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PROPOSED REDUCTION OF CAR CRASH INJURIES THROUGH IMPROVED SMART RESTRAINT DEVELOPMENT TECHNOLOGIES (PRISM)

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CONTENTS

Executive summary

The PRISM project was a 5th framework European Commission (EC) project with a consortium led by MIRA, which comprised MIRA, TRL, VSRC, TU Graz, TNO, Daimler-Chrysler, CIDAUT, DALPHIMETAL and TRW. TRL's contribution to the PRISM project was jointly funded by the European Commission (EC) and the Department for Transport (DfT). This report describes the work undertaken by TRL as part of the PRISM research programme. Further details of the PRISM project, along with completed and approved project deliverables, may be accessed via the official PRISM project website at www.prismproject.com. This report focuses on the TRL's input to the project, therefore providing detail on the aspects of the PRISM project supported by the DfT.

The broad objectives of the PRISM project were to investigate the likely future societal and financial benefits of implementing 'smart' restraint system technologies and to develop guidelines on how to assess and validate the performance of 'smart' restraint systems. Current legislative and consumer automotive impact tests typically assess the injury risk to a 50th percentile dummy in a standard posture under a limited range of impact conditions. However, the potential variables influencing a real occupant's injury risk are far greater and include variations in the impact conditions (speed and direction) in addition to the size and posture of the occupant. To cope with the wider circumstances influencing an occupant's injury risk it is anticipated that 'smart' restraint systems will be needed that adapt to the specific impact conditions and react to different occupant positioning and biomechanical tolerances to injury. At present, the potential benefits and best methods for assessing the performance of 'smart' restraint systems are uncertain; contributing input to this topic was the main objective of PRISM.

Work Package 1 (WP1) of the PRISM project included a review of available accident data and current 'smart' restraint system technologies. Future technologies were detailed by examining patent archives. In addition, a photographic study of European seating positions was carried out, and experiments to identify pre-crash postures were undertaken, both for the driver and front seat passenger. Work Package 2 (WP2) involved identifying and justifying the important injury types from the reviewed accident data in WP1. Those injury mechanisms were analysed and defined using ten "injury scenarios". These injury mechanisms were then used to assess how 'smart' restraint systems might be developed to mitigate these injuries. In WP3 a series of investigations using numerical simulations were performed to determine the potential benefits that advanced restraint systems might have in reducing occupant injury risk. WP 4 then considered a comparison of the critical injury scenarios identified and assessed in WP2 and WP3 with existing (global) legislation and standards in order to formulate improved guidelines for defining and assessing the functional requirements of 'smart' restraint systems.

Three MADYMO compartment models were developed representing the confines of a generic super-mini, small family and midi-MPV vehicles. The predictive performance of the models was evaluated and found to be comparable to those that could be expected from a four or five star rated EuroNCAP vehicle. Therefore, it was confirmed that the models provided a suitable baseline level of performance for investigating the benefits that 'smart' restraint systems might confer in reducing occupant injury risk compared with current models.

Both Hybrid III and human body models were used in WP3. It was found that the kinematic responses of human body models were very different from those of dummy models. The pelvis of the human body models tended to rotate over rather than under the lap belt, experiencing a greater amount of extension in the lumber spine compared with flexion in the lumbar spine and pelvis under ride of the belt for the Hybrid III dummy model. Human body models were found to have greater flexibility in the spine compared with dummy models, such that the chests of the human body models tended to strike the airbag at an angle. The chest of the 50th percentile Hybrid III dummy model hit the airbag square on. The greater biofidelity of the human body models strongly suggests that any virtual assessment of smart restraint systems should use these models as assessment tools. Supporting this, under EuroNCAP impact conditions, the 50th and 95th percentile human body models provided predictions of injury risk greater than those of the 50th percentile Hybrid III dummy model. Under

more angled impact conditions the 50th percentile Hybrid III dummy model provided higher predictions of injury risk.

A range of driver and front seat passenger postures (as identified in the photo study and pre-impact studies) were assessed. It was found that those postures or actions which resulted in an occupant position which deviated from regulatory test postures tended to result in higher predictions of occupant injury risk.

A restraint adaptation study was carried out in order to improve the response of the restraint system to a range of occupant sizes. Adapting the restraint system to the specific characteristics of an occupant resulted in considerable reductions in predicted occupant injury risk. Reductions in predicted injury risk greater than 65% were achieved for the 95th percentile human body model.

In the context of the UK, the two priority areas which provide the greatest potential benefit are ‘smart’ systems designed to mitigate driver and passenger chest injury. Respectively these options are estimated to give a financial benefit of 197.1m GBP and 193.9m GBP per annum based on the injury risk benefits identified within WP3 of the PRISM project. The third scenario which was found to give considerable financial savings was the reduction of femur injuries. The exact cause of these injury types was not fully investigated within the PRISM project so the adapted systems were assessed only on a reduction in the femur axial load. Based on this condition it was found there was potential for a financial benefit of 114.8m GBP per annum.

The PRISM has produced a series of data sheets which covered each of the ten identified injury scenarios. These data sheets were intended to provide all the relevant information on injury mechanisms, injury causation, and frequency of injury in a user-friendly manner, with the intention that this information could be used by industry to aid the effective development of ‘smart’ restraint technologies. The data sheets also contained suggestions on the test and evaluation strategies which could be adopted to assess the performance of the smart restraint system in mitigating the injuries identified.

This report describes the PRISM project but focuses on those areas of work conducted by TRL and therefore reports on the work which funding from the UK Department for Transport contributed to. All reports produced by the PRISM project for the EC are included on CD. In addition, the modelling data generated by the project is also included in CD format as well as the technical papers produced and presented under this contract.

1 Introduction

1.1 General

The PRISM project was a 5th framework European Commission (EC) project with a consortium led by MIRA, which comprised MIRA, TRL, VSRC, TUG, TNO, Daimler-Chrysler, CIDAUT, DALPHIMETAL and TRW. TRL's contribution to the PRISM project was jointly funded by the European Commission (EC) and the Department for Transport (DfT). This report describes the work undertaken by TRL as part of the PRISM research programme. Further details of the PRISM project, along with completed and approved project (R prefixed) deliverables, as referenced in this report, may be accessed via the official PRISM project website at www.prismproject.com when these documents are fully approved for release. This report focuses on the TRL's input to the project, therefore providing detail on the aspects of the PRISM project supported by the DfT.

Car occupant casualties resulting from road traffic accidents in the UK, although reducing, still account for 1,769 car occupant fatalities, 15,522 serious casualties and 171,051 slight casualties per annum (DfT, 2004). Improvements in the crashworthiness of cars and improvements in the performance and standard safety restraint system specification have contributed to a 32% reduction in the rate of car occupants killed or seriously injured compared to the 1994-1998 average (DfT, 2004). However, the numbers of occupants killed or injured still represents a significant number and these casualties may be reduced further with the implementation of adaptive or 'smart' restraint technologies which adapt the system response to both impact and occupant characteristics. Traditionally, restraint systems such as seat belts and airbags have been tested either in conjunction with, or independent from, the vehicle and have used a limited range of occupant or crash conditions. Inevitably, this has led to systems which may be optimised to a greater degree for an 'average' occupant or a 'typical' impact. In reality, accidents occur over a wide range of impact speeds and configurations and involve occupants with a wide range of physical characteristics. Therefore, a major challenge in the further improvement in secondary (passive) safety would be to develop systems which offer improved levels of protection over a greater range of crash conditions, and which can provide a greater level of protection for a greater range of the occupant population. The definition of a 'smart' restraint, for the purposes of the PRISM project, was a restraint system which can adapt its response according to factors such as:

- Occupant size (including mass, stature etc.)
- Occupant position
- Position of adjustable vehicle items (such as seat, steering wheel etc.)
- Seat belt usage
- Number of occupants and their seating location
- Presence of child restraint systems
- Presence of significant animate or inanimate objects
- Detection and /or measurement of occupant bio-mechanical properties
- Measurement of vehicle crash pulse / structural impact behaviour
- Pre-crash sensing

Currently, vehicle and restraint system manufacturers develop restraint systems for vehicles in the European market vehicles to comply with EC Directives 96/79/EC, 96/27/EC, 77/541/EEC (to their latest amendment levels) as a minimum requirement. However, most manufacturers achieve systems that have a performance which exceeds the legislative requirement. Whilst many manufacturers consider restraint system performance for occupants such as 5th percentile female and 95th percentile male, few, if any, design and develop for smaller or larger occupants than these. Other vulnerable groups such as the elderly, the disabled or pregnant women may be considered, but the compromises required using existing technology mean that protection provided by systems are not optimal for such groups.

Injuries due to road accidents are a problem that can be controlled if adequate attention is given to accident and injury prevention strategies. Secondary safety systems have been shown to be very effective in the reduction injury occurrence and injury severity. Secondary safety can be considered in two linked areas. The first relates to the structural crash performance of the vehicle. This is dictated by the design and how well the vehicle structure manages the impact acceleration characteristics and the amount of intrusion into the occupant compartment. The second relates to the restraint of the occupant using seatbelt and airbag to control the occupant deceleration and prevent interaction with the interior of the vehicle during an impact.

The application of energy absorbing interiors, seatbelts, head restraints, and more recently airbags, have all improved the restraint of occupants and reduced occupant fatalities and injuries. However, despite the significant improvements in vehicle safety which have been achieved in the past 25 years, accident data shows that injuries are still being sustained in real crashes which should not occur in vehicles which have satisfied the regulatory tests using a 50th percentile dummy in specific crash configurations. As a result, it can be hypothesised that ‘smart’ restraint systems have the potential to offer a greater level of protection and may significantly reduce the societal and economic cost of road accidents.

1.2 The PRISM project

The PRISM project was an EC 5th Framework programme project. The primary research objectives of the project were:

- To review existing European accident data and current "state of the art" smart technologies, to assess the potential effects of smart restraints on the European accident statistics.
- To obtain European statistical data regarding the actual locations of occupants within vehicles, to allow determination of realistic worst case occupant "event start positions" for impact events.
- To investigate the effects of pre-impact occupant kinematics, (for example under pre-impact braking) to determine worst case occupant "impact start positions".
- To identify impact conditions and pre-crash occupant positions worthy of detailed study and to evaluate the issues and likely effects of smart restraints on those accidents.
- To identify, create and use advanced computer models that allow the effective evaluation of such accident types.
- To generate standard guidelines to define and evaluate the functional requirements of smart (or adaptive) restraints.
- To investigate the likely future societal and financial benefits of implementing ‘smart’ restraint system technologies in order to mitigate the injury risk to vehicle occupants in automotive accidents.
- To develop guidelines and best practices on how to assess and validate the performance of ‘smart’ restraint system technologies.

The PRISM project was structured into the following Work Packages (WP):

Work Package 1: Data collection – This WP involved a review of available accident data and current ‘smart’ restraint system technologies. Furthermore, future technologies were detailed by examining patent archives. In addition, a photographic study of European seating positions was carried out and experiments to identify pre-crash postures were undertaken both for the driver and front seat passenger.

Work Package 2: Scenario analysis – This involved identifying and justifying the important injury types from the accident data reviewed in WP1. Those injury mechanisms which could potentially benefit from improvements/advancements in restraint system technologies were assessed.

Work Package 3: Evaluation of scenarios – For the injury scenarios identified in WP2, a series of investigations using numerical simulations were performed to determine the potential benefits that advanced restraint systems might have in reducing occupant injury risk.

Work Package 4: Recommendations – This WP involved a comparison of the critical injury scenarios identified and assessed in WP2 and WP3 with existing (global) legislation and standards in order to formulate improved guidelines for defining and assessing the functional requirements of 'smart' restraint systems

A further Work Package, WP5, related to the project management activities of the project. The PRISM programme Work Packages in which TRL contributed to are listed in Table 1(below) and are described in more detail in the following sections. TRL's contribution was funded jointly by the DfT and the EC. Furthermore, an additional work item outside the remit of the PRISM project, but funded by the DfT was a Regulatory Impact Assessment (RIA) which identified and assessed the effect (and affected parties) of potential legislation or codes of practice arising from this research.

Table 1. Summary of PRISM Work Packages

	WP1	**WP2**	**WP3**	**WP4**	**WP5**
Lead partner	TUG	MIRA	TRL	MIRA	MIRA
Approximate TRL contribution to WP (% of total WP value)	29%	15%	25%	10%	8%
Other partners contributing to WP	MIRA, TNO, TRW, DALPHI, VSRC, CIDAUT, TRL	MIRA, TNO, TRW, DALPHI, VSRC, CIDAUT, TRL	MIRA, TUG, DALPHI, TRW, TNO, CIDAUT	TUG, TNO, TRW, DALPHI, CIDAUT, TRL	TUG, TRL

These Work Packages are discussed in more detail in the following sections.

2 PRISM Work Package 1: Data collection

2.1 WP1 Introduction

The aim of this Work Package was to collect data relating to the current and future status of ‘smart’ restraint systems and to provide background data to support the following research programme. This Work Package consisted of several tasks:

- A ‘state of the art’ and patent search relating to ‘smart’ restraint systems, components and technologies
- A summary of public domain crash data
- A definition of an analysis methodology for accident data
- An investigation of occupant position by photo studies
- Occupant dynamic response studies

2.2 WP1 Task 1.1: ‘State of the art’ and patent search relating to ‘smart’ restraint systems, components and technologies

This task was carried out by TUG with initial input from the entire consortium. Each partner proposed a list of key words that were relevant to vehicle safety and vehicle restraint systems. These were collated into a database of 369 entries which were used to perform an initial document, literature and patent search of the available and future technologies related to vehicle safety and vehicle restraint systems.

A literature review was undertaken across a number of scientific publications, manufacturer’s product publications and web search engines. Relevant examples were selected from a wide range of information to illustrate current knowledge and technologies related to vehicle restraint systems. Solutions which offered the technology required by smart restraint systems were discussed. The relevant documents, in electronic form, were collected in an electronic database, which formed part of the report and could be used for further and detailed study of particular points of interest.

A patent search relevant to vehicle safety and vehicle restraint systems was also carried out in order to review patent source (vehicle-manufacturer, supplier, private inventor etc) and patent criteria (restraint-, sensing-, detection-, triggering systems etc.). A patent database was populated in an electronic format to provide fast and immediate access to various possible technical solutions that may offer potential for ‘smart’ restraint systems.

2.3 WP1, Task 1.2: Summary of relevant ‘public domain’ crash test data and restraint-related vehicle features

TRL led this task which aimed to identify differences in the performance of current restraint systems. TRL obtained approval from EuroNCAP to use existing crash test data to compare the performance of a range of vehicles in each car class, provided the car models were not identified. This was the only source of detailed crash test data available as other sources in the public domain were limited by either the level of detail or scope of the data.

The examination of crash test data concentrated on tests performed under the EuroNCAP programme and provided details from the following impact types:

- Frontal impact (40% overlap, 64 kph into deformable barrier)
- Side impact (50 kph, deformable barrier)

The analysis of EuroNCAP data led to the identification of 'corridors' for the occupant compartment acceleration pulse in each specific impact type. This enabled a generic pulse for each car class to be developed for a EuroNCAP frontal impact. This formed an input to modelling activities in WP3 described later in this report. The data also enabled biomechanical performance ‘corridors’ for each car class to be developed. This analysis concentrated on head and chest injury since these are the body regions known to be injured in the majority of serious and fatal casualties. Furthermore, these body regions were considered likely to be most affected by improvements in the performance of the main components of the restraint system.

TRL also examined the restraint systems fitted to the current fleet. The analysis also considered cars selected for the EuroNCAP programme (vehicles manufactured after 1996). The research regarding restraint feature fit was organised into classes of vehicles and considered 199 vehicles manufactured between 1996 and 2005. Analysis of the type of restraint feature fitted to vehicles was essential to establishing a 'baseline restraint system' that was used in later modelling activities.

If was noted that vehicles fitted with dual stage airbags generally performed well in their class and, on average, achieved lower driver head acceleration values than cars fitted with single stage airbags. However, some of the single stage airbags performed better when considering the front seat passenger. The vehicles with dual stage airbags also performed well in their class in terms of chest compression.

It was found that all post-1997 models were fitted with at least a single stage driver airbag as standard. Models manufactured from 2002 onwards were more likely to be fitted with a higher specification restraint system. Furthermore, adaptive, or ‘smart’, restraint systems were fitted to several vehicles manufactured from 2003 onwards. Of those vehicles assessed, one small family car, two large family cars and two small MPVs were fitted with dual stage airbags. Fuller details of the car specifications are provided in the R2 report produced by TRL. This study recommended that a baseline restraint system for the modelling activities in WP3 should comprise a single stage driver and front seat passenger airbags with seatbelts equipped with pyrotechnic pre-tensioners and 4kN load limiters.

2.4 WP1, Task 1.3: Method of database analysis

The aim of this task was to determine an applicable analysis methodology for each of the available accident databases which had been made available by partners of the PRISM project. The consortium defined a methodology to extract as much information as possible out of each of the available databases: CCIS, Hannover, GIDAS, UK Fatals, Dalphimetal, and Stats19.

TRL provided expertise in order to compare the structure of each existing database to determine which data could be used effectively. Taking into account the limitations brought about by insufficiently detailed data, the confidentiality of data, quality of documentation and the sampling method of each data recording scheme, it was decided that only two sources were suitable for the PRISM project: GIDAS and CCIS. Unfortunately, there were delays obtaining the information from GIDAS due to the data analysis logistics. Therefore, the decision was taken to use CCIS as the primary data source but with comparative checks to other European data to ensure that the results of the data analysis were applicable to Europe in general. This approach proved successful and the analysis of the data provided input for the later activities relating to the selection of injury scenarios.

The method used for the accident data analysis was to identify injury types which occur frequently in impacts where the injury type or injury severity was unexpected. This was analysed by examining injury types broken down by Equivalent Test Speed (ETS) to determine those injury types which would benefit most from the implementation of ‘smart’ restraint systems. A fuller account of this task (completed by VSRC) is contained in the R3/R5 EC report.

2.5 Support for WP1, Task 1.4 Investigate occupant position by photo studies

The objective of this task was to investigate the range of postures which occupants adopt (as drivers or passengers in a vehicle) and to assess the incidence of extreme out of position occupants. This is important because the position of occupants within the vehicle has an effect on the performance of the restraint system, which may offer a different level of protection compared to that when tested with a dummy seated in a "standard" position. This task involved the analysis of the seating position of drivers via photographic data collection. MIRA and TUG conducted this area of the research, although the whole consortium were consulted and provided comments on the data collection methodology.

The first part of this task comprised a literature study which identified existing data. A total of over 5,000 samples (captured stills from films) were taken from 6 test sites, 2 in the UK, 2 in Austria and 2 in Spain. These samples were analysed to determine occupant longitudinal, lateral and upper limb locations. A Microsoft Access database was built and populated and was used to analyse the occupant positioning within the vehicle. To ensure the same quality of data collection, a common methodology for data collection was derived. Each study was made up of two data collection sites (one highway, one urban). TRL's role in this Work Package was to advise MIRA who co-ordinated on technical aspects of the data collection, analysis and presentation. This work is reported in EC report R4A.

2.6 WP1, Task 1.5 Occupant dynamic response studies

The objective of this task was to determine an appropriate pre-impact occupant position to be used in the modelling activities of WP3. The principle behind this was to model, as realistically as possible, the position of the occupant prior to the impact event, since the position of the occupant may alter under pre-impact braking or attempted avoidance manoeuvres. TRL conducted the assessment of the driver response in parallel with MIRA, who conducted the tests concerning the front seat passenger. Both these assessments involved using subjects to examine the response of the occupant. These tests for the driver and front seat passenger are described in detail in the R4B and R4C reports respectively.

TRL's work in this task concentrated on the investigation of driver responses in straight-line emergency braking events. The investigation of the driver response in this type of emergency situation allowed characterisation of the position which was adopted by drivers immediately prior to impact from a number of defined initial or "start" positions. These initial positions were determined from the work in Task 1.4 of the PRISM research, which used video analysis to determine the most frequently occurring "non-standard" positions adopted by vehicle occupants. Thus, the rationale was to identify the pre-impact positioning of the driver from a range of "normal" driving postures seen on the road.

The work was conducted using the TRL driving simulator and involved forty participants selected from TRL's subject database. The responses of each participant were recorded at five emergency events throughout the simulated route. The emergency event was created by a vehicle emerging from a side road and stopping in front of the participant. These emergency events were balanced with false events in which the emerging vehicle continued across the road. The route selected for this simulation was through rural countryside and small villages. The participants drove along a main road with several smaller roads entering from each side in the form of T-junctions and crossroads. Light traffic flow was selected to be representative of such a road type. This also reduced the likelihood of some participants slowing down because of other vehicles. The route was 27.7km long and took approximately 20 minutes to complete.

At five points along the route a car emerged out of a junction on the left-hand side of the road and stopped directly in the middle of the road in front of the participant. The side roads that these vehicles entered from were obscured by buildings or trees. Figure 1 demonstrates one of the junctions, with the emerging vehicle obscured by the building and then stopped in the centre of the road. Additionally, at five points on the route, there were dummy events where the vehicle either stopped at the junction or continued across the crossroads without stopping. The real and dummy events were interspersed to reduce the expectancy of participants that a vehicle would stop in front of them when such a junction was approached. Participants were instructed to drive at 55mph (88.5kph) throughout the simulation. This speed was selected based on the findings of a pilot study, which found this speed to be optimal to allow participants to react to events, but still required an emergency response. Further details of the trial route and the timing of events are presented in the EC report R4B.

Figure 1. Vehicle emerging from side road to create an emergency event

2.6.1 Initial Positions

The participants were instructed to adopt five different initial positions at specific points during their drive along the route. These postures were based upon those noted in the photographic study (see 2.1.4). The instructions were given via a series of recorded messages which were activated at set distances ensuring that the instructions were given at the correct time regardless of the speed of the vehicle. The positions were as follows; again it should be noted that the vehicle was a right-hand drive vehicle:

- Standardised position, FMVSS 208
- Left hand on the radio
- Mobile phone in left hand and being held up to left ear
- Right hand on sun visor
- Right arm on door arm rest, with right hand not on the wheel

The order in which participants undertook each initial position was balanced so that each event was performed an equal number of times with each initial position. This meant that each initial position was tested at each of the events (chronologically from event one to five), therefore making the response form each initial position unbiased.

2.6.2 Data Recording

Four cameras were located in the car to record the position of the participant. The positions of three of the cameras are shown in Figure 2. The fourth camera was located above the car, pointing through the sunroof to show the driver in plan view. The reasons for the camera positions selected are as follows:

- The overhead camera showed the driver in plan view and allowed the hand positions to be observed.
- The camera located on the nearside of the car showed the position from the side (to measure fore-aft movement).
- The camera above the driver's right shoulder showed the hands on the steering wheel and the vehicle instruments.
- The dashboard camera was used to monitor the face of the driver to ensure that they were able to continue the study.

Cameras were selected such that they could provide high quality images under low light conditions. The dashboard camera was a pencil type to be less obvious and provide less distraction to the driver. A video mixer was used to synchronise the images which were recorded using a VHS video recorder. An example of the images produced is shown in Figure 3.

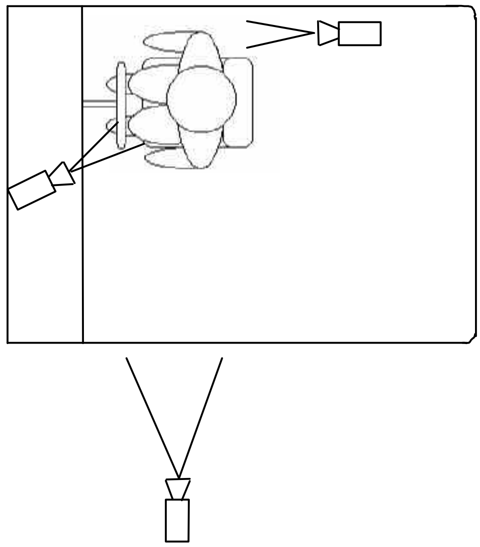


Figure 2. Schematic of camera positions

Figure 3. Example of camera images

In addition to the camera data, the pressure exerted on the seat back by the participant and the force exerted on the brake pedal were recorded. This data was used to determine the response of the driver to the emergency event.

2.6.3 Results

The results showed that the typical response to this type of emergency event was to brace rearward into the seat and to straighten the arms against the steering wheel. If a participant was undertaking an activity that meant their hand was removed from the wheel, the general response was to keep the hand in the position it was in. From the videos the distance between the ear canal (auditory meatus) and the front of the head restraint was measured. The centre of gravity (CoG) of the head is 80mm in front of the ear canal, assuming the head is level, Beier *et al* (1980). The distance from the occupant's nose to the steering wheel was also recorded. Measurements were performed before and during each event. The measurements taken are illustrated in Figure 4.

Figure 4. Occupant position measurements

Table 2 and Table 3 contain the measurements for pre-event, during event and the change for each occupant.

Table 2. Head Centre of Gravity to head restraint distance

	Pre-event head CoG to head restraint (mm)	Head CoG to head restraint (mm)	Increase in distance (mm)
Maximum	520	510	170
Minimum	220	180	-240
Mean	311.3	281.2	-31.5
Standard Deviation	54.8	58.7	51.6

On average the participant moved the CoG of their head 31.5mm closer to the head restraint during the event as a result of bracing their arms. There was a large variability on this value, often depending on the initial position that they had to adopt. For example, smaller individuals had to lean forward to reach the radio and hence were further from the head restraint at the start of the event and remained further forward than normal despite bracing.

Table 3. Distance from tip of nose to top of steering wheel

	Pre-event nose to top of steering wheel (mm)	Nose to top of steering wheel (mm)	Increase in distance (mm)
Maximum	690	680	-130
Minimum	320	390	230
Mean	526.8	549.7	28.8
Standard Deviation	70.8	64.2	51.9

The average increase in distance between the occupant's nose and the steering wheel during the event was 28.8mm.

Information on the height of the subjects was used to produce scatter plots, upon which the heights of the Hybrid III dummy sizes are shown (see Figure 5 and Figure 6).

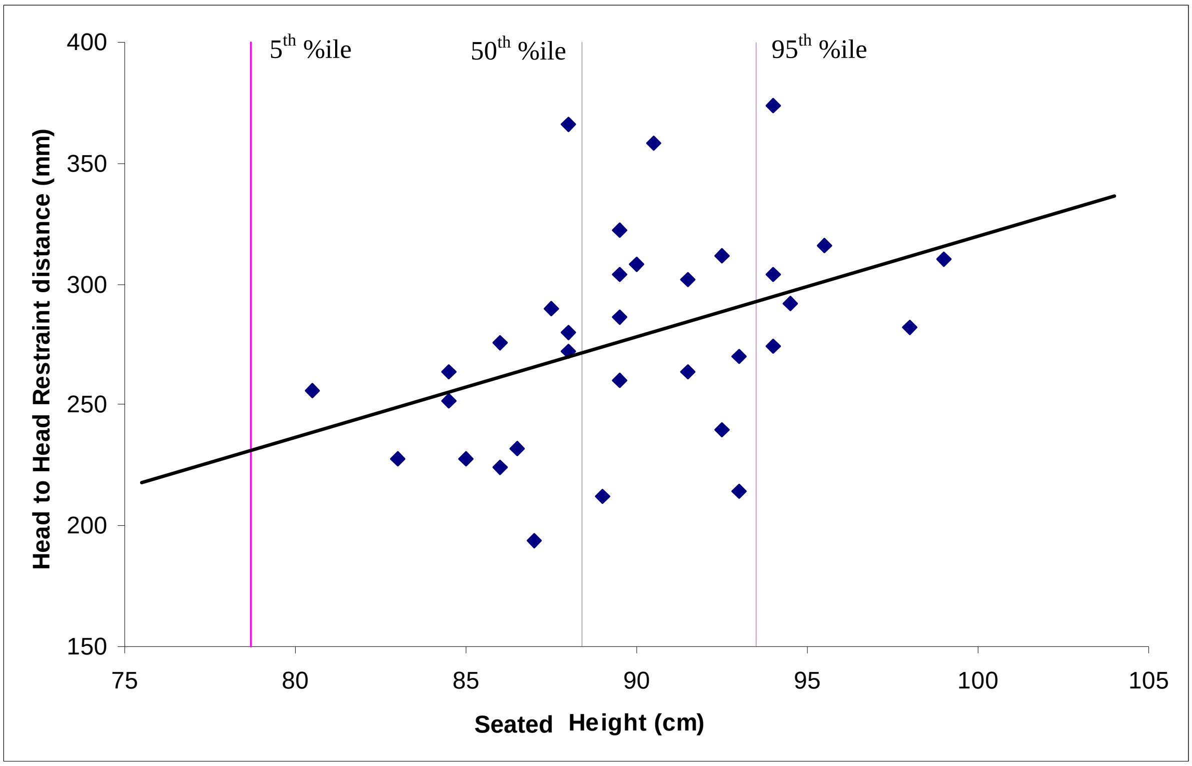


Figure 5. Scatter plot with trend line and HIII dummy sizes marked

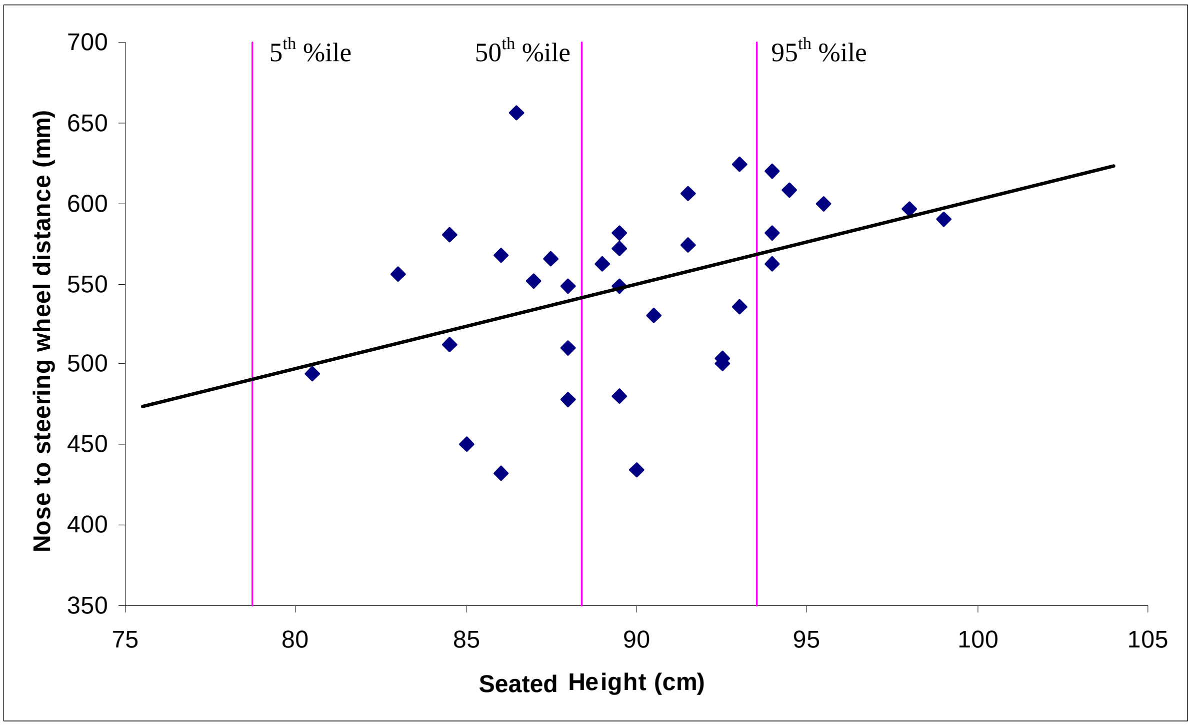


Figure 6. Scatter plot with trend line and HIII dummy sizes marked

The main conclusions from this study were:

- The participants subjectively rated the realism of the simulator study, with 97.5% of participants rating it as ‘very realistic’ or ‘realistic’, thus supporting the validity of the results for a straight line braking event of this type.
- Each one of the forty participants experienced five emergency events and although the experiment was fully balanced with false initial positions and false events, they generally reduced the vehicle speed after experiencing the first event. However, the response to all five events was still representative of a true emergency situation despite the fact that the number of collisions on events after the first was lower. Consideration of the driver posture and back contact found that the reactions on all events were very similar.
- All participants braked during the emergency event. Thus, it was concluded that during an emergency event in which the obstacle is visible and the driver has an opportunity to react, the driver’s right foot will be positioned on the brake pedal at the point of impact. This may have implications for the injury mechanism of femur fractures discussed later in this report.
- Drivers tended to stay in the initial position which had been adopted just prior to the emergency event. For example, it was observed that in most instances participants kept their hands in the locations they were in at the start of the event, rather than replacing both hands to the steering wheel. For example:
    - 87% kept hand on sun visor
    - 82.5% kept arm on arm rest
    - 82.5% kept hand on or near radio
- During the braking manoeuvre, drivers tended to straighten their arms (reducing the angle at the elbow) and push the upper torso rearward into the seat. This resulted in an average rearward movement of the driver’s head of 28mm. Back pressure measurements showed that the force and the contact area increased during the emergency event.
- Drivers exhibited little lateral movement, with the major motion in the fore-aft direction. The fore-aft response of each participant over the five initial positions was averaged and analysed against their seated height. This was then compared with the seated heights of the 5th, 50th and 95th percentile Hybrid III dummies. This analysis showed that the modelling should use the following values to represent the average distance between the nose and the steering wheel of drivers at the end of the straight line emergency event:
    - 5th percentile – 482mm
    - 50th percentile – 561mm
    - 95th percentile - 574mm
- The following minimum distances between the nose and steering wheel were recorded as:
    - 5th percentile – 390mm
    - 50th percentile – 410mm
    - 95th percentile - 420mm
- The pre-event positioning of the driver was closer to the steering wheel than during or after the emergency event. The minimum distance recorded between the tip of the nose and the steering wheel during pre-event driving was 320mm. Thus, it is possible that if the driver had insufficient time to react to this type of emergency situation, especially in the case of a driver of small statue, that the driver’s face may be in close proximity to the airbag.

