Adult front car occupant thorax injury experience following frontal impacts

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ABSTRACT

The following paper presents the nature and mechanism of injuries sustained in frontal impacts, focusing on car to car impacts. It was found that the body regions most frequently sustaining severe to fatal injuries were the legs and the thorax. The nature and mechanism of the injury sustained was investigated only for the thorax injuries, due to their potentially life threatening nature. The analysis revealed that the most frequent cause of the injury recorded was the seatbelt for low severity injuries and the front structure of the vehicle for higher severity injuries. An analysis of the effect of load limiter technology in the restraint system showed that the proportion of occupants who sustained 'no thorax injury' did not increase when a load limiter was fitted to the restraint system. However, a decrease in the 'organ' and 'organ and skeletal' injuries was observed in the load limiter sample. Sample size and variation mean that these findings are not conclusive.

INTRODUCTION

Following the introduction of the European frontal and side impact directives and EuroNCAP, significant improvements have been made to car secondary safety. Even so, there are still about 1,600 car occupants killed and 15,000 seriously injured in Great Britain (GB) annually (Road Casualties Great Britain 2006)[1]. Approximately 50 to 60 percent of these occur in frontal impacts. One of the next steps to improve frontal impact protection further is to improve compatibility in vehicle-to-vehicle impacts.

To this end, the European Enhanced Vehicle-safety Committee (EEVC) Working Group 15 (Compatibility and Frontal Impact) is working to develop an integrated set of test procedures to assess a vehicle's frontal impact performance, including its compatibility. The assessment of the likely benefit for improved vehicle compatibility was undertaken as part of a 5th framework European Commission project called VC-COMPAT[2] published in 2006.

The benefit analysis (GB only) performed in the VC-COMPAT project predicted that, even with improved compatibility, thorax injury would still be a substantial problem in frontal car impacts. Further work is needed to understand whether changes in vehicle design have affected the mechanism of thorax injury sustained in car frontal impacts and how, if at all, the mechanism has changed. This understanding is needed to accurately direct future research and test procedures. For example, one possible reason could be that, because EuroNCAP has encouraged cars to have stronger compartments, the thorax injury mechanism in car frontal impacts is no longer predominantly related to compartment intrusion but to the car's deceleration and the performance of the restraint system. If this were the case, it would have a major effect on the direction of future work as currently the focus is on the development of test procedures to improve a car's structural performance to reduce compartment intrusion.

BACKGROUND

Much research has been performed to understand compatibility, with three main influencing factors being identified: structural interaction, frontal force matching and compartment strength.

Structural interaction is relevant for all frontal impacts and describes how well vehicles interact with their impact partner, either another vehicle or a road-side obstacle[3]. If the structural interaction is poor, the energy absorbing front structures of the vehicle may not function as efficiently as designed, leading to an increased risk of compartment intrusion at lower than designed impact severities and a less optimum compartment deceleration pulse.

Also, 'triggering' of the restraint system may be sub-optimal due to a less predictable crash pulse. Examples of poor structural interaction are override (where a vehicle rides up over its impact partner) and the fork effect (where the longitudinals of a vehicle misalign in a horizontal plane).

A vehicle's frontal force levels are related to its mass. In general, heavier vehicles have higher force levels as a result of the current test procedures and manufacturers' desire to keep crush space to a minimum[4]. As a consequence, in a collision between a light vehicle and a heavy vehicle, the light vehicle absorbs more than its share of the impact energy as it is unable to deform the heavier vehicle at the higher force level required. Matched frontal force levels would ensure that both vehicles absorb their share of the kinetic energy, which would reduce the risk of injury for the occupant in the lighter vehicle.

Compartment strength is an important factor for self-protection, especially for light vehicles. In an event where vehicle front structures do not absorb the impact energy as designed, the compartment strength needs to be sufficiently high to ensure minimal compartment intrusion. Beyond this, there is scope for better optimisation of the car's deceleration pulse to minimise restraint induced deceleration injuries.

METHODOLOGY

The analyses described in this report have been performed using data from the Co-operative Crash Injury Study (CCIS). CCIS is an ongoing project, which has collected real world car occupant crash data since 1983 and conducts approximately 1,000 car injury crash investigations per year. Occupant injuries are coded in accordance with the Abbreviated Injury Scale (AIS)[5]. AIS is a threat-to-life scale and every injury is assigned a score, ranging from 1 (minor cuts, bruises etc) to 6 (currently untreatable). The Maximum AIS score a casualty sustains is termed MAIS.

A comprehensive overview of the methodology involved in the CCIS can be found at www.ukccis.org.

The CCIS dataset used in this analysis contained information about 17,314 occupants involved in 8,395 accidents that occurred between 1998 and 2007.

