# A NUMERICAL INVESTIGATION INTO THE EFFECTIVENESS OF "SMART" RESTRAINT SYSTEMS IN MITIGATING INJURY RISK UNDER "REAL WORLD" ACCIDENT CONDITIONS

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## ABSTRACT

This paper presents the value of "smart" restraint systems in mitigating the injury risk to occupant's in a greater range of impact conditions than those presently considered in current regulatory and consumer impact tests. The work was carried out under the European 5th framework project PRISM (**P**roposed **R**eduction of car crash **I**njuries through improved **SM**art restraint development technologies). A generic MADYMO compartment model of a typical European midi-MPV was developed with a conventional restraint system for the modelled driver. To identify variables that need to be considered in the performance of a "smart" restraint system and subsequently assess potential adaptations that could be made to a restraint system, two simulation studies were carried out with the developed model. The first of these studies investigated the influence that the following variables have on driver injury risk: occupant size (using both a Hybrid-III and human body models), the reclined position of the seat, the bracing response of the driver and thoracic fracture. Based on the models' predictions it is implied that the kinematics and predicted injury risk of various sizes of human model are very different from those of a 50th percentile Hybrid-III dummy and that the reclined position of the seat and bracing response of the driver increases injury risk. It was not clear if fractures in the thoracic region would contribute to an increase in injury risk to other body regions. In the second simulation study investigations were performed to assess alterations that could be made to the modelled restraint system to adapt its performance to better protect different occupant sizes. It was concluded that if it were possible to adapt restraint characteristics to the specific occupant size, injury risk could be lowered.

## INTRODUCTION

Current regulatory and consumer impact tests generally assess the effectiveness of restraint systems in protecting an averaged size dummy in a standard seated posture under a limited range of impact conditions. In comparison, the potential variables influencing a real occupant's injury risk are more numerous and include the type and severity of the impact and the specific characteristics of the occupant (stature, weight, gender, seated posture, injury tolerance, etc.). Such issues have been discussed and highlighted in previous research (Holding *et al*, 2001, Schöneburg *et al*, 2003) and accident data studies (McCarthy *et al*, 2001, Cuerden *et al* 2001, Frampton *et al*, 2000). The potential therefore exists for hazardous impact conditions to arise that are not assessed by current testing protocols and conventional restraint systems are possibly not optimally developed for protecting occupants in these more diverse impact conditions.

To cope with the wider circumstances of occupant injury risk it is expected that "smart" restraint systems will be needed that are able to adapt to the specific impact conditions and react to different occupant positioning and biomechanical tolerances. In response to the expected development and implementation of these systems in European cars the European 5th Framework project PRISM (**P**roposed **R**eduction of car crash **I**njuries through **SM**art restraint development technologies) was started in December 2002. Overall, the objectives of PRISM are to investigate the likely benefits of implementing "smart" restraint system technologies and to develop guidelines on how best to assess and validate the performance of these "smart" restraint systems.

The objective of Work Package 3 (WP3) of the PRISM project was to assess the value of "smart" restraint systems in mitigating the injury risk to occupants in a greater range of impact scenarios than those presently considered in current regulatory and consumer impact tests. For this reason, an assessment of the injury risk to occupants in a greater range of impact conditions has been made. These results were used to identify injury risks that could be mitigated by the implementation of "smart" restraint systems and assess their applicability through potential "smart" alterations in a series of different scenario simulations. This paper details some of the predicted results obtained from the simulations completed under WP3 of the PRISM project.

## METHODOLOGY

In order to assess the value of "smart" restraint systems in mitigating the injury risk to occupants the following methodology was adopted (WP3 of the PRISM project). A MADYMO compartment model of a generic midi-MPV with a conventional restraint system was developed to represent the majority of the European, post-2001, midi-MPV fleet. As EuroNCAP is the current measure against which occupant protection is tested in Europe it was decided to use EuroNCAP as a baseline to assess the performance of the developed model. A midi-MPV EuroNCAP frontal impact was simulated with this generic model including a Hybrid-III model and evaluated against a variety of midi-MPV EuroNCAP test results. With the evaluated model two simulation studies were carried out. The first was to identify variables that needed to be considered in the performance of a "smart" restraint system such as occupant size, posture and bracing and the second to assess potential changes that could be made to a restraint system to better protect different occupant sizes. For the studies it was decided to include human body models since they allow the injury risk of varying occupant sizes to be investigated and potentially provide a more general insight into human-like behaviour during a crash.

Two further MADYMO compartment models were developed representing the confines of a generic super-mini and a small family vehicle so that investigations of the influence that vehicle size have on occupant injury risk could be completed. However, only samples of the predictions from the midi-MPV compartment model are reported in this paper.

**Development of the models**

**Generic midi-MPV compartment model -** The geometry of the midi-MPV compartment model was based on an average of basic measures taken from four post-2001 European MPV vehicles. The emphasis was to develop a generic midi-MPV compartment model representing the typical confines of a European midi-MPV. The term 'midi' used for the model describes the fact that the measures were made of the larger vehicles found in the EuroNCAP small MPV class.

The compartment model was developed with no simulated intrusion and the motion of the modelled seat, steering wheel and column was rigidly fixed to that of the modelled compartment for simulated impacts. It was felt that this model setup was sufficient for simulating the injury risk in EuroNCAP impacts where it is normal to observe relatively little intrusion or relative displacement of the internal compartment structures.

**Restraint and airbag models -** The initial setup of the modelled restraint system for simulating EuroNCAP impact conditions consisted of a belt with 4 kN load limiting at the shoulder, buckle pre-tensioning and a 55 litre single-stage frontal airbag model, as adapted from the standard MADYMO 6.2-alpha frontal impact application. An overview of the modelled belt setup is provided in Figure 1 and additional nominal values for the setup of the modelled restraint system for simulating EuroNCAP impact conditions are provided later in Table 1 of the paper. In the absence of specific data for developing the restraint system model these were estimated from the project consortiums working knowledge of these systems. Overall, the intention was to develop a modelled restraint system with a performance of safety consistent with that found in the majority of vehicles being released in the current European market.

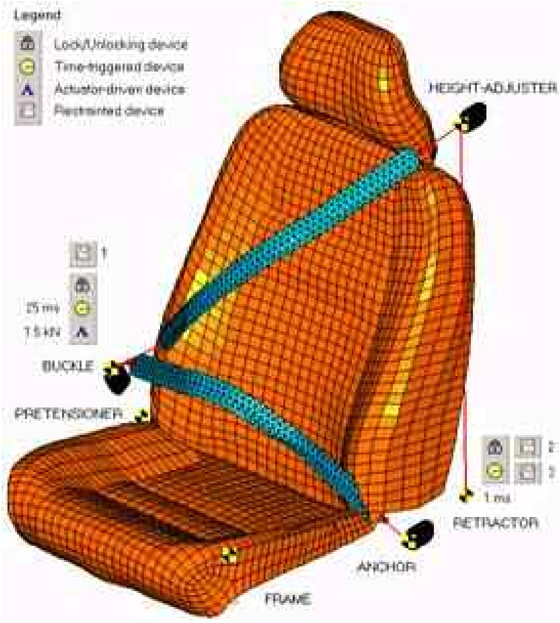
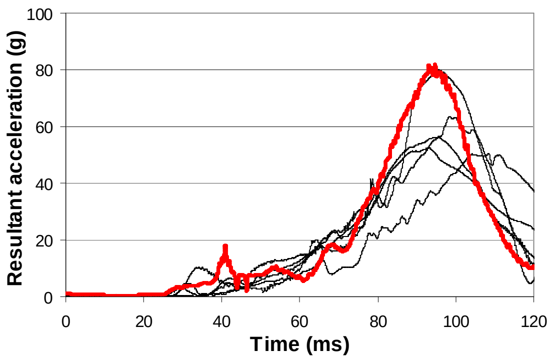