3 PRISM Work Package 2: Identification of important injury types

3.1 Support for WP2, Task 2.1 Analysis of accident data

This analysis of the various accident data was performed in accordance with the methodology determined in Task 1.3 and focussed on determining the types of injury which might be mitigated by an effective smart restraint system. VSRC led this task, with TRL and the rest of the consortium providing input to the analysis methodology. The aim of this task was to identify trends in the accident data relating to injury types which occurred in airbag equipped vehicles in impacts for which the type or level of injury was unexpected. The CCIS database was used as the data source analysed. The case selection criteria and the results of this task are fully described in the EC report R3/5.

3.2 Support for WP2, Task 2.2 Brainstorm of accident data reviews and start position studies to identify key injury scenarios

The objective of this task was to identify the important mechanisms under which smart restraints could improve occupant safety. The accident data findings were reviewed to identify the key injuries and the entire consortium then participated in a workshop to define specific injury types and trends. These consisted of:

- Important injury mechanisms as identified from the available accident data
- Specific accident conditions of interest
- Possible pre-impact occupant positions, derived from photo studies and study of pre-impact kinematics.

It was decided that the first approach to the modelling activities should use impact types from legislation and consumer testing, since in these cases the crash pulse was known.

3.3 Support for WP2, Task 2.3 Determine methods for analysing each accident type identified

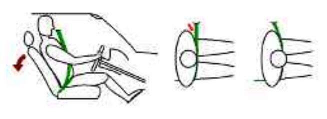
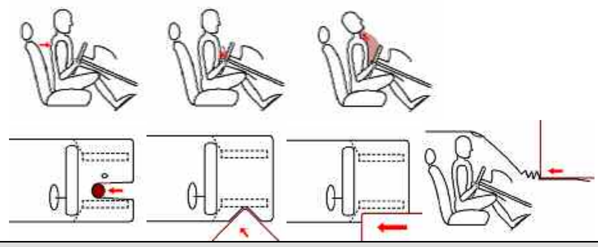
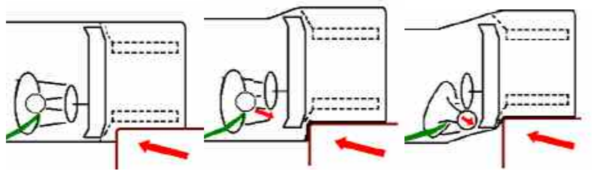
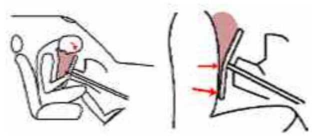
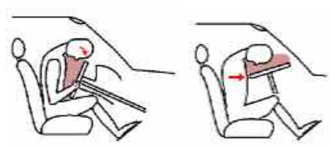
The objective of this task was to determine a priority order for analysing the selected injury types and an appropriate analysis methodology for each of these, in order to identify which new occupant models must be generated to support the analysis of these injury mechanisms.

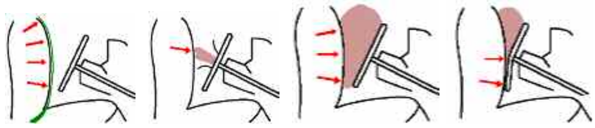
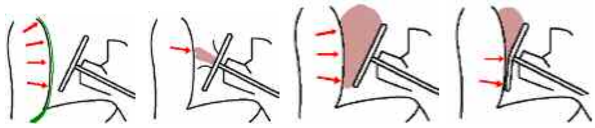
Using the data collected from WP1 and the key issues from WP2, Task 2.2, boundary conditions and variable sets were developed for the parametric studies in the modelling of these situations (WP3). The development of a priority order for undertaking the selected impact conditions was based on the decision analysis from Task 2.2, the requirements for generating new occupant models and the modification of generic restraint models. This area of the research was reported by VRSC in the EC report R5.

3.4 Important injury scenarios defined by the PRISM project

The process of determining the main injury scenarios from the CCIS accident data is detailed in the PRISM report produced by VSRC (EC report R3/R5). The following describes the aforementioned injury types derived from detailed case reviews of CCIS accident cases.

Table 4. Summary of the problem "accident scenario" conditions identified in the PRISM accident data analysis

1 Small Driver Close to the Airbag	
Small drivers who typically sit close to the steering wheel are at risk of serious chest head and neck injuries from a range of sources – airbag cover contact, airbag "punch-out", under chin loading and lack of ride-down distance before steering wheel contact.	
2 Injuries to Large Driver	
Large drivers are often reclined to prevent roof contact. This leads to poor diagonal belt positioning, with extensive forward motion and can allow severe 'submarining' under the lap belt.	
3 Very Late Deployment	
Similar in some respects to the small driver case, but this is a dynamic version that affects all statures. Poor crash pulse discrimination in "soft" impacts (pole, angled offset, shallow overlap and under ride) allows excessive driver forward motion before deployment, leading to a similar injury set to small driver.	
4 Driver Misses Airbag	
Angled offset and shallow overlap crashes cause vehicle rotation and displacement of the dashboard / steering wheel inboard (by up to 500mm). The driver then misses the airbag and has heavy head contact with either the lower A-pillar, the outboard dash, the driver face vent or the top of the door casing.	
5 Airbag Bottoms Out	
Driver impacts the steering wheel indirectly through the airbag – 2 types: Head through the top edge of the airbag or the chest simply overloads the airbag and penetrates through deforming the rim and loading the hub.	
6 Steering Wheel Edge Strike	
Driver impacts the steering wheel directly with minimal protection from the airbag – 2 types: Head over the top of the airbag, or steering wheel upward rotation and chest impact. Radial loading at "on-spoke" position is particularly aggressive.	
7 Header Rail Strike	
Some instances of moderate under runs with some header rail intrusion, but not a total loss of head space. Severe head injuries against deformed header rail or truck rear through the windscreen.	

8 Chest Injury General	
Large numbers of chest injuries in crashes for no readily apparent reasons. Few cases with crash severity exceeding 56 km/h, no major steering wheel intrusion, no pattern of driver age or proximity issues	
9 Femur Fractures	
Large numbers of femur fractures in crashes for no apparent reasons. Few cases with crash severity exceeding 56 km/h, no major fascia intrusion, no pattern of driver age or proximity issues.	
10 High injury risk to small front seat passengers	
Large numbers of chest injuries in crashes for no readily apparent reasons. Few cases with crash severity exceeding 56 km/h, no major steering wheel intrusion, no pattern of driver age or proximity issues	

4 PRISM Work Package 3: Analysis of selected accident conditions

4.1 WP3: Introduction

TRL was Work Package leader for WP3 and co-ordinated the PRISM modelling activities. This Work Package consisted of the following main tasks:

- Task 3.1: Geometric study of production vehicle interiors
- Task 3.2: Generate new occupant and generic restraint models
- Task 3.3: Undertake a parametric study on each accident condition
- Task 3.4: Estimate likely benefits (injury risk mitigation)

The following sections describe the modelling work carried out under the PRISM project.

4.2 Task 3.1: Geometric study of production vehicle interiors

TNO developed generic MADYMO vehicle compartment models with identical front seat restraint and airbag systems. Within each of the compartment models, dummy and human occupant models were fitted to provide predictions of injury risk for simulated impact conditions. The impact conditions were simulated by applying crash pulse data obtained from both full scale crash tests and from full-scale Finite Element (FE) simulated vehicle to vehicle impacts to the compartment models.

Three generic compartment models were developed by TNO which represented a cross section of the interiors of the following classes of vehicle on European roads:

- Super-mini
- Small family
- Midi-MPV

Within the choice of the vehicles to be modelled, it was considered that large family cars and executive cars were generally safer compared with their smaller counterparts and therefore these larger vehicle classes were excluded. Furthermore, MPV's are generally stiffer than other vehicle classes, and as such experience more severe impact pulses.

The geometries of each compartment model were based on average measures of the following four vehicle interiors in each modelled vehicle class:

Super-mini - Ford Ka (2000), Citroen C3 (2003), Daihatsu Cuore, Opel Corsa (2000)

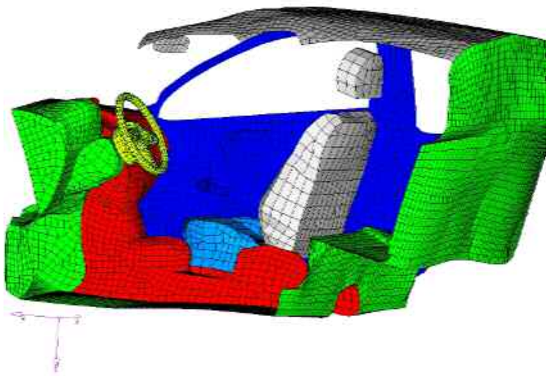
Small family - Peugeot 307 (2001), Volkswagen Golf 5 (1998), Ford Focus (1999), Renault Megan II (2003)

Midi-MPV - Renault Scenic (2001), Citroen Picasso (2001), Ford Fusion (2002), Opel Meriva (2003)

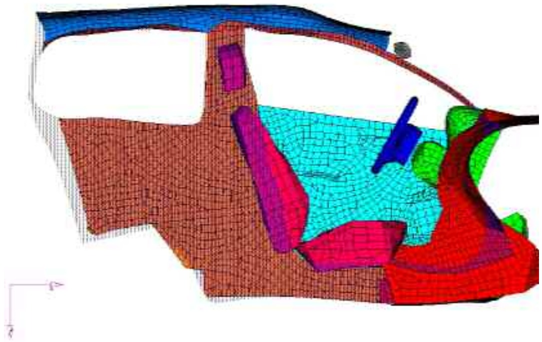
It was decided to focus primarily on new vehicle models since the main objectives of the PRISM project were to investigate the potential application of 'smart' restraint systems to the current fleet.

The interiors of the chosen vehicles were measured by TNO using a 3D FARO measuring arm. This process is described more fully in the EC report R6/R7.

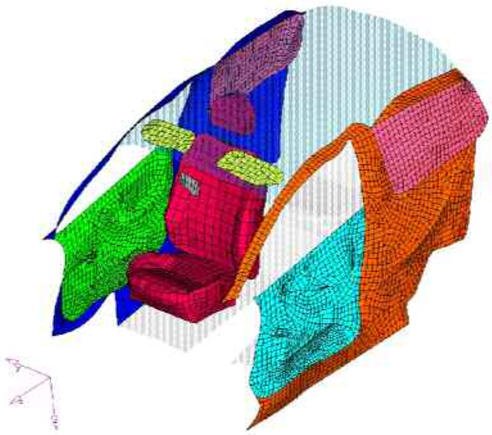
Having finalised the main outline of the compartment model in each vehicle class, rigid facet surfaces were added to the wire-frame models to define the geometrical profile of the MADYMO compartment models. Example images of the final faceted structure developed for the compartment models are presented in Figure 7.



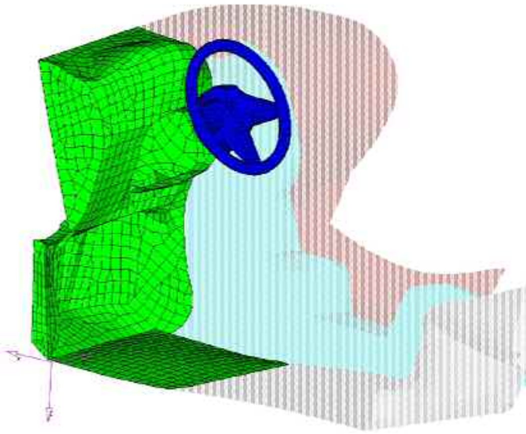
Side view – Driver side



Side view – Passenger side



Iso-parametric – Top view



Driver dash and steering column

Figure 7. Example images of the MADYMO compartment models

The seat models were set-up so that the fore-aft and vertical position of the seat and the inclination of the seat back angle could be adjusted. These adjustments were required either to fit various sizes of occupant model (as detailed later) into the compartment models or to match the set-up of the model to pre-defined seating arrangements for the driver and passenger (*e.g.* reclined or upright). The extent of the adjustments that could be made to these seat parameters were based on comparable measures made on the vehicles on which the geometry of the compartment models was based.

The same steering wheel system was modelled in each compartment model, as shown in Figure 7. This was modelled rigidly locked to the motion of the compartment model. Thus, deformation in the modelled steering column and steering wheel was not considered.

In each compartment model the same initial baseline set-up of the modelled restraint system for the driver and front seat passenger was created. This consisted of a frontal airbag, a three-point belt with buckle pre-tensioner, and load limiting at the shoulder. The baseline restrain system used in these models was the system identified by TRL in Task 1.2. As such, it was anticipated that the predicted level of safety from the models would be representative of that associated with the majority of vehicles found on European roads. A schematic detailing the baseline configuration of the modelled belt system is presented in Figure 8.

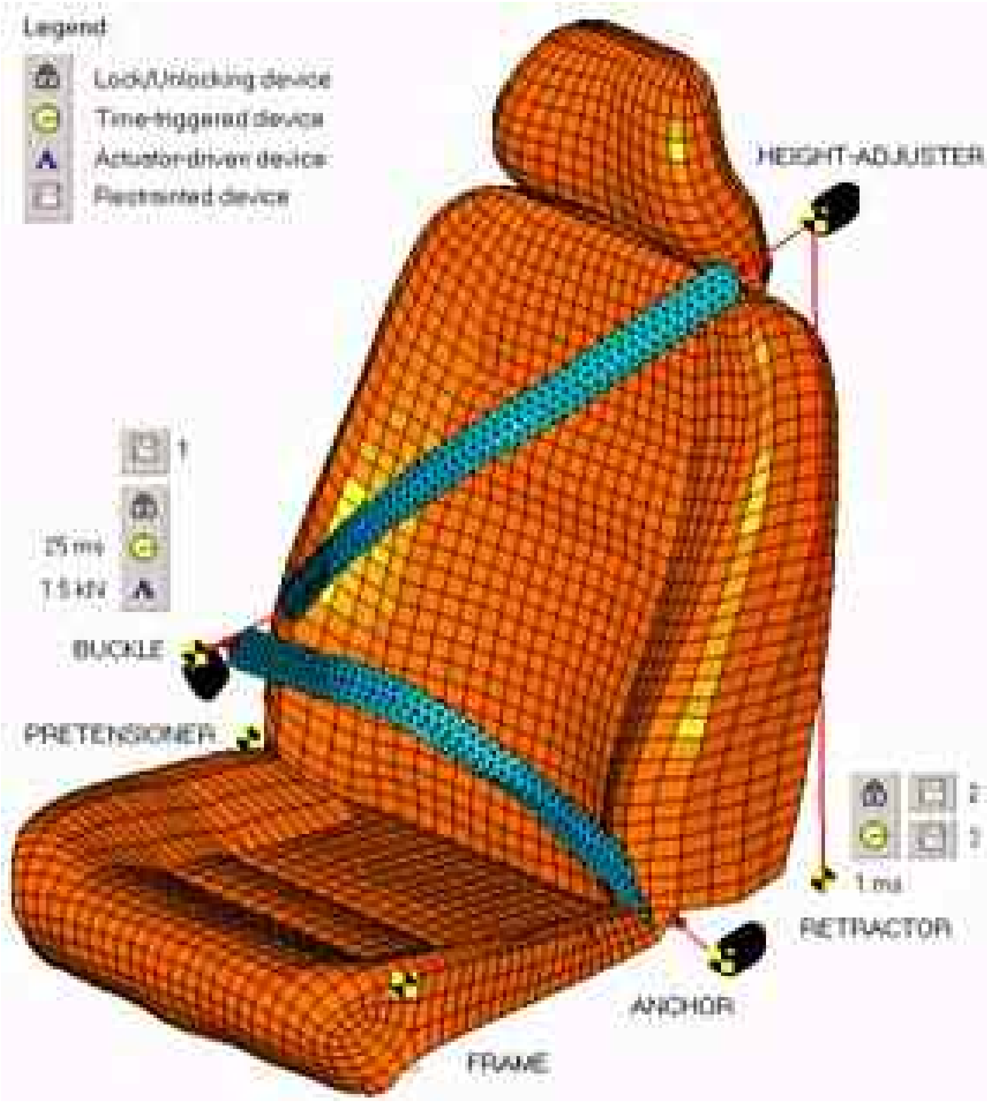


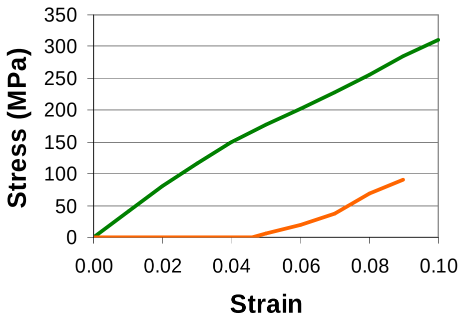
Figure 8. Schematic of the modelled belt system in the compartment models

4.3 Task 3.2: Generate new occupant and generic restraint models

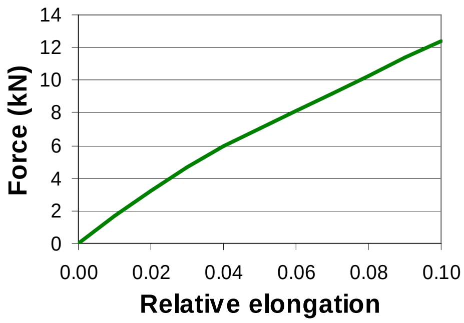
This section describes the set-up of the model.

4.3.1 Three-point belt system

The segments of the modelled lap and shoulder belt which were fitted around the occupant model were represented with FE TRIAD shell elements. This provided a more accurate approach of simulating the interactions between the belt and occupant models. Simplified multi-body belt segments were attached to the ends of the FE belt segments. These were used to anchor the belt system to the vehicle structure and to thread the belt system through the lap buckles and shoulder anchorages. The properties of the modelled belt webbing are shown in Figure 9.



FE belt stiffness characteristics
Green = loading characteristics,
Red = unloading characteristics



Multibody belt stiffness characteristics
Loading characteristics only (*i.e.* perfectly elastic response)

Figure 9. Stiffness characteristics of the modelled belt webbing

The location of the belt anchorages in each compartment model were measured from the vehicles on which the compartment model geometries were based. The vertical position of the shoulder belt anchorage was adjustable in each compartment model with ranges of adjustment averaged from the ranges of adjustment measured in each class of vehicles. The range of adjustment in the upper anchorages was approximately 15cm, while the remaining anchorages of the belt system were fixed with respect to the compartment model. In simulated impacts the shoulder anchorage was adjusted to the stature of the occupant. For 50th percentile occupant models the height adjustment for the anchorage was set at the middle of the range of vertical adjustment and the vertical adjustment set at the lower and upper limits of this range for the smaller and larger occupant models respectively.

4.3.2 Retractor

A retractor was represented in each modelled belt system. This was located at the lower shoulder belt anchorage, as indicated in Figure 8. In each model run the modelled retractor was locked at 1ms into the simulated impact.

4.3.3 Pre-tensioner

The modelled pre-tensioner was located at the belt buckle, as shown in Figure 8. When fired this exerted a maximum force of 1.5kN on the belt and was able to recoil up to 100mm of belt slack. It was modelled with a translational joint in parallel with a spring having a uniform load in compression of 1.5kN and initially compressed by 100mm. At the beginning of each simulation the translational joint was initially locked, but at a pre-determined time during the simulated impact the translational joint was unlocked. If the belt load was below 1.5kN, the compressed spring stretched, removing slack from the belt system. The pre-tensioner was locked again when the velocity of the modelled pre-tensioner reached a positive velocity of 1mm.s^{-1}. Extension of the pre-tensioning spring was in the negative direction. Hence, a positive velocity is reached when the pre-tensioning spring extends by 100mm, or when the loading in the belt was sufficient to compress the pre-tensioning spring.

4.3.4 Load limiter

Initially a 4kN load limiter was represented in the model. As shown in Figure 8, this was located between the vehicle structure and the shoulder belt anchorage and was modelled with a spring having the loading response as described in Figure 10. This shows approximately 15mm of belt spool in the retractor before the 4kN load limit is reached in the belt. No limits were placed on the amount of belt feed from the modelled load limiter.

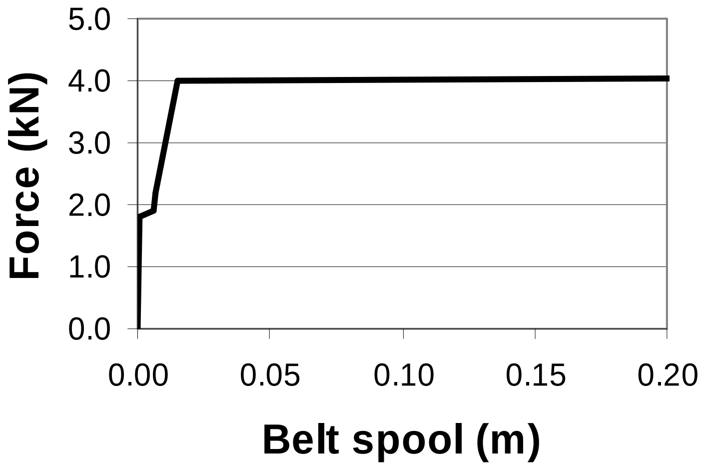


Figure 10. Loading response of the modelled load limiter

4.3.5 Driver and front seat passenger airbag

The driver airbag model was adapted from the standard MADYMO 6.2-alpha driver application. It was a standard folded circular airbag model with, after re-sizing, a volume of approximately 55 litres. Vent-holes were simulated in the airbag model, which opened at a threshold pressure of approximately 50KPa. The airbag was assumed to have a coated fabric with no airbag permeability simulated. Airbag self-contact was not simulated in order to reduce model run times. This was an adequate assumption provided the airbag effectively deployed prior to interactions with the occupant model.

The front seat passenger airbag model provided a generic representation of a passenger airbag. It had a two stage inflation characteristic. The airbag fabric had permeability and a vent-hole was simulated. The size and orientation of this airbag model was modified to provide an adequate representation of the interaction of a dummy occupant with a passenger airbag. Details on the structure and set-up of both the driver and passenger airbag models are provided in Figure 11 and Table 5.

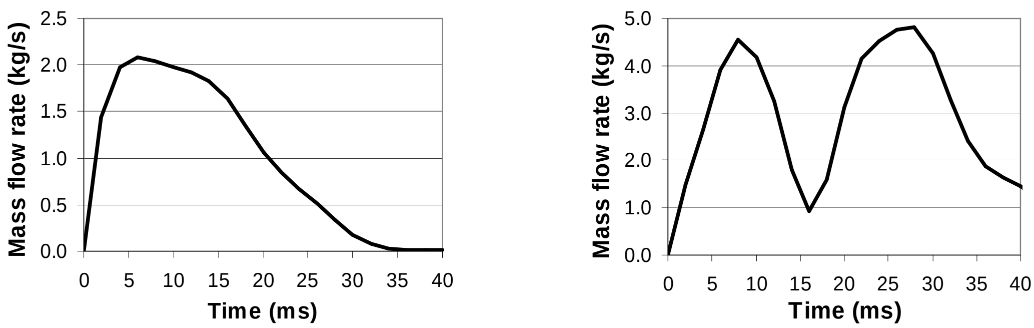


Figure 11. Mass flow rate characteristics of the driver and passenger airbag inflators - occupant models

Table 5. Structure and set-up of the driver and airbag models

		Driver airbag	**Passenger airbag**
Size		**55 litres**	**120 litres**
Airbag material properties	Thickness	0.5mm	0.38mm
	Young's modulus	250MPa	300MPa
	Density	750kg.m^{-3}	700 kg.m^{-3}
	Damping coefficient	0.1Ns.m^{-1}	0.05
	Poisson's ratio	Not given	0.3
Airbag discharge	Pressure differential for airbag opening	50kPa	0.0kPa
	Contiguous time for pressure	7.5ms	0.0ms
	Delay after contiguous time exceeded	1.0ms	0.0ms
	Airbag trigger time	Tuned to impact – 25 ms for EuroNCAP	Tuned to impact – 25 ms for EuroNCAP
	Permeability of the airbag		0.042
Inflator	Exit temperature	500 K	574
	Gas mixture	N_2 mol fraction = 1.0	N_2 = 0.7222 O_2 = 0.13386 CO_2 = 0.016 H_2 = 0.0189 H_20 = 0.10789
	Radius of jet	0.025 m	0.025 m
	Inflator mass flow rate characteristics	See Figure 11. Mass flow rate characteristics of the driver and passenger airbag inflators - occupant models	See Figure 11. Mass flow rate characteristics of the driver and passenger airbag inflators - occupant models

4.4 Occupant models

The following MADYMO occupant models were used:

- Hybrid III - 5th and 50th percentile
- Human body model - 5th, 50th and 95th percentile

In comparison to the Hybrid III models, the human body models are designed to provide a more biofidelic response and it was anticipated that these would provide an enhanced capability for assessing occupant injury risk in automotive impact conditions. However, one limitation of using the human models was that many of the injury criteria used for assessing occupant injury risk are based on the behaviour of the Hybrid III and as such it is uncertain if the same criteria are applicable to the responses of the human models, which have very different structures from the dummy models. However, it was considered applicable to use the injury criteria based on the dummy responses for the human models to provide a relative indication of how accident variables influence occupant injury risk. Images of both sets of occupant models are presented in Figure 12. Application of all these occupant models into the various compartment models are detailed further in the R7 report of the project.

5th percentile faceted Hybrid III	50th percentile faceted Hybrid III	5th percentile human body model	50th percentile human body model	95th percentile human body model

Figure 12. The occupant models fitted into the MADYMO compartment models

Further to the standard 5th, 50th and 95th percentile occupant sizes, additional work was completed to gather relevant data that could be used to develop a more appropriately sized occupant model representative of a large European male. Ultimately, it was decided not to develop this larger occupant model within the PRISM project, since the 95th percentile model was considered adequate for assessing the injury risk to larger occupants. However, the details of this work are presented in Appendix A of the EC report R6/R7. Overall it was concluded from this study that the current weight of the 95th percentile Hybrid III dummy (103kg) is approximately 8% lower than that of a comparable European male and the height of the 95th percentile dummy (1.84m) was estimated to be approximately 2% lower than that of a comparable European male.