The original VC-COMPAT project conducted its analysis on vehicles registered after 1995 and up to 2005. A criticism of the original VC-COMPAT benefit analysis, was that cars designed and manufactured before and after the introduction of the frontal impact directive and EuroNCAP were grouped together in the sample, so that the improvements introduced in more recent generations of cars were not taken into account, and therefore the predictions overestimated the likely benefits associated with improved compatibility. To gain a greater understanding of how thorax injury and the corresponding mechanisms of injury have changed with vehicle and restraint design improvements in recent years, the dataset has been split into two subsets: occupants in cars registered from 1992-1997 ('old'), and occupants of cars registered in 2000 to 2007 ('new'). These subsets, with a clear separation between newer and older vehicles, were used to assess how improved vehicle structures and improved occupant restraints of newer cars have affected the predicted benefits of compatibility, particularly for thorax injuries.

Within these subsets, the samples analysed were chosen based on the following criteria:

- Only front outboard occupants were included.
- The most severe impact that was experienced was to the front of the vehicle.
- The vehicle did not roll over before the most severe impact.
- The injury severity, measured by MAIS (Maximum AIS severity score), was known for the occupant.
- The occupant was belted at the time of the accident.

The sample sizes, unless otherwise stated, were 1,786 occupants for the 'new' dataset and 1,854 occupants for the 'old' dataset.

To ensure that the datasets were roughly equivalent, a comparison exercise, looking for any confounding factors, was conducted. The following variables within the CCIS dataset were compared:

- The age distribution of the occupants in each sample
- The ETS for the impact
- The Delta-V for the impact
- The Police severity assigned to the impact (used as an initial notification for case selection)
- The object that was hit in the collision
- The kerb mass of the vehicles

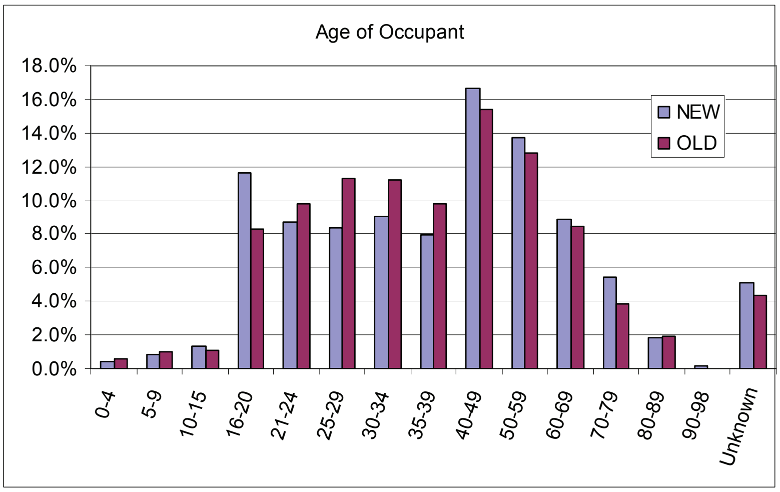

Figure 1 Age distribution of the occupants

It was found that the 'old' and 'new' datasets were significantly different with respect to the age profile of the injured casualties. The occupants of cars in the two datasets have a different age range distribution profile; although shows that the distributions are of broadly similar shape.

Both the collision severity (measured in terms of Equivalent Test Speed, ETS) and injury severity are typically greater for the old dataset compared to the new. However, car front structures are becoming stiffer and this directly affects the calculation of the ETS. Increases in stiffness reduce the amount of residual structural deformation, which is the basis for calculating ETS for CCIS investigated cars Therefore, the ETS may be underestimated for new cars compared to old, and the CCIS project's technical management team are currently investigating this phenomenon. Based on the data currently available from CCIS, it is considered that the differences in the ETS values observed between the new and old cars at the thorax AIS 3+ injury level are greater than might be explained by a calculation error based on inappropriate (too low) stiffness parameters being used in the collision severity algorithm alone. Additional explanatory factors are therefore required, and the most likely is felt to be that the increased stiffness of vehicles is contributing to new car occupants experiencing more deceleration based injury through greater seat belt webbing loading.