**Figure 1. Setup of the modelled belt system.**

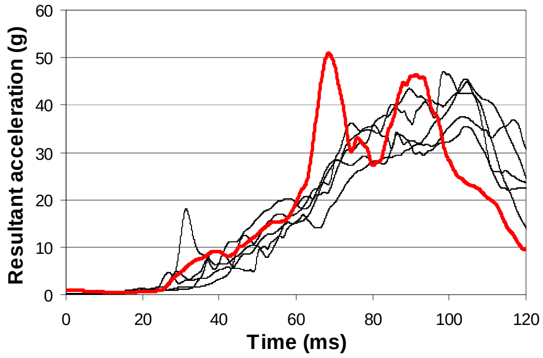
**Evaluation of the compartment model**

It was anticipated that coupled with the compartment model the performance of the restraint system would provide a predicted level of safety consistent with that of a generic European midi-MPV. This anticipated performance of safety for the model was tested by comparing model predictions against equivalent measures obtained from a series of EuroNCAP tests completed on an equivalent size of vehicles. For the EuroNCAP simulation a MADYMO 50$^{th}$ percentile Hybrid-III dummy model was positioned in the driver seat of the midi-MPV compartment model and the EuroNCAP pulse from one of the tested vehicles was applied to the compartment model.

Figure 2 provides examples of the comparisons made. It was found that the predictions from the Hybrid-III dummy model were comparable in magnitude to equivalent measures of the Hybrid-III dummies in the EuroNCAP impact tests. The predicted dummy chest acceleration in Figure 2 does deviate from that measured at approximately 70 ms. This was found to be due to a vertical component of chest acceleration coinciding with the contact of the legs with the modelled submarine bar and not a problem associated with the manner in which the restraint system had been modelled. Therefore, despite this deviation in the model's behaviour, it was felt that it was sufficiently developed for assessing the relative rather than absolute influence that alterations in impact conditions have on an occupant's injury risk.




**Driver head**




**Driver chest**

**Figure 2. Comparison of predicted 50th percentile Hybrid-III dummy responses (red lines) with equivalent measures (black lines) from EuroNCAP impact tests of five different midi-MPV vehicles.**

## PARAMETER VARIATION STUDIES

The following frontal impact simulation studies were completed with the midi-MPV compartment model:

- An assessment of potential variables that may need to be considered in the performance of a "smart" restraint system.
- An assessment of adaptations that could be made to a restraint system in order to better protect different occupant sizes.

### Assessment of potential variables to consider in the performance of a "smart" restraint system

The purpose of this study was to investigate how selected accident variables influence occupant injury risk in order to determine possible factors that may need to be considered in the operation of "smart" restraint systems. Chosen accident variables investigated in this study were identified from accident data analysis, photographic studies (Bingley *et al*, ESV 2005, paper 319), simulated driver (Couper and McCarthy, 2004) and passenger (Morris *et al*, ESV 2005, paper 320) pre-impact response investigations completed in earlier stages of the PRISM project. The accident variables investigated and reported on in this paper and the reasons behind their inclusion in the investigation were as follows:

**Occupant size (baseline model runs) -** Current regulatory and consumer impact tests concentrate on the impact response of a 50th percentile Hybrid-III dummy. Results from McCarthy *et al* (2001) and the accident data analysis of the PRISM project (not currently reported) indicated that there was an increased injury risk to larger and smaller vehicle occupants. It is also questionable that dummy responses provide an adequate representation of the real human response in vehicle impacts. As such a series of frontal EuroNCAP simulations were completed with the 5th, 50th and 95th percentile human body models released with the 6.1 version of the MADYMO code. It was anticipated that these models would provide a more representative biofidelic response compared with that of the Hybrid-III dummy model providing an insight into the potential injury risk to real humans in an impact. Injury predictions from these model runs were then compared against equivalent predictions obtained from the evaluation model run using the 50th percentile Hybrid-III dummy model detailed above. For the model runs involving the 5th and 95th percentile human body models the seat position and upper anchorage for the belt were altered to comfortably fit the various occupant sizes in the compartment model. Changes made to the seat and belt anchorage positions matched limits for these variables measured in the vehicles on which the dimensions of the compartment model were based. Furthermore, the predictions from the human body models detailed in this section provided a baseline against which predictions from additional model runs using the human models could be compared.

**Reclined 95th percentile driver -** It was found from the results of the PRISM '*Photographic Study*' (Bingley *et al*, 2005) that larger occupants tend to adopt a more reclined driving posture. This deviates from the seat setup for regulatory and consumer impact tests. Results from the PRISM '*Accident Data Study*' implied that this could be a contributory factor to injury risk, which is supported by the increased injury risk to larger occupants discussed above. To consider this setup a simulated EuroNCAP impact was completed in which the 95th percentile human model was set in a reclined posture with the seat reclined a further 20° from the baseline EuroNCAP frontal simulations detailed above. Predictions from this model run were then compared against equivalent predictions from the baseline 95th percentile human body model run.

**Occupant bracing -** In the PRISM pre-impact braking studies of Couper and McCarthy (2004) it was noticed that drivers, on perceiving a simulated hazard, tended to brace themselves prior to an imminent vehicle impact. The bracing response was characterised by the drivers pushing against the steering wheel and bracing their feet against the brake and footwell. However, this response does not match the setup of current regulatory and consumer impact tests, which are possibly more representative of occupants who are unaware of or have insufficient time to react to an impending impact. Occupant bracing in the model was represented by locking the motion of the hands and feet to that of the compartment model up until the point that the loading through the modelled occupant's arms exceeded a defined limit. During this period all joints in the occupant model were locked. When the loading in the arms exceeded the defined loading limit the hands were then freed from the motion of the compartment model and the joints in the occupant model were unlocked. This then allowed the human model to passively interact with the modelled restraint system and the confines of the compartment model. It was not certain what load a typical adult could support through their arms in an impact. As such this limit was set at 1 kN through each arm, which was considered a reasonable upper limit that could be supported by an adult with locked arms. The use of the 1 kN limit served an initial purpose of investigating the influence of this bracing response on an occupant's injury risk. Further investigations with more accurate loading limits for the arms could be conducted if the limit was found to have a significant influence on the predicted injury risk or if the loading limit for the arms was later found to be considerably greater than 1 kN. Predictions from this bracing simulation were compared against equivalent predictions from the 50$^{th}$ percentile EuroNCAP baseline model run detailed above.

