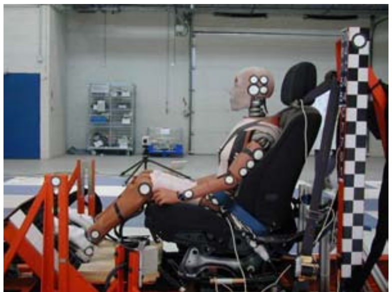

Figure 6 : setup with 5th

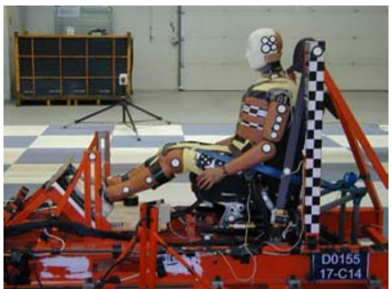

Figure 7 : setup with 50th

Figure 8 : setup with 95th

1-2-2°) Performance assessment method

If we assume that hard contact of lower legs with the dashboard is at the origin of the injuries, one possibility to assess the performances of a restraint system for this body region is to calculate the knee forward movement during the test. We make the assumption that the knee displacement is the same as the pelvis displacement. We consider that in full scale test, when the knee is loaded by the dashboard, the pelvis can continue its forward displacement more than that of the knee by rotating around the tibia. It means that the knee forward displacement is lower than that of the pelvis. We can then assume that, with a given seat, the smaller the pelvis forward displacement is, the lower is the risk for the occupant's leg to be injured. This displacement can be calculated by 2 methods: a double integration of the pelvis acceleration and a wire sensor fixed on the rear part of the pelvis and attached to the sled. To do so, the dummies used for this test campaign were instrumented in the pelvis region as below:

- accelerometers in X & Z directions (with the pelvis SAE-J211 reference), providing $\ddot{X}_{pelvis}(t)$ and $\ddot{Z}_{pelvis}(t)$
- angular velocity sensor providing Ω(t), the integration of which gives the pelvis rotation angle θ (t) due to the relative torso/leg movement
- wire sensor between the sled (behind the seat) and the pelvis
- accelerometer in X direction on the sled
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The figure 9 describes the different measurements and axis involved in the tests.

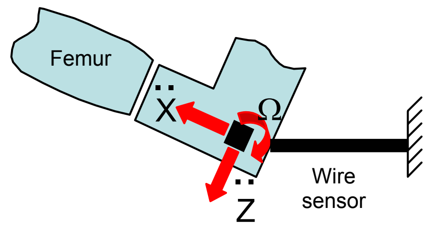


figure 9 : description of the sensors involved in the tests and their axis.

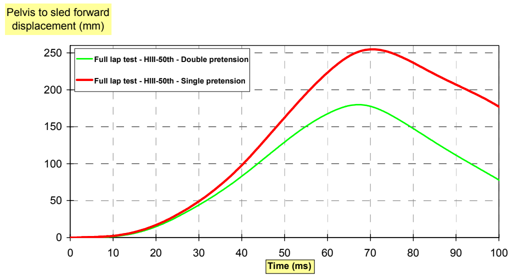
The pelvis forward movement relative to the sled can be calculated using the following formula:

$$Pelvis - Displacement =$$
$$\iint_t (\ddot{X}_{pelvis}(t)\cos\theta(t) + \ddot{Z}_{pelvis}(t)\sin\theta(t))dt^2 - \iint_t \ddot{X}_{Sled}(t)dt^2$$

If the accuracy of this formula can be discussed in full scale test, depending on the structure behavior, it gives reliable results when using a sled.

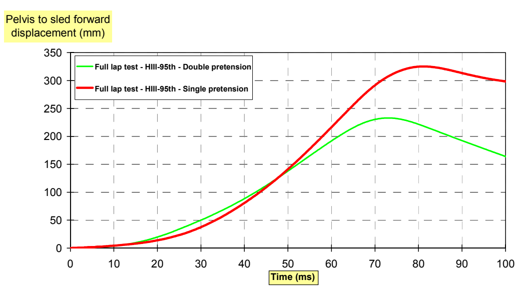
1-2-2°) Tests results

Graph 1 compares the pelvis forward displacement obtained by double integration of pelvis traces for a 50th percentile with double or single pretension during a full lap test. The pelvis displacement decreases from 255mm in the single pretension test to 180mm in the dual pretension test. It appears that the performance is much better thanks to the double pretension for the 50th occupant size



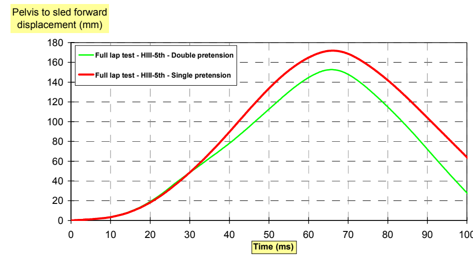
Graph 1 : pelvis forward displacement of 50th percentile during 56km/h full lap test

Graph 2 compares the pelvis forward displacement obtained by double integration of pelvis traces for a 95th percentile with double or single pretension during a full lap test. Here again, the pelvis displacement is reduced, decreasing from 325mm in the single pretension test to 233mm in the dual pretension test. For the 95th occupant size also, it seems that the performance is much better thanks to the double pretension.