4.5 Evaluation of the models developed for PRISM

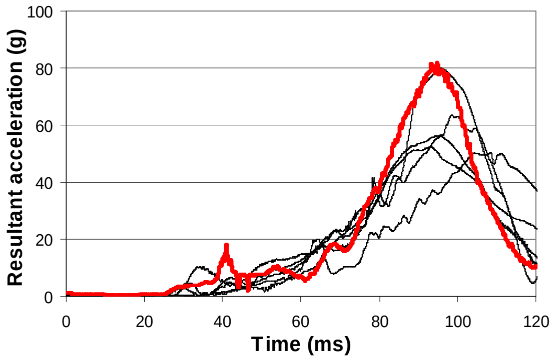
Following the development of the compartment models two evaluations of the models' predictions were completed as follows:

- An evaluation of the models' predictive accuracy
- An evaluation of the IT platform dependency of the models' predictions

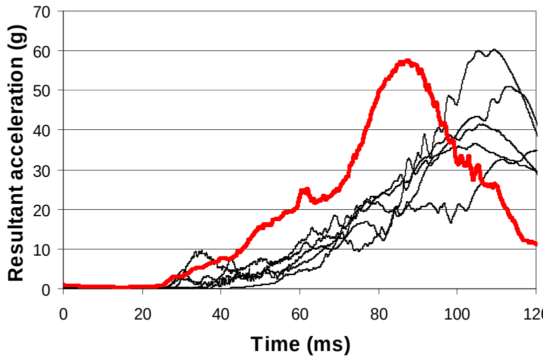
4.5.1 Evaluation of the models' predictive accuracy

For this evaluation, the predictions from simulated EuroNCAP impacts (red line on figures below) were compared against comparable measures made in full-scale EuroNCAP impact tests (black lines on figures below).

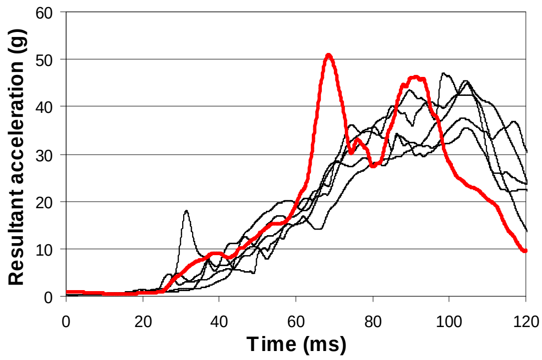
An example of the results obtained from this set of comparisons is shown in Figure 13. Differences were found in the timing and peak responses predicted by the models compared with those measured. However, the magnitude of the model predictions was comparable to those measured in the tests, which were the main feature to confirm in the evaluation.



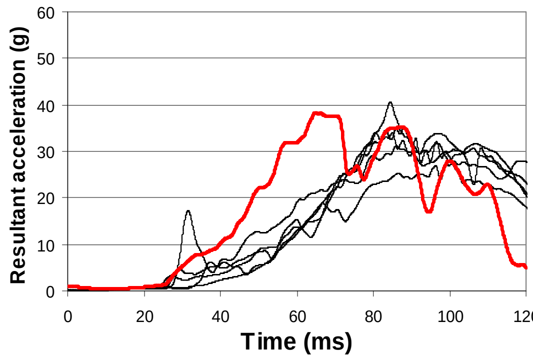
Driver head



Passenger head



Driver chest



Passenger chest

Figure 13. Comparison of measured and predicted head and chest accelerations for a midi-MPV under EuroNCAP impact conditions

4.5.2 Evaluation of the IT platform dependency of the models' predictions

It was agreed in WP3 that five separate organisations would carry out MADYMO model runs under WP3 of the PRISM project (TNO, TRL, Dalphimetal, CIDAUT and TUG). Each organisation ran simulations on different IT platforms, which presented some concerns, as it is known that running the same model on different IT platforms can influence model predictions. This presented concerns over the validity of comparing predictions from model runs simulated by the different contributors of the PRISM project. To address and assess the scale of this problem a "Round-Robin" investigation was completed in which the contributing organisations completed the same model run on their separate IT platforms and the predictions compared.

The set-up for the "Round-Robin" model run included a 50th percentile faceted dummy model positioned in the driver and front seat passenger location of the small family compartment model. A small family EuroNCAP impact pulse, matching that used in the evaluation of the model's predictive accuracy was applied to the compartment model.

Example comparisons of the predictions from the "Round-Robin" model runs are provided in Figure 14 and Figure 15. As is shown in these results, there were very small differences in the predictions from the model when run on the different IT platforms used by the PRISM consortium. However, the differences were well within accepted tolerances. Hence, it was found that there should be no concerns in making direct comparisons of model predictions deriving from different sources within PRISM.

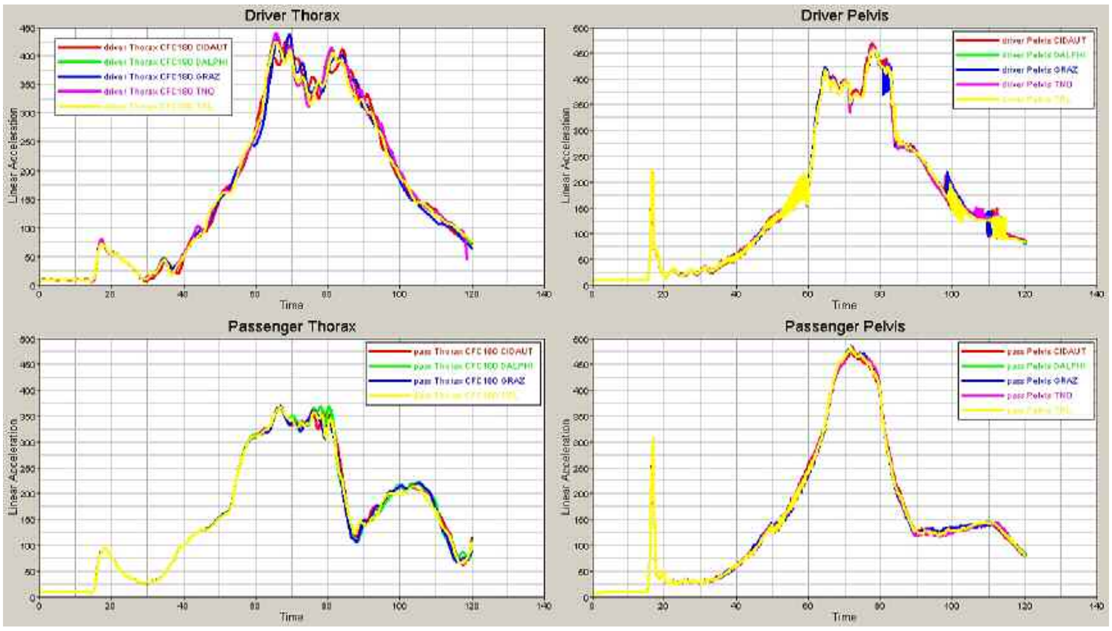


Figure 14. "Round robin" comparisons of dummy responses

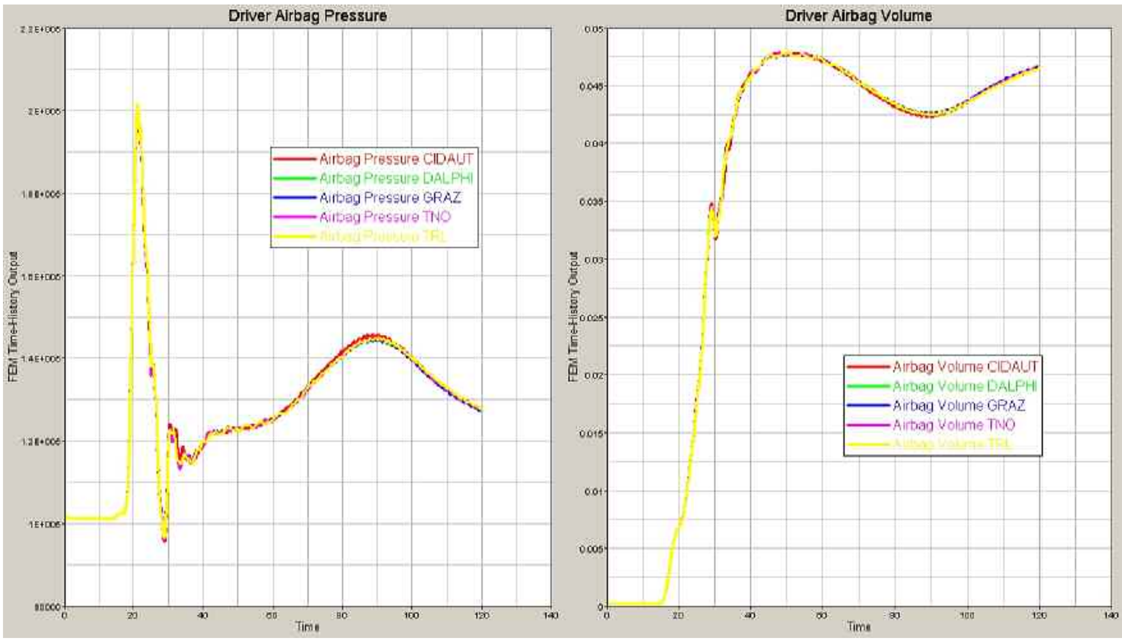


Figure 15. "Round robin" comparisons of modelled airbag responses

4.6 Model set-up: discussion

It is implied from the evaluation that the models predict a level of safety that is comparable to that of four to five star rated EuroNCAP vehicles. The intention of the PRISM project was to look at the protection of vehicle occupants above and beyond current regulatory and consumer impact test conditions. As such, developing compartment models with predicted behaviours that already match the upper safety requirements of EuroNCAP provides a suitable baseline from which to investigate how the safety of occupants could be further improved through the implementation of 'smart' restraint systems.

A number of assumptions were made during the development of the models in order to simplify their construction. One major assumption was to ignore the influence that compartment intrusion has on injury risk. With respect to regulatory and consumer impact test procedures it was felt that this was an adequate assumption, as intrusion is generally minimal under these impact conditions, especially for high-scoring EuroNCAP models. However, under different impact conditions, the applicability of this assumption is less certain. It is therefore expected that there are limitations to the types of impact for which the models could provide reliable and representative predictions of occupant injury risk. It was contemplated early on in the PRISM project that impacts involving excessive intrusion into the compartment would not be investigated in WP3 as there is little that can be done to the set up of the restraint system to prevent the inevitable injuries. Furthermore, it was appreciated that there would be difficulties in obtaining reliable intrusion data to apply in the models. Although compartment intrusion was not simulated, it was felt that this would not have a significant effect on the conclusions drawn as the impact conditions were carefully chosen and the absence of intrusion considered in the interpretation of the model predictions.

4.7 Model set-up: conclusions

Several MADYMO compartment models have been developed representing the confines of generic super-mini, small family and midi-MPV vehicles. All the compartment models have been developed with the same initial baseline restraint system for the driver and front seat passenger consisting of a three-point belt, buckle pre-tensioner and load limiting at the shoulder. The predictive performance of the models was evaluated by simulating a series of EuroNCAP impact conditions with the models. For these model runs the compartment models were fitted with MADYMO facet 50^{th} percentile Hybrid III dummy models. Predictions from the dummy models were then compared against comparable measures obtained from dummies in EuroNCAP impact tests completed on equivalent classes of vehicles to those modelled. It was found that the predictions from the models were comparable to those that could be expected from a four or five star rated EuroNCAP vehicle. This has confirmed that the models provide a suitable baseline level of performance for investigating the benefits that ‘smart’ restraint systems might have in reducing occupant injury risk in impact conditions beyond current test protocols. Details of the application of the models investigating the benefits of ‘smart’ restraint systems can be found in the EC report R7.

4.8 Task 3.3: Parametric modelling

4.8.1 General

The impact conditions were simulated with the compartment models by applying crash pulse data to the compartment models. Dummy and human occupant models were fitted into the compartment models to provide predictions of occupant injury risk for the simulated impact conditions investigated.

Model parametric investigations concentrated on investigating the effectiveness of ‘smart’ restraint systems in frontal impacts for belted drivers and front seat passengers only. The compartment models were not developed to simulate vehicle intrusions and this presented difficulties in simulating side impacts where intrusion of the compartment has a considerable influence on the injury risk to occupants. However, it should be noted that the side impact accident data provides a basis for future modelling activities.

4.8.2 Impact conditions modelled

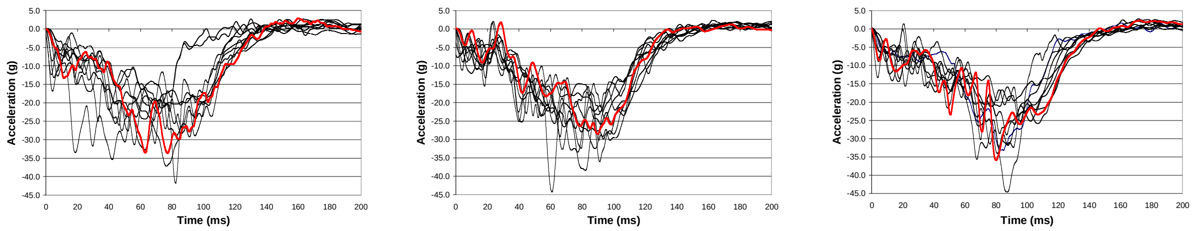
The following four sets of crash pulse data were applied to the compartment models during the parametric investigations:

- 40% Offset Deformable Barrier (ODB) impacts at $64km.h^{-1}$ (EuroNCAP)

- Full width rigid barrier impact at 56km.h^{-1} (USNCAP)
- Low severity crash pulses
- FE generated vehicle to vehicle crash pulses

40% ODB impacts at 64km.h^{-1} (EuroNCAP)

EuroNCAP is a prominent driver of automotive occupant safety in Europe. Consequently, it was decided that the influence that this kind of impact, with additional variations, has on injury risk should be investigated further in order to consider potential enhancements or extensions to the test procedure. Both left and right B-pillar crash pulse data from EuroNCAP impact tests completed on super-minis, small family and midi-MPV vehicles were gathered. From the crash pulses obtained a single crash pulse was chosen to apply to each MADYMO compartment model. The chosen pulse was determined by double integrating the obtained B-pillar acceleration pulses and examining the resulting displacement curves for the average response. Figure 16 details the B-pillar crash pulses that were reviewed and also highlights in red the EuroNCAP pulse applied to each compartment model.

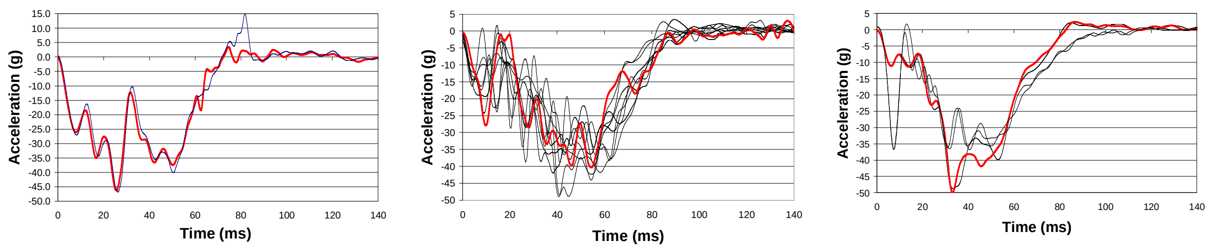


Super-mini | Small family | Midi-MPV

Figure 16. EuroNCAP B-pillar crash pulses investigated (in black) and applied (in red) to the compartment models for the parametric investigations

Full width rigid barrier impact at 56km.h^{-1} (USNCAP)

USNCAP crash pulse data was applied to the compartment models to provide more severe impact conditions to EuroNCAP. USNCAP crash pulse data for comparable vehicle classes to those modelled were gathered from the US National Highway Traffic Safety Administration website (www-nrd.nhtsa.dot.gov). The procedure used to apply the USNCAP crash pulse to each compartment model matched that used in the selection of the EuroNCAP crash pulses detailed above. Figure 17 details the USNCAP B-pillar crash pulses (both left and right) that were reviewed and highlights in red the ones that were applied to each compartment model. Only the results from one super-mini USNCAP test were available and crash data on midi-MPVs was also limited.



Super-mini | Small family | Midi-MPV

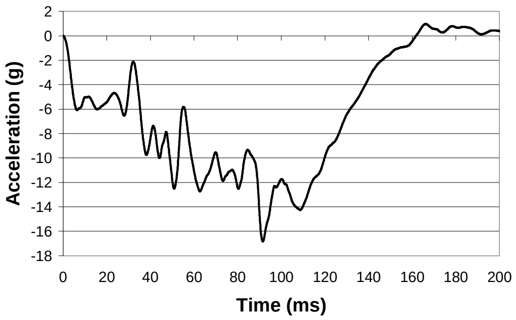
Figure 17. USNCAP B-pillar crash pulses investigated and applied (in red) to the compartment models for the parametric investigations

Low severity crash pulses

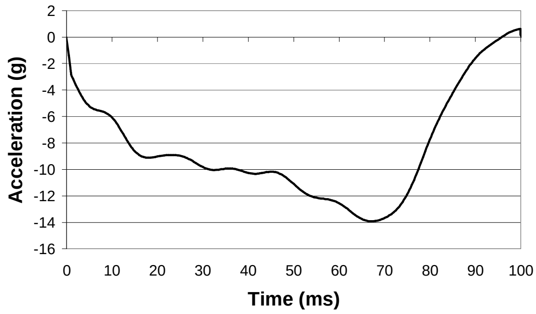
Two low severity crash pulses were investigated in the parametric studies. These were intended to be representative of the following impact conditions:

- A 40km.h^{-1} impact of a mid-size family car into an ODB
- A 26km.h^{-1} 100% overlap impact of a mid-size family car into a rigid barrier.

Earlier investigations of accident data completed under the PRISM project had identified that injuries were still occurring under relatively low severity crash pulses. Consequently, it was decided to use the above pulses to investigate the possible causes of injuries under these relatively low severity impact conditions and establish if 'smart' restraint systems could be used to mitigate any potential injury risk. Time histories of the two low severity crash pulses are presented in Figure 18.



40km.h^{-1} pulse



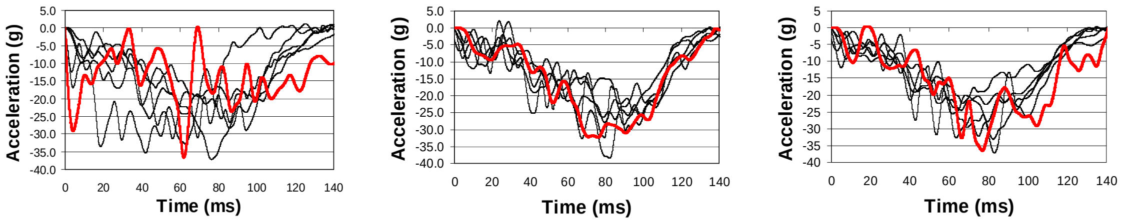
26km.h^{-1} pulse

Figure 18. The low severity crash pulses applied to the compartment models for the parametric investigations

<u>FE generated vehicle to vehicle crash pulses</u>

Full-scale finite element (FE) vehicle models were used to develop crash pulses that were different from those typically obtained under standard test protocols. These crash pulses were also generated to more closely match typical impact conditions identified in the accident data analysis of the PRISM project.

Three FE vehicle models representing a geo-metro (super-mini), Chrysler neon (small family) and Chrysler voyager (midi-MPV) were used to develop the FE crash pulses. All the FE vehicle models were downloaded from the US National Crash Analysis Center website (http://www.ncac.gwu.edu/vml/models.html). The Chrysler Voyager model was the only comparable MPV vehicle type available for the FE work; it was chosen as it represents the structure and dynamic characteristics (for example higher Centre of Gravity) of this vehicle type, despite being larger than European midi-MPVs. Although the three vehicle models represented similar classes of vehicles to those on which the MADYMO compartment models were based it was considered that their impact behaviours may not be comparable to those of typical European vehicles. Consequently, confidence in applying these models for developing alternative crash pulses was tested by simulating EuroNCAP impacts with the models and then comparing the predicted crash pulses against the measured EuroNCAP pulses reviewed in Figure 16. It was found through examination of the model animations that the crashworthiness of the FE vehicle models was extremely poor and was not representative of EuroNCAP rated vehicles. For instance, it was found that there was considerable deformation of the vehicle compartments especially at the sills and roof. However, despite these problems it was found that the predicted crash pulses for the small family and midi-MPV vehicle models were comparable to those measured, as shown in Figure 19 and that the structure of these two models was adequate to provide acceptable predictions of vehicle kinematics under a wider range of impact conditions.. In contrast, the predicted crash pulse from the super-mini vehicle was considered to provide a poor representation of the measured results and it was decided not to use this particular model further. Due to restrictions in both finances and time, further crash pulses were generated using the midi-MPV compartment model only.



Geo-metro (Super mini) | Chrysler Neon (Small family) | Chrysler Voyager (midi-MPV)

Figure 19. Comparison of predicted EuroNCAP B-pillar crash pulses (in red) with equivalent test crash pulses (in black)

Altogether two additional FE crash pulses were generated for the midi-MPV compartment model. The following impact conditions were used to develop these crash pulses:

- 45° Chrysler Voyager to Chrysler Voyager impact with both vehicles travelling initially at a speed of 30mph.
- 10% offset Chrysler Voyager to Chrysler Voyager impact with both vehicles travelling initially at a speed of 30mph.

The decision for creating these impact conditions was based on investigations of accident data completed in earlier stages of the PRISM project. Furthermore, it was anticipated that both impacts would introduce a greater amount of lateral and rotational vehicle motion possibly encouraging the simulated occupant to impact different and, possibly more injurious, features of the vehicle interior. Images illustrating the set-up of these simulated impacts are presented in Figure 20.

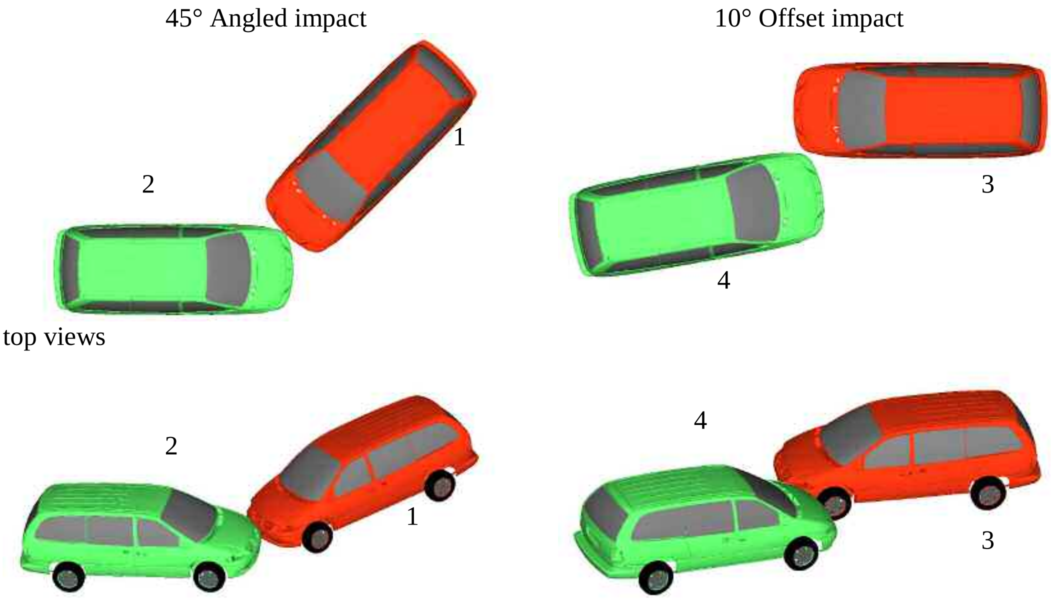


Figure 20. Set-up of the impacts simulated with Chrysler FE vehicle model. Numbers on vehicles are referenced later in this report

In the instance of the EuroNCAP and USNCAP crash pulses only the fore-aft B-pillar crash pulse was applied to the compartment models. In contrast, for the FE crash pulses it was possible to obtain and apply a more complete set of kinematics to the compartment models, including the fore-aft, lateral, vertical, pitch and yaw motions of the simulated vehicles. The roll motion was not applied as this was relatively small and also introduced greater complexity in applying this third rotational motion to the midi-MPV compartment model.

4.9 Parametric model runs

Two phases of parametric model runs were completed as follows:

- Parametric model runs assessing accident variables to consider the performance of 'smart' restraint systems
- Parametric model runs assessing the benefits of 'smart' restraint systems in reducing injury risk

All the model run files and predictions from the parametric investigations were added to a database of results. Details of the information contained in this database can be found in Appendix B of the EC report R6/R7. In addition Appendix B of R6/R7 lists the main model runs and injury predictions obtained for the PRISM parametric investigations.

As indicated in Appendix B a large number of model runs were completed in the parametric investigations and it was beyond the scope of the project to analyse and assess fully the predictions from all the model runs for the purposes of this report. Hence, the next two sections of the report detail only the main analysis and results of the models' predictions from the parametric investigations.

Prior to detailing the parametric investigations it is important to highlight that during the project five updates were made to the baseline set-up of the compartment models. These updates were made to rectify problems identified in the analysis of the model's predictions.

Parametric model runs to assess accident parameters in terms of injury outcome

This phase of model runs was completed to identify the most important accident parameters in terms of injury outcome and how these might be mitigated by the implementation of 'smart' restraint systems. Although the numbers of variables anticipated to influence occupant injury risk are numerous, for the purposes of this investigation the variables were:

- Impact conditions
- Vehicle class
- Occupant size (human and dummy model responses)
- Occupant posture
- Reclined large driver
- Occupant bracing
- Thoracic fracture
- Steering column position

4.9.1.1 Impact conditions

Regulatory and consumer impact test procedures typically investigate how a limited set of impact conditions influence injury risk. Investigations were completed with the compartment models to determine how a broader and more divergent set of impact conditions influence occupant injury risk. The investigations have so far been limited to determining the differences in the predicted injury risks associated with EuroNCAP impact conditions compared with those predicted for the FE generated full-scale vehicle to vehicle impact conditions detailed in Figure 20.

4.9.1.2 Vehicle class

Equivalent impact conditions were simulated with the three MADYMO compartment models developed under the PRISM project. Comparisons of these model predictions were made to consider the influence that differences in vehicle geometry have on occupant injury risk.

4.9.1.3 Occupant size (human and dummy model responses)

Current regulatory and consumer impact tests concentrate on the impact response of a 50^{th} percentile Hybrid III dummy. However, results from McCarthy *et al* (2001) and the accident data analysis of the PRISM project indicate that there is an increased injury risk to larger and smaller vehicle occupants under equivalent impact conditions. Furthermore, it is questionable that dummy responses provide an adequate representation of the real human response in vehicle impacts, especially under impact conditions different from conventional impact test conditions. Model runs were therefore completed with the 5^{th}, 50^{th} and 95^{th} percentile human body models and predictions from these models were compared against equivalent predictions from a 50^{th} percentile Hybrid III dummy model. It was intended that these comparisons would also provide an insight into the potential differences in impact response and injury risks of dummies compared with humans.

For the model runs involving the 5^{th} and 95^{th} 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 those variables measured in the vehicles on which the dimensions of the compartment models 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.

4.9.1.4 Occupant posture

A wide variety of postures were observed in the PRISM “photographic study” although the large proportion (over 90%) of drivers and front seat passengers maintained postures representative of that defined in FMVSS208. However, it is possible that the greatest proportion of injuries are sustained by occupants with non-standard postures. Consequently, model runs were completed to assess the influence that other common postures observed in the PRISM “photographic study” (Bingley *et al*, 2005) have on injury risk.

<u>Reclined large driver</u>

It was found in the results of the PRISM ‘*Photographic Study*’ of Bingley *et al*, (2005) that larger occupants tend to adopt a more reclined driving posture than that typically investigated in conventional test protocols. It was felt that the more reclined posture was necessary in order for larger occupants to fit within the confines of smaller vehicles. Results from the PRISM ‘*Accident Data Study*’ implied that the seat back angle adopted by a driver could be a contributory factor to injury risk and this observation is supported by the evidence found in previous studies of accident data completed by McCarthy *et al* (2001). The majority of the occupant models had been set-up to have a posture closely matching that of conventional crash tests as defined in FMVSS208. To consider the response of a reclined large driver model additional model runs were completed in which the seat back angle was increased by a further 20 degrees to the conventional model set-up. With the exception of the seat back angle and the posture of the occupant model, no other parameters defining the set-up of the compartment model, such as the fore-aft position of the seat and the position of the belt anchorages, were changed.

<u>Occupant bracing</u>

In the PRISM pre-impact braking studies of Couper and McCarthy (2004) it was observed that drivers tended to brace themselves prior to a simulated 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. In current regulatory and consumer impact tests dummies are set-up with a posture that is possibly more representative of drivers in a relaxed driving state who are unaware of, or had insufficient time to react to, an impending impact. Although difficult to substantiate, it was estimated that the driver bracing response is exhibited in a large proportion of vehicle impacts and, as such, it was considered important to assess its influence on occupant injury risk.

Occupant bracing was represented in the models 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 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 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 locked arms in an impact and, this limit was set at 1kN through each arm, which was considered reasonable. The use of the 1kN limit served an initial purpose of investigating the influence of the bracing response on an occupant's injury risk. It was thought that further investigations, with more accurate loading limits for the arms, could be conducted if this 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 1kN.

Thoracic fracture

Following the PRISM '*Accident Data Analysis*' and the study completed by McCarthy *et al* (2001), it was rationalised that bone 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 of greater concern for older occupants who were at a greater risk of injury than their younger counterparts.

To represent the thoracic fracture response in the models, two approaches were tried involving modifications to the performance of the modelled restraint system. In the first of these approaches known as "*belt fuse*", additional belt length was introduced to the modelled shoulder belt when the load through the shoulder belt segment exceeded a defined limit. It was estimated that this simulated belt response would approximate the sudden failure of osseous 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 slack was introduced at the shoulder belt segment under shoulder belt loads of 1, 2 and 5kN for three model runs. These initial belt lengths and belt loads were estimated to fulfil the immediate requirement for investigating the influence that thoracic fracture has on the injury risk to body regions other than the thorax. A further model run was completed in which a progressive 12cm of belt slack was introduced under a linearly rising belt force up to 300N based on belt slack measures of vehicle occupants performed in the PRISM project. Model runs using these belt slack and loading conditions were completed with the belt slack introduced at the shoulder only and a further model run was completed with the slack distributed between the shoulder and buckle part of the diagonal belt.