**Thoracic fracture -** It was rationalised, following the PRISM '*Accident Data Analysis*', that fractures in the thoracic body region could affect the performance of the restraint system during an impact and consequently influence the injury risk to body regions other than the thorax. This was considered to be a greater concern for older occupants who, as found in the PRISM '*Accident Data Analysis'* and the study completed by McCarthy *et al* (2001), were at a greater risk of injury than their younger counterparts. In order to consider the possible consequences of this behaviour simulations were completed in which additional belt length was introduced to the modelled belt system when the shoulder belt load exceeded a defined limit. It was anticipated that this belt representation in the model would approximate the sudden failure of thoracic features, such as the ribs, sternum or clavicle and the redistribution of load onto alternative body regions. For this investigation 6 cm of belt was introduced at the shoulder under shoulder belt loads of 1, 2 and 5 kN resulting in three model runs in total. These belt length and belt loads were estimated to fulfil the immediate requirement of investigating the influence that thoracic fracture has on the injury risk to body regions other than the thorax. The occupant model used in these model runs was the 50$^{th}$ percentile human body model and the compartment model was subjected to the EuroNCAP frontal impact pulse. Predictions from these model runs were then compared against those obtained for the baseline 50$^{th}$ percentile human body model run.

### Restraint system adaptations for different occupant sizes

A series of parameter studies were completed to determine the required setup of the modelled restraint system to limit the injury risk under EuroNCAP frontal impact conditions of a 50$^{th}$ percentile Hybrid-III dummy and 5$^{th}$, 50$^{th}$ and 95$^{th}$ percentile human body models. In these studies a number of restraint system parameters were varied across a specified range, presented in Table 1. The stochastic pre-processor ADVISER (Dalenoort *et al*, 2005) was used to generate the model run files for the parameter study. Altogether 50 model parameter runs were completed with each occupant model resulting in 200 model runs in total. Best Latin Hypercube sampling was used to determine the setting of the restraint system parameters in the model runs. This sampling distributes the samples over the design space, while maintaining its random character.

An overall injury risk prediction from the baseline model runs was used as a baseline against which improvements in the performance of the adapted restraint systems could be assessed. The overall injury risk prediction used to assess performance improvements in the modelled adapted restraint systems was a predicted form of the Injury Severity Score (ISS). Predictions of $HIC_{36}$, the highest of Chest 3ms, Combined Thoracic Injury (CTI) criterion, the knee forces for the human model and the femur forces for the Hybrid-III dummy model were obtained. These predictions were then compared against injury risk curves available on the US National Highways Traffic Safety Administration (NHTSA) website (www.nhtsa.dot.gov) to obtain Abbreviated Injury Scores (AIS). A reduced form of the ISS was then calculated for each model run based on these estimated AIS scores. A femur load cell was not available in the human models and explains why knee force was used to assess predicted injury risk in the legs. From all the estimated ISS values, the lowest ones were considered to correspond to the best performing restraint systems, within the variations performed in the current study.

## RESULTS

Analysed predictions from the model runs were to injury criteria associated with the head and chest: $HIC_{36}$, Chest deflection and CTI. Lap belt loads were analysed in some of the model studies to provide a relative measure of the potential injury risk to the abdomen in the absence of an accepted injury criterion for assessing abdominal injuries. Analysis of the modelled occupant kinematics was also performed in order to capture potentially hazardous conditions that may not be highlighted by conventional injury criteria.

**Table 1**
**Parameters varied in the restraint system adaptation study for different occupant sizes**

| Restraint system parameter | Range of variability (nominal value) |
|---|---|
| Airbag mass flow | 50–150% (100%) |
| Airbag fire time | 10-40ms (25ms) |
| Load limiter | 2–7kN (4.1kN) |
| Pre-tensioner | 1-4kN (always < load limiter) (1.5kN) |
| Pre-tensioner fire time | 10-40ms (25ms) |

### Results – Assessment of potential accident variables that would need to be considered in the performance of a "smart" restraint system

<u>**Occupant size (baseline model runs) -**</u> *Occupant kinematics*: Figure 3 provides the initial and 120 ms posture of the occupant models for the comparable EuroNCAP simulations completed with the 50$^{th}$ percentile Hybrid-III dummy model and the 5$^{th}$, 50$^{th}$, and 95$^{th}$ percentile human models. It was noticed in the simulations that unlike the 5$^{th}$ percentile human model and 50$^{th}$ percentile Hybrid-III models the heads of the 50$^{th}$ and 95$^{th}$ percentile human models struck the roof/windscreen of the compartment model. The head of the 50$^{th}$ percentile human model struck the roof/windscreen following rebound from the frontal airbag. Due to the rebound from the airbag the head contact with the roof/windscreen was of relatively low severity as indicted by the low head injury risk predictions obtained for this model run discussed later. In contrast the 95$^{th}$ percentile human model struck the roof/windscreen as it went forward into the airbag and experienced a much greater predicted head injury risk. The predicted head strikes with the roof/windscreen were partly attributed to the 50$^{th}$ and 95$^{th}$ percentile human models' spines that experienced a large amount of rotation about the vertical axis, which allowed the unrestrained shoulder and head to move further forward with respect to the compartment. This was found to be greatest in the 50$^{th}$ percentile human model as shown in Figure 4. In comparison there was very little vertical spine rotation in the 5$^{th}$ percentile human model and no noticeable rotation in the 50$^{th}$ percentile Hybrid-III model.

A further factor contributing to the head strike was that the pelvis's of the 50$^{th}$ and 95$^{th}$ percentile human models translated rather than penetrated into the seat during the impact and the pelvis of the models (though more so in the 95$^{th}$ percentile human model) rotated over the top of the lap belt, so elevating the position of the head within the confines of the compartment model. This was coupled with a considerable amount of stretching in the thoracic and cervical spines of the 50$^{th}$ and 95$^{th}$ percentile human models. In contrast the pelvis's of the 5$^{th}$ percentile human and 50$^{th}$ percentile Hybrid-III models penetrated into the seat and dropped under rather than rotated over the lap belt and experienced considerably less stretching in the spine. This point is emphasised by the differences in the peak seat loads predicted for the 50$^{th}$ percentile Hybrid-III model and the 50$^{th}$ percentile human models, which were respectively 9.0 kN and 2.3 kN.

*Injury predictions*: The injury predictions from the models were normalised to allow for the different injury tolerances of the various occupant sizes. The normalising process was based on the experimental data gathered by Mertz *et al* (2003). It was determined from this work that in order to normalise the injury risk of a 5$^{th}$ percentile occupant to that of a 50$^{th}$ percentile occupant the $HIC_{15}$, chest deflections, neck extensions, and lap belt loads should be scaled by 0.9, 1.96, 1.22 and 1.37 respectively. Comparable scaling factors determined for a 95$^{th}$ percentile occupant were respectively 1.04, 0.75, 0.9 and 0.84. Although predicted $HIC_{36}$ rather than $HIC_{15}$ was obtained from the models in this present study it was still considered more meaningful to use the proposed scaling factors for $HIC_{15}$ than compare absolute head injury risk predictions for the various occupant sizes. No additional normalisation was made to allow for differences in the behaviour of human and Hybrid-III dummy model responses.

