Adaptive vehicle structures for secondary safety

by A Thompson, M Edwards, O Goodacre, G Coley, M Keigan, J Broughton and R Cuerden

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Approvals

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Executive summary

Following the introduction of the European frontal and side impact Directives and EuroNCAP, car manufacturers have successfully improved car occupant safety. Even so, there are still about 1,500 car occupants killed and 15,000 seriously injured in GB annually. In general, current car structures and restraint systems are optimised to perform well in the legislative and consumer rating tests. However, these tests only represent a small fraction of the full range of real world crashes, hence current car structures and restraint systems are non-optimal for many crashes. To enhance crash safety further, car structures and restraint systems need to be ‘adaptable’ so that they can offer optimal protection in all crashes.

An adaptable structure is one that can change its properties, such as its stiffness, depending on the configuration and severity of the crash experienced, to optimise its performance to minimise injury risk.

Much research has been conducted into adaptive structures focused on their technical design, operational ability, actuation methods, necessary supporting technologies, etc. However, virtually no work has been performed to determine the potential benefit in adopting these systems, in terms of lives saved and injuries prevented. This information is needed both by governments and industry to be able to undertake cost benefit type analyses to determine which adaptable structures offer the greatest potential and indeed whether any such systems will offer sufficient benefit to justify their cost.

The main objectives of this project were:

- To investigate, review and classify state of the art adaptive structures, concepts and technologies.
- To develop a methodology to estimate the potential benefit of adaptive structures in crashes; and to use this to estimate the benefit of a ‘generic’ adaptive concept, which represents the likely response of a typical adaptive system.

The review of state of the art structures, concepts and technologies relating to adaptive structures showed that current proposals for adaptive structures are fairly limited. The largest number of systems are currently based on the concept of altering the frontal force levels of the vehicle, and the majority of these have major technical feasibility drawbacks.

The generic concept selected as an example to be used for the benefit analysis was an adaptive frontal structure which can adjust its frontal force levels to optimise the occupant compartment deceleration pulse for different frontal collision configurations, in particular severity and overlap. The main reasons for selecting this concept were that a large proportion of the adaptive systems reviewed were based on this concept and it has a potentially large target population.

A methodology was developed to estimate the benefit for GB for the introduction of the adaptive structure. This utilised the newly available linked STATS19 / SHIPS accident database in combination with the detailed CCIS accident database to identify the target population, whilst computer simulation and injury risk curves were used in order to estimate the effectiveness of the structure by calculating the reduction in risk of AIS level injury to the head and thorax.

The national benefit for GB for the introduction of an adaptable frontal structure on all cars was estimated. It was predicted that a significant benefit could be expected in terms of AIS 2+ and AIS 3+ head and thorax injury. The benefit for head and thorax injuries at AIS 5+ level was likely to be small as there were very few of these type of injuries in the target population. However, there was an issue with the probability of injury predicted by the model and the likelihood of injury in the CCIS database. Although similar trends were observed, with an increasing likelihood/probability of injury as the impact speed increased, the model predicted that the risk of injury was significantly higher than the likelihood of injury in the CCIS database. This was unexpected as the CCIS database uses a stratified sampling technique that is weighted to select more serious injuries, and therefore the CCIS likelihood of injury should be greater than the risk of injury. The over-prediction of the probability of injury by the model may affect the validity of the results, and further investigation is required in order to understand and resolve this issue.

Glossary

AIS	Abbreviated Injury Score
ACEA	Association des Constructeurs Européens d’Automobile (European Automobile Manufacturers Association)
CCIS	Co-operative Crash Injury Study
CTI	Combined Thoracic Injury
ER	Electrorheological
ETS	Estimated Test Speed
GB	Great Britain
HIC	Head Injury Criterion
MAIS	Maximum Abbreviated Injury Score
MPV	Multi-Purpose Vehicle
MR	Magnetorheological
SHIPS	Scottish Hospital In-Patient System
SMA	Shape Memory Alloy
STATS19	National Road Accident Database of accidents reported by or to the police for Great Britain.

1 Introduction

Following the introduction of the European frontal and side impact Directives and EuroNCAP, car manufacturers have successfully improved car occupant safety. Even so, there are still about 1,500 car occupants killed and 15,000 seriously injured in GB annually. In general, current car structures and restraint systems are optimised to perform well in the legislative and consumer rating tests. However, these tests only represent a small fraction of the full range of real world crashes, hence current car structures and restraint systems are non-optimal for many crashes. To enhance crash safety further, car structures and restraint systems need to be ‘adaptable’ so that they can offer optimal protection in all crashes.

An adaptable structure is one that can change its properties, such as its stiffness, depending on the configuration and severity of the crash experienced, to optimise its performance to minimise injury risk. They differ from standard structures, whose impact-absorbing capabilities vary passively according to crash severity. Adaptable structures are likely to use pre-crash sensing to supply information about the crash configuration and maximise the amount of time available for them to adapt. It should be noted that pre-crash sensing is also likely to be used to take measures to avoid or reduce the severity of the crash using, for example, pre-crash braking. This illustrates that, if adopted, adaptable structures will, most likely, form part of an integrated safety system in a future car.

Much research has been conducted into adaptive structures focused on their technical design, operational ability, actuation methods, necessary supporting technologies, etc. However, virtually no work has been performed to determine the potential benefit in adopting these systems, in terms of lives saved and injuries prevented. This information is needed both by governments and industry to be able to undertake cost benefit type analyses to determine which adaptable structures offer the greatest potential and indeed whether any such systems will offer sufficient benefit to justify their cost.

To fill this knowledge gap, the main objectives of this project were:

- To investigate, review and classify state of the art adaptive structures, concepts and technologies.
- To develop a methodology to estimate the potential benefit of adaptive structures in crashes; and to use this to estimate the benefit of a ‘generic’ adaptive concept, which represents the likely response of a typical adaptive system.

The approach taken for this work was as follows. Firstly, current adaptive structure systems, concepts and related technologies were investigated, reviewed and classified. Using this information a generic concept was selected, based on parameters such as the size of its target population and technical feasibility. Following this, a methodology to estimate the potential benefit of this concept was developed and applied.

2 Investigation and Review of State of the Art Adaptive Structures, Concepts and Technologies

A review of the state of the art adaptive structures, concepts and technologies was performed. The approach taken was firstly to define the limitations of current secondary safety systems, which effectively determined the opportunities or requirements for adaptive structures. Following this, a review of adaptive structure concepts and the technologies necessary to make them technically feasible was performed according to impact configuration, i.e. frontal, side, etc. Next, a review of proposed systems was performed. Again, this review was performed by impact configuration and also identified the technical feasibility and target population for each system. Finally, from this, a generic adaptive concept was selected as an example to help develop the benefit assessment methodology.

The review also searched for previous work to estimate the potential benefit of adaptive structures and found no reported work. The only work found was for adaptive restraint systems and even this was limited.

The following sections report the objectives and results of this work, but firstly a definition of an adaptive structure is given for clarity.

2.1 Definition of an Adaptive Structure

Secondary safety systems are designed to reduce the level of injury for persons involved in a collision by operating in the “crash unavoidable” and “in crash” phases (Figure 1). An adaptive structure is a particular type of secondary safety system, which can change its properties depending on the configuration and severity of the crash experienced, to optimise its performance to minimise injury risk. These changes can include: mechanical movement of components in a system; regulation of various parameters that allow components to move/deform at certain rates; adaptation of the physical properties of a material in a system such as the viscosity of a fluid, etc. Adaptable structures differ from standard structures, whose impact-absorbing capabilities vary passively according to crash severity. Adaptable structures are likely to use pre-crash sensing to supply information about the crash configuration and help maximise the amount of time available for them to adapt. It should be noted that pre-crash sensing is also likely to be used to take measures to avoid or reduce the severity of the crash using, for example, pre-crash braking. This illustrates that, if adopted, adaptable structures will, most likely, form part of an integrated safety system in a future car.

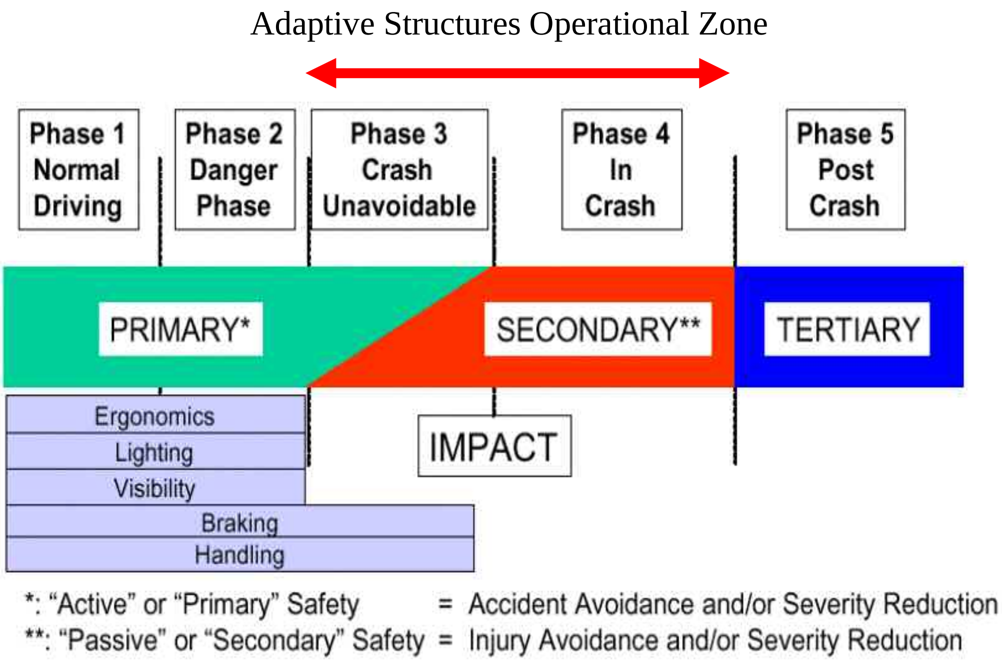

Figure 1: ACEA Safety Model

2.2 Objectives

The objectives of this review were:

- To investigate, review and classify current adaptive structure systems and concepts by target population, likely effectiveness, technical feasibility etc.
- To select a candidate concept or system to be modelled in order to use the concept or system as an example to develop the benefit assessment methodology

2.3 Limitations of current systems and requirements for adaptive systems

Current vehicle safety designs focus on achieving optimal performance in regulatory and consumer rating laboratory crash tests. This provides optimised protection for occupants when involved in crashes similar to these tests i.e. a similar impact severity and similar structural interaction with the target object. However in collisions where the impact is not similar to that in the laboratory test i.e. the impact severity is lower or the structural interaction is different, then the crash performance of the vehicle(s) in the collision is non-optimal. In order to optimise the crash performance of a vehicle in different impact types (impact speed, collision partner, overlap etc.) the vehicle must be able to adapt to the crash scenario encountered. This can be achieved by using an adaptive vehicle structure.

In order to adapt to the crash scenario, it is required that the vehicle can sense the relevant parameters of the accident scenario to process whether adaptation is necessary and what level of adaptation would provide optimal crash performance. The sensing can be provided by a number of different types of sensors. These include: sensors measuring host vehicle dynamics such as velocity, ride height etc; pre-crash sensors measuring closing velocity of host vehicle and possible collision partner, location of optimal impact point of collision partner such as sill or bumper etc; impact load sensors measuring the force of the crash.

An important requirement in determining the acceptability of an adaptive structure system is the failure mode. The failure mode is the level of adaptation that occurs if the system were to fail such as an electronics failure or if the system failed in the impact itself. A system can be defined as having a 'fail-safe mode' if the system still offers levels of protection similar to those seen in regulatory laboratory testing should the system fail. The system must also receive no false signals which may actuate the system when no crash is imminent or occurring.

Another requirement of an adaptive system that could practically be installed in vehicles is that it should not add a significant amount of mass to the vehicle as this will have a negative effect on vehicle performance such as acceleration, fuel economy, etc. A further requirement is that there should be no significant increase in cost to install the system on new vehicles. An increase in manufacturing costs increases the sale cost to the consumer and are therefore keeping these costs to a minimum is favourable. Another requirement of an adaptive system is that the system should occupy minimal packaging space, since packaging space in a vehicle is limited due to styling constraints and increased demand for compartment space.

In frontal impacts there are many factors that affect the crash performance of a vehicle. The stiffness of the frontal structure of a vehicle is normally fixed, and therefore in lower velocity impacts, the full crush distance is not utilised, resulting in a non-optimal deceleration pulse. A further limitation is that in offset impacts, the effective stiffness is lower than in a full width impact, thus resulting in a non-optimal deceleration pulse. Another aspect that can affect crash performance in an impact is compatibility between the host vehicle and the collision partner. The compatibility factors which limit non-adaptive vehicle structures are frontal force levels and structural interaction. Manufacturers desire for improved packaging i.e. increased compartment space, has minimised the available frontal crush length, therefore heavier vehicles have higher frontal force levels than lighter vehicles, thus absorbing less kinetic energy in an impact between a light and heavy vehicle. Poor structural interaction in impacts e.g. override and the fork effect can produce reduced frontal crush level effectiveness. All of these issues can limit the performance of the current systems, often by affecting the deceleration of the occupant compartment which can induce higher injury severity, particularly for occupants with lower biomechanical tolerances such as elderly occupants.

In side impacts, optimal occupant protection is achieved by accelerating the occupant as ‘gently’ as possible without applying injurious high point loads to any body region. In theory this could be achieved with a rigid vehicle side structure and padding between the occupant and vehicle side optimised for the severity of the impact. In practice, as vehicle side structures are much less stiff than vehicle frontal structures, there is much occupant compartment intrusion in a side impact and optimal occupant protection involves careful control of the complex interaction of the intruding side structure, the padding, in particular that offered by the airbag system, and the occupant. In general, this interaction is optimised for the legislative and consumer test conditions and as it is so complex it is difficult to adapt it for other impact configurations. As the padding provided by the airbag is much easier to control than the structure, it is likely that designers of adaptable systems will first focus on the airbag. The focus for adaptable structures for side impact is more likely to be the front of the striking car. This is because the geometry and stiffness of the striking car is one of the major influencing factors on occupant injury, so much opportunity exists to adapt the front of the striking car for side impact as at present it is optimised for frontal impact. Parameters which could be adapted include:

- A reduction of the stiffness of the front of the rails to give better stiffness matching between the striking vehicle’s front and the struck vehicle’s side which would enable the striking vehicle to absorb a larger proportion of the impact energy.
- A change in the geometry of the striking vehicle to enable better engagement of the struck vehicle’s main side structures.

In vehicle impacts with vulnerable road users (pedestrians and cyclists), vehicles with non-adaptive structures are compromised because they also have to meet other requirements such as vehicle occupant visibility, vehicle aerodynamics and vehicle styling. However, adaptive structures give the opportunity to overcome these compromises and allow designers to offer protection levels above those needed to meet the current regulatory and consumer rating requirements and also offer protection in areas not included in the scope of current regulations, such as the A pillars.

2.4 Concepts and Technologies

This section describes and discusses the adaptive structure concepts reviewed and the technologies necessary for some of these concepts to be realised. The concepts reviewed are categorised by collision type, namely frontal, side and vulnerable road user impacts.

2.4.1 Frontal impacts

2.4.1.1 Alter frontal force level

The first concept for an adaptive structure to solve some of the limitations of current frontal impact designs is to alter the frontal force level of the frontal structure of the vehicle dependant upon the collision scenario e.g. lowering the frontal force levels for lower velocity impacts. Altering the frontal force level of the frontal structure (e.g. longitudinal rails) will allow for optimal occupant compartment deceleration to be achieved for more than one crash scenario. This concept could consist of a system that had just 2 settings (i.e. higher force level or lower force level), or could be a system where the frontal force level of the rails could be varied infinitely between the minimum and maximum force level possible in the system.

2.4.1.2 Alter height of impact point

Another concept for frontal impacts is to alter the height of the impact point for better structural interaction. Ensuring that the preferred impact points of the vehicles are aligned so as to induce crushing of the rails etc will achieve lower deceleration levels than if the preferred impact points were not aligned. Again, this concept should help optimise the occupant compartment deceleration pulse.

2.4.1.3 Transfer load between longitudinal rails

A further concept for frontal impacts is to transfer some of the load between the longitudinal rails in an offset impact. This will require a connection between the rails to transfer the load. This will utilise the crushing capacity in both longitudinal rails, therefore distributing the load between both rails.

2.4.1.4 Reposition the occupant

Another concept to reduce occupant injury is to move the occupant in the vehicle to allow more space for the restraint system to protect and decelerate the occupant. Such a system would work by sensing that an impact was about to occur and move the seat rearwards to reduce injuries caused to the occupants, particularly those seated further forwards. A disadvantage of this concept is that it could distract or even hinder the driver taking accident avoidance or mitigation actions, for example it could cause the removal of the driver’s foot from the brake pedal.

2.4.1.5 Alter the force levels of vehicle interior

Another concept is to alter the force levels of areas of the vehicle interior which may cause contact induced injuries to occupants of the vehicle. By altering the force levels of such areas based on the impact severity and/or occupant information (e.g. seating position, mass etc.), deceleration of the contacted body part, and thus injury severity, can be reduced.

2.4.2 Side impacts

2.4.2.1 Reposition the occupant

The first concept reviewed of an adaptive structure to solve some of the limitations of current side impact designs was to move the occupant to a position where the likelihood of injury is reduced. In a side impact this is upwards and/or away from the side which is to be impacted. The reduced forces on the occupant and reduced likelihood of contacting part of the interior contribute to reducing the injury severity levels.