The second modelling approach, known as "*belt displacement*", used to investigate the influence of thoracic injury on overall injury risk, was to move the lap and shoulder belt forward of the occupant model in the initial set-up. This approach effectively introduced belt slack into the restraint system at the very beginning of the simulated impacts. Model runs were completed in which the belt was moved forward of the occupant model by 2cm and 5cm.

Steering column position

A set of model runs were completed assessing the influence that steering column position has on occupant injury risk. In these model runs alterations were made to the fore-aft position and steering wheel inclination within expected ranges. Model runs were completed in which the initial position of the steering wheel was moved 3cm rearward and 5cm forward. Inclination of the steering wheel was altered by ±5°.

4.10 Results: Assessment of important accident parameters

Chosen injury predictions from the model runs analysed in this phase of work included HIC_{36}, chest deflection and CTI. 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 5th percentile occupant to that of a 50th percentile occupant, the HIC_{15}, chest injury predictions and neck extensions should be scaled by 0.9, 1.96 and 1.22 respectively. Comparable scaling factors determined for a 95th percentile occupant were 1.04, 0.75 and 0.9.

Although predicted HIC_{36}, rather than HIC_{15}, was predicted by the models, in this present study it was considered more representative to use the proposed scaling factors for HIC_{15} than compare absolute head injury risk predictions for the various occupant sizes. Lap belt loads were also analysed in some of the studies to provide a relative measure of the potential injury risk to the abdomen and pelvis in the absence of accepted injury criteria for assessing the potential for injuries in these body regions. Lap belt loads were also used to provide a relative indication of the loads going through the modelled belt systems. In addition to the separate injury criteria, an injury severity score (ISS) was calculated for the occupant models in each model run to provide an overall measure of the predicted injury risk. Details of the method of calculating this are presented later in section 4.11. In addition to the predicted values, the predicted occupant kinematics were also analysed in order to identify potentially hazardous conditions that may not be highlighted by conventional injury criteria predictions.

Overall, injury risks predicted by the models for the investigated impact conditions were low. It is felt that this was partly due to the fact that the models were based on the safety systems and impact behaviours of 4 or 5 five star rated vehicles. As such the analysis of the model predictions has concentrated on the relative influencing trends rather than the absolute differences between model predictions.

4.10.1 Results - Impact conditions

The kinematics of the occupant models in the 45° impacts was very different from those of the EuroNCAP impact conditions. Under the EuroNCAP conditions the occupant model moves forward striking the centre of the airbag and the diagonal belt is maintained across the chest. In contrast, for the 45° impact the occupant model translates diagonally across the surface of the seat and there appears to be an increased likelihood of the belt wrapping around the neck of the occupant model. This was especially noticeable when the responses of the 50th percentile Hybrid III model were compared under these impact conditions (Figure 21). Furthermore, irrespective of the fire times for the airbag (25 or 48ms), under the 45° FE impact conditions, the kinematics of the 50th and 95th percentile human body models were very similar. The offset FE impact kinematic response of the occupant model was similar to that of the 45° impact conditions.

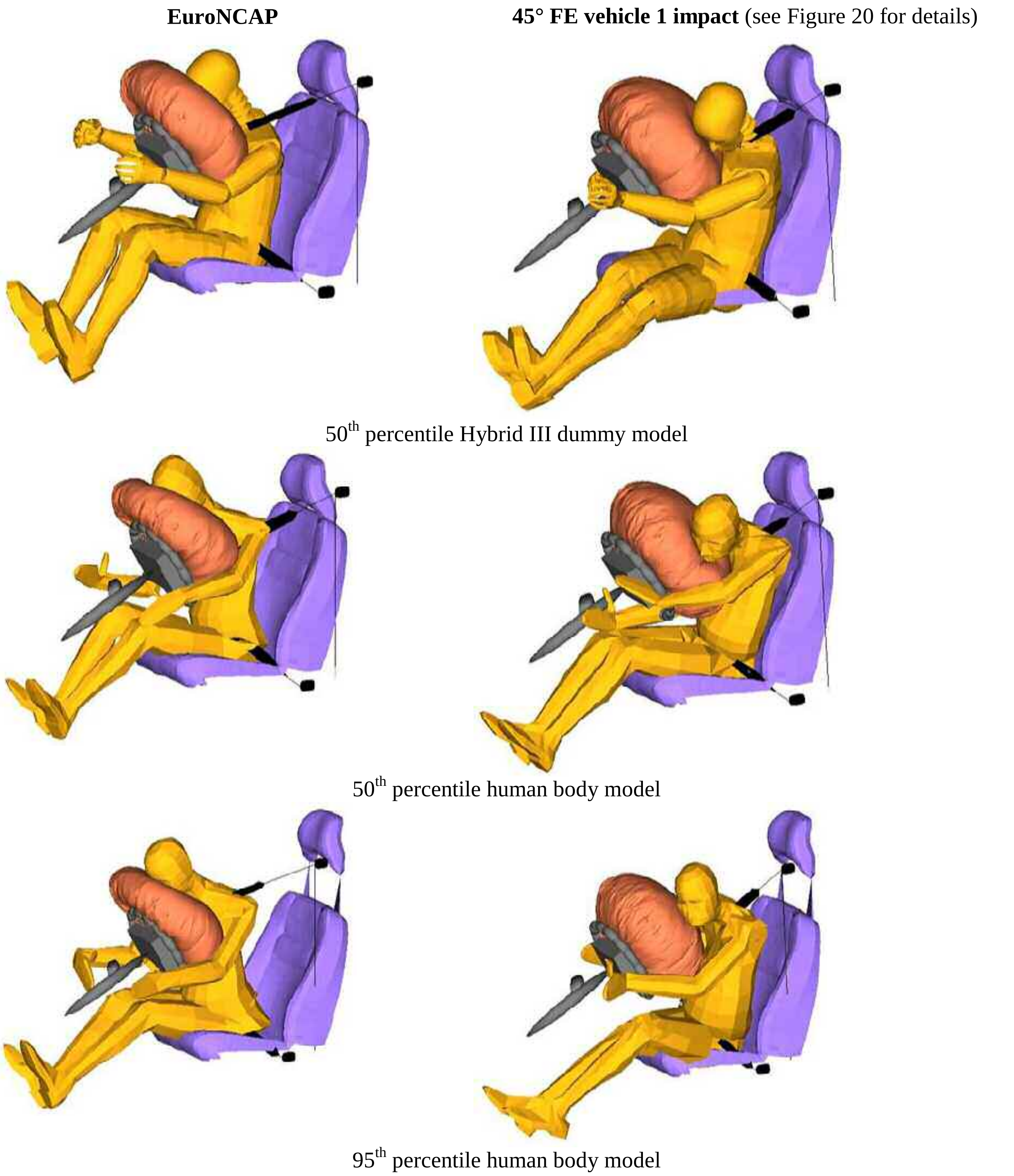


Figure 21. Comparison of occupant kinematics under a EuroNCAP and a 45° vehicle to vehicle impact at 100ms into the simulated impacts

Under the 45° and offset impact conditions, the arm, shoulder and legs tended to strike the door and door glazing and the head tended to glance the door glazing during the 45° impact before striking the side of the airbag. This was more severe for the larger occupant model. In contrast, during the EuroNCAP impacts the head struck the centre of the frontal airbag.

Injury predictions were analysed by comparing model predictions from parametric model runs against equivalent predictions from chosen baseline model runs, as illustrated in Figure 22. In this instance the baseline predictions were obtained from simulated EuroNCAP impact conditions with Human and Hybrid III dummy models. The values in brackets represent those predicted for the baseline model run and the plotted values the deviation in the predictions from the parametric model runs. Figure 22. Influence that impact conditions have on predicted occupant injury risk. Baseline predictions (in brackets) are for EuroNCAP impact conditions

provides the injury predictions from the model runs investigating impact conditions. Using the 50th percentile Hybrid III dummy model it is shown that going from a EuroNCAP impact to a 45° impact the overall predicted ISS increased by over 130%. The main factor influencing this response is the predicted injury risk for the neck and head. These responses were possibly influenced by the modelled belt wrapping around the neck. For the model runs involving the human body models, predictions of overall injury risk were approximately 50% lower for the FE impact conditions than they were for the EuroNCAP impact conditions

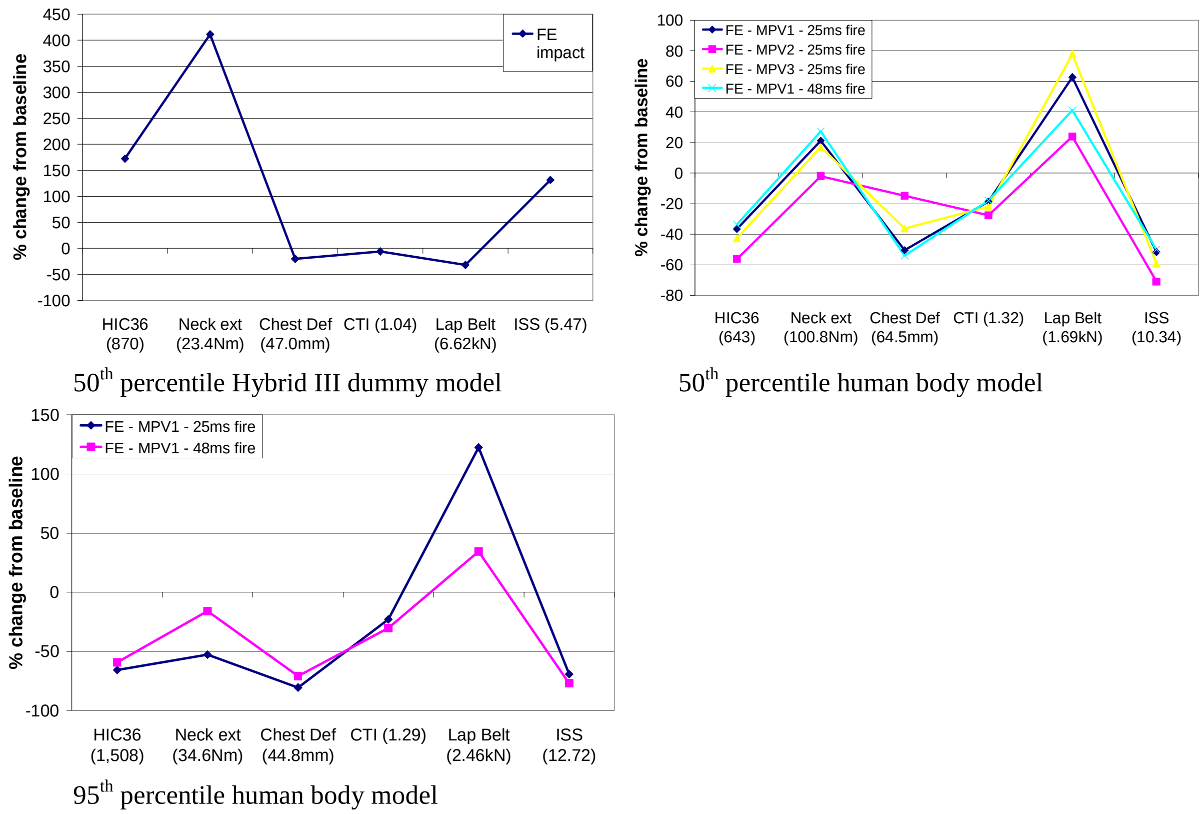
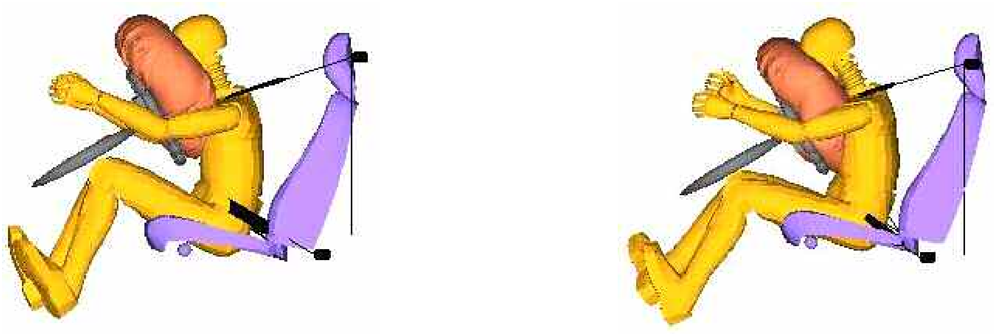


Figure 22. Influence that impact conditions have on predicted occupant injury risk. Baseline predictions (in brackets) are for EuroNCAP impact conditions

4.10.2 Results - Vehicle class

In the super-mini compartment model the knees and hips of the 50th percentile Hybrid III dummy model were flexed more than those of the same occupant model in the larger midi-MPV compartment model as shown in Figure 23. This is likely to influence the loading direction and consequently the injury risk to the joints and bones of the lower limbs.

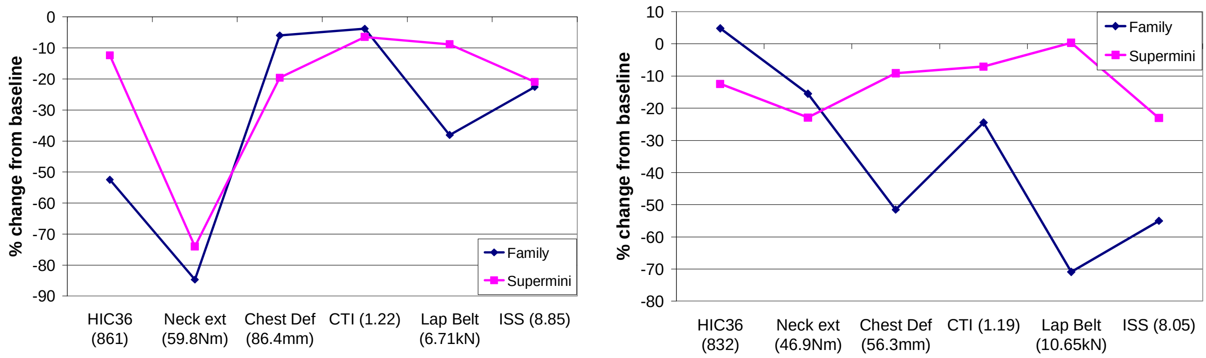
In general the kinematics of the 5th percentile Hybrid III dummy model were similar for all compartment models. However, it was noticeable that in the super-mini and midi-MPV compartment models that the abdomens of the 5th Hybrid III dummy models struck the lower edge of the steering wheel as a result of the airbag not having adequate time to deploy.



Super-mini   Midi-MPV

Figure 23. Differences in the leg impact response of the 50th percentile Hybrid III dummy model for USNCAP impact conditions

Injury predictions for this set of model runs are presented in Figure 24. As shown, the injury predictions for the small family and super-mini compartment model are generally lower than those for the larger midi-MPV compartment model.



50th Hybrid III model   5th Hybrid III model

Figure 24. Influence that vehicle class has on predicted occupant injury risk. Baseline predictions (in brackets) are for the midi-MPV compartment model

4.10.3 Results - Occupant size (human and dummy models)

Unlike the 5th and 50th percentile human body models and the 50th percentile Hybrid III dummy model, the head of the 95th percentile human model struck the roof/windscreen of the compartment model under the EuroNCAP impact conditions, as shown in Figure 25.. It was further noted that the head of the 95th percentile human body model struck the airbag 15ms later than that of all the other occupant models. In contrast the head of the 5th percentile human body model struck the airbag during its inflation, hitting the airbag earlier than any of the other occupant models.

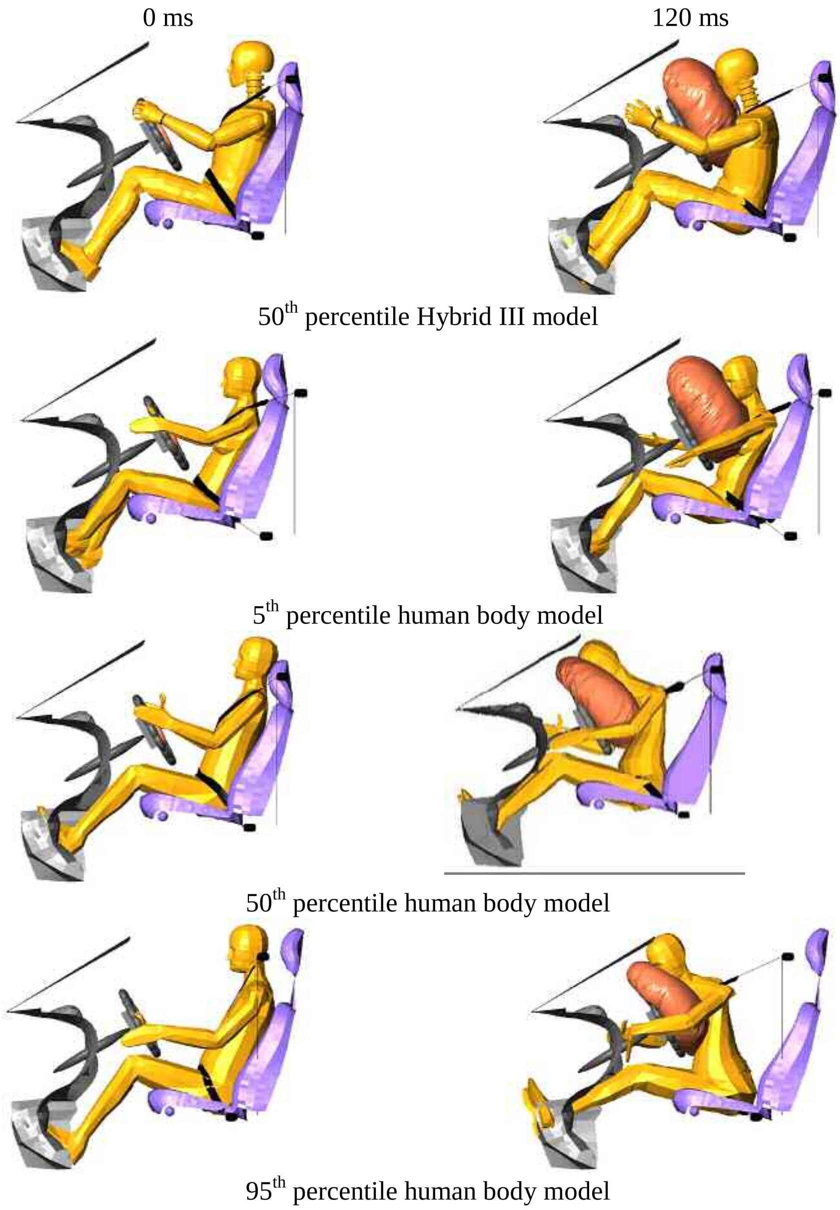


Figure 25. Images from the simulated EuroNCAP impacts completed with the 50th percentile Hybrid III dummy model and the 5th, 50th and 95th percentile human body models

For the EuroNCAP impact conditions the pelvis of the 50th and 95th percentile human body models rotated over rather than under the lap belt with the lumbar spine in extension. In contrast the pelvis of the 50th percentile Hybrid III model dropped into the seat and was maintained under the lap belt with the lumbar spine of the model in flexion. Overall the human body models, especially the 50th and 95th percentile models, demonstrated more spine rotation and stretching than the 50th percentile Hybrid III dummy model.

The horizontal and vertical head excursion of the 50th percentile human body model was greater than that of the 50th percentile Hybrid III dummy model, as shown in Figure 25. The head of the 50th percentile human body model tended to wrap over the top of the airbag whereas the head of the 50th percentile Hybrid III dummy model tended to hit the airbag more in the centre. It was also noticeable that the chest of the 50th percentile Hybrid III dummy model hit the airbag square on. However, greater rotation in the spine of the 50th and 95th percentile human body models lead to the chests of these models striking the airbag at an angle. In general, the unrestrained shoulder of these models had a greater forward excursion with an increased likelihood for the diagonal belt to slip off, as shown in Figure 26. Due to its close proximity to the airbag, the 5th percentile human body model appeared to be well restrained by the airbag and belt system, with the airbag effectively pinning the model into the seat. However, the knees appeared to experience more severe impacts with the front facia and trim than 50th or 95th percentile human body models.

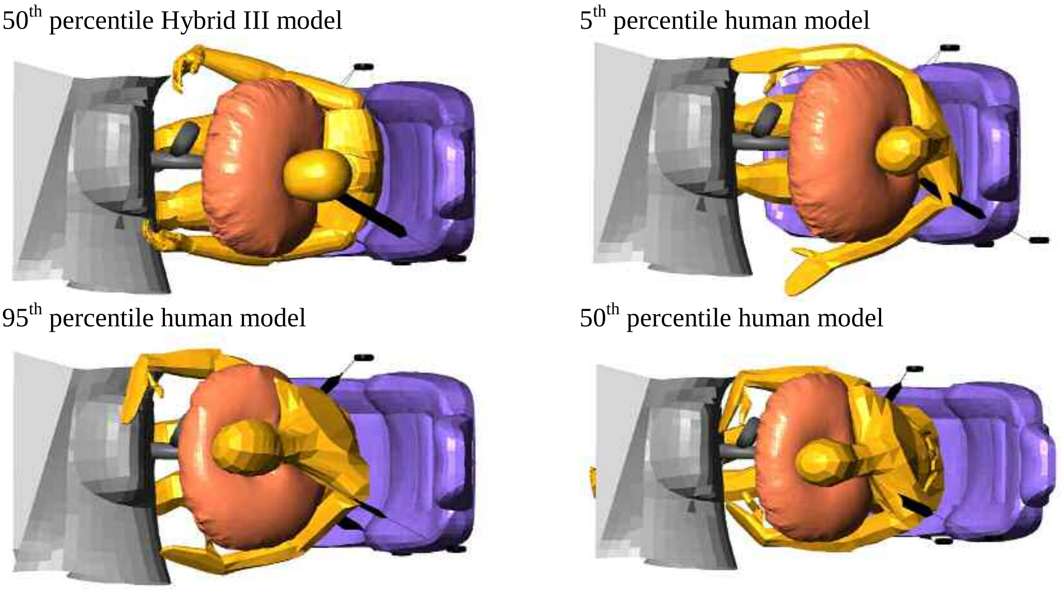
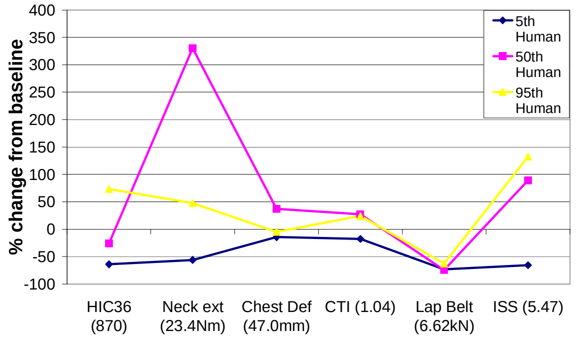
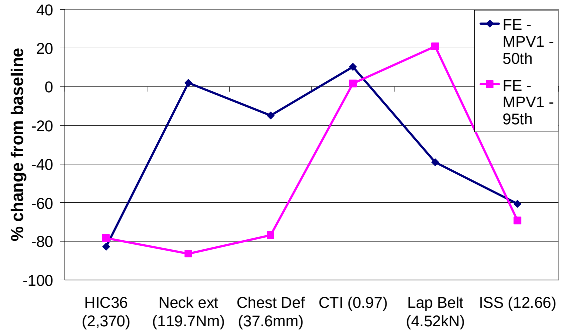


Figure 26. Differences in the unrestrained shoulder excursions of various occupant sizes of occupant model under EuroNCAP impact conditions at 120ms

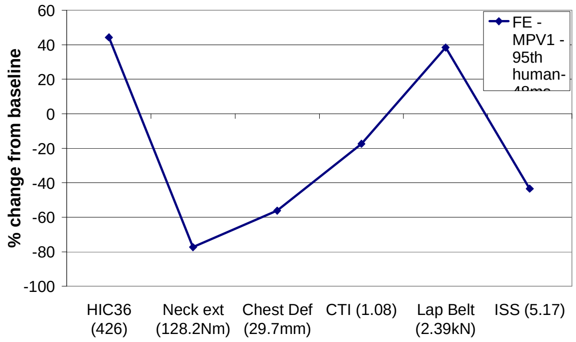
During the angled FE impacts, the heads of both the 50th percentile Hybrid III dummy model and the 50th percentile human body model glanced the door glazing while the head of the 95th percentile human body model had a more acute impact with the door glazing. Despite these differences in the head contact, the predicted HIC for the 95th percentile human body model was considerably lower than that predicted for the 50th Hybrid III model, as shown in Figure 27. As noticed previously, in Figure 21, the diagonal belt tended to wrap around the neck of the Hybrid III model for these impact conditions and it is felt that this contributed to unrealistically high predictions of HIC and neck extension for this particular model run. It was further noticed that the head of the 95th percentile human body model tended to strike the airbag 20ms later than its 50th percentile counterpart during the FE angled simulated impacts, irrespective of the fire time of the frontal airbag (25ms and 48ms).



EuroNCAP impact conditions
Baseline = 50th Hybrid III dummy model



FE vehicle 1 impact (Figure 20)
Baseline = 50th Hybrid III dummy model
(airbag fire time 25ms)



FE vehicle 1 impact (see Figure 20)
Baseline = 50th human body model (airbag fire time 48ms)

Figure 27. Influence that occupant size has on predicted occupant injury risk. Values in brackets are baseline predicted responses

As shown in Figure 27, all the 5th percentile human body model predictions of injury risk, with the exception of CTI and chest deflection, were at least 50% lower than those predicted by the 50th percentile Hybrid III dummy model for the EuroNCAP impact conditions. Alternatively, with the exception of the lap belt load, injury predictions for the 50th and 95th percentile human body models were above those predicted by the 50th percentile Hybrid III dummy models for the EuroNCAP impact conditions. For the FE angled impact conditions, the injury risk predictions of the 50th and 95th percentile human body models were generally above those of the 50th Hybrid III dummy model. Overall, it is implied from these predictions that the occupant model (dummy or human) providing the greatest prediction of occupant injury risk is highly dependent on the impact conditions.

For the FE impact conditions it is predicted that the 50th percentile Hybrid III dummy model is at greater risk than the 50th and 95th percentile human body models. Overall, for the FE angled impacts, the 95th percentile human body model has the lowest predicted risk of injury irrespective of the time at which the airbag is fired.

4.10.4 Results - Occupant posture

Postures shown in Figure 28 are mainly self explanatory with the exception of the "driver restraint position". This posture was intended to be representative of the posture of a braced occupant who may push themselves further back into the seat. As such, for the "driver restraint position" the 50th percentile Hybrid III dummy model has been displaced a further 5cm rearward compared with the baseline seated posture. Further model runs were completed to assess the influence that slight alterations in the seat back angle have on occupant injury risk.

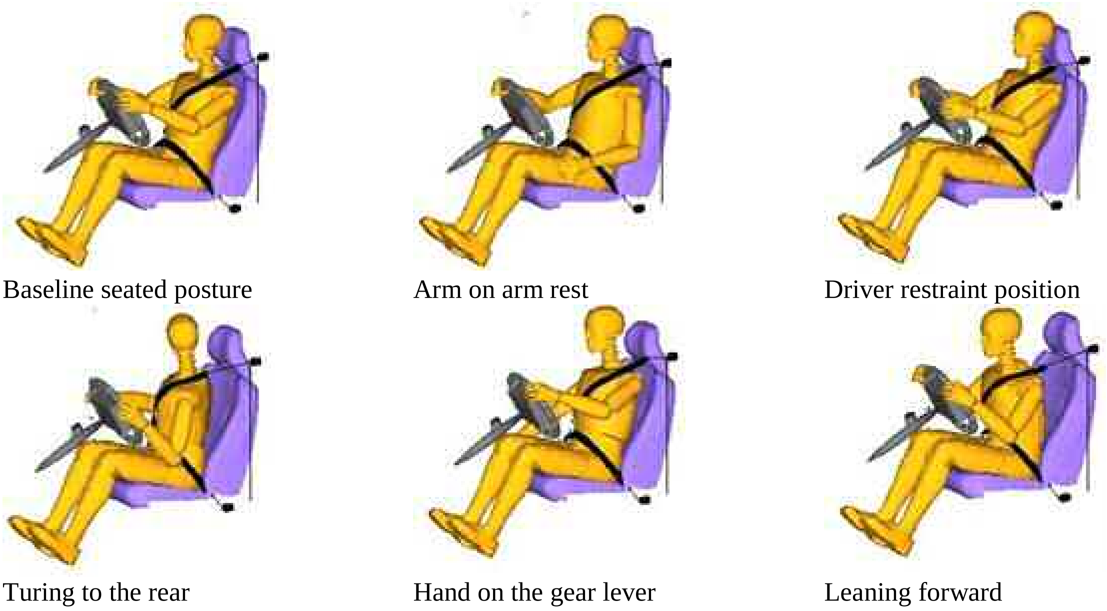
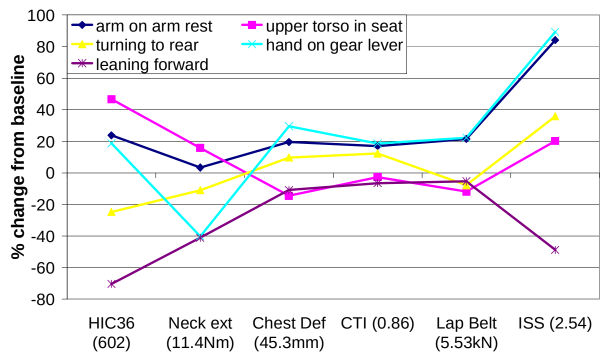


Figure 28. Variations in driver posture reviewed in the parametric investigation of accident variables

For the baseline, arm on arm rest, driver restraint position and hand on gear lever model runs the kinematics of the 50th percentile Hybrid III dummy model were very similar. When turning to the rear, the shoulder of the model is struck by the inflating airbag. This initial contact helps to decelerate the head and leads to a lower predicted HIC compared with the baseline posture, as shown in Figure 29. However, turning the Hybrid III model to the rear introduced initial torques into the spine and neck of the model. Consequently, during the model run the chest and head rotate to assume a posture similar to the baseline. As such, with the exception of the initial occupant response, the general kinematics of the impact when the Hybrid III model is turned to the rear is generally comparable to that of the baseline model run.

