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An In-depth Study of Abdominal Injuries Sustained by Car Occupants in Frontal Crashes

Richard Frampton, James Lenard
Loughborough University, UK

Sabine Compigne
Toyota Motor Europe

ABSTRACT - Currently, neither abdominal injury risk nor rear seat passenger safety is assessed in European frontal crash testing. The objective of this study was to provide real world in-depth analysis of the factors related to abdominal injury for belted front and rear seat occupants in frontal crashes. Rear occupants were significantly more at risk of AIS 2+ and 3+ abdominal injury, followed by front seat passengers and then drivers. This was still the case even after controlling for occupant age. Increasing age was separately identified as a factor related to increased abdominal injury risk in all seating positions. One exception to this trend concerned rear seated 15 to 19 year olds who sustained moderate to serious abdominal injury at almost the same rate as rear occupants aged 65+. No strong association was seen between AIS 2+ abdominal injury rates and gender. The majority of occupant body mass indices ranged from underweight to obese. Across that range, the AIS 2+ abdominal injury rates were very similar but a small number of very obese and extremely obese occupants outside of the range did exhibit noticeably higher rates. An analysis of variance in the rate of AIS 2+ abdominal injury with different restraint systems showed that simple belt systems, as used by most rear seat passengers, were the least protective. Increasing sophistication of the restraint system was related to lower rates of injury. The ANOVA also confirmed occupant age and crash severity as highly associated with abdominal injury risk. The most frequently injured abdominal organs for front seat occupants were the liver and spleen. Abdominal injury patterns for rear seat passengers were very different. While they also sustained significant injuries to solid organs, their rates of injury to the hollow organs (jejunum-ileum, mesentary, colon) were far higher even though the rate of fracture of two or more ribs did not differ significantly between seat positions. These results have implications for the design of restraint systems, particularly in relation to the occurrence of abdominal injury. They also raise issues of crash protection for older occupants as well as the protection afforded in different seating positions.

INTRODUCTION

The adoption of offset frontal crash testing in Europe from 1996 resulted in good casualty reductions in real crashes (Frampton et al. 2002). The introduction of the frontal test directive (EU Directive 96/79/EC) and the higher severity EuroNCAP procedure (Hobbs et al. 1999) improved vehicle structural performance and encouraged the development of better seat belt systems and airbag restraints. Currently however, abdominal injury risk is still not assessed, nor is the safety of rear seat passengers. The regulatory dummy for frontal crash in Europe is the Hybrid III which does not allow for the assessment of abdominal organ injuries. From 2009, Japanese NCAP has introduced the Hybrid III small female into the rear seat to assess submarine occurrence but this uses an on/off evaluation based on iliac crest load sensors and no objective measurement of the abdomen load is included. There is still a need to define the most suitable instrumentation for a dummy abdomen and to understand crash circumstances, injury types and injury sources in order to do this.

Klinich et al (2010), provide a comprehensive summary of real world abdominal injury studies in

the US dating back to 1980. They report that most of the studies focussed on front row occupants and were subject to belt use rates and airbag fitment at the time when the data was collected. The Klinich study purports to be more representative of the current occupant population in the US because most were belted and were in airbag equipped cars. The study did not focus on rear seat occupants and because of different restraints and frontal impact legislation in the US, the results may not be directly comparable to a European car fleet.

In the UK, Hill, Parkin and Mackay (1996) investigated seat belt related injuries to front seat occupants using in-depth UK crash data. They found that 13% of AIS 2+ belt related injuries for drivers were to the abdomen, the corresponding figure for front passengers was 10%. Rear seat occupants were not considered. Additionally, the dataset used comprised crashes from 1992 to 1995. This contained vehicles which had been constructed before the advent of the EU frontal crash directive and EuroNCAP. A more recent UK study (Frampton and Lenard, 2009) did however, highlight the need for a reduction in rear seat belt loads on the abdomen, as one of the requirements

for crashworthiness improvement in more modern vehicles.

In France, Lamielle et al (2006), used in depth crash data to examine the effect of restraint type, crash severity and occupant seating position on abdominal injury risk. The study covered vehicles constructed over a wide time period (1970 to 2005), although correction factors were added to account for differences in vehicle structural stiffness (and the corresponding effect on crash severity calculation) for older vehicle designs. A more recent study by Martin et al (2010), confirmed the higher risk of sustaining a moderate or severe abdomen injury for rear passengers compared to front. Using 1996-2006 Rhône road trauma registry data, the author showed that among car belted occupants who sustained at least one serious injury, 16% of the rear passengers had abdomen injuries, compared to 7% of drivers and 10% of front seat passengers.

The objective of the present study was to conduct a real world analysis of the factors related to abdominal injuries for belted occupants in frontal crashes using in-depth crash data populated with a group of contemporary European vehicles.

METHOD

Crash injury data from the UK Co-operative Crash Injury Study (CCIS) were interrogated. The CCIS study selects passenger cars for investigation using a stratified sampling procedure based on maximum injury severity. It includes crashes involving towed cars less than seven years old at the time of the crash in geographical regions selected to represent urban and rural roads in Great Britain (Mackay et al. 1985, Hassan et al. 1995). In those regions, the study aims to cover all police-reported serious and fatal injury crashes and about 10% of slight injury crashes.

The database contained detailed information on vehicle crash severity estimated by the Energy Equivalent Speed (EES), structural performance and restraint performance together with photographic documentation of the vehicle exterior and interior along with forensic evidence relating to injury causation. Detailed data were available for occupants, including age, seating position, restraint type and seatbelt use. Injury outcome was recorded using the Abbreviated Injury Scale (AAAM 1990). Detailed injury information was available for each occupant in the study including maximum AIS by body region and Maximum Abbreviated Injury Score (MAIS). Fatally injured occupants were additionally documented with post-mortem information, a requirement for accidental death in the UK.

The data covers the CCIS collecting period June 1998 to March 2010 and represents the completed

database for this time period. The working data sample for the abdominal injury study was selected according to the criteria below:

- Passenger cars equipped with driver airbag (ensuring reasonably modern design)
- Single Frontal impact within $\pm 30^\circ$ of the vehicle longitudinal axis (no rollover).
- Belted occupants ≥ 10 years .
- All involved occupants (incl. non injured).

This sample selection yielded 4183 occupants in 3249 vehicles. 75% of the occupants were drivers, 21% were front seat passengers and 4% were outboard rear seat passengers. Occupant body regions were classified using the body regions from the AIS 1990 revision. In the text, "head" refers to injuries to the head and face, "neck" includes the cervical spine, "chest" includes the thoracic spine, "abdomen" includes the lumbar spine, "upper extremity" has been abbreviated to "arms" and lower extremity to "legs". The sample data contained 136 drivers with AIS 2+ abdominal injuries and 46 with AIS 3+ level injuries. There were 60 front passengers with AIS 2+ abdominal injuries and 22 with those injuries at the AIS 3+ level. Of rear seat passengers, 44 sustained AIS2+ abdominal injury, while 22 sustained AIS3+ injury.

