Enabling Protection for Older Children

SEVENTH FRAMEWORK PROGRAMME
THEME 7
Transport (including AERONAUTICS)

EPOCh 218744

FINAL PROJECT REPORT

Work Package Number 1
Task Number 1.1
Literature review, accident analysis and injury mechanisms

by C Visvikis, M Pitcher, B Girard, A Longton, M Hynd

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	Name	Date Approved
Administrative coordinator	Maria McGrath Maria McGrath	01/07/2009
Technical coordinator	Marianne Hynd MHynd	01/07/2009

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Executive summary

The implementation of Directive 2003/20/EC, dated 8 April 2003 (which amends Directive 91/671/EEC) means that children up to 150 cm in height must use a child restraint appropriate to their size when travelling in cars or goods vehicles fitted with seat belts. The affect of this legislation has led to children remaining in child restraints until they are older (up to 12 years old, depending on their height).

This report reviews the latest information relating to the injuries received by older children in car accidents. The focus was on the key injury mechanisms and the measurement capabilities needed by a dummy that represents children of this size.

In particular, the report looks at how and where these older children are being injured whilst travelling in vehicles. It establishes the main priorities for the body areas that need to be protected by restraint systems and will therefore feed into the identification of requirements for a measurement tool (i.e. dummy). The study took the following approach:

I. Review the latest literature and current research relating to older children;

II. Review accident data, relating to older children, from the previous work of CREST, CHILD, NPACS, EEVC etc. relating specifically to older children (where available);

III. Identification of injury priorities and loading conditions;

IV. Summarise injury mechanisms and prioritise for front and side impacts.

The review found that while many studies of child injury mechanisms include older children in their sample, very few studies describe in detail the types of injuries received by older children specifically. This shortfall of information was addressed, in part, by carrying out a small investigation of the Cooperative Crash Injury Study (CCIS) database, from the UK. The CCIS analysis supported the findings of the literature review.

The head was an important body region for both front and side impact collisions. In each case, the principle mechanism of injury was direct contact with the interior of the vehicle, resulting in skull fracture and/or local brain injury. Non-contact injuries due to inertial loading may also occur (typically in front impact), and can have serious consequences, but they are rare in older children. It is important, therefore, that head excursion is minimised during front impact collisions and that the child restraint displays good head containment in side impacts. These features are currently necessary to reduce the risk of head contact with the vehicle interior. Linear and rotational head acceleration must also be minimised to reduce the risk of non-contact head injury. A dummy that is designed to represent older children must be capable of assessing these aspects of the performance of a child restraint.

Neck injuries were rare in the literature and in the CCIS analysis. However, a dummy must be capable of recording neck forces and moments to ensure that a child restraint system does not permit excessive loads to this body region (in order to achieve a benefit elsewhere).

Chest injuries were also rare; nevertheless, major organs are found in the chest. A child restraint must be capable of distributing the impact forces over a wide area in a front impact collision and must protect a child from intruding structures in a side impact. A dummy that represents older children must be capable of measuring both chest acceleration and compression, in order to mitigate these risks.

The abdomen was an important body region, especially for front impact collisions. The review found that the principle injury mechanism was loading from the adult seat belt at the site of the injured organ. This can result from submarining and/or from misplacement of the belt. A dummy that represents older children must be capable of detecting when submarining is taking place.

While pelvis injuries were relatively rare, the design of a dummy pelvis is important for a realistic interaction with the restraint system in front impact. In addition, measurements in the pelvis could help to determine when submarining is taking place. Direct loading of the pelvis is important in side impact collisions and hence a dummy must be capable of distinguishing the level of protection that a child restraint provides from intruding side structures.

Finally, extremity injuries were found in both front and side impact collisions. The principle mechanism of injury was loading applied (to the extremity) by the vehicle interior, resulting in fracture. In the past, these injuries have been classified as a low priority for children, with priority being given to serious and life threatening injuries. From the review of literature and accident studies EPOCh agrees that this prioritisation is currently relevant to older children.

1 Introduction

The implementation of Directive 2003/20/EC, dated 8 April 2003 (which amends Directive 91/671/EEC) means that children aged 3 or more years old and up to 150 cm in height or 12 years old, must use a child restraint appropriate to their size when travelling in cars or goods vehicles fitted with seat belts. The affect of this legislation has led to children remaining in child restraints until they are older (up to 12 years old, depending on their height).

Research into the anatomy and development of older children has been conducted to help identify the injury mechanisms of older children.

A review of current and existing research was also conducted with particular interest in how and where older children are being injured whilst travelling in vehicles. This included a review of the work from the previous research projects; CHILD and NPACS.

Accident data that was reviewed previously by the NPACS and CHILD projects along with recent data from the CCIS and CARE databases has been analyzed to highlight accidents involving older children.

This has enabled the main priorities for the body areas that need to be protected by restraint systems designed for older children to be established, for both front and side impact. This has then allowed requirements for the measurement capabilities of the dummy to be identified.

2 Background

In order to understand better the scope of the project, this section summarises the anatomy and development of older children, current practices in restraint design, legislation on child restraint use and corresponding trends, and finally, collision data.

2.1 Anatomy and development of older children

Young children tend to have a continuous growth rate; however, on entering puberty, they experience growth spurts of 7 to 8 cm per year. These are due to an increase, of up to 8 fold, of the growth hormone in the body system. Children of 10 to 12 years of age are on average 140 to 150 cm in height. Girls usually reach their peak height at around 12 years of age whereas boys reach peak at around 14 years of age. Both sexes see weight increases in relation to their growth in height, however the largest increase is seen later on in puberty. Older children weigh between 30 and 40kg irrespective of sex, which can be extrapolated to being half of their future adult weight. At this stage of growth, most of the weight gain comes from the developing bones and musculature in the limbs and the spine (Tanner, 1989).

Growth starts initially from the limbs. The bones grow in length through ossification centres, at their endings. The bones become stronger and more plastic from their centre out, as the lengthening process occurs. These changes are accompanied by muscle strengthening which ensures protection and support for the growing bones. During puberty, growth is more noticeable as the feet and hands grow larger followed by the arms and legs (Tanner, 1989).

The torso lengthens, which allows thoracic breathing to occur. The lengthening is mainly due to vertebral growth. The vertebrae grow in height and become stronger and compact. The cushioning discs between the vertebrae also mature and extend to offer stronger protection. The joints between the vertebrae change angle, which modifies the child's posture and the rib cage descends. This is accompanied by a rise in lung volume, due to increased rib displacement referred to as the bucket handle movement. The ribs rise vertically as well as horizontally thus increasing the volume of the chest. This movement combined with the expanding number of breathing pockets called alveoli, allows for greater respiratory capacity (Brant *et al.*, 2008). Hip widening also occurs, which allows the abdominal contents to drop down and also helps to allow thoracic breathing. This is found especially in girls, due to the presence of oestrogen, a sex hormone that activates ossification centres at the hip joints. In younger children, the abdomen is prominent resulting in the "pot-belly" effect. This is because the torso and the hips are not wide enough to allow the contents to sit lower down in the abdomen. As the hips widen, the abdominal muscles also strengthen which reduces the "pot-belly" and pushes the contents gradually into place. Until this occurs, the major organs such as the liver, which is the abdomen's largest organ, the stomach, the spleen, which is crucial for blood production, and the gastrointestinal tract, are fully exposed (Nahum and Melvin (eds.), 2001; MacGregor, 2000).

Finally, the shoulders widen, which also helps in terms of thoracic breathing. This is emphasised for boys through sex hormones which also induces a distinct increase in muscle mass compared to that with girls (MacGregor, 2000; Tanner, 1989).

Another body area of interest for this project is the head and neck. Bone thickening and the closing of the space between the bones of the skull occur earlier in childhood. However, older children experience a change in their facial features, for example the forehead lengthens, the brow ridge becomes more prominent, the jaw extends forward and the facial muscles develop. As mentioned earlier, the vertebrae mature and the child's posture changes. The neck muscles also increase in size to provide stronger support for the head (Nahum and Melvin (eds.), 2001).

All these changes happen over a period of 5 to 6 years depending on the individual, and careful consideration needs to be given to the fact that children aged 10 to 12 years are only at the very beginning of these processes. Thus their body is not fully mature like an adults, nor immature as in young children.

2.2 Current practices in child restraint design for older children

Currently, there are different types of child restraint systems (CRSs), which are made in different sizes to fit different mass groups of children, corresponding to United Nations Economic Commission for Europe (UN-ECE) Regulation 44. The main seats used for older children are booster systems with or without a backrest. Booster systems with backrests are referred to as booster seats and those without backrests are referred to as booster cushions. To conform to the Regulation, a child restraint must meet a series of design and construction requirements and pass a series of performance tests, the main ones of which are summarised briefly below.

Booster systems, with 'Universal' approval, are all non-integral restraints which use the adult seatbelt to restrain both the child to the CRS and the CRS to the vehicle. Booster cushions raise the child in order to guide the adult seat belt to fit on the lap just below the pelvis. Booster seats provide enhanced protection over a booster cushion by also routing the diagonal portion of the adult belt over the shoulder and providing some protection from side impacts through wing-like extensions around the torso and head.