Graph 2 : pelvis forward displacement of 95th percentile during 56km/h full lap test

The graph 3 compares the pelvis forward displacement obtained by double integration of pelvis traces for a 50th percentile with double or single pretension during a full lap test. Here again, the pelvis displacement is reduced, decreasing from 172mm in the single pretension test to 153mm in the dual pretension test. For the 5th occupant size also, it seems that the performance is much better thanks to the double pretension.



Graph 3 : pelvis forward displacement of 5th percentile during 56km/h full lap test

For the 6 previous tests, the pelvis maximum forward displacements are summarized below:

Pelvis maximum forward displacement from accelerometers (mm)			
Configuration / Occupant size	5th percentile	50th percentile	95th percentile
Double pretension	153	180	233
Single pretension	172	255	325
Reduction	**11,0%**	**29,4%**	**28,3%**

The reduction of pelvis displacement reaches around 29% for both 50th and 95th percentile occupants and 11% for 5th occupants. This is supposed to reduce significantly the knee and tibia contacts in the IP, and also reduce the knee and lower legs injuries.

The same approach is made with the wire sensor traces, whose the maximum for each test is summarized below:

Pelvis maximum forward displacement from wire sensor (mm)			
Configuration / Occupant size	5th percentile	50th percentile	95th percentile
Double pretension	128	176	199
Single pretension	164	255	277
Reduction	**22,0%**	**31,0%**	**28,2%**

The trend is the same as in the previous results, since the displacement reached with a double pretension system is, for both 50th and 95th percentile occupants, reduced of around 29% respective to a single pretension system. We also notice that for 5th occupants, the results lead to a 22% reduction in pelvis displacement between both configurations.

We can stress that the results between the 2 measurements methods, accelerometers and wire sensor, give exactly the same results for the 50th dummy size whereas it presents some discrepancies for 5th and 95th dummies. In these 2 cases, it seems that the wire sensor results is lower than those obtained with accelerometers, but the ratio between single and double pretension pelvis displacement is pretty the same with the 2 methods for these 2 occupant sizes.

Thanks to this set of results, we can assume that the double pretension system should significantly reduce the knee contact with the IP, and we expect from this a reduction of lower injuries in real accident data for the vehicles equipped with such advanced restraint systems.

2°) EFFICIENCY OF DOUBLE PRETENSION IN REAL WORLD

To confirm all the developments carried out by Renault in term of safety, the LAB, Laboratoire d'Accidentologie et de Biomécanique, is in charge of performing for Renault in-depth analysis of real accidents occurring on French roads. In-depth crash investigations have been carrying out at LAB since 1970. There are actually two kinds of investigations. The first one concerns secondary safety. The goal is to understand the injury mechanisms in real-world crashes in order to improve occupant safety in cars by the means of protection devices or car structure. Almost all car manufacturers all over the world and even public research institutes have been carrying out that kind of study for decades. Specially trained accidentologists collect relevant information about types and violence of impacts, car deformations and occupant injuries and feed it into a corresponding database. They don't need to go on the scene of the crash. Information is collected by accidentologists a few days or a few weeks after the crash at hospitals and at wreck garages. This methodology leads to a wide range of researches estimating risk curves or evaluating the effectiveness of on-board protection devices.

The second one deals with primary safety. French car manufacturers started this activity in the early nineties, when it appeared that secondary safety would necessarily have limits and that there was a need for crash avoidance as well as a need for occupant protection. The challenge in this field is to understand the crash process, purpose new functions for active safety systems, and eventually to evaluate the effectiveness of new safety devices or avoidance systems on any kind of motorized vehicles.

In any case, agreements are signed with the French ministry of Justice to allow that kind of technical work on crashes apart from judicial process involving drivers at fault. Investigations are exclusively technical and are carried out for research purposes only.

In France, three institutes are presently carrying out that kind of in depth investigations with regards to primary safety concerns: the National Research Institute for Transport and Safety (INRETS) and The European Center for Safety Studies and Risk Analysis (CEESAR) with LAB (Laboratoire d'Accidentologie, de Biomécanique et d'étude du comportement humain).

As for secondary safety oriented investigations, LAB has identified two study designs. The first design aims at getting a representative sample of impacts and impact violence of cars involved in a road crash in France. For this purpose, all crashes involving a passenger car with at least one occupant injured are investigated in a restricted sample area in the West of Paris. About 200 cars and their occupant injuries are examined in-depth every year. The sample rate is relatively small as about 90 000 passenger cars are involved in injury crashes every year in France.