For the purpose of analysis, restraints were classified into five types: simple three point retractor belt (B); belt and pretensioner (B+P); belt and airbag (B+A); belt, pretensioner and airbag (B+P+A); and belt, pretensioner, load limiter and airbag (B+P+LL+A).

An exploratory analysis of variance in the rate of AIS 2+ abdominal injury was conducted with a focus on detecting the influence of restraint system features not normally fitted to the rear seats while controlling for at least some other possible causal factors. The computation and presentation of results was carried out in a conventional manner (Hoaglin, Mosteller and Tukey, 1991).

The exploratory analysis of variance in the rate of AIS 2+ abdominal injury relied on a number of assumptions. The number of parameters (dependent variables) and the number of categories or values within each parameter were effectively constrained by the number of cases available as there needed to be enough cases in each cell (combination of parameter values) to form an estimate of the rate of abdominal injury. A preliminary investigation using age (three categories), gender (two categories), impact severity EES (three categories) and restraint system (five categories) - thereby spreading the 4183 occupant sample across 90 cells - indicated that the effect of gender was small and negligible compared to the other three parameters. Gender was therefore omitted from the analysis,

reducing the number of cells to 45 and improving the reliability of the estimate of the rate of abdominal injury by roughly doubling the number of cases in each cell. The characteristics of the restraint system considered in the analysis were three-point seat belts, pretensioners, load limiters and airbags. Ideally seating position (driver, front passenger, rear passenger) would also have been included to reflect the potential influence of seat design and seat belt geometry; however this was precluded by the high association of seating position with restraint system features in this sample: for example, all drivers had an airbag but no rear passengers. Occupants for whom age, restraint system or injury were not fully specified were excluded from the ANOVA analysis. The categories of restraint system features used in the analysis excluded all combinations of load limiter without an airbag as these were too infrequent to support an estimate of AIS 2+ abdominal injury rate. Cases where the impact severity was not specified were included because these constituted a significant proportion of the total.

RESULTS

General Sample Characteristics

Vehicle Manufacture Year. The majority of vehicles in the sample (84%) were manufactured after 1996 with 46% manufactured after 2000. Figure 1 shows the distribution of manufacture year for the sample.

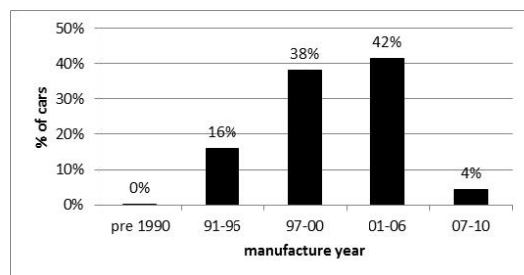


Fig 1. Vehicle Manufacture Year

Vehicle Restraint System Components. Restraint systems fitted in the sample vehicles are shown in figure 2 for each occupant seating position. All drivers had an airbag, 90% a pretensioner, 17% a load limiter and 13% an anti-submarining seat. Regarding front seat passengers, 61% had an airbag, 90% a pretensioner, 18% a load limiter and 13% an anti-submarining seat. No rear seat passengers had an airbag but 7% had a pretensioner, 3% a load limiter and 10% an anti-submarining seat. Care needs to be exercised when considering the fitment of load limiters and anti-submarining seats as these are not always evident upon vehicle examination.

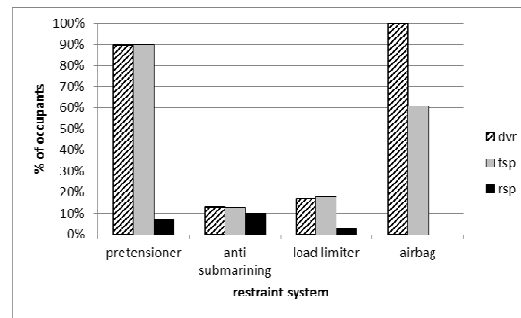


Fig 2. Restraint Systems by Seating Position

Vehicle Crash Severity. Crash severity could not be calculated for all crashes due to a variety of confounding factors in the field. In this sample, crash severity had been calculated for 55% of vehicles (1795/3249). Figure 3 shows the EES for all cars and then separately for cars with and without rear seat passengers. Where EES was known, it can be seen that the distribution of crash severity was very similar for rear and for front seat occupants with the majority of impacts falling between 20km/h and 40km/h. 91% of impacts occurred below 50 km/h and 97% fell below 60km/h.

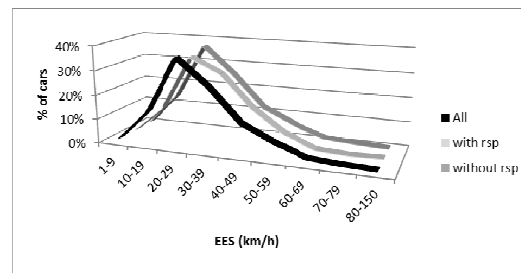


Fig 3. EES Distributions with and without Rear Seat Passengers

Vehicle Dashboard Intrusion. The extent of maximum residual dashboard intrusion was known for 97% (3159/3249) of cars. 94% sustained intrusion of 0-240mm, 4% sustained 250-440mm and 1% sustained 450-1500mm.

Occupant Gender. Of the 4183 occupants, 75% were drivers, 21% were front seat passengers and 4% were rear seat passengers. Overall, 57% of occupants were male and 43% female. Figure 4 shows the gender distribution by seating position. The majority of drivers were male (64%). The majority of front seat passengers were female (66%). In the rear, 57% of occupants were female.

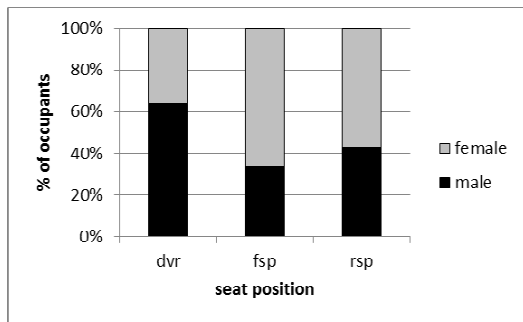


Fig 4. Gender by Seating Position

Occupant Age. Figure 5 shows the age distribution by seating position for the sample occupants. The age of almost all occupants was known. 52% of all occupants were aged 15 to 40 and 20% of all occupants were aged over 60. 2% of all occupants were aged 10 to 14 and 9% were aged 15 to 19. There was a higher proportion of drivers in the 25 to 60 age group (66%) compared to the other seating positions. There was a higher proportion of front seat passengers in the 60+ age group (26%) compared to other seating positions. There were lower proportions of rear seat passengers aged 25+ years old than in any other seating positions but the rear seats had the highest proportion of occupants in the 10 to 19 age group (45%).

