OCCUPANT PROTECTION PERFORMANCE IN SIDE IMPACT COLLISIONS PRECEDED BY PRE-CRASH DEPLOYMENT OF ON-BOARD SAFETY SYSTEMS

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ABSTRACT

This paper presents a simulation methodology for developing new automotive safety systems in an integrated manner that ensures optimal exploitation of benefits of predictive sensing and occupant restraints.
The investigation was performed using the combination of available simulation techniques for modeling Advance Driver Assistance Systems (PreScan software) and simulating the behavior of dummies and real humans under certain load conditions (MADYMO software and Active Human Model (AHM)).
The methodology was applied to investigate the occupant protection in side impact collisions making use of pre-crash deployed safety systems, such as pre-crash thorax airbag, inflatable seat bolsters, movable seat and a combination of them. The impact load on the dummy was derived from the simulation of the full FE vehicle under Euro NCAP Side Impact Testing protocol conditions.
The results obtained showed the clear potential of adopting an integrated safety system for side impact protection applications. When the collision is detected in advance the time gained can be exploited to increase the overall occupant protection by deploying safety countermeasures prior to the crash. Keeping the occupant further from the intrusion zone, reducing the relative impact velocity and controlling the occupant motion when entering the in-crash phase were key to significantly reduce the injury risk.
To realize the above phenomena, different pre-crash concept occupant motion solutions were defined and investigated: pre-crash deployed thoracic airbag, pre-crash deployed side-bolsters and pre-crash deployed laterally moving seat. Additionally combinations of each solution were investigated. The simulation analysis showed the best protection is ensured by the system combined of side-bolsters and moving seat deployed before the collision, in which case the overall injury risk was lowered from 130% to 44%, when expressed as values normalized with respect to high performance Euro NCAP limits.

INTRODUCTION

Worldwide, the number of people killed in road traffic crashes each year is estimated at almost 1.2 million, while the number of people injured could be as high as 50 million [1, 2, 3]. Without increased efforts and new initiatives, the total number of road traffic deaths worldwide and injuries is forecast to rise by some 65% between 2004 and 2030 becoming the fifth most likely cause of death [4].
Improving vehicle safety is a key strategy used in addressing international and national road casualty reduction targets and in leading to a safer road traffic system. It is also one of the major research areas in automotive engineering [5]. The safety of vehicle occupants has evolved recently due to the market implementation of new sensing technologies that enable to predict and identify hazardous road traffic situations and thus actively prevent or mitigate collisions. The upcoming safety developments lead to the potential future integration of these technologies with the conventional passive safety, where the safety systems are deployed based on crash sensing.
The integrated safety system proposed for the future focuses on managing the information from the predictive sensing about the imminent collision and communicating it to the on-board restraint systems to optimally protect the occupants and thus further reduce the injury risk in case of a collision. Developing an integrated safety system doesn't mean only to fuse together the active and passive systems. The work behind the fusion concerns the necessity of first developing the system in an integral manner and then studying and assessing what is its global effect on the injury mitigation.

Being at the beginning of the development of this new family of safety systems, at the moment there's lack of literature reference regarding this topic. New experimental methods and simulation tools for evaluating the efforts of pre-crash dynamics on the occupant injury risk during the crash phase are needed.
The present paper shows and proposes a simulation methodology created to support an integrated safety system development process for side collision application. Analyzing traffic accident statistics, it comes out that side impact is one of the car accident typologies and also one of the most critical sources of fatalities. According to the American Insurance Institute for Highway Safety (IIHS), side impact crashes accounted for 27 percent of passenger vehicle occupant deaths in the United States in 2009 [6].
The higher level of danger related to the side impact, if compared to the one caused by frontal crashes, lies in the considerably lower energy absorption capabilities of side structures and consequently larger intrusion and higher risk of injuries resulting from the contact with them [7]. The limitations of further improvements to vehicle safety for the side impact collisions motivate the development of innovative methods to lower the injuries and make the vehicle safer.
This paper presents the methodology for developing and testing the integrated safety system for side collision application and provides a safety performance overview of different pre-crash occupant protection countermeasures compared to a regular in-crash protection system used as a performance reference.

METHODOLOGY

Tools

The methodology used in the study follows the one illustrated in the paper published at SAE International in 2013 by M. Velardocchia at al. [8] in which a virtual integrated safety development platform was created and assessed. The methodology consists of the coupled and complementary use of two software packages: PreScan and Madymo [8]. PreScan was used for accident scenarios modeling and for designing the sensing and control systems for the side collision recognition, whereas Madymo was utilized for assessing the effects of pre-crash deployment of the thorax airbag.
In the Figure 1 the schematic illustration of the methodology and its tools derived from the previously published investigations [8] is presented. The analysis starts from the real world scenario that determines input boundary conditions for PreScan in which the vehicle maneuvering is being simulated. The results produced by PreScan simulation are then fed to MADYMO in order to simulate pre- and in-crash crash actions on the occupant motion. The consequent effects on the in-crash phase determine the injury values, thus the occupant response.

