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CAR SAFETY FOR CHILDREN AGED 4-12

Real world evaluations of long-term injury outcome, head injury causation scenarios, misuse, and pre-crash maneuver kinematics

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Stockholm 2013

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Published by Karolinska Institutet. Printed by Universitetsservice US-AB.

ISBN 978-91-7549-124-0

ABSTRACT

Child casualties in car crashes have decreased over the years. Nevertheless, occupant safety in rear seats, especially for children 4-12 years old, needs further attention because motor vehicle crashes remain the leading cause of death and long-term health consequences for children. The aim of this thesis was to obtain comprehensive knowledge of real-life situations for restrained, forward-facing, rear-seated children aged 4-12 years, in frontal car crashes as a basis for vehicle safety improvements to reduce long-term health consequences.

The thesis is comprised of four studies based on child-specific data from Sweden and the US. Study I was based on injury data from insurance claim files, covering 2619 injured children in Sweden. Study II was an experimental study of restraint misuse, including 130 Swedish children. Study III analyzed crash data included 27 cases from two US databases, to determine injury causation scenarios. Study IV was a driving study of how pre-crash maneuvers affect child occupant kinematics with 16 children included.

The results of Study I emphasized the importance of looking beyond acute, severe injuries and also examine injuries (regardless of initial injury severity) resulting in permanent medical impairment. The vast majority of injuries with the higher degree of permanent medical impairment were severe injuries to the head. The most frequent injuries leading to permanent medical impairment were minor injuries to the neck and head. To reduce the risk of head injuries among children in car crashes, a fundamental step is to ensure that vehicle restraint systems are adapted to the child, physically and behaviorally, and that the child is properly restrained. An experimental study (Study II) of children using integrated booster cushions compared to aftermarket belt positioning booster cushions, showed that misuse related to buckling up, a problem for decades, can be reduced to a minimum by the design of an integrated booster cushion. Minimizing misuse will lead to increases in proper positioning of the restraint on the child and may translate to reductions in head injury risk. Therefore, car manufacturers should focus on integrated booster cushions, preferably as standard equipment.

Even with proper use, however, restrained children in rear seats sustained head injuries in frontal impacts by impacting their heads on the side interior and on the seat back in front of them. Oblique impacts and pre-crash steering maneuvers contributed to both these injury-causation scenarios (Study III). Therefore, pre-crash steering maneuvers were further explored in a driving study and it was confirmed that these common pre-crash maneuvers can result in an unstable restraint situation that may potentially compromise rear occupant safety in the event of a crash (Study IV).

In conclusion, the primary recommendation as a result of this research is to protect the head and neck of child occupants from both minor and severe injuries, since all severity levels of injuries may result in long-term consequences. Frontal impacts, including oblique impacts or maneuvers prior to impact, need to be addressed to develop “tolerant” restraint systems. Furthermore, it is recommendable to design and use vehicle-built-in restraint systems to improve crash safety among children, by facilitating proper use of the restraint and placement on the child, as has been previously done for front-seated adults. To incentivize vehicle manufacturers to accelerate the implementation of child safety improvements within their vehicles, an assessment of child safety for 4-12-year-old children should be included in consumer rating programs and legal requirements.

LIST OF PUBLICATIONS

This thesis is based on the following four papers, referred to in the text by their roman numerals.

I. Bohman K, Stigson H, Krafft M. Long-term medical consequences for child occupants 0-12 years injured in car crashes. Submitted 2013.

II. Osvalder AL, Bohman K. Misuse of booster cushions - an observation study of children's performance during buckling up. Annals of Advances in Automotive Medicine. 2008 Oct;52:49-58.

III. Bohman K, Arbogast KB, Boström O. Head injury causation scenarios for belted, rear-seated children in frontal impacts. Traffic Injury Prevention. 2011 Feb;12(1):62-70.

IV. Bohman K, Stockman I, Jakobsson L, Osvalder AL, Boström O, Arbogast KB. Kinematics and shoulder belt position of child rear seat passengers during vehicle maneuvers. Annals of Advances in Automotive Medicine. 2011 Oct;55:15-26.

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LIST OF ABBREVIATIONS AND DEFINITIONS