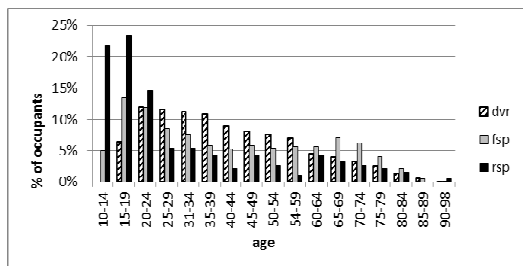


Fig 5. Age by Seat Position

Body Mass Index (BMI). The BMI indicates the level of body fat in an individual. In this report it was calculated from mass (kg)/(height (m))². BMI indicators used were the following:

Underweight <18.5, normal 18.5-25, overweight 26-30, obese 31-35, very obese 36-40, extremely obese >40.

Height and weight were not always available for the occupants in this sample. Height was unknown for 57% of occupants while weight was unknown for 58%. Figure 6 shows the BMI for all occupants and then by seating position.

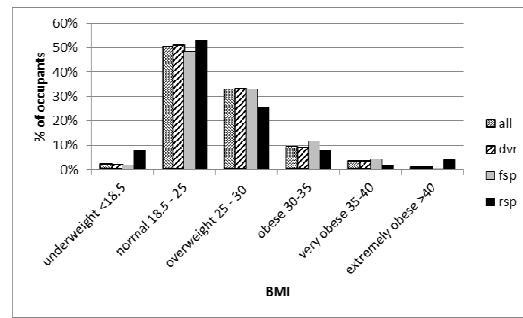


Fig 6. Body Mass Index by Seating Position

Of all occupants, 51% were classed as normal, with 33% classed as overweight. Underweight and extremely obese occupants formed only a relatively small percentage of occupants in each seating position. The largest proportion of occupants in each seating position were classed as normal. There was a lower proportion of rear seat passengers classed as overweight compared to other seating positions but a higher proportion of underweight and extremely obese persons.

Occupant MAIS. The maximum abbreviated injury score or MAIS represents the overall injury severity to an occupant. 241 of 4183 occupants had an unknown MAIS. Figure 7 shows the MAIS distribution for all occupants and then by individual seat positions. There were slightly more front seat passengers injured to MAIS 2 than occupants of other seating positions. However, the distributions of overall injury severity were similar between seating positions.

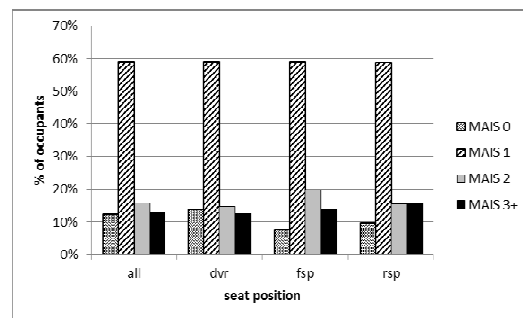


Fig 7. MAIS by Seating Position

Occupant Factors Related to Abdominal Injury

Abdominal Injury Rate by Seat Position. The maximum injury severity to the abdomen is shown in figure 8 for all occupants and then by seating position. 237 of 4183 occupants had an unknown abdominal injury severity. The rate of AIS 2+ abdominal injury was 6% for all occupants while the AIS 3+ rate was 2%.

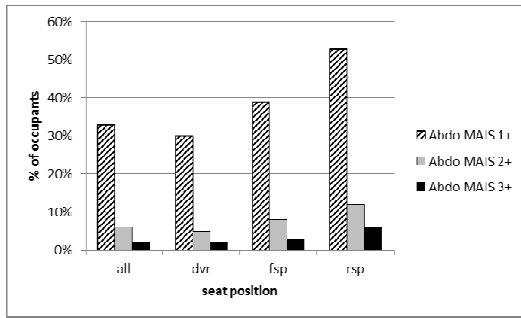


Fig 8. Abdominal Injury Severity by Seating Position

The abdominal injury risk increased from driver, through front seat passenger to rear seat passenger, at all levels of severity. The rate of AIS 2+ injury for rear passengers was 12%, twice as high as that for drivers and 1.5 times higher than that for front seat passengers. The rate of AIS 3+ injury for rear passengers was 6%, three times higher than for drivers and twice as high as that for front seat passengers. More than 50% of rear passengers sustained AIS 1+ abdomen injuries.

AIS 2+ Abdominal Injury by Seat Position and EES. Figure 9 shows the distributions of EES by seating position for occupants with AIS 2+ abdominal injury. Again, EES was not known for all cases. For drivers it had been calculated in 79 of 136 cases (58%), for front passengers in 42 of 60 cases (70%) and for rear passengers in 15 of 22 (68%) of cases.

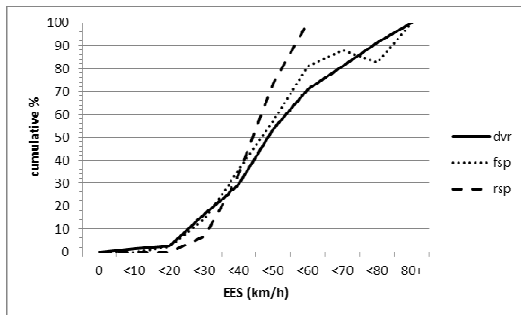


Fig 9. EES and Seat Position for AIS 2+ Abdominal Injury

Crash severity did not differ by much between seating positions. Although injury to rear occupants occurred at slightly lower speeds compared to the other seating positions. 73% of rear occupants sustained injury below 50km/h, while below that EES, 53% of drivers and 57% of front seat passengers sustained injury.

Abdominal Injury Rate by Age. The rates of AIS 2+ and AIS 3+ abdominal injury are shown by occupant age in fig 10.

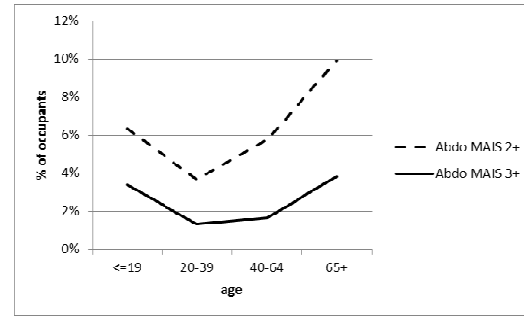


Fig 10. Maximum Abdominal Injury by Age

There was a trend for abdominal injury risk to increase with age from 20 years old. This was more pronounced at AIS 2+. However, figure 10 also indicates that the rate of moderate and serious abdomen injury was high for occupants under the age of 19. Their rates of injury were higher than those for the 20-39 and 40-64 age groups, although not quite as high as the rates for the oldest occupants in the 65+ band. Of the occupants up to 19 years old with AIS 2+ abdomen injury, 88% were aged 15 to 19 while 12% were aged 10 to 14. Of the occupants up to 19 years old with AIS 3+ abdomen injury, 93% were aged 15 to 19 while 7% were aged 10 to 14.