Figure 5 provides the percentage difference between the normalised predictions from the human body models against those predicted by the 50$^{th}$ percentile Hybrid-III model. It shows that all the 5$^{th}$ percentile human model's predictions of injury risk, with the exception of neck extension were at least 50% lower than those predicted by the 50$^{th}$ Hybrid-III dummy model. The predicted neck extension for the 5$^{th}$ percentile was 13% greater than that of the 50$^{th}$ percentile Hybrid-III dummy model. It was unexpected to find that the lap belt load for the 95$^{th}$ percentile human model was 64% lower than that predicted by the 50$^{th}$ percentile Hybrid-III dummy model. Further examination of the model animations and predictions attributed this response to the fixed anchorages defined for the restraint systems in the model. Moving the seat backwards for the 95th percentile human model run placed the belt buckle in a more vertical alignment with its anchorage point. During the model run the belt buckle rotated a greater amount about its anchorage point for the 95th percentile model run than it did for the other occupant sizes. This effectively introduced additional belt slack into the belt system and limited the loads through the lap belt. All other analysed injury predictions for the 95th percentile human model were above those predicted by the 50th percentile Hybrid-III dummy model. Higher neck extensions for the 50th and 95th percentile human models were found to occur at the initial stages of the heads' contacts with the inflated airbag. Chest compression for the 50th percentile human model was over 50% greater than that predicted by the 50th percentile Hybrid-III model. Overall it was implied from the model's predictions that the injury risk for a 50th and 95th percentile human models is greater than that of a 50th percentile Hybrid-III dummy model. In contrast, the overall lowest injury risk was predicted for the 5th percentile human model.

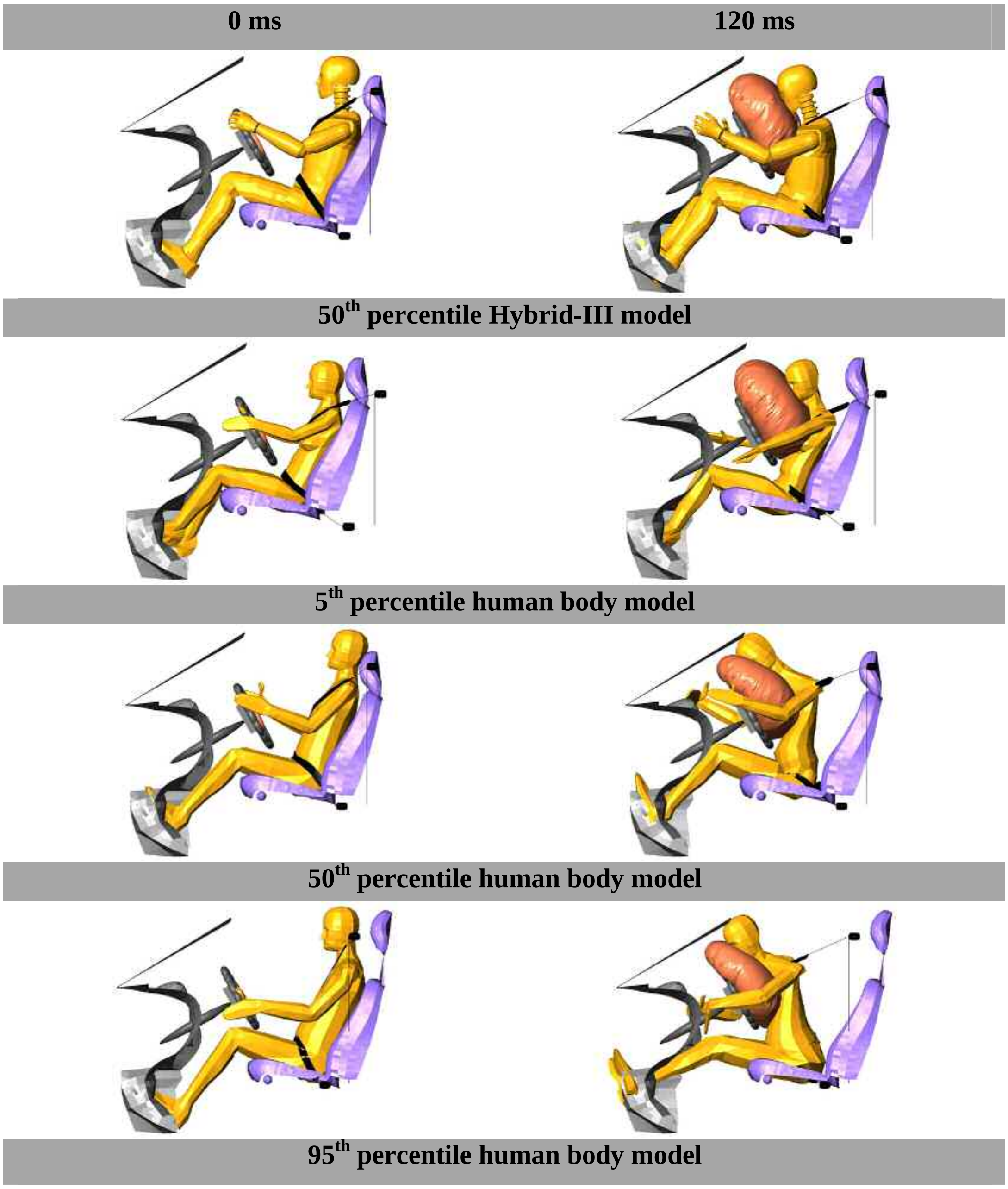



**Figure 3. Frames from the animations of the 50th percentile Hybrid-III and 5th, 50th and 95th percentile human body models for the midi-MPV EuroNCAP simulated impacts (baseline model runs).**

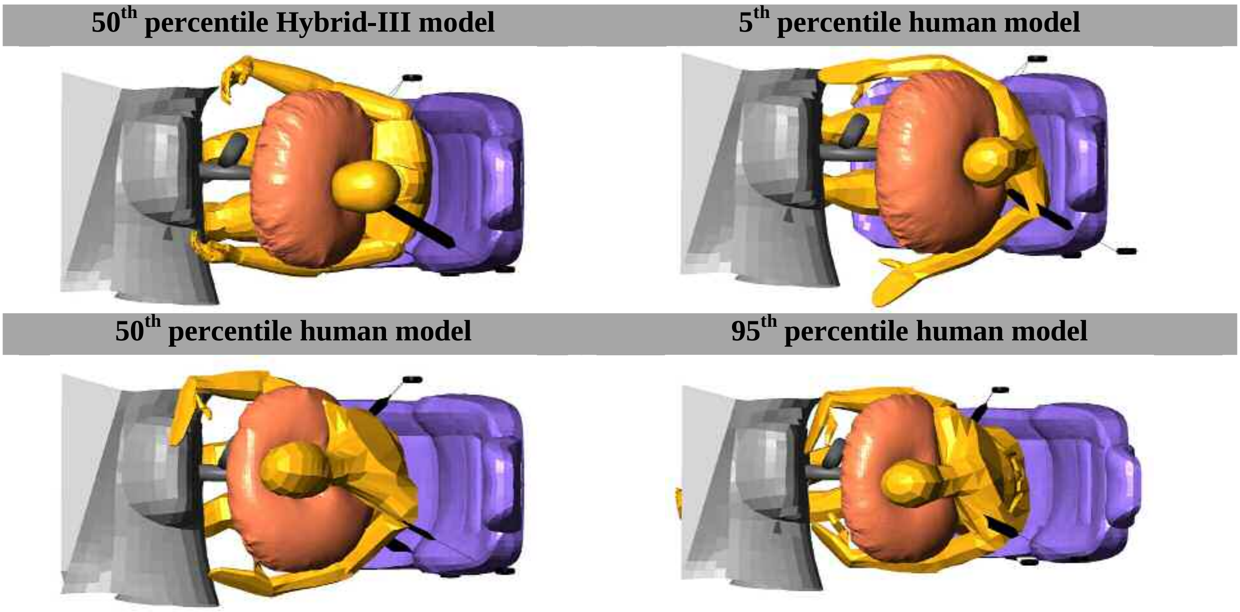



**Figure 4. Observed differences in the rotations experienced by the spines of the 50th percentile Hybrid-III and 5th, 50th and 95th percentile human models for the midi-MPV EuroNCAP simulated impacts (baseline model runs).**