Acute injury	The initial diagnosis of the injury.
AIS	Abbreviated Injury Scale. An anatomical-based scoring system to determine the severity of single injuries based on survivability of the injury. The scale ranges from 1=minor, 2=moderate, 3=serious, 4=severe, 5=critical, 6=fatal. The scale was established by the Association of the Advancement of Automotive Medicine. AIS3+ means all injuries at an AIS3 level and higher.
Belt pretensioner	A function that can be added to the retractor. It is activated early in the crash and tightens the belt on the occupant.
BPB	Belt Positioning Booster cushion. A cushion that elevates the child to be positioned in the vehicle to ensure proper seat belt to fit the child. See also high-back BPB.
B-pillar	The vertical side structure (pillar) dividing the front and the rear door in the vehicle.
CRS	Child Restraint System. A system specially designed and adapted to restrain a child (0-12) in the vehicle and to protect the child from injury or death in motor vehicle crashes.
IBC	Integrated Booster Cushion, belt positioning booster built-in to the vehicle.
IC	Inflatable Curtain. A side airbag inflated at head level along the side of the vehicle, in general covering the head area for both front seat and rear seat occupants.
ISOFIX	An international standard for attachment points for CRS in vehicles.
High-back BPB	High-back Belt Positioning Booster cushion
MAIS	The single maximum AIS injury of an occupant
MTBI	Mild Traumatic Brain Injury
MVC	Motor Vehicle Crash
NCAP	New Car Assessment Program
NHTSA	National Highway Traffic Safety Administration
PDOF	Principal Direction of Force
PMI	Permanent Medical Impairment
WAD	Whiplash Associated Disorder. A whiplash trauma is an acceleration-deceleration mechanism of energy transferred to the neck, which may cause a whiplash injury and it can result in a variety of symptoms.
WHO	World Health Organization

1 BACKGROUND

1.1 TRAFFIC CRASHES – A WORLDWIDE PUBLIC HEALTH PROBLEM FOR CHILDREN

Road traffic safety is defined as conditions and factors related to road traffic crashes and other traffic incidents leading to fatalities or severe injuries to road users (ISO, 2012).

Road traffic injuries are a global health problem. Every year, 1.3 million people are killed and up to 50 million more injured (WHO 2011). Road traffic injuries were the eighth cause of death for people of all ages in 2010 (Lozano et al. 2012) and in the 5-14-year age group they were the secondary cause of death in 2002 (WHO 2008). In Europe, road traffic injuries are the leading cause of death in children and young adults (5-29 years) (WHO 2009a). In Sweden, of all the child (0-17) fatalities due to accidents during 1993-2003, 214 (64%) were due to road traffic injuries (Trafikverket, 2013).

Children in families with low socioeconomic status are at greater risk when travelling in both developing countries as well as developed countries (WHO 2004). In developed countries the majority of fatalities are motor vehicle occupants, and a child in a family with lower socioeconomic status is more likely to be improperly restrained (Gustafsson and Cosini 2003). In the developing countries, the majority of fatalities are vulnerable road users such as pedestrians, bicyclists and occupants of powered two wheelers (WHO 2009c). Furthermore, a child in a low-income family is more likely to be a vulnerable road user, with its associated increased risk (Nantulya and Reich 2002; Hippisley-Cox et al. 2002).

For each fatality there are thousands of injured people, and several sustain long-term impairment. Road traffic injuries can therefore be regarded as one of the larger public health problems, especially for children. Furthermore, traffic intensity is increasing and without progress in road traffic safety, fatalities and injuries are expected to increase by 65% from 2000 to 2020 worldwide and estimated to become the fifth cause of death by 2030 (WHO 2011). This increase is mainly due to the increased numbers of road traffic injuries in developing countries (WHO 2004).

In developed countries, fatalities and severe injuries to child occupants in motor vehicle crashes (MVCs) have decreased over the years. In Sweden, the number of fatally injured children (0-14) in MVCs has decreased from an average of 26 fatalities annually in the eighties to an average of 4 fatalities annually in the early 2000s (Carlsson et al. 2013). In the US, child traffic fatalities in children (0-15) have decreased from 3289 fatalities in 1994 to 1428 fatalities in 2010 (NHTSA 1997; NHTSA 2011a). Still, MVCs were the leading cause of death in 2009 among children (0-14) in the US (NHTSA 2012).

A child, per definition by the United Nations (UN), is a person from birth until 18 years old (UN 2013). In this thesis, if not otherwise stated, the UN’s definition of a child is used. From section 1.1.4 the thesis focuses on children aged 4-12 and the word child will be used to refer to children aged 4-12.

1.1.1 Measuring loss of health

There are several ways of classifying injuries and measuring health outcomes after a trauma (AAAM 2005; Coons et al. 2000; Mackenzie et al. 1996). However, in the field of automotive safety, studies investigating injury outcome focus primarily on the immediate diagnosis following the crash (Arbogast et al. 2010; Loftis et al. 2011a). The most common scale used in these assessments is the Abbreviated Injury Scale Score (AIS). The coding system describes the severity of specific injuries in relation to the risk of death and the scale ranges from one (AIS1), being a minor injury and low risk of death, to six (AIS6); a life threatening injury (Gennarelli et al. 2008; AAAM 2005). Other scales such as the ISS (Injury Severity Scale) use the AIS scale and address the whole body injury severity by taken into account injuries to the three most injured body regions (Baker et al. 1974). None of the AIS-based scales have a child-based assessment or predict long-term consequences.

There are several ways of predicting long-term injury outcome in terms of impairment, but no method is as internationally accepted as the AIS for acute injury outcome. WHO has identified three categories of long-term consequences (WHO 1980, WHO 2001): impairment, disability and handicap:

- Impairment is any loss or abnormality of psychological, physiological or anatomical structure or function.
- Disability is any restriction or lack (as a result of impairment) of the ability to perform an activity considered normal for a human being.
- Handicap is a disadvantage for a given individual, resulting from impairment or a disability that limits or prevents the fulfillment of a role that is normal role for that individual.