Abdominal Injury rate by Age and Seat Position. Figure 11 shows the rate of AIS 2+ abdominal injury by age group and seating position. For both drivers and front passengers the rate of abdominal injury increased with age although the rate for front passengers was generally higher than that for drivers. Irrespective of age, rear seat occupants generally had the highest rates of AIS 2+ abdominal injury. Figure 11 also indicates that for occupants younger than 20 or older than 65, the rear seat is the most high risk position for AIS 2+ abdominal injury. Young (<20) front seat passengers and drivers between 20 and 39 had the lowest rates of abdomen injury.

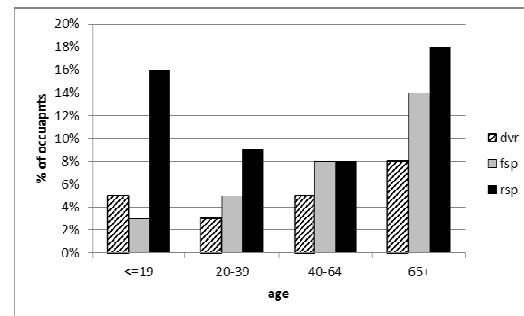


Fig 11. AIS 2+ Abdominal Injury Rate by Age and Seating Position

Abdominal injury Rate by Gender. The rate of AIS 2+ abdomen injury was 5.4% for males and 5.7% for females. The rate of AIS 3+ abdomen injury was 1.9% for males and 2.9% for females. Figure 12 shows the rate of AIS 2+ abdominal injury by gender and seating position. In all seating positions, there did not appear to be a major difference in rates between males and females. Irrespective of gender, the rates were higher in the rear seat compared to other seating positions.

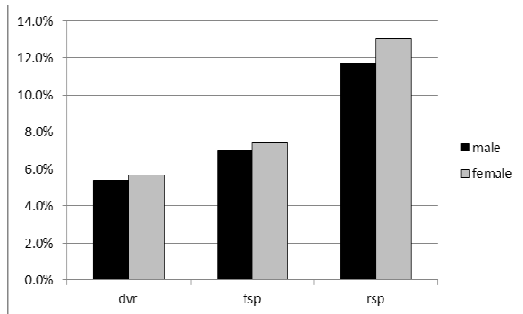


Fig 12. AIS 2+ Abdomen Injury Rates by Gender and Seat Position

Abdominal Injury Rates and BMI. Figure 13 shows the rates of AIS 2+ abdominal injury by body mass index.

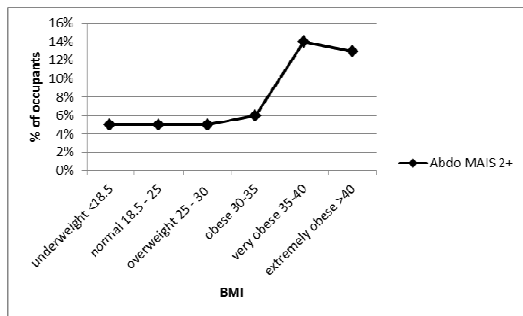


Fig 13. AIS 2+ Abdominal Injury Rates by BMI

There appears to be no major effect on AIS 2+ abdominal injury rates with increasing BMI until the occupant becomes very obese or extremely obese.

Table 1 shows the AIS 2+ abdominal injury rate by BMI and seat position where BMI was known. In each cell of the cross tabulation the rate was calculated from total number of occupants in each cell divided by number of occupants with AIS 2+ abdominal injury in each cell and expressed as a percentage. In some cells it is difficult to draw conclusions on injury rate where there are small numbers, the extremely obese occupants being a case in point. Nevertheless, for normal, overweight and obese occupants the AIS 2+ abdominal injury rate does not differ much between the driver and front passenger seats. Table 1 also shows that most very obese and extremely obese occupants with AIS 2+ abdominal injury were drivers. It is

recommended that a case review of those crashes with very obese and extremely obese occupants be carried out to determine what, if any, special factors contributed to the increased abdominal injury rate.

Table 1. AIS 2+ Abdominal Injury Rate by BMI and Seat Position

BMI	DVR	FSP	RSP
Underweight	0/27 (0%)	1/6 (17%)	1/4 (25%)
Normal	31/668 (5%)	10/144 (7%)	0/26 (0%)
Overweight	19/438 (4%)	5/97 (5%)	1/12 (8%)
Obese	7/119 (6%)	2/35 (6%)	1/4 (25%)
Very obese	6/44 (14%)	2/13 (15%)	0/1 (0%)
Extremely obese	1/11 (9%)	1/2 (50%)	0/2 (0%)

Restraint Systems and Occupant Injury

Type of Restraint System and Occupant Seating Positions. Occupant injury outcome was investigated in relation to restraint system type. It is important to be aware of the occupant seating populations using these systems (figure 14). The majority with simple belt systems (B) were rear seat occupants (74%) with the remainder being front seat passengers (26%). The overwhelming majority of occupants with belt + pretensioner (B+P) were front seat passengers (96%). The majority with belts + airbag (B+A) were drivers (93%). The majority of occupants with belts, pretensioners and airbags (B+P+A) were drivers (86%). Drivers also formed the largest group (79%) of occupants with belt + pretensioner + load limiter + airbag (B+P+LL+A).

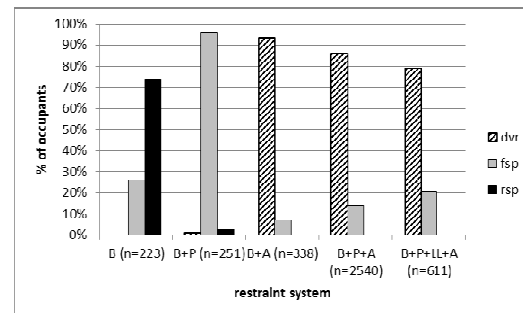


Fig 14. Seating Populations for Different Restraint Systems

EES for Occupants Using Different Restraint Types. EES was known for 46% of B, 31% of B+P, 39% of B+A, 54% of B+P+A and 81% of B+P+LL+A systems. Figure 15 shows the cumulative EES distributions for each restraint system. The plots (running from front to rear of the 3-D figure) are first the B system, then B+P, then B+A, then B+P+A, then B+P+LL+A. Where EES was known, figure 15 suggests that crash severity was similar between restraint system types.