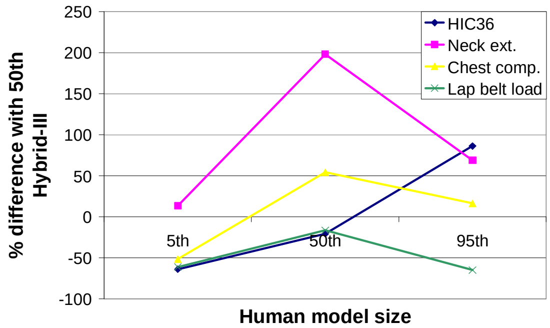



**Figure 5. Percentage differences in the injury predictions from the 5th, 50th and 95th percentile human models against those of the 50th percentile Hybrid-III dummy model for a EuroNCAP simulated impact.**

<u>**Reclined 95th percentile driver -**</u> *Occupant kinematics*: In the initial seated posture the shoulders of the reclined 95th percentile human model were behind the upper anchorage leading to a poor fit of the diagonal belt across the chest as characterised by a considerable gap between belt and chest (Figure 6). Similar poor belt fits were observed for reclined front seated passengers in the PRISM '*Passenger Pre-Impact Response Study*' of Morris *et al*, (2005). The head of the reclined model was also initially lower than that of the comparable baseline 95th percentile human model shown in Figure 3. In contrast to the baseline 95th percentile human model, which slides across the seat, the pelvis of the reclined model initially submarined into the seat penetrating it 15mm more than that of the baseline model. The underside of the dummy struck the submarine bar, which led to a high seat contact for the reclined model compared with that of the 95th percentile baseline model response. The pelvis rotated anti-clockwise as viewed in Figure 6, over the lap belt and subsequently the head of the reclined occupant was driven upwards into the roof/windscreen of the compartment. As a consequence of the relatively large amount of initial belt slack the reclined model moved further forward in the seat during the impact and this led to the upper part of the abdomen striking the lower part of the steering wheel possibly increasing the injury risk to the abdomen. Furthermore, there was less vertical rotation of the reclined modelled spine compared with that of the baseline 95th percentile model run. This is evident by comparing the top view of the reclined model in Figure 6 with the comparable image in Figure 4.

*Injury predictions*: As shown in Figure 7 the HIC, neck extension and lap belt load of the reclined occupant were over 70% greater than the equivalent injury measures predicted by the baseline 95th percentile human model. The lap belt load for the reclined model was 242% greater than that of the baseline 95th percentile model. This was attributed to the greater forward excursion of the reclined model in the seat during the impact. However, the difference in the chest deflection for the baseline and reclined occupant models was less than 4%. Based on these predictions it would appear that reclined occupants experience a greater risk of injury in an impact.

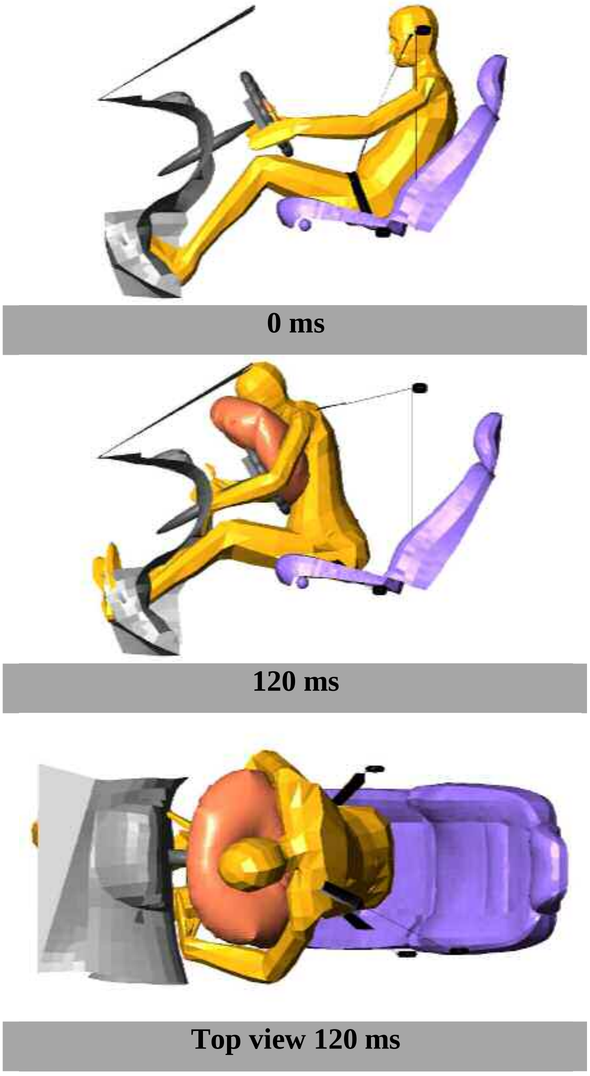



**Figure 6. Frames from the model run investigating the influence that a reclined posture has on the predicted injury risk from a 95th percentile human model**

**Occupant bracing -** *Occupant kinematics*: The simulated bracing response delayed the forward excursion of the 50th percentile human body model by up to 25ms. Furthermore, the penetration of the braced occupant into the compartment seat was 10mm (25%) more than the seat penetration predicted for the baseline model run with no simulated occupant bracing. No other obvious differences were noticed in the response of the braced and baseline 50th percentile human model responses.

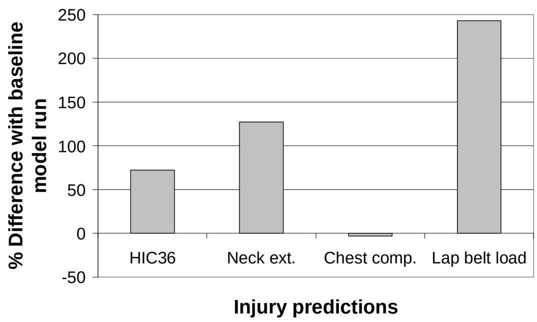



**Figure 7. Percentage differences in the injury predictions from the reclined 95th percentile human model against those of the baseline 95th percentile human model.**

*Injury predictions*: All investigated injury predictions from the braced 50th percentile human model were between 5 and 20% greater than those obtained for the baseline 50th percentile human model (Figure 8). It was implied from this set of results that bracing in an impact, which is not considered in the current setup of regulatory and consumer impact tests, appears to increase the injury risk to an occupant.