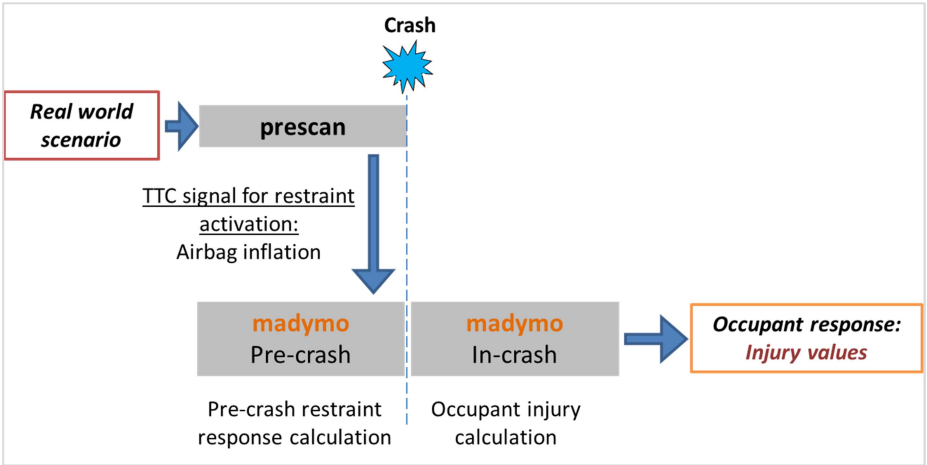


Figure1. The methodology: combined usage of PreScan and Madymo.

The parameters used to give a quantification of the injuries on the occupant in the EuroNCAP side impact test protocol refer to head, chest, abdomen and pelvis; more details about injuries parameters are available in the Appendix section. Since the Head Protection Criteria (HPC) is typically not significant in these crash conditions and has a low value when compared to the low performance limits, this was not used in the present study as protection performance parameter.

The focus of this study was then on the rib deflection, on the viscous criterion, on the abdomen peak force and on the pubic symphysis peak force. In particular, the protection system performance was based on the comparison with respect to the high performance limits (see Figure 2) of the EuroNCAP "Side Impact Test Protocol", version 5.2, from November 2011.

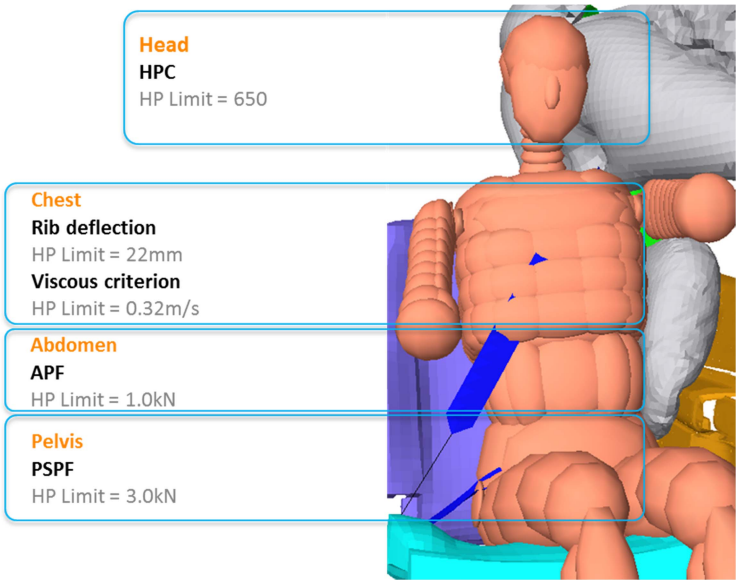


Figure2. EuroNCAP high performance protection criteria in side impact.

Case study scenario

The present study was carried out with the aim of modeling a side impact scenario which represents real accident data gathered by surveys. M. Velardocchia et al. [8] points out that typical side impacts occur in urban areas, when one of the two vehicles involved runs a red traffic light, other traffic control such as a stop or yield sign, or tries to perform an incorrect maneuver for turning and driving into another road.
Resting upon this information a representative scenario was selected as object of the investigation and modeled with PreScan. The scenario represents an urban intersection in daylight conditions, where a couple of generic compact cars are involved in a side impact (Figure 3).