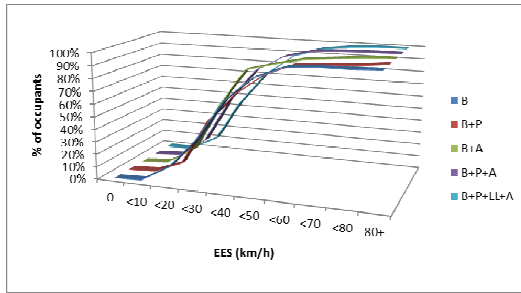


Figure 15. EES Distributions for Different Restraint System Types

Table 2. AIS 2+ Rates by Body Region for Different Types of Restraint

Body Region	Restraint Type				
	B	B+P	B+A	B+P+A	B+P+L+A
head	6%	4%	3%	5%	4%
neck	4%	1%	2%	2%	3%
chest	16%	15%	14%	12%	13%
abdomen	14%	4%	5%	4%	8%
pelvis	3%	<1%	5%	3%	4%
arms	13%	15%	12%	11%	13%
legs	4%	6%	16%	12%	14%
MAIS 2+	37%	31%	28%	27%	31%
n	223	251	338	2540	611

Injury Rates by Restraint Type. Table 2 shows the body region AIS 2+ rates by type of restraint as

well as the occupant MAIS. The MAIS 2+ rate was highest for the B restraint system and lowest for the B+P+A system. The rate of leg injury was lowest of all for the B system (4%), slightly below that for the B+P system at 6%. By contrast, the leg injury risk was much higher for the B+A, B+P+A and B+P+A+LL systems. The head, neck, chest and pelvis injury rates showed no great variation between the systems. The B system showed an AIS 2+ abdominal injury rate far above that of any of the other systems. Chest and abdominal injury rates between B and B+P systems were similar but the abdominal injury rate was 14% for the standard belt compared to just 4% for the pretensioned belt.

Comparative Effects of Age, Restraint Type and Crash Severity on AIS 2+ Abdominal Injury. The dataset for analysis of variance is provided in Annex 1. It provides the number of occupants with AIS 2+ abdominal injury for each of the 45 combinations of restraint system, EES and age considered in the analysis. In aggregate, 189 of 3558 occupants incurred an abdominal injury of this severity, a rate of 5.3%. The population of the individual cells ranged from 5 to 450 with a median value of 40. Figure 16 presents the effects and residuals of the analysis of variance. The main effects of age, restraint type and crash severity are shown and labelled individually. The interaction effects and residuals are provided alongside box-and-whiskers showing median values, quartiles and range. The common value, i.e. average value of the 45 cell rates, was 7.2%. Among the main effects, the 50+ age group had an additional +4.9% injury rate while the 18-29 and 30-49 groups each had a lower rate of around half this magnitude; the higher speed group (EES 30+ km/h) had an additional 6.3% rate of injury while the unknown and lower (EES 0-29 km/h) speed groups had a reduced rate of injury of -1.9% and -4.4% respectively. Taking the three-point seat belt alone (B) as a baseline (+3.2%), progressively better injury rates were offered by the B+P (+0.9%), B+A (-0.4%), B+P+L+A (-0.9%) and B+P+A (-2.8%) systems.

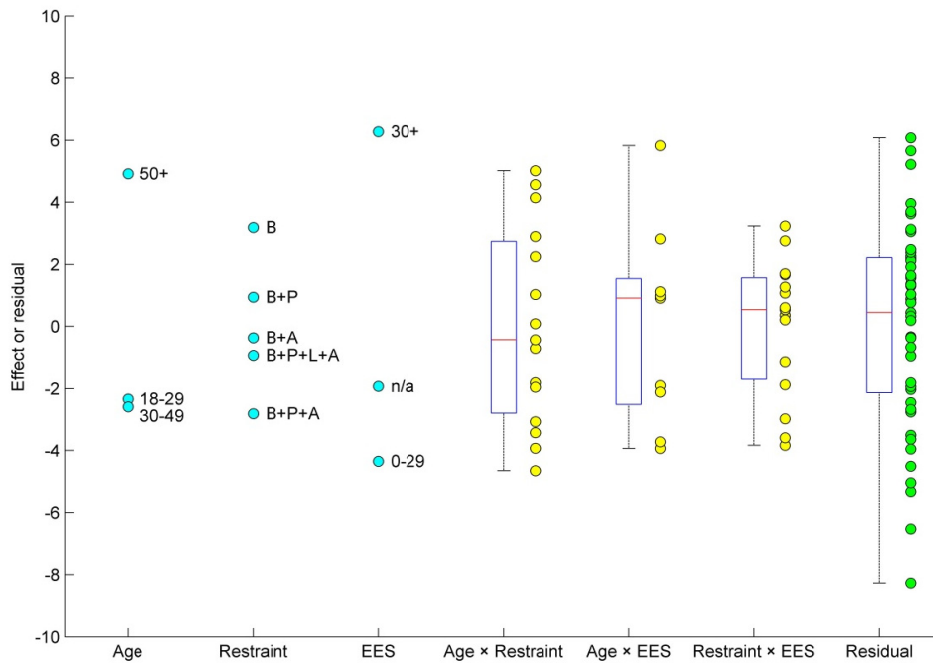


Figure 16. Side-by-side Plot of Effects and Residuals for Rate (%) of AIS 2+ Abdominal Injury

Table 3 is an ANOVA table for the rate of abdominal injury. The total variation about the overall mean, i.e. the corrected total sum of squares, is 3167 (5515-2348). The fit provided by the main effects age (545), restraint (180) and EES (931) accounts for over half (52%) of the variation on this measure.

Table 3. Mean Squares for Rate (%) of AIS 2+ Abdominal Injury

	SS	d.f.	MS
Common	2348	1	2348
Age	545	2	273
Restraint	180	4	45
EES	931	2	466
A x R	431	8	54
A x E	412	4	103
R x E	206	8	26
Residual	463	16	29
Total	5515	45	

Abdominal Organ Injury

Organs of the Abdominal Cavity. The abdominal cavity consists of hollow organs (intestine, colon, duodenum, mesentery, stomach and bladder) and solid organs (liver, spleen, kidneys, and pancreas) as shown in figure 17.

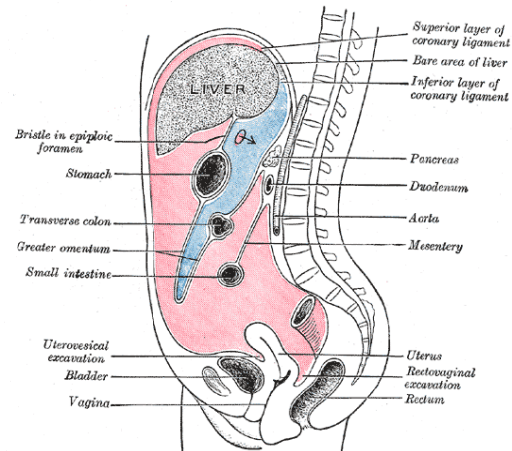


Fig 17. Abdominal Organs

Abdominal Organ Injury Rates. Figure 18 shows the AIS 2+ abdominal organ injury rates for all occupants in the study.

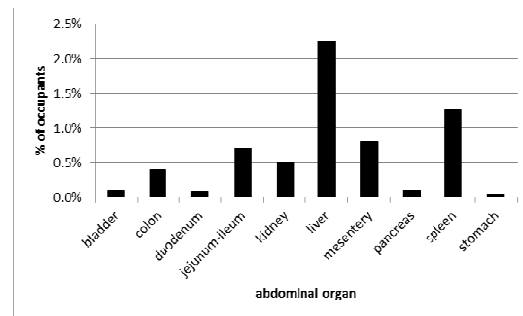


Fig 18. Abdominal Organ Injury Rates

It is clear that the liver was by far the most frequently injured abdominal organ. This was followed by the spleen and then the jejunum-ileum and mesentery. The colon and kidneys were then the next most frequently injured organs. Bladder, duodenum, pancreas and stomach injuries were infrequent.