When leaning forward, it appears the upper torso and head of the Hybrid III model is abruptly stopped by the inflating airbag. The head excursion of this model is lower than it is for the baseline model run. However, flexing the lumber spine of the Hybrid III model to achieve a leaning forward posture introduces initial torques. These propel the chest and head backwards and away from the inflating airbag at the onset of the simulation. This helps to reduce the load on the head of the model and explains why this model run produces the lowest predictions of injury risk, as shown in Figure 29. The remaining postures provided predictions of overall injury risk as much as 20% above that predicted for the baseline posture.



Baseline = Baseline posture (see Figure 28)

Figure 29. Influence that occupant posture has on predicted injury risk. Values in brackets are baseline predicted responses

Slight alterations in the reclined posture of the 50th percentile Hybrid III dummy model under the EuroNCAP impact conditions resulted in no obvious changes in the kinematics of the occupant model. Reclining the seat by 5° slightly increased the predicted ISS and reclining it by a further 8° slightly reduced the ISS, as shown in Figure 30. Both alterations to the seat back angle increased the predicted HIC response by approximately 10%. However, neck extension reduced with seat back angle and this reduction was considerable when the seat was reclined by 8°. Overall, the change in predicted ISS with seat back angle was within 10% of the baseline response.

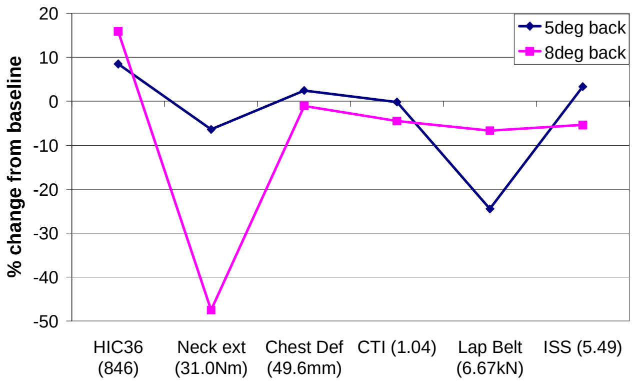


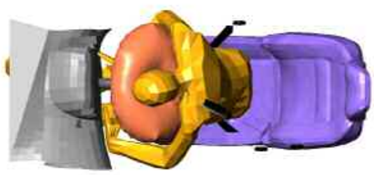
Figure 30. The influence that small alterations in the reclined posture of the 50th percentile Hybrid III dummy model have on occupant predicted injury risk

4.10.5 Results - Reclined large driver

The initial set-up and response of the 95th percentile human body model in the reclined posture is shown in Figure 31. The main points to notice in the initial set-up are that the shoulders of the reclined 95th percentile human body model were behind the upper anchorage. This lead to a poor fit of the diagonal belt across the chest. Similar poor belt fits were observed for reclined front seated passengers in the PRISM '*Passenger Pre-Impact Response Study*' of Morris *et al*, (2005).

0ms

120ms



Top view 120ms

Figure 31. Images from the model run investigating the influence that a reclined posture has on the predicted injury risk of a 95th percentile human body model

Despite the lower seated posture of the reclined 95th percentile human body model, its head struck the roof / header rail during the simulated impact. However, in comparison to the baseline set-up where the head imparted into the header rail (Figure 27) the head of the reclined occupant model was driven upwards into the header rail following submarining of the pelvis into the seat and consequential rotation of the pelvis over the top of the lap belt.

As a consequence of the relatively poor fit of the diagonal belt across the chest of the reclined occupant model, its excursion within the compartment model was greater than that of the baseline 95th percentile human body model. This resulted in the upper part of the abdomen hitting the lower part of the steering wheel, possibly increasing the injury risk to the abdomen. Contact of the abdomen with the steering wheel was also aided by the fact that the airbag was pushed further upward than in the baseline case.

As shown in Figure 32, the predicted HIC, neck extension and lap belt load of the reclined occupant model were over 50% greater than the equivalent injury predicted for the baseline 95th percentile human body model. Overall, the predicted ISS for the reclined human body model was over 30% greater than that for the baseline model. In general, it is implied from these predictions that a larger reclined occupant is at a greater injury risk compared with their upright counterpart.

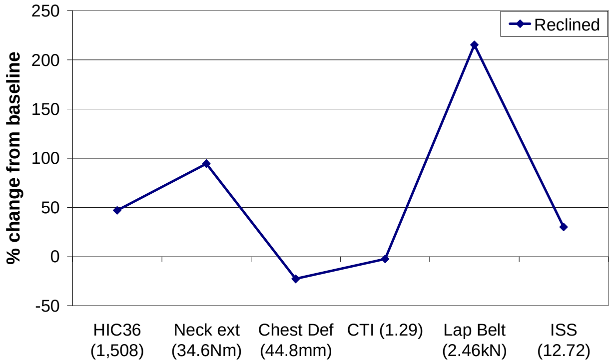


Figure 32. The influence that a reclined posture has on the predicted injury risk for a 95th percentile human body model under EuroNCAP impact conditions. Baseline predictions (in brackets) are for the upright model

4.10.6 Results - Occupant bracing

Occupant bracing was simulated by keeping the arms of the human model rigid and only allowing them to "unlock" when the force exceeded 1kN. The bracing response delayed the forward excursion of the 50th percentile human body model by up to 25ms. Consequently, bracing delayed the contact of the head and chest with the airbag and was the only noticeable difference between the braced and baseline kinematics.

Overall injury predictions from the braced 50th percentile human model were between 5 and 20% greater than those obtained for the baseline 50th model, as shown in Figure 32. Although differences between the model predictions are small, the general trend would appear to be that occupant bracing increases injury risk.

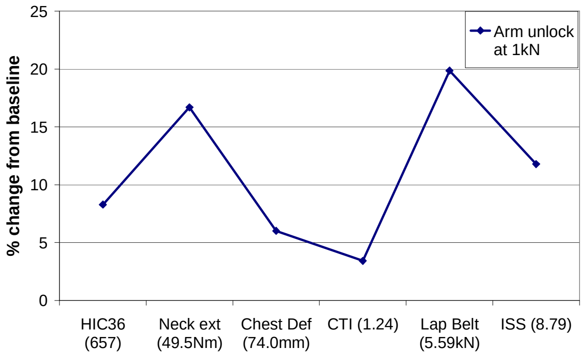
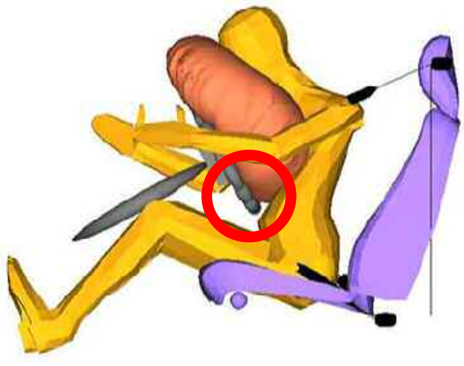


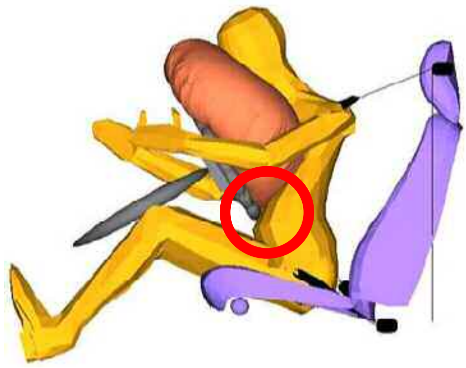
Figure 33. The influence that occupant bracing has on the predicted injury risk of a 50th percentile human body model under EuroNCAP impact conditions. Baseline predictions (in brackets) are for the non-braced model

4.10.7 *Results - Thoracic fracture*

With belt length introduced under loads of 1, 2 and 5kN it was noticeable that there was a greater forward excursion of the human body model, especially at 2kN and 5kN. Because of the greater forward excursion the abdomen of the model struck the lower part of the steering wheel during the runs, as shown in Figure 34. This contact with the steering wheel was caused by the fact that the airbag is displaced further upwards when no belt slack is introduced.



Baseline model

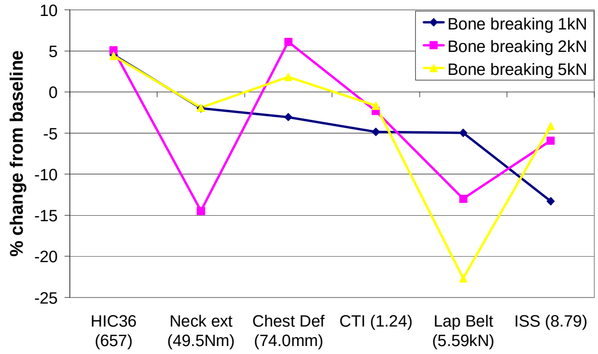


Belt length introduced under 5kN belt load

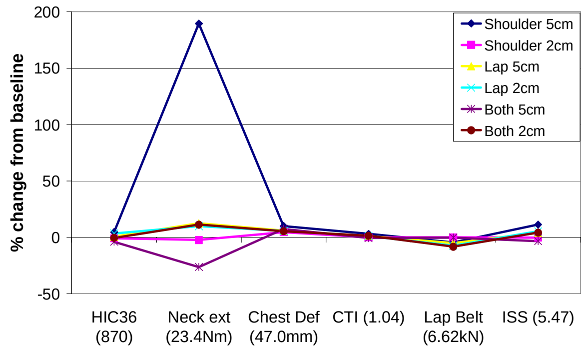
Figure 34. Abdomen strike of the lower part of the steering wheel as belt length is introduced during the model run to simulate thoracic fracture

When belt slack was introduced into the initial set-up of the model there were no obvious differences in the kinematics of the 50th percentile Hybrid III dummy model. It was expected that the initial slack introduced into the belt system was removed by the pre-tensioner when it fired. As such, it is thought that a much greater amount of initial belt slack would need to be introduced to dramatically influence the kinematics of the model. Similar responses and conclusions were made for the model run in which 12cm of belt slack was introduced under a linearly increasing load of 300N.

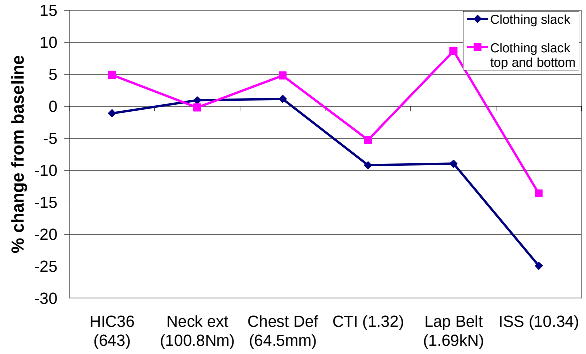
Injury predictions from the model runs are presented in Figure 35. In general it was noticeable that where the human body model has been applied in these model runs the overall predicted injury risk was lower than the baseline response. The use of the 50th percentile Hybrid III dummy model tended to result in an increase of the overall predicted injury risk. There are no clear indications that thoracic fracture increases the injury risk to other body regions.



Belt fuse simulations
Baseline = 50th percentile human model



Belt displacement simulations
Baseline = 50th percentile Hybrid III model



Belt fuse simulations
Baseline = 50th percentile human model

Figure 35. The influence that thoracic fracture / belt slack has on predicted injury risk. The values (in brackets) represent the baseline model predictions

4.10.8 Results - Steering column position

There were no obvious differences in the kinematics of the 50th percentile Hybrid III dummy models for this set of model runs. The chosen alterations in the position of the steering wheel had a limited (<10%) influence on the overall ISS, as shown in Figure 36. However, the alterations in the steering wheel did have a much greater (>20%) influence on the head and neck injury predictions.

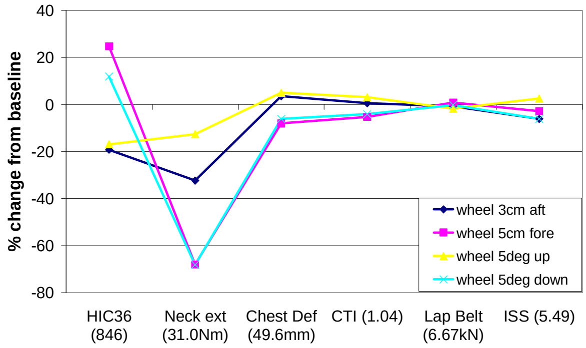


Figure 36. The influence that small alterations in the steering wheel position have on the predicted injury risk of a 50th percentile Hybrid III dummy model under EuroNCAP impact conditions. The values (in brackets) represent the baseline model predictions.

4.10.9 Discussion

It is implied from the model predictions that there are wider circumstances influencing injury risk than those considered in current regulatory and consumer impact tests. The influence that eight variables have on occupant injury risk has been investigated in the parametric model runs, although this is by no means an exhaustive list. Additional factors include the susceptibility of occupants to injury brought on by age or disease, hazards to pregnant women and the unborn child and the broader possibilities of the variables that have already been considered.

In general it was found that the model predictions implied that the severity of the injuries would be low and this presented difficulties in assessing the absolute influence that the accident variables have on occupant injury risk. Therefore, the analysis concentrated on the trends, rather than absolute predictions. From this analysis it is implied that certain variables have a clear influence on occupant injury risk and that in order to improve occupant protection, test procedures need to be extended to accommodate these variables.

Although injury model predictions were generally low, what has not been considered in the work to date is the inter-dependencies that the accident variables have on occupant injury risk, which might yield higher injury risk predictions. For instance, two variables that have a small negative influence on occupant injury risk may have a much larger negative influence if coupled together in the same impact conditions. There is thus further work that could be completed to establish the exact influence that variables have on occupant injury risk.

4.10.9.1 Impact conditions

It is apparent from the parametric investigations that impact conditions can have a considerable influence on the kinematics of an occupant and the internal features of the vehicle that they strike. Regulatory and consumer impact tests are limited to a precisely defined set of impact conditions which may not be representative of the impact conditions under which injuries are occurring. It is felt that test protocols which encourage the use of virtual testing over a greater range of impact conditions would be a possible way forward for addressing this issue.

The difficulty in obtaining impact crash pulses different from standard test protocols limited the investigations. Under these divergent impact conditions there are also uncertainties in the amount of compartment intrusion and the response of the restraint systems, *i.e.* which systems will operate and when. This explains why, under the angled FE crash pulses, model runs were completed with two different fire times for the restraint system due to uncertainties on when the airbag would fire under these impact conditions. To provide precise predictions of injury risk it is important that numerical models are developed with detailed and accurate data. If the future intention is to apply models to investigate a more diverse set of impact conditions, there is a requirement for more information to be gathered through full-scale crash tests and simulations on the dynamic response of the vehicle and the restraint systems.

A noticeable interaction in the model predictions was the increased likelihood of the belt to wrap around the neck of the 50^{th} percentile Hybrid III dummy model during simulated angled impacts. There are obvious doubts as to the influence that this interaction could have on an occupant's injury risk, but potential injuries might include crushing of the trachea or rupture of a carotid artery. Presently accepted neck injury criteria are generally applicable to injuries associated with osseous structures and the spinal column and possibly do not assess the potential for injury to the soft tissues of the neck. This raises potential concerns about the adequacy of the available injury criteria and the dummies, for assessing injury risk under more diverse impact conditions, especially as the dummies are uni-directional test devices. To improve occupant safety it is therefore likely that better test devices need to be developed in order to consider injury risk under a broader set of impact conditions. This needs to be complimented with enhanced injury criteria which will be more able to assess the likely incidence of a greater variety of injuries.

4.10.9.2 Vehicle class

The main points of interest from this set of model runs was the increased likelihood of injuries to the legs of 50th percentile occupants in the smaller classes of vehicles and an overall lower predicted injury risk for occupants in the smaller compartment models. The anticipation at the onset of the work was that injury risks would possibly be greater in the larger midi-MPV vehicles due to them typically experiencing larger crash pulses in tests. It would seem that the model predictions have followed this expectation, but examination of the measured dummy test responses could help clarify if the trends predicted by the models match those that are actually observed.

4.10.9.3 Occupant size (human and dummy model responses)

It was found that the kinematic behaviour and predicted injury risk of human models is very different from those of a 50th percentile Hybrid III dummy model. If this observation is consistent with expected behaviours in real accidents, it emphasises the concern that restraints may be optimised for the responses of dummies and not for humans. This is supported by the fact that predicted injury values for the 50th and 95th percentile human models in this work were in some instances 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 25. In practice and evident from the PRISM '*Photographic Study*' (Bingley *et al*, 2005), smaller female occupants are more likely to lean further forward and therefore increase their injury risk in an impact.

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 diagonal 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 the human body models predict 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 (PMHS) 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.

It is apparent that improvements need to be made with the human models to improve confidence in their application for assessing injury risk in vehicle accidents and this will require more validation of the models responses against a greater variety of PMHS test data. At this stage human body models do not provide adequate replacements for dummies in assessing the injury risk in vehicle environments, but they do provide a complementary tool to provide a more rigorous assessment of injury risk. However, one clear advantage of the human body models is the ability to apply this in all impact conditions. Dummies are generally designed for uni-directional impact conditions which may limit their application if test procedures were to look at a broader range of impact conditions.

With alterations in occupant size, the main differences to note were that the head of the 95th percentile human body model struck the roof / header rail and the delay in head impact with the airbag as occupant size increased. Occupant size would appear to be an important variable to consider in improving occupant safety and developing test procedures that accommodate a wider variety of occupant sizes would be a benefit in this respect.

4.10.9.4 Occupant posture

It was envisaged that postures deviating from regulatory test postures tended to result in higher predictions of occupant injury risk. However, it is uncertain how important this variable is when it is considered in the PRISM "*Photographic study*" (Bingley *et al*, 2005), that the majority of occupants tended to maintain a standard baseline posture. It is possible that most people sustaining injuries in a vehicle accident are in a standard posture or alternatively there exists the likelihood that a higher percentage of those in postures that differ from the test set up are more susceptible to injuries. However, considerable changes in the predicted head and neck injury risk were obtained through slight adjustments in the seat back angle. It is implied from these results that alterations in posture do not have to be too dramatic to provoke considerable changes in occupant injury risk.

A further complication of investigating occupant posture was that initial torques were introduced into the joints of the Hybrid III model when its posture was altered and these had a considerable influence on the injury predictions. It is also expected that greater difficulties might be encountered in modifying the posture of the dummy in order to assess the influence that posture has in physical tests. Torques will be introduced in anatomical joints in order to maintain specific postures but it is uncertain how those generated in the dummy model are representative of anatomical joints. The uni-directional impact nature of the dummy model also brings into question the applicability of applying the dummy for investigating the influence that posture has on occupant injury risk. The main points to take from the investigations of occupant posture are that this would appear to influence occupant injury risk, but it is debatable how significant this is based on the results of the photographic study. Furthermore, the available tools may not be adequate for investigating this variable.

Reclined large driver

It is evident from the model predictions that a change in the posture of a large occupant to a reclined driver posture has a significant influence on increasing occupant injury risk. The main factor influencing this change in injury risk would appear to be the effect this posture has on the initial fit of the belt system across the chest. It is implied that this is an important factor to consider in test procedures as the PRISM "*Photographic study*" (Bingley *et al*, 2005) identified this to be a common posture for large drivers, especially in small vehicles.

Occupant bracing

Based on earlier work in the PRISM project it is evident that drivers aware of an imminent impact demonstrate a common bracing response. However, there is still uncertainty as to the association of this response with actual injuries. Model predictions implied that the trend was for predicted injury risk to increase with occupant bracing though the observed changes were small (<10%). It is possible that the basic modelling approach used to simulate occupant bracing has not provided an adequate representation of the influence that this has on occupant injury risk. For instance the modelled bracing response 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. Further work is needed to clarify the extent to which occupant bracing influences occupant injury risk.

Thoracic fracture

Ideally it would have been more representative to modify the structure of the occupant models used in these model runs to simulate the fracture response of the thorax. However, the approaches adopted of introducing additional belt length either during or at the beginning of the model run provided a quick means of establishing if thoracic fracture could contribute to injuries to other body regions. The main problem identified from this work was that thoracic fracture is likely to increase the forward excursion of the occupant and the potential for the abdomen to strike the lower edge of the steering wheel. This was evident when additional belt length was introduced during the model run.

Introducing slack in the belt system at the beginning of the model run had little influence on predicted injury risk as the initial slack was taken up by the modelled pre-tensioning device. It implied that a greater amount of initial belt slack would need to be introduced into the belt system in order to influence occupant injury risk.

Steering column position

Many cars allow the driver to alter the position of the steering wheel to improve their comfort. Based on the model predictions it is suggested that these alterations can have a considerable influence on the head and neck in an impact and would appear to be an additional variable to consider in test protocols assessing injury risk.

4.10.10 Conclusions - Parametric model runs assessing accident variables to consider in the performance of 'smart' restraint systems

MADYMO compartment models were applied in a series of parametric investigations to assess how eight accident variables influenced occupant injury risk. The main observations from this work for each accident variable investigated are as follows:

Impact conditions

- Impact conditions were found to have a considerable influence on the kinematics and injury risk of occupants and on the internal features of the vehicle that an occupant strikes.
- For impact conditions that cause greater amounts of vehicle rotation and lateral movement there is an increased likelihood of the diagonal belt to wrap around the neck of an occupant with the potential of injury to the soft tissues of the neck. It is questionable that current neck injury criteria are adequately developed for assessing this injury risk.
- Difficulties exist in obtaining crash pulses, vehicle intrusion data and occupant restraint responses under impact conditions different from standard test protocols. Such data needs to be obtained from full-scale crash tests and simulations in order to develop models that can provide accurate predictions of occupant injury risk.

Vehicle class

- It was predicted that the legs are at greater risk of injury in smaller classes of vehicles.
- Overall, the predicted injury risk was lower for the super-mini and small family compartment models compared with the larger midi-MPV compartment model.

Occupant size (human and dummy model responses)

- It was predicted that the heads of larger occupants are at greater risk of impacting the roof / header rail in frontal impacts compared with their smaller counterparts.
- As the size of an occupant increases the delay in head contact with the airbag increases.
- The kinematic responses of human body models are very different from those of dummy models.

- The pelvis of the human body models tended to rotate over rather than under the lap belt experiencing a greater amount of extension in the lumber spine compared with flexion in the lumbar spine and pelvis underride of the belt for the Hybrid III dummy model.
- Human body models were found to have greater flexibility in the spine compared with dummy models, such that the chests of the human body models tended to strike the airbag at an angle. The chest of the 50th percentile Hybrid III dummy model hit the airbag square on.
- During frontal impacts there was an increased likelihood for the shoulder of the human body model to slip out of the diagonal belt.
- Under EuroNCAP impact conditions the 50th and 95th percentile human body models provide predictions of injury risk greater than those of the 50th percentile Hybrid III dummy model.
- Under more angled impact conditions the 50th percentile Hybrid III dummy model provided higher predictions of injury risk. The legs and knees of smaller occupants appear to be at greater risk of injury than their larger counterparts.

<u>Occupant posture</u>

- Postures deviating from regulatory test postures tended to result in higher predictions of occupant injury risk.
- Making dramatic changes to the posture of the Hybrid III dummy model introduces initial torques in the joints of the model which have a considerable influence on predicted injury risk. It is uncertain how representative the initial torques are of those in anatomical joints.
- Hybrid III dummies are specifically designed for assessing injury risks in uni-directional impact conditions. As such it is questionable how representative it is to apply this dummy to assess the influence that occupant posture has on injury risk.

<u>Reclined large driver</u>

- A substantial change in the posture of a large occupant to a reclined driver posture has a considerable influence on increasing occupant injury risk compared with their upright counterpart.
- Even with the lower seated posture of the reclined large occupant it was predicted that the head may still be at serious risk of striking the roof / header rail.
- A large reclined driver has a poor initial fit of the diagonal belt across the chest. This contributes to higher predictions of injury risk, greater predicted forward excursions of the occupant model and an increased likelihood for the abdomen to strike the lower edge of the steering wheel.

<u>Occupant bracing</u>

- Occupant bracing delayed the forward excursion of the occupant within the compartment model.
- It is implied from the trends in the model predictions that bracing in an impact increases the injury risk of an occupant.

<u>Thoracic fracture</u>

- It is suggested from the model predictions that fractures in the thorax may lead to a greater forward excursion of the occupant increasing the likelihood of the abdomen striking the lower edge of the steering wheel.

<u>Steering column position</u>

- Small alterations in the fore and aft movement and inclination of the steering wheel have a considerable influence on the predicted injury risk of the head and chest.

4.11 Parametric model runs assessing the benefits of 'smart' restraint systems in reducing injury risk

In the accident data analysis of the PRISM project, the main injuries to occupants and the anticipated manner in which they had occurred were categorised into ten "injury scenarios" (Table 1)

4.11.1 Adaptation of the restraint system

A series of parametric model runs were completed to determine the reductions in predicted injury risk that could be achieved by adapting chosen parameters of the modelled restraint system for different sizes of occupant model. Details on the parameters varied and the range over which they were varied are presented in Table 6. The baseline values in Table 6 refer to the initial set-up of the modelled restraint system as decided upon by the PRISM consortium.

EuroNCAP impact conditions were simulated in the restraint system adaptation model runs and, since these showed that the occupant responses in all three vehicles were similar, only the midi-MPV compartment model was considered. The influence of adapting the restraint systems on predicted injury risk were assessed for the 5th, 50th and 95th percentile human body models and the 50th percentile Hybrid III model.

Table 6. Adapted parameters and range variations in the restraint system adaptation study

Parameter	Baseline value	Min	Max
Load limiting level (kN)	4.1	2.0	7.0
Pre-tensioning level (kN)	1.5	1.0	4.0
Pre-tensioning firing (ms)	2	10	40
Driver airbag firing (ms)	25	10	40
Driver airbag mass flow rate ($kg.s^{-1}$)	1	0.5	1.5
Passenger airbag firing (ms)	25	10	40
Passenger airbag venting	2.143	1.0715	3.2145
Passenger airbag permeability	0.042	0.021	0.084

A predicted form of the Injury Severity Score (ISS) was obtained from each model run and used to assess if adaptations to the set-up of the restraint system reduced the overall predicted injury risk. The approach for obtaining predicted ISS values involved the following steps:

1 - Obtain predicted injury values

For the 200 model runs predicted values of HIC_{36}, Neck loading (Nij), Chest deflection, Combined Thoracic Injury (CTI) criterion, the knee joint forces for the human body models and the femur forces for the Hybrid III dummy model were obtained. A femur load cell is not available in the human models and therefore knee force was used to assess predicted injury risk in the legs of these occupant models.

2 - Evaluation of AIS values

The predicted injury values were compared against injury risk curves available on the US NHTSA website (http://www.nhtsa.dot.gov/cars/rules/rulings/AAirBagSNPRM/PEA/pea-III.n.html) to obtain Abbreviated Injury Score (AIS) probabilities. As examples, Figure 37 and Figure 38 show the injury risk curves to convert CTI and HIC values respectively into AIS probabilities. Similar curves are available to convert the other predicted injury values obtained from the occupant models into AIS probabilities.

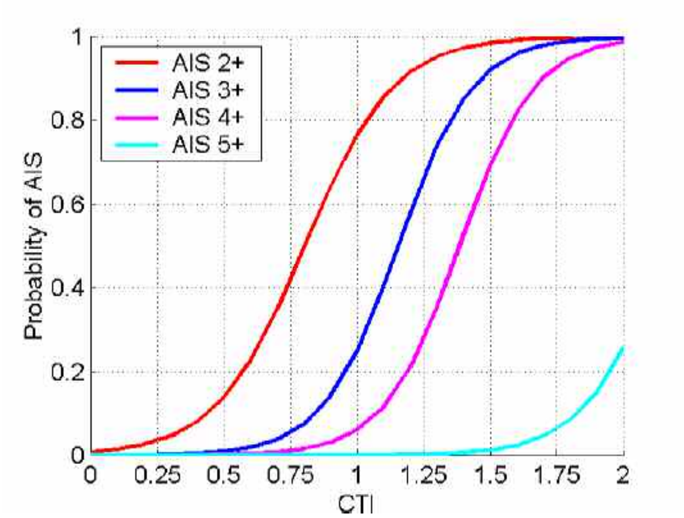


Figure 37. Injury risk function for CTI

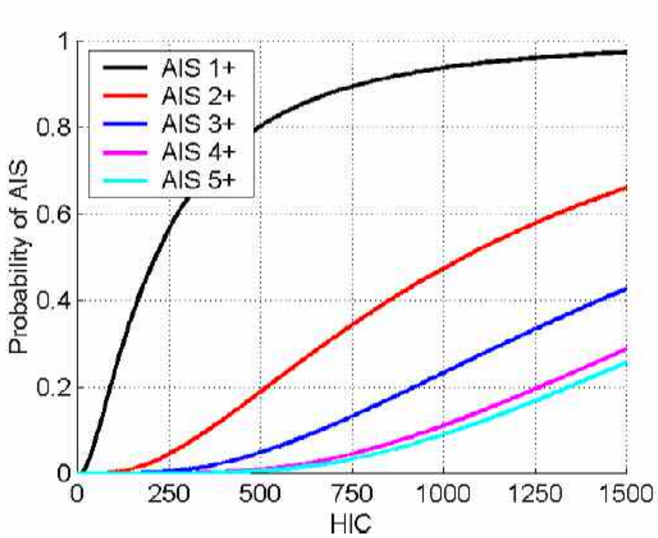


Figure 38. Injury risk function for HIC

The curves, which are more generally known as the injury risk functions, have been proposed by various researchers on the basis of experimental data and historical research (Eppinger *et al*, 1998). The experiments forming the basis of the functions were performed within the regulatory range of interest up to critical values. For higher injury values the plotted approximations are therefore more heuristic. Mathematical expressions of the curves were used to calculate a vector of probabilities (AIS=0,1,2,3,4,5,6) by subtracting each AIS probability at the predicted injury value from the next AIS probability (Kuchar *et al*, 2001). For each injury type a vector of AIS probabilities is computed which is converted into an expected AIS value according to

$$E(X) = \sum_{i=1}^{6} w_i P_{wi}(X)$$

where: X= Injury value
E= Expected AIS value
P_{wi}= Probability of AIS level w_i
w_i= AIS level 0,1,2,3,4,5,6

The expected AIS values for each injury mechanism may be converted into an overall body criterion using normalized cost functions to obtain communal costs (HARM) or using the Injury Severity Scale (ISS) (Wismans *et al*, 1994).