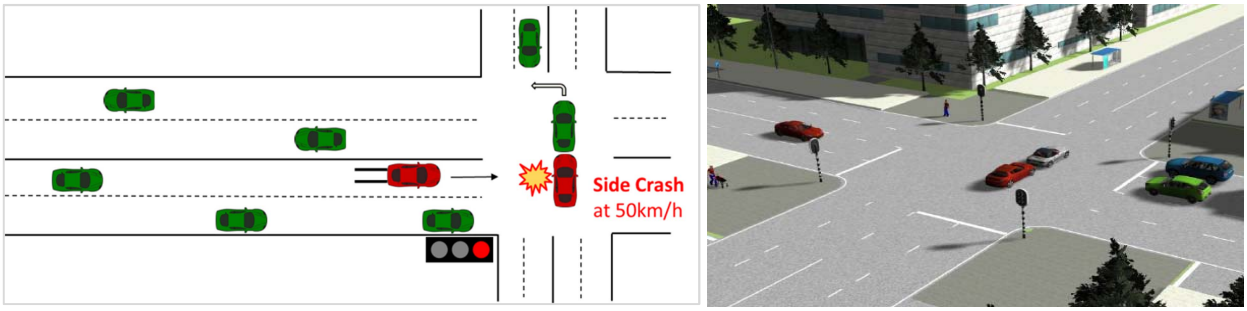


Figure3. Studied side impact scenario.

At the moment of impact the struck car (hosting the side impact pre-crash system) is stationary on the road crossing, queuing for a left turn. It is blocking the lane for the upcoming traffic from perpendicular direction. The striking car on the perpendicular lane is initially travelling at 60 km/h, fails to notice the red traffic light, and collides with the struck car at a velocity of 50 km/h, after an emergency braking performed by the driver.
The scenario represents the layout of a real life side impact and the resulting accident dynamics is in line with the one required by European regulatory [9] and consumer [10] side test protocols, where the car under examination is struck by a mobile deformable barrier (MDB) moving at 50 km/h and colliding at an angle of 90 degrees with respect to the tested vehicle.

The test condition parameters are as follows:
1. Impacted car speed: 0 km/h (stationary);
2. Impacting car speed: 50 km/h;
3. Angle of impact: 90 degrees;
4. Side of impact: driver side.

Pre-Crash Detection System

The vehicle that undergoes the side impact is equipped with two idealized surrounding sensors located on the impact side of the vehicle and at the same location in the vehicle longitudinal direction. The two sensors are:
    1. Short Range Radar (SRR) with a single detecting beam;
    2. SRR with 20 scanning beams.

Besides the different number of scanning beams, the other scan parameters are the same for both radars:
1. Horizontal scan;
2. Maximum range: 30[m];
3. Field of View (FoV) in Azimuth: 80[°];
4. Field of View in Elevation: 3.5[°];
5. Heading angle: 70[°];
6. Total scanning frequency: 100[Hz].

The two radars work constantly together although each one is assigned a specific task: the single beam radar detects the objects inside the field of view, pre-selects collidable ones and calculates the time to collision (TTC); in parallel the multiple beam radar is in charge of identifying vehicles among the collidable objects. Making use of the data from the two radars and fusing them, the detection algorithm is able to identify the presence of a collidable vehicle. When the TTC of a collidable vehicle is less than 0.6s, then the necessary condition to activate the desired on-board pre-crash device is satisfied.
A detection performance assessment of the algorithm was executed in [8]: results showed that the system could detect an impending side collision 150ms before this actually took place, in the worst case. Starting from this assumption and considering an additional margin of risk, all the studied pre-crash countermeasures that will be showed in the following paragraph were always triggered not more than100ms before the crash.

Vehicle Model And Restraint Systems

The side impact dynamics and the consequent injuries on a hypothetical occupant sitting in a vehicle equipped with collision detection system and pre-crash restraint systems were studied by building and using a virtual vehicle model with the tool MADYMO.
The side impact load on the driver was obtained by giving the side structure (B-pillar and door) and the seat a prescribed motion as obtained from the simulation of a Finite Element (FE) full vehicle system impacted by a Mobile Deformable Barrier (MDB) at the speed of 50 [km/h].
The vehicle model representation is simplified, as limited to the components relevant for the interaction with the occupant in the side impact collision load case: the seat, door and B-pillar. The door model is built using Multibody techniques and consists of several parts representing the elements of door structure and door trim. The external geometry of each element is represented by rigid FE models that are assigned to the corresponding door part and form together the entire door. The deformation of the door during the collision (door intrusion) is represented by prescribed motion of the bodies of appropriate door parts. The local deformability of the door trim that results from the interaction with the occupant is represented in a simplified manner using translational joints between the external trim geometry and underlying moving bodies. The compliance of the joints is restrained using distance-force characteristics that were tuned to represent the local deformability of each part of the door including the crushable and energy absorbing structures. The seat and the B-pillar motion resulting from the collision deformations is prescribed in a similar manner as for the door. The contact characteristics and material properties of the seat cushion were tuned in order to simulate accurate interactions with the dummy during its relative motion.
The base Madymo model also contains: a 3-point seat belt, a curtain airbag and a seat mounted thorax airbag.
The seat belt insertion points are attached to the B-pillar and the seat. The seat belt is equipped with a retractor and a pretensioner. The pretensioner was triggered at the time of 8ms after the crash in all considered cases; the curtain and the thorax airbags are also triggered 8ms after the crash.
The curtain airbag is a cushion of about 35liter in size. This is attached to nodes moving according to the deforming structure simulated in the full FE vehicle crash mentioned above.