The Functional Capacity Index (FCI) measures impairment and was developed to estimate injury outcome one year post injury, and each single AIS 1990 (AIS code established 1990) description was assigned an estimated disability score (Mackenzie et al. 1996). However, the scale has been criticized for modest or even poor correlation to permanent impairment one year after injury (McCarthy and Mackenzie 2001; Schluter et al. 2005) and, as with the AIS, it is validated for adult data only.

All Swedish insurance companies use the approach known as “Grading Medical Impairment” to assess long-term consequences post-injury (Sveriges Försäkringsförbund 2004). Predicted injuries leading to permanent medical impairment are also the national definition of severe injuries used by the Swedish authority since 2008 (SRA 2008), which is based on the work on risk of permanent medical impairment by Folksam (Malm et al. 2008). The principles of grading medical impairment have developed since the beginning of the 20th century and physicians have reached a consensus. An injury is assigned a degree of temporary or permanent medical impairment between 1% and 99%. A medical impairment is considered permanent when no further improvement in physical and/or mental function is expected with additional treatment.

Collection of injury data and the description and assessment of injury severity play an important role in the process of prioritizing legislation, research and the development of injury prevention countermeasures. Previous efforts have highlighted challenges in correlating the immediate assessment of the severity of an injury for adult occupants with long-term consequences (Nygren 1984; Gustafsson et al. 1985; Galasko et al. 1986; Bradford et al. 1994; Malm et al. 2008). Consequences of injuries to children, in similarity to adults, are described mainly by the AIS score, but there is limited knowledge of the correlation between AIS levels and the risk of long-term consequences for children. A pioneer, Tingvall (1987), studied permanent medical impairment with an impairment degree of 10% or higher among children injured in motor vehicle crashes, showing an overall risk of 0.6%. The landscape of child safety in motor vehicle crashes has changed since Tingvall’s study. New priorities for countermeasures have been identified for adults when studying long-term consequences of injuries after a MVC, such as whiplash protection. To further advance child safety, long-term consequences for children must be studied to understand if safety development priorities for children are adequate.

1.1.2 Injuries and fatalities in motor vehicle crashes

There are studies showing injury patterns for child occupants after motor vehicle crashes. Tingvall (1987) showed that the head needs to be prioritized both in terms of fatalities and long-term consequences. More recent studies have also shown that the head is the most commonly injured body region for severe acute injuries, regardless of restraint system and crash direction (Durbin et al. 2003; Howard et al. 2004; Arbogast et al. 2004). Traumatic brain injuries are the leading cause of death among children (0-16) in motor vehicle crashes (Adekoya et al. 2002; Scheidler et al. 2000; Thompson et al. 2003; Carlsson et al. 2013). Surviving the acute phase of a severe traumatic brain injury often results in persistent neuropsychological sequelae for years after the injury (Aitken et al. 2009; Anderson et al. 2005; Taylor et al. 2002; Yeates et al. 2002). Even brain injury that resolves after six months will affect a child’s learning ability during the healing period.

Furthermore, researchers, including the World Health Organization’s “Task Force on Mild Traumatic Brain Injury”, have also recognized mild traumatic brain injury (MTBI) as an important public health problem (Cassidy et al. 2004). MTBI is induced by a force to the head, direct or indirect, resulting in a rapid onset of short-lived impairment of neurological function that resolves spontaneously (WHO 2012). MTBI has been associated with symptoms such as loss of consciousness of less than 30 minutes, posttraumatic amnesia of less than 24 hours and an initial Glasgow Coma Scale (GCS) of 13 or higher (Carroll et al. 2004). However, loss of consciousness is not a prerequisite for the diagnosis of MTBI. The risk of fatality following an MTBI is low (Kuppermann et al. 2009), but a child may show persistent symptoms for months, often referred to as post-concussive symptoms (Barlow et al. 2010; Dean and Sterr al. 2013; Zemek et al. 2013). These include a number of symptoms such as headache, dizziness, fatigue, irritability, difficulty in concentrating and performing mental tasks, impairment of memory, insomnia, and reduced tolerance to stress (WHO 2012). Post concussive symptoms may result in persistent learning problems and compromise the child’s education (Savage et al. 2005). Although most symptoms resolve within one year, some children (0-18), 2.3%, still had post-concussive symptoms one year after sustaining an MTBI (Barlow et al. 2010).

In side impacts, in addition to head injuries, the thorax and abdomen are the most commonly injured body regions at an AIS3+ level to restrained children aged 4-12 years (Bohman et al. 2009). When taking into account AIS2+ injuries, the extremities also become a frequently injured body region (Orzechowski et al. 2003).