2.4.2.2 Optimise padding protection

Another concept is to optimise the padding protection for low severity impacts. The objective of this is to reduce the deceleration of the occupant or particular body parts of the occupant in an impact. This is particularly important for occupants with lower injury thresholds, such as elderly occupants.

2.4.3 Vulnerable road users

2.4.3.1 External airbags

The first concept reviewed was the introduction of external airbags to the vehicle. These could be installed in various areas on the front of the vehicle, in particular on ‘hard’ areas such as the A-pillars, to offer ‘cushioning’ for pedestrian and cyclist impacts to help reduce their risk of injury.

2.4.3.2 Raised bonnet

Another concept for adaptive systems for vulnerable road user protection is to raise part of the bonnet to allow it more space to deform, so that it can better ‘cushion’ the impact of pedestrians and cyclists to help reduce their risk of injury.

2.4.4 Technologies

The implementation of many concepts will only be possible with the use of advanced technologies. Many of these technologies are currently being developed to ensure that they can be used practically in ‘real-world’ vehicle safety applications.

One such technology is the use of field-responsive fluids. A field-responsive fluid is a material which reacts to the application of a field to the fluid by changing the rheological properties of the fluid i.e. the flow of the fluid. Examples of field-responsive fluids for which a vehicle safety application is foreseeable are magnetorheological (MR) and electrorheological (ER) fluids, which increase in apparent viscosity as a magnetic field or electric field, respectively, are applied to the fluid. The main advantage of MR fluid over ER fluid is that the shear stress (which creates the apparent increase in viscosity) achievable is much higher (up to 100kPa for MR compared to 5kPa for ER) [Butz and von Stryk, 2002]. However MR fluid is approximately twice as dense as ER fluid. The main drawback with using a field-responsive fluid in vehicle safety applications is that if the system were to fail, the fluid would have limited viscosity and thus provides little or no resistance to an impact.

A further technology which may be used in adaptive structures is a shape-memory alloy (SMA). These could feasibly have two functions in adaptive vehicle structures. The first function would be for the SMA to operate as an actuator. One form of SMA actuators is to send an electric current through an SMA spring, which will alter the force produced by the spring. This could be used in applications such as moving the occupant in a vehicle. Another function of an SMA would be to act as a ‘smart’ structure. The advantage of using an SMA as a structure is that it can undergo large changes in it’s physical properties, which could be adapted to the crash condition. The major disadvantage of using an SMA as a smart structure for most mechanical functions is that the maximum stress and strain levels possible decrease as the SMA undergoes a cycle, however as the SMA will only operate once (i.e. adapting for the crash condition) then this will not be a major issue [Stalmans and van Humbeeck, 1995].

Another technology with a likelihood of future use in adaptive structures is pre-crash sensing. Some of this technology is used on current production vehicles to trigger active braking systems and adaptive restraint systems. Pre-crash sensing can utilise one of, or a combination of, radar, lasers and cameras to monitor the position and closing velocity of possible collision partners.

A further technology that may be used to aid adaptive structures is vehicle occupant sensing. This technology uses sensors to measure various parameters about the occupant which may include occupant weight, position of the occupant from the steering wheel etc. These parameters can then be used to alter adaptive crash systems to the optimum level of protection for the specific occupant. This technology is currently used on some production vehicles for adaptive restraint systems; however it could feasibly be used to assist in adapting vehicle structures for occupant protection.

2.5 Adaptive Systems

Based on the concepts described above, many possible adaptive structural systems have been proposed. Each of these systems was reviewed and categorised by considering its objectives, its target population, and its technical feasibility which included an assessment of the likelihood of its adoption into production vehicles. The results of this review are presented in tabular form in Appendix A. Relevant references are listed in Appendix B. A summary of these results is given below.

2.5.1 Frontal Impacts

2.5.1.1 Alter frontal force level

The first systems reviewed were those that altered the frontal force levels of the vehicle. These included a system that used friction pads acting on beams in the position of longitudinal rails to control the deceleration of the vehicle in an impact where the pressure applied to the friction pads is dependant upon the impact force. Another system uses hydraulic cylinders in place of the longitudinal rails where the hydraulic flow rate is controlled to provide optimum deceleration in an impact, dependant upon the impact force. Both of these systems share the same technical feasibility issues due to large increases of mass and cost, components which take up significant packaging space and a necessity for components to be capable of retracting underneath the occupant compartment which may not be feasible apart from in larger MPV-type vehicles. If these systems fail, the default mode for the systems would provide minimal protection to the occupants.

Two further systems that can alter the force levels of the frontal structure of the vehicle are firstly a system that uses pyrotechnic charges to reduce the force level of the longitudinal rails and a system that uses pyrotechnic charges to remove two C-section profiles that are attached to a box-section longitudinal rail. The charges are either activated or not activated if the impact force is low or high respectively. This system weakens the beams, which allows them to fail at lower frontal force levels. This system would require sensors to recognise the impact force very early in the impact, which may not be feasible with current sensors. The advantages of this system are that there would be a low to moderate level of mass increase, a moderate cost increase, the amount of packaging space required is minimal and the failure mode is to fail-safe.

Further systems that alter the force levels of the frontal rail utilise rheological fluid. These systems either use rheological fluid-impregnated solids or a rheological fluid damper system. The primary disadvantages of these systems are that the technology has not yet matured to a level where it can be used for vehicle safety applications and that the failure mode for these systems would not offer suitable levels of protection should the system fail.

2.5.1.2 *Alter height of impact point*

Systems were reviewed that altered the impact point of the vehicle to improve structural interaction. These included firstly a system that alters the ride height of the vehicle using the current vehicle active suspension system and secondly a system that deploys two vehicle supporting members underneath the vehicle to alter the ride height. Both systems aim to align the front bumper of the host vehicle with a preferable target on the collision partner such as the front bumper for frontal collisions or the sill of a target vehicle for side collisions. A third system, for use on larger vehicles such as an SUV, uses an actively hinged bumper assembly to drop an underrun guard below the bumper level. All of these systems will require pre-crash sensing to detect that a crash is imminent and to sense the position of the preferable impact point on the collision partner. The first system described would not create a large increase in mass or cost as the mechanical system, i.e. an active suspension system, is already fitted to some vehicles. However, the other two systems would, most likely, result in large mass and cost increases, and also provide packaging difficulties as the components would need to be stored in the vehicle frontal structure area. Another technical feasibility issue that may arise is if two vehicles in a frontal impact both have a system to alter their ride height, as the system may only have time to make one height adjustment, in which case one vehicle may drop to the initial level of the collision partner whilst the other vehicle may rise to the initial level of the collision partner, which would obviously negate the benefit of introducing the system. To overcome this potential problem, communication between the vehicles may be necessary.

2.5.1.3 *Transfer load between longitudinal rails*

The principle of the next type of system reviewed was to transfer load from the loaded longitudinal rail to the unloaded longitudinal rail to better optimise energy absorption and the occupant compartment deceleration. The first such system reviewed operated using a cable system which connects rods which are located inside the longitudinal beams and attached at the bumper crossbeam end, so that as the rod in the loaded rail retracts under the occupant compartment the opposite rod is forced to retract, crushing the rail it is attached to. The other system reviewed transferred the load using hydraulics. Two cross-fed hydraulic cylinders are attached to the vehicle next to the longitudinal rails. As one longitudinal is loaded, the adjacent hydraulic piston is retracted which transfers the hydraulic fluid to the opposite cylinder, forcing the piston to retract and thus loading the initially unloaded longitudinal. Both of these systems would increase the vehicle’s mass and cost significantly, and would need to occupy packaging space in the front of the vehicle and under the occupant compartment that is not freely available on modern production vehicles.

2.5.1.4 *Reposition the occupant*

An adaptive structure system that repositions the occupant in the vehicle involves moving the vehicle seat rearwards. Pre-crash sensing would sense that a collision was imminent and send signals to actuators which move the vehicle seat rearwards to increase the distance for the restraint system to decelerate the occupant. This system is already installed on a production vehicle for the front seat passenger and therefore can be seen as technically feasible.

2.5.1.5 *Alter the stiffness of vehicle interior*

Adaptive structure systems that alter the stiffness of areas which may cause contact induced injuries include systems which use either hydraulic or rheological piston systems to retract the steering wheel at a rate optimal for driver head deceleration. These systems alter the field on the rheological fluid or alter the hydraulic fluid flow rate dependant upon the impact force and occupant information (mass, seating position etc.) to regulate the rate of retraction. These systems will both create mass and cost increases. However as the steering wheel will retract after the airbag has been impacted by the occupant, there is sufficient time for the force of the impact to be sensed and thus the rate of retraction of the steering wheel can be processed. Another system that may alter the stiffness of areas which may cause contact induced injuries is a knee protection apparatus, which retracts the knee contact area using a hydraulic system to optimise the deceleration of the lower extremities of the occupant, thus putting a reduced load on the body through the restraint system. This system operates in a similar manner to the steering wheel retraction systems, by using data sensed about the impact severity and occupant to determine the optimum rate of retraction. This system would create a moderate increase in mass and a large increase in cost thus reducing the likelihood of adoption in a vehicle as knee airbag restraint systems are probably more cost and weight effective.

2.5.2 Side impacts

2.5.2.1 Reposition the occupant

The adaptive structure system for repositioning the occupant in the vehicle for side impacts operates in a similar manner to repositioning the occupant in the vehicle for frontal impacts. However the actuation will move the vehicle seat away from the impacted side, and/or upwards. Systems to move vehicle seats in impacts are already available on some productions vehicles and therefore can be seen as technically feasible.

2.5.2.2 Alter the stiffness of the vehicle interior / Optimise padding protection

In a side impact, the occupant may contact the armrest of the vehicle which may result in injurious high point loads if the armrest stiffness is high. To overcome this problem an adaptive armrest has been proposed which collapses the upper face of the armrest, using either electronic actuation with crash sensors or mechanical linkages connected to the outer shell of the door, when a side impact is detected. This system will create a moderate increase in mass and cost of the car; however the effectiveness of the system is likely to be low, particularly as a well designed non-adaptive armrest will not contribute greatly to the occupant injury severity.

Optimisation of padding protection for side impacts is currently available on production vehicles in the form of side airbags; however this is classed as an adaptive restraint as opposed to an adaptive structure and therefore was not considered for further in this review.

2.5.3 Vulnerable road users

The adaptive structures reviewed for vulnerable road users were based on two concepts, external airbags and ‘pop-up’ bonnets.

2.5.3.1 External airbags

The first system reviewed used a windscreen airbag, which inflates up from underneath the vehicle bonnet to protect the head of the pedestrian or cyclist from impact with the windscreen. The system is triggered by sensors in the vehicle bumper. This system would create a low to moderate increase in mass and cost. However, the foreseeable effectiveness would be high, and with pedestrian impact sensors already in use on production vehicles, the technology is available. Another system was reviewed which introduces a frontal airbag onto the vehicle. This system uses pre-crash sensing to identify that a pedestrian impact is imminent and deploys an airbag at the front of the bonnet/bumper area to cover the bonnet/bumper/grille area. This system would create only moderate mass and cost increases; however the pre-crash sensing required is a technology that has yet to mature to a level suitable for use.

2.5.3.2 ‘Pop-Up’ bonnet

Another adaptive system which is currently in use on some production vehicles is the ‘pop-up’ bonnet. This system uses a mechanical device to raise the rear edge of the bonnet when an impact with a pedestrian is detected. The additional space under the bonnet allows it to deform more without contacting any stiff areas such as the engine, thus offering greater ‘cushioning’ for the impact of the pedestrian, in particular the head. This system is already in use on some production vehicles and thus can be seen as technically feasible.

2.6 Discussion

The review above shows that the number of adaptive structural systems proposed is limited, with the majority of them based on the concept of altering the frontal force levels of the vehicle to optimise the vehicle’s deceleration pulse. Also, it should be noted that the majority of systems proposed have major technical feasibility problems to overcome before they will become viable. However, as the technology required for many of the adaptive concepts evolves, in particular that for pre-crash sensing which can detect characteristics of object that will be impacted, then many of these problems are likely to be overcome. Systems where the technology has matured, such as pedestrian impact sensors for use in pop-up bonnets, are already available on production vehicles, demonstrate that manufacturers are prepared to employ adaptive structures on their vehicles if the technology, feasibility, and cost effectiveness of the system are available and viable.

2.7 Selection of Example Adaptive Structure

The concept selected as an example to be used for the benefit analysis was an adaptive frontal structure which can adjust its frontal force levels to optimise the occupant compartment deceleration pulse for different frontal collision configurations, in particular severity and overlap. The main reasons for selecting this concept were that a large proportion of the adaptive systems reviewed were based on this concept and it had a potentially large target population.

3 Estimation of Benefit of Selected Adaptive Structure

The aim of this work was to estimate the potential benefit, in terms of casualty reductions, of fitting the selected adaptive system to cars in Great Britain. As mentioned above, the adaptive concept selected was an adaptive frontal structure which can adjust its force levels to optimise the occupant compartment deceleration pulse.

To calculate the benefit of this concept, the first step was to make some assumptions about its performance. Based on these assumptions the next step was to derive a methodology to calculate the benefit. The derived methodology followed the usual approach for performing benefit type analyses; firstly to estimate the target population, i.e. the number of casualties that are likely to experience a reduction in their risk of injury as a result of the introduction of the countermeasure; secondly to calculate the effectiveness of the countermeasure, i.e. the reduction in injury risk offered by the countermeasure to those casualties in the target population; and finally to calculate the benefit by multiplying the number of casualties in the target population by the countermeasure effectiveness.

For this analysis the CCIS and STATS19 / SHIPS accident databases were used to identify the target population and computer simulation was used to estimate the effectiveness of the adaptive frontal structure. The details of this work are described below.

3.1 Performance of Adaptive Frontal Structure Concept

To minimize the injury to car occupants during a frontal crash a first step is to ensure that the occupant compartment is strong enough to prevent significant collapse to give the occupant a survival space within which the restraint system can operate. The next step is to ensure that not only the restraint system is optimised but also the compartment crash pulse generated by the vehicle structure.

Previous research has shown that the deceleration pulse shape generated by a current car, which has an increasing deceleration level throughout the impact, is far from optimal and that a pulse with a constant deceleration shape is much better [Wykes et al. 1998]. More recent work states that for low velocity crashes a constant deceleration pulse is the optimal shape whereas for high crash velocities a high-low-high crash pulse shape as shown in Figure 2 is optimal [Witteman 2005].

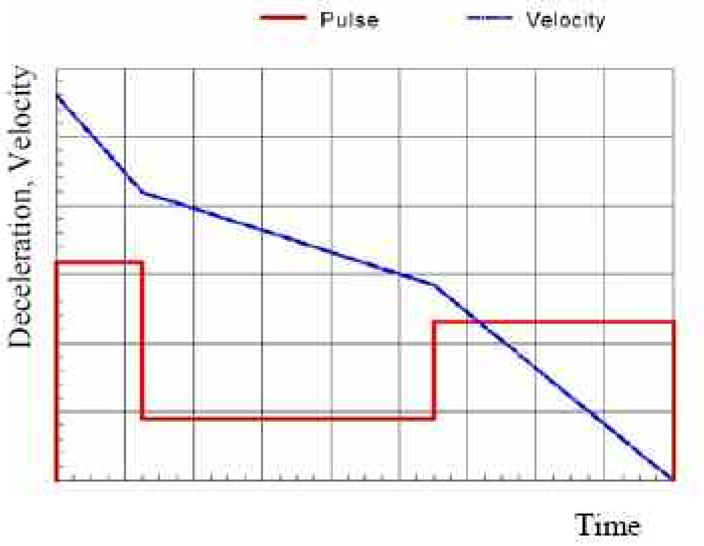

Figure 2: Optimal deceleration pulse for high velocities.

The reason that this phased pulse shape is optimal for high crash velocities is that it is better tuned to the restraint system. The high deceleration at the beginning of the impact offers a better pulse to trigger the restraint system, the low deceleration in the middle of the impact ensures that the occupant does not impact the airbag at too high a velocity and the high deceleration at the end of the impact stops the occupant before he contacts any interior structures. However, an adaptive system of the future is likely to have pre-crash sensing which can be used to trigger the restraint system, so a high deceleration at the beginning of the impact for this purpose would not be necessary. Also, the airbag stiffness and firing time could be tuned so that the velocity of the occupant impacting it was not too large. Taking this into account it can be assumed, as a first approximation, that a constant deceleration pulse shape is optimal for impacts of all velocities for future vehicles with pre-crash sensing and advanced restraint systems.

Another factor which affects the optimisation of the pulse is the crush or ride-down distance. This should be maximised for impacts of all velocities to ensure that deceleration levels are as low as possible.

A conventional car has three main load paths which determine its frontal force levels and hence the compartment deceleration pulse. These are the two main longitudinal structures and the load path formed when the engine contacts the firewall. In an impact these load paths are engaged to varying degrees dependent upon the impact configuration, in particular the overlap and the velocity.

For full width impacts all of these load paths may be engaged whereas for offset impacts only one longitudinal member and possibly the engine firewall load path will be engaged. This leads to current car's exhibiting higher frontal force levels and hence higher compartment deceleration pulse levels for a full width impact compared to an offset impact as shown below especially at the beginning of the impact (Figure 3). It should be noted that the crush or ride-down distance for the full width impact was less than that for the offset impact , 0.7 m compared to 1.0 m respectively. This was because the car was not able to crush as much in the full width impact compared to the offset impact because the engine limited the crush depth in the full width impact whereas in the offset impact the engine could rotate to allow greater crush. The result of less ride-down in the full width impact was an increase in the deceleration level which was why the peak deceleration levels in the full width impact were approximately the same as those in the offset impact even though the full width impact pulse had a more constant shape.