The thorax airbag has a volume of about 10.5liter; the inflator used reaches 223kPa when inflated in a 10liter closed tank. Its permeability is set to 0.5% and vent hole diameter is 6.2mm.
The reference model so far described was then modified so that pre-crash protection systems could be implemented and studied. The three investigated restraint systems presented in this paper are:

1. Pre-crash thorax airbag

The pre-crash thorax airbag was already investigated and assessed in [8]. In the current study it is again mentioned for comparison with the other proposed solutions. The optimization study performed previously brought as result a thorax airbag model with the same cushion shape and material as in the reference model, which is deployed 100ms earlier than the reference thorax airbag (effectively 92ms before the crash). Furthermore, when the airbag deploys the vent hole (whose equivalent diameter is in this case 8.3mm) is still closed; only later, 15ms after the crash, the vent hole is opened.

2. Pre-crash inflatable seat bolsters

The solution with the inflatable seat bolsters was studied by Daimler-Benz AG for the Experimental Safety Vehicle program in 2009, called ESF 2009 [11, 12]. Following the information available about this study, two inflating bolsters located respectively in the seat cushion and in the seat back cushion (only on the impact side) were implemented in the base Madymo model. They have been modeled as two ellipsoids attached to their own translational joint. The countermeasure is triggered 92ms before the crash; when the system is deployed, the ellipsoids move 40mm towards the dummy, pushing it towards the center of the vehicle. In particular, one ellipsoid acts on the thorax and the abdomen of the dummy, whereas the other ellipsoid pushes its pelvis and its outer leg. The bolsters can move back to their initial position according to a load characteristic specifically tuned to minimize the chest deflection of the dummy in the phase preceding the contact with the thorax airbag. The thorax airbag is the same as in the reference model, therefore is deployed 8ms after the crash.

3. Pre-crash moving seat

Similar to the inflatable seat bolsters also the pre-crash moving seat was part of the ESF 2009 program [13]. The driver seat in the reference model is already attached to a joint and is moving with a prescribed motion during the in-crash phase. In the pre-crash phase it has been given an additional displacement of 50mm towards the center. The seat starts moving 92ms before the crash and stops at time t=0ms, whereas the thorax airbag is the same as in the reference model, therefore is deployed 8ms after the crash. The pre-crash seat travel was represented as prescribed motion following the S-shape displacement in time (see Figure 4). The resulting acceleration transmitted to the seat to execute the prescribed motion accordingly to the assumed seat motion, requires application of external force of 4.7kN, with the assumption that the total weight of the moving system (occupant and seat) amounts to 100kg. The plots illustrating the mechanics of the pre-crash seat motion are presented in the Figure 4.

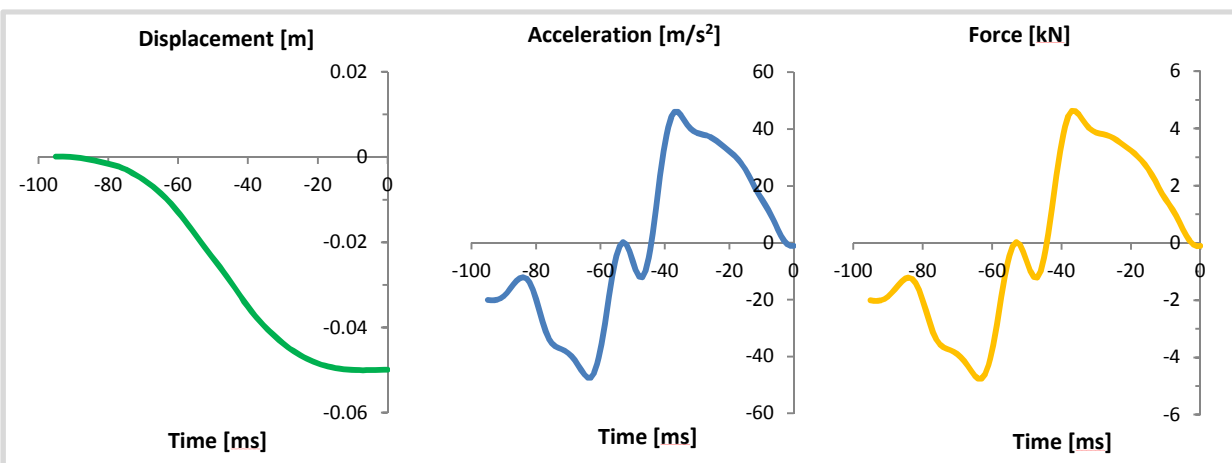


Figure4. Pre-crash moving seat displacement, acceleration and force plots.