In frontal impacts, restrained children (0-14) sustain head injuries as well as injuries to the thorax, abdomen and extremities (Orzechowski et al. 2003; Kuppa 2005). Abdominal injuries are typically seat-belt related and sustained by children restrained by the seat belt alone. A study of 4-7-year-old children on belt positioning boosters reported no abdominal injuries whatsoever in frontal crashes (Durbin et al. 2003).

According to US statistics, the fatality risk in children aged 0 to 7 is higher in rollover and side impacts, but due to the high frequency of frontal impacts they accounted for 35% of all fatalities, while side impacts accounted for 26% and rollover 29% of all fatalities (Viano and Parenteau 2008a). In Sweden, from 1992 to 2011, 33% of all child fatalities in ages 0 to 14 were in frontal impacts, 27% were side impacts and 29% were rollovers (Carlsson et al. 2013). The same conclusions were drawn when focusing on non-fatally injured children in car crashes, where frontal crashes are the most frequent although the injury risk is lower compared to side impacts and rollovers (CIRP 2008).

Overall, the head should be protected in motor vehicle crashes to reduce the number of fatalities and severely injured children.

1.1.3 Injury prevention

Haddon's matrix is a framework used in injury prevention and is often applied to vehicle safety (Haddon 1980). Table 1 is based on Haddon's matrix, the time frame is divided into before, during and after the crash; and domains of influence are divided into human, vehicular and environmental, respectively. This framework aids in the understanding of important aspects of child occupant protection in MVCs.

Table 1 The injury prevention matrix, based on Haddon's strategies (Haddon 1980), showing possible factors influencing injury during the three crash phases; pre-crash, crash and post-crash. The shaded areas would, according to Bohman, require special focus to improve child safety.

Phase	Human Factors	Vehicles and Equipment Factors	Environmental Factors
Pre-crash	Information Attitudes Legal requirement Enforcement	Roadworthiness Lightning Braking Speed management	Road design Road layout Speed limits
Crash	Use of restraints Misuse of restraints	Occupant restraints Other safety devices Crash-protective design	Crash-protective roadside objects
Post-crash	Triage Access to medics Treatment	Ease of access Fire risk	Rescue facilities Traffic congestion

Improvements associated with environmental factors as well as vehicle and equipment factors during pre- and post-crash phases are beneficial to all road users. However, to specifically improve child occupant safety, special focus is needed for human factors and on vehicle and equipment factors during pre-crash and in-crash (Table 1). Improvements should be specially designed and aimed toward children, and may differ from interventions aimed toward adults. Thus, vehicle restraint systems should be adapted to provide optimal child protection.

The post-crash phase regarding human factors may also be child-specific in terms of treatment to reduce the short- and long-term consequences of injury. For example, rehabilitation of cognitive aspects after brain injury may differ for children and adults, since children may not have reached certain milestones in their cognitive development at the time of injury as compared to adults.

Child anatomy

One reason for the need for special interventions and countermeasures for children is that they, in several aspects, are not small versions of adults (Tarrière 1995). There are differences in anthropometry as well as anatomical changes during growth. Such aspects are important to understand in order to develop effective restraint systems for children.

The relative length and mass of different body regions varies between children and adults, particularly for the head (Burdi et al. 1969). Furthermore, the sitting height of an average 4-year-old is two thirds the average male, and the shoulder width is half the width of a midsized male (Figure 1). An average 12-year-old reaches a similar sitting height and shoulder width as a small female (Pheasant and Haslegrave 2006).

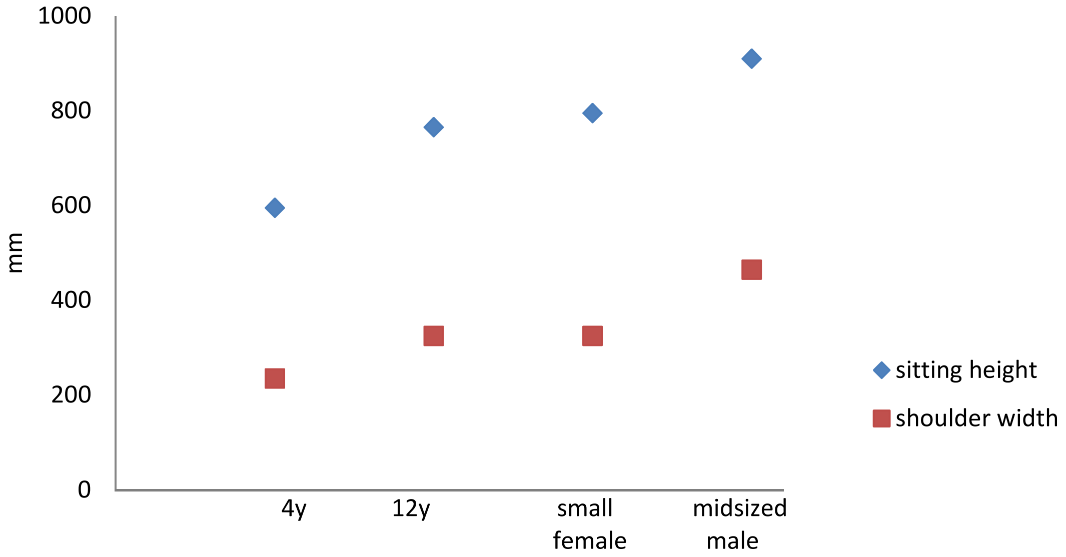


Figure 1 The sitting height and shoulder width of an average 4-year-old child, 12-year-old child, a small female and a midsized male individual (Pheasant and Haslegrave 2006).