3 - Evaluation of ISS

A reduced form of the ISS was then calculated for each model run based on the estimated AIS scores. The estimated ISS value from each model run was then compared and the lowest were considered to correspond to the best performing restraint systems, within the variations performed in the current study.

It should be noted that the use of ISS in this approach may obscure results because the overall injury is considered rather than specific injuries or body regions. However, when the effect of improvements to a restraint system is considered, this is best achieved by assessing the overall injury.

4.12 Results – Restraint system adaptation study

A comprehensive analysis of the influence and sensitivities that changes in the restraint system parameters had on the predicted injury risk is contained in Appendix D of the EC report R6/R7. This covers the possible analysis that might be taken by a restraint system developer to understand the important parameters of the restraint system that should be altered in order to reduce an occupant's injury risk.

The main intentions of the restraint system adaptation study were to establish the possible benefits and reductions in occupant injury risk that might be achieved by adapting (making 'smart' alterations) the set-up of the restraint system to the size of the occupant. With this intention in mind the predictions from the model runs were analysed to establish the model run with each occupant model that provided the lowest overall predictions of ISS. The set-up of the restraint system in these model runs could be considered to be the best adapted restraint system for each occupant model.

Figure 39 compares the predicted injury risk for each occupant model when fitted with the baseline and best adapted restraint system for each occupant model. As is shown in these results the adapted restraint systems have brought about a reduction in predicted ISS for all the occupant models. Considerable reductions in overall predicted ISS were obtained for the 95th percentile human body model driver and passenger and the 50th percentile human body model passenger. Table 7 and Table 8. detail the changes made to the set-up of the baseline restraint system for each occupant model to achieve the reductions in predicted ISS as presented in Figure 39

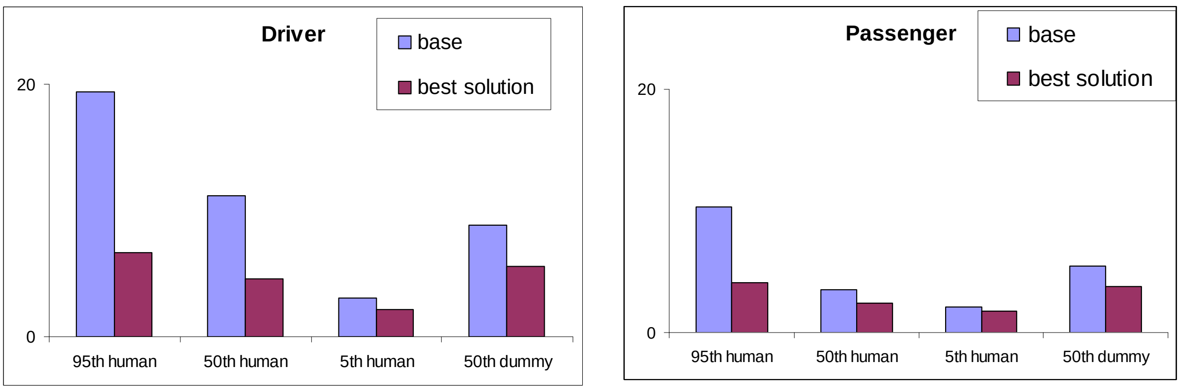


Figure 39. Comparison of the overall ISS predicted for the baseline (base) and best adapted (best solution) restraint system for each occupant model

Table 7. Set-up of the baseline and best adapted restraint system for each occupant driver model

Parameter	Baseline	50th Hybrid III	5th human body	50th human body	95th human body
Load limiting level (kN)	4.1	6.85	5.75	3.15	5.55
Pre-tensioning level (kN)	1.5	3.67	1.03	1.15	2.23
Pre-tensioning fire time (ms)	2.0	19.3	18.7	20.5	27.7
Airbag fire time (ms)	25	33.1	22.3	35.5	39.7
Change in airbag mass flow rate	1	1.37	1.33	1.31	1.45

Table 8. Set-up of the baseline and best adapted restraint system for each occupant passenger model

Parameter	Baseline	50th Hybrid III	5th human body	50th human body	95th human body
Load limiting level	4.1	5.25	5.25	3.25	4.45
Pre-tensioning level (kN)	1.5	2.35	2.35	2.89	3.07
Pre-tensioning fire time (ms)	2	25.9	25.9	37.3	24.7
Airbag permeability	0.042	0.062	0.062	0.051	0.043
Airbag fire time (ms)	25	22.3	22.3	39.7	38.5
Airbag venting	2.143	1.14	1.14	2.21	2.51

4.13 Results: How 'smart' restraints can mitigate the identified injuries

4.13.1 Adaptation of the restraint system

The performance of the adapted restraint system was then compared with the baseline system for each of the ten injury scenarios identified from an analysis of the accident data (Table 4). The following sections describe the results for each of these injury scenarios in the context of how 'smart' restraint systems might be developed to mitigate these injuries.

4.13.2 Small driver out-of-position (OOP)

The PRISM compartment models were primarily developed to perform trend studies and extensive parameter variations. To save CPU time relatively simple airbag models were included in the models which were not capable of accurately representing the interaction between a deploying airbag and an occupant. One of the main limitations of these airbag models is that they did not simulate self contact, *i.e.* the contact that occurs between the fabric of the airbag as it unfolds. This presented problems in accurately predicting the injury risks to out-of-position small drivers. However, additional model runs comparing the responses of an OOP 5th percentile Hybrid III dummy model with and without airbag self-contact were completed to demonstrate the influence that airbag self contact has on the injury predictions. The initial position of the occupant model in these model runs is given in Figure 40.

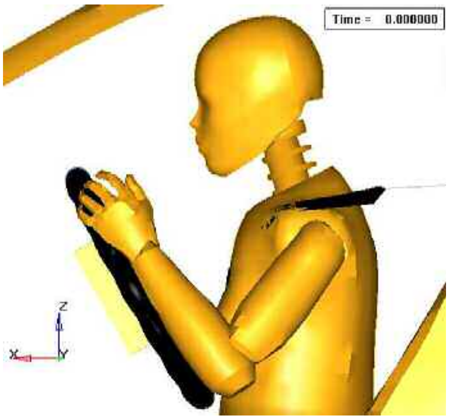
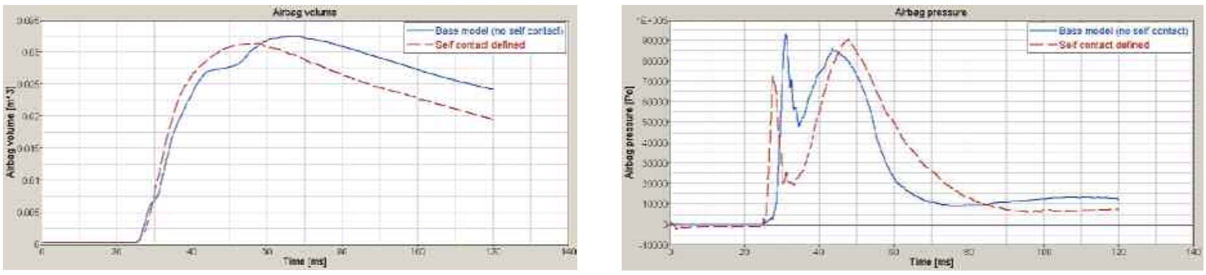


Figure 40. The initial position of the 5th percentile Hybrid III dummy model in the OOP model runs assessing the modelled airbag's performance

It was found that the model run with airbag self contact took four times longer than the model run with no airbag self contact. The predicted airbag volume and pressure for both model runs is given in Figure 41. Because of the early interaction between occupant and airbag, the airbag does not reach its final volume of 55 litres in either case.

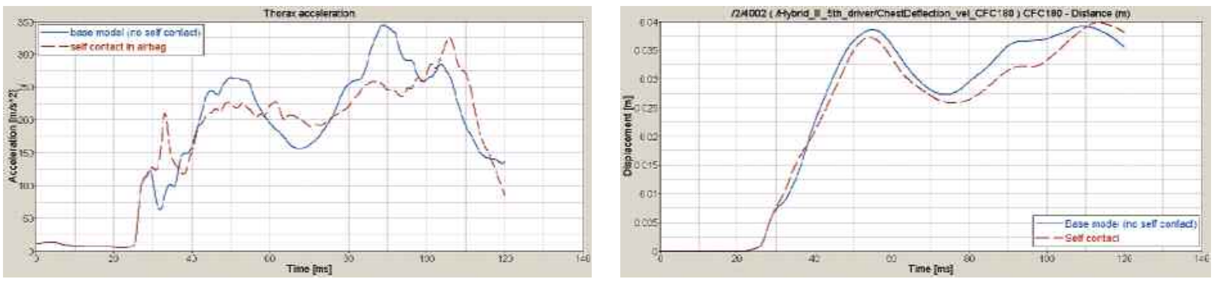


Airbag volume

Airbag pressure

Figure 41. The influence that airbag self contact has on airbag volume and pressure against time (ms). Blue line = no self contact, red line = with self contact

Predicted thorax acceleration and chest compression for both model runs are given in Figure 42. The loading of the thorax is similar in both model runs.

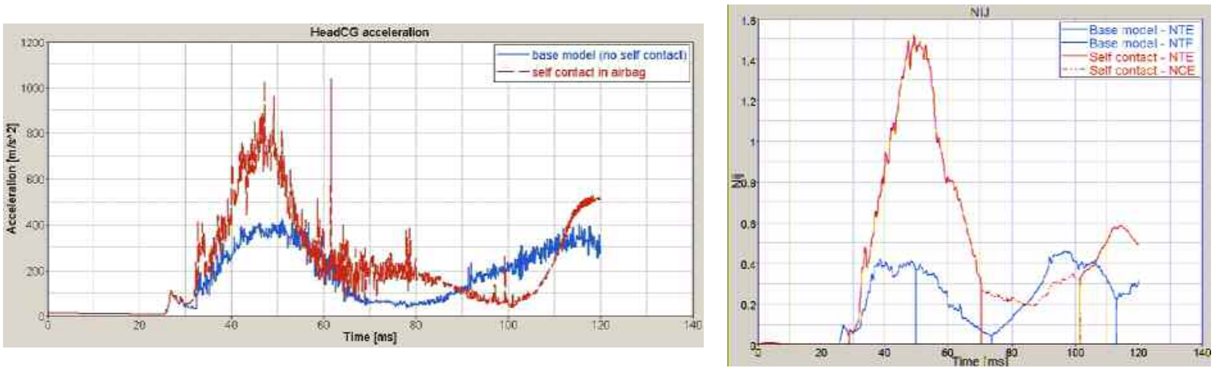


Thorax acceleration

Chest compression

Figure 42. The influence that airbag self contact has on predicted thorax acceleration and chest compression against time (ms). Blue line -= no self contact, red line = with self contact

The head acceleration and the neck loading (Nij) are given in Figure 43. For the airbag self contact model run, the dummy head acceleration and the neck loading are considerably higher. The “punch out” effect, introducing the higher head / neck loading (starting at t = 26 ms), is more obvious for the model run with airbag self contact.



Head acceleration | Neck loading: Nij

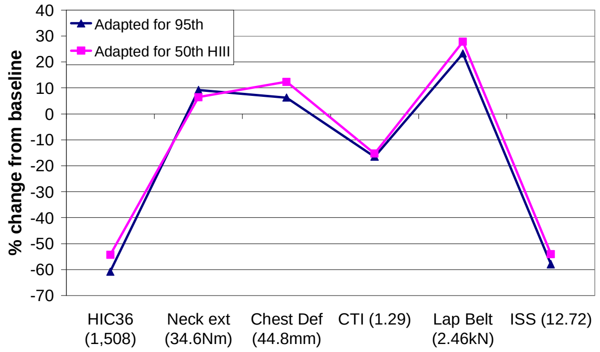
Figure 43. The influence that airbag self contact has on the predicted head acceleration and neck loading (Nij) against time (ms). Blue line = no self contact, red line = with self contact

The main differences observed in the simulations described above are in head / neck loading, and not in chest acceleration or chest deflection. Since the head / neck body region might be critically loaded in OOP scenarios it is determined from the model runs that detailed airbag models are required to investigate the injury risks to occupants in OOP impacts.

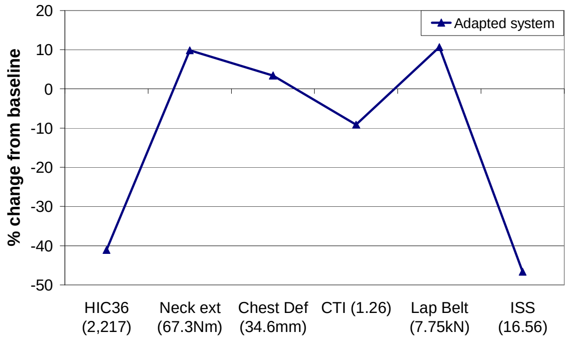
4.13.3 Injuries to large drivers

Model predictions compared in this part of the investigation looked at how adapting the restraint system under EuroNCAP impact conditions influenced the injury risk of the 95th percentile human body model both in an upright and reclined posture. An additional model run was also completed in which the 95th percentile human body model was fitted with the restraint system adapted for the 50th percentile Hybrid III dummy model. It was rationalised in this part of the investigation that restraint system designs are currently being optimised to the responses of Hybrid III dummies and the additional model run was completed to assess if the restraint system adapted for the 50th Hybrid III dummy model would benefit the 95th percentile human body model. Further comparisons were made to see if the adaptation of the restraint system for EuroNCAP conditions benefited the 95th percentile human body model under the FE vehicle 1 impact conditions (Figure 20), with an airbag fire time of 25ms.

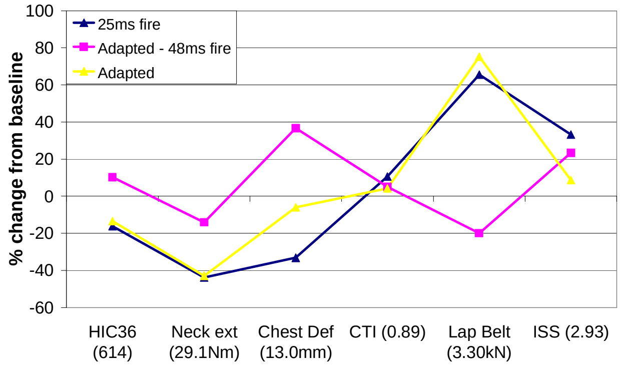
Figure 44 shows the influence that an adapted restraint system had on the predicted injury risk of the 95th percentile human model for the impact conditions discussed above. When the restraint system is adapted for a 95th percentile human model or a 50th percentile Hybrid III dummy model there are considerable reductions (<50%) in the overall predicted injury risk for the 95th percentile human model. Slightly greater reductions in overall predicted injury risk are obtained when the restraint system is adapted specifically to the responses of the 95th percentile human body model. The greatest reductions in predicted injury risk are obtained for the head, with reductions in HIC being greater than 50%. This was due to the adapted restraint system preventing the head of the model from striking the roof/header rail.



EuroNCAP



EuroNCAP – reclined occupant model



FE vehicle 1 impact (Figure 20)

Figure 44. The influence of an adapted restraint system on the predicted injury responses of the 95th percentile human body model

The adapted system for the upright 95th percentile human body model provides additional protection for a reclined 95th percentile occupant model. When the restraint is adapted reductions in overall ISS predicted injury risk are greater than 45 %. HIC is reduced by 40% from 2217 to 1330. Changes in the other model predictions for this model run are less than 10%. Following these results an additional model run was completed in which the upper belt anchorage was attached to the back of the seat rather than to the B-pillar in order to promote a better fit of the diagonal belt over the chest. The difference in the set up of this model run can be seen in Figure 45. Even with the belt system not adapted the reattachment of the diagonal belt led to reductions in predicted HIC of over 58 % from an original prediction of 2217 and an almost 20% reduction in the overall predicted ISS value. The main benefit of this passive alteration to the restraint system is that the head of the 95th percentile human body model is prevented from striking the roof/header rail during the simulated impact.

Upper belt anchorage on B-pillar		Upper belt anchorage on seat

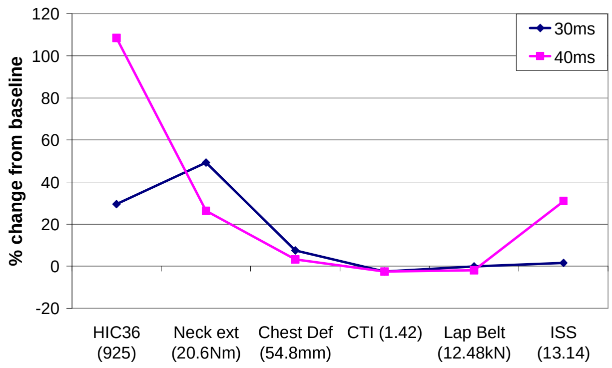
Figure 45. Difference in the fit of the diagonal belt system when it is attached to the B-pillar and to the seat for a reclined large occupant

Under the FE vehicle 1 impact conditions (see Figure 20) there appears to be no obvious benefit of using the EuroNCAP adapted restraint system, but the result appears to be dependent on when the airbag would fire under these impact conditions. With an airbag fire time of 48ms (Baseline response) the adapted restraint system appears to increase the overall ISS predicted injury risk by 23%. In contrast with an airbag fire time of 25ms the predicted ISS is reduced by approximately 20% when the adapted restraint system is used.

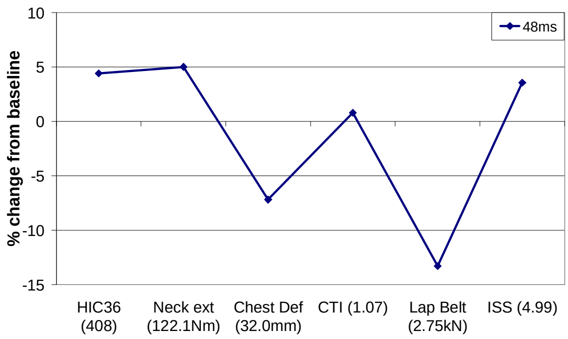
4.13.4 Late deploying airbag

For the USNCAP impact conditions it was noticed that the delay in the powering of the airbag lead to a greater forward excursion of the occupant model. Past an inflation time of 30ms the abdomen of the 50^{th} percentile Hybrid III occupant model strikes the steering wheel. With inflation times greater than 40ms the airbag model would not be sufficiently inflated to provide adequate predictions of injury risk. The anticipation is that with an inflation time greater than 40ms the occupant model would experience serious head and neck injuries through the interaction of the head with the inflating airbag or through head contact with the steering wheel. Injury predictions for the USNCAP model runs show that the delay in airbag firing increases the predicted head and neck injury values, as shown in Figure 46. However the overall ISS injury risk prediction is only increased considerably when the airbag fire time is set at 40ms.

Under the 45° FE impact, the kinematics are not greatly influenced by the time at which the airbag fires as the head of the model strikes the door glazing prior to striking the fully inflated airbag. It is anticipated that problems with the inflation of the airbag under these impact conditions would only arise if the inflation time was around 90ms to 100ms, which would allow the head to be close enough to the steering wheel to be impacted by the inflating airbag.



50th Hybrid III, USNCAP impact conditions
Baseline = 25ms airbag fire time



50th human body model – FE vehicle 1 impact (Figure 20)
Baseline = 25ms airbag fire time

Figure 46. The influence that airbag fire time has on predicted occupant injury risk. The Baseline predictions are (in brackets).

4.13.5 Occupant misses airbag

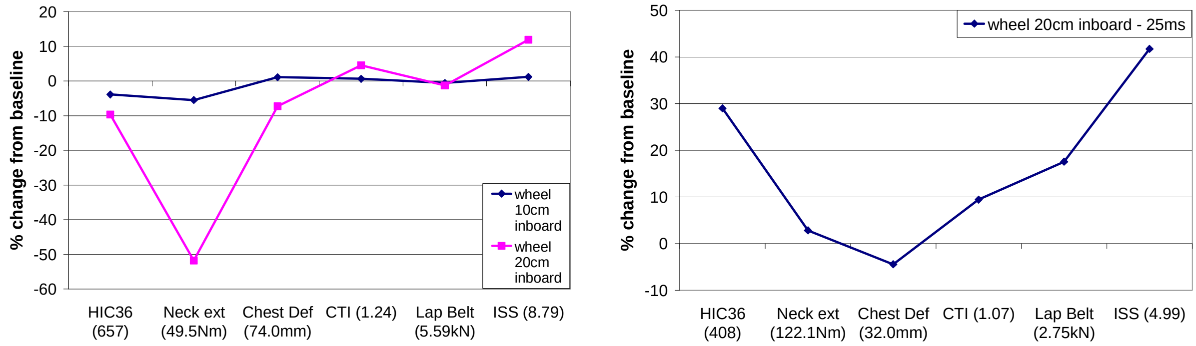
It was anticipated that this injury mechanism could be caused by the displacement of the airbag during the impact, or a result of the impact conditions causing the kinematics of the occupant to miss the airbag (or a combination of both). In this part of the investigation, model runs, in which the steering wheel position was initially moved in-board by 10cm and 20cm respectively, were completed. Furthermore, the FE angled impact conditions (Figure 20) introduced a large amount of vehicle rotation in the impact which would cause the occupant model to miss the airbag. Consequently, additional model runs were completed investigating how the combined rotational motion of the vehicle and the inboard translation of the steering wheel influence the potential for the occupant to miss the airbag and the associated predicted occupant injury risk.

Figure 47 shows the differences in the head interaction with the airbag when the steering wheel position is translated in-board for the EuroNCAP impact conditions. As the steering wheel is moved in-board, the head impacts further away from the centre of the airbag. In the instance where the steering wheel is translated 20cm in-board, the head has the greatest forward excursion. This increases the likelihood of the head striking intruding features of the compartment. However, as shown in Figure 48 the predictions of HIC and overall injury risk were all within 10% of each other for the EuroNCAP impact conditions. It is suggested from the injury predictions that movement of the steering wheel inboard for the EuroNCAP impact conditions results in lower neck injury predictions. This was reduced by up to 50% when the steering wheel was moved 20 cm inboard.

For the 45° FE vehicle impact, the inboard translation of the steering wheel results in the head of the 50th percentile human body model completely missing the airbag. In contrast when the steering wheel is not translated the head has a glancing blow with the airbag. Inboard movement of the steering wheel in this model run led to considerable increases in the overall predicted injury risk. Predicted ISS was at least 40% above the baseline response and HIC was 30% above the baseline response.

Baseline response | Steering wheel moved 10cm inboard | Steering wheel moved 20cm inboard

Figure 47. Difference in the head impact with the airbag as the steering wheel is translated inboard



EuroNCAP
Airbag fire time = 25ms

45° FE vehicle 1 (Figure 20)
Airbag fire time = 25ms

Figure 48. Predicted responses showing how movements in the steering wheel position influence occupant injury risk. Figures in brackets are the values from the baseline EuroNCAP simulation.

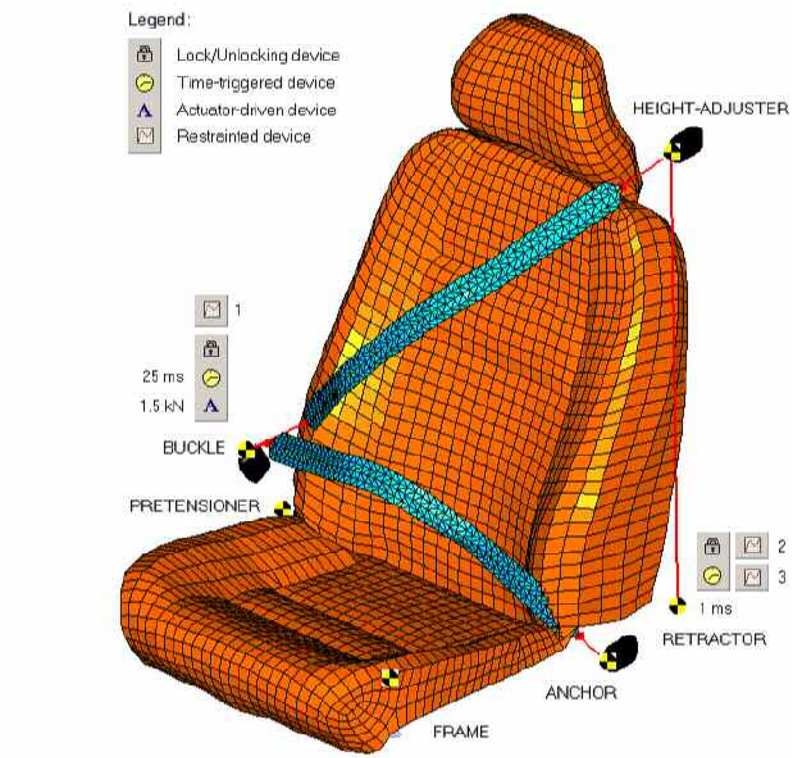
4.13.6 Airbag "bottoming out"

In the parametric investigations of accident variables (Section 4.9.1) it was noticed that, under certain circumstances, the abdomen or lower thorax of the occupant models struck the lower edge of the steering wheel. This could be considered to be consistent with the air bag "bottoming out". Instances of where this occurred in the model predictions were as follows:

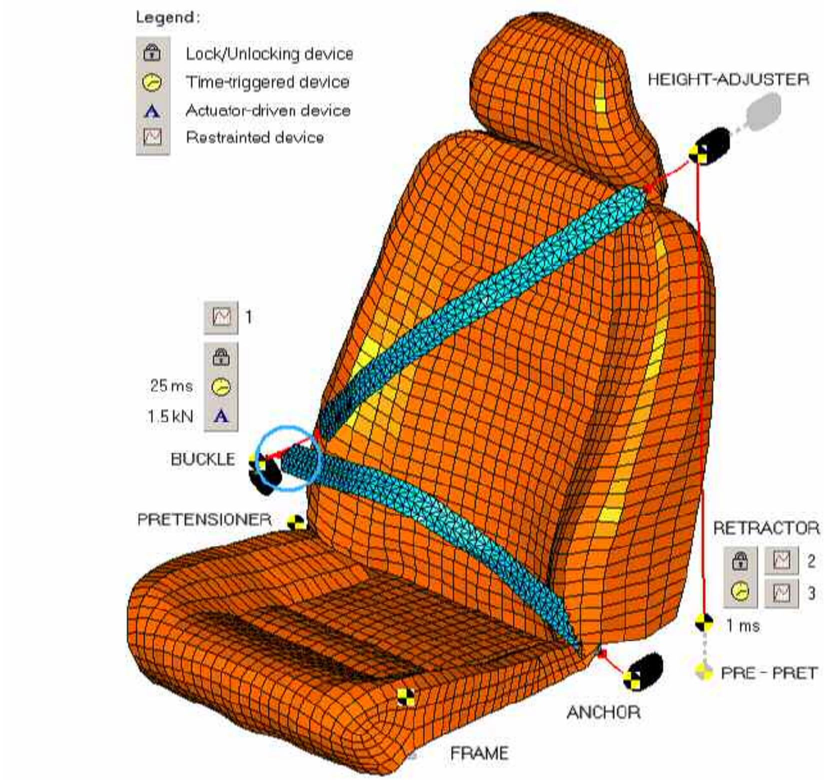
- When additional belt slack was introduced into the belt system under loads of 2kN and 5kN in order to represent thoracic fracture.
- For the reclined 95th percentile human body model under EuroNCAP impact conditions
- For delayed airbag firing (>15ms) or no airbag firing in the case of the Hybrid III 50th percentile model in USNCAP impact conditions
- 5th percentile human body models under USNCAP impact conditions in the Super-mini and midi-MPV compartment models

In all these instances the contact with the steering wheel was due to the airbag being displaced upward or not being deployed sufficiently to prevent the occupant model from striking the lower part of the steering wheel. It was noticed for the reclined large occupant investigations (as detailed above) that adapting the restraint system prevented the abdomen from striking the steering wheel. Furthermore, this was also found to be the case if the upper anchorage for the belt was moved from the B-Pillar to the seat (Figure 45). It is implied from these predictions that adaptations can be made to the restraint system to prevent the bag from bottoming out.

In addition to these observations of the previous model runs and adaptation studies, further model runs were completed investigating the influence that a pre-pre-tensioning system might have on limiting the risk of the bag bottoming out for large occupants during an impact. From the accident analysis it was concluded that this occurs mainly with a large, heavy occupant and, in order to reduce the injury risk in this scenario, the added value of a pre-pre-tensioning device was investigated utilising the midi-MPV compartment model. The driver airbag was altered until a hard contact between the occupant and steering wheel was obtained as a result of the bottoming out of the airbag. This was achieved by scaling the original mass flow rate of the airbag by a factor of 0.6 and the contact between the occupant and windshield was removed. A 95^{th} percentile human body model was positioned in the seat in the most rearward position and, in order to install a pre-pre-tensioning device in the vehicle model, a number of alterations were made to the original primary restraint system, as shown in Figure 49.



Original restraint system.



Restraint system augmented with Pre-pre-tensioning system.

Figure 49. Alterations made to the restraint system for the pre-pre-tensioning study for large driver occupant

For both the driver and passenger, a pre-pre-tensioning body with a small mass (0.1 kg) was included. A translational pre-pre-tensioning joint was placed between the retractor joint and the attachment-to-the-vehicle joint and the bracket retractor joint was changed into a translational joint. 5cm of joint motion was prescribed to the pre-pre-tensioning joint, 25ms prior to the start of the simulated impact, resulting in belt forces of approximately 2.5kN at the retractor and 1.5kN at the shoulder belt. This level was chosen to be less than the retractor level, but similar to maximum pretension levels.

Some additional alterations were performed to make the system work properly. To prevent belt collapse the FE lap belt is slightly shortened at the buckle side, such that the FE part is not pulled through the buckle and aborts the simulation; see the blue circle in Figure 49. Furthermore, the buckle pre-tensioner joint was locked to prevent strong rotation of the buckle pre-tensioner.

Finally, it was noted that the fit of the belt system for the 95^{th} percentile human body model for both the driver and passenger was not optimal due to the fore-aft position of the height-adjuster with respect to a 95^{th} percentile occupant. To investigate the effect of moving the height-adjuster backwards, simulations have been performed both with and without a pre-pre-tensioning system, with different height-adjustment and fore-aft positions.