An overview of the above-mentioned pre-crash safety systems is presented in Figure 5.

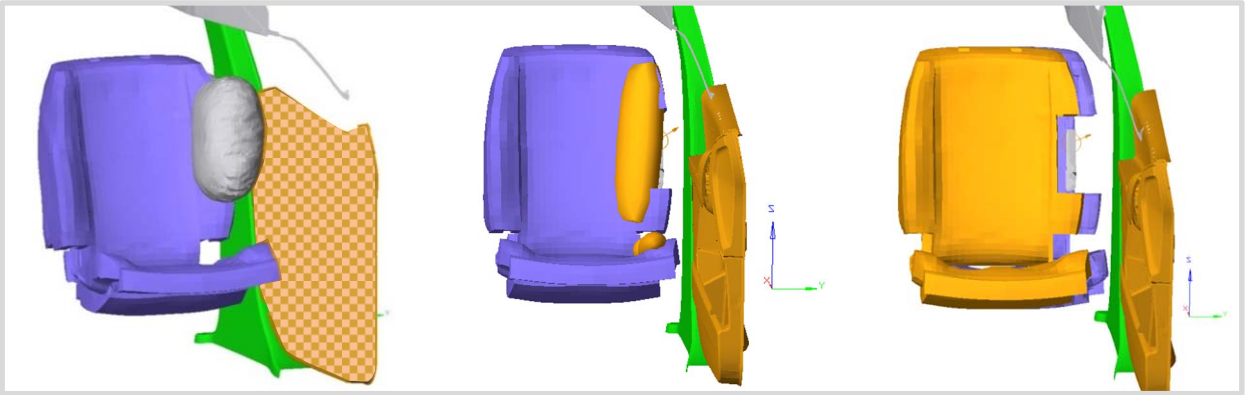


Figure5. Pre-crash safety systems; from left: thorax airbag, inflatable seat bolsters and movable seat.

The occupant dummy used throughout the complete investigation is the ES-2re Q Madymo ellipsoid dummy model.