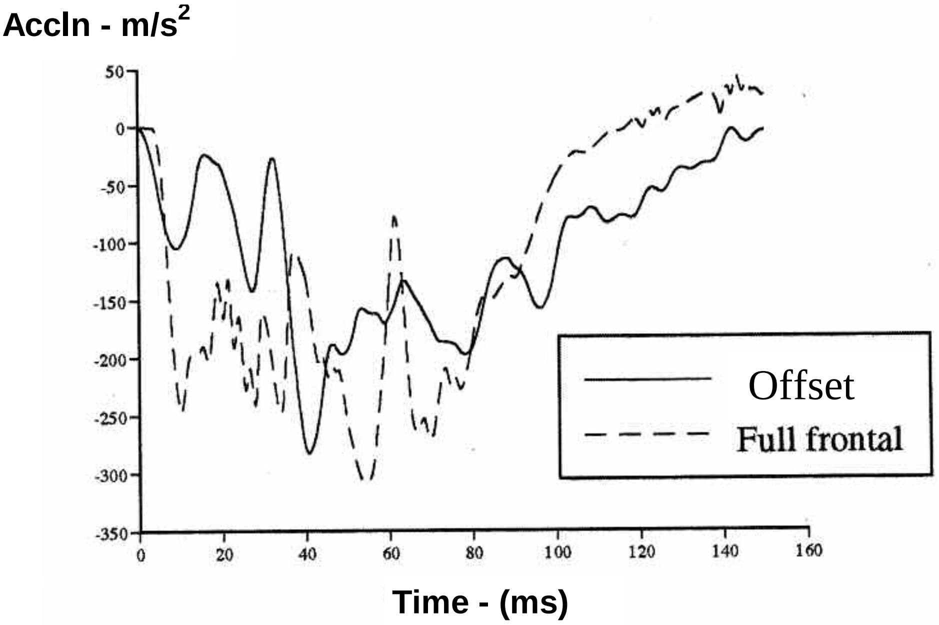

Figure 3: Comparison of compartment deceleration pulses from an offset car to car impact and a full overlap rigid barrier impact, both with a delta V of 56 km/h.

To be able to calculate the benefit of the adaptive frontal structure concept which can adjust its force levels to optimise the occupant compartment deceleration pulse, assumptions about its performance had to be made. Because this was the first analysis of its kind, it was decided to assume that the adaptive frontal structure behaved in an ideal manner so that an upper bound to the benefit of this concept could be determined.

For this purpose, the first assumption was that the adaptive structure would only perform in frontal impacts where the car had sufficient capability to absorb the impact energy in its frontal structure without significant compartment intrusion. It was also assumed that adaptive structures would only be introduced into the vehicle fleet after the implementation of measures to improve a vehicle's frontal impact compatibility. The improved frontal impact compatibility of cars is expected to prevent intrusion in frontal collisions up to the test severity, which is currently 56 km/h [Edwards et al. 2007].

The range of accidents in which the adaptable structure was assumed to perform were those with speeds greater than or equal to 20 km/h and less than 60 km/h because cars generally perform in this manner in legislative and consumer rating tests, which have test speeds ranging from 56 km/h to 64 km/h. The next assumption was that the structure was sufficiently adaptable to be able to alter the car's frontal force levels to give a constant compartment deceleration pulse shape for impacts in which at least one of the car's main longitudinal structures was engaged, as it was assumed that the adaptable structure would be incorporated into these structures. This was assumed to include frontal impacts with overlaps greater than or equal to 20 percent. It was also assumed that the force level could be adapted to allow maximum crush of the car's structure independent of the velocity of the impact, thus assuming that the magnitude of the compartment deceleration was minimised.

In summary it was assumed that the adaptable concept would alter the car's frontal force levels:

- To give a constant compartment deceleration pulse for frontal impacts with an overlap ≥ 20% and velocities ≥ 20 km/h and < 60 km/h Estimated Test Speed (ETS)[1].
- To utilise the maximum available crush in frontal impacts for velocities ≤ 60 km/h ETS.

3.2 Accident Databases

In order to calculate the benefit for the introduction of the adaptive structure, two accident databases were used – a national database (STATS19 / SHIPS) and a detailed accident database (CCIS). A detailed accident database was required in order to identify the target population for the introduction of the adaptive structure as all of the parameters that were required to identify the target population were not available in the national database.

3.2.1 STATS19 / SHIPS

For this analysis road accident data from Scotland for 1998-2005 has been linked with medical data from the Scottish Hospital In-Patient System (SHIPS). Full details of the linkage method used are available in Broughton & Keigan, 2007 which is an updated version of the method that was used in earlier linkage studies [Stone, 1985; Keigan et al, 1999].

3.2.1.1 The STATS19 file

All road accidents involving personal injury and at least one vehicle occurring on the highway ('road' in Scotland) that were reported to the police within 30 days are recorded in the National Road Accident database (STATS19). Details of accident circumstances and the vehicles and casualties involved are recorded in annual files.

3.2.1.2 The SHIPS file

The Scottish Hospital In-Patient System (SHIPS) data were supplied by the Healthcare Information group of NHS National Services Scotland. The data were released to TRL under a confidentiality

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[1] Estimated Test Speed: Accident severity measure calculated from measurements of the vehicle's deformation.

statement for users of NHS patient data. Episodes (casualties) with an 'Emergency - Road Traffic Accident' type of admission or a specified Road Traffic Accident diagnostic code on the hospital discharge that were admitted and discharged within the years 1998 to 2005 were selected.

Among the large number of variables provided within this file there are six diagnosis codes that are based on the International Classification of Diseases (ICD) codes [World Health Organisation, 1992]. that use the ICD10 format. These provide details of injuries by body region that include, for example, ICD10 codes S00-S09 are injuries to the head and S20-S29 are injuries to the thorax.

The Abbreviated Injury Scale (AIS) is an internationally recognised method of measuring injury severity. It was originally developed by a committee of specialists for use in crash investigation and has been revised several times to cover a wider range of injuries. The AIS is based on threat to life. The AIS scale is as follows:

- AIS 0 No injury
- AIS 1 Minor injury
- AIS 2 Moderate injury
- AIS 3 Serious injury
- AIS 4 Severe injury
- AIS 5 Critical injury
- AIS 6 Maximum injury

The body is divided into 8 regions and an AIS score is assigned to each region; the MAIS for a particular casualty is the maximum of the AIS scores assigned and is used to summarise overall injury severity.

3.2.1.3 Enhanced dataset

To facilitate classifying the ICD10 injuries into AIS98 format a mapping system developed at the University of Navarra [Apollo, 2006] was adopted. For this analysis the most severe injury of AIS 2 or higher for the individual body regions of interest, i.e. the head and thorax, have been assigned.

Records from the enhanced dataset have been chosen using the following STATS19 criteria:

- Accident data from 1998 to 2005 inclusive
- First point of impact on the vehicle was frontal
- No rollover
- Front seat occupants of cars or taxis
- Casualties aged 12 and over

3.2.2 CCIS

The UK’s Co-operative Crash Injury Study (CCIS) is one of Europe’s largest car occupant injury causation studies. The programme of research started in 1983 and continues to investigate real life car accidents. Multi-disciplinary teams examine crashed vehicles and correlate their findings with the injuries the victims suffered to determine how car occupants were injured. The objective of the study is to improve car crash performance by continuing to develop a scientific knowledge base, which is used to identify the future priorities for vehicle safety design as changes take place.

The study carefully selects accidents to be representative of injury car crashes that occur in the UK and so can be used to predict national trends. The real world evidence that CCIS provides allows safety improvements to be measured and potential future benefits to be predicted.

CCIS has the aim of investigating how car occupants are injured in crashes and helping to develop injury countermeasures, such as legislation and design solutions for improved car occupant protection. This is achieved by:

- Investigating the pattern of occupant injuries and their severity for all car crash scenarios
- Defining the population and relative frequency of different crash types
- Developing an understanding of the causes and mechanisms of injury to car occupants
- Investigating the effect of vehicle safety features on occupant injuries and providing information on the crashworthiness of vehicles
- Identifying the needs for improved vehicle safety as changes take place
- Providing biomechanical information for researchers who are developing crash test dummies.

Detailed examinations of approximately 1,500 accident-damaged cars and car-derived vans were carried out per year in phases 6 and 7 of the CCIS project. Crashes were selected for consideration (became notifications) if at least one involved car was less than seven years old at the time of the accident, contained an injured occupant and was towed from the scene.

CCIS uses a stratified sampling procedure, where all crash notifications (accidents) involving a killed or seriously injured occupant in a towed car less than seven years old at the time of the accident must be investigated. From the remainder of the crash notifications which met the CCIS criteria, crashes were chosen for investigation randomly to ensure the contractual numbers of cars were examined and that the ‘slight’ accidents are representative. Therefore, the CCIS database both has biases towards newer vehicles and more seriously injured casualties.

Once an accident qualifies as a CCIS notification and the decision is made to investigate, every effort is made to examine all the cars involved in the collision. Vehicle investigations are typically carried out between 24 and 72 hours after the collision at a recovery garage. There are seven different regional teams who were contracted to investigate a fixed number of vehicles per year.

The data in CCIS is collected by skilled vehicle examiners and includes detailed computerised records of the vehicle damage and intrusion, evidence of occupant contacts with the vehicle interior and the seat belt or airbag use or status.

More information on the data collection methods employed can be found at www.ukccis.org.

The CCIS data set used for the calculation of benefit was taken from CCIS Phases 6, 7 & 8, which comprised accidents that occurred between 1998 and 2007, and was defined using the following criteria:

- Front seat occupants of passenger cars (or car derivatives)
- Occupants aged 12 or over to exclude young children in child seats
- Frontal impact (significant impact)
- All collision partners included
- Primary Direction of Force (PDF) between 11 and 1 o’clock
- No rollover
- Known ETS (Estimated Test Speed)
- Vehicle manufactured in 1998 or later
- Known occupant injury
- Known occupant gender

This produced a data set containing 2040 occupants, 1773 of which were belted and 267 of which were unbelted. This was considered to be an equivalent data set to the STATS19 / SHIPS data set described previously.

3.3 Methodology Outline

A 4-step methodology was developed to estimate the benefit of the adaptive frontal structure concept described above using detailed (CCIS) and national (STATS19 / SHIPS) accident databases and computer modelling. The benefit was calculated in terms of the expected reduction in head and thorax injuries at the AIS 2+, AIS 3+ and AIS 5+ levels. AIS 2, AIS 3 and AIS 5 injuries represent moderate, serious and critical injuries, respectively. These particular body regions were chosen because they formed a large proportion of moderate and serious injuries for belted occupants (Figure 4) and generally are more susceptible to fatal and life threatening injuries. Another reason for this choice was that thorax injury is likely to be more sensitive to changes that the adaptive system will offer, i.e. changes in the car's deceleration pulse, than other body regions, as the deceleration pulse is a major contributory factor to seat belt loads, which in turn are closely related to chest injury [Mertz et al 1991, Petitjean et al. 2002]. It should be noted that this methodology could be extended at a later date to include injuries to other body regions, such as the neck and leg for which dummy injury risk criteria are available. Dummy injury risk criteria are needed to calculate the risk of injury and system effectiveness from the dummy response measured in test or simulation.

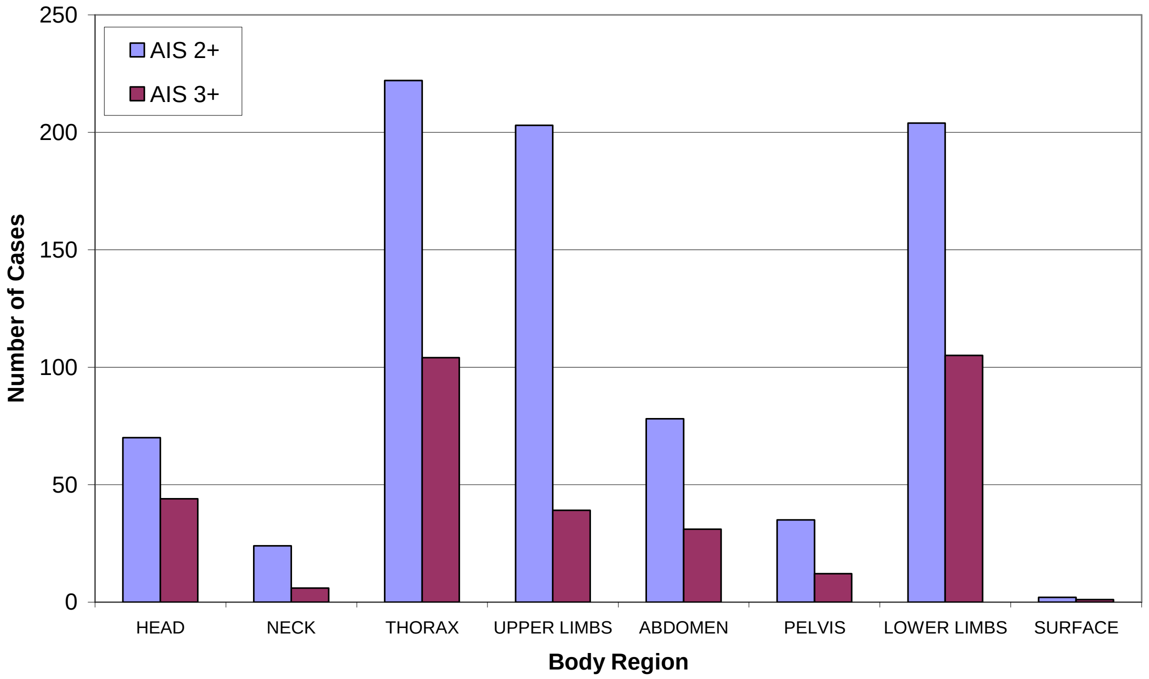

Figure 4: Injury distribution by body region for belted occupants in CCIS data set (1773 belted occupants), showing proportion of head and thorax injuries.

Note: The distribution counts body regions rather than occupants, so each case in the figure above represents the highest AIS level injury sustained by an occupant in the specified body region. An occupant with AIS 2+ injuries to multiple body regions would be counted as a case in each body region where an injury was sustained.

The methodology developed used a standard approach to calculate the benefit, which was to identify the target population (the casualties who are likely to experience a reduction in their injury risk as a result of introducing the countermeasure), to estimate the effectiveness of the countermeasure (in this case the adaptive frontal structure) and then to derive the benefit by multiplying these two quantities.

As described in Section 3.1, the performance of the adaptive structure was assumed to be dependent on accident parameters such as the severity and overlap. Also, it was assumed that there would be no benefit for casualties not wearing a seatbelt. Because these parameters are not recorded in the national accident databases, target population groups had to be identified using the detailed accident database (CCIS) in a similar manner to that used previously by Cuerden (Cuerden at al 2001). Following this approach, the next step was to calculate the effectiveness of the adaptive structure for the casualties in each of the target population groups. Computer simulation was used to do this. Next the benefit was calculated for each target population group and summed to give a benefit for the casualties in the selected accident sample in the detailed accident database. Finally, this benefit was scaled to estimate the benefit for Great Britain (GB) using the national accident databases.

The main steps in the methodology are summarised below:

- Identification of target population groups in detailed accident (CCIS) data sample.

  It was assumed that the adaptive system could offer benefit for casualties in frontal impact accidents in which the severity was greater than or equal to 20 km/h and less than 60 km/h ETS and the overlap greater than 20 percent (Section 3.1). The casualties at AIS 2+ and AIS 3+ levels in accidents that met these conditions were identified and categorised into target population groups according to the accident severity and configuration as shown in the table below.

Table 1: Target population group categorisation.

Accident Configuration (Overlap percentage)	**Accident Severity (ETS km/h)**			
	20 - 29	30 - 39	40 - 49	50 - 59
60 – 100 % (Full Frontal)	✓	✓	✓	✓
20 – 59 % (Offset)	✓	✓	✓	✓

  This was necessary because the adaptive system effectiveness was found to be dependent upon these parameters.

- Calculation of effectiveness of adaptive structure for casualties in each target population group.

  Computer models of a standard car and a car with an adaptive frontal structure were constructed. These models were used to predict dummy injury criteria values for standard and adaptive cars in crashes representative of the accidents seen by each of the target population groups. Following this, the dummy injury criteria values were converted into injury probabilities using injury risk curves, such as the Prasad Mertz expanded Head Injury probability curves shown in Figure 5 below [NHTSA/rules, 1997].

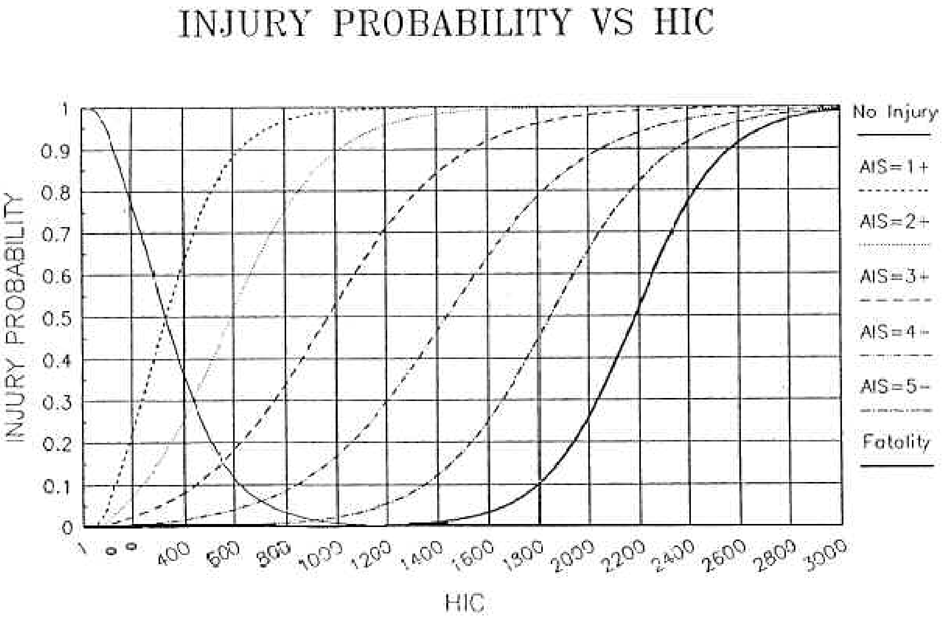

Figure 5: Head Injury risk probability curve.