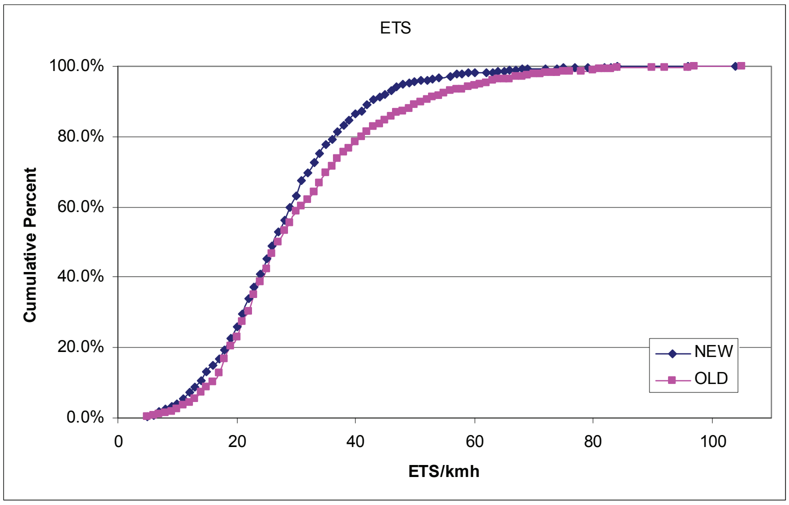

Figure 2 ETS for the single most severe impact

CCIS preferentially samples newer cars; an older car can only be included if it collided with a newer car. This leads to another difference between the two datasets, with proportionally more car-to-car impacts in the old car sample, and more single-vehicle accidents in the new car sample.

RESULTS

Repeat of the VC-COMPAT analysis

The analysis conducted for the VC-COMPAT project was repeated, using the same methodology, on the 'old' and 'new' datasets.

Model 1 removes all injuries caused by an intruding internal front structure. Model 2 removes all injuries caused by contact with any internal front structure, regardless of intrusion.

Table 1 Summary of casualty benefits estimated by compatibility models

Dataset	Impact partner	% casualty reduction			
		Model 1: intrusion		Model 2: contact	
		Fatal	Serious	Fatal	Serious
Old cars	Car-car (n=1323)	16.9	10.2	23.1	26.3
	Car-large vehicle (n=257)	5.8	3.2	17.7	9.6
	Car-object (n=232)	2.9	8.0	4.5	16.1
New cars	Car-car (n=1221)	12.7	7.1	21.8	26.0
	Car-large vehicle (n=228)	5.5	3.2	8.4	15.1
	Car-object (n=325)	10.1	13.0	15.8	29.4
VC-COMPAT	Car-car (n=2031)	14.0	10.1	23.9	27.3
	Car-large vehicle (n=434)	0.9	4.0	12.9	13.8
	Car-object (n=572)	13.8	10.3	21.7	22.6

In general, the results from the 'new' car and the 'old' car dataset are broadly similar to the results of the VC-COMPAT dataset. This would be expected because there is a large overlap in the year of manufacture of the cars involved: the VC-COMPAT dataset included cars built in 1996 or later, and this overlaps with both 'old' and 'new' datasets used in the current analysis. The lower percentages seen in the 'new' car dataset when compared to the VC-COMPAT dataset for car-car impacts are due to the differences in the proportion of impact types contained in the two datasets. The percentage of fatalities mitigated in car-large vehicle accidents differs between the 'new' car dataset and the VC-COMPAT dataset, but this change is exaggerated because of the low number of fatalities involved. The same can be said of the differences in the percentage of fatalities mitigated in the car-object group.

A larger benefit is estimated for the car-car impacts in the 'old' car dataset compared to the 'new' car dataset. This suggests that the newer cars have improved in terms of safety in this type of impact compared to the older cars, although there are still improvements to be made.

Further to the validation of the original VC-COMPAT results indicated in **Table 1**, additional repeated analysis, not presented in this paper, again shows that thorax injuries are not significantly mitigated by the compatibility models in either old or new cars.

Analysis of the body region injured

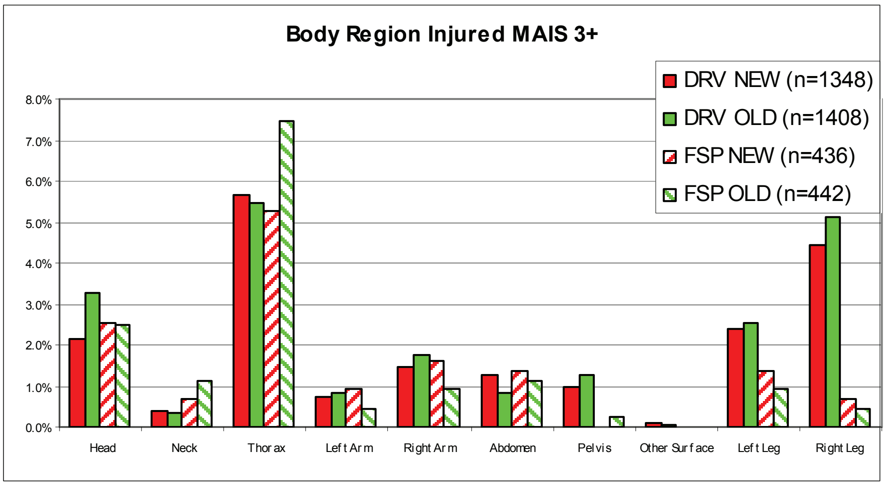

Figure 3 Body region injured at MAIS 3+, by occupant position

Figure 3 shows the percentage of injuries sustained at the MAIS 3+ level, that is, serious and life threatening injuries. At this level it can be seen that the main regions injured are the thorax and the legs. Although possible, life threatening injuries to the legs are relatively infrequent, so the thorax can be said to be the most life threatening area injured in frontal impacts at the MAIS 3+ level. The remainder of this paper will therefore concentrate on injuries sustained to the thorax and investigate the mechanism of injury and any confounding factors that may alter the injury severity sustained by the occupant. In the figure, DRV indicates the Driver and FSP indicates the front passenger.