The measured belt forces are shown in Figure 50. Five different phases can be discerned. During the so-called pre-crash phase (phase I) the pre-pre-tensioning system, if included, is active. At time t = 0, the actual crash starts and phase II commences. 25ms after the start of the crash, the airbags and the buckle-pre-tensioner are fired (start of phase III). During phase III, belt forces are increasing in the retractor belt until a certain threshold (4.1kN) is reached, where the load limiter becomes active (phase IV). At a certain point in time, the belt forces reduce and the crash phase ends (phase V).

Even though some small changes in the belt loads are induced, it can be seen that, in general, the belt loads are very similar with the inclusion of the pre-pre-tensioning system. Evidently, during the pre-crash and initial crash phase (phases I and II) the loading of the belt is different, due to the firing of the pre-pre-tensioning system. The influence of firing the buckle pre-tensioner is clearly visible in both cases, but the effect is smoother in the case with pre-pre-tensioning. This holds true particularly for the buckle belt and anchor belt loads.

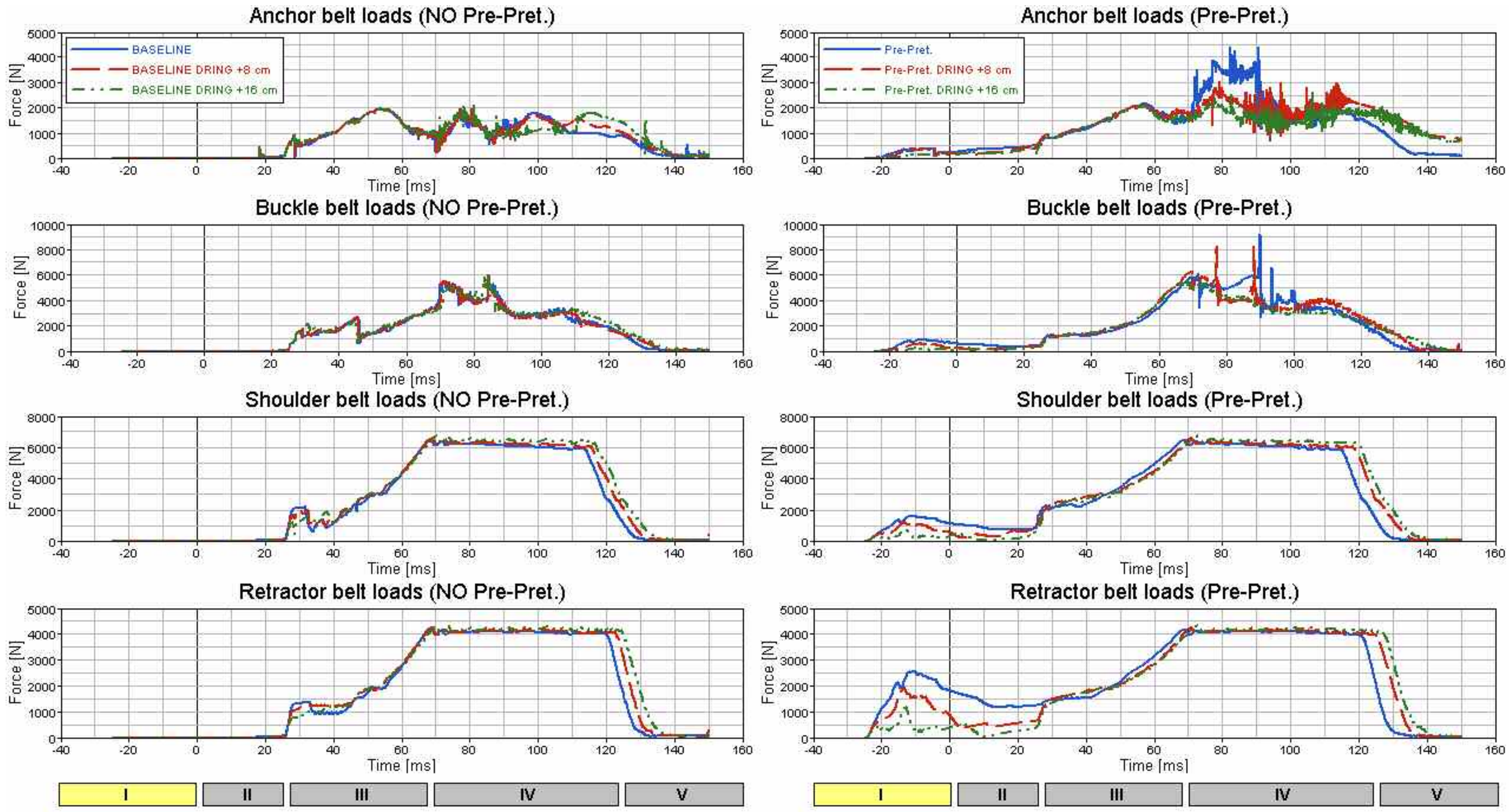


Figure 50. Belt forces of the anchor belt (top), buckle belt (mid-top), shoulder belt (mid-bottom) and retractor belt (bottom) for the scenarios without(left) and with (right) pre-pre-tensioning. The yellow bar indicates pre-crash phase, the grey bars several stages in the crash phase.

In Figure 51 the acceleration of the head, the chest and the pelvis are shown. Underneath the graphs a bar with the five different phases has been placed in order to be able to correlate the peaks with a certain stage during the crash. The pelvis and chest acceleration signals both look comparable during all runs. Also the effect of firing the buckle pre-tensioner is seen more clearly from the chest and pelvis signals in the case without the pre-pre-tensioning system. For the head acceleration it can be seen that there is almost no difference between the cases with and without pre-pre-tensioning. This is a direct result of the non-optimal fore-aft position of the height adjuster, which is positioned in the B-pillar and is therefore fixed in respect of its fore-aft positioning. The 95th percentile human body model is positioned with its shoulder inline with the B-pillar and, consequently, the belt does not fit well across the shoulders. As such, the pre-pre-tensioning system will only increase the tension in the belt, instead of pulling the human model into the seat. Relocating the height-adjuster to just behind the shoulder line (80mm rearwards) lowered the maximum head acceleration. This was comparable with pre-pre-tensioning. By relocating the height-adjuster 160mm rearwards, in both cases, the maximum head acceleration was considerably lowered.

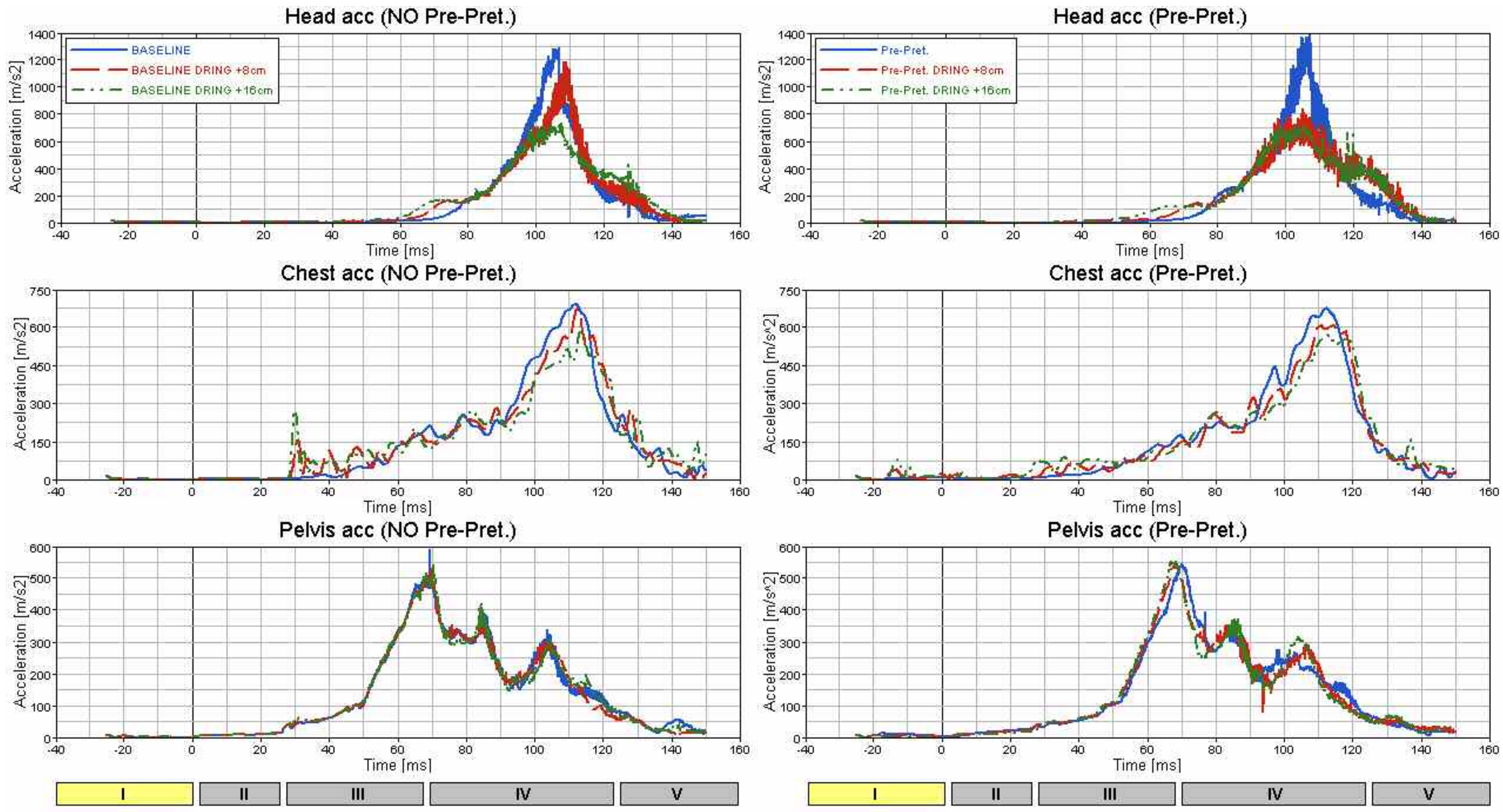


Figure 51. Accelerations of the head (top), chest (mid) and pelvis (bottom) for the scenarios without (left) and with (right) pre-pre-tensioning. The yellow bar indicates pre-crash phase, the grey bars several stages in the crash phase.

Instances where the airbag bottoms out occur mainly with larger, heavy occupants. In order to reduce the injury risk in this scenario, the added value of a pre-pre-tensioning device was investigated. Two conclusions can be drawn:

- The alignment of the belt system is very important for larger occupants and those that are in the rearmost seating position. The position of the height adjuster or D-Ring in respect to the shoulder line of the occupant plays an important role in restraining the occupant properly during forward motion.
- The effectiveness of a pre-pre-tensioning device depends heavily on the alignment of the belt system and, when this is correct, the slack can be effectively removed. Whilst chest and pelvis accelerations only change marginally, the maximum head acceleration is significantly lowered.

4.13.7 Steering wheel edge strike

One of the anticipated mechanisms responsible for this accident scenario was a large change in the inclination of the steering wheel during the impact. Small alterations in the inclination of the steering wheel were investigated in the parametric investigations of accident variables, but these did not result in any dramatic strikes by the occupant models on the edge of the steering wheel and also had a limited influence on predicted injury risk.

4.13.8 Header rail strike

In the parametric investigations of accident variables it was observed that header rail strikes only occurred in model runs with the 95th percentile human body model under EuroNCAP impact conditions. The head of this model also struck the header rail when in a reclined posture under EuroNCAP impact conditions. In each of these instances it was noticed that adapting the restraint system, as investigated above (Figure 44), prevented the head of the model from striking the header rail, reducing the predicted HIC from 1,508 to 603 for the standard EuroNCAP impact conditions and from 2,217 to 1,330 when in a reclined posture for the EuroNCAP impact conditions.

As detailed in the investigation above, a further model run showed that attaching the upper anchorage of the belt system to the seat rather than to the B-pillar also prevented the head of the 95th percentile human body model from striking the header rail, reducing the predicted HIC by 58% from 2217 to 932.

4.13.9 Chest injury

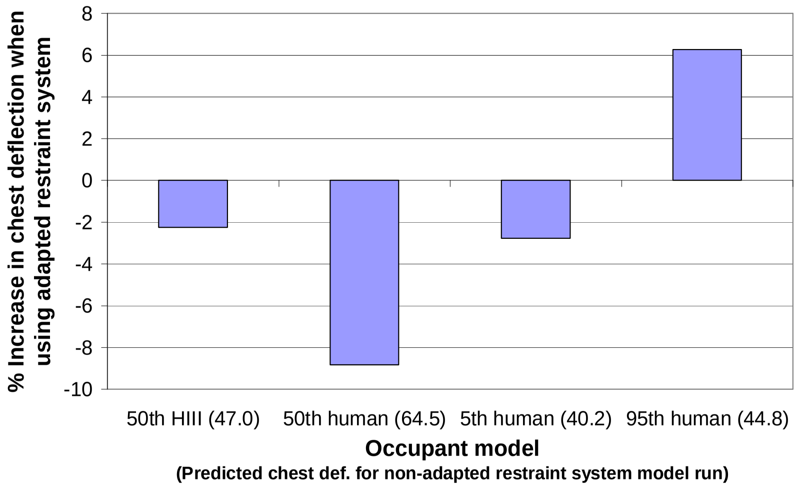
Chest injury predictions from previous comparable model runs, with and without adapted restraint systems (Table 7) were compared. The restraint system was adapted for each specific occupant model under EuroNCAP impact conditions. The intention of the comparison was to consider how adapting the restraint system influenced predicted chest injury risk and to assess if the adaptation of the restraint system under EuroNCAP impact conditions provided additional benefits in reducing chest injury risk under the FE vehicle 1 impact conditions (Figure 20) with an airbag fire time of 25ms.

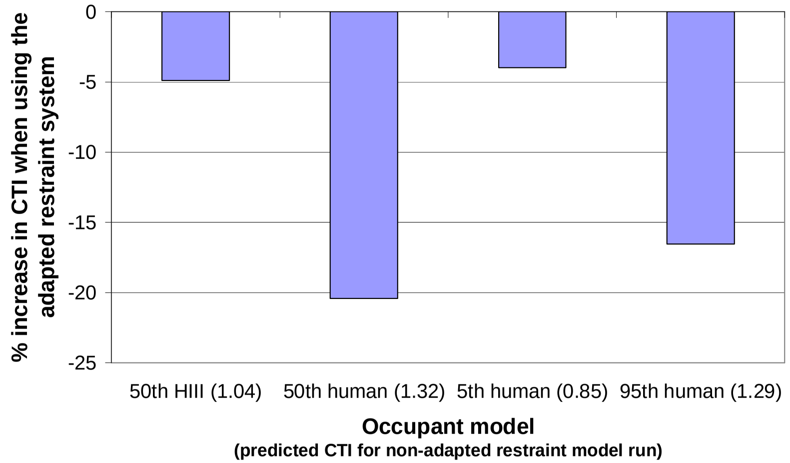
The results from these comparisons are presented in Figure 52.. For the EuroNCAP impact conditions it is noticeable that the influence the adapted restraint system has on the predicted chest deflections of the various occupant models is less than 10%. The adapted restraint system had a much greater influence on the predicted CTI, especially for the 50th and 95th percentile human body models where reductions greater than 15 % were achieved.

Under the FE impact conditions, use of the adapted restraint system had a limited influence on the predicted CTI for the 50th and 95th percentile human body models. The chest deflection for the 95th percentile model was increased by 40%, but, as shown in figure 52, this was only 8.7mm with the non-adapted restraint system under these impact conditions. Further comparisons, similar to those presented in Figure 52., were performed but differences were found to be less than 10% between the predictions from model runs with and without the adapted restraint systems. These comparisons included model runs in which the 95th percentile human body model was reclined and model runs with two sizes of the human body model under the 45° FE vehicle 1 impact with the airbag fire time set at 48ms.

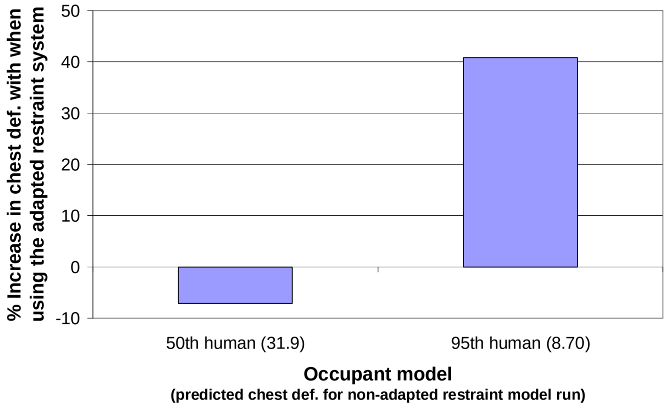
In addition to the predictions reviewed above, additional model runs were completed specifically for this part of the investigation to establish if increasing the belt width in the model could be used to reduce predicted chest injury risk. This could not be considered to be a 'smart' alteration of the restraint system, but was anticipated to be a passive and more straightforward alteration that could be made to the set-up of the restraint system in order to reduce chest injury risk. Increases of 25% and 50% were made to the width of the belt and model runs were completed with the 50th percentile Hybrid III dummy model in the midi-MPV under EuroNCAP impact conditions.

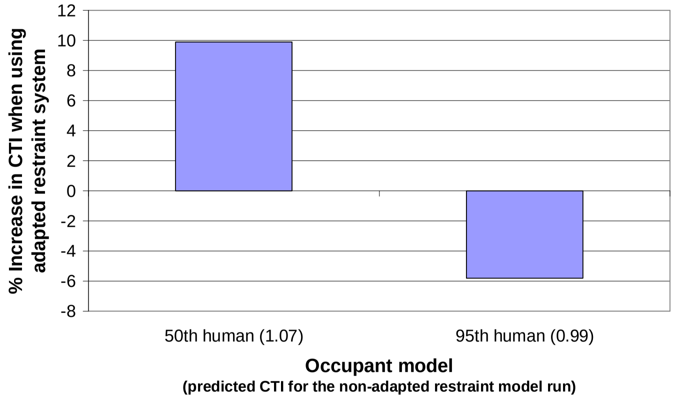
Differences in chest injury predictions between these model runs and a comparable model run in which the width of the belt was not changed were less than 10%. Although these differences are small it is suggested that, due to its construction, the response of the Hybrid III dummy model chest is a crude tool for assessing the influence of belt width on predicted injury risk. It was felt that a more appropriate means of assessing this is required.





EuroNCAP impact conditions
Airbag fire time = 25ms





FE vehicle 1 impact conditions (Figure 20).
Airbag fire time = 25ms

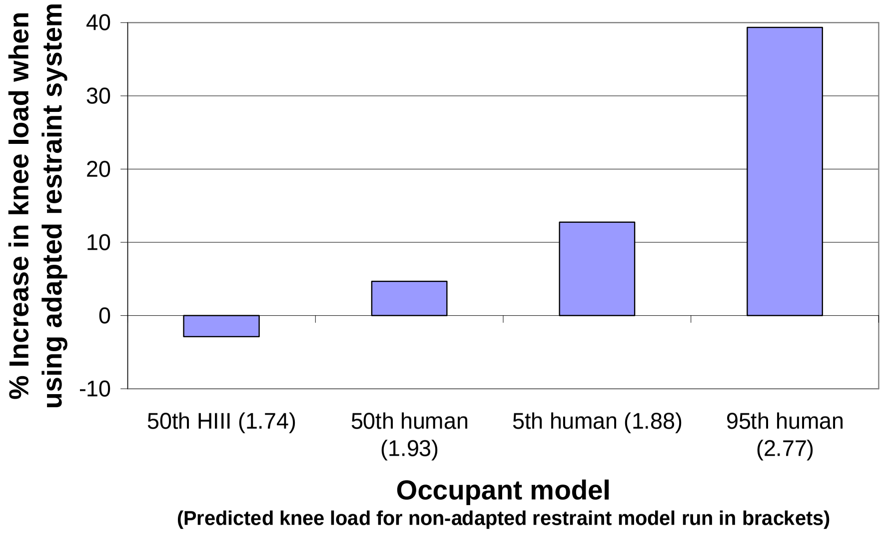
Figure 52. Change in predicted chest injury risk with adaptation of the restraint system.

4.13.10 Femur fractures

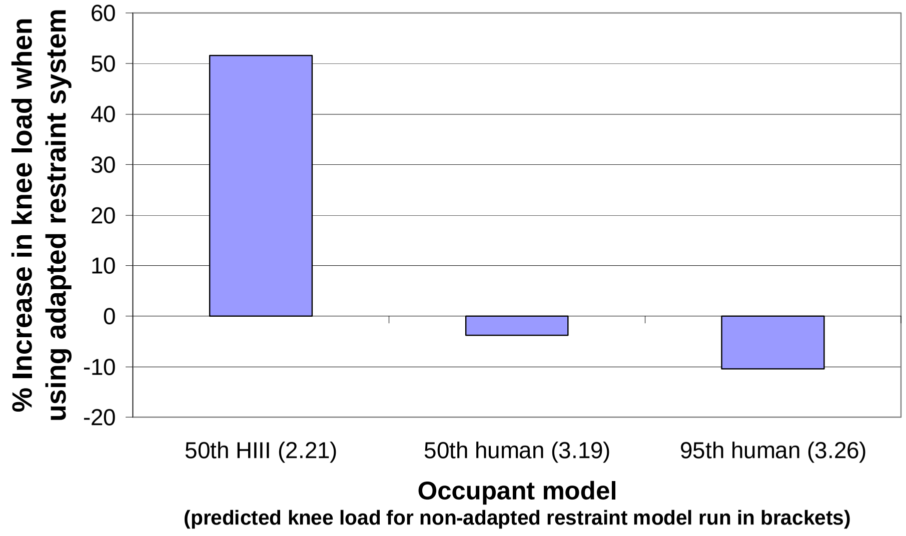
Predicted knee loads from comparable model runs with and without adapted restraint systems (Table 7) were compared. As noted above, the restraint systems in the study were adapted for each specific occupant model under EuroNCAP impact conditions. The intention of the comparisons made here was to assess how adapting the restraint system influenced predicted leg injury risk under EuroNCAP impact conditions and the FE vehicle 1 impact conditions (Figure 20) with an airbag fire time of 25ms. Results from these comparisons are presented in Figure 53

For the EuroNCAP impact conditions it is noticeable that considerable increases in the knee loads are obtained for the 95th percentile human model when the restraint system is adapted. It is not certain what is influencing this difference in the response, as the kinematics of the models with and without adapted restraint systems are very similar. It could possibly be explained by the restraint system allowing the occupant model a greater amount of forward excursion in order to limit the injury risk to other essential features such as the head and chest. Further work would be needed to investigate this. For the other occupant models the adaptation had less than a 10% influence on the predicted knee / femur loads.

Under the FE vehicle 1 impact conditions (see Figure 20) there are considerable increases (50%) in the knee load for the 50th percentile Hybrid III dummy model. The use of the adapted restraint system in the alternative impact conditions had a limited influence on the predicted injury risk to the legs of the 50th and 95th percentile human body models. Further comparisons, similar to those presented in Figure 53, were performed for additional impact conditions but differences were found to be less than 10% between the predictions from model runs with and without adapted restraint systems.



EuroNCAP impact
Airbag fire time = 25ms



FE vehicle 1 impact (Figure 20)
Airbag fire time = 25ms

Figure 53. Percentage increase in predicted knee/femur load when the restraint system is adapted to the specific response of the occupant model

4.13.11 Injury risk to small front seat passengers

To improve the response of the restraint system, model runs were completed investigating adaptations to the baseline restraint system in order to reduce the predicted injury risk of the 5th percentile human body model passenger. The results from this work were used as part of the investigation to assess the overall improvements that adaptations to the set-up of the restraint system had in reducing the injury predictions for the 5th percentile human body model passenger. Differences in the set-up of the baseline and best adapted restraint system for this are detailed in Table 8. above. Using these two set-ups for the passenger restraint system, model runs were completed with the midi-MPV compartment model under EuroNCAP impact conditions and with an airbag fire time of 25ms. Further model runs were completed with the same two restraint systems, but with the airbag switched off in order to assess if this would provide additional benefits in reducing passenger injury risk to small front seat passengers.

With no firing of the airbag there was a greater forward excursion of the head compared to the instances when the airbag did fire. This excursion was greatest for the condition in which the airbag did not fire and the restraint system was not adapted. In contrast, when the airbag did fire the greatest excursion of the head was obtained for the adapted restraint system.

As shown in Figure 54. not firing the airbag, whether the restraint system was adapted or not, had a detrimental influence on the predicted HIC response and the overall ISS injury risk prediction. The figure shows that reductions in HIC (>50%) were achieved by adapting the restraint system to the 5th percentile human body model responses, but this had a limited effect in reducing the overall predicted injury risk due to the initially low HIC prediction of 225 for the baseline model run. Greater benefits were achieved by adapting the restraint system in the instance where the airbag did not fire. Adapting the restraint system in this instance reduced the overall predicted injury risk by 50 %.

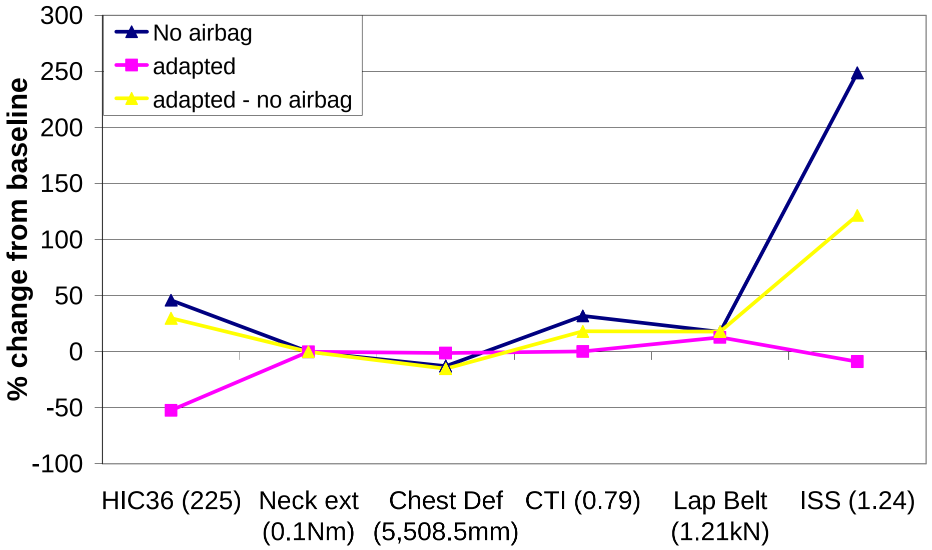


Figure 54. The influence of predicted injury risk on the 5th percentile human body passenger model when the restraint system is adapted. Baseline response (values in brackets) is with a non-adapted restraint system with airbag.

4.14 Discussion

In general, all injury risk predictions from the models in this set of parametric investigations were low and this presented difficulties in determining the potential benefits of ‘smart’ restraint systems to reduce the injury risks in the ten “accident scenarios”, although in some cases the adaptation of the restraint system resulted in significant improvements compared to the baseline system. However, it is important to remember that the models were developed and validated against vehicles with four and five star EuroNCAP test ratings. As such, it could be expected that the injury predictions from the models would be relatively low. Furthermore, for the ten "accident scenarios" it has not been possible to determine common impact conditions for what are effectively "injury" rather than "accident scenarios". This presented difficulties due to uncertainties on how the models should be set-up to recreate the injuries. It is also possible that available dummies and injury criteria may not be adequately developed for assessing the injuries seen in the accident data; this is an area which requires further research. Additional background work would seem to be necessary in order to understand the common accident mechanisms that are causing the identified injuries defined in the "accident scenarios" and determine if these are still relevant problems in modern vehicles. This point is particularly relevant as the reviewed accident data included vehicles that were built ten years ago.

As a consequence of these problems the modelling work has been used in this part of the parametric investigations to provide additional background understanding of the potential injury mechanisms. Trends in the model predictions, although sometimes small, have been used to provide an indication of the potential benefits that smart restraints might offer.

4.14.1 Restraint system adaptation study

It would appear from the model predictions that there may be potential benefits from actively adapting the responses of the restraint system to reduce injury risks according to the characteristics of the occupant. It is important to consider that the investigations have been an adaptation rather than an optimisation of the restraint system. *i.e.* discrete, statistically random alterations made to the set-up of the restraint system with the one leading to the lowest predictions of injury risk determined as the best adapted restraint. Hence, there exists the potential for further fine tuning (optimisation) of the modelled restraint systems to improve their performance for the various sizes of occupant model. Similar parameter studies to those presented in this work have been completed by other researchers investigating the influence that occupant size and mass has on injury risk and how adaptations to the set-up 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 5^{th}, 50^{th} and 95^{th} 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 study.

In the earlier modelling studies presented above, the investigators also considered greater variations in occupant size to the conventional 5^{th}, 50^{th} and 95^{th} 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 5^{th}, 50^{th} and 95^{th} percentile Hybrid III models, 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 and should not be restricted to standard 5^{th}, 50^{th} and 95^{th} 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 these discrete sizes.

In contrast to the previous work discussed above, the PRISM study has so far limited investigations to the injury risk to 5^{th}, 50^{th} and 95^{th} percentile body sizes. However, unlike the previous studies this present work has concentrated on investigating adaptations that could be made to the set-up 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 necessarily those indicated by Hybrid III 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 model predictions, the adapted restraint systems determined in this work are dependent on the applied overall injury risk approach. The set-up 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.

4.14.2 Small driver out-of-position (OOP)

It is evident from the model runs completed in this part of the investigation that the small driver out-of-position injury risk is a specific problem that requires detailed airbag models if this is to be investigated accurately with numerical simulation. The introduction of airbag self contact into the set-up of an OOP model run was found to have a considerable influence on increasing both the predicted injury risk and the model run time. However, these investigations have only studied one limitation in the set-up of the airbag model for investigating OOP occupants. An additional limitation is that the model assumes uniform pressure in the airbag. Techniques for modelling gas flows within airbags are currently under development in EC projects (APROSYS SP7, EC-ADVANCE). However, although the likelihood is that these developments will improve the accuracy of modelling OOP passenger interactions with airbags there is a considerable penalty on the run time of models simulating gas flows within airbags, which are substantially higher than for uniform pressure methods.