The injury probabilities were then used to estimate the effectiveness of the adaptive structure for each target population group expressed in terms of the injury reduction proportion, r, calculated using the following equation:

$$r = [1 - \frac{P_a}{P_s}]$$

where P_a is the probability of injury related to the adaptive structure and P_s the probability of injury related to the standard vehicle structure.

- Calculation of benefit for casualties in CCIS dataset sample.

  The proportional benefit for the casualties in the CCIS dataset sample was estimated by calculating the benefit for the casualties in each target population group and summing them as shown in the equation below.

  $$B = \sum_n Tp_n * r_n$$

  where B is the benefit, Tp the number of casualties in the target group and r the injury reduction proportion.

- Estimation of benefit for GB by scaling proportional benefit calculated for CCIS data sample.

  Equivalent data samples of frontal accidents were formed using national and CCIS data. The number of casualties and injuries in the national data were determined and scaled using the benefit proportions calculated above to give the national benefit.

3.4 Description of Model

To estimate the effectiveness of the adaptive frontal structure computer simulation was used. Using version 6.4 of the MADYMO software, a simplistic mass spring system was created to represent the mass and crush stiffness properties of two vehicles, one representing a full frontal impact (overlap 60 – 100 %) and the other a frontal offset impact (overlap 20 -59 %). The stiffness properties of the spring were calculated from the B-Pillar acceleration profiles measured in the two physical tests. The acceleration signals were filtered and integrated twice to allow force-deflection characteristics to be derived. The model was set up applying an initial speed to the mass that represented the test speed and the acceleration time histories were outputted and compared to the original test data. Further simulations were then conducted at different speeds. Using a non-linear spring system to model the vehicle deceleration in this way will overestimate the vehicle's stiffness in lower speed impacts as the spring stiffness is based on the deceleration pulses from physical tests at higher speeds. Therefore it is recommended that further work should consider the use of a more detailed model of a vehicle's front in order to improve the accuracy of the computer simulations.

A generic vehicle model, as included in the MADYMO applications directory, was used to assess the effects of the collision pulse on the occupant motion and injury criteria (Figure 6).

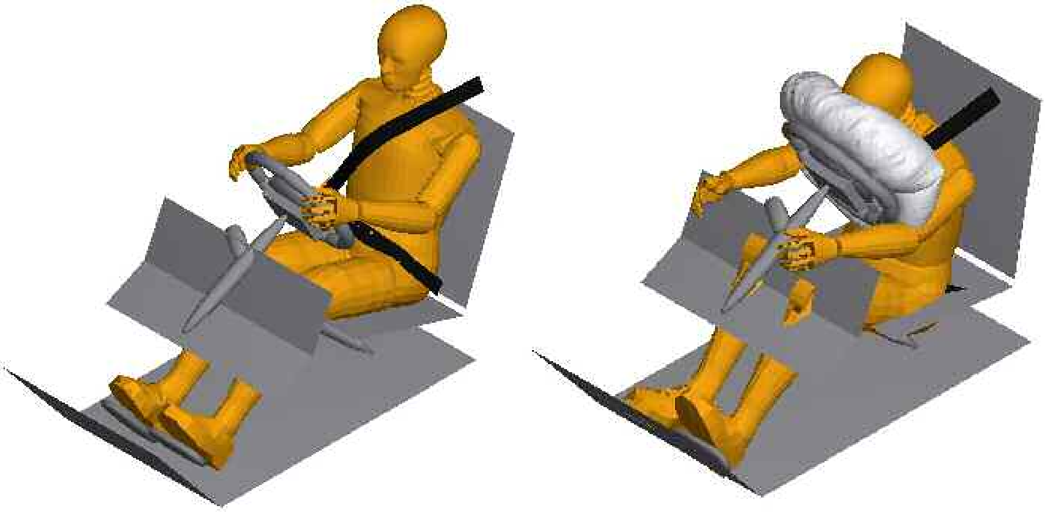

Figure 6: MADYMO generic vehicle model.

The generic model included a driver's single stage airbag and seatbelt with a pre-tensioner and load limiter. The trigger times for the airbag and pre-tensioner were varied with impact type and impact speed. The times for both the airbag and pre-tensioner were 10 ms and 15 ms (for both the 45 and 55 km/h impacts) for the full frontal and offset tests respectively. The airbag trigger times were increased to 23 ms and 28 ms for the full frontal and offset tests, respectively, at impact speeds of 25 and 35 km/h.

Acceleration pulses were calculated from the MADYMO models, based on the derived spring properties, and were directly applied to the occupant compartment models. The simulations using the spring were classed as the standard runs, with HIC_{15}, CTI, Chest Deflection, Chest Acceleration and Head Accelerations outputted.

The MADYMO model was evaluated against the Hybrid III dummy injury criteria values, measured in the physical tests. Due to the generic nature of the compartment model used, it was not possible to match precisely the injuries from the test and simulation, as the restraint systems of vehicles are specifically tuned to their crush characteristics. However, the outputs from the simulations were deemed to be representative of the physical tests (Table 2).

Table 2: Comparison of dummy outputs for the simulations and physical tests in full frontal and offset configurations.

		HIC15	HIC36	Head Peak Acceleration (g)	Head 3ms exceedence (g)	Chest Deflection (mm)	Thorax Acceleration (g)	CTI
Full Frontal	Physical test	N/A	756	82	79	47.6	55	1.085
	56km/h simulation	763	959	84	82	49.9	55	1.1057
Offset	Physical test	N/A	472	54	54	36.2	42	0.84
	56km/h simulation	486	612	71	69	47.0	43	0.95

3.5 Benefit Estimation

3.5.1 Identification of target population groups

The detailed accident data in the CCIS data set described in Section 3.2.2 was used to identify the target population groups where a benefit from the introduction of an adaptive structure might be expected.

As the introduction of the adaptive structure was expected to optimise the deceleration pulse of a vehicle in a frontal impact in order to enable better occupant ride-down, the main group expected to benefit were occupants that had sustained restraint-induced injury rather than injury through contact with the vehicle interior. As such, it was assumed that there would be no benefit for unbelted occupants as the most likely cause of injury would be through contact with the vehicle interior, and therefore unbelted occupants were excluded from the data set.

This removed 267 unbelted occupants, producing a data set containing 1773 belted occupants, 1404 of which were drivers and 369 were front seat passengers. The breakdown of the data set by ETS and Overlap is shown in Table 3.

Table 3: CCIS data set used for the benefit analysis.

Configuration (Overlap Percentage)	Accident severity (ETS km/h)						*Total*
	0-19	20-29	30-39	40-49	50-59	60+	
0-19 %	90	39	28	8	3	1	*169*
20-59 %	186	270	147	76	26	8	*713*
60-100 %	90	317	280	127	43	34	*891*
Total	*366*	*626*	*455*	*211*	*72*	*43*	*1773*

As described previously, the adaptive structure would only be expected to have a benefit for occupants in vehicles with an ETS of between 20 and 60 km/h, and an overlap of greater than 20 percent. As such, a target population within the CCIS data set was identified within these limits which contained 1286 occupants.

Table 4: Target population for benefit analysis indicated by grey shading.

Configuration (Overlap Percentage)	Accident severity (ETS km/h)						*Total*
	0-19	20-29	30-39	40-49	50-59	60+	
0-19 %	90	39	28	8	3	1	*169*
20-59 %	186	270	147	76	26	8	*713*
60-100 %	90	317	280	127	43	34	*891*
Total	*366*	*626*	*455*	*211*	*72*	*43*	*1773*

The distribution of potential confounding factors including gender, age and object hit was compared for the target population and the original CCIS data set, which showed that there were no significant differences that might affect the benefit calculation.

3.5.2 Effectiveness of Structure

To assess the potential injury reduction factors by utilising adaptive vehicle structures, the injury criteria measured in the simulations were compared, for a particular impact type and speed, between the standard and adaptive structures.

The adaptive structures were modelled by using the maximum vehicle deformation calculated for the spring force deflection characteristics. Based on the test speed and ride down distance, an average acceleration level and associated time were determined and applied directly to the occupant compartment model.

The results of the simulations are shown below in Table 5 and Table 6.

Table 5: Simulation results for full frontal impacts.

	HIC_{15}	HIC_{36}	Head Peak Acceleration (g)	3MS Head Acceleration (g)	Chest Deflection (mm)	Thorax Acceleration (g)	CTI
Physical Test	N/A	756	82	79	47.6	54.5	1.085
55 km/h Standard	763	959	84	82	49.9	55	1.1057
45 km/h Standard	570	677	77	73	49.5	50	1.04
35 km/h Standard	360	444	67	62	46.8	40	0.92
25 km/h Standard	209	304	50	48	44.1	33	0.8
55 km/h Adaptive	469	606	70	67	47.4	42	0.93
45 km/h Adaptive	215	320	49	48	41.7	26	0.71
35 km/h Adaptive	71	99	32	31	34.9	16	0.52
25 km/h Adaptive	5	10	11	10	19.3	9	0.29

Table 6: Simulation results for offset impacts.

	HIC$_{15}$	HIC$_{36}$	Head Peak Acceleration (g)	3MS Head Acceleration (g)	Chest Deflection (mm)	Thorax Acceleration (g)	CTI
Physical Test	N/A	472	54.4	53.6	36.2	41.8	0.84
55 km/h Standard	486	612	71	69	47	43	0.95
45 km/h Standard	373	543	61	59	43.7	34	0.81
35 km/h Standard	141	213	42	41	38.7	22	0.63
25 km/h Standard	84.9	107	35	34	38.9	23	0.64
55 km/h Adaptive	312	433	59	56	43.2	30	0.76
45 km/h Adaptive	108	158	38	36	38.1	20	0.61
35 km/h Adaptive	28	40	22	21	27.4	12	0.4
25 km/h Adaptive	1	2.8	6	6	15	6	0.22

The injury criteria clearly show that the full frontal impact is more severe than the offset impact, and furthermore, that the adaptive structures have a significant effect on the injury predictors.

Injury risk curve equations for the head and chest were used to determine the probability of AIS2+, AIS3+ and AIS 5+ injuries based on the HIC$_{15}$ and CTI values calculated in the models. The risk curves are shown in Figure 7 and Figure 8.

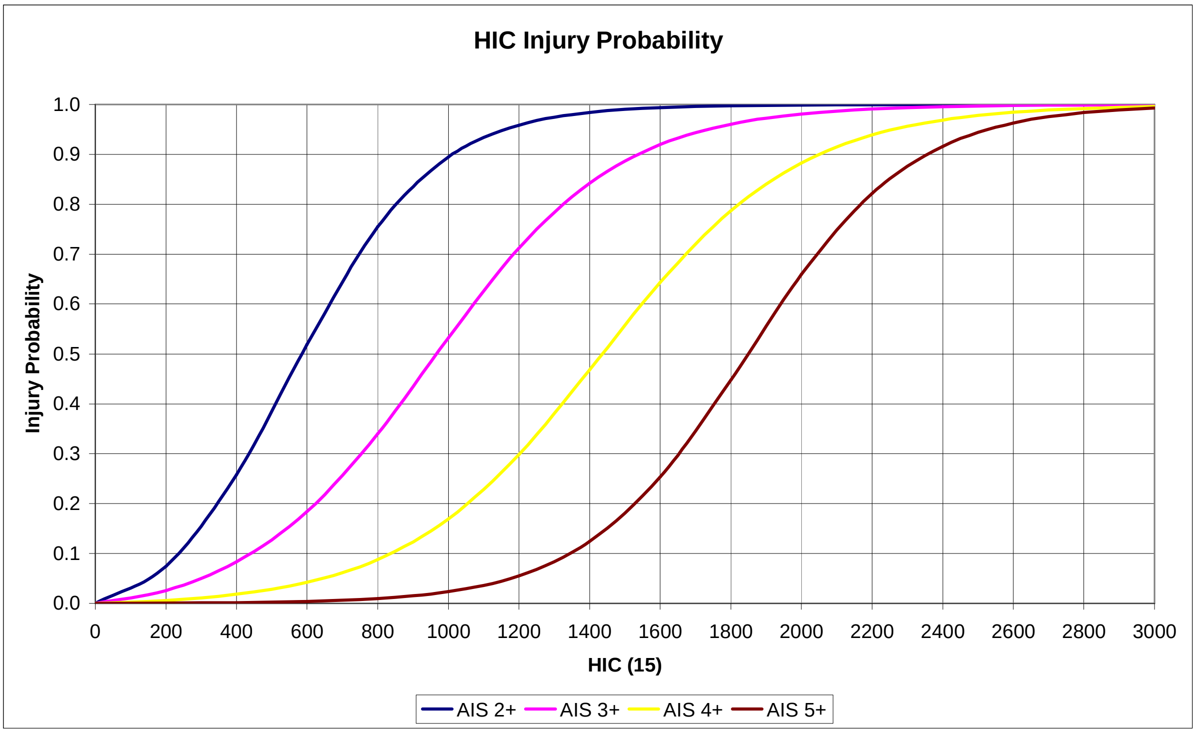

Figure 7: Injury probability curves for head injury (HIC$_{15}$).

Head Injury Criteria (HIC) Injury Probability Equations [NHTSA/rules, 1997]:

$$AIS2+ = \frac{1}{1+e^{\left(\left(2.49+\frac{200}{HIC}\right)-(0.00483*HIC)\right)}}$$

$$AIS3+=\frac{1}{1+e^{\left(\left(3.39+\frac{200}{HIC}\right)-\left(0.00372*HIC\right)\right)}}$$

$$AIS4+=\frac{1}{1+e^{\left(\left(4.9+\frac{200}{HIC}\right)-\left(0.00351*HIC\right)\right)}}$$

$$AIS5+=\frac{1}{1+e^{\left(\left(7.82+\frac{200}{HIC}\right)-\left(0.00429*HIC\right)\right)}}$$

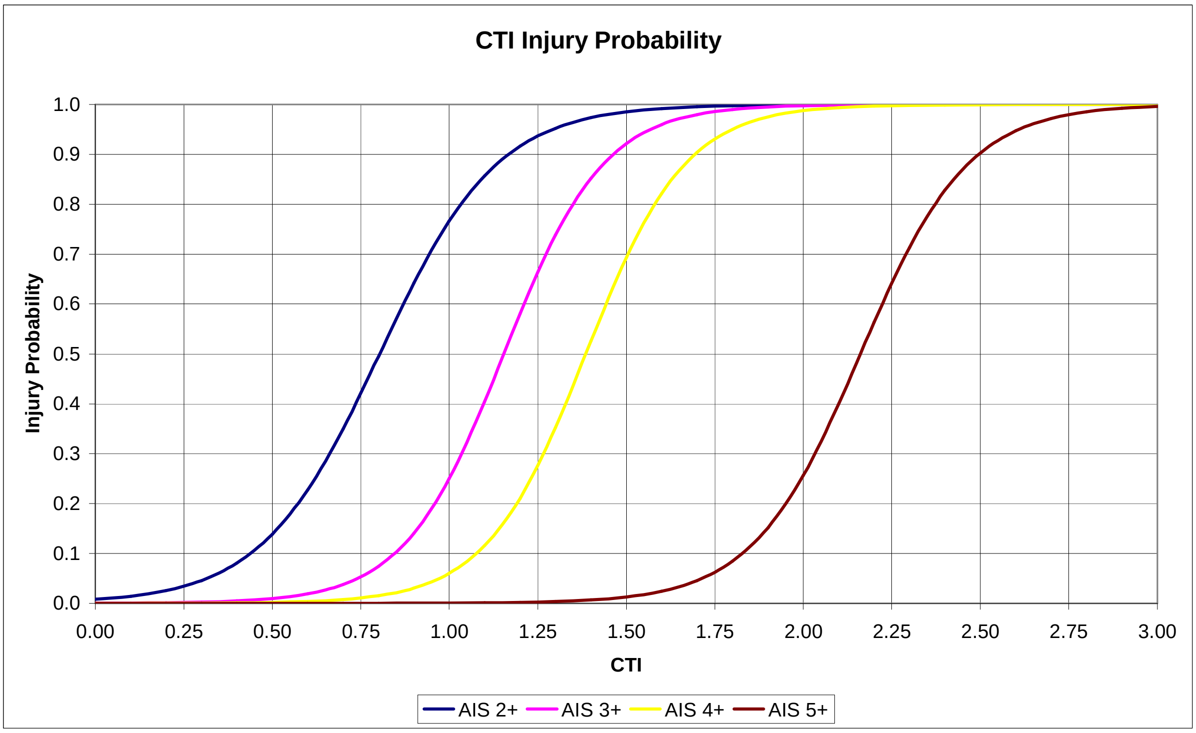

Figure 8: Injury probability curves for chest injury (CTI).

Combined Thoracic Injury (CTI) was used as a measure for chest injury as it combined two independent chest injury criteria, deflection and acceleration, and was therefore more convenient to use than two independent criteria.