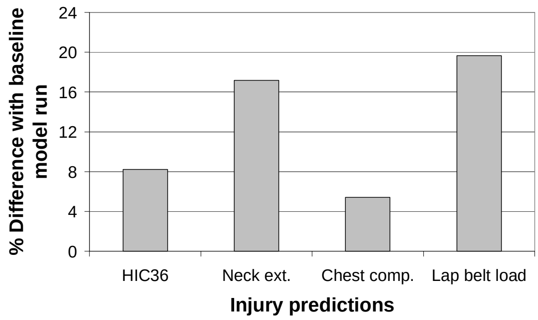



**Figure 8. Percentage differences in the injury predictions from the braced 50th percentile human model (1 kN limited arm load) against those of the baseline 50th percentile human model.**

**Thoracic fracture –** *Occupant kinematics*: For all three model runs in which thoracic fracture was simulated the abdomen of the 50th percentile human model contacted the lower part of the steering wheel. Based on these predictions it is implied that thoracic fracture could increase the possible injury risk to the abdomen. This could have been anticipated due to the additional belt length added to the restraint system during the simulated impacts. No further differences in the kinematics of the model runs simulating thoracic fracture with those of the baseline model run were observed.

*Injury predictions* – With simulated thoracic fracture all $HIC_{36}$ predictions were slightly higher than the predicted $HIC_{36}$ from the baseline 50th percentile human model run (less than 5 % difference as shown in Figure 9). Both neck extension and lap belt load were lower for the thoracic fracture model runs by between 3 and 15% and 5 and 23% respectively. Although differences in the chest deflections were less than 5% this set of results was obsolete for this particular investigation as the objective was to investigate the influence that a fracture in the thoracic body region might have on the injury risk to other regions of the body. As such it could be expected for this set of model runs that the chest injury risk for the thoracic fracture model runs was already greater than that for the baseline 50th percentile human model run. The lower predicted belt loads for the model runs imply that there was a reduced injury risk to the abdomen, possibly counteracting the increased injury risk brought about by the contact of the abdomen with the steering wheel as discussed above. Based on these predictions it was not possible to suggest if thoracic fracture would have an increased injury risk to body regions other than the thorax.

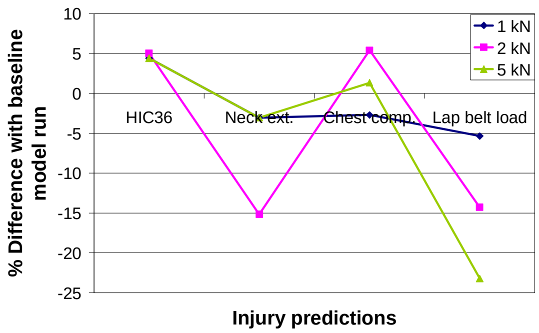



**Figure 9. Percentage difference in the injury predictions from the thoracic fracture response model runs with those predicted by the baseline 50th percentile human model run.**

**Results – Restraint system adaptations for different occupant sizes**

The adaptations made to the parameters of the modelled restraint system and the subsequent injury predictions from the occupant models in the parameter model runs were visualised using the 'snake view utility' in ADVISER, as shown in Figure 10. This figure shows how three adaptations made to the setup of the modelled restraint system (black lines) influenced the predicted injuries from the 95th percentile occupant model. The blue line provides the setup and outputs from the 95th percentile occupant model for the baseline model run with no restraint system adaptations. The magnitude of values set for the adapted restraint system parameters is indicated by the black vertical lines in the left hand side of Figure 10 and the magnitude of the occupant model's injury predictions is provided in the red vertical lines on the right hand side of the figure. As can be appreciated, the snake view provides an instant overview of the influence that variations in model inputs have on model predictions. For this investigation the snake views were used to provide an instant indication of the adaptations of the modelled restraint system that provides the lowest overall occupant injury risk. It is indicated from the example of the results obtained for the 95th percentile occupant model shown in Figure 10 that increasing the load limiting level is the dominant parameter in mitigating the overall injury risk for the 95th percentile human model. However, despite the high load limiting force levels and corresponding high belt forces predicted for the 95th human model the chest injury risk is decreased with respect to the baseline simulation.

The predicted ISS for the baseline and best adapted restraint systems for the 50th percentile Hybrid-III and 5th, 50th and 95th percentile human body models is given in Figure 11. The greatest reduction in predicted ISS is achieved for the 95th percentile human model, with a reduction of up to 65% from the baseline situation in which there is no restraint system adaptation for occupant size. A major point contributing to this reduction in predicted ISS was that the best performing adaptation to the restraint system prevented the head of the 95th percentile human model from impacting the roof/windscreen of the compartment (Figure 12). It was found in the PRISM '*Accident Data Study*' that similar roof/windscreen head strikes to those predicted by the baseline model runs do occur. As such it is indicated from the models' predictions in this work that adaptations could be made to the setup of the restraint systems to prevent head strikes with the roof/windscreen.

Predicted ISS for the 50th percentile human model was reduced by approximately 50% and minor reductions in injury risk were achieved for the 5th percentile human model and the 50th percentile Hybrid-III dummy model. The low reduction in the injury risk to the 5th percentile human model was possibly a consequence of the low initial injury risk for this model in the baseline case, as shown in Figure 5. Low reductions for the 50th Hybrid-III dummy model could be expected on account of its exclusive use in assessing the performance of restraint systems in current regulatory and consumer impact tests.

The current parameter adaptation study of the modelled restraint system has investigated a relatively limited (50 in total) set of variations in the set up of the modelled restraint system in order to mitigate injury risk for a variety of occupant sizes. There are additional configurations of the restraint system that could yield greater reductions in the predicted ISS. In this respect the current parameter study provides an improved rather than an optimized restraint system solution for each occupant size. Even so, based on the reduction of predicted ISS for all four scenarios (5th, 50th, 95th percentile human models and 50th Hybrid-III dummy model), it is implied from the models' predictions that if the restraint systems could be adapted to the most optimal setup for the particular occupant, "smart" restraint systems could considerably improve overall occupant safety. The compartment models developed in the PRISM study could support the optimisation of such systems.