The CRS must be secured to the car structure. The child or a carer must be able to remove the belt from the child and remove the child independently. For this group of restraint the child must also be able to remove the belt on their own.

Different performance tests are carried out on the booster systems and these include dynamic frontal impacts, overturning tests and energy absorption tests.

The impact tests are accomplished with the use of child anthropometric devices (child dummies) appropriate for the restraint. The restraint should prevent the motion of the child continuing forward beyond a certain distance relative to a point on the test bench and mitigate loading above a set level. No parts on the restraint should break and the belt should not unlock or move from the belt guides.

Most seats are injection moulded with polystyrene inserts and are designed to absorb as much energy as possible in front impacts. The cover of the seat must also meet toxicity and flammability requirements.

The overturning test rotates the restraint with a child dummy and assesses how much the dummy's head moves past a set distance compared to the original position relative to the seat.

2.3 Legislation on child restraint use for older children

The European Directive 2003/20/EC states that occupants of motor vehicles must wear seat belts and use appropriate child restraint systems.

This Directive also states that children who are below 150cm in height and/or under 12 years of age must be seated in a child restraint. The Directive currently allows countries to restrain children with the minimum height of 135cm by the adult seatbelt; however, it is thought to be only temporary. Germany, Italy, Austria, Ireland, Luxembourg, Greece, Hungary, Poland, Portugal have already enforced the 150cm rule whereas other European countries opted for the 135cm requirement.

Child restraint systems must conform to the UN-ECE Regulation 44. The Regulation classifies restraints by child mass, which for older children only goes up to 36kg. This corresponds to Group III (children of 22kg to 36kg), which is the largest group currently available in the Regulation. This classification reflects that Regulation 44 was developed to allow assessment of CRSs designed for children up to the age of about 10 years. This now needs updating to allow provision of restraint systems that are designed for children up to a height of 150cm.

The retention system of a child restraint may be of two classes; integral and non-integral. An integral restraint is where the retention of the child within the restraint system is independent of any means directly connected to the vehicle. A non-integral restraint is where the retention of the child within the restraint system is dependent upon any means directly connected to the vehicle.

2.4 Trends in restraint use by older children

Before the European Directive 2003/20/EC came into effect it was common for children above the age of four years to be restrained by only the adult belt and very unlikely for a child above six years old to be on a booster system.

The current situation, as mentioned above, is that some countries require children to be in a CRS until they are 150cm in height or have reached twelve years old, whilst others require children to be in CRSs until they are 135cm in height or have reached twelve years old.

This has led to the use of booster systems by older children and to the availability of 'high backed' booster systems in the market place.

From accident analysis data, it was shown that in Belgium, even though the restraint use is compulsory it is poorly respected, or the restraint system is not used correctly (Javouhey et al., 2006). The majority of older use only the adult seat belt (99%) rather than booster cushions (1%) (Vesentini and Willems, 2007).

2.5 Involvement of children in collisions

An accident study, looking at children of all ages, from the late 1990's (Johannsen, 2004) showed that 48% of the children using a CRS properly suffered head injuries and 15% suffered injuries to the abdominal area (Figure 1). In this sample, head injuries are the most prevalent. Abdominal injuries and injuries to the extremities rank as the second body region sustaining injuries. This does not, however show specifically the effects of children travelling in booster systems or identify how many older children the data relate to.

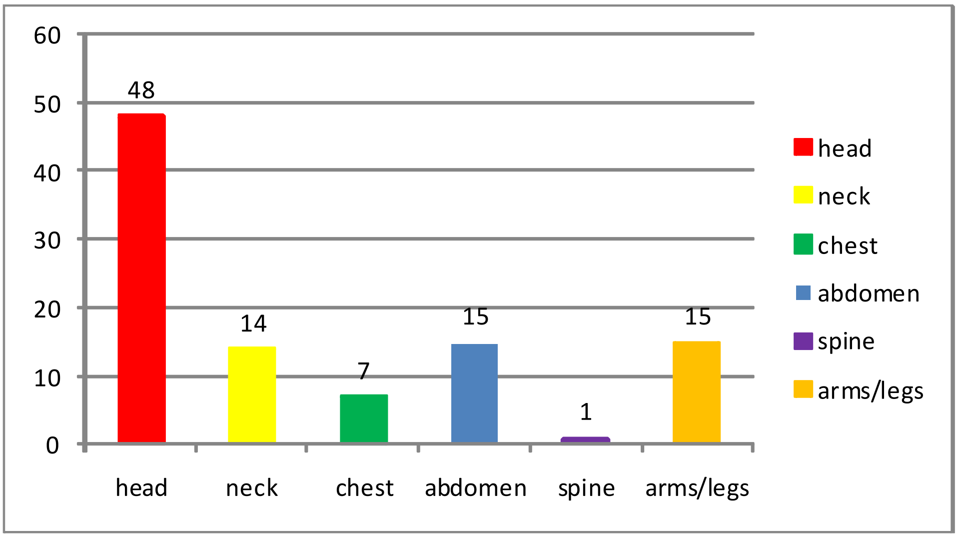


Figure 1: Percentage distribution of injuries by body region for children using CRS properly (reproduced from Johannsen, 2004)

Figure 2 shows the injury severity of the different body regions of 415 children of all ages and restraint use. The head region received the majority of injuries, followed by the abdomen, neck, limbs and chest. The most severe injuries were found in the head, followed by the limbs.

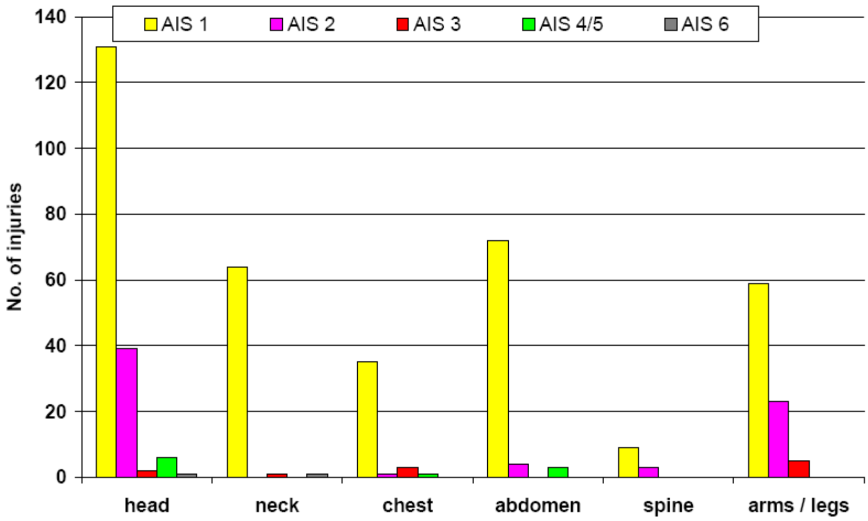


Figure 2: Injuries of 415 children of all ages and restraint use (reproduced from Johannsen, 2004)

Figure 3 shows the picture for 200 children of all ages and using a CRS and is broadly similar to that above.

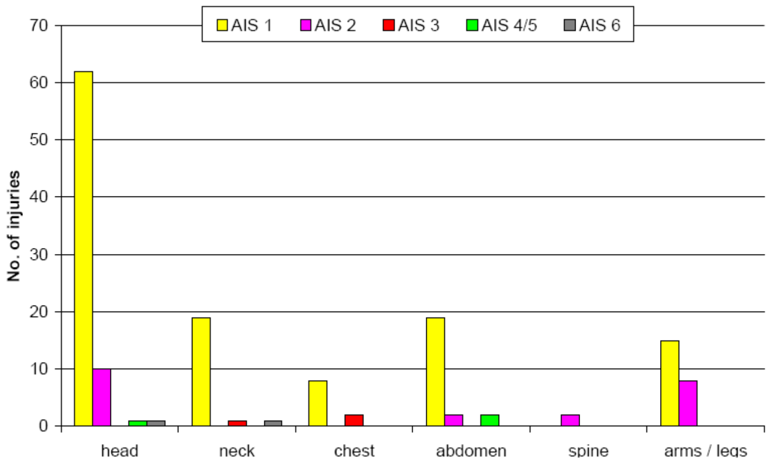


Figure 3: Injuries of 200 children using a CRS (reproduced from Johannsen, 2004)

Johannsen refers to an assessment of "harm", which is a weighted injury frequency, in Figure 4. This shows that the body region most likely to be injured is the head followed by the abdomen.

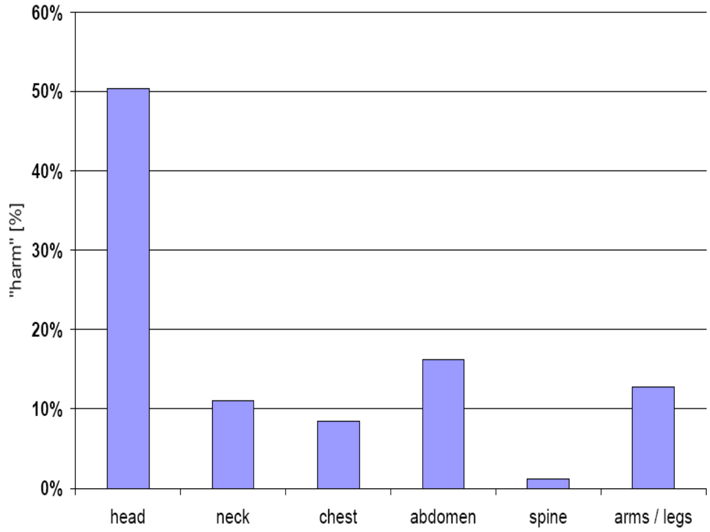


Figure 4: Calculated harm for different body regions of 415 children (reproduced from Johannsen, 2004)

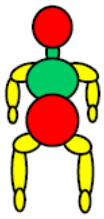
This data is from a publication written in 1997 and as such it is unlikely any older children included in the sample were seated on child restraints. At the immature development stage of younger children the head and neck need a high level of protection. In older children, due to the anthropometric changes, the priority relies on the head, chest and abdomen.