Figure 4 presents the distribution of anatomic structures of the thorax that are injured at two different injury severities. The bars represent the percentage of the total sample size of the dataset. When an occupant sustains a significant injury to the thorax it mostly involves the internal and/or skeletal structures, apart from the thoracic spine. Because we are considering only a single body region, the term HAIS (Highest AIS score) is used instead of MAIS.

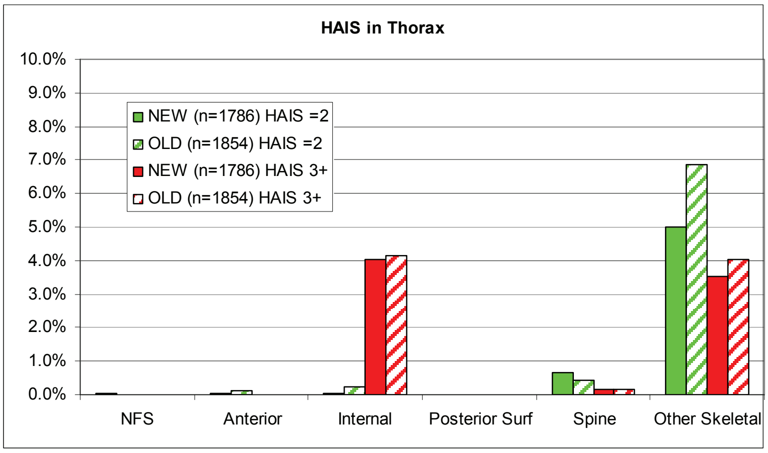

Figure 4 Highest AIS score in the thorax

Further investigation into the relationship between thorax injury severity and age, not presented here, showed that, for both drivers and front passengers, the number of severe thorax injuries as a proportion of the total number of injuries sustained by occupants in that age range, increases as the age of the occupant increases. This is in line with the results of cadaver tests, where it was found that deflection-based injury to the thorax was dependant on age, with risk of injury increasing with age[6].

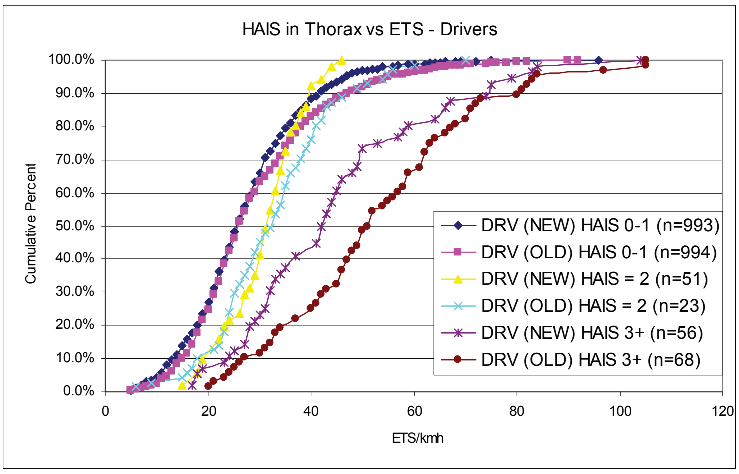

Figure 5 The highest AIS score in the thorax vs the ETS of impact - Drivers only

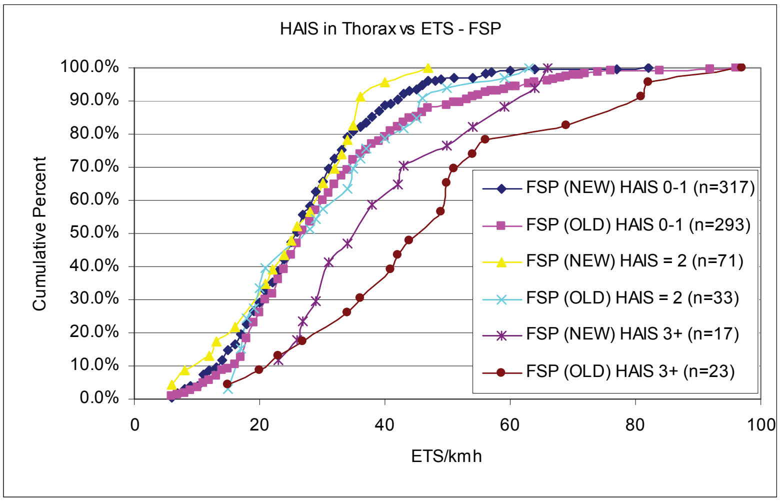

Figure 6 The highest AIS score in the thorax vs the ETS of impact - front passengers only