The cervical vertebrae of the child differ from that of the adult (Ramrattan et al. 2012). The neck muscles and ligaments that support the relatively large head are weak. The combination of a large head and weak neck place the child at greater risk for head and neck injuries than adults. The injury pattern to the cervical spine changes about the age of 8, with younger children (1-8) usually suffering upper cervical injuries and older children (8-16) more frequently suffering lower cervical injuries, a pattern similar to adults (Platzer et al. 2007).

The ribcage of the child has a larger proportion of cartilage than adults, resulting in higher flexibility of the thorax and a decreased risk of rib fracture. However, due to its flexibility, there is still a risk for injuries to internal organs within the ribcage.

Throughout childhood and adolescence, the pelvic bones continue to grow in all three dimensions and ossification of the cartilaginous tissue continues, much later than for other bones of the body (Gray and Clemente 1984). Therefore, special lap-belt geometry is needed for children to prevent the lap belt from loading the abdomen. Restraint systems must be adapted to children in order to provide safety and ensure a proper fit (Burdi et al. 1969; Reed et al. 2013).

Vehicle restraints

Children are recommended to be seated in the rear seat (Durbin 2011) and US data shows that 69% of rear seat occupants are 14 years or younger (Kent et al. 2007). The focus of this thesis is on rear-seated children.

The three-point seat belt is the basic restraint system in a vehicle and prevents the occupant from impacting the vehicle interior. It also prevents ejection and injury between occupants within the vehicle. The seat belt distributes loading to strong body parts, including pelvic bones, the thoracic ribcage and clavicle. Three-point seat belts are mandatory in all seating positions in all European and North American vehicles. The middle position in the rear seat was the last place to be included in the legal requirements.

Seat belts may include a belt pretensioner, activated early in the crash. The pretensioner reduces slack in the belt system resulting in earlier restraint of the occupant, which is beneficial to protection in terms of energy absorption. Seat belts may also include a load limiter, which reduces belt force at controlled levels and loading on the occupant due to the belt. These advancements are common in the front seat, but not the rear (Kent et al. 2007).

Seat belts reduce fatalities among children, with an effectiveness ranging from 48% to 54% in the 5-14 age group (NHTSA 1999). Seatbelt use reduced fatalities between 55-75% in adult rear-seated occupants (Zhu et al. 2007).

Frontal airbags are rare in the rear seat, but side airbags protecting the head are standard in a vast majority of vehicles. Side airbag curtains, which normally cover the rear occupant's window down to the window sill, have been shown to cause a reduction in fatality risk to drivers by 37% (McCartt and Kyrchenko 2007). Thorax side airbags are uncommon in the rear seat, but benefits of thorax side airbags to children can be expected (Andersson et al. 2012; Bohman et al. 2009; Bohman and Sunnevang 2012). Benefits to adults are found for the front seat (Loftis et al. 2011b), showing a fatality reduction of 26% (McCartt and Kyrchenko 2007). As yet, no harm to children's heads or thoraxes by side airbags has been detected (Arbogast and Kallan 2007; NTHSA 2007).

Child restraint systems

As early as 1987, Tingvall (1987) recommended built-in child restraint systems for children of all ages, including both forward and rear-facing child seats. However, as a rule, vehicle manufacturers do not provide child safety restraints integrated in the vehicle as they do for adult occupants. Therefore, vehicle manufacturers make their own child restraint systems (CRS) available to the dealer or recommend suitable CRSs for the specific vehicle. However, many families buy a CRS aftermarket, which have been developed separately from the vehicle. Besides, WHO (2013) points out the difficulties of achieving high usage of child restraint systems not originally installed in vehicles.

CRSs are designed to protect infants and children up to 10-12 years of age. Rear-facing infant seats for the youngest occupants are standard in many countries. In a frontal crash the load is distributed to the posterior of the head, neck, torso and pelvis. This particular loading results in reduced forces to the neck during the crash as well as protection for the head, since it will be supported by the seat back and kept within the protective side-wings. In Sweden and in the other Nordic countries, the child is recommended restraint in a rear-facing child seat until the age of four or five. Most other countries advise the transfer of the child at about 1-2 years of age to a forward-facing seat equipped with a four- or five-point integrated belt harness.

The CRSs are normally attached to the vehicle with the vehicle seat belt, but there is also an international standard for attachment points in vehicles, ISOFIX, to facilitate proper CRS attachment to the vehicle. ISOFIX was introduced in 1997, and became mandatory in Europe in 2011. However, knowledge of ISOFIX among parents is limited (Levi et al. 2012).