2.5.1 Front impact

2.5.1.1 Injury patterns for children in front impact

Injury severity according to body region and CRS

For children using a Booster seat and adult seat belt (group II/III):



Wismans *et al.* (2008) looks at children using booster systems. The study was carried out before older children were using child restraint systems and those children using child restraints are likely to be aged between 3 and 6 years. The report concluded that the head is the most important body region, in terms of frequency of severe injuries.

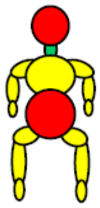
The relative importance of abdominal injuries increases with such restraint systems compared to child restraints with a harness. This is because the penetration of the lap section of the seat belt into the abdomen of the child can cause injuries to the liver, spleen, and kidneys. The protection of the abdominal area is therefore a high priority to ensure good protection of children using a CRS that uses the adult seat belt to restrain the occupant directly.

Chest injuries are not frequently reported for children seated on booster seats with a backrest. However, as the chest cavity protects vital organs, it remains an important body segment. In general chest injuries occur through chest compression, but often occur without rib fractures due to the chest compliance of children.

The pelvis rarely suffers serve injuries in frontal impact and therefore is not a priority body region.

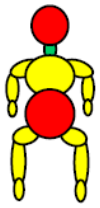
Limb fractures often occur, but were reported to be generally low in severity and therefore are not a major priority in terms of child protection.

Booster cushion and adult seat belt (group II/III):



Wismans *et al.* (2008) also reported that the main body regions, for this limited age range of children, injured on booster cushion type CRSs are the same as for booster seats. In comparison with booster seats, an increase of the number of chest injuries is found, due to the fact that children using these CRSs are generally older (less compliant chest) than the ones using booster seats. From the age of the sample and the typical restraint use at that time, the older children referred to using booster systems in the report are likely to be from 3 to 6 years old.

Adult seat belt:



Wismans *et al.* (2008) also found that in many of the accident cases where older children were injured they were only restrained by the adult seat belt, while if they had been using a CRS, their injuries would have been reduced.

The main body regions injured when only using the adult seat belt are similar to the ones using booster cushions. However the injuries are generally more severe especially in the abdominal area.

The European Enhanced Vehicle-safety Committee (EEVC) Working Group 18 Report: Child Safety - February 2006 (EEVC, 2006) compared the injuries suffered by children using a booster cushion and those who only used the adult seat belt. From the age of the sample and the typical restraint in use at that time, the older children referred to in the report, using booster systems are likely to be aged between 3 to 6 years old. An increase in abdominal injuries was observed in cases without the booster cushion. It was concluded that this was due to a difference in kinematics of the child due to the poor positioning of the lap section of the seat belt.

Table 1 shows a comparison of injuries sustained by children using a booster cushion compared to only using the adult seat belt. The table shows that there were a higher percentage of AIS 3+ neck injuries to children on boosters, whilst there were more AIS 3+ chest injuries sustained by children using only the adult seat belt. In both cases a high number of limb fractures were observed.

Table 1: Comparison of injuries: booster cushion and seat belt only (reproduced from EEVC, 2006)

	Booster cushion + Seat belt		Adult seat belt only	
Number of children with medical information	108		148	
Number of Injuries for:	**AIS1+**	**AIS 3+**	**AIS1+**	**AIS 3+**
Head	39	7	44	8
Neck	22	11	25	6
Chest	24	9	45	18
Abdomen	28	9	68	27
	AIS1+	**Fracture**	**AIS1+**	**Fracture**
Limbs	53	25	88	38

Both EEVC (2006) and Wismans *et al.* (2008) concluded that in a frontal impact, the main priority should be to protect the head of the occupant for all types of child restraints for older children.

The chest and abdominal injuries increase in frequency and severity for older children over the age of 3 years compared to the younger children who are in a harness restraint type system. Therefore based on the findings from these reports, the recommended body regions to be protected, for children who have outgrown harness systems, are the head, neck, chest, abdomen, lumbar spine and pelvis.

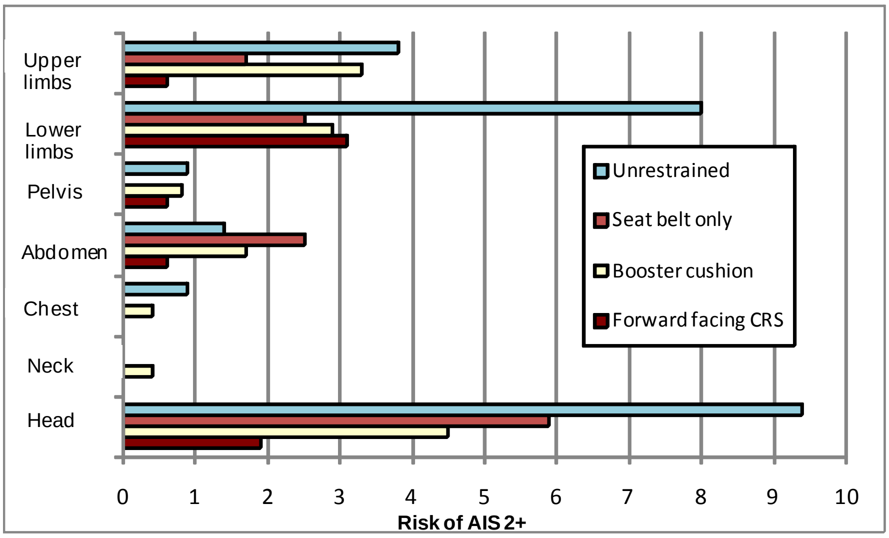


Figure 5: Comparison of injury risk per body segment for different types of CRS (reproduced from EEVC, 2006)

Analysis in EEVC (2006) compared the injury risk per body segment for different types of child restraints (Figure 5). The children in this sample using different restraint methods are also likely to fall into different age bands. It is reported that the risk of a severe head injury for children restrained in forward facing child seats with a harness in a frontal crash is lower than all other restraint type systems. The risk of a head injury is even lower than the risk of having a lower limb fracture. The risk of injury in the abdominal area is also lower than other restraint systems due to the fact that children are not directly in contact with the seat belt when restrained with restraint systems with a harness.

Children restrained using a booster cushion with the seat belt have a risk of 4.5 out of 100 of having a severe head injury and 1.7 out of hundred of having an abdominal injury. These injury risks are over double those likely for the child in the harness seat. Children on boosters are likely to be older and therefore taller than the children in harness systems, so they are at more risk of making head contact with the interior of the vehicle. However their risk of injury is much less than when using only the adult seat belt and for children who are not restrained at all.

The use of a booster cushion shows an important decrease in injury risk to the head, chest, pelvis and limbs. The risk of having a severe injury to the neck and abdomen is higher than for unrestrained children, however where there are belt induced injuries, it is likely that other, more serious injuries have been mitigated.

2.5.1.2 Factors affecting injury of children in front impact

Velocity

Cheung and Le Claire (2006) conducted a review of the UK STATS 19 accident data, with particular interest in the distribution of casualties by road speed limit. It was reported that roads with speed limits of 48 km/h (30 mph) and 96 km/h (60 mph) contained the highest number of Killed or Seriously Injured (KSI) casualties (Figure 6). This data includes all children under 12 involved in an accident between 1998-2003.

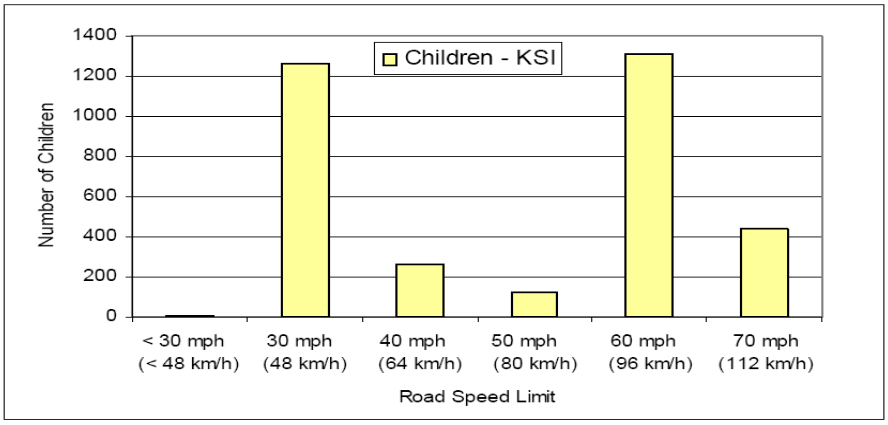


Figure 6: Number of KSI children by road speed limit (reproduced from Cheung and Le Claire, 2006)

Cheung and Le Claire (2006) also investigated the distribution of front impact severity in the TS97 database. This database contains information for accidents that occurred in 1996-1997, for a region south of Munich in Germany. Figure 7 shows the distribution for front impact 'Degree of Damage' for different Energy Equivalent Speeds (EES) from the TS97 database. This shows that around 70% of the accidents occur with an EES of 0-50 km/h, and 50-70 km/h accidents account for the remaining 30%.