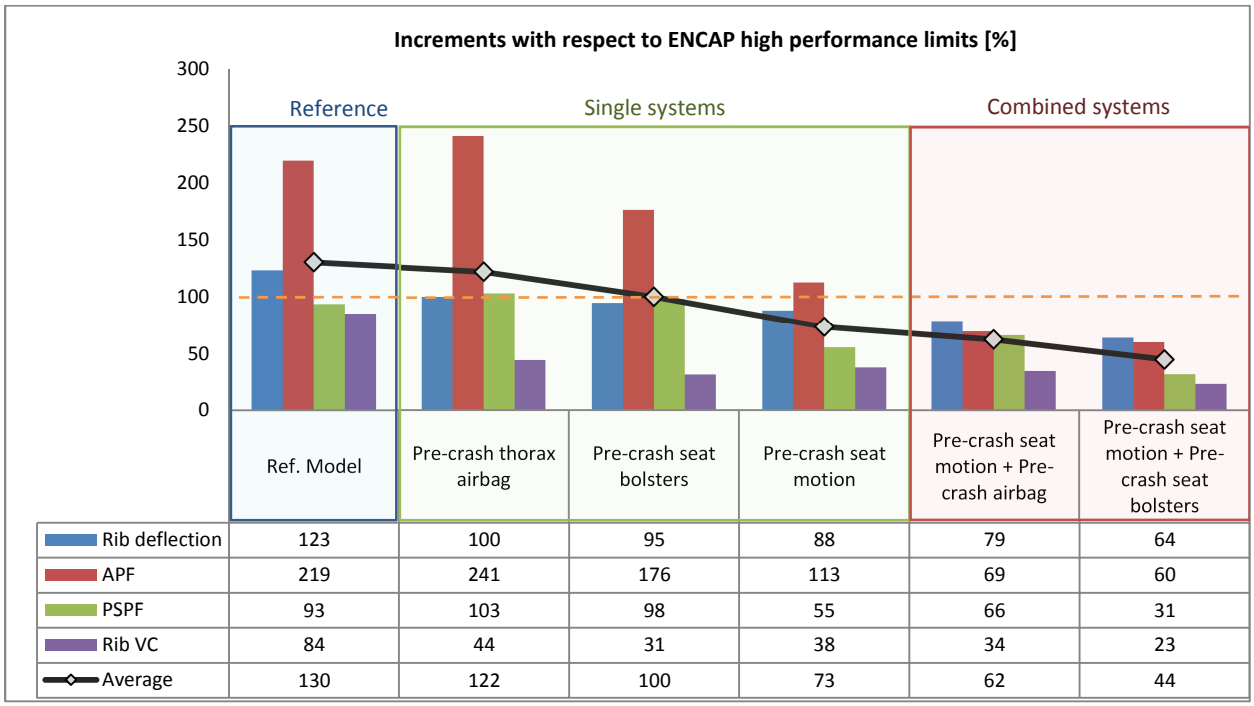
INVESTIGATION APPROACH

The need for the assessment of the potential of pre-crash activated protection systems arose directly from the results of the study [8] about the integrated safety potential in a side impact load case.
When using a pre-crash thorax airbag (with the specifics as described in the paragraph above), the chest deflection could be significantly improved. This confirmed the assumption that by pushing away the driver from the intrusion zone towards the center of the vehicle, it could be possible to significantly reduce the chest injuries. For rib deflection and rib VC parameters, the explained strategy led to reductions of about 20% and 50% respectively. Unfortunately a side effect was also observed, because APF and PSPF injury parameters showed a degradation of about 10 percent. The significance of the problem was related not only to the degradation of APF and PSPF injury parameters, but also to the fact that the APF, came dangerously close to the EuroNCAP protocol low performance limit, and thus could be considered as a significant limitation of the investigated system.
The analysis showed that the airbag, when deployed, interacts directly only with the thoracic and abdominal dummy regions, while the pelvic region is not loaded. This interaction generates the torque that causes lateral rotation of the dummy before the in-crash loading occurs. As a consequence, the pelvis and abdomen are not optimally restrained by the seat and by the thorax airbag respectively. In order to address the unwanted dummy rotation, and APF and PSPF deterioration, the dummy would need a more homogeneous push along the entire upper body region in the pre-crash phase.
Starting from these considerations, the first objective of the study was to find alternative solutions to the pre-crash thorax airbag which allow intervening more effectively on the occupant motion. The second objective was to quantify their potential as well as to make a comparison between the systems and with respect to the base model.
The reference protection system together with the investigated pre-crash occupant protection systems whose results are presented in the following paragraph, are listed below:

1. In-crash thorax airbag
2. Pre-crash thorax airbag
3. Pre-crash inflatable seat bolsters
4. Pre-crash moving seat
5. Pre-crash moving seat together with pre-crash thorax airbag
6. Pre-crash moving seat together with pre-crash inflatable seat bolsters

RESULTS

The injury values produced by the ES2-re dummy in the simulations are presented in Figure 6. Each value represents the ratio (expressed in percentage) between the calculated dummy injury value and the related high performance limit according to the EuroNCAP protocol (see Figure 2).



	Ref. Model	Pre-crash thorax airbag	Pre-crash seat bolsters	Pre-crash seat motion	Pre-crash seat motion + Pre-crash airbag	Pre-crash seat motion + Pre-crash seat bolsters
Rib deflection	123	100	95	88	79	64
APF	219	241	176	113	69	60
PSPF	93	103	98	55	66	31
Rib VC	84	44	31	38	34	23
Average	130	122	100	73	62	44

Figure6. Result overview: protection performance comparison among the different investigated solutions.

The safety performance of the reference model and of the pre-crash thorax airbag is the same as the one mentioned in the [8] and is here reported for a wider and more complete results analysis and discussion. As already mentioned in the Investigation Approach section, the most critical parameter for the dummy in the reference model is the APF, which is only 300N below the low performance limits and no less than 1.2kN above the high performance limits. Whereas the pre-crash thorax airbag showed good potential in the reduction of the chest related injuries, with no possibility to decrease the problematic APF, all the other investigated countermeasures provided an overall increased protection to the dummy, as this was observed for the chest, for the abdomen and for the pelvis.
The two single system solutions, namely the pre-crash inflatable seat bolsters and the pre-crash moving seat decreased the averaged injuries of the dummy from 130% to 100% and 73% respectively, with respect to the EuroNCAP high performance limits. Although the better protection of the chest area is comparable between the two systems, the main difference was encountered at the level of the abdomen and of the pelvis: the inflatable seat bolsters did not decrease the PSPF and could only reduce the APF by about 20%, whereas the moving seat could almost half both APF and PSPF. Therefore the overall protection performance of the moving seat was the best among the single system solutions.
Combining the pre-crash seat motion with the pre-crash airbag or pre-crash seat bolsters shows an increased potential in the dummy injury reduction when compared to both the reference model and the moving seat solution. The most important achievement is that all the injury peak values fall below the high performance threshold including APF. The model in which the pre-crash moving seat is combined with the inflatable seat bolsters could achieve an APF reduction of 73% with respect to the reference system, meaning about 1.6kN of less force acting on the abdominal area; the APF reduction for the other combined solution equals 68%. These results indicated that in case of fusion of two protection systems, no degradation of the overall injury performance occurred; rather there is potential for further improvements of injury levels. Only the PSPF peak value measured in the moving seat and pre-crash airbag combination increased slightly, although it remained safely below its reference value and below the high performance limits.