At about the age of four, the child is usually transferred to a belt-positioning booster (BPB) or high-back BPB, meaning a belt-positioning booster with a backrest. BPB is not a restraint system, since the child is restrained by the vehicle seat belt. The BPB is more of a geometry modifier, elevating the child. In France the BPB is normally called “rehausser” which can be translated as “make higher”, which is correlated to the function of the BPB. By elevating the child 70-100 mm, the vehicle seat-belt geometry can be adapted to the child. The BPB keeps the lap belt on the upper thighs/pelvis, preventing the lap belt from loading the abdomen. The BPB also improves the shoulder belt position. Many high-back BPBs have pronounced side wings, and are often marketed as offering side impact protection. Another version of a BPB is the vehicle built-in booster cushion, referred to as an integrated booster cushion (IBC), that is designed to restrain occupants without the need of adding aftermarket products to the vehicle. There are IBCs designed to offer two levels of height in order to improve belt fit depending on the size of the child (Figure 2) (Jakobsson et al. 2007).

When the child can bend its knees comfortably over the vehicle seat bench and simultaneously maintain contact with the seat back without slouching and moving their buttocks forward, the child can be safely seated without a BPB. A generic transition age that applies to all children is difficult to specify since the transition from being restrained by a BPB to a seat belt alone depends on the anthropometry of the child and the cushion length of the vehicle. In practice, a child could have a proper belt fit without a BPB in one vehicle but not in another. In the US, BPBs are recommended from 8 to 12 years of age (NHTSA 2011b; Durbin et al. 2011). In Europe, the legal requirements range from 135 cm to 150 cm. Swedish law requires age-appropriate CRS-use until the child is 135 cm tall (corresponding to a midsized 9-year-old) and the recommendation is for children up to 10-12 years.

Since child restraints are not generally built into the vehicle, a wide range of aftermarket products must be used instead.

a) **b)**

Figure 2 a) A 10-year-old (to the left) restrained on stage one of the integrated booster cushion (IBC), a 12-year old (in the middle) restrained on the seat bench and a 5-year-old (to the right) restrained on stage two of the IBC.
b) Integrated booster cushions (courtesy of Volvo).

Effectiveness of child restraint systems

Based on Swedish data, the effectiveness of rear-facing child restraints compared to forward-facing child restraints in reducing AIS2+ injuries was 79% for children aged 1-4 (Tingvall 1987). Several other studies support the recommendation that the youngest children should be restrained rear-facing (Henary et al. 2007; Sherwood and Crandall 2007; Arbogast et al. 2002; Isaksson-Hellman et al. 1997; Stalnaker 1993, Tingvall 1987). In the US, infant seats and forward-facing child seats have reduced the risk of fatality by approximately 70% for infants, who are mainly rear-facing, and between 54% and 76% for toddlers compared to being unrestrained (Zaza et al. 2001; Rice and Anderson 2009a; Hertz 1996).

Belt positioning booster seats have an injury-reducing effect of up to 55% for children aged 4-8 in all crash directions, and no difference in injury-reducing effect could be distinguished between high-back BPBs and BPBs. The same study also showed that the injury-reducing effect was greater for near-side impacts (68%) than for frontal impacts (41%) (Arbogast et al. 2009). However, the fatality risk for children 4-8 years old restrained on BPBs compared to seat belts only, shows contradictory results for fatality effectiveness (Rice and Anderson 2009b; Mannix et al. 2012; Ma et al. 2012).

The above studies have excluded misuse if detected and coded in the database. However, it could be assumed that misuse conditions are sometimes included in the database without being coded, since misuse can be hard to detect. The effectiveness of the child restraints can probably be further improved, if misuse is limited.

If children are prematurely upgraded to the seat belt alone as their primary form of restraint, the risk of submarining and associated abdominal injuries increases (Davies 2004; Durbin et al. 2003). Also, due to increased discomfort, with shoulder belt closer to the neck, there may be an increased risk of the child putting the belt behind its back or under its arm, and thereby increasing the risk of injury in the event of impact.

1.1.4 Non-usage and misuse

Younger children (0-3) clearly benefit from being restrained in rearward facing child restraint systems. From 13 years and older, children have in general the stature of at least small adult female. This group of children needs further research to reduce their injury risk, but since they fit into adult restraint systems, they are not further included in this thesis. Therefore, the remainder of this thesis will focus on the children from 4 to 12 years and their restraint systems.

Child restraint systems have been proven to have injury-reducing effects. However, not all children use a CRS, and when used not all CRSs are used correctly.