Figure 5 and Figure 6 present, for occupants injured at different severity levels, the distribution of ETS values at which those injuries were sustained. The figures show that, both for the driver and front passenger the severity of the injury sustained to the thorax increases as the ETS increases. The higher average ETS for the HAIS 3+ occupants in the old car dataset can be clearly seen here, but caution should be exercised when making conclusions, due to the low sample size.

As well as the differences outlined above regarding the ETS distributions of the datasets for HAIS 3+ thorax injuries, there are also other differences in the characteristics of the datasets for this subset of occupants, and these are shown in Table 2.

Table 2 Characteristics of Occupants with AIS 3+ Thorax injury

		New (n=1786)	**Old (n=1854)**
Gender	% Male	63.6%	53.2%
Age(years)	25%ile	37	34
	50%ile	56	54
	75%ile	69	66
Object hit	% Car	57.5%	67.6%
ETS (km/h)	% Unknown	26.2%	18.0%
	25%ile	30	37
	50%ile	42	50
	75%ile	53	63

This table shows that, although comparable, there are differences between the samples when considering those occupants that have sustained a serious injury to the thorax. There are more males in the ‘new’ car sample, but when the age distribution of the sample is assessed the ‘new’ car sample contains older occupants; this could be due to demographics but further work is needed to understand the reason.

The differences in the ETS distributions of the vehicles between the new and old datasets have been discussed above. Similarly, the over-representation of car to car impacts in the ‘old’ dataset is seen to apply to the HAIS 3+ thorax subset as well. To address any possible bias introduced by this, further analysis will focus on car to car impacts only. Taking account of other types of object hit (large vehicle, two-wheeler, wide object, narrow object etc) would be fruitless, since the sample sizes would be too small.

Analysis of the mechanism of Thorax injury

The analysis presented thus far has focused on the severity and location of the injuries sustained. The next section of the results further investigates these injuries and focuses on their nature and causation mechanisms.

Wherever possible, injuries in the CCIS database are attributed to causation agents. Figure 7 shows the distribution of AIS scores for the injuries associated with each causation agent, in the two vehicle subsets. Note that, since it is possible for an occupant to have multiple injuries, the sample size quoted for any injury level analysis will be higher than the number of occupants that are in the sample.

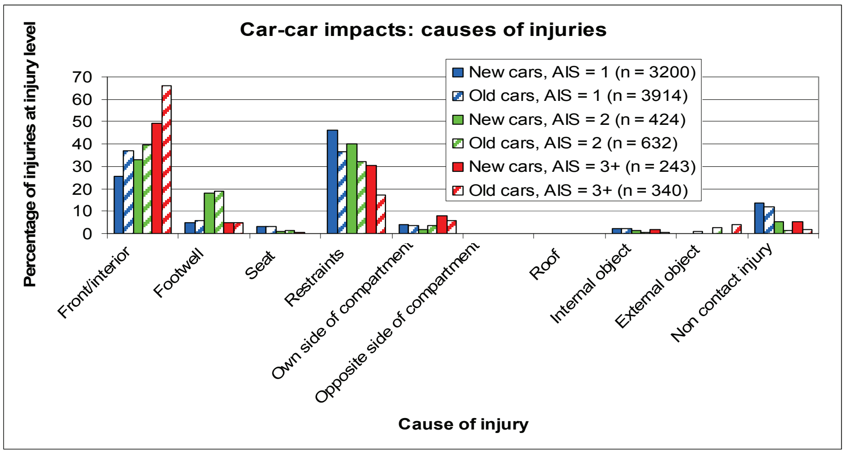

Figure 7 Causes of injury for car to car impacts

The main recorded causes of the injuries in car to car impacts were the front/interior structure and the restraint system. It should be noted that the non-contact injuries are mainly AIS 1 injuries: these are predominantly 'whiplash' or strain injuries. Overall, the number of injuries that are caused by the front/interior structure are higher than the number caused by the restraint, but when severity is taken into account, it is noted that there is a shift in the main mechanism of injury; low severity (AIS < 3) injuries are predominantly caused by the restraint system and high severity (AIS = 3+), by the front structures of the vehicle. In addition to this, as the injury severity rises, the restraint system is responsible for a greater proportion of injuries in new cars compared to old.