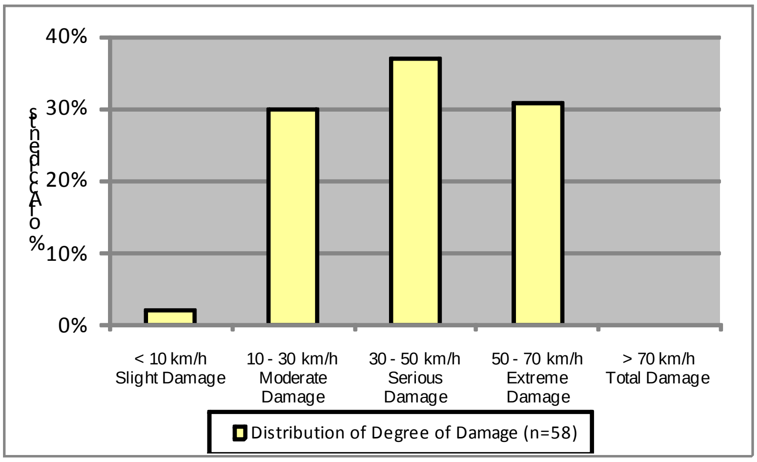


Figure 7: Percentage distribution of front impact accidents at the five Degrees of Damage (reproduced from Cheung and Le Claire, 2006)

Cheung and Le Claire (2006) concluded that there was a direct collation between the seriousness of injuries to children and the severity of the impact.

Based on all the information for front impacts where the change in velocity was known:

- The majority of accidents involving children occurred with vehicle change in velocity (Δv) of between 30 and 39 km/h or an EES of 30-50 km/h.
- 50 % of slight child injuries occur below a Δv or EES of about 30 km/h and 95% below of 50 km/h.
- 50 % of serious child injuries occur below a Δv or EES of about 50 km/h and 95% below of 70 km/h.

2.5.2 *Side impact*

2.5.2.1 Injury patterns for children in side impact

Injury severity according to body region and CRS

The EEVC Working Group 18 Report: Child Safety - February 2006 (EEVC, 2006) Child Safety Report (EEVC, 2006), analysed the CREST[1] accident database and concluded that for side impact, the distribution of the injuries according to the different body regions is given in Figure 8. Head injuries accounted for 65 percent of all the severe injuries recorded in all restraint types. It was concluded that the current level of protection provided to prevent the occupant's head contacting rigid parts inside the vehicle or an intruding object is at present not sufficient.

Severe injuries also frequently occur in the chest and abdomen body regions. These injuries were mainly observed when the child was sitting on a booster cushion or just using the adult belt and not in CRSs that have side wings for protection. For systems without side wing protection, the chest accounted for 22% of the injuries and the abdomen 16% of injuries.

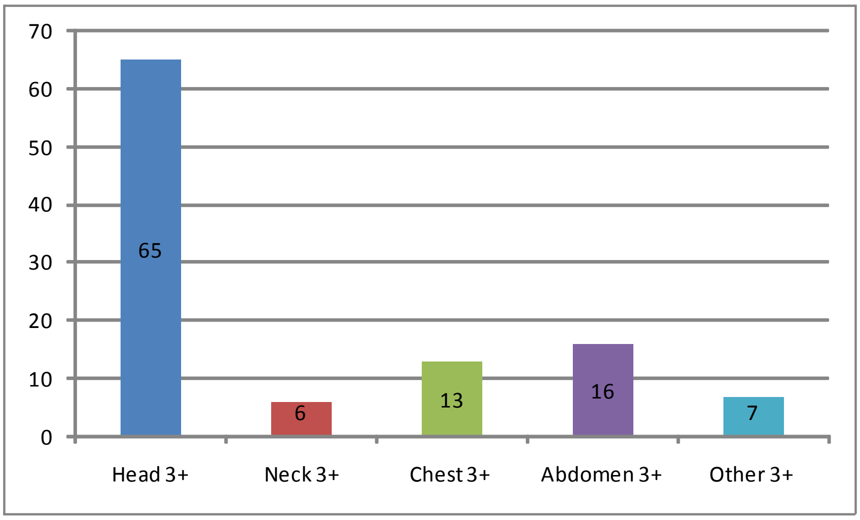


Figure 8: Side Impact AIS 3+ injuries from CREST accident database (reproduced from EEVC, 2006)

Figure 8 shows that the neck is less frequently injured than the other regions. However the neck injuries occurred mainly in young children using forward or rearward facing child restraint systems. Though the number of neck injuries observed was low, in each of the CREST accident cases an AIS3+ injury was observed, and the child was fatally injured. Whether this is a concern for older children is unknown, as the lack of accident data means no trends can be seen.

EEVC (2006) also analysed the CSFC database, where side impact collisions represented 16% of the total accidents. The CSFC database is a record of children of all ages involved in accidents in rural regions in France 1995-96. 206 children were involved in these accidents, of which 37% of children were uninjured, 43% sustained minor injuries and 20% were severely injured.

Further analysis looked at the breakdown of injuries for only the struck side of the vehicle. This showed that the body area most often injured was the head with 42%, with upper limb injuries at 29% and abdominal injuries representing 19% (Figure 9).

[1] CREST (Child Restraint System for Cars) was project funded by the European Commission.

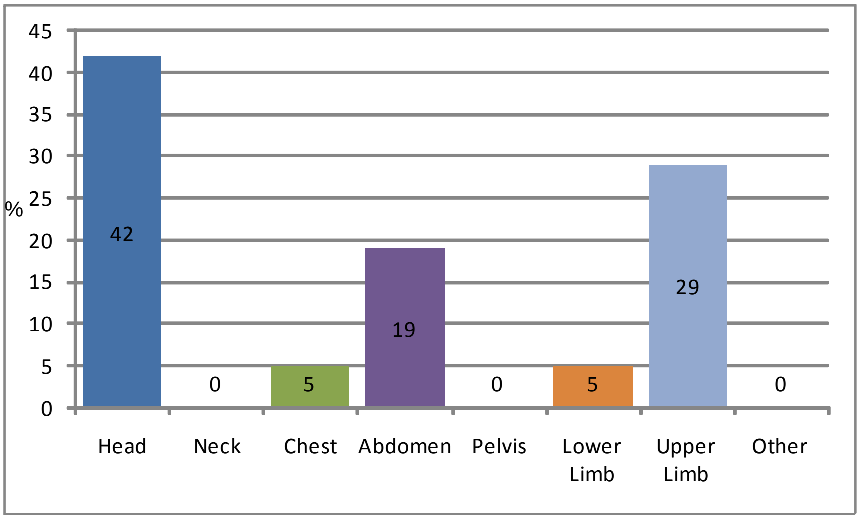


Figure 9: Side impact struck side occupant injury frequency (reproduced from EEVC, 2006)

EEVC (2006) concluded that there were not enough cases to draw a strong conclusion for severe injuries suffered by children during side impact collisions. However injuries to the head were very frequent and seemed to account for around 75% of the total body area injured for children involved in side impacts, who were restrained in forward facing child seats on the struck side. For children using booster type restraints head injuries only account for around 50% of the injured body regions and 40% for children only using the adult seat belt.

This difference is not only due to the type of restraint system but also to the difference in height of the children and the corresponding impact areas with the interior of the vehicle. The study was carried out before older children were using child restraint systems so those children restrained are likely to be aged up to 6 years.

Lesire *et al.* (2006) conducted an analysis of CREST and CHILD accident data related to side impacts. They presented a summary of the injury severity for all children under 12 involved in side impact accidents (Figure 10). The chart shows that around 50% of the children suffered only slight or no injuries. However this data includes accidents for restrained children of all ages. It is unlikely that many of the children over 6 years old would have been using a CRS.

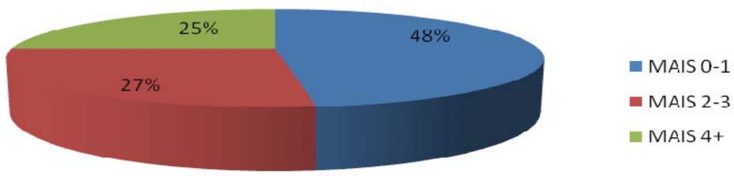


Figure 10: Side impact injury severity (reproduced from Lesire *et al.*, 2006)

Lesire *et al.* (2006) was however able to identify 35 children in the database that were using booster seats or booster cushions on the struck side of the vehicle. It is most likely that these children will be aged 3-6 years old, as these would be the main users of booster type CRSs at the time. Analysis of the seriously injured showed that head injuries represent over 50% of the injuries (Figure 11). The chest is the next largest percentage injured body region with 17% and the abdomen representing 9%. The upper and lower limbs both represent around 10% of the injuries.