Besides the injury values, the simulations provided also other useful information necessary for the comprehension and the analysis of the results. Each system, as already highlighted in this paper, intends to give the dummy an initial impetus towards the center of the vehicle. The animation output shows the differences between how each investigated solution had acted on the dummy pre-crash motion and is presented in the Figure 7.

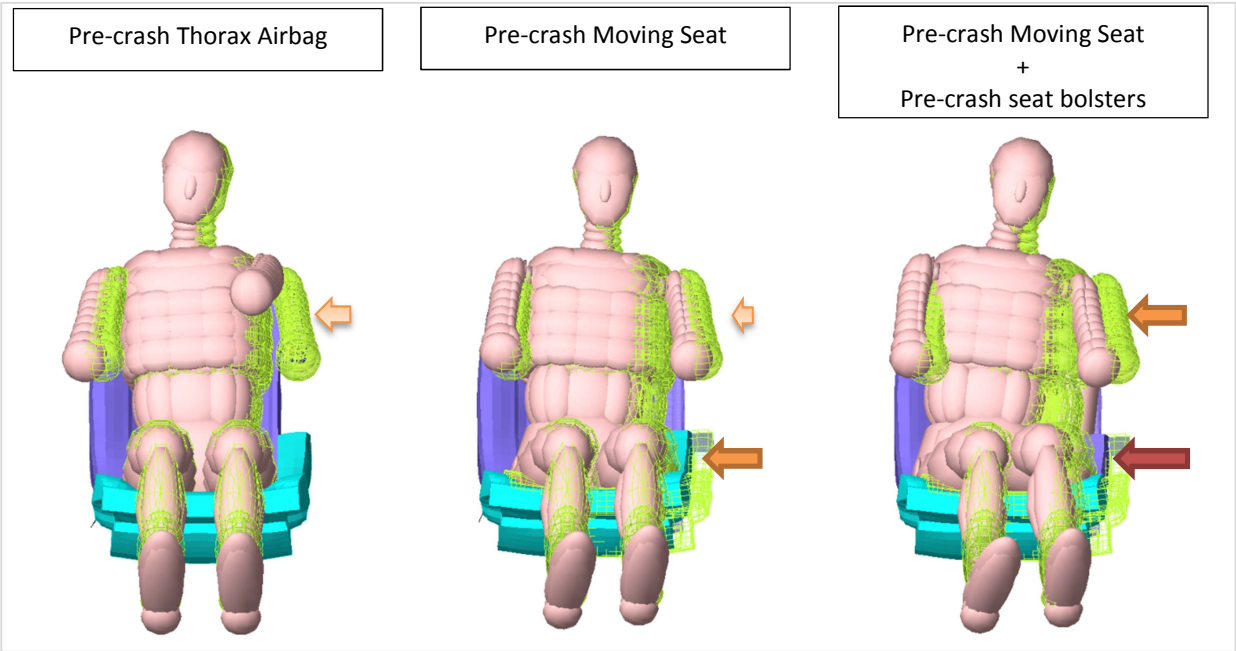


Figure7. Dummy position at the crash time t = 0ms in three different models. Green coloring is used for reference dummy model position.

The first investigated solution, the pre-crash thorax airbag, pushes the dummy directly on the rib cage, resulting in a rotation of the upper body around the pelvis which itself does not move significantly (see Figure 7). When the side structures start intruding into the vehicle, the first contacts occur with the pelvis and with the abdomen which are not protected by the airbag, causing a worsening of APF and PSPF. Only the thorax, which is already supported by the cushion, can be efficiently protected.
The direction of the upper body rotation observed for the other four studied solutions was different; two of them are taken as example and presented in Figure 7, in order to show and explain this different behavior.
In the pre-crash moving seat solution, the seat pushes the dummy mostly from the pelvis. Because of the inertia the upper part of the body tends to remain in the original position; the contact of shoulder and chest with the seat back cushion gives some additional support to the dummy during the desired pre-crash motion, although the dummy is clearly rotated outwards. Despite this, the effective relative distance of chest, abdomen and pelvis from the door is increased, whereas the head stays almost in the initial position.
Similar considerations can be made on the last pictured solution (see Figure 7), the combination of the moving seat and the inflatable seat bolsters. Also in this case the upper body is rotated outward as a result of the direct push of the seat cushion on the pelvis. There is however a difference, which consists in the higher overall force applied to the dummy and which is directly depending on the fact that during the pre-crash seat motion also the inflatable seat bolsters are deployed.
Each system performed differently from the other but the common factor was that, in all the cases, the effect of acting on the occupant motion before the crash was always beneficial. The injury curves showed a close and direct link between the injury peak values and the time when these were measured: the more significant push on the dummy, the faster it moved away and the bigger the gap from the intrusion zone. As a consequence the loads on the dummy body regions started later and less and less intensely, as the intrusion velocity and the related effect on the dummy decreases during the crash from the peak value (at crash time t=0ms) to zero, when the maximum intrusion is measured.
Besides the importance of giving the dummy more space and initial velocity at the moment of the crash, the results showed the importance of the upper body orientation. In particular, having the dummy upper body orientated outward was found to be consistently effective in the reduction of all the injury values, throughout all the