As a consequence of the present modelling limitations it has not been possible to investigate potential ‘smart’ alterations that could be made to the set-up of the restraint system in order to reduce the predicted injury risk to OOP small occupants. However, it is speculated that suitable countermeasures for this problem might include altering the inflation characteristics of the airbag, pulling the occupant back into the seat, translating the seat backwards at or prior to the imminent impact or moving the steering wheel inboard towards the dashboard and allowing adequate space for the airbag to inflate. These and additional adaptations of the restraint system can be investigated through modelling once a rigorous simulation of a deploying airbag has been developed.

4.14.3 Injuries to large drivers

It was found that adapting the restraint system for a specific impact condition could be used to reduce the injury risk to larger occupants. However model predictions implied that the benefits may not necessarily be as great under all impact conditions.

One of the main problems identified for larger drivers was the potential for them to recline the seat and dramatically reduce the performance of the seatbelt as the head and shoulders fall behind the upper anchorage of the belt on the B-pillar. An obvious countermeasure investigated to overcome this problem was to fit seatbelt to the seat rather than to the fixed B-pillar of the vehicle. This was found to improve the safety performance of the belt for reclined occupants. Further work needs to be completed to assess the benefits that this might provide for occupants of different sizes. Such alterations to the set-up of the belt system would require that the seat is structurally sound to support the loads going through the diagonal belt and the implications that this might have on vehicle design need to be fully investigated and realised before firm recommendations can be made on the benefits of moving the upper belt anchorage from the B-pillar to the seat.

4.14.4 Late deploying airbag

The predicted injury risk was increased when the deployment of the airbag was delayed. The obvious countermeasure to avoiding this problem would be to fire the airbag at the correct point during the impact. This approach would require that sensors are better able to recognise a broader range of impact conditions and deploy the airbag according to the specific impact conditions. Such developments could be encouraged through appropriate enhancements of the test protocols.

Under more angled impacts, in which the head strikes the door glazing, the fire time for the frontal airbag appeared to have a limited influence on the predicted injury risk for the range of fire times considered (up to 48ms). This timing was considered representative of an appropriate fire time, should the system be able to sense the impact effectively. It is considered that under these impact conditions greater problems might have been evident if the airbag fired very late (90ms to 100ms) when the head would be closer to the airbag. The predictions from these additional model runs justify the need to time the inflation of the airbag to the specific impact characteristics.

4.14.5 Occupant misses the airbag

There are no obvious indications from the model predictions that poor airbag contact in isolation would increase an occupant’s overall injury risk. It is anticipated that further factors account for occupant injury risk when the driver misses the airbag. One of the main points will possibly be for the head to strike intruding features of the vehicle.

Impact types that result in the driver missing the airbag include large rotations of the vehicle during impact and considerable translations of the steering wheel. For this latter point it is rationalised that maintaining the position of the steering wheel and column in an impact may prevent the occupant from missing the airbag. As recommended in some of the other accident scenarios detailed above, this could be encouraged through development of test protocols that ensure that the steering wheel does not move under a broader range of impact conditions. Under large rotations of the vehicle, ‘smart’ adaptations to the restraint system may be used to reduce the lateral translation of the occupant within the confines of the vehicle or side airbags used to prevent the occupant from hitting the door. However, sensor systems would need to be adequately developed to ensure that side airbags fire at the appropriate time in the course of the impact.

4.14.6 Airbag “bottoming out”

It was found in a number of the simulated impact conditions that the abdomen of the occupant models struck the lower edge of the steering wheel. In many of these instances it has not been possible to investigate countermeasures to prevent this impact and reduce the potential injury risk to the chest and abdomen. It was found that introducing an adapted restraint system and even fixing the upper belt anchorage to the seat for a reclined 95th percentile human body model did not prevent the abdomen from striking the steering wheel during EuroNCAP impact conditions. Although not investigated, it is anticipated that delays in the firing of the airbag, which also resulted in the abdomen striking the steering wheel, could be addressed by ensuring that restraint systems respond at the correct period of the impact through better sensing and adaptation of the restraint system. Such improvements could be encouraged through the development of the test procedures to consider a broader range of impact conditions. Removing belt slack, as investigated in the pre-pre-tensioning studies was also found to provide additional benefits in reducing the likelihood of the chest and abdomen from striking the steering wheel. Consequently, in addition to ‘smart’ adaptations to the restraint systems, it is also proposed that passive adaptations to the sensor systems and the restraint may provide additional benefits by preventing the airbag from bottoming out.

4.14.7 Steering wheel edge strike

It was identified in the data that injuries for this accident scenario were possibly a consequence of considerable changes in the inclination of the steering wheel during an impact. Based on this understanding it would seem rational that the best means of counteracting this particular problem would be to prevent large changes in the steering wheel inclination during impacts. For instance, limits are placed on anticipated safe movements of the steering column under EuroNCAP impact conditions, but the limited movement of the steering wheel may not be applicable under all impact conditions. It would appear that the most obvious recommendation to make for this accident scenario should be that test protocols are enhanced to ensure that the steering wheel inclination does not exceed certain limits under a broader range of impact conditions.

4.14.8 Injuries from header rail strike

Adapting the restraint system to the responses of both upright and reclined 95th percentile human body models prevented the head from striking the roof and header rail of the compartment models. Similar benefits were also achieved if the upper anchorage of the belt was fitted to the seat rather than to the fixed B-pillar for the reclined model.

Header rail strikes in the accident data were found to be consistent with intrusion of the roof and header rail during impacts and, as such, it is uncertain how representative of this the larger occupant model strikes of the header rail are, within the impact conditions of the investigated accidents. However, the main benefit of adapting the restraint system, especially for the larger occupant model, was to reduce the head trajectory within the confines of the compartment model. Based on these predictions it could be interpreted that adapting the restraint system will reduce the likelihood of the head striking intruding features of the compartment such as the header rail.

4.14.9 Chest injury

It is implied from the model predictions that the adaptations made to the restraint system for occupant size had a limited influence on predicted chest deflection, but reductions of 15% in CTI for the 50th and 95th percentile human body models were obtained under EuroNCAP impact conditions. No obvious reductions in chest injury risk were obtained by using the adapted restraint system under alternative impact conditions. Based on these results it is difficult to anticipate the specific adaptations that should be made to the set-up of the restraint system to reduce chest injury risk. Optimising the performance of the restraint system to the responses of the specific occupant would appear to provide benefit, although it is expected that reducing the loading through the chest will be of greatest benefit to older occupants who are believed to have a reduced tolerance to injury. Consequently, as well as occupant size, it is expected that ‘smart’ alterations in the set-up of the restraint system should also consider the injury tolerance of the specific occupant.

Possible countermeasures for reducing the loading and injury risk to the chest might include altering the pressure of the airbag and load limiter characteristics so that there is better spread of the load over the head and chest. Increasing the belt width was a further countermeasure that was investigated. However, the expected benefits of increasing belt width were not predicted by the models because of anticipated shortcomings in the structure of the Hybrid III dummy model and its associated injury criteria. It is implied from these findings, if correct, that improved assessment techniques may be required to investigate potential countermeasures to reducing chest injury risk.

4.14.10 Femur fractures

There were no obvious indications that adapting the restraint system would lead to reductions in the risk of femur fractures. In fact, in certain instances the predicted femur injury risk was greater with an adapted restraint system. Consequently, although ‘smart’ restraints may be able to reduce overall injury risk, additional countermeasures may be required to maintain improved injury risks to specific body regions such as the legs. It is important to ensure that injuries for which the understanding and measurement of injury potential is less well known are not compromised by the use of ‘smart’ restraint systems. Countermeasures for reducing femur fractures may, for example, include improvements in the performance of knee bolsters specific to the size of the occupant.

4.14.11 Injury risk to small front seat passengers

Adaptation of the restraint system resulted in only a small reduction in the overall predicted injury risk for the 5th percentile human body model passenger. This was mainly attributed to a very low HIC in the base model (225), which meant that the potential to reduce injury was limited. These investigations were completed under a relatively limited set of impact conditions. Greater reductions in predicted injury risk might be expected under alternative impact conditions. De-powering the airbag in order to reduce predicted injury risk for small front seat passengers does not appear to provide any obvious benefits.

4.14.12 Summary of parametric model runs assessing the injury benefit of 'smart' restraints

Model parametric investigations have been completed to determine the benefits of adapting the restraint system to specific occupant characteristics and the benefits of 'smart' restraint systems in reducing the injury risk for ten "accident scenarios" determined from the PRISM accident data analysis. The main observations from this work were as follows:

<u>Restraint system adaptation study</u>

Adapting the restraint system to the specific characteristics of an occupant resulted in considerable reductions in the predicted occupant injury risk. Reductions in predicted injury risk greater than 65% were achieved for the 95th percentile human body model.

<u>Accident scenario 1 – Small driver out-of-position (OOP)</u>

- In order to accurately predict the injury risk to OOP occupants it is necessary to have advanced airbag models.
- Suggested adaptations that may help to reduce the injury risk to small OOP drivers include modifying the inflation characteristics of the airbag, pulling the occupant back into the seat, translating the seat backwards at or prior to the imminent impact or moving the steering wheel inboard towards the dashboard allowing adequate space for the airbag to inflate.

<u>Accident scenario 2 – Injuries to larger drivers</u>

- "Smart" alterations to the set-up of the restraint system were found to reduce the predicted injury risk for the 95th percentile human body model.
- It was found that the use of a 'smart' restraint system developed under a specific set of impact conditions may not necessarily provide equivalent or positive reductions in predicted injury risk under all impact conditions.
- Reclined larger drivers promote a poor fit of the diagonal belt across the chest. Adapting the restraint system will help to reduce injury risk under these impact conditions.
- Fitting the upper belt anchorage to the seat rather than to the B-pillar reduced the predicted injury risk for a larger reclined occupant.

<u>Accident scenario 3 - Late deploying airbag</u>

- Predicted injury risk increased with delays in the deployment of the airbag.
- In order to reduce injury risks through late deployments of the airbag it is anticipated that sensor technology should be required that is better able to recognise the impact conditions and initiate deployment of the airbag at the most appropriate point during the impact. Such developments could be encouraged through appropriate enhancements of test protocols.

<u>Accident scenario 4 - Occupant misses the airbag</u>

- It is anticipated that further accident mechanisms that account for occupant injury risk, such as compartment intrusion, must come into play when the driver misses the airbag.

- It is anticipated that injury risks associated with the driver missing the airbag may be reduced by maintaining the position of the steering wheel and column during an impact. This could be encouraged through developments of test protocols that ensure that the steering wheel does not move under a broader range of impact conditions.
- "Smart" alterations to the restraint system and the use of side airbags could prevent the occupant from hitting the door in impacts that introduce large amounts of vehicle rotation.

Accident scenario 5 – Bag bottoming out

- Adapting the restraint system especially for the reclined 95th percentile human body model prevented the abdomen from striking the steering wheel, reducing the likelihood of the airbag from bottoming out. Fitting the upper belt anchorage to the seat rather than to the fixed B-pillar also prevented this.
- It was shown that pre-pre-tensioning devices that anticipate an impending impact may prevent the airbag from bottoming out and reduce the potential injury risk.
- It is anticipated that in addition to 'smart' and passive adaptations of the restraint system, improvements in the sensor systems, which ensure appropriate deployment of the airbag system under a broader range of impact conditions, could help to prevent the airbag from bottoming out. Such developments could be encouraged through enhancements to test protocols.

Accident scenario 6 – Steering wheel edge strike

- In order to avoid this injury scenario it is anticipated that test protocols should be enhanced to ensure that the steering wheel inclination does not exceed defined limits under a broader range of impact conditions.

Accident scenario 7 – Injuries from header rail strike

- Adapting the restraint system to the responses of both upright and reclined 95th percentile human body models prevented the head from striking the roof and header rail.
- Fixing the upper belt anchorage to the seat rather than to the fixed B-pillar for the reclined 95th percentile human body model prevented the head from striking the header rail.
- Adapting the restraint system reduced the head trajectory of the larger occupant model within the confines of the compartment model. This will reduce the likelihood of the head striking intruding features of the compartment such as the header rail.

Accident scenario 8 - Chest injury risk

- Adapting the restraint system for different occupant sizes may help to reduce the likelihood of chest injuries.
- As chest injuries appear to be a common problem associated with older occupants, it is implied that 'smart' restraint systems need to be able to consider differences in the injury tolerance of occupants as well as occupant.
- It was predicted that increasing the belt width had no obvious benefits in reducing chest injury risk. It is speculated that this result is a consequence of the inadequacies of the Hybrid III dummy chest and associated injury criteria. It is implied that improved assessment techniques may be required to investigate potential countermeasures to reducing chest injury risk.

Accident scenario 9 – Femur fractures

- There were no obvious indications that adapting the restraint system would lead to reductions in the risk of femur fractures. In fact instances were found where the use of an adapted restraint system led to an increase in the predicted injury risk for the femur.

- It was implied from the model predictions that specific countermeasures, such as adaptive knee bolsters may be required to reduce the risk of femur fractures.

Accident scenario 10 - High injury risk to small front seat passengers

- Adapting the restraint system for a 5th percentile human body model resulted in small reductions in overall predicted injury risk.
- De-powering the frontal airbag for a small front seat passenger provided no reductions in overall predicted injury risk.

5 Evaluating the benefits of smart restraint systems

TRL has produced a Regulatory Impact Assessment (RIA) based on the PRISM research for the UK Department for Transport. Using the MADYMO modelling data, TRL has estimated the annual benefits associated with the successful implementation of ‘smart’ restraint systems which address the injury mechanisms identified in the PRISM project. Table 9 shows the benefits from fitting ‘smart’ restraint systems in terms of the reduction in risk of serious or fatal (AIS 3+) injury. The benefits were assessed using MADYMO numerical simulation under WP3 of the PRISM project in order to develop restraint systems adapted to each occupant size. The following assumptions were made in the calculation of benefits:

- It was assumed that none of the current fleet has ‘smart’ systems.
- The only ‘smart’ systems that have been considered are those which adapt to occupant size and impact type. Further systems could potentially provide greater benefits.
- The ‘smart’ restraints were primarily assessed using EuroNCAP impact conditions. It is assumed that the relative benefits seen in these impact types apply across all impact types. This assumption was verified by parameter studies conducted within PRISM using alternative impact conditions.
- It is assumed that ‘smart’ restraint systems can provide no benefit in Scenario 3 (Very late deployment) and Scenario 7 (Header rail strike), as these can be considered to be crashworthiness and / or sensing-dependent impact types. Development in these areas may provide benefits that allow ‘smart’ technologies to be applied effectively to these injury mechanisms.
- Benefits in terms of slight injury have not been considered as it is believed that the main focus and area of benefit from smart systems is the mitigation of serious and fatal injuries.

Table 9. Estimated decrease in injury risk by applying a ‘smart’ restraint system (derived from MADYMO modelling)

Occupant height	Decrease in risk by scenario									
	1	2	3	4	5	6	7	8	9	10
5th %ile	85.2%	-	-	28.1%	82.8%	82.8%	-	85.2%	22.0%	85.9%
50th %ile	-	-	-	28.1%	26.9%	26.9%	-	30.8%	31.0%	70.5%
95th %ile	-	64.9%	-	28.1%	64.9%	64.9%	-	81.3%	65.0%	86.4%

Using the assumptions and benefits stated above, the number of casualties prevented by the installation of smart restraint systems may be estimated using the risk reductions (Table 9) and the estimated distribution of annual casualties. The resulting estimated annual casualty reductions are presented in Table 10.

Table 10. Estimated number of casualties prevented by use of 'smart' restraint systems

Occupant height	Injury severity	Casualties saved (by injury scenario number – see Table 4)							
		1	2	4	5	6	8	9	10
<1.64m	Fatal	6	0	0	3	4	26	6	24
	Serious	59	0	4	31	38	270	63	429
1.63 - 1.79	Fatal	0	0	1	1	2	14	12	20
	Serious	0	0	9	23	28	223	205	352
>1.79	Fatal	0	0	0	1	1	12	9	3
	Serious	0	8	5	30	36	314	228	48
ALL	**Fatal**	**6**	**0**	**1**	**6**	**7**	**52**	**27**	**47**
	Serious	**59**	**8**	**17**	**84**	**103**	**808**	**496**	**828**

Table 11. Average value of prevention per casualty (RCGB 2004)

Injury severity	Monetary value GBP
Fatal	1,384,440
Serious	155,560

Using the values for the prevention of serious and fatal casualties presented in Table 11, the savings values were applied to the estimated number of casualties prevented in each injury scenario. The estimated annual savings associated with the prevention of these casualties are presented in Table 12, below. This shows the priority areas for the encouragement and development of smart restraints in terms of the priority injury mechanisms (see Figure 1 for injury scenario descriptions) which adaptive restraints should address.

Table 12. Estimated financial value associated with casualty reduction for each scenario

Injury severity	Financial saving in GBP by injury scenario (see Table 4)							
	1	2	4	5	6	8	9	10
Fatal	7.9m	0.4m	1.5m	7.7m	9.4m	71.4m	37.7m	65.0m
Serious	9.2m	1.2m	2.6m	13.1m	13.1m	125.7m	77.1m	128.9m
TOTAL	**£17.1m**	**£1.6m**	**£4.1m**	**£20.7m**	**£25.3m**	**£197.1m**	**£114.8m**	**£193.9m**

The two options which provide the greatest potential benefit are 'smart' systems designed to mitigate driver and passenger chest injury. Respectively these options would give a financial benefit of 197.1m GBP and 193.9m GBP per annum (for Great Britain) based on the benefits identified with the systems developed in the PRISM project. By developing systems which provide benefits to these injury scenarios there would be benefits in some of the other scenarios. This is because, although combined with other injury types, chest injury was found to be the dominant injury mechanism in many of the scenarios.

The third scenario which was found to give considerable financial savings was the reduction of femur injuries. The exact cause of these injury types was not fully investigated within the PRISM project so the adapted systems were assessed only on a reduction in the femur axial load. Based on this condition it was found there was potential for a financial benefit of 114.8m GBP per annum.

It should be noted that some adapted systems may promote ‘submarining’ and actively use femur loading to reduce the loading on the chest and head, therefore when designing systems to benefit one option it is necessary to consider the implications for different body region injury mechanisms.

The implementation of these ‘smart’ restraint systems should be encouraged and several methods of achieving this have been described in the separately produced RIA. Alterations to the dummy sizes and test speeds in the EuroNCAP programme are likely to lead to the most rapid implementation of effective smart systems. However, alterations to the regulation would guarantee improvements in protection offered to a broader range of the population. With respect to both of these implementation methods, the injury criteria for different body regions should be reassessed in order to improve injury mitigation for car occupants.

6 Work Package 4. Evaluation of ‘smart’ systems

The PRISM project partners produced a series of data sheets which covered each of the ten identified injury scenarios. These data sheets were intended to provide all the relevant information on injury mechanisms, injury causation and frequency of injury in a user-friendly manner, with the intention that this information could be used by industry to aid the effective development of ‘smart’ restraint technologies. The data sheets also contain suggestions on the test and evaluation strategies which could be adopted to assess the performance of the ‘smart’ restraint system in mitigating the injuries identified.

These datasheets are presented in the R9/R10 report, to which TRL contributed interpretation of the modelling results upon which the recommendations are based, as well as reviewing the documents.

7 Conclusions

Under the European 5th Framework project PRISM, two numerical studies have been completed using a midi-MPV compartment model that has been developed and evaluated to investigate the value of 'smart' restraint systems in mitigating occupant injury risk. The results and outcome of this work have been presented, discussed and concluded within separate sections of this report. This section gathers together the conclusions derived from all of the work.

7.1 Development and evaluation of the MADYMO compartment models

Several MADYMO compartment models were developed representing the confines of a generic super-mini, small family and midi-MPV vehicles. All the compartment models were developed with the same initial baseline restraint system for the driver and front seat passenger consisting of a three-point belt, buckle pretensioner and load limiting at the shoulder.

The predictive performance of the models was evaluated by simulating a series of EuroNCAP impact conditions with the models. It was found that the predictions from the models were comparable to those that could be expected from a four or five star rated EuroNCAP vehicle.

It was confirmed through the evaluation of the model predictions that they provide a suitable baseline level of performance for investigating the benefits that 'smart' restraint systems might have in reducing occupant injury risk in impact conditions beyond current test protocols.

Predictions from equivalent model runs completed by each contributing partner of the PRISM consortium were compared. It was found that the model predictions from these separate sources were very similar. This confirmed that the IT platforms used by each contributor had a limited influence, alleviating concerns over comparing predictions from model runs on different platforms.

The potential exists to develop the models further and investigate injury risk under a more diverse range of impact conditions. However, for the time being it is felt that the models are adequately developed for the application in parametric investigations assessing the benefits of 'smart' restraint systems. In the future, improved models are required, but this development is limited by other factors such as lack of appropriate injury criteria and injury tolerance data.

7.2 Parametric model runs assessing accident variables to consider in the development of 'smart' restraint systems

- Impact conditions were found to have a considerable influence on the kinematics and injury risk of occupants and on the internal features of the vehicle that an occupant strikes.
- For impact conditions that cause greater amounts of vehicle rotation and lateral movement there is an increased likelihood for the diagonal belt to wrap around the neck of an occupant, with the potential of injury to the soft tissues of the neck. It is questionable that current neck injury criteria are adequately developed for assessing this injury risk.
- Difficulties exist in obtaining crash pulses, vehicle intrusion data and occupant restraint responses under impact conditions different from standard test protocols. Such data needs to be obtained from full-scale crash tests and simulations in order to develop models that can provide accurate predictions of occupant injury risk.
- It was predicted that the legs are at greater risk of injury in smaller classes of vehicles.
- Overall the Predicted injury risk was lower for the smaller super-mini and family compartment models compared with the larger midi-MPV compartment model.
- It was predicted that the heads of larger occupants are at greater risk of impacting the roof / header rail in frontal impacts compared with their smaller counterparts.

- As the size of an occupant increases the delay in head contact with the airbag increases due to the kinematics of the different sizes of occupant.
- The kinematic responses of human body models are very different from those of dummy models. The pelvis of the human body model tended to rotate over rather than under the lap belt, experiencing a greater amount of extension in the lumber spine compared with flexion in the lumbar spine and pelvis under ride of the belt for the Hybrid III dummy model. Human body models were found to have greater flexibility in the spine compared with dummy models, such that the chest of the human body models tended to strike the airbag at an angle. The chest of the 50th percentile Hybrid III dummy model hit the airbag square on.
- During frontal impacts there was an increased likelihood for the shoulder of the human body model to slip out of the diagonal belt.
- Under EuroNCAP impact conditions the 50th and 95th percentile human body models provided predictions of injury risk greater than those of the 50th percentile Hybrid III dummy model. Under more angled impact conditions the 50th percentile Hybrid III dummy model provided higher predictions of injury risk.
- The legs and knees of smaller occupants appear to be at greater risk of injury than their larger counterparts.
- Postures deviating from those used in regulatory test postures tended to result in higher predictions of occupant injury risk.
- Making dramatic changes to the posture of the Hybrid III dummy model introduces initial torques in the joints of the model which have a considerable influence on predicted injury risk. It is uncertain how representative the initial torques are of those in anatomical joints.
- Hybrid III dummies are specifically designed for assessing injury risks in uni-directional impact conditions. As such it is questionable how representative it is to apply this dummy to assess the influence that occupant posture has on injury risk.
- A change in the posture of a larger occupant to a reclined driver posture has a considerable influence on increasing an occupant's injury risk.
- Even with the lower seated posture of the reclined larger occupant it was predicted that the head may still be at serious risk of striking the roof / header rail.
- A larger reclined driver promotes a poor initial fit of the diagonal belt across the chest. This contributes to higher predictions of injury risk, greater predicted forward excursions of the occupant model and an increased likelihood for the abdomen to strike the lower edge of the steering wheel.
- Occupant bracing delayed the forward excursion of the occupant within the compartment model.
- It is implied from the trends in the model predictions that bracing in an impact increases the injury risk of an occupant.
- It is suggested from the model predictions that fractures in the thorax may lead to a greater forward excursion of the occupant increasing the likelihood of the abdomen striking the lower edge of the steering wheel.
- Small alterations in the fore and aft movement and inclination of the steering wheel have a considerable influence on the predicted injury risk of the head and chest.

7.3 Parametric model runs assessing the benefits of ‘smart’ restraint systems in reducing injury risk

Adapting the restraint system to the specific characteristics of an occupant resulted in considerable reductions in predicted occupant injury risk. Reductions in predicted injury risk greater than 65% were achieved for the 95^{th} percentile human body model.

Injury scenario 1 – Small driver out-of-position (OOP)

In order to accurately predict the injury risk to OOP occupants it is necessary to have advanced airbag models, although this will have a considerable influence on increasing model run times using current computing capabilities.

Suggested alterations that may help to reduce the injury risk to small OOP drivers include altering the inflation characteristics of the airbag, pulling the occupant back into the seat, translating the seat backwards at or prior to the imminent impact or moving the steering wheel inboard towards the dashboard allowing adequate space for the airbag to inflate.

Injury scenario 2 – Injuries to large drivers

‘Smart’ alterations to the set-up of the restraint system were found to reduce the predicted injury risk for the 95^{th} percentile human body model. It was found that the use of a ‘smart’ restraint system developed under a specific set of impact conditions may not necessarily provide equivalent or positive reductions in predicted injury risk under all impact conditions.

Reclined larger drivers promote a poor fit of the diagonal belt across the chest. Adapting the restraint system will help to reduce injury risk under these impact conditions.

Fitting the upper belt anchorage to the seat rather than to the B-pillar reduced the predicted injury risk for a larger reclined occupant.

Injury scenario 3 - Late deploying airbag

Predicted injury risk increased with delays in the deployment of the airbag. In order to reduce injury risks through late deployments of the airbag it is anticipated that better sensor technology is required that is able to recognise the impact conditions and initiate airbag deployment at the most appropriate point during the impact. Such developments could be encouraged through appropriate enhancements of test protocols.

Injury scenario 4 - Occupant misses the airbag

Injury risks associated with the driver missing the airbag may be reduced by maintaining the position of the steering wheel and column during an impact. This could be encouraged through developments of test protocols that ensure that the steering wheel does not move under a broader range of impact conditions.

“Smart” alterations to the restraint system and the use of side airbags could be used to prevent the occupant from hitting the door in impacts that introduce large amounts of vehicle rotation.

Injury scenario 5 – Airbag bottoming out

Adapting the restraint system especially for the reclined 95^{th} percentile human body model prevented the abdomen from striking the steering wheel, reducing the likelihood of the airbag bottoming out. Fitting the upper belt anchorage to the seat rather than to the fixed B-pillar also prevented the abdomen of the 95^{th} percentile human body model from striking the steering wheel.

It was shown that pre-pre-tensioning devices that anticipate an impending impact may prevent the airbag from bottoming out and reduce the potential injury risk.

It is anticipated that in addition to ‘smart’ and passive adaptations of the restraint system, improvements in the sensor systems which ensure appropriate deployment of the airbag system under a broader range of impact conditions could help to prevent the airbag bottoming out. Such developments could be encouraged through enhancements of test protocols.

Injury scenario 6 – Steering wheel edge strike

In order to avoid this injury scenario it is anticipated that test protocols should be enhanced to ensure that the steering wheel inclination does not exceed defined limits under a broader range of impact conditions.

Injury scenario 7 – Injuries from header rail strike

Adapting the restraint system to the responses of both upright and reclined 95th percentile human body models prevented the head from striking the roof and header rail.

Fixing the upper belt anchorage to the seat rather than to the fixed B-pillar for the reclined 95th percentile human body model prevented the head from striking the header rail.

Adapting the restraint system reduced the head trajectory of the larger occupant model within the confines of the compartment model. This will reduce the likelihood of the head striking intruding features of the compartment such as the header rail.

Injury scenario 8 - Chest injury risk

Adapting the restraint system for different occupant sizes may help to reduce the likelihood of chest injuries. As chest injuries appear to be a common problem associated with older occupants it is implied that 'smart' restraint systems need to be able to consider alterations in the injury tolerance of subjects as well as occupant size in order to reduce chest injuries.

It was predicted that increasing the belt width had no obvious benefits in reducing chest injury risk. It is speculated that this result is a consequence of the inadequacies of the Hybrid III dummy chest and associated injury criteria. It is implied that improved assessment techniques may be required to investigate potential countermeasures to reducing chest injury risk.

Injury scenario 9 – Femur fractures

There were no obvious indications that adapting the restraint system would lead to reductions in the risk of femur fractures. In fact, instances were found where the use of an adapted restraint system led to increases in the predicted injury risk for the femur.

It was implied from the model predictions that specific countermeasures such as designing knee bolsters to the specific size and response of the occupant will be required to reduce the risk of femur fractures.

Injury scenario 10 - High injury risk to small front seat passengers

Adapting the restraint system for a 5th percentile human body model resulted in small reductions in overall predicted injury risk. Model runs indicated that de-powering the frontal airbag for a small front seat passenger provided no reductions in overall predicted injury risk.

7.4 Benefit assessment

The two options which provide the greatest potential benefit are smart systems designed to mitigate driver and passenger chest injury. Respectively these options would give a financial benefit of 197.1m GBP and 193.9m GBP per annum (for Great Britain) based on the benefits identified with the systems developed in the PRISM project. By developing systems which provide benefits to these injury scenarios there would also be benefits in some of the other scenarios. This is because, although combined with other injury types, chest injury was found to be the dominant injury mechanism in many of the scenarios.

The third scenario which was found to give considerable financial savings was the reduction of femur injuries. The exact cause of these injury types was not fully investigated within the PRISM project so the adapted systems were assessed only on a reduction in the femur axial load against currently available injury risk relationships. A restraint system designed to mitigate this injury type was estimated to have a potential financial benefit of 114.8m GBPper annum.

7.5 Test and evaluation strategies for ‘smart’ restraint systems

The PRISM project produced a series of data sheets which covered each of the identified injury scenarios presented in Table 4. These data sheets provide all the relevant information on injury mechanisms, injury causation and frequency of injury in a user-friendly manner, with the intention that this information could be used by industry to aid the effective development of ‘smart’ restraint technologies. The data sheets also contain suggestions on the test and evaluation strategies which could be adopted to assess the performance of the smart restraint system in mitigating the injuries identified. TRL’s activity in this Work Package was to input expertise within the PRISM consortium meetings and to review and suggest comments on the datasheets. These are included within the EC report R9/R10.

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