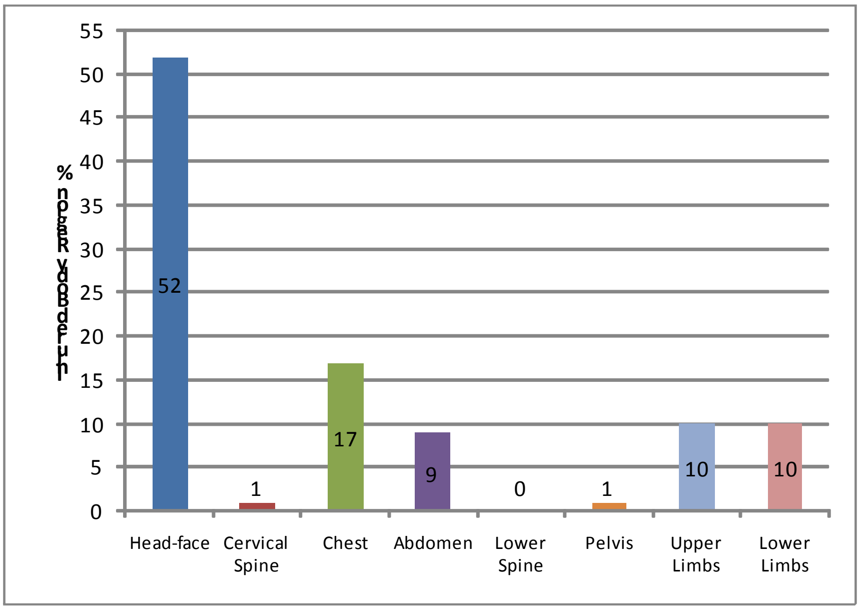


Figure 11: Injured body regions for children using booster type restraints (reproduced from Lesire *et al.*, 2006)

Lesire *et al.* (2006) also identified 49 children in the CREST and CHILD databases who were only restrained using the adult seat belt. It is most likely that the majority of these children would have been aged over 6 years old, due to restraint use at the time.

The percentage of head injuries is slightly less than for children using booster type restraints, at around 40%. The chest and abdomen injuries are relatively similar in percentage compared to children using the booster type restraints. There is a reduction in upper limb injuries, but an increase in pelvis and lower limb injury percentages (Figure 12).

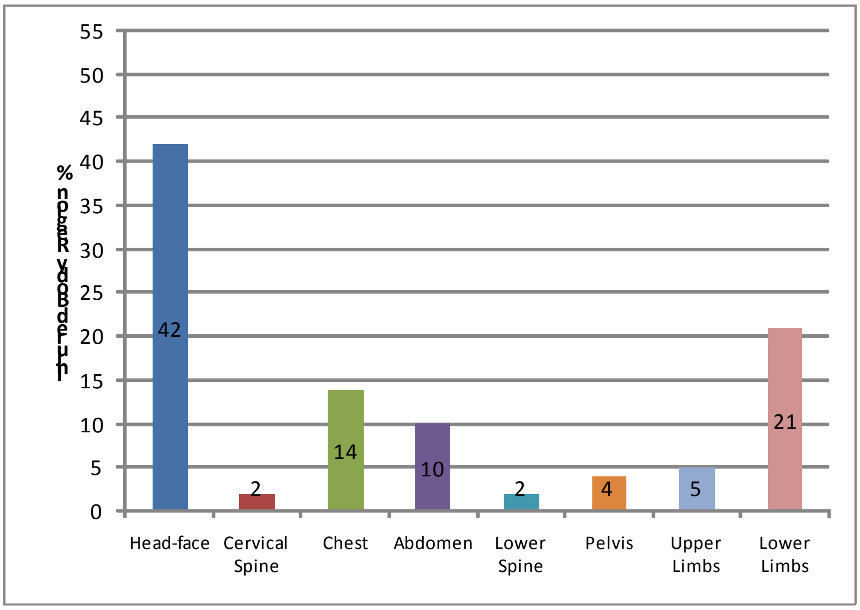


Figure 12: Injured body regions of children using only the adult seat belt (reproduced from Lesire *et al.*, 2006)

Lesire *et al.* (2006) concluded that in side impact the injury causations for children on the struck side of the vehicle were:

- Head injuries are the most frequent injuries and occur due to head contact with rigid parts of the vehicle interior.

- Chest and abdomen injuries are the next most frequently injured body regions and occur due to compression through door panel contact.
- Upper limb injuries are more frequent for children using booster type restraints and are also usually caused by door panel contact.
- Pelvis and lower limb injuries become sufficiently more frequent for children only restrained by the adult seat belt as the is no protection from intrusion.

2.5.2.2 Factors affecting injury of children in side impact

Velocity

Cheung and Le Claire (2006) analysed several different accident databases which contained side impact collisions. Based on this analysis of these side impact cases where the impact velocity was known, the following conclusions were made:

- The majority of accidents involving children occur with a vehicle change in velocity (Δv) of 15-25 km/h or an energy equivalent speed (EES) 30-50 km/h
- 95% of all cases involving children (regardless of restraint) occur with a Δv of less than 50 km/h
- 50% of slight injuries occur with an EES less than 30 km/h
- 50% of severe injuries occur with an EES less than 50 km/h
- 95% for both slight and severe injuries occur with an EES less than 70 km/h

Intrusion

Lesire *et al.* (2006) used accident data from the CREST and CHILD databases to investigate the affect of vehicle intrusion on the injury severity of children in side impact. It was found that vehicle intrusion has a direct influence on the injury severity of children.

Eighty-one percent of restrained children seated on the struck side of the vehicle where there was no direct intrusion received no or slight injuries and only less than 14% receive serious injuries. For the cases where direct intrusion was present a 1/3 were uninjured or slightly injured, with a further 1/3 receiving moderate injuries and 1/3 seriously or fatally injured.

The fact that intrusion has a direct influence on injury severity is further corroborated by the breakdown of injury severity compared to maximum intrusion (Figure 13). The graph shows that over 300mm intrusion will result in over 50% MAIS 4+ injuries for the occupant. Below 200mm intrusion the MAIS 4+ percentage is less than 20%.

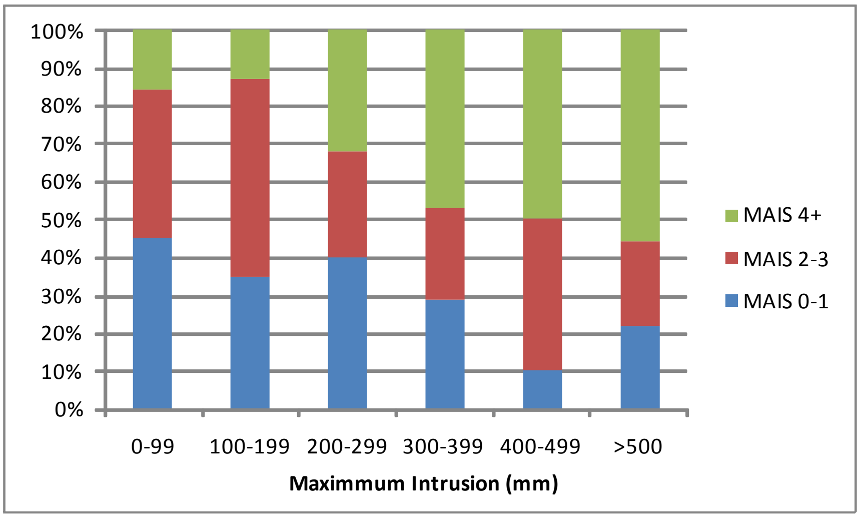


Figure 13: Injury severity percentage for different amounts of side impact intrusion (reproduced from Lesire *et al.*, 2006)

2.6 Involvement of older children in collisions

The European Road Safety Observatory (www.erso.eu) is a pilot web site established during the SafetyNet project (an integrated project funded by the European Commission). The web site includes basic traffic safety facts, which are delivered in a series of fact sheets. The fact sheets are based on data from the CARE (Community database on Accidents on the Road in Europe) database. Table 2 shows that 735 older children were killed in police-reported collisions across the European Union (EU-19) in 2006 (ERSO, 2008).

Table 2: Fatalities by gender and age in EU-19 in 2006 (reproduced from ERSO, 2008)

Age (years)	Female	Male	Both sexes
5 – 9	102	155	257
10 – 14	164	314	478
Totals	**266**	**469**	**735**

While the CARE data presents European-wide information, more detailed analysis is impossible. The information has therefore been supplemented with data from the UK.

Table 3 shows that there were 4,193 older child casualties reported to the police in Great Britain in 2007 and the killed or seriously injured casualties amounted to 157. All of these children were car passengers. The data were obtained from Road Casualties Great Britain 2007: Annual Report (DfT, 2008). While it is likely that very few, if any, fatal accidents are not reported to the police, research shows that a significant proportion of non-fatal injury accidents are not reported (Ward *et al.*, 2006). In addition, police may underestimate the severity of injury due to the difficulty in distinguishing severity at the collision scene (DfT, 2008). Nevertheless, Table 3 provides an overview of the involvement of older children in personal injury road accidents in a typical country in Western Europe.