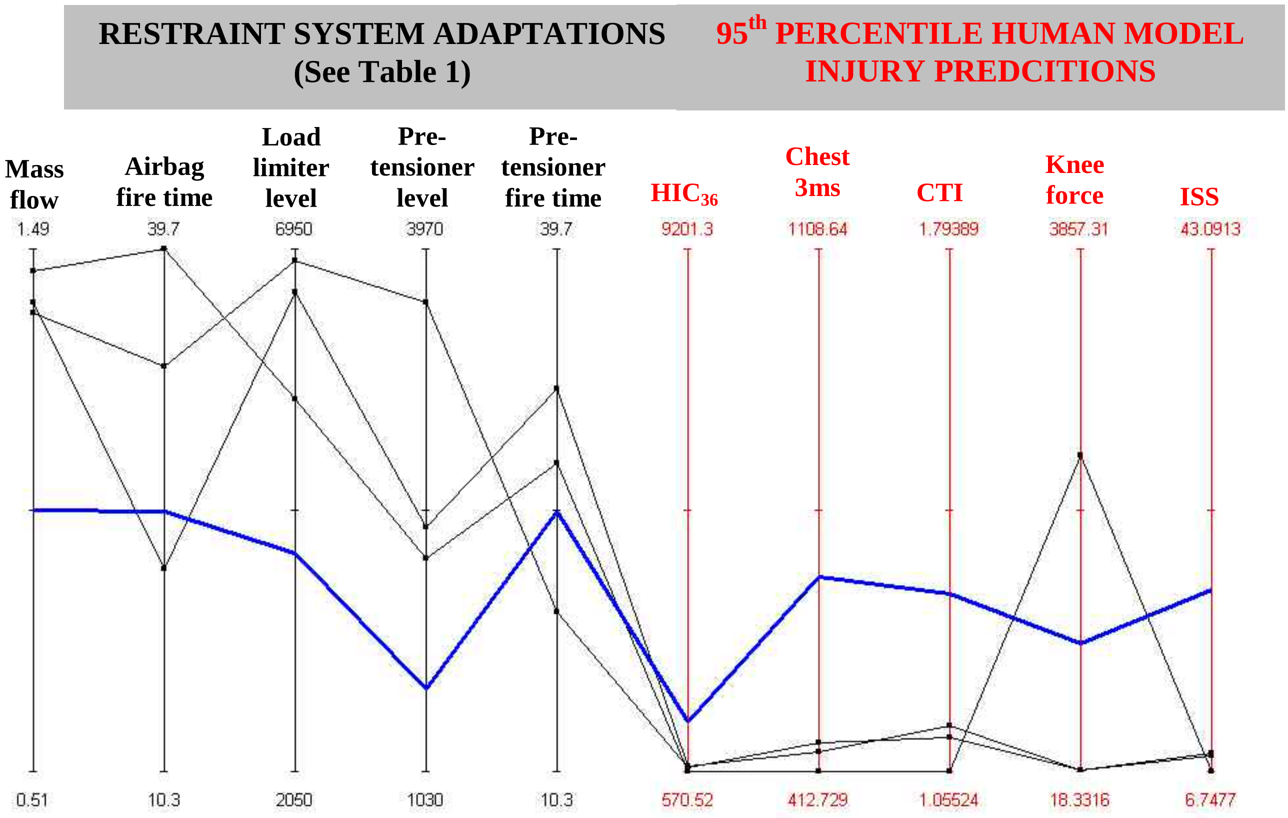



**Figure 10. Example results from the restraint system adaptation model runs completed with the 95th percentile human body model. Baseline restraint system parameter values and the 95th percentile human model's injury predictions are indicated by the blue line.**

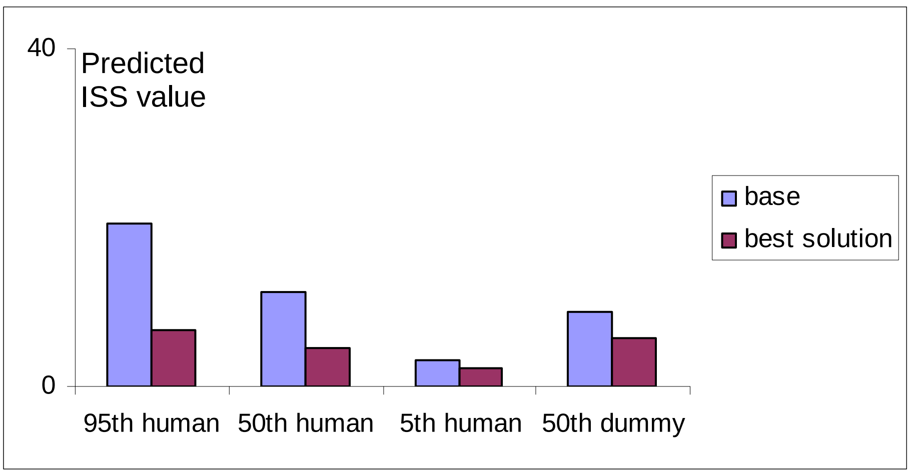
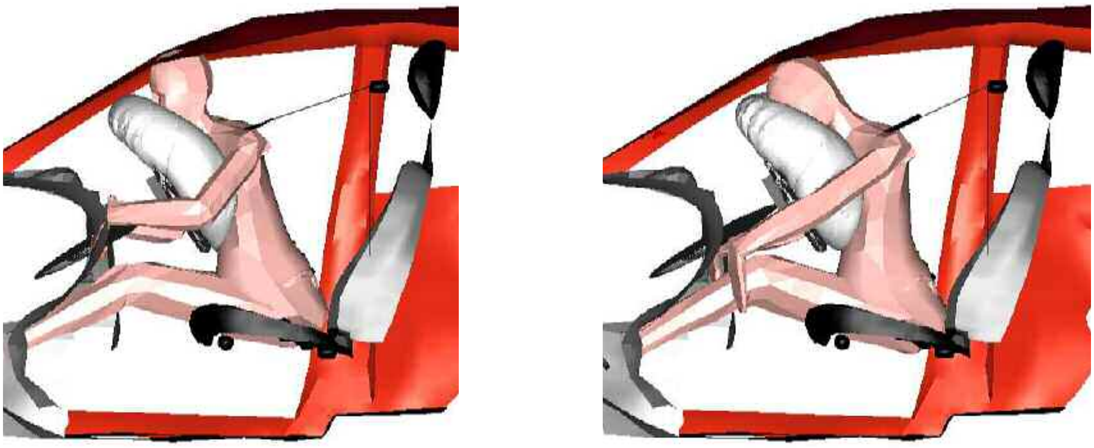



**Figure 11. Comparison of the overall injury risks predicted for the baseline simulations and for the best adapted restraint system for each occupant size.**



**Baseline response of 95th percentile human model – Head to roof contact** | **Response of 95th percentile human model with adapted restraint – No head to roof contact**

**Figure 12. Baseline response and adapted restraint system response of the 95th percentile human model.**

**DISCUSSION**

It is implied from the models' predictions in this work that there are wider circumstances influencing injury risk that are not considered in current regulatory and consumer impact tests and that "smart" alterations of the restraint system could be made that could reduce the injury risk for all vehicle occupants.

With respect to comparisons of the predictions from human and dummy models it has been found that the responses of human models are very different from those of a 50th percentile Hybrid-III dummy model. If this observation is consistent with expected behaviours in real accidents this emphasises the concern that restraints may be optimised for the responses of dummies and not humans. This is supported by the fact that predicted injury values for the 50th and 95th percentile human models in this work were greater than those of a 50th percentile Hybrid-III dummy model. Unexpectedly, the predicted injury risk for the 5th percentile human model was lower than that of the 50th percentile Hybrid-III dummy model despite contrary evidence in the published literature. For instance, McCarthy *et al* (2001) found that greater injury risk is associated with older vehicle occupants, heavier taller males and smaller lighter females. In view of these findings it was proposed by them that "smart" restraint systems would prove most beneficial in protecting these occupant groups. It is anticipated that the low injury predictions for the 5th percentile human model obtained in this work are the result of an ideal initial seat posture for the 5th percentile human model shown in Figure 3. In practice, and evident from the PRISM '*Photographic Study*' (Bingley *et al,* 2005), smaller female occupants are more inclined to lean further forward and therefore increase their injury risk in an impact. This issue will be investigated further in future work within the PRISM project.

Increases in injury risk were also predicted by the models if the reclined position of the seat is increased and the occupant braces in an impact. In addition to the variations in occupant size and differences predicted in the injury risk of human's compared with dummies, these factors would appear to be additional points that could or should be considered in the response of a "smart" restraint system. However, especially in the instance of simulating the braced occupant response, a basic modelling approach has been adopted to represent this behaviour in the model. This effectively delayed the impact of the occupant with the airbag but neglected to consider how additional bracing actions such as muscle tensing affect injury risk. The predicted increased injury risk with occupant bracing found in this study could therefore be an inherent feature of the occupant model or the manner in which bracing was represented in the model. Similar conclusions could be made about the manner in which thoracic fracture was represented in the models. In the predictions from these model runs it was not clear if thoracic fracture would promote an increased injury risk in alternative body regions other than the thorax. It is considered that further modelling work could be completed to investigate in greater detail how these factors influence occupant injury risk.