investigated solutions. The described position shows to work effectively in the distribution of the load on the dummy as it enters the in-crash phase with an angle which is very similar to the one that it will get throughout the loading phase: this prevents the 'pendulum' effect observed when using the pre-crash thorax airbag, thus allowing a more evenly distributed load on the dummy.

CONCLUSIONS

The paper intends to present a methodology based on the coupled use of two software packages to simulate road accident scenarios by designing a side collision detection system (PreScan) and assessing the effects of pre-crash strategies on injury parameters on a virtual dummy model (Madymo).
The investigation into different pre-crash deployed injury conceptual countermeasures showed that the most effective occupant motion control system is the one in which the pre-crash inflatable seat bolsters system is coupled with the pre-crash moving seat solution. The two countermeasures are triggered simultaneously 92ms before the crash, while the thorax airbag and the seat belt pretensioner are trigger 8ms after the crash as in the reference model. With this proposed occupant protection it was possible to bring the peak values of rib deflection, APF, PSPF and VC, below the EuroNCAP high performance limits.
The most significant improvement were obtained on the APF, as this was lowered by 73% with respect to the reference system, meaning about 1.6kN of less force acting on the abdominal area. The rib deflection that in the reference model was above the high performance limits could be decreased by 48%. The average of the four injury parameters peak values dropped by about 65%.
The other investigated solutions showed also a significant potential in reducing injury values in all body regions and outlined the real potential of the integrated safety systems for side impact scenarios and which of the occupant motion control strategies are the most effective for injury risk reduction. It can be summarized that the key biomechanical phenomena that contribute most to the occupant protection for side impact loadings are:

a) increased distance between the occupant and parts of the vehicle that intrude during the side impact, that results in decreased contact speed between occupant and intruding parts
b) initial occupant velocity in the same direction as the impact direction, that additionally reduced the contact velocity between occuapnt and intruding parts
c) initial outward rotation of the lower body that results in a more equal distribution of the contact interaction between occupant nad intruding parts

Similar, conceptual level observations were previously published in [11].
Introduction of predictive sensing to the side collision protection and utilizing the information about the upcoming collision to take actions on the occupant pre-crash kinematics, results in the global occupant injury risk reduction. The aim was to demonstrate the potential of the new design concepts which are still not possible to implement in series production and/or are currently only mentioned in the literature, so as to stimulate discussion of the necessary technological developments.
The investigation was limited to the specific crash conditions and does not show the sensitivity of the proposed solutions to different load cases. In order to assess the total potential of predictive sensing for side impact collision application, future studies are needed to prove the usefulness of the proposed approach for other load cases, different occupant sizes and different vehicle types and sizes.
Integrated Safety is a new region of automotive safety and does not have established simulation methods in place. The combined use of PreScan and Madymo for side pre-crash study is one of the first applications of both software packages together for the Integrated Safety purposes. The use of this method requires expertise in both active and passive safety areas and additional effort from the user in terms of interface handling throughout the use of both software suits. It should be also noted that Madymo was originally designed for in-crash simulations, and its functionalities are not yet fully optimized for pre-crash problem analysis. One Madymo limitation is the lack of validated side impact dummy models for low-g loadings that occur during the pre-crash phase.
In conclusion, given the significant injury damage, typically accompanying side impact collisions and the yet limited understanding of the potential for integrated safety to address this issue, this paper intends to initiate the interest in further research that can exploit new predictive technologies to reduce the harm caused by side impact.

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APPENDIX

1. APF

The Abdominal Peak Force is a measure of injury to the abdomen: APF is the maximum side abdominal strain criterion and is expressed as the highest value of the sum of the three forces [N] measured at each abdominal load cell (front, middle and rear) on the impact side.

2. HPC

The Head Protection Criteria is the standardized maximum integral value of the head acceleration.

3. PSPF

PSPF is the criterion for pelvis strain during side impact and is determined by the maximum strain on the pubic symphysis, expressed in [kN].

4. RDC

The Rib Deflection Criteria is the criterion for the deflection of the ribs, expressed in millimeters [mm], in a side impact collision.

5. VC

Also called as Viscous Injury Response, VC is an injury criterion for the chest area. The VC value [m/s] is the maximum crush of the momentary product of the thorax deformation speed and the thorax deformation. Both quantities are determined by measuring the rib deflection.