Table 3: Older child casualties by age band and severity in 2007

Age (years)	Killed	Seriously injured	Slight	All severities
5 – 7	6	60	1,443	1,509
8 – 11	6	97	2,581	2,684
Totals	**12**	**157**	**4,024**	**4,193**

In order to gain more detailed information about older children and their injury patterns, accident cases involving children aged from 6 to 12 years were obtained from the Cooperative Crash Injury Study (CCIS) database[2]. The data span the years from mid 1998 to mid 2008. There were 277 children involved in a front impact collision for all restraint types and injury levels. Figure 14 shows the distribution of restraint type for these children.

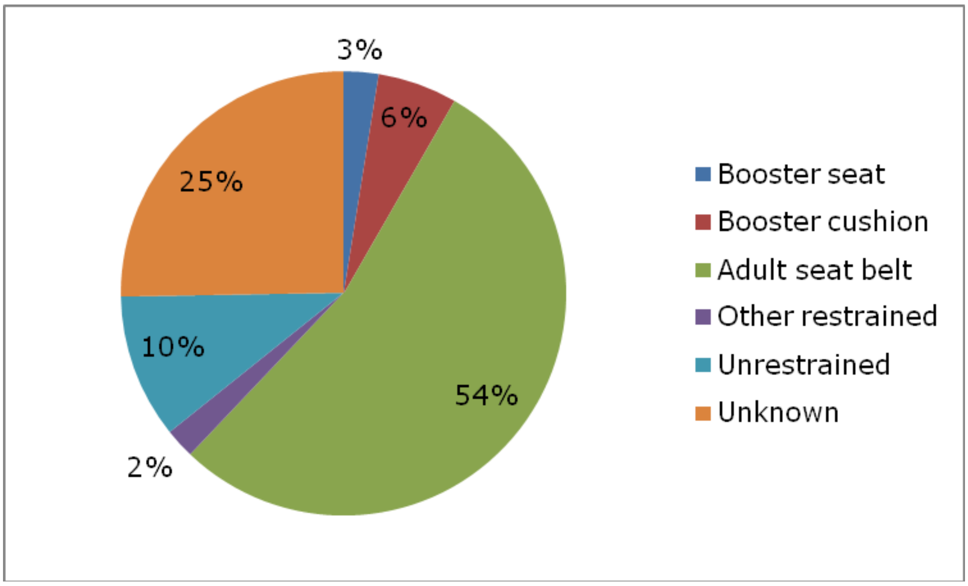


Figure 14: Restraint type for children aged 6 to 12 years in front impacts (n=277)

There were 127 children involved in a side impact for all restraint types and injury levels. Figure 15 shows the distribution of restraint type for these children.

[2] CCIS is one of the world's largest studies of car occupant injury causation. Each year the project investigates more than twelve hundred crashes involving cars or car derived vans (www.ukccis.org).

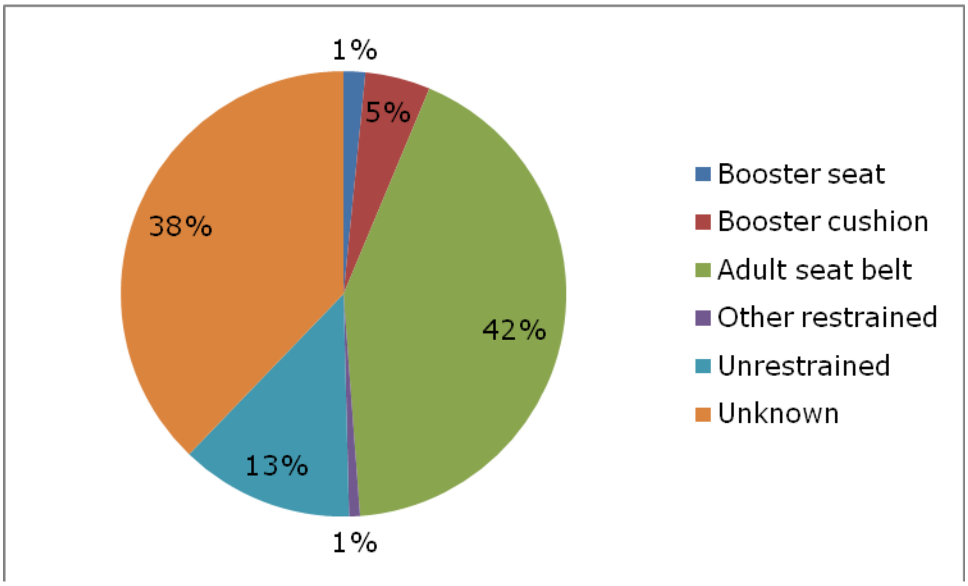


Figure 15: Restraint type for children aged 6 to 12 years in side impacts (n=127)

There is a large proportion of unknown restraint use in the CCIS database, which could affect any conclusions drawn from these data.

Figure 14 and Figure 15 show that during this ten year period, which was mostly prior to the new seatbelt wearing Directive coming into force in the UK, the adult seat belt was the most common type of restraint for children aged six to twelve years, and there were a greater proportion of children unrestrained than there were using child restraint systems.

3 Overview of collision studies

3.1 Front impact

3.1.1 Injury patterns for older children in front impact

Table 4 shows the injury distribution with respect to restraint type for the older children in the CCIS database that were involved in a front impact. The adult seat belt was the most common type of restraint system for these children. Unfortunately, there were too few cases involving children in booster seats and booster cushions to comment on the performance of these devices in comparison with the adult seat belt. It is interesting to note, however that there were no AIS>2 injuries to the children restrained in booster seats.

Table 4: Injury distribution with respect to restraint type for children aged 6 to 12 years

Restraint type	Total	MAIS0		MAIS1		MAIS2		MAIS≥3		Unknown	
		n	%	n	%	n	%	n	%	n	%
Booster seat	7	1	14.3	5	71.4	0	0.0	0	0.0	1	14.3
Booster cushion	16	1	6.3	8	50.0	1	6.3	2	12.5	4	25.0
Adult seat belt	149	20	13.4	107	71.8	8	5.4	5	2.7	9	6.0
Other restrained	6	1	16.7	2	33.3	0	0.0	1	16.7	2	33.3
Unrestrained	29	6	20.7	15	51.7	4	13.8	3	10.3	1	3.4
Unknown	70	17	24.3	36	51.4	4	5.7	3	4.3	10	14.3
Total	**277**	**46**	**16.6**	**173**	**62.5**	**17**	**6.1**	**14**	**5.1**	**27**	**9.7**

Fifteen restrained children (aged 6 to 12 years) received AIS≥2 injuries. Details about these children are shown in Table 5. The average age of the injured children was 9.3 ± 2.0 years. Where reported, the average velocity change (Δv) was 48 km/h, indicating that the collisions were moderate to severe in severity. Six children were seated in the front passenger seat and 9 children were seated in the rear outboard seats.

Table 5: Cases of AIS≥2 injury in restrained children aged 6 to 12 years

Case	Age	Restraint type	Seating position	MAIS (Body region)	PDOF/Δv (km/h)	Object hit
1	9	Adult seat belt	Rear nearside	2 (Head)	12/44	Car
2	10	Adult seat belt	Front seat	2 (Head)	12/Unknown	Car
3	7	Adult seat belt	Front seat	2 (Upper extremity)	12/47	Car
4	10	Adult seat belt	Rear offside	2 (Upper extremity)	1/32	Car
5	11	Adult seat belt	Rear nearside	2 (Upper extremity)	1/50	Car
6	12	Adult seat belt	Rear nearside	2 (Abdomen)	12/Severe	Car
7	11	Adult seat belt	Rear nearside	2 (Abdomen)	1/50	Car
8	7	Adult seat belt	Front seat	2 (Abdomen)	12/43	Car
9	10	Adult seat belt	Front seat	3 (Upper extremity, lower extremity)	12/Unknown	MPV or LGV
10	12	Adult seat belt	Front seat	3 (Thorax)	12/Unknown	Car
11	6	Adult seat belt	Rear nearside	3 (Abdomen)	1/53	Car
12	11	Adult seat belt	Front seat	3 (Abdomen)	12/79	Car
13	8	Booster cushion	Rear nearside	2 (Head)	12/31	Car
14	8	Booster cushion	Rear nearside	4 (Head)	12/Unknown	Car
15	7	Booster cushion	Rear nearside	4 (Neck)	12/Unknown	Wide object (>41cm)

There were 18 AIS≥2 injuries among the 15 children. The distribution of injuries is shown in Figure 16. Most injuries occurred in the head (n=4), upper extremities (n=4) or the abdomen (n=6).