Abdominal Organ Injury Rates and Seat Position. Figure 19 shows how abdominal injury organ rates vary by seat position.

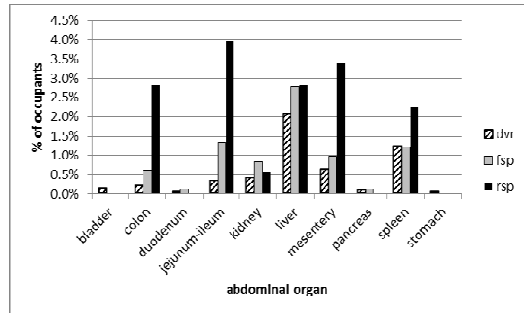


Fig 19. Abdominal Organ Injury Rates by Seat Position

The most frequently injured organs for drivers were the solid organs of the liver and spleen. For front passengers, the liver was also the most frequently injured organ followed by the jejunum-ileum and spleen. Jejunum-ileum injury was rare for drivers. Organ injury patterns for rear seat occupants were very different to those for drivers and front passengers. While injury to the liver was significant, injury to the hollow organs of the jejunum-ileum, mesentery and colon were the most frequent. In fact, the rate of injury to these hollow organs far outweighed the rates for drivers and front passengers. Rear seat passengers also had the highest rate of injury to the solid organ that is the spleen.

Injured Abdominal Organs and Fractured Ribs. The rate of fracture of 2 or more ribs did not differ significantly between seat positions. For drivers it was 5.2%, for front passengers 6.8% and for rear seat passengers 6.2%. The distribution of abdominal organ injuries with 1 or no rib fracture (<=1 rib #) and with 2 or more rib fractures (>=2 rib #) suggests that some organs are particularly associated with multiple rib fracture. Figure 20 shows the association of rib fractures with abdominal injuries. The majority of liver (71%), mesentery (66%) and spleen (66%) injuries were associated with 2 or more rib fractures. All bladder and pancreas injuries were associated with 2 or more rib fractures. Where 2 or more rib fractures occurred, the rate of AIS 2+ liver and spleen injury was much higher than where 1 or no rib fracture occurred (double the rate for the spleen and three times the rate for the liver).

The majority of colon (69%), duodenum (67%) and jejunum-ileum (61%) injuries were associated with 1 or no rib fracture, while all stomach injuries were associated with 1 or no rib fracture.

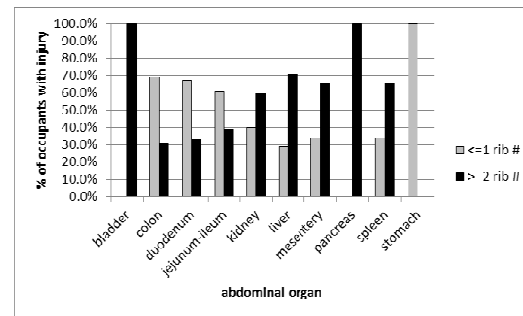


Fig 20. Association of Abdominal Organ Injury with Number of Rib Fractures

DISCUSSION

The data sample used to investigate abdominal injury in frontal crashes consisted mainly of cars manufactured from 1997 onwards and 46% were manufactured from 2001 onward. In addition to an airbag, almost all drivers had pretensioned belts. Most front passengers had pretensioned belts and about 60% had an airbag. Most rear occupants had a standard retractor belt with no pretensioner and no airbag. Anti submarining seat pans and load limiters were not as common as other enhanced restraint features for the occupants in this study.

There were gender differences between seating positions. The majority of drivers were male and the majority of front passengers female. In the rear, 57% were female. In terms of age, the driving seat had the highest proportion of occupants aged between 25 and 60 (66%). There was a higher proportion of front passengers in the 60+ age group than in the other seat positions (26%). Significantly, the rear seats contained the highest proportion of teenagers, 45% were in the 10-19 age group. In terms of BMI, Most occupants were classed as either normal or slightly overweight. At the extremes, underweight and very obese persons formed only a small percentage of occupants in each seat position.

In those cases where crash severity was known, it could be seen that the EES distributions were similar for cars with and without rear seat occupants. Furthermore, the MAIS distributions were also very similar between drivers, front passengers and rear passengers. What was different were the rates of abdominal injury for each seat position. It could be clearly seen that the rear occupants were at highest risk of abdominal injury at all levels of severity while drivers were at the lowest risk and this concurs with results found by Lamielle et al (2006) and Martin et al (2010). In the present study, crash severity distributions for

occupants with AIS 2+ abdominal injury appeared to be very similar between seat positions. Therefore, it was necessary to investigate other reasons for the apparent difference in injury risk.

There appeared to be a significant link between age and abdominal injury risk with important implications for development of biomechanical tolerance levels. Generally, the rate of AIS 2+ and 3+ injury increased from 20 years old and upwards, with the highest rates occurring for the 65+ age group. This is in agreement with results from Lamielle et al (2006) and Yamada (1970) who showed that the tensile strength of the abdominal organs decreased with age. This age factor was not seen in the recent study of US vehicles by Klinich et al (2010).

The current study showed that the rear seat generally exhibited the highest rate of AIS 2+ abdominal injury, irrespective of age. What is interesting is that the rear seat rate for occupants younger than 20 was second only to that for those aged 65+ and this is not explained on the basis of increased frailty. 88% of the young occupants with AIS 2+ abdominal injury in the rear were between 15 and 19 years old where an adult belt system is applicable. These cases need to be examined in greater detail to determine what factors contributed to the apparent high risk of abdomen injury to teenage rear seat occupants.

There appeared to be little effect of gender on rates of AIS 2+ abdominal injury. This was also the case when individual seat positions were examined. In the case of drivers, this result suggests that belt pretensioning systems and airbags are effective in protecting female drivers from the steering wheel.

Wang (2003) reported that abdominal injuries decrease with increasing BMI for males and females. In the present study, the occupant BMI did not appear to affect the rate of injury until the occupant became very obese or extremely obese and then the rate of injury was much higher than in the general sample population. It should be noted that these very large occupants only formed 10 of 240 (4%) of occupants with AIS 2+ abdomen injury and most were drivers. It is recommended that these rare cases be examined in-depth in order to determine if any special factors contributed to the injuries.

Occupant injury outcome was investigated in relation to restraint system type. Restraints were divided into 5 classifications. Simple three point retractor belt (B) [mainly rear seat occupants], belt + pretensioner (B+P) [mainly front seat passengers], belt + airbag (B+A) [mainly drivers], belt + pretensioner + airbag (B+P+A) [mainly drivers] and belt + pretensioner + load limiter + airbag (B+P+LL+A) [mainly drivers]. For each of

the restraint system groups, crash severity distributions (where known) were remarkably similar.