Combined Thoracic Injury (CTI) Injury Probability Equations [NHTSA/rules, 1999]:

$$AIS2+=\frac{1}{1+e^{4.874-(6.036*CTI)}}$$

$$AIS3+=\frac{1}{1+e^{8.224-(7.125*CTI)}}$$

$$AIS4+=\frac{1}{1+e^{9.872-(7.125*CTI)}}$$

$$AIS5+=\frac{1}{1+e^{14.242-(6.589*CTI)}}$$

The injury probabilities were then used to calculate the injury reduction value, r, using the following equation:

$$r = [1 - \frac{P_a}{P_s}]$$

where P_a is the probability of injury related to the adaptive structure and P_s the probability of injury related to the standard vehicle structure.

The injury reduction factors calculated using the equations above are shown in Table 7, below. A value of 0 indicates no reduction in injury (i.e. no benefit) and a value of 1 indicates a 100 percent reduction in injury (i.e. full benefit).

Table 7: Injury reduction factors for head (HIC) and chest (CTI) for changing impact configurations.

		HIC Reduction Factor			CTI Reduction Factor		
		AIS 2+	AIS 3+	AIS 5+	AIS 2+	AIS 3+	AIS 5+
Full Frontal Impact	55 km/h	0.52	0.64	0.76	0.21	0.59	0.69
	45 km/h	0.82	0.83	0.88	0.55	0.87	0.89
	35 km/h	0.97	0.96	0.97	0.77	0.93	0.93
	25 km/h	1.00	1.00	1.00	0.91	0.97	0.97
Offset Impact	55 km/h	0.55	0.55	0.62	0.39	0.70	0.71
	45 km/h	0.91	0.89	0.91	0.53	0.74	0.73
	35 km/h	1.00	1.00	1.00	0.68	0.79	0.77
	25 km/h	1.00	1.00	1.00	0.89	0.94	0.93

The injury probabilities predicted by the model for the standard car (without the adaptive structure) at each impact configuration, calculated using the injury probability equations described previously, were compared to the likelihood of injury in the CCIS target population, calculated by dividing the number of head and chest injuries by the number of cases in each impact configuration (Table 8). This showed that although similar trends were observed, with an increasing likelihood/probability of injury as the impact speed increased, the model appeared to significantly over-predict the risk of injury when compared to the CCIS likelihood of injury. For example, for a full width impact at 30 – 39 km/h the model predicted an injury probability of approximately 67 percent for AIS 2+ chest injury, whilst the CCIS data showed a likelihood of injury of approximately 17 percent.

Table 8: Comparison of model injury probability and likelihood of injury in CCIS, showing significantly higher injury probability predicted in the model. Cells outlined in red indicate example case described above.

		Model injury probability						Likelihood of injury in CCIS data set					
		HEAD			CHEST			HEAD			CHEST		
Configuration	**Overlap**	**AIS 2+**	**AIS 3+**	**AIS 5+**	**AIS 2+**	**AIS 3+**	**AIS 5+**	**AIS 2+**	**AIS 3+**	**AIS 5+**	**AIS 2+**	**AIS 3+**	**AIS 5+**
Offset	**50-59**	36.49%	11.99%	0.00%	70.83%	18.92%	0.03%	0.00%	0.00%	0.00%	12.50%	12.50%	0.00%
	40-49	22.71%	7.32%	0.00%	51.05%	7.92%	0.01%	2.33%	0.00%	0.00%	13.95%	4.65%	0.00%
	30-39	3.81%	1.36%	0.00%	24.89%	2.17%	0.00%	0.92%	0.00%	0.00%	12.84%	0.00%	0.00%
	20-29	1.17%	0.44%	0.00%	26.03%	2.33%	0.00%	1.62%	0.40%	0.00%	7.69%	2.02%	0.00%
Full Width	**50-59**	71.77%	30.71%	0.03%	86.14%	41.44%	0.10%	13.64%	4.55%	0.00%	18.18%	4.55%	0.00%
	40-49	47.81%	16.51%	0.01%	80.70%	30.70%	0.06%	3.26%	1.09%	0.00%	19.57%	10.87%	0.00%
	30-39	21.30%	6.87%	0.00%	66.95%	15.86%	0.03%	2.38%	0.79%	0.00%	17.46%	4.37%	1.59%
	20-29	8.04%	2.74%	0.00%	49.55%	7.42%	0.01%	1.61%	0.65%	0.32%	5.48%	1.29%	0.32%

The over-prediction of the injury probability by the model compared to the detailed accident data in CCIS was unexpected, as the CCIS database has a stratified sampling procedure that is weighted to select higher injury severity accidents. The likelihood of injury in CCIS for AIS 2 injuries and above should be greater than the risk of injury calculated by the model.

The reason for this over-prediction by the model is unclear. There are several possible contributory factors which may have influenced this. Firstly, the simplistic mass spring system used in the model uses a non-linear spring to simulate a vehicle’s crush characteristics in an impact, but this is likely to overestimate the stiffness of a car in a low velocity impact as it is based on the deceleration pulse of a car in a test at 56 km/h. In turn this will overestimate the severity of the compartment deceleration pulse leading to the over-prediction of the occupant injury.

Another factor that may have influenced the results was the overestimation of the overlap in the definition of the full width crash configuration. In the accident data, a full width impact was considered to be an impact with an overlap of between 60 and 100 percent. The simulation results were based on the deceleration pulse from a full width test (100 percent overlap), where there is less ride-down as more of the car’s front structure is engaged. Therefore, for the real-world crashes in the full width category in CCIS it is likely that the cars would have experienced more ride-down as less of the cars’ structures would have been engaged at 60 – 90 percent overlap.

A third possible contributory factor is the suitability of a dummy for predicting injury risk. Research suggests that a dummy’s sternal deflection criterion is not a good predictor of injury caused by loading from the restraint system, as it was not able to correctly differentiate between load limiters and airbag combinations [Petitjean et al. 2002]. The CTI criterion was also highly influenced by head contact with the steering wheel. Therefore, the simulation and physical test results with the Hybrid-III dummy, and therefore the associated injury probabilities, may not have accurately represented the injury risk of a human.

It is recommended that further work is undertaken to further investigate the difference in the injury risk predicted by the model and the likelihood of injury in the CCIS data set, and to subsequently understand and resolve the issues.

3.5.3 Proportional Benefit

The expected benefit for the introduction of the adaptive structure was calculated for the occupants in the CCIS target population, described previously in Table 4. The number of occupants within the CCIS target population that had sustained head or chest injury at AIS 2+, AIS 3+ and AIS 5+ levels was calculated, and these are shown in Table 9, Table 10, Table 11, Table 12, Table 13 and Table 14. Only the highest injury in each body region was counted for each occupant. It should be noted that the AIS 3+ and AIS 5+ injury groups are subsets of the AIS 2+ injury groups. Occupants that sustained a head injury of AIS 2 or higher and also a thorax injury of AIS 2 or higher are counted in both the head and thorax injury categories.

Table 9: Occupants in CCIS target population with Head AIS 2+ injury.

Configuration (Overlap Percentage)	Accident severity (ETS km/h)						*Total*
	0-19	20-29	30-39	40-49	50-59	60+	
0-19 %	0	1	1	0	1	0	*3*
20-59 %	4	4	5	7	1	4	*25*
60-100 %	1	5	9	7	9	11	*42*
Total	*5*	*10*	*15*	*14*	*11*	*15*	*70*

Table 10: Occupants in CCIS target population with Head AIS 3+ injury.

Configuration (Overlap Percentage)	Accident severity (ETS km/h)						*Total*
	0-19	20-29	30-39	40-49	50-59	60+	
0-19 %	0	0	0	0	1	0	*1*
20-59 %	3	1	4	4	1	4	*17*
60-100 %	1	2	4	4	6	9	*26*
Total	*4*	*3*	*8*	*8*	*8*	*13*	*44*

Table 11: Occupants in CCIS target population with Head AIS 5+ injury.

Configuration (Overlap Percentage)	Accident severity (ETS km/h)						*Total*
	0-19	20-29	30-39	40-49	50-59	60+	
0-19 %	0	0	0	0	1	0	*1*
20-59 %	1	0	0	3	1	0	*5*
60-100 %	0	1	0	0	0	3	*4*
Total	*1*	*1*	*0*	*3*	*2*	*3*	*10*

Table 12: Occupants in CCIS target population with Thorax AIS 2+ injury.

Configuration (Overlap Percentage)	Accident severity (ETS km/h)						*Total*
	0-19	20-29	30-39	40-49	50-59	60+	
0-19 %	1	2	2	1	1	0	*7*
20-59 %	13	20	23	14	7	3	*80*
60-100 %	6	17	51	29	14	18	*135*
Total	*20*	*39*	*76*	*44*	*22*	*21*	*222*

Table 13: Occupants in CCIS target population with Thorax AIS 3+ injury.

Configuration (Overlap Percentage)	Accident severity (ETS km/h)						*Total*
	0-19	20-29	30-39	40-49	50-59	60+	
0-19 %	1	2	0	0	1	0	*4*
20-59 %	3	5	7	9	7	3	*34*
60-100 %	2	4	17	16	9	18	*66*
Total	*6*	*11*	*24*	*25*	*17*	*21*	*104*

Table 14: Occupants in CCIS target population with Thorax AIS 5+ injury.

Configuration (Overlap Percentage)	Accident severity (ETS km/h)						*Total*
	0-19	20-29	30-39	40-49	50-59	60+	
0-19 %	0	0	0	0	1	0	*1*
20-59 %	0	0	2	3	2	1	*8*
60-100 %	0	1	5	0	3	8	*17*
Total	*0*	*1*	*7*	*3*	*6*	*9*	*26*

The breakdown of head and chest injury in the target population showed that there were a very low number of AIS 5+ injuries in the target population, with 5 occupants experiencing AIS 5+ head injury and 16 experiencing AIS 5+ thorax injury. This represented a very small proportion of the 1773 belted occupants in the CCIS data set (0.3 percent and 0.9 percent, respectively), which was considered to be too low to perform a meaningful benefit analysis. As such, AIS 5+ injuries were excluded from the benefit analysis.

The introduction of adaptive structures into the vehicle fleet is not expected to occur before the introduction of improved frontal impact compatibility, and as such certain considerations regarding this needed to be taken into account in the benefit analysis. Improved frontal impact compatibility is expected to enable the structures of opposing vehicles in frontal crashes to engage better, thereby allowing more of the impact energy to be absorbed by the frontal structures. Improved frontal impact compatibility also aims to control the deceleration pulse in a frontal impact, which is something that adaptive structures could help to do. By improving the energy absorption of the frontal structure, frontal impact compatibility is expected to prevent intrusion into the occupant compartment in crashes up to the test speed of 56 km/h. Therefore, in a vehicle fleet where improved frontal impact compatibility has been introduced it can be assumed that there would be no compartment intrusion in frontal impacts up to the test speed.

The type of injuries sustained by an occupant in a frontal impact are different in vehicles where there is intrusion and in vehicles where there is no intrusion. Injuries in vehicles with intrusion are more likely to be contact-induced whereas injuries in vehicles where there is no intrusion are more likely to be restraint-induced. Because of this, the target population was split into cases where there was no intrusion and cases where intrusion was present.

For the purposes of this analysis, intrusion was defined as being present if there was 5 cm or more intrusion on the same side of the vehicle as the occupant at either facia level or knee contact level. Within the target population of 1286 cases, shown previously in Table 4, there was no intrusion in 1083 cases and intrusion was present in 203 cases.

An analysis of potential confounding factors between the cases where there was intrusion and the cases where there was no intrusion is shown in Table 15. This showed that, in general, there was a similar distribution of factors between the groups. There were a few differences in the distribution of the object hit, with higher incidences of collisions with LGVs and HGVs observed in the cases where intrusion was present, but this was considered to be a realistic factor of the type of impact and was not considered to be a confounding factor. There was also a higher proportion of occupants in the 35 to 44 year old age group in cases where there was intrusion compared to the cases where there was no intrusion, the reason for which was not known. However, it was not considered to be a factor that would have a significant effect on the analysis.

Table 15: Analysis of confounding factors between cases where there was no intrusion and cases where there was intrusion present.

		Target population		No intrusion		Intrusion present	
		No.	%	No.	%	No.	%
Total cases		1286	*100*	1083	*100*	203	*100*
Gender	Male	724	*56.3*	606	*56.0*	118	*58.1*
	Female	562	*43.7*	477	*44.0*	85	*41.9*
Age Group	12-16	21	*1.6*	18	*1.7*	3	*1.5*
	17-24	280	*21.8*	238	*22.0*	42	*20.7*
	25-34	265	*20.6*	225	*20.8*	40	*19.7*
	35-44	237	*18.4*	189	*17.5*	48	*23.6*
	45-54	182	*14.2*	157	*14.5*	25	*12.3*
	55-64	144	*11.2*	121	*11.2*	23	*11.3*
	65 +	157	*12.2*	135	*12.5*	22	*10.8*
Object hit	Car / car derivative	984	*76.5*	836	*77.2*	148	*72.9*
	Two-wheeler	3	*0.2*	3	*0.3*	0	*0.0*
	MPV/LGV	79	*6.1*	60	*5.5*	19	*9.4*
	HGV/PSV/Other	59	*4.6*	43	*4.0*	16	*7.9*
	Pole/narrow object	32	*2.5*	30	*2.8*	2	*1.0*
	Wide object	123	*9.6*	106	*9.8*	17	*8.4*
	Unknown	6	0.5	5	*0.5*	1	*0.5*

The injuries sustained in vehicles where there was no intrusion were most likely to have been non-contact injuries which were restraint-induced. As the adaptive structure would be expected to provide an optimal deceleration pulse in all frontal crashes, it was assumed that all restraint-induced injuries would be reduced to a level that would be observed in a crash with an optimal deceleration pulse. As such, all of the occupants within the target population that experienced injuries in the relevant injury groups (i.e. Head AIS 2+, Head AIS 3+, Thorax AIS 2+ and Thorax AIS 3+) in vehicles where there was no intrusion were assumed to be in the potential benefit population. The actual benefit would be calculated from this potential benefit group based on the reduction factors derived in the simulations.

The most likely cause of injuries in a crash where there was ‘significant’ compartment intrusion on the same side of the vehicle as the occupant is through contact with the vehicle interior. As the benefit from the potential adaptive structure assumes that there would only be benefit for restraint-induced injuries, it was not considered that there would be a benefit for occupants in cars where there was ‘significant’ intrusion on the occupant’s side. However, it is expected that the introduction of an adaptive frontal structure to vehicles in the fleet would not occur before the introduction of improved compatibility. If an assumption was made that the improved compatibility of vehicles in the future vehicle fleet would lead to the complete removal of compartment intrusion in car frontal impacts less than 60 km/h ETS, then it could be expected that all the crashes where intrusion currently occurs would become non-intrusion crashes. As such, there would be a benefit population expected for these cases which would assume the same proportional benefit as in non-intrusion crashes. This is on the basis that occupant injury levels are not ‘generated’ in the calculation of benefit, i.e. that the number of occupants sustaining injuries in the crashes where the intrusion would have been removed cannot be greater than the number sustaining injuries in the crashes which have intrusion in the current target population. In other words, in the future vehicle fleet it was assumed that there will still be the same number of crashes in the target population as in the current accident data, but the benefit analysis for the adaptive structure assumed that all of these crashes would be non-intrusion crashes.

In order to estimate a benefit for occupants in crashes where there was intrusion, but where the methodology assumed that there would be no intrusion in future crashes, a new ‘factored’ group was created. The number of head and thorax AIS 2+ and AIS 3+ injuries at each ETS and overlap category in this new group were estimated based on the percentage likelihood of injury in the cases where there was no intrusion. For example, in an offset crash (20 – 59 percent overlap) at an ETS of 40 – 49 km/h where there was no intrusion, 6 occupants out of the 43 occupants in that impact configuration experienced AIS 2+ thorax injury (14 percent). There were 33 occupants in crashes of the same impact configuration where there was intrusion present, so the ‘factored’ group was assumed to have 14 percent of 33 occupants, or 4.6 occupants. The maximum number of occupants estimated to be injured in the ‘factored’ group was defined as the number of occupants injured in each impact configuration in the original intrusion group, as injuries could not be ‘created’ in the target population. The number of occupants injured in the new ‘factored’ group were added to the existing occupants injured in the group with no intrusion to create a combined benefit population.

The injury reduction factors that were calculated from the results of the simulations, described previously in Section 3.5.2, were used to calculate the benefit for the occupants in the combined benefit population for each injury group. The calculated benefit for each injury group in the CCIS data set is shown in Table 16.

Table 16: Calculated benefit in CCIS data set.

Injury group	Occupants in data set	Occupants in target population	Occupants in combined benefit population	Calculated Benefit (Occupants)		
				Offset	*Full Frontal*	Total
Head AIS 2+	70	47	30.2	*6.6*	*19.2*	25.7
Head AIS 3+	44	26	9.2	*1.0*	*7.0*	8.0
Thorax AIS 2+	222	175	153.2	*34.3*	*72.8*	107.1
Thorax AIS 3+	104	74	44.7	*8.5*	*30.4*	39.0

The main factor that is not recorded in STATS19 but is recorded in CCIS is seat belt use. Therefore, in order to scale the benefit calculated at CCIS level up to national level, the unbelted occupants that were excluded from the CCIS data set at the start of the analysis needed to be accounted for in the calculation of the proportional benefit. The number of belted and unbelted occupants in each of the injury groups is shown in Table 17.

Table 17: Proportion of belted and unbelted occupants in each injury group in CCIS.