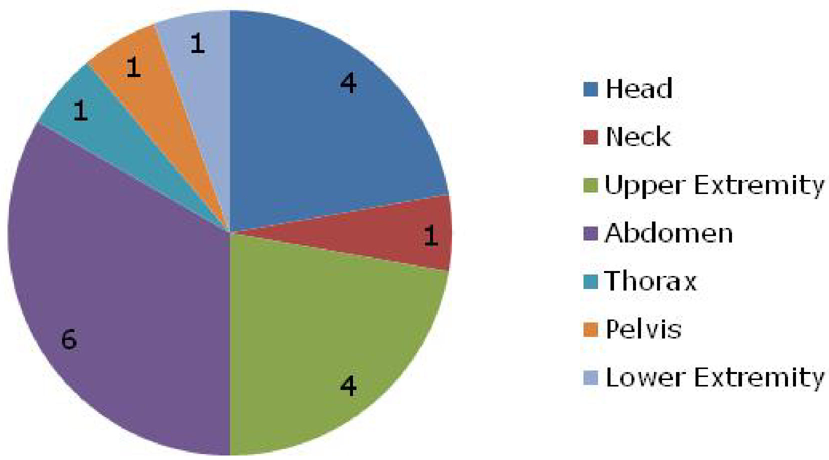


Figure 16: Distribution of AIS≥2 injuries (n=18) among restrained children

While the number of children receiving an AIS≥2 injury was low in the CCIS sample, similar findings have been reported in the literature. García-España and Durbin (2008) analysed a sample of 761 children aged 8 to 12 years with AIS≥2 injuries. They found that head injury was the most common injury (60%), followed by injury to the face (9%), upper extremity (9%) and abdomen (9%). However, the study relied on driver reports for information on injury and restraint use, etc, and did not distinguish between front and side impact.

3.1.2 Factors affecting injury of older children in front impact

The velocity change of the case vehicle is often associated with a greater injury severity for the occupants. Unfortunately, the velocity change was unknown for most of the children in Table 5 with serious injuries and greater (i.e. AIS≥3). For example, in Cases 14 and 15, the child received an AIS4 injury but the velocity change of their car was unknown. In Case 15, it seems likely that the collision was severe since their car struck a wide object (>41cm). This could have been a tree, a building or a piece of roadside furniture.

Intrusion into the seating position is also associated with greater injury severity. In Case 9, the child was seated in the front passenger seat of a car involved in a collision with a multi-purpose or light goods vehicle. The child received serious injuries to their extremities, which seem likely to have resulted from intrusion of the facia and footwell.

Another factor associated with greater injury severity is misuse of the restraint system. Unfortunately, no information was available on the presence of misuse in the sample of cases.

3.1.3 Factors affecting the performance of child restraint systems for older children in front impact

The CCIS sample comprised 277 children aged 6 to 12 years and including all restraint types and injury levels. Twenty-three of these children were known to be using a child restraint system: 7 were in a booster seat, while 16 were on a booster cushion. Table 5 reveals that none of the children in booster seats received AIS≥2 injuries, while three children on booster cushions were injured at that level. Unfortunately, there were too few cases of children using child restraint systems to establish any clear associations or contributory factors related to the performance of the devices.

3.2 Side impact

3.2.1 *Injury patterns for older children in side impact*

Table 6 shows the injury distribution with respect to restraint type for the older children in the CCIS database involved in a side impact. The adult seat belt was the most common type of restraint system for these children. Once again, there were too few cases involving children in booster seats and booster cushions to comment on the performance of these devices in comparison with the adult seat belt.

Table 6: Injury distribution with respect to restraint type for children aged 6 to 12 years

Restraint type	Total	MAIS0		MAIS1		MAIS2		MAIS≥3		Unknown	
		n	%	n	%	n	%	n	%	n	%
Booster seat	2	0	0.0	2	100.0	0	0.0	0	0.0	0	0.0
Booster cushion	6	1	16.7	5	83.3	0	0.0	0	0.0	0	0.0
Adult seat belt	54	14	25.9	32	59.3	2	3.7	3	5.6	3	5.6
Other restrained	1	0	0.0	1	0.0	0	0.0	0	0.0	0	0.0
Unrestrained	16	2	12.5	6	37.5	2	12.5	4	25.0	2	12.5
Unknown	48	13	27.1	20	41.7	6	12.5	2	4.2	7	14.6
Total	**127**	**30**	**23.6**	**66**	**52.0**	**10**	**7.9**	**9**	**7.1**	**12**	**9.4**

Five restrained children (aged 6 to 12 years) received AIS≥2 injuries. Details of the sample are shown in Table 7. The average age of the injured children was 7.8 ± 2.2 years. Where reported, the average velocity change (Δv) was 26 km/h. One child was seated in the front passenger seat and four children were seated in the rear outboard seats.

Table 7: Cases of AIS≥2 injury in restrained children aged 6 to 12 years

Case	Age	Restraint type	Seating position	MAIS (Body region)	PDOF/Δv (km/h)	Object hit
1	11	Adult seat belt	Rear nearside	2 (Head)	1/Unknown	HGV or PSV
2	6	Adult seat belt	Front seat	2 (Head)	11/25	MPV or LGV
3	6	Adult seat belt	Rear offside	4 (Head)	3/17	Car
4	9	Adult seat belt	Rear nearside	3 (Thorax)	10/27	Car
5	7	Adult seat belt	Rear nearside	2 (Lower extremity – left and right)	10/34	Car

There were 8 AIS≥2 injuries among the 5 children. The distribution of injuries is shown in Figure 17. Half of the injuries occurred in the head (n=4).

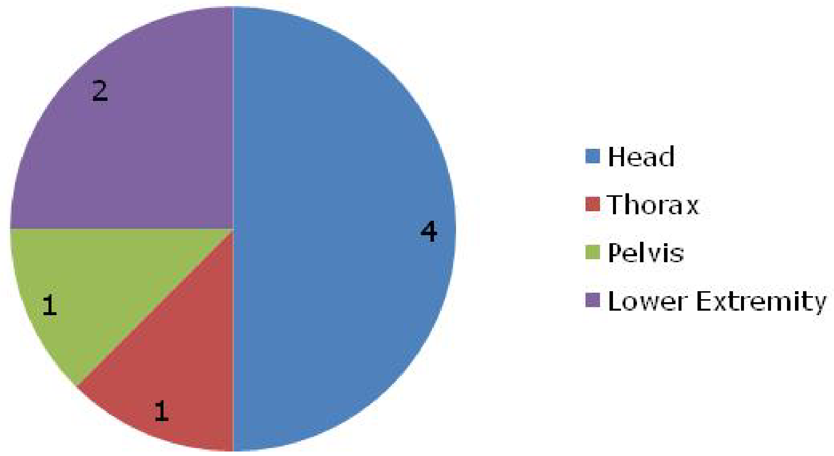


Figure 17: Distribution of AIS≥2 injuries (n=5) among restrained children

Similar findings were reported in the literature, although sample sizes were small. For example, Arbogast *et al.* (2001) described 6 cases involving children with AIS≥2 injuries and aged 5 to 9 years. Head injuries were the most common (AIS≥2) injuries in this group. In the same study, head injuries were the most common AIS≥2 injuries from a sample of 8 10 to 15 year old children; however, extremity injuries occurred more often than in any other age group. Howard *et al.* (2004) also found the head and the extremities to be the most common location for AIS≥2 injuries in older children aged 7 years and above.

3.2.2 Factors affecting injury of older children in side impact

There were too few cases with AIS≥2 injuries to identify any trends associated with the likelihood or severity of injury for older children in side impact. However, in general, the proximity of the child to the intruding side structures, and the level of intrusion into the passenger compartment are important. In four of the five cases in Table 7 the child was seated on the struck side of the car. Another consideration is the performance of the car in side impact. At least two of the five cars that the children in Table 7 were travelling in were unlikely to have been approved to UN-ECE Regulation 95.

3.2.3 Factors affecting the performance of child restraint systems for older children in side impact

The CCIS sample comprised 127 children aged 6 to 12 years and including all restraint types and injury levels. Eight of these children were known to be using a child restraint system: 2 were in a booster seat, while 6 were in a booster cushion. Table 7 reveals that none of the children on booster cushions and booster seats received AIS≥2 injuries. It was impossible, therefore, to make any meaningful comments on the performance of the child restraint systems in side impact.

4 Mechanisms of injury in older children

4.1 Front impact

4.1.1 Injury mechanisms by body region for older children in front impact

Many studies of child injury mechanisms in front impact collisions include older children in the sample. However, very few studies describe in detail the types of injuries received by older children specifically. Section 3 revealed the importance of head, abdomen and extremity injuries. While the evidence is limited, it appears that most head injuries in older children result from direct contact with the interior of the vehicle (Agran *et al.*, 1987). This causes the skull to deform with the risk of fracture and/or local brain injury. Head contact can also induce relative motion of the brain with respect to the skull. Contact can occur for a variety of reasons. These include vehicle intrusion into the child's seating position or excessive head excursion due to incorrect or inappropriate restraint use. Non-contact head injuries are rare in older children. Nevertheless, in high severity collisions, acceleration (or deceleration) of the head can result in inertial loading that leads to brain injury. Similarly, the risk of basilar skull fracture with neck injury, which has been reported extensively in the literature for younger children, does not seem to be found in older children (Jakobsen *et al.*, 2005).

The most common abdomen injury mechanism in older children is adult seat belt loading directly at the site of the injured organ (Arbogast *et al.*, 2007). This can result from submarining (where the pelvis slips under the lap part of the seat belt) and/or from an initial misplacement of the belt, for instance, due to a slouched posture. Injuries to the lumbar spine seem to be rare in older children, particularly when the diagonal part of the seat belt is used correctly. Individual cases were discussed by Brown and Bilston (2007) and were associated with "high severity" collisions.