The MAIS 2+ rate was highest for the B restraint system but this does not suggest that occupants using the system were at highest risk of AIS 2+ injury in all body regions. In fact, the rate of leg injury was lowest of all for the B system. At 4%, slightly below that for the B+P system at 6%. By contrast, the leg injury rate was much higher for the B+A, B+P+A and B+P+A+LL systems. This is hardly surprising since those systems were mainly associated with drivers compared to the B system (mainly rear occupants) and B+P systems (mainly front passengers). It is testimony to the effectiveness of modern restraints that the head, neck, chest and pelvis injury rates showed no great variation between the systems despite the driver positions posing a potentially higher risk to those body regions. The Achilles heel of the B system appears to be in regard to abdominal injury. The AIS 2+ rate was far above that of any of the other systems and suggests shortcomings of a standard retractor belt. It is particularly interesting to compare chest and abdominal injury rates between the B and B+P systems in order to gain some insight into the possible effectiveness of a pretensioner. AIS 2+ chest injury rates were similar between the systems but the abdominal injury rate was 14% for the standard belt compared to just 4% for the pretensioned belt. Verification of the effectiveness of pretensioners in the rear would need to consider the populations of the rear and front passenger positions as well as any differences due to seat design, belt geometry and the effect of knee loading on the dashboard.

Figure 16, the side-by-side ANOVA plot of effects and residuals was derived from the source dataset without any statistical modelling or assumptions - it followed purely by arithmetic operations. The same applies to the table of mean squares as presented in table 3 because it does not report the F statistic, the use of which is based on assumptions about the underlying data (e.g. homoscedasticity, that the variance of data in groups is the same). The relatively low number of cases in some of the non-airbag groups in particular provided a reason to be cautious about applying a statistical model to the data. The influence of the low-count cells was discernible in the difference between the average rate of AIS 2+ abdominal injury in the sample population (5.3%) and the ANOVA "common value" (7.2%), the latter of which gives equal weight to each cell value irrespective of its population. Statistical tests would gain most traction among the airbag groups; however a motivation for conducting the current analysis was precisely to consider the potential benefit of adding restraint system refinements to the back seats.

The high association of seating position with certain features of the restraint system (figure 1) prevented the inclusion of seating position as a factor in the analysis, as mentioned above. As a consequence, the effect of seat design (bucket versus bench) and seat belt geometry could not be formally distinguished from the restraint system type using this particular sample. Nevertheless, a picture emerged associating older occupants (50+) and higher speeds (EES 30+ km/h) with greater risk of abdominal injury risk. Where impact severity was unknown (EES "n/a") the result lay between the higher (30+ km/h) and lower (0-29 km/h) groups, suggesting that the unknown speeds ranged across both categories. The effects for the two younger age categories (18-29 and 30-49), while distinct from the older age group (50+), were very close to each other. These results are consistent with those from previous work (Lamielle et al, 2006), as well as the indications from univariate analysis conducted in this paper, and tend to provide confidence in the findings on the effect of restraint system, a less explored area. Controlling for occupant age and crash severity, increasing sophistication of the restraint system was related to lower rates of abdominal injury, the exception being the seat belt-pretensioner-load limiter-airbag system (B+P+L+A). This raises the possibility that the addition of a load limiter to a seat belt-pretensioner-airbag system (B+P+A) does not result in a further reduction of the risk of abdominal injury; however in the absence of statistical confidence limits and a detailed case review of individual cases, it is reported here as a provisional observation or phenomenon in the accident sample rather than as a concrete finding. Of relevance to the potential development of restraint systems in the rear seat was that the belt plus pretensioner showed an AIS 2+ abdominal injury rate of +0.9% above the common value of 7.2% compared to 3.2% for a simple belt system.

In terms of the sample as a whole, it was quite clear that, at the AIS 2+ level, the liver was by far the most frequently injured abdominal organ. This was followed by the spleen and then the jejunum-ileum and mesentery. The colon and kidneys were then the next most frequently injured organs. Bladder, duodenum, pancreas and stomach injuries were infrequent. Lamielle et al (2006) showed similar low counts of bladder, duodenum, pancreas and stomach injuries at the AIS 3+ level.

The most frequently injured organs for drivers were the solid organs of the liver and spleen. For front passengers, the liver was also the most frequently injured organ followed by the jejunum-ileum and spleen, although the jejunum-ileum injury rate was 4 times higher for front passengers compared to drivers. The reason for this is unclear and would warrant further investigation.

Injury patterns for rear seat occupants were very different to those for front seat occupants. While injury to the liver and spleen was significant, the hollow organs of the jejunum-ileum, mesentery and colon were the most frequently injured. In fact, the rate of injury to those hollow organs far outweighed the rates for drivers and front passengers. The jejunum-ileum is slung from the rear abdominal wall by the mesentery and is extremely mobile. It sits below the liver as does the colon. These organs are not protected by the lower ribs and it is reasonable to assume that injury to them is frequently caused by compression of the abdominal cavity via the seat belt lap section. The study by Lamielle et al (2006) reported that the hollow organs are more frequently injured for front passengers and rear occupants compared to drivers. The Lamielle study also reported no significant differences in the rate of hollow organ injury between front passenger and rear occupant. Here, contrary to the findings of Lamielle et al, colon, jejunum-ileum and mesentery injury rates were much higher for the rear occupants compared to front passengers. Quite why this is so is unclear. Although the Lamielle study focussed on AIS 3+ injuries compared to AIS 2+ here, it is reasonable to assume that the injury mechanisms are not so different between the two severity levels.

Klinich et al (2010) found that if an occupant sustained AIS 2+ rib fractures, the odds of the occupant sustaining an AIS 2+ abdominal injury increased dramatically. In the current study, more AIS 2+ solid organ injury did occur with 2 or more rib fractures compared to 1 or no rib fracture. Due to the anatomical position of the liver and spleen it is easy to conclude that fractured ribs were a direct cause of injury. Conversely, however, colon, duodenum, jejunum-ileum and stomach injuries were more associated with 1 or no rib fracture. These hollow organs are situated below the lower ribs and could be directly compressed via a seat belt lap section (the pancreas and duodenum are situated at the back of the abdominal cavity and would require significant cavity compression before they were compressed). Interestingly, the mesentery, pancreas and bladder are also situated well below the rib cage but injuries to these organs were more often associated with 2 or more rib fractures. One possibility is that when the rib cage is compromised the belt can penetrate further into the abdomen. The rate of fracture of two or more ribs did not differ significantly between seat positions yet organ injury patterns were quite different between rear and front occupants. It therefore seems likely that, for the hollow organs at least, direct abdominal loading by the seatbelt plays a more significant part in injury causation in the rear.