	Belted Occupants	Unbelted Occupants	*Total*
Head AIS2+	70	39	*109*
Head AIS3+	44	21	*65*
Thorax AIS2+	222	41	*263*
Thorax AIS3+	104	33	*137*
Total in data set	*1773*	*267*	*2040*

It was assumed that there would be no benefit from the introduction of the adaptive structure to unbelted occupants, so the proportional benefit for each of the groups was calculated based on the calculated benefit for belted occupants compared with the combined figure of belted and unbelted occupants in each injury group (Table 18).

Table 18: Calculation of proportional benefit in STATS19/SHIPS equivalent data set.

	Number in CCIS data set, including unbelted	Calculated benefit	*Proportional benefit (%)*
Head AIS2+	109	25.7	*23.58*
Head AIS3+	65	8.0	*12.31*
Thorax AIS2+	263	107.1	*40.72*
Thorax AIS3+	137	39.0	*28.47*

These figures for proportional benefit were applied to the national data.

3.5.4 GB Benefit

The benefits of adaptive structures have been estimated by analyses of detailed CCIS data. CCIS records only a sample of car accidents, so it is necessary to express these estimates in terms of national totals and STATS19 data, and this section describes how this has been done.

The normal STATS19 data record only the reporting officer's opinion of injury severity: killed (within 30 days), seriously injured or slightly injured. This classification is too crude for the present application, but more detailed injury coding is available from the database achieved by matching STATS19 and SHIPS records (described in Section 3.2.1). This database contains details of all car occupants injured in Scotland and treated as hospital in-patients, and the ICD codes from the hospital records allow the MAIS to be calculated by body region.

Several of the criteria applied to the CCIS data to identify those who could potentially benefit from adaptive structures exist in the STATS19 data. The STATS19 data were extracted using the following selection criteria:

> Car driver or front seat passenger, age 12+, injured in a car with first point of impact=front, car did not roll over.

The following Tables separate car occupants who satisfy these criteria from those who do not. Ideally the criteria would include ‘wore seat belt’, but this is no longer recorded in STATS19.

Table 19 presents an analysis of the car driver and front seat passenger records from 1998 to 2005 from the matched STATS19/SHIPS dataset. For example, there were 914 injured drivers and passengers who met the inclusion criteria, were present in both STATS19 and SHIPS records, were recorded by the police as seriously injured and had Thorax MAIS=2. Another 614 drivers were present in SHIPS but not STATS19 records, i.e. they attended hospital but the accidents were not recorded in STATS19. It is impossible to know which of these satisfied the STATS19-based criteria, the numbers will be estimated using the proportions from the STATS19 records. Note that appreciable numbers of casualties recorded by the police as slightly injured were also inpatients; they should have been coded as seriously injured and need to be included in the analysis. The fatal casualties, however, will be excluded from the calculations.

Table 19: Car driver and front seat passenger casualties, 1998-2005, by thorax AIS

	STATS19 severity							Grand Total
	Fatal		Serious		Slight		blank	
Thorax MAIS	no	yes	no	yes	no	yes		
2	4	7	382	914	153	300	614	2374
3	12	13	235	212	44	34	162	712
4		2					1	3
6		1	1	1	1		2	6
blank	51	33	1404	1730	422	440	2066	6146
Grand Total	67	56	2022	2857	620	774	2845	9241

Notes: no=occupants do not meet criteria, yes= occupants meet criteria
MAIS=blank then occupants in STATS19 but not SHIPS records
STATS19 severity=blank then occupants in SHIPS but not STATS19 records

The calculation of benefits necessarily assume that all casualties in Scotland that could have benefited from an adaptive structure would have been treated as hospital inpatients and recorded in SHIPS. This assumption is probably valid for MAIS=3+, but some casualties with MAIS=2 may have been treated as outpatients. Consequently, the results for MAIS=3+ should be reliable, but the results for MAIS=2+ may be underestimates.

Figure 6 shows the number of cases in the selected SHIPS data with MAIS=2+ for one or more body regions. Note that the Figure counts body regions rather than casualties: for example, a casualty with MAIS 2+ injuries to head and thorax would be counted twice. The Figure shows that the head and thorax sustained the highest proportion of AIS 2 and AIS 3+ injuries, with the exception of the upper and lower extremities, which correlates with the injuries by body region observed in the CCIS database.

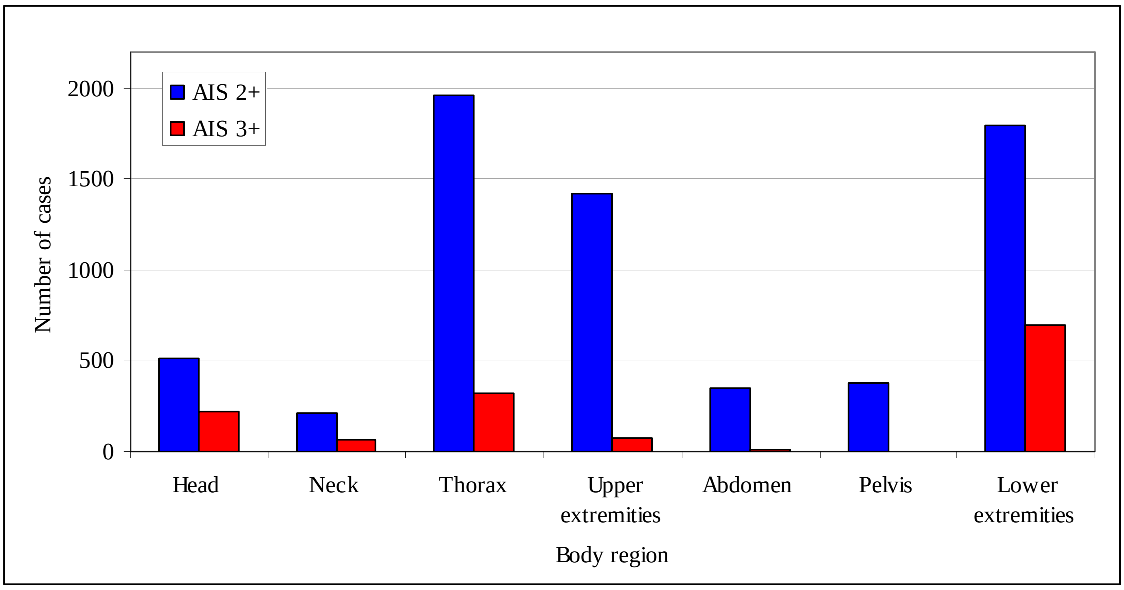

Figure 9: Body regions with MAIS=2+ in the selected SHIPS data.

The key data from the matched STATS19/SHIPS dataset are presented in Table 20. Corresponding STATS19 totals from Scotland and Great Britain are also included, these will be used to scale up the benefit estimates for Scotland to national figures. Note that these are 8-year totals, so annual totals would be about 1/8th of these figures.

Table 20: Car driver and front seat passenger casualty totals, 1998-2005

	SHIPS data				STATS19 data, Serious	
	Head MAIS		Thorax MAIS		Scotland	Great Britain
meets criteria?	2+	3+	2+	3+		
yes	517	221	1961	324	6,873	67,311
no	580	265	1095	369	4,116	47,793

Note: SHIPS data include linked STATS19 Serious and Slight casualties and unlinked SHIPS casualties

To illustrate how the benefit estimates derived from CCIS can be converted into nationally representative figures, suppose that it is estimated that adaptive structures would reduce the number of casualties with thorax MAIS=2+ by 10%. The figure of 1961 in Table 20 would then reduce by 196, i.e. the expected (8-year) casualty benefit in Scotland would be 196. 6,873/67,311=10.21% of the national total of serious casualties that meet the criteria are injured in Scotland, so the expected national casualty benefit would be 196/0.1021=1920

Table 21 presents the results from the final CCIS-derived effectiveness estimates. The first row, A, shows the number of SHIPS car occupant casualties aged 12+ with these injuries. The second row, B, shows the number of these that satisfied the selection criteria, and the CCIS effectiveness estimate C is applied to these to find the number that are expected to benefit. D, the final effectiveness estimate, is expressed relative to A, and the national casualty benefits are estimated as described above. Note that the benefits for MAIS=2+ may be somewhat underestimated, for the reason discussed above.

Table 21: Estimated benefits from adaptive structures, 1998-2005

	Head MAIS		Thorax MAIS	
	2+	3+	2+	3+
SHIPS casualties (A)	1097	486	3056	693
Potential beneficiaries (B)	517	221	1961	324
CCIS effectiveness (C)	23.6%	12.3%	40.7%	28.5%
Estimated benefit, Scotland (D= B*C)	122	27	798	92
Effectiveness (E=D/A)	11.1%	5.6%	26.1%	13.3%
Estimated benefit, Great Britain (F=D/0.1021)	1195	266	7817	904
Casualties, Great Britain (G=F/E)	10744	4760	29931	6787

Note: Annual totals are approximately 1/8th of these figures.

The estimated national (GB) benefits can be summarised as follows:

- on average, 3741 car front seat occupants received MAIS 2+ thorax injuries per year. If all of these cars had had adaptive structures then 978 (26.1%) of them would actually have been uninjured or received MAIS 1 thorax injuries, so 3741 would have been reduced by 978,
- on average, 848 received MAIS 3+ thorax injuries per year, if all cars had had adaptive structures then this would have been reduced by 113 (13.3%),
- on average, 1343 received MAIS 2+ head injuries per year, if all cars had had adaptive structures then this would have been reduced by 149 (11.1%),
- on average, 595 received MAIS 3+ head injuries per year, if all cars had had adaptive structures then this would have been reduced by 33 (5.6%).

4 Discussion

The investigation of the potential benefit for the introduction of an adaptive frontal structure that can optimise the deceleration pulse in a frontal impact showed that a significant benefit could be expected in terms of reduction in head and chest AIS 2+ and AIS 3+ injuries. However, the benefit for head and thorax injuries at AIS 5+ level was likely to be small as there were very few of these type of injuries in the target population.

However, there was a significant issue with the injury probabilities which were calculated using the results from the computer simulations and the head and thorax injury risk curves. Similar trends were observed, with the likelihood of head and thorax AIS 2+ and AIS 3+ injury increasing as the impact speed increased. However, the risk of injury calculated by the model significantly over-estimated the likelihood of injury that was observed in the accident data. This was especially unusual as the CCIS database uses a stratified sampling procedure which is weighted to select higher severity impacts, so it was expected that the likelihood of injury in the CCIS database would be higher than the risk of injury calculated by the model. The reason for this over-prediction by the model is unclear. There are several possible contributory factors which may have influenced this. These factors include the simplistic mass spring model not being representative of the stiffness characteristics of the front of a car and over-estimating the stiffness at lower speeds; the definition of the overlap groups for full width impacts in the accident data over-estimating the actual overlap and therefore the stiffness of the front structure; and also, the unsuitability of the Hybrid-III dummy used in the model to predict injury risk. This issue calls into question the validity of the results of the benefit analysis, and it is therefore recommended that further work is undertaken to investigate the difference in the injury risk predicted by the model and the likelihood of injury in the CCIS data set, and to subsequently understand and resolve this issue.

This analysis concentrated on injuries to the head and thorax, as these are areas where there is potential for life-threatening injury. However, the accident data showed that there were also AIS 2+ and AIS 3+ injuries to other body regions in frontal impacts. In particular, there was a high frequency of injury to the lower limbs which was not addressed by this analysis. Therefore, once the issues regarding the calculation of injury risk described above are resolved, it is recommended that the analysis is extended to include other body regions in order to provide a more detailed estimation of benefit.

Another area where further investigation may be required is the effect of the introduction of the adaptive structure on the injuries sustained by elderly occupants. Research has shown that restraint-induced thoracic injury in frontal impacts is heavily dependent on age, with a 70-year-old having significantly higher probability of sustaining an injury due to chest deflection than a 30-year-old [Kent et al., 2003] (Figure 10).

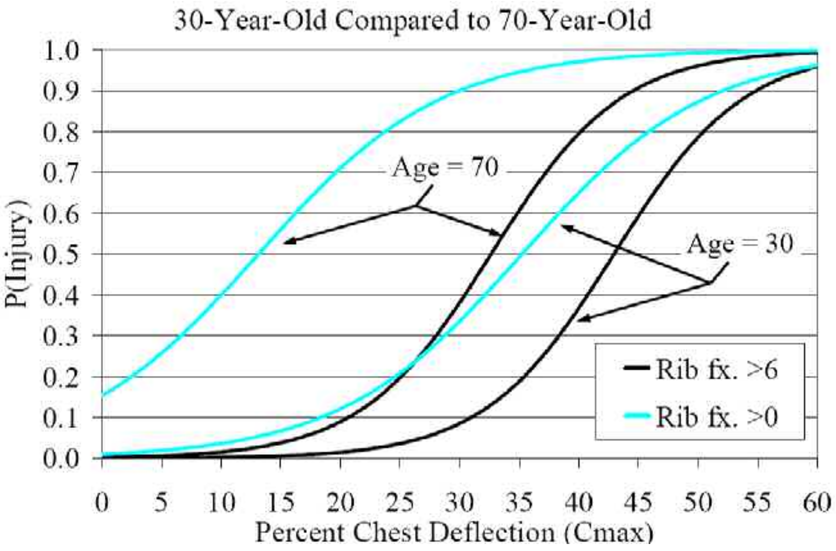

Figure 10: Comparison of probability of serious chest injury (multiple rib fracture) for 30-year-old and 70-year-old.

Elderly occupants have lower biomechanical limits than younger occupants, so are more likely to sustain injury. Occupants over the age of 65 made up approximately 12 percent of the target population, but sustained approximately 28 percent of the AIS 2+ and AIS 3+ thorax injuries recorded in the target population. Because of this increased susceptibility to injury, the elderly may not benefit from the introduction of adaptive structures, especially for more serious and fatal injuries, as they may still sustain serious injury even with the optimised deceleration pulse that an adaptive structure would aim to provide. Therefore it is recommended that further work be undertaken to consider elderly occupants in more detail.

A benefit for the introduction of an adaptive structure into the vehicle fleet has been calculated in terms of reduction in AIS 2+ and AIS 3+ head and chest injuries. However, in order to determine whether the costs of introducing an adaptive structure into the vehicle fleet are viable a monetary value needs to be calculated for the benefit. Currently for GB, monetary values are available for casualties on the police injury severity scale of “serious” or “fatal”, but they are not available for injuries on the AIS scale. Therefore, the AIS scale injuries either need to be converted into the police injury severity scale or a new methodology needs to be developed to attribute monetary value directly to AIS injury levels.

Several methods of calculating monetary values for injuries are already in existence. An example of this type of methodology is HARM, which is used in the US and has derived monetary values for AIS injuries. HARM estimates are calculated by multiplying the frequency estimates of the incidence of injured people at each severity level by the unit cost estimates of the average losses for that severity of injury, and is either calculated economically (Economic Harm) or including the value for reduced quality of life (Comprehensive Harm). The main deficiency of this type of HARM measurement is its dependency on MAIS, and therefore it does not adequately take multiple injuries into account. There are also examples of calculating HARM by body region in order to overcome the dependency on MAIS, although these have some inconsistencies which would need to be resolved before this method could be used [European Passive Safety Network, 2002].

Another method of calculating the monetary value uses a ‘willingness to pay’ approach that assigns a cost, as a proportion of the cost of fatality, to an injury state which includes factors such as time to recover, whether as an in-patient or out-patient, permanent disability and scarring [Welsh et al., 2006].

It is recommended that further work is undertaken to develop a methodology to calculate the cost for GB for the introduction of an adaptive structure by attributing monetary values to the AIS injury severity scale.

5 Conclusions

5.1 Investigation and Review of State of the Art Structures, Concepts and Technologies

The review of state of the art structures, concepts and technologies relating to adaptive structures showed that current proposals for adaptive structures are fairly limited. The largest number of systems are currently based on the concept of altering the frontal force levels of the vehicle, and the majority of these have major technical feasibility drawbacks. However, systems where the technology has matured, such as pedestrian impact sensors for use in pop-up bonnets, are already available on production vehicles, demonstrate that manufacturers are prepared to employ adaptive structures on their vehicles if the technology, feasibility, and cost effectiveness of the system are available and viable.

The concept selected as an example to be used for the benefit analysis was an adaptive frontal structure which can adjust its frontal force levels to optimise the occupant compartment deceleration pulse for different frontal collision configurations, in particular severity and overlap. The main reasons for selecting this concept were that a large proportion of the adaptive systems reviewed were based on this concept and it had a potentially large target population.

5.2 Estimation of Benefit of Selected Adaptive Structure

A methodology was developed to estimate the benefit for GB for the introduction of the adaptive structure. This utilised the newly available linked STATS19 / SHIPS accident database in combination with the detailed CCIS accident database to identify the target population, whilst computer simulation was performed in order to estimate the effectiveness of the structure by calculating the reduction in risk of AIS level injury to the head and thorax.

The national benefit for GB for the introduction of an adaptable frontal structure on all cars was estimated. It was predicted that a significant benefit could be expected in terms of AIS 2+ and AIS 3+ head and thorax injury. The benefit for head and thorax injuries at AIS 5+ level was likely to be small as there were very few of these type of injuries in the target population. However, there was an issue with the probability of injury predicted by the model and the likelihood of injury in the CCIS database. Although similar trends were observed, with an increasing likelihood/probability of injury as the impact speed increased, the model predicted that the risk of injury was significantly higher than the likelihood of injury in the CCIS database. This was unexpected as the CCIS database uses a stratified sampling technique that is weighted to select more serious injuries, and therefore the CCIS likelihood of injury should be greater than the risk of injury. The over-prediction of the probability of injury by the model may affect the validity of the results, and further investigation is required in order to understand and resolve this issue.