Injuries to the extremities of older children are likely to result from interaction with parts of the vehicle interior. Jermakian *et al.* (2007) described the lower extremity injuries in a sample of children in forward facing child restraints. Although the oldest child was only 5 years old, some of the key mechanisms are likely to be the same for older children. Jermakian found that a loose child restraint attachment and/or intrusion of the vehicle seat back in front of the child were important contributing factors. The main injury mechanism is loading applied to the extremity from the vehicle interior resulting in fracture.

4.2 Side impact

4.2.1 Injury mechanisms by body region for older children in side impact

The principle mechanism of injury of children in side impact collisions is contact with the vehicle interior, which can occur either with or without significant intrusion (Howard *et al.*, 2007). While the effects of the greater seating height of older children, and their different biomechanical properties, have not been investigated in detail, it is clear that protection of the head is just as important in older children as it is in younger children. Severe head injury can occur, even in cases with no, or minor, intrusion.

While head injury can occur irrespective of the presence or level of intrusion, injuries to other body regions are more likely to occur when the side structure of the car intrudes into the child's seating position. For example, Arbogast *et al*. (2001) described a number of pelvis and femur fractures in children aged 10 to 15 years who were restrained in adult seat belts. The children were seated on the struck side on the vehicle adjacent to the intrusion. Howard *et al.*, (2007) reported similar injuries for children of all ages.

5 Discussion

Children aged between 10 and 12 years old are in the process of puberty and developing into adults. It is therefore important to treat them as specific category of children and not as young adults, which includes protecting them suitably as a passenger in a vehicle. The European Directive 2003/30/EC was designed to do this by stating that all children under 12 years old, or under 150cm must use a child restraint. However this Directive does miss-match with the current child restraint regulation UN-ECE R44, which specifies that child restraints are designed to accommodate a maximum occupant weight of 36kg, (which is less than the 50th percentile mass of a 150cm child).

5.1 Injury mechanisms

The review of previous literature investigating the main injury mechanisms and injury types has provided some common conclusions for both front and side impact. However, most of the previous studies were conducted before the change in restraint use law, hence children over 6 years of age were unlikely to have been using child restraints at the time. The majority of injury data for children using booster restraints will be for children aged 4-6. However with this in mind common injury trends can still be seen between children using booster restraints and those who only used the adult seat belt.

For the reason that there were very few previous studies involving older children, although it was outside of the project scope, a small investigation into data for older children specifically was conducted. This short study was conducted to analyse recent data in the CCIS database and summary information from CARE database for accidents that only involved 6-12 year old children. Although there were few cases involving older children these databases the main injury body regions identified corroborated the findings of the previously conducted studies.

5.1.1 Front impact injuries

For front impact, the main injury body region that was identified by previous studies was the head. Head injuries were also identified in the CCIS database as one of the main injuries. The main injury mechanism for head injury is head contact with rigid parts of the vehicle interior. As a child grows in stature their head excursion will increase. Hence their likelihood of contacting the vehicle interior also increases.

The abdomen is a frequently injured body region and is particularly important to protect as it contains several vital organs. The main injury mechanism is submarining of the child under the lap section of the seat belt. This can be very severe for children who are not using a booster restraint, as the lap belt is not positioned correctly in relation to the child's pelvis. This can also occur due to slouching of the occupant. It is therefore important that the new dummy is capable of mimicking this injury mechanism and has the instrumentation to determine when submarining is occurring.

Protection of the chest was also identified as being important as it contains vital organs. As a child develops more of the vital organs become protected by the ribs, as the ribcage grows. Chest injuries seem to be less frequent for children using booster restraints with backrests, than booster cushions or only the adult seat belt, which may be due to the backrest positioning the diagonal section of the belt correctly and securely.

Upper and lower limb injuries are also frequently recorded in front impact. These are normally due to contact with rigid parts of the vehicle interior. Previously they have been deemed to be low priority because it would be difficult for the dummy to be able to measure limb loading.

5.1.2 Side impact injuries

For side impact the main injury body region was also identified by previous studies as the head. The main injury mechanism for head injury is due to the head contacting parts of the vehicle interior or an intruding object.

Chest and abdomen injuries are common for children using booster restraints or just the adult seat belt. These injuries are usually caused by compression of the child through door panel contact. The right hand side of a child is particularly susceptible to injury as that is where the liver is located.

Upper and lower limb injuries and pelvis injuries are also frequently recorded in side impact. These are normally due to contact with the vehicle door panel. Lower limb and pelvis injuries are particularly frequent for children who use only the adult seat belt as there is no side protection provided from the intruding structures.

5.2 Important factors

5.2.1 Velocity

5.2.1.1 Front impact

A review of real world accident severity reported that the majority of front impacts occur between 10km/h and 70km/h. A separate review investigated the road speed limit in accident cases where serious injuries to children occur. This showed that the majority of serious injuries occurred on roads with either a speed limit of 30 mph (48 km/h) or 60 mph (96 km/h).

The current regulation test UN-ECE R44 is based on a 50 km/h impact and therefore is able to ensure that a child restraint protects children in an accident up to that severity.

The NPACS front impact consumer test was designed to represent an accident with a higher severity (Δv 65 km/h) to ensure the child restraints were capable of providing protection for the children at higher severity accidents. It is therefore important that the new dummy can be used at a range of impact speeds in order to be able to assess fully a child restraint's ability to protect a child from the majority of accidents that would cause serious injuries.

5.2.1.2 Side impact

A review of real world accident severity reported that half of side impact accidents that result in slight injuries to children have an EES of less than 30 km/h and that half of serious injuries occur at an EES less than 50 km/h. It is therefore important that the new dummy can be used at a range of impact speeds in order to assess fully a child restraint's ability to protect a child from the majority of accidents that would cause injuries in side impact.

5.2.2 Side impact intrusion

Lesire *et al.* (2006) reported that there was a direct relationship between vehicle intrusion and the injuries sustained by the occupant on the struck side of the vehicle. Below 200mm, the MAIS≥4 percentage is less than 20%; however above 300mm intrusion, the percentage of MAIS≥4 is approaching 50%. Therefore it is important that the dummy produces realistic kinematics in a side impact test with an intruding door. If the dummy is designed too stiff it will create unrealistic measurements if contacted by the intruding door. The shoulder of the dummy should also have some compliance, and absorb a some of the load as a child would and not be too rigid.

6 Conclusions

- The implementation of EU Directive 2003/30/EC means the new dummy needs to be capable of sufficiently assessing a child restraint designed for a child up to 150cm or 12 years old.
- Although the majority of research of injuries sustained by children using booster restraints is limited to children under 6 years old there are comparisons with injuries sustained by children only using the adult seat belt.
- For front and side impact the main injury body region is the head. In both types of accident, injury is caused due to contact with an external rigid object. It is therefore important that the exposure risk of the head is minimised. This would mean a short excursion in front impact and good head containment in side impact.
- The abdomen and chest are the next most significant body regions to protect as this is where the majority of a child's vital organs are located. In a front impact it is important that the child does not submarine under the lap belt. In a side impact it is important that the child restraint provides side protection from the door panel or an intruding object.
- The pelvis has also been identified as an area to protect in side impact, as again it is important the child restraint provides protection from the door panel or an intruding object.
- Limb injuries occur frequently in both front and side impacts, however they have previously been classed as low priority as they are deemed to be low in severity and difficult for the dummy to measure.

7 Recommendations

Based on the findings from the literature and accident data review the following recommendations are made for the minimum instrumentation that the new dummy should have:

7.1 Head

- Identified as the most important body region, the head needs to be capable of measuring both linear and angular accelerations.
- The excursion of the head needs to be measured as part of the assessment of a front impact.
- The containment of the head needs to be measured as part of the assessment of a side impact.

7.2 Abdomen

- The dummy needs to be capable of determining when the abdomen is being loaded and if possible the level of loading.

7.3 Chest

- The chest needs to be capable of measuring both linear accelerations and compression of the ribs (D_x for front impact, D_y for side impact).

7.4 Pelvis

- The pelvis needs to be capable of moving to allow the dummy to reproduce submarining in a front impact sled test. The pelvis could include an angular sensor.
- The pelvis needs to be capable of measuring linear accelerations.

7.5 Neck

- Although not identified a major injury body region for older children, neck forces and moments need to be measured in both the upper and lower neck, to ensure a child restraint is not creating excessive loads in the neck. These measurements are also required for the NPACS assessment.

7.6 Limbs

- Limb injuries occur frequently in front and side impact accidents and therefore consideration should be made as to whether the dummy needs to be capable of measuring loads in the arms and legs, without affecting the kinematics.

Acknowledgements

The work described in this report was carried out by the EPOCh consortium. The authors are grateful to the EC, the primary investors in the EPOCh project.

We also appreciate the contribution from Kees Waagmeester, Mark Burleigh, Erik Salters, David Hynd, Jolyon Carroll and Costandinos Visvikis for their input to the quality review of this document.

The results of this work were reported at the EPOCh dissemination meeting in Paris, June 2009. Present were representatives from EEVC, CASPER, BASt, EuroNCAP and an informal GRSP group.

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Glossary of terms and abbreviations

Energy equivalent speed (EES)