The second design aims at evaluating the effectiveness of protection systems supplied in newer cars. 150 cars involved in (mostly) severe crashes are chased all over the country each year. The only selection criterion is that the car must be a newer one, mostly Renault and PSA cars, equipped with the most recent safety devices.

The collection of the information about crashed cars takes about one and a half hour in the garage. Complementary collection is made afterwards at the hospital with the authorization of the medical doctors and the patients. Most of the data is then coded and filled in a special database. Information that cannot be coded is conserved in original dockets along with photos and sketches.

The two teams at CEESAR and LAB have investigated about 14 000 passenger cars, i.e. 25 000 occupants and 65 000 injuries since 1970, which makes this database one of the most important one in Europe.

Therefore, we can measure the real efficiency of advanced restraint systems fitted in new cars, once enough accidents involving these new cars have been studied. Now that the Renault range is composed of 8 models fitted with double pretension, some of them existing since 2001, it is now possible to have a reliable feedback from the real accident data that can provide LAB. From this database, we have considered the following accidents in 2 samples :

- Frontal impact from 11 to 1 O'Clock
- Belted occupants, drivers only, since they are supposed to be more exposed to hazards through steering wheel
- The body region that is studied includes all the limbs from hip to tibia and all AIS2+ injuries are considered.
- 3 ranges of EES (Energy Equivalent Speed) are considered to highlight the difference in performance according to the accident severity : [40-49km/h], [50-59 km/h] and [60-80km/h]
- A first sample S1 with other cars from LAB database, limited to the cars with a first launch from 1990

(conception year), which are not supposed to be equipped with double pretension. In this sample, all the vehicles from the second set detailed below are removed.

A second sample S2 with vehicles equipped with a double pretension (Laguna, Vel Satis, Espace IV, Mégane II, Scenic II, Mégane II Convertible, Modus, Clio III). We also looked at depth of intrusion in the two samples since it is admitted that intrusion can cause lower legs injuries and that intrusion is expected to be more predominant in old vehicles than in newer ones. The calculation of the effectiveness of double pretension then takes into consideration the intrusion parameter.

The sample obtained from the above requests are composed of:

- In sample S1 : 993 involved drivers, among which 196 are injured on the considered limbs, with a AIS2+ severity
- In sample S2 : 114 involved drivers, among which 5 are injured on the considered limbs, with a AIS2+ severity. In this sample, we must stress that the double pretension system is mainly composed of lap belt pretensioners. Due to a smaller distribution in production cars, the Pelvis Restraint Cushion is not yet sufficiently represented to draw any conclusion on that specific device.

AIS2+ risk (ρ_i) in each EES range can be calculated as follows :

$$\rho_i = AIS2 + risk = \frac{number - of - AIS2 + drivers}{n_i}$$

where n_i is the number of involved drivers in the EES range, and confidence interval is [ρ-2σ ; ρ+2σ], where σ is the standard deviation defined below :

$$\sigma = \sqrt{\frac{\rho(1-\rho)}{n_i}}$$

Table 1 and 2 present, in the 3 EES ranges and for the 2 samples of cases, the distribution of involved and injured people, the AIS2+ risk (ρ) and the confidence interval :

	Sample S1			
	Total	EES range (km/h)		
		EES 40-49	EES 50-59	EES 60-80
Involved drivers	993	295	375	323
AIS2+ injured drivers	196	14	65	117
AIS2+ risk (ρ)		5%	17%	36%
Confidence interval		$[3\%-7\%]_{95\%}$	$[13\%-21\%]_{95\%}$	$[13\%-41\%]_{95\%}$

Table 1 : data for sample S1 (vehicles with single or no pretension)

	Sample S2			
	Total	EES range (km/h)		
		EES 40-49	EES 50-59	EES 60-80
Involved drivers	114	43	30	41
AIS2+ injured drivers	5	0	0	5
AIS2+ risk (ρ)		0%	0%	12%
Confidence interval		$[0\%-0\%]_{95\%}$	$[0\%-0\%]_{95\%}$	$[2\%-22\%]_{95\%}$

Table 2 : data for sample S2 (double pretension vehicles)

The efficiency E_i of the restraint systems fitted in vehicles of sample S2 can be calculated for each EES range from the AIS2+ risks in EES range i of sample S1 (ρ_{i1}) and sample S2 (ρ_{i2}), as follows:

$$E_i = 1 - \frac{\rho_{i1}}{\rho_{i2}}$$

An overall efficiency can also be calculated by weighting the risks of injuries in the two samples by EES values and intrusion values. Actually, the severity distribution of accidents in the LAB database does not match the real distribution since this database contains comprehensive studies in a given area and in-depth studies on specific vehicles. We have therefore associated the above data with an assumed, distribution of the severity:

EES Values (km/h)	
40-49	60%
50-59	30%
60-80	10%

The overall effectiveness can then be deduced by:

$$e = 1 - \left(\frac{\sum_i wi * Ri}{\sum_j wj * Rj} \right),$$

with i, index for cars with double pretensioners, j index for cars without double pretensioners, and w the weighting factors for EES and intrusion values.