Another trend shown is a shift between the proportion of injuries that occur due to restraint and front/interior loading in new cars compared to old cars. The new cars have more injury causation assigned to the restraint loading (regardless of injury severity) and conversely the old vehicles have more injuries assigned to the front/interior structure. This could be due to the post EuroNCAP drive, by legislation and vehicle manufacturers, to reduce the level of compartment intrusion that vehicles suffer in frontal impacts.

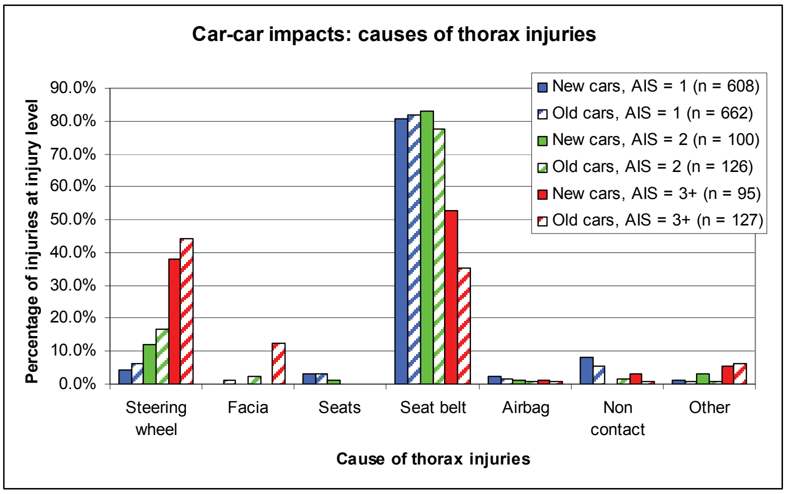

Figure 8 Causes of thorax injuries in car-car impacts

As previously shown, the main regions injured in frontal impacts were the thorax and lower extremities. The focus was deemed to be thorax injury due to the potentially life threatening nature of thorax injuries. It can be seen (Figure 8) that the majority of AIS 1 and AIS 2 thorax injuries are caused by the restraint system. When the more serious, AIS 3+, thorax injuries are considered the steering wheel is also a significant cause. However, the most obvious difference between old and new cars is that a larger percentage of AIS 3+ thorax injuries are caused by the restraint system in new cars compared to old cars.

Finally, the nature of the injury sustained to the thorax was assessed and compared to the functions of the restraint system present in the vehicle that the occupant was injured in. The analysis again only focuses on car-car impacts.

The different types of thorax injury sustained were grouped into skeletal only, organ only, skeletal and organ, and other injuries. Injuries classed in the vessels, thoracic spine and whole area in the AIS 1990 coding manual were included in the analysis, but grouped in the 'other' section. There were very few cases where the occupant had only a vessel injury and in the majority of cases they had either a skeletal or organ injury in addition; as such these vessel injuries have been included in the later categories where possible.

The type of restraint was defined by the level of functions fitted to the system. A 'normal' seat belt was defined as one where no load limiter or pretensioner device was fitted to the restraint system.

In addition to an analysis of the nature of the thorax injury and the restraint system, the age of the occupants and severity of the accident (measured by ETS) were also analysed; these are known to affect the injury severity score sustained and were also earlier identified as being slightly different when comparing the two datasets.

Occupants of 'old' and 'new' cars that had sustained AIS 2+ injuries to the thorax were compared.

Table 3 Occupants with AIS 2+ thorax injuries, comparison of old and new cars

	Old cars	New cars
Number of occupants	164	127
Only a skeletal thorax injury	67.7 %	65.4 %
Only an organ thorax injury	11.0 %	8.7 %
Skeletal and organ	20.1 %	24.4 %
Other thorax injury	1.2 %	1.6 %
Occs with clavicle fracture	12.2 %	12.6 %
Occs with AIS 2+ abdomen injury	19.5 %	18.1 %
Occs with pelvis fracture	7.3 %	8.7 %
Normal belt	9.8 %	1.6 %
Pretensioner	9.1 %	3.1 %
Load limiter & pretensioner	0.0 %	3.9 %
Airbag and normal belt	2.4 %	4.7 %
Airbag & pretensioner	11.6 %	17.3 %
Airbag & pretensioner & load limiter	0.0 %	51.2 %
Other / not known	67.1 %*	18.1 %

**Note the Other/Not Known for old car occupants is high due to a change in CCIS protocols for recording of restraint system type.*

The most frequent injury type for both the new and old car data sets was 'skeletal only', followed by 'skeletal and organ' and then 'organ only' injuries. However, there were slight differences in the proportions of these injury types for each data set. These differences are not believed to be significant based on this comparison alone, given the previously mentioned difference in age distribution between the two datasets.