Non-usage of belt positioning boosters

The use of CRSs varies depending on the country and the child's age. Typically, CRS usage is high for younger children and decreases with increasing age (CIRP 2008). In the US 2009, 41% of 4-7-year-old children were restrained on boosters, 32% were restrained by seat belt only, and 13% were unrestrained (NHTSA 2010). The same trends were seen in Europe (Willis et al. 2006). A Swedish study showed that among children in rear seats in Volvos, 45% of 7-year-olds were seated on belt positioning booster seats, 50% were restrained by the seat belt alone, and 5% were unrestrained (Jakobsson et al. 2005). An observational study (Gustafsson et al. 2011) of 5000 children aged 0-10 in Sweden, showed that 4% of children aged 7-10 were not restrained at all. Of the children (7-10) who were restrained, 69% were seated on a booster seat or booster cushion. Furthermore, of all children (0-10) restrained by the seat belt alone, half were improperly restrained due to belt slack, shoulder belt far out on the shoulder, poor lap belt position on the abdomen, or shoulder belt positioned under the arm.

Reasons for non-use of BPB were short trips, children riding with friends, and refusal (Bingham et al. 2006). In the US, education and free BPBs have been identified as important factors to increase BPB usage (Ehiri et al. 2006). Built-in boosters are perceived as less childish compared to after-market BPB (Bohman et al. 2007) and could further increase their use. Legal requirements and enforcement also contribute to increased use of CRSs (Eichelberger et al. 2012; Winston et al. 2007).

In developing countries CRS use is uncommon. China has a modern vehicle fleet, but one observational study has shown significant non-use of CRSs (children aged 0 to 4 years) and only 6% were restrained by a seat belt at all (Pan et al. 2012). In Malaysia, one observational study reported 27% CRS usage by 0-9-year-olds (Kulanthayan et al. 2010). There may be several reasons, but the cost of the child restraint relative to the average wage was probably a critical factor (WHO 2009b) as well as a lack of accurate safety knowledge (Erkoboni et al. 2010). In many developing countries, CRS use is not mandatory (WHO 2009b). The enforcement of CRS use is generally weak, whereby only 9% of all countries have effective enforcement of CRS use (WHO 2013). Public awareness is another important factor related to CRS use (WHO 2008).

Use of CRSs is the first essential step towards improved child safety, and important ways to increase the use of CRSs are legal requirements, enforcement, education and access to CRSs which are easy to use (Bingham et al. 2006; Ehiri et al. 2006).

Misuse

Misuse of BPBs is frequent, and in Australia, the US and Europe between 40-67% of BPB misuse has been observed (Koppel et al. 2013; O'Neil et al. 2009; NHTSA 2004; Willis et al. 2006). In Germany, misuse levels of BPBs were 52%, 60% and 61% in observational studies conducted in 1995, 2000 and 2008, respectively, with 82-95% of all misuse graded as moderate or severe (Hummel et al. 2008). Misuse is typically documented in observational studies, but is not always easy to determine in crash investigations. Valent et al. (2002) showed that AIS2+ injured children (4-7) from NASS-CDS (1995-1999) had roughly 4% improper use, which does not mirror observational studies showing a misuse of 40-67%. Gotschall et al. (1997), studied 121 restrained, injured children (0-12) admitted to hospital, and through physical evidence, interviews with emergency medical technicians, vehicle occupants and children's caretakers, it was established that 15% of all children were improperly restrained with the shoulder belt behind the back. Skjerven-Martinsen et al. (2011) found incorrect use of restraints (harness or shoulder belt behind the back or off the shoulders) as a contributing factor to severe injury or fatality in children (0-16).

There are several conditions classified as misuse. An observational study of 2287 children showed the most common misuses included the shoulder belt being placed over the guiding loops (36%), shoulder belt not in mid-shoulder position (28%), excessive belt slack (24%), and shoulder belt either behind the child's back (9%) or under their arm (10%) (O'Neil et al. 2009). Sub-optimally restrained children are at higher injury risk than optimally restrained children in crashes (Bilston et al. 2007b; Nance et al. 2004; Valent et al. 2002; Brown et al. 2006). The lap belt routed above one or both guiding loops may result in the lap belt being positioned on the abdomen and therefore increasing the risk of abdominal injury in a crash. Reconstruction of child occupants in car crashes showed misuse of restraints resulting in increased motion of the torso and head, increasing the risk of impacting the interior of the vehicle (Bilston et al. 2007b). Excessive belt slack is likely to occur when an additional belt is pulled out in order to route the belt over the guiding loops and the belt is not tightened afterwards, resulting in increased head excursion, and therefore increased risk of head injury. Improper placement of the shoulder belt behind the back or under the arm may result in an increased risk of head injury due to increased forward head excursion (Gotschall et al. 1997, 1999).

Misuse of BPB is well-documented but no significant reductions in its incidence have been observed. Recently, Koppel et al. (2013) showed that despite new CRS legislation in Australia, misuse of BPBs remains at high levels. Most suggestions (Desapriya et al. 2004; Blair et al. 2008; Simpson et al. 2002) to reduce misuse of BPBs center on increasing information, educating parents, stronger enforcement, and designated check points which provide individualized feedback and corrective actions. There are also consumer rating programs rating the ease of use of BPBs (Råd&Rön 2011).