The overall effectiveness is then 88 %, with a confidence interval at 95 % of [56% ; 97 %]

3°) DISCUSSION

The two aims of this paper were :

- to evaluate the performance of the double pretension as an advanced restraint systems through laboratory tests, involving several occupant sizes
- to check the efficiency in decreasing the lower legs injuries in real accidents.

The performance has been assessed with a sled test campaign. The setup included seat and full seat belt systems taking into account on one hand a dual pretension system, and on the other hand, a single pretension system. The test configuration chosen for these tests is a full lap test 56km/h, which is supposed suitable to assess any restraint performance. The performance is assessed in term of pelvis forward displacement, since this displacement is assumed to be linked with injuries. It is expected that, for a given vehicle, a smaller pelvis displacement will reduce the lower legs injuries. 3 adult dummy sizes were involved, all equipped with accelerometers and angular velocity sensor in the pelvis, and also a wire sensor measuring directly the pelvis displacement.

Whatever the occupant size considered, it clearly appears that the double pretension reduce the pelvis displacement compared to a single pretension, up to 30% for 50^{th} and 95^{th} occupant sizes, and between 11 and 22 % for the 5^{th} occupant size, depending on the measurement methods.

The two measurements methods lead to the same tendency between the different restraint systems type, though the values are different, especially for 5^{th} and 95^{th} percentile. This could be explained by the fact that the initial tension is not under control, and that pelvis could begin to move forward without pulling out the wire. Moreover, the wire is fixed behind the pelvis on the top part, inducing differences due to the pelvis rotation.

Anyway, both methods indicate that the dual pretension restraint system reduces the pelvis displacement with respect to a single pretension one.

The accident database from LAB has been used to check the efficiency of the dual pretension restraint systems compared to the rest of the fleet. The investigation has been carried out by selecting the drivers in frontal impact, in vehicles for which the first registration is after 1990 only. This sample has then been split in cars equipped with a dual pretension system and cars without. Each sample described above has been split in three severity ranges, starting from 40km/h. The injuries taken into account are all those related to lower legs, including hip, and the studied gravity is AIS2+.

The AIS2+ risk in each severity range has been determined for the 2 samples of vehicles. It allows calculating the global efficiency of a dual pretension restraint system, which reaches 93%. The efficiency found through the accident data clearly shows that lower legs injuries are strongly reduced in these vehicles compared to previous vehicles generations. This efficiency result could seem quite high especially if we assume that it is only based on the pelvis displacement comparison. Actually, the first set of cars taken from the LAB database includes quite old cars that are not fitted even with a single pretension. We can then assume that the pelvis displacement in those cars are higher and produce more severe lower legs injuries. That is why the 30% reduction in pelvis displacement observed in the test campaign, between single and dual pretension, is not in line with the efficiency found through accident data. This reduction would much higher than 30% if we compare dual pretension with no pretension, and this would be more in line with the global efficiency of 93% found through accident data.

One can also stress that it is possible that the decreasing of lower legs injuries is associated with structure intrusion reduction and not only the outcome of advanced restraint systems. We agree that such advanced restraint systems fitted in a car presenting a lot of intrusion (footwell and dashboard) won't be of some use since a dashboard contact will occur. Nevertheless, one additional case has been studied from the LAB database : a recent car without intrusion (eg no structural modifier in the EuroNCAP frontal impact) but equipped with a single pretension. The sample is too small and the values non significant enough to be presented here, but the first trend is to have AIS2+ injuries from 50km/h EES, whereas with a dual pretension system, these injuries appear above 60km/h. A small structural intrusion could then considered as a first step towards a strong reduction of lower legs injuries but is not enough for very severe accidents.

Due to the statistic sample size, it is not possible yet to observe differences in term of efficiency between pelvis pretensioner and Pelvis Restraint Cushion but we expect that it will be possible in the future. Nevertheless, the first feedback from the Pelvis Restraint Cushion behaviour is positive. The figure 10 presents a picture of the Pelvis Restraint Cushion after interaction with the driver in a real accident. The deformation shows clearly the impacts of left and right part of the pelvis. This pattern is exactly the same as that observed in tests with dummies. We can then expect a decrease of the lower legs injuries thanks to this device.

Figure 10 : Pelvis Restraint Cushion after interaction with the driver in a real accident