6 Recommendations for Further Work

The following recommendations for further work are made:

- The high injury probabilities for head and chest AIS 2+ and AIS 3+ injury predicted by the model and injury risk curves significantly over-estimated the likelihood of injury that was observed in the CCIS accident database, which called into question the validity of the overall benefit calculated for the introduction of the adaptive structure. Therefore, further investigation is required in order to understand and resolve this problem.
- This analysis concentrated on injuries to the head and thorax, as these are areas where there is potential for life-threatening injury. However, the accident data showed that there were also AIS 2+ and AIS 3+ injuries to other body regions in frontal impacts. In particular, there was a high frequency of injury to the lower limbs which was not addressed by this analysis. Therefore, it is recommended that the work is extended to include other body regions in order to provide a more detailed estimation of benefit.
- Elderly occupants have lower biomechanical limits than younger occupants, so are more likely to sustain injury. Occupants over the age of 65 made up approximately 12 percent of the target population, but sustained approximately 28 percent of the AIS 2+ and AIS 3+ thorax injuries recorded in the target population. These elderly occupants might not benefit from the introduction of adaptive structures to the same extent as a younger occupant, as the optimisation of the deceleration pulse may not significantly reduce their high risk of injury. Therefore, it is recommended that the work is extended to consider elderly occupants in more detail.
- In order to complete a full cost benefit analysis for the introduction of an adaptive structure a methodology is required in order to convert the benefit in terms of AIS injury reduction into a monetary value. Currently for GB, monetary values are available for casualties on the police injury severity scale of “serious” or “fatal”, but they are not available for injuries on the AIS scale. Therefore, the AIS scale injuries either need to be converted into the police injury severity scale or a new methodology needs to be developed to attribute monetary value directly to AIS injury levels. Further work is recommended to develop this methodology so that the monetary value of the potential benefit of the introduction of an adaptive structure can be calculated.

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Further information on CCIS can be found at http://www.ukccis.org

References

Apollo Project (2006).
http://www.unav.es/preventiva/traffic_accidents/pagina_5.html
University of Navarra – Apollo Project.

Association for the Advancement of Automotive Medicine (1998). *The abbreviated injury scale*, 1998 revision. Des Plaines, USA.

Butz T and von Stryk O (2002). *Modelling and Simulation of Electro- and Magnetorheological Fluid Dampers*. ZAMM Volume 82, No. 1, pp. 3-20.

Broughton J, Keigan M and James F J (2001). *Linkage of hospital trauma data and road accident data*. TRL Report 518. Wokingham: TRL Limited.

Broughton J and Keigan M (2007). *Linking STATS19 and Scottish Hospital In-patient data for the SafetyNet Project*. TRL Report PPR 207. Wokingham: TRL Limited.

Cuerden R, Hill J, Kirk A and Mackay M (2001). *The Potential Effectiveness of Adaptive Restraints*. IRCOBI, 2001.

Edwards M, Cuerden R, Davies H (2007). *Current Status of the Full Width Deformable Barrier Test.* 20th International Technical Conference on the Enhanced Safety of Vehicles, Lyon, June 2007.

European Passive Safety Network (2002). *Report: Impairment Scaling and Injury Costs*. Proceedings of Workshop. TRL. June 2002.

Keigan M, Broughton J and Tunbridge R J (1999). *Linkage of STATS19 and Scottish hospital in-patient data – analyses for 1980-1995*. TRL Report 420. Wokingham: TRL Limited.

Kent R, Patrie J, Poteau F, Matsuoka F, Mullen C (2003). *Development of an age-dependent thoracic injury criterion for frontal impact restraint loading*. Paper 72, 18th International Technical Conference on the Enhanced Safety of Vehicles, May 2003, Nagoya, Japan.

Metz H, Horsch J, Horn G and Lowne R (1991). *HYBRIDIII Sternal Deflection associated with Thoracic Injury Severities of Occupants Restrained with Force-Limiting Shoulder Belts*. SAE Detroit, MI USA 1991.

NHTSA/rules, 1997 http://www.nhtsa.dot.gov/cars/rules/rulings/80g/80g.html

NHTSA/rules, 1999 http://www.nhtsa.dot.gov/cars/rules/rulings/AAirBagSNPRM/PEA/Index.html

Petitjean A, Lebarbe M, Potier P, Trosseille X, Lasau J (2002). *Laboratory reconstructions of real world frontal crash configurations using the HYBRIDIII and THOR dummies and PMHS*. Stapp Car Crash Journal, Vol 46, pp27-54, 2002.

Stalmans R and von Humbeeck J (1995). Shape Memory Alloys: Functional and Smart. Smart Materials and Technologies – Sensors, Control Systems and Regulators Seminar, Prague Czech Republic.

Stone R D (1984). *Computer linkage of transport and health data*. Laboratory Report LR1130, Wokingham: TRL Limited.

Welsh R, Morris A, Frampton R, Thomas P (2006). *A Review of Secondary Safety Priorities*. Undertaken on behalf of Department for Transport. PPAD 9/33/129. S0316/VF.

Witteman W (2005). *Adaptive Frontal Structure Design to achieve Optimal Deceleration Pulses***.** 19th International Technical Conference on the Enhanced Safety of Vehicles Washington DC, USA, Paper No. 05-0243.

World Health Organisation (1992). *International Statistical Classification of Diseases and Related Health Problems*. Tenth Revision. Geneva.

Wykes N, Edwards M & Hobbs A (1998) *Compatibility Requirements for Cars in Frontal and Side Impact*, 16th International Technical Conference on the Enhanced Safety of Vehicles,Windsor.

Appendix A. Summary of Adaptive Systems

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
1	Impact energy absorption by sliding structural members on friction pads	Car/car derivative	Frontal Impacts	Belted vehicle occupants	The crushable longitudinals are replaced by undeformable U-profile beams. In a crash these beams are forced backwards and each slide along two friction pads, supported by brake cylinders, absorbing the energy of the impact. The beams slide under the occupant compartment during the crash. The system is equipped with a cable connection system to share loads between the two longitudinals if only one side of the vehicle front is loaded, as in an offset or oblique crash. The friction pressure can be hydraulically altered leading to variable force level. Servo valves are used to regulate pressure and volume flows, and can respond within a few milliseconds. It is calculated that for a 1100 kg vehicle the pressure for the brake pads has to vary between 5 and 25 bar. The temperature increase after a 64 km/h crash is only about 85 degrees for the pads and the profiles.	This structure allows the car to adapt its frontal force level, depending on the crash velocity. The maximum length of the crumple zone can always be used, without intrusion of the occupant compartment. The system is designed for both full or partial offset and direct or oblique contact.	Mass increase: High due to the addition of hydraulic friction system. Cost increase: High due to hydraulic friction system, cabling system and sensors. Packaging difficulty: High due to necessity for beams to be able to retract under compartment, possible in larger MPV type vehicles, smaller vehicles may not have the packaging space. Operational difficulty: High. Will require rapid sensing of the impact force and rapid hydraulic regulation to control pressure on friction pads. This may be beyond the limits of current sensors and regulators. Effectiveness: Moderate. If the system works as designed, the injury severity levels of occupants will be reduced. This would require significant testing of the system. High feasibility issues, however, indicate that the system is unlikely to appear on production vehicles and therefore full-scale testing of the system is unlikely.
		Car/car derivative	Side Impacts (Bullet Vehicle)	Belted vehicle occupants			
		Car/car derivative	Side Impacts (Target Vehicle)	Vehicle occupants			

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
2	Impact energy absorption by deployable buffer with structural fuses	Car/car derivative	Frontal Impacts	Belted vehicle occupants	A deployable adaptive car buffer is equipped with controllable energy dissipaters, so-called structural fuses. A system of sensors recognizes type of crash loading and activates energy absorbing components in the sequence that guarantees optimal dissipation of impact energy.	This adaptive crashworthiness concept can be applied directly to the supporting frame structure (e.g. in trucks or railway coaches) or to specially designed crash protecting zones (e.g. frontal part of the high speed TGV coaches). It can be applied also to protect regular cars against collisions. The deployment concept helps to increase significantly the crash space, especially for side impacts.	Mass increase: High due to addition of deployable buffer Cost increase: High due to addition of deployable buffer, pre-crash sensing devices, and actuation devices Packaging difficulty: High as deployable buffer must occupy space in the frontal area of the vehicle Operational difficulty: High as pre-crash sensors must be used to convey a signal to operate the buffer and sensors must detect the impact force to operate the structural fuses Effectiveness: Moderate. If the system works as designed, the injury severity levels of occupants will be reduced. This would require significant testing of the system. High feasibility issues, however, indicate that the system is unlikely to appear on production vehicles and therefore full-scale testing of the system is unlikely.
		Car/car derivative	Side Impacts (Bullet Vehicle)	Belted vehicle occupants			
		Car/car derivative	Side Impacts (Target Vehicle)	Vehicle occupants			

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
3	Adaptive Crash Structure (Balls in Tube)	Car/car derivative	Frontal Impacts	Belted vehicle occupants	Four or more balls are positioned inside a tube. During a low speed impact the balls slide down the tube without engaging. In a high speed (high energy) impact the increased resistance in the device is such that the balls are forced outward by the shaped piston head deforming the tube to an expanded shape as the piston passes down the tube. This action absorbs considerably more energy, thus converting the crash structure from soft to stiff. The piston passes down the tube continuing to absorb energy until at the required point they pass out of the end. The crash element is thus expended allowing the normal crush of the front longitudinals to take place.	In the case of an impact between a large and a small vehicle the crash structure force level of the larger vehicle required for the protection of its occupants will overwhelm the crash structure of the smaller vehicle. This structure can sense the nature of the impact being experienced and adapt force level and energy absorption accordingly.	Mass increase: Moderate (12kg increase proposed) Cost increase: Low (£12.60 per vehicle proposed) Packaging difficulty: Low due to the system replacing the longitudinal rails Operational difficulty: Moderate. Possible that the system could 'jam' in oblique impacts Effectiveness: High. Simulations from the manufacturer indicate significant reductions in peak occupant deceleration (up to 21g reduction in a 15 degree 80kph ODB simulation).
		Car/car derivative	Side Impacts (Bullet Vehicle)	Belted vehicle occupants			
		Car/car derivative	Side Impacts (Target Vehicle)	Vehicle occupants			

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
4	Adaptive Ride Height	Car/car derivative	Frontal Impacts	Belted vehicle occupants	Sensors measure host vehicle dynamics, target vehicle threat assessment and target vehicle bumper or doorsill location. Data processed and suspension adjusted to alter ride height to level to optimise forces and declaration in the impact.	This system reduces incompatibility between vehicles in both frontal and side impacts, thus reducing the injury severity to vehicle occupants in the Host Vehicle and target vehicle.	Mass increase: Low as system utilises the current vehicle active suspension system Cost increase: Low as system utilises the current vehicle active suspension system Packaging difficulty: Low as system utilises the current vehicle active suspension system Operational difficulty: High. Will require advanced pre-crash sensing systems to sense that an impact is likely to occur and where the optimal impact point on the collision partner is. There is also a possible technical conflict if two vehicles in a collision have the system, as if the control system is not a rapid feedback system then the impact points of the vehicles could be misaligned in the impact Effectiveness: Moderate. If the system operates as designed then there will be a benefit to introducing the system, however extensive testing will need to be undertaken before it is introduced
		Car/car derivative	Side Impacts (Bullet Vehicle)	Belted vehicle occupants			
		Car/car derivative	Side Impacts (Target Vehicle)	Vehicle occupants			

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
5	Retardation sensed rail explosions	Car/car derivative	Frontal Impacts	Belted vehicle occupants	Deceleration measured by sensors for each rail. Explosive charges on longitudinal rails are detonated at optimum time/crush level to prevent buckling and increase the crumpling deformation distance.	This system adjusts the rigidity of the rails to reduce force level mismatching between vehicles. The method of adjusting rigidity also induces crumpling of the rails thus reducing the likelihood of buckling. This will reduce deceleration levels for frontal impacts and reduce injury severity for vehicle occupants in target vehicle hit by Host Vehicle in side impacts.	Mass increase: Low as system utilises lightweight charges and detonators. Cost increase: Moderate as system uses inexpensive charges and detonators but more expensive sensors and control systems. Packaging difficulty: Low, charges and detonator unit require minimal space Operational difficulty: High. Would require very early detection of the impact load to adapt to the impact force. Current vehicle impact force sensors would be unlikely to detect the load early enough in the impact. Effectiveness: Moderate. If the system operates as designed then there will be a benefit to introducing the system, however extensive testing will need to be undertaken before it is introduced
		Car/car derivative	Side Impacts (Bullet Vehicle)	Belted vehicle occupants			
		Car/car derivative	Side Impacts (Target Vehicle)	Vehicle occupants			

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
6	Active bumper crossbeam using sliding shape-memory alloy members	Car/car derivative	Frontal Impacts	Belted vehicle occupants	Several sliding members attached perpendicular to front section of bumper crossbeam. Actuator either allows or doesn't allow rear end of sliding member to pass through slits in a base member dependant upon whether low or high force level is required respectively for optimum energy absorption.	This system adjusts the rigidity of the rails to reduce force level mismatching between vehicles. Deceleration levels for frontal impacts and injury severity for vehicle occupants in target vehicle hit by Host Vehicle in side impacts will all be reduced	Mass increase: Moderate due to addition of sliding and supporting members and actuators to the bumper section Cost increase: High due to use of expensive shape-memory alloys, actuators and supporting members Packaging difficulty: Moderate. System replaces current bumper crossbeam, but realistically will occupy more space than previous bumper crossbeam Operational difficulty: High. Would require very early detection of the impact load to adapt to the impact force. Current vehicle impact force sensors would be unlikely to detect the load early enough in the impact. Effectiveness: Low. Only adjusts force level in the vehicle bumper, thus effectiveness in an impact is over a short distance.
		Car/car derivative	Side Impacts (Bullet Vehicle)	Belted vehicle occupants			
		Car/car derivative	Side Impacts (Target Vehicle)	Vehicle occupants			

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
7	Hydraulically Controlled Frontal Car Structure	Car/car derivative	Offset frontal impacts	Belted vehicle occupants	2 cross-fed hydraulic cylinders attached to crossbeams, parallel and adjacent to longitudinals. As one longitudinal (and thus hydraulic cylinder) becomes loaded, the hydraulic fluid flows to the opposite hydraulic cylinder, and thus loads the opposite longitudinal.	The objective of this system is to transfer some of the impact energy from the loaded longitudinal rail to the unloaded longitudinal rail in an offset impact.	Mass increase: High due to addition of 2 large hydraulic cylinders Cost Increase: High due to addition of 2 large hydraulic cylinders Packaging difficulty: High due to addition of 2 large hydraulic cylinders Operational difficulty: Low. Simple mechanical system should work for most overlaps and impact angles. Effectiveness: Moderate. Could increase the likelihood of reduced occupant injury in an offset impact.