Similar parameter studies to those presented here have been completed by other researchers investigating the influence that occupant size and mass has on injury risk and how adaptations to the setup of the restraint system could be made to reduce predicted levels of injury risk (Happee *et al*, 1998b, Iyota and Ishikawa, 2003 and Holding *et al*, 2001). Holding *et al* (2001) obtained predicted reductions of up to 41, 18 and 23% in $HIC_{36}$, chest acceleration and chest compression respectively, by varying seat belt anchor height, pre-tensioner stroke, load limiter maximum force and airbag size and vent area, for a family of Hybrid-III dummy models. They went on to substantiate some of these predicted improvements in restraint system performance in sled tests with 5th, 50th and 95th percentile Hybrid-III dummies with standard and adapted restraint systems. Similar levels of improvement in restraint system performance have been observed in the predictions from the models used in the work described in this paper.

In the earlier modelling studies presented above, the investigators also considered greater variations in occupant size to the conventional 5th, 50th and 95th percentile body proportions considered in this present study. They investigated, in simulated vehicle impacts, the injury risks to occupants with tall and thin and short and squat proportions, and found that the scope of the injury risk problem is greater than that associated with conventional dummy proportions. In the work of Iyota and Ishikawa (2003), it was found that even with adapted restraint systems for 5th, 50th and 95th percentile Hybrid-III dummy models investigations with occupant models having a different body mass index to the conventional body proportions could still experience an elevated injury risk. These findings support the need to optimise the restraint system properties to the individual requirements of the occupant proportions and should not be restricted to standard 5th, 50th and 95th percentile dummy sizes. Furthermore, this links with the important issue that adapted or “smart” restraint systems should not compromise the safety of occupants whose characteristics are different from those on which the restraint system have been adapted for.

In contrast to the previous work discussed above, the PRISM study has so far limited investigations to the injury risk to 5th, 50th and 95th percentile body sizes. However, unlike the previous studies this present work has concentrated on investigating adaptations that could be made to the setup of the restraint system to mitigate the injury risk to various sizes of human rather than dummy occupant models. It has been found, based on model predictions only, that the human response is very different from that of a dummy. Consequently adapted “smart” restraint systems and conventional passive restraint systems should manage the injury risks associated with real occupants and not those of dummies. In the restraint system adaptation study presented here it is important to remember that improvements in restraint system performance were gauged with an overall body injury risk criterion based on a predicted form of ISS. Therefore, in addition to the models’ predictions the adapted restraint systems determined in this work are dependent on the applied overall injury risk approach. The setup of the adapted restraint systems for instance could be different from those determined in the work presented here if a different overall injury criterion or different types of predicted injury criteria were used to assess overall injury risk.

In comparison to the Hybrid-III dummy model it was found that the human models used in this study predicted greater chest compression, greater flexibility and stretching in, the lumbar, thoracic and cervical spine, and greater rotation in the spine about the vertical axis, increasing the likelihood of the restrained shoulder rolling out of the belt. These observations match those made by Happee *et al* (2000). Although this overall behaviour subjectively appears more biofidelic than that of the dummy model there are still uncertainties concerning the accuracy with which it predicts the response of real occupants. It is anticipated that the dynamics of the human model are more exaggerated than those of a real human and this should be considered when interpreting the results of this study. One particular concern arising from this work was the unexpected response of the pelvis to rotate over rather than submarine under the lap belt. This appeared to contribute to a considerable amount of bending in the lumbar spine of the human model. It is possible that the positioning of the belt anchorages and low initial position of the lap belt over the abdomen could have accounted for this behaviour. However, an additional feature noticed in the kinematics of the human models was that the lap belt was found to sit forward of the modelled pelvis. This is possibly due to a relatively stiff Hybrid-III pelvis characteristic defined for the human model in the lower pelvic region, as described by Happee *et al* (2000). In the actual impact conditions it is expected that the lower abdomen would deform more than was observed in the human models, to the point where the lap belt would be firmly engaged over the bony structures of the pelvis, such as the iliac wings. Further simulation work would be needed to clarify the significance of this response on the model’s behaviour, especially in the region of the pelvis. However, extensive validations of the human model’s predictions have been made against volunteer and Post Mortem Human Surrogate test data (Happee *et al* 2000 and 1998a). In this earlier work it was found that the human models do exhibit many comparable biofidelic responses.

## CONCLUSIONS

Under the European 5th Framework project PRISM, two numerical studies have been completed using a midi-MPV compartment model that has been developed to investigate the value of “smart” restraint systems in mitigating occupant injury risk. The first of the numerical studies investigated the influence that the following variables have on driver injury risk: occupant size, the reclined position of the seat, the bracing response of the driver and the influence that thoracic fracture has on the injury risk of other body regions. The object behind this numerical study has been to determine the importance of these variables in the operation of “smart” restraint systems to mitigate occupant injury risk. It is necessary to place caution on the interpretations that can be made on the models’ predictions, but in consideration of this the general conclusions of this study were as follows:

- A MADYMO compartment model of a generic European midi-MPV with conventional restraint system has been developed.
- Predictions from the compartment model compare well against comparable EuroNCAP injury crash data.
- The human models demonstrate a greater amount of flexibility in the spine and a very different crash response to a 50$^{th}$ percentile Hybrid-III dummy model. This predicted difference in the behaviour of human and dummies may need to be considered in the performance of “smart” restraint systems.
- For simulated EuroNCAP frontal impacts the pelvis’s of the 50$^{th}$ and 95$^{th}$ human models rotated over rather than under the modelled lap belt. The pelvis of the 50$^{th}$ percentile Hybrid-III and 5$^{th}$ percentile human body models submarined the lapbelt. This was possibly due to variations in the positioning of the lapbelt across the different occupant models or a factor associated with the modelled stiffness of the pelvis for the human models.
- Predicted injury risks for the 50$^{th}$ and 95$^{th}$ percentile human body models were in general greater than those predicted by a 50$^{th}$ percentile Hybrid-III dummy model for EuroNCAP impact conditions.
- Predicted injury risks for a reclined 95$^{th}$ percentile human model were greater than those for a comparable non-reclined occupant model.
- It was predicted by the model that occupant bracing would increase occupant injury risk.
- There were no obvious indications in the models’ predictions that fractures in the thoracic body region would significantly influence the overall injury risk of other body regions.

Overall, it is predicted that “smart” restraint systems should consider in their performance the impact response of humans and not those of dummies. The reclined posture of the occupant and their bracing response would also appear to be additional factors to consider in the performance of a “smart” restraint system.

The second simulation study was performed to assess alterations that could be made to the modelled restraint system to adapt its performance to better protect different occupant sizes. It was concluded from the model’s predictions in this study that considerable reductions in occupant injury risk can be achieved if the restraint system is adapted to the responses of different sizes of occupant. In this particular study a 65% reduction in overall predicted injury risk was achieved for the 95$^{th}$ percentile human body. It is proved by this work that the compartment models of the PRISM project could be used to support investigations optimising the performance of “smart” restraint systems to consider a wider variety of accident variables.

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