CONCLUSIONS

This study of contemporary European frontal car crashes showed that rear passengers have a substantially higher rate of AIS 2+ and AIS 3+ abdominal injury compared to front seat passengers and drivers. It confirms the need for further development of tools and restraints to address abdominal injury risk, particularly in the rear seat.

Some of the results in this paper have important implications for the development and choice of biomechanical tolerance levels for the abdomen. No strong association was seen between AIS 2+ abdominal injury rates and gender. The majority of occupant body mass indices ranged from underweight to obese. Across that range, the AIS 2+ abdominal injury rates were very similar but a small number of very obese and extremely obese occupants outside of the range did exhibit noticeably higher rates of injury. There was a strong general trend for increasing AIS 2+ and AIS 3+ abdominal injury rates with increasing age, in all seating positions. One exception to the trend concerned rear seated 15 to 19 year olds who sustained moderate to serious abdominal injury at almost the same rate as rear occupants aged 65+. A consideration of injury tolerance for older car occupants is increasingly important as the older population of car users increases but further work is required to determine the factors related to teenage abdominal injury in the rear.

The analysis of real world crashes was also able to provide information of relevance to restraint system design. An analysis of variance in the rate of AIS 2+ abdominal injury with different restraint systems showed that simple belt systems, as used by most rear seat passengers, were the least protective. Increasing sophistication of the restraint system was related to lower rates of injury. Furthermore, injury patterns for rear seat occupants were different to those for front seat occupants. In the rear, while AIS 2+ injuries to the liver and spleen were notable (mainly associated with 2 or more rib fractures), the hollow organs of the jejunum-ileum, mesentery and colon were the most frequently injured. In fact, the rates of AIS 2+ injury to those hollow organs was much greater than the rates for drivers and front passengers and suggest the possibility of abdominal loading below the rib cage (the majority of jejunum-ileum and colon injuries were associated with 1 or no rib fracture).

ACKNOWLEDGEMENTS

This paper uses accident data from the UK Co-operative Crash Injury Study (CCIS) collected from 1998 to 2010. CCIS was managed by TRL Limited on behalf of the UK Department for Transport (DfT) Transport Technology and

Standards Division who funded the project along with Autoliv, Ford Motor Company, Nissan Motor Company and Toyota Motor Europe. Daimler-Chrysler, LAB, Rover Group Ltd, Visteon, Volvo Car Corporation, Daewoo Motor Company Ltd and Honda R&D Europe(UK) Ltd have also funded CCIS. The data were 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.

The authors are grateful to Toyota Motor Europe for sponsoring the research presented in this paper.

REFERENCES

- Abbreviated Injury Scale 1990 Revision. Association for the Advancement of Automotive Medicine, 1990.
- EU Directive 96/79/EC, Frontal Crash Protection, 1996.
- Frampton, R.J., Welsh, R.H., Thomas, P.D. Belted Driver Protection in Frontal Impact - What Has Been Achieved and Where do Future Priorities Lie? Association for the Advancement of Automotive Medicine, Tempe, Arizona, 2002.
- Frampton, R.J., Lenard, J. The Potential for Further Development of Passive Safety. Association for the Advancement of Automotive Medicine, Baltimore, Maryland, 2009.
- Hassan, A.M., Hill, J.R., Parkin, S., Mackay, G.M. Secondary Safety Developments: Some Applications of Field Data. Autotech 1995; ImechE; 1995.
- Hill, J.R., Parkin, S., Mackay, M. Injuries caused by Seat Belt Loads to Drivers and Front Seat Passengers. Association for the Advancement of Automotive Medicine, Vancouver, British Columbia, 1996.
- Hoaglin, D.C., Mosteller, F.M., Tukey, J. W. Fundamentals of Exploratory Analysis of Variance. Wiley, New York, 1991.
- Hobbs, C.A., Gloyns, P., Rattenbury, S. Euro NCAP, Assessment Protocol and Biomechanical Limits. Version 2, 1999. Euro NCAP, Brussels, 1999.
- Klinich K.D., Flannagan, C.A.C., Nicholson, K., et al. Factors Associated with Abdominal Injury in Frontal, Farside, and Nearside Crashes. Stapp Car Crash Journal, Vol. 54, pp. 73-91, 2010.
- Lamielle S., Cuny, S., Foret-Bruno, J.Y., et al. Abdominal Injury Patterns in Real Frontal Crashes: Influence of Crash Conditions, Occupant Seat and Restraint Systems. Association for the Advancement of Automotive Medicine, Chicago, Illinois, 2006.

Mackay, G.M., Galer, M.D., Ashton, S.J., et al. The Methodology of In-depth Studies of Car Crashes in Britain. SAE Technical Paper Number 850556, Society of Automotive Engineers, Warrendale, PA, 1985.

Martin, J.L., Lardy, A., Compigne, S. 2010, Specificities of Rear Occupant Protection: Analysis of French Accident Data. IRCOBI Proceedings, Hanover, 2010.

Wang, S.C., Bednarski, B., Patel, S., et al. Increased Depth of Subcutaneous Fat is Protective against Abdominal Injuries in Motor Vehicle Collisions. Association for the Advancement of Automotive Medicine, Lisbon, 2003.

Yamada H. Strength of Biological Materials. Williams and Wilkins, Baltimore, 1970.

ANNEX 1

Dataset for Analysis of Variance in Rate of AIS 2+ Abdominal Injury

Restraint	EES	Age	AIS 2+	N	Rate
B	0-29	18-29	1	15	0.07
		30-49	0	5	0.00
		50+	0	6	0.00
	30-150	18-29	5	20	0.25
		30-49	0	9	0.00
		50+	5	15	0.33
	Unknown	18-29	2	32	0.06
		30-49	2	21	0.10
		50+	4	31	0.13
B+P	0-29	18-29	0	14	0.00
		30-49	1	8	0.13
		50+	0	9	0.00
	30-150	18-29	1	11	0.09
		30-49	1	6	0.17
		50+	3	11	0.27
	Unknown	18-29	3	48	0.06
		30-49	0	40	0.00
		50+	1	59	0.02
B+A	0-29	18-29	0	28	0.00
		30-49	0	28	0.00
		50+	1	8	0.13
	30-150	18-29	0	14	0.00
		30-49	1	23	0.04
		50+	5	17	0.29
	Unknown	18-29	2	46	0.04
		30-49	2	77	0.03
		50+	6	71	0.08
B+P+A	0-29	18-29	1	179	0.01
		30-49	4	234	0.02
		50+	4	232	0.02
	30-150	18-29	11	188	0.06
		30-49	17	218	0.08
		50+	17	179	0.09
	Unknown	18-29	8	275	0.03
		30-49	21	450	0.05
		50+	18	361	0.05
B+P+L+A	0-29	18-29	0	53	0.00
		30-49	1	77	0.01
		50+	5	82	0.06
	30-150	18-29	5	78	0.06
		30-49	5	82	0.06
		50+	20	92	0.22
	Unknown	18-29	0	24	0.00
		30-49	1	42	0.02
		50+	5	40	0.13
			189	3558	0.053