Previous analysis has shown that injuries are commonly caused by the restraint (seat belt). The design of the vehicles in the 'old' car dataset largely pre-dates the introduction of EuroNCAP in 1997 and the European Union (EU) frontal impact legislation in 1998, although some of them will have been designed to anticipate the legislation and improved safety criteria. These vehicles will therefore have a range of structures with associated differing performance during an impact situation. It is not possible to analyse the performance of a restraint system within the vehicle without being able to control for the structural improvements which are believed to have had a significant influence on the injury outcome of the occupant. Therefore, to evaluate the performance of the restraint system alone, injuries in the 'new' vehicle dataset only were assessed. The new vehicles were registered post 2000 and nearly all had been designed to meet the EU frontal impact directive. Their structural performance is believed to be less of a confounding issue with respect to how the restraint system has performed than is the case for the 'old' cars. The new vehicles were all sampled equally and there is less bias with respect to the occupant characteristics (age and gender) and collision severity (ETS) when this group is divided by restraint system specification

Table 4, Figure 9 and Figure 10 compare the types of thoracic injury sustained by MAIS 2+ occupants in new vehicles with and without load limiters fitted. There were 146 occupants in the former group (129 with known ETS) and 51 in the latter (47 with known ETS). This is in line with the current trend for the vast majority of modern cars to be equipped with front seat belt load limiter technology.

Table 4 New cars, car-car impacts, occupants with MAIS 2+ injuries: comparison of restraint systems

	Airbag + pretensioner	**Airbag + pretensioner + load limiter**
Number of occupants	51	146
Only a skeletal thorax injury	23.53%	32.88%
Only an organ thorax injury	5.88%	2.74%
Skeletal and organ thorax injury	13.73%	10.27%
Occs with other thorax injury	29.41%	28.08%
No thorax injury	27.45%	26.03%
Occs with clavicle fracture	7.84%	11.64%
Occs with AIS 2+ abdomen injury	9.80%	13.01%
Occs with pelvis fracture	5.88%	6.85%

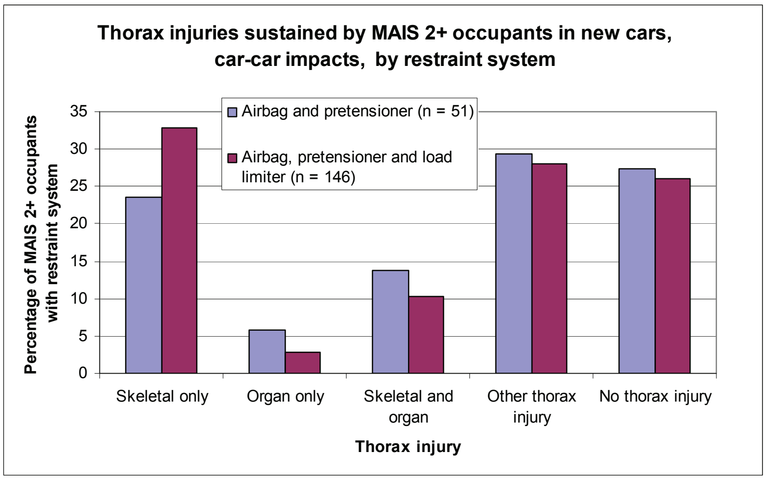

Figure 9 Thorax injuries sustained by MAIS 2+ occupants in new cars by type of restraint system

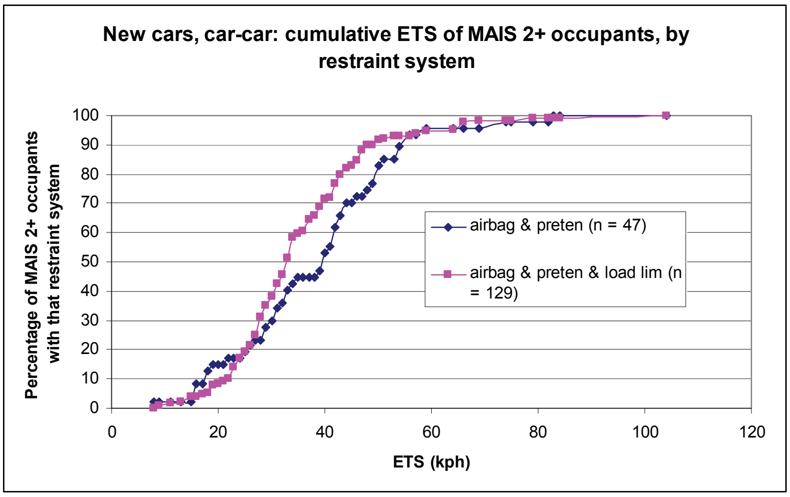

Figure 10 Cumulative ETS of occupants with MAIS 2+ injuries in new cars, by restraint type

Figure 10 shows the ETS distribution for the two groups. Occupants of vehicles equipped with load limiters appear to have sustained their injuries at slightly lower crash severities. However, numbers in the non-load limiter group are small.