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
8	Disconnecting Energy Absorbing Members Using Pyrotechnics	Car/car derivative	Side Impacts (Bullet Vehicle)	Belted vehicle occupants	Two C-section profiles attached to the longitudinal rails using pyrotechnic connectors. The pyrotechnics are detonated and thus force level reduced if optimum for impact severity.	This system adjusts the rigidity of the rails to reduce force level mismatching between vehicles. The method of adjusting rigidity also induces crumpling of the rails thus reducing the likelihood of buckling. This will reduce deceleration levels for frontal impacts and reduce injury severity for vehicle occupants in target vehicle hit by Host Vehicle in side impacts.	Mass increase: Moderate due to addition of additional C-section profiles. Cost increase: Moderate due to addition of C-section profiles, charges, detonators and control systems Packaging difficulty: Low due to system occupying space previously occupied by longitudinal rails Operational difficulty: High. Would require very early detection of the impact load to adapt to the impact force. Current vehicle impact force sensors would be unlikely to detect the load early enough in the impact. Effectiveness: Moderate. If the system operates as designed then there will be a benefit to introducing the system, however extensive testing will need to be undertaken before it is introduced
		Car/car derivative	Side Impacts (Target Vehicle)	Vehicle occupants			
		Car/car derivative	Offset frontal impacts	Belted vehicle occupants			

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
9	Energy absorption by hydraulic cylinder	Car/car derivative	Side Impacts (Bullet Vehicle)	Belted vehicle occupants	Two hydraulic cylinders placed alongside (or in place of) longitudinal rails in which the flow rate of the hydraulic cylinders can be varied according to the impact severity, thus varying the force required to move the piston back in an impact	This system can alter the rate at which the vehicle decelerates to reduce deceleration levels of the occupant compartment. Flow rate is infinitely variable between zero and maximum flow.	Mass increase: High due to addition of 2 large hydraulic cylinders Cost Increase: High due to addition of 2 large hydraulic cylinders Packaging difficulty: High due to addition of 2 large hydraulic cylinders Operational difficulty: High. Will require rapid sensing of the impact force and rapid hydraulic regulation to control the flow rate of the cylinders. This may be beyond the limits of current sensors and regulators. Effectiveness: Moderate. If the system works as designed, the injury severity levels of occupants will be reduced. This would require significant testing of the system. High feasibility issues, however, indicate that the system is unlikely to appear on production vehicles and therefore full-scale testing of the system is unlikely.
		Car/car derivative	Side Impacts (Target Vehicle)	Vehicle occupants			
		Car/car derivative	Offset frontal impacts	Belted vehicle occupants			

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
10	Adaptive Collapsible Steering Column	Car/car derivative		Belted drivers in Host Vehicle.	A steering wheel column is supported by a supporting structure which is in contact with shear variable fluid (magnetorheological/electrorheological etc.). The shear strength of the fluid is adjusted to vary the resistance to collapsing of the steering column.	This system can alter the rate at which the steering column collapses to reduce deceleration levels of the upper body of the driver. Shear strength dependent upon impact force. Could feasibly work in tandem with driver sensors e.g. seating position from the steering wheel, mass etc	Mass increase: Moderate due to addition of rheological fluid and associated piston system Cost increase: High due to addition of rheological fluid and associated piston system Packaging difficulty: Moderate. System will occupy more space than current steering column design Effectiveness: Rheological fluid technology has not yet matured enough to be used for this design however the system could become feasible in the future

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
11	Adaptive energy-absorbing materials using magnetorheological fluid impregnated cellular solids	Car/car derivative	Side Impacts (Bullet Vehicle)	Belted vehicle occupants	A cellular solid is impregnated with magnetorheological fluid. The force level of this composite can be varied by controlling and adjusting the magnetic field strength in the vicinity of the material	This system adjusts the rigidity of the rails to reduce force level mismatching between vehicles. The method of adjusting rigidity also induces crumpling of the rails thus reducing the likelihood of buckling. This will reduce deceleration levels for frontal impacts and reduce injury severity for vehicle occupants in target vehicle hit by Host Vehicle in side impacts.	Mass increase: Moderate. The longitudinal rails are replaced by the system, but the system will have increased mass due to the mass of the fluid which is high density due to the high volume of ferrous material present in the fluid Cost: High due to the addition of rheological fluid and associated control system Packaging difficulties: Low due to the system occupying the space that the longitudinal rails occupied previously Operational difficulty: High. Will require rapid sensing of the impact force and rapid actuation Effectiveness: Moderate. If the system works as designed, the injury severity levels of occupants will be reduced. This would require significant testing of the system and development of the rheological technology
		Car/car derivative	Side Impacts (Target Vehicle)	Vehicle occupants			
		Car/car derivative	Offset frontal impacts	Belted vehicle occupants			

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
12	Energy absorbing steering assembly	Car/car derivative	Frontal Impacts	Belted drivers in Host Vehicle.	The steering column in a vehicle acts as the piston in a hydraulic cylinder. The flow rate of the hydraulic system can be varied dependant upon impact force.	The objective of this system is to optimise the deceleration of the upper body of the driver. This is achieved by varying the flow rate of the hydraulic system, and thus the retraction rate of the steering column.	Mass increase: Moderate due to addition of the hydraulic system Cost increase: High due to the addition of the hydraulic system, control system, regulators and sensors Packaging difficulty: Moderate. Will take up more space than traditional steering column assembly Operational difficulty: Moderate. Hydraulic regulator speed may not be fast enough for this system to work effectively. However, as the steering wheel will be required to retract late in the crash, there will be sufficient time for the impact force to be detected. Effectiveness: Low. Would increase the likelihood of reduced injury, however cost, mass packaging and operational difficulties will be unlikely to justify the adoption of the system
		Car/car derivative	Side Impacts (Bullet Vehicle)	Belted drivers in Host Vehicle.			

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
13	Active Armrest For Side Impact Protection	Car/car derivative	Side Impacts (Target Vehicle)	Vehicle Occupants in seats next to vehicle doors.	In regular use, the armrest on the inside of a vehicle door remains rigid with a distinct sharp edge. When a crash is sensed, the upper face of the armrest is collapsed by either electronic actuation or mechanical linkages.	The objective of this system is to alter the structure of the compartment to reduce the likelihood of contact induced occupant injuries.	Mass increase: Moderate due to addition of actuation system Cost increase: Moderate due to necessity of actuation device, control system and impact sensors Packaging difficulty: Low as the system occupies space in the armrest Operational difficulty: Low. System should operate as desired and only operate when desired Effectiveness: Low. Would have little impact on the likelihood of contact induced occupant injuries that couldn't be solved with careful static armrest design

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
14	Pop-up bonnet for Pedestrian Protection	Car/car derivative	Pedestrian and cyclist impacts	Pedestrians and cyclists	Sensors in the bumper sense when a pedestrian has been impacted and rapidly raise the bonnet to offer a less rigid area for the pedestrian head and upper body to contact	The objective of this system is to reduce the impulse on the head and upper body of the impacted pedestrian	Mass increase: Moderate due to addition of actuation system Cost increase: Moderate due to necessity of actuation device, control system and impact sensors Packaging difficulty: Moderate as the system occupies space under the bonnet Operational difficulty: Low. System is already operational on vehicles, thus operates as desired Effectiveness: High. This system will have a high level of effectiveness in reducing pedestrian injury severity.

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
15	Windscreen Airbag for Pedestrian Protection	Car/car derivative	Pedestrian and cyclist impacts	Pedestrians and cyclists	Sensors in the bumper sense when a pedestrian has been impacted and deploy airbags from under the bonnet to cover the lower windscreen and A-pillar.	The objective of this system is to reduce the impulse on the head and upper body of the impacted pedestrian	Mass increase: Moderate due to addition of actuation system Cost increase: Moderate due to necessity of actuation device, control system and impact sensors Packaging difficulty: Moderate as the system occupies space under the bonnet Operational difficulty: Low. System can operate utilising the same technology as pop-up bonnets, thus system will operate as desired Effectiveness: High. This system will have a high level of effectiveness in reducing pedestrian injury severity.

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
16	Underbody Vehicle Supporting Pillar Members	Car/car derivative	Frontal Impacts	Belted vehicle occupants	When it is sensed that a vehicle is likely to override the Host Vehicle in a collision, 2 pillar members are deployed to support the vehicle directly on the ground.	This system reduces incompatibility between vehicles in both frontal and side impacts, thus reducing the injury severity to vehicle occupants in the Host Vehicle and target vehicle.	Mass increase: High due to addition of supporting pillar members Cost increase: High due to addition of supporting pillar members and pre-crash sensors Packaging difficulty: High as when non-operational, supporting pillar members will occupy space in the frontal structure of the vehicle Operational difficulty: High. Will require pre-crash sensing and target vehicle impact point sensing to process how far the pillars need to be extended. Effectiveness: Moderate. If the system operates as designed then there will be a benefit to introducing the system, however extensive testing will need to be undertaken before it is introduced
		Car/car derivative	Side Impacts (Bullet Vehicle)	Belted vehicle occupants			
		Car/car derivative	Side Impacts (Target Vehicle)	Vehicle occupants			

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
17	Active Hinged Bumper	Car/car derivative	Frontal Impacts (Target Vehicle)	Belted vehicle occupants	In a vehicle with a high bumper (e.g. SUV) there is a tendency to override smaller vehicles in collisions. In order to reduce the height of the impact point, an active hinged bumper assembly is deployed. When it is sensed that a collision will occur with a vehicle with a lower frontal structure than the Host Vehicle, actuators deploy the bumper assembly (possibly by pyrotechnics) to reduce the height of the impact point.	The objective of this system is to increase compatibility where the initial incompatibility is due to different heights of the vehicle frontal structures. This will reduce the likelihood of one vehicle overriding another and thus reduce injury severity for occupants of the target vehicle in both frontal and side impacts.	Mass increase: High due to addition of hinged bumper Cost increase: High due to addition of hinged bumper, actuation and locking system, and pre-crash sensing devices. Packaging difficulty: Moderate as system will have to occupy space underneath the frontal structure of the vehicle Operational difficulty: High. Will require pre-crash sensing to detect imminent collision. Will require rapid actuation of the system to achieve objectives
		Car/car derivative	Side Impacts (Target Vehicle)	Vehicle occupants			

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
18	Plastically Deformable Inflatable Bonnet Support	Car/car derivative	Pedestrian and cyclist impacts	Pedestrians and cyclists	Sensors in the bumper sense when a pedestrian has been impacted and rapidly raise the bonnet using a plastically deformable inflatable bonnet support. When the pedestrian strikes the bonnet, the plastically deformable inflatable bonnet support deforms to absorb the energy of the impact, thus not deforming the bonnet.	The objective of this system is to reduce the impulse on the head and upper body of the impacted pedestrian. A secondary objective is to provide a system which reduces the amount of damage caused to the vehicle due to the impact.	Mass increase: Moderate due to addition of actuation system Cost increase: Moderate due to necessity of actuation device, control system and impact sensors Packaging difficulty: Moderate as the system occupies space under the bonnet Operational difficulty: Low. System uses similar technology as pop-up bonnets, therefore should operate as desired Effectiveness: Low. This system should reduce injury severity to pedestrians, however the secondary objective may not be realised as the inertia in the impact will cause the bonnet to deform

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
19	Vehicle Occupant Knee Protection Apparatus	Car/car derivative	Front-seated Belted Occupants	All Impacts (Host Vehicle)	A contact force detector senses the force produced by the occupant knee hitting a knee protection area. The knee protection area is attached to a mechanical drive unit which moves the knee protection area to reduce the force on the knee.	The objective of this system is to reduce the injury severity of the lower extremities and control the upper torso kinematics of the occupant by reducing the forces on the knee.	Mass increase: High due to addition of mechanical drive unit Cost increase: High due to addition of mechanical drive unit Packaging constraints: Moderate as area behind knee contact area is largely free due to EuroNCAP modifier scoring system Operational difficulty: Moderate. Hydraulic regulator speed may not be fast enough for this system to work effectively. However, as the knee contact area will be required to retract late in the crash, there will be sufficient time for the impact force to be detected.

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
20	Vehicle Frontal Airbag System	Car/car derivative	Pedestrian and cyclist impacts	Pedestrians and cyclists	When it is sensed that an impact with a pedestrian is about to occur, a T-shaped airbag is inflated from the bumper/grille area to cover the bumper/grille/front of bonnet area to cushion the impact of the pedestrian on the front of the vehicle.	The objective of this system is to reduce the impulse on the lower body of a large pedestrian (e.g. adult) and on the upper body of a small pedestrian (e.g. child), to reduce the injury severity of the pedestrian.	Mass increase: Moderate due to addition of airbag system Cost increase: High due to addition of pre-crash sensing system Packaging constraints: Moderate as system will occupy space in the front of the vehicle near the front bumper/grille Operational difficulty: High. System will require pre-crash sensing to recognise the collision partner to activate the frontal airbag if it is believed to be a pedestrian Effectiveness: Moderate. If system operates as desired, then the likelihood of injury for the pedestrian is reduced, however significant testing and development of the pre-crash sensing devices will be required

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
21	Crash damper with magnetorheological fluid	Car/car derivative	Side Impacts (Bullet Vehicle)	Belted vehicle occupants	An energy-absorbing crash damper contains MR fluid. Sensors in the front of the vehicle detect the impact force in a collision, and alter the magnetic field around the damper to alter the viscosity of the fluid, which adjusts the rate that the damper crushes.	This system can alter the rate at which the vehicle decelerates to reduce deceleration levels of the occupant compartment. Viscosity of the fluid is infinitely variable between zero and maximum flow.	Mass increase: High due to addition of crash damper structure and MR fluid. Cost increase: High due to addition of crash damper structure, MR fluid, control system and actuation system Packaging difficulty: Moderate. System could replace existing longitudinal rails, however the system is likely to occupy more space than the longitudinal rails. Operational difficulty: Will require rapid sensing of the impact force. This may be beyond the limits of current sensors. Effectiveness: Moderate. If the system works as designed, the injury severity levels of occupants will be reduced. This would require significant testing of the system. High feasibility issues, however, indicate that the system is unlikely to appear on production vehicles and therefore full-scale testing of the system is unlikely.
		Car/car derivative	Side Impacts (Target Vehicle)	Vehicle occupants			
		Car/car derivative	Offset frontal impacts	Belted vehicle occupants			

Ref No.	Name of Adaptive System	Field of Application/Target Population			Description	Objectives	Feasibility
		Host Vehicle	Target Accident Types	Target Casualty Groups			
22	Movable Vehicle Seat	Car/car derivative	Frontal Impacts	Belted vehicle occupants	Pre-crash sensors detect that an impact is imminent and move the seat of the vehicle to a position that will provide increased safety for the occupant of the seat. In a frontal impact this would be to move the seat rearwards, and in side impacts this would be to move the seat sideways (away from the impacted side) and/or upwards.	The objective of this system is to move the occupants of the vehicle into positions that will reduce the injury severity sustained in an impact.	Mass Increase: Moderate due to addition of mechanical device to move the position of the seat Cost increase: High due to addition of mechanical actuation system and pre-crash sensing device Packaging difficulty: Moderate as actuation device occupies space under the vehicle seat Operational difficulty: Low. System used on some current production vehicles therefore system can operate as desired Effectiveness: Moderate
		Car/car derivative	Side Impacts (Bullet Vehicle)	Belted vehicle occupants			
		Car/car derivative	Side Impacts (Target Vehicle)	Vehicle occupants			

Appendix B. Adaptive System References

Reference	Document title	Document author
1	Adaptive Frontal Structure Design to achieve Optimal Deceleration Pulses	Willem Witteman, Technische Universiteit Eindhoven, Mechanics of Materials/Vehicle Safety, The Netherlands. Paper Number 05-0243
2	Adaptive Impact Absorbers –The Concept, Design Tools and Applications	Jan Holnicki-Szulc and Marcin Wikło *Institute of Fundamental Technological Research, Warsaw, Poland, holnicki@ippt.gov.pl*
3	Adaptive Crash Structure (Balls in Tube)	Mike Baldwin, Corus Automotive Engineering, 22nd June 2006, Project Nr 1586
4	Adaptive Vehicle Safety System For Collision Compatibility	Kwaku O. Prakah-Asante, Manoharprasad K. Rao. Ford Global Technologies. United States Patent No. 6,944,544. 13th September 2005
5	Front Structure In A Vehicle	Johnny K Larsson, Clas Jernström. AB Volvo. United States Patent No. 6,302, 476. 16th October 2001
6	Apparatus For Controlling Stiffness Of A Vehicle Body	Shunji Suzuki, Yuta Urushiyama. Honda Motor Co., Ltd. United States Patent No. 7,090,288. 15th August 2006
7	The Necessity Of An Adaptive Vehicle Structure To Optimize Deceleration Pulses For Different Crash Velocities	WJ Witteman, RFC Kriens. Technische Universiteit Eindhoven, The Netherlands. Paper Number 320
8	Adaptive Crashworthiness Of Front-End Structure Of Motor Vehicles	Marian Ostrowski, Jan Holnicki-Szulc, Paulius Grivkevicius. SAE Paper No. 2007-01-1180
9	The Necessity Of An Adaptive Vehicle Structure To Optimize Deceleration Pulses For Different Crash Velocities	WJ Witteman, RFC Kriens. Technische Universiteit Eindhoven, The Netherlands. Paper Number 320
10	Adaptive Collapsible Steering Column	Rex R. Struble, Ernst M. Faigle. TRW Inc. United States Patent No. 6,296,280. 2nd October 2001

Reference	Document title	Document author
11	Adaptive energy-absorbing materials using magnetorheological fluid impregnated cellular solids	Suraj S Deshmukh and Gareth H McKinley. Department of Mechanical Engineering and Institute of Soldier Nanotechnologies (ISN), Massachusetts Institute of Technology, Cambridge, MA 02139, USA. 6th December 2006
12	Motor Vehicle	Martin Holly, Andrew Scott. Rover Group Limited. United States Patent No. 6,116,648. 12th September 2000.
13	Active Armrest For Side Impact Protection	A. Mangala M. Jayasuriya, Nripen Kumar Saha. Ford Global Technologies, Inc. United States Patent No. 6,568,743. 27th May 2003.
14	Designing Road Vehicles For Pedestrian Protection	J R Crandall, K S Bhalla, N J Madeley. Center for Applied Biomechanics, University of Virginia, USA. BMJ Volume 324. 11th May 2002.
15	Designing Road Vehicles For Pedestrian Protection	J R Crandall, K S Bhalla, N J Madeley. Center for Applied Biomechanics, University of Virginia, USA. BMJ Volume 324. 11th May 2002.
16	Underbody Crash Device For A Vehicle	Gregory Frederick, Phillip Przybylo, Xiaowei Li, Saeed Barbat, Hikmat Mahmood. Ford Global Technologies LLC. United States Patent No. 7,237,828. 3rd July 2007.
17	Active Bumper Assembly	Timothy A. DePottey, David W. Schneider, Charles J. Sherwin. Autoliv ASP, Inc. United States Patent No. 6,764,118. 20th July 2004.
18	Safety Arrangement For A Vehicle	Rikard Fredriksson, Yngve Haland. Autoliv Development AB. United States Patent No. 7,246,677. 24th July 2007.
19	Vehicle Occupant Knee Protection Apparatus	Yazuki Motozawa, Daisuke Fuji, Hidekazu Nishimura, Yoichi Amano. Honda Motor Co., Ltd. United Sates Patent No. 7,240, 920. 10th July 2007.

Reference	Document title	Document author
20	Vehicle Frontal Airbag System	Cherie Alexander, Steven Hailstone, Paul Curry. Universal Propulsion Company. United States Patent No. 7,073,619. 11th July 2006.
21	Investigation Of Adaptive Vehicle Body Structure Concepts With Respect To Different Crashworthiness Requirements	Johnannes Vetter, Jörg Hoffman, Albrecht Kretzschmar. Siemens Restraint Systems GmbH. Paper V19. 6th International Symposium and Exhibition on Sophisticated Car Occupant Safety Systems. Karlsruhe, Germany 2002.
22	A Generic Evaluation Methodology For Advanced Safety Systems	Ronald de Lange. APSN Conference. 18th September 2007. Maastricht, The Netherlands.