Proper use of BPBs is needed to reduce the risk of injury and achieve optimal protection. Therefore, misuse of BPB needs further attention.

1.1.5 Children’s positions during car rides

Naturalistic driving studies where cameras are installed in vehicles have become a common method to analyze driver behavior during normal driving. Some driving studies of children have been conducted, and it has been shown that children sit differently compared to standard seating procedures of crash test dummies (Andersson et al. 2010; Charlton et al. 2010; Jakobsson et al. 2011; Forman et al. 2011). In a driving study with 3-6-year-old children in two different high-back BPBs, the children spent the majority of the time in an upright position with limited contact between the shoulder and the seat and their heads partly or completely out of the side wings of the seat with more pronounced side wings (Andersson et al. 2010). When comparing these user positions with crash test dummies seated according to test protocols, Bohman et al. (2010) concluded that the children spontaneously chose sitting postures with less shoulder contact compared to crash test dummies. In contrast, sleeping children (7-9) were supported by the side support of the high back belt positioning booster, and the shoulder belt remained on the shoulder to a greater extent compared to children seated on high-back BPBs or directly on the seat bench (Forman et al. 2011).

In a driving study (Jakobsson et al. 2011) including older children (8-11) seated on a BPB or directly on the vehicle seat bench, the children adopted a reclining position. The BPB kept the children more centralized, while sitting directly on the seat bench often resulted in shoulder belt contact with the neck. To escape chafing of the neck, the children rotated or leaned more inboards in the vehicle.

Extreme sitting postures were limited in time, and generally, the child had a specific purpose on these occasions, such as reaching for something and then returning to a normal user position (Jakobsson et al. 2011; Andersson et al. 2010; Osvalder et al. 2013).

In conclusion, driving studies of children aged 4-12 highlighted that user positions were not always equivalent to crash test dummies’ in-crash positions, but the user position still represents part of the spectrum of “normal” positions.

1.1.6 Legal requirements and consumer-rating programs

The use of child restraints can be increased by mandatory child restraint laws and their enforcement (Zaza et al. 2001; NHTSA 2008). Child restraint laws have been proven effective in reducing fatalities and severe injuries (Eichelberger et al. 2012; Mannix et al. 2012). There is also a strong correlation between parents’ restraint use and their children’s restraint use (NTHSA 2006). Consequently, increasing seat belt use by the driver through legal requirements will increase child restraint use as well. In general, legal requirements are well established in developed countries, while developing countries have limited regulation.

Safety standards requiring the dynamic testing of child safety in the rear seat of actual vehicles differ between countries. Typically, dynamic vehicle tests are performed to evaluate front seat safety in frontal and side impacts, and overall there is no child crash test dummy included in any regulatory, complete vehicle test for either frontal or side impact tests (Table 2). CRSs are typically evaluated on test benches or in the vehicle body in sled tests (ECE R44, FMVSS 213). In these tests, the bench is designed to simulate the rear seat of a generic vehicle. Hence, the actual fit and the dynamic interaction in a vehicle have not been not evaluated. A built-in CRS is tested with the complete vehicle; however, no standards specify the tests.

New Car Assessment Programs (NCAP) are vehicle consumer-rating programs established throughout the world. The assessment for the protection of rear-seat occupants varies between programs. An overview of the legal requirements and of NCAP protocols in several countries, with respect to rear-seated crash test dummies in dynamic vehicle testing, side and frontal, is summarized in Table 2. Some programs have included an adult crash test dummy or the youngest child crash test dummy in the rear seat, but no consumer rating program has included a child crash test dummy restrained by the vehicle restraint system. As a result, rear-seat safety does not benefit from the NCAP testing protocol to the same extent as front seat safety. In other consumer rating programs, the CRSs are rated separately from the vehicle.

No safety standards or consumer programs evaluate the effect of the vehicle restraint system on any child crash test dummy in dynamic vehicle testing.

Table 2 An overview of rear seat legal requirement testing and New Car Assessment Programs (NCAP) in several countries, including crash test dummies during dynamic side (*S*) and frontal (F) vehicle testing, based on legal requirements and test protocols from different countries.

Crash test dummy	Australia	China	Europe	India	Japan	Korea	US
Legal requirement							
Child (<4 years)	-	-	-	-	-	-	-
Child (6 or 10 years)	-	-	-	-	-	-	-
5th percentile adult female	-	-	-	-	-	-	S
50th percentile adult male	-	-	-	-	-	-	-
Consumer rating programs							
Child (<4 years)	-	-	F, S	N/A	-	-	-
Child (6 or 10 years)	-	-		N/A	-	-	-
5th percentile adult female		F[1], S[1]	-	N/A	F	-	S
50th percentile adult male	-	-	-	N/A	-	-	-

F= dummy in frontal impact, S =dummy in side impact, -=no dummy in test, N/A=not applicable, no consumer rating program. 1) Crash test dummy included in the test but not included in the final rating.

Effects of legal requirements and consumer-rating programs