In Figure 9 the presence or absence of a load limiter has little influence on the percentage of occupants that have 'no thorax injury'. If a load limiter was reducing injuries in the thorax, particularly those caused by restraint loading, which earlier analysis has shown to be a major cause of injury, it would be expected that an increase in the number of occupants with 'no thorax injury' in the load limiter sample would be observed. This is not the case and it can be seen that the influence of the load limiter varies with respect to the anatomical structure damaged. Thus, we see a reduction in the proportion of more serious ('organ' and 'skeletal and organ') injuries, together with an increase in the proportion of 'skeletal' injuries, which tend to be less serious. There is therefore some evidence that load limiters have had a positive effect, but this analysis has not been able to quantify the magnitude of any improvement, partly because of the relatively small differences observed between injury rates with and without load limiters. It is also recognised that load limiters have been grouped together, when in reality it is known that they have different performance characteristics, which are tuned in conjunction with the overall restraint system. This is likely to mean that some restraint systems perform better than others for different occupant groups.

Conclusions

- An initial comparison of the two datasets comprising 'new' and 'old' car occupant groups showed that there were significant differences between them and these are acknowledged to have some influence on the comparisons which have been made in this paper. However, these differences have been borne in mind in the interpretation of the results.
- Applying the VC-COMPAT compatibility models to the 'new' and 'old' car datasets resulted in a predicted benefit that was similar to that in the original analysis. A greater benefit was predicted for old cars, compared to new cars, showing that the rate of intrusion and contact induced thorax injury has decreased in newer cars. However the analysis showed that thorax injuries are not significantly mitigated by the compatibility models in either old or new cars. This is the same as the findings in the original VC-COMPAT project. Serious injuries to body regions such as the legs and arms were reduced by over 50 % for the contact model, whereas injuries to the thorax were only reduced by about 15 %.
- The main body regions injured at the AIS 3+ level for both the old and new datasets were the thorax and the lower extremities.

- An important observation was that AIS 3+ thorax injury was seen at a lower collision severity in the new car dataset compared to the old car dataset. However, possible underlying factors behind this observation include the different occupant demographics between the datasets and the increased stiffness of new cars, which could cause both an under estimation of the collision severity (ETS) and increased risk of deceleration induced injury.
- The most frequently cited causes of thorax injuries, in car to car impacts, are the seat belt and steering wheel. The seat belt is more frequently recorded as the cause of AIS 3+ injury for occupants of the new car dataset whereas the steering wheel was the principal cause of these injuries in the old car dataset. Differences between the dataset characteristics, namely the lower collision severity and occupant age, are likely to have contributed to this. However, it should be noted that the new car occupants still experience intrusion of the forward structures and therefore still experience some interior contact injuries due to intrusion into the compartment environment.
- For the new car dataset it was seen that when 'load limiters' were present less serious thoracic injury occurred compared to when they were not. This was due to a change in the distribution of injuries with reductions in the generally more serious 'organ and skeletal' and 'organ only' injury categories and a proportional increase in the 'skeletal only' injuries.
- In summary, the analysis has highlighted that thoracic injury remains a priority for future vehicle injury mitigation improvements.

Recommendations for the Way Forward

- Although this report has begun to classify the nature of the thoracic injury sustained by occupants of cars registered post 2000, more in-depth biomechanical studies are needed to evaluate the loading mechanisms in more detail. This is especially true for oblique chest loading by the seat belt webbing.
- A limitation of the work undertaken to date is that the load limiter technologies have been grouped together. Future work should seek to categorise the technologies with respect to their performance characteristics and link to the overall restraint system specification.
- There would be advantages for future work to correlate the cars' structural loading and the restraint system performance and assess the injury output controlling for the two.
- One of the possible factors affecting the comparison of the new and old car datasets was the possible under-estimation of the collision severity (ETS) for new cars. The CCIS technical team are currently developing the project's protocols to account for any potential bias in the calculations that are used to determine ETS for old and new cars.

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This report used accident data from the United Kingdom Co-operative Crash Injury Study (CCIS) collected during the period 1998-2007.

Currently CCIS is managed by TRL Limited, on behalf of the DfT (Transport Technology and Standards Division) who fund the project along with Autoliv, Ford Motor Company, Nissan Motor Company and Toyota Motor Europe. Previous sponsors of CCIS have included Daimler Chrysler, LAB, Rover Group Ltd, Visteon, Volvo Car Corporation, Daewoo Motor Company Ltd and Honda R&D Europe(UK) Ltd.

Data was collected by teams from the Birmingham Automotive Safety Centre of the University of Birmingham; the Vehicle Safety Research Centre at Loughborough University; TRL Limited and the Vehicle & Operator Services Agency of the DfT.

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

The views expressed in this report belong to the authors and are not necessarily those of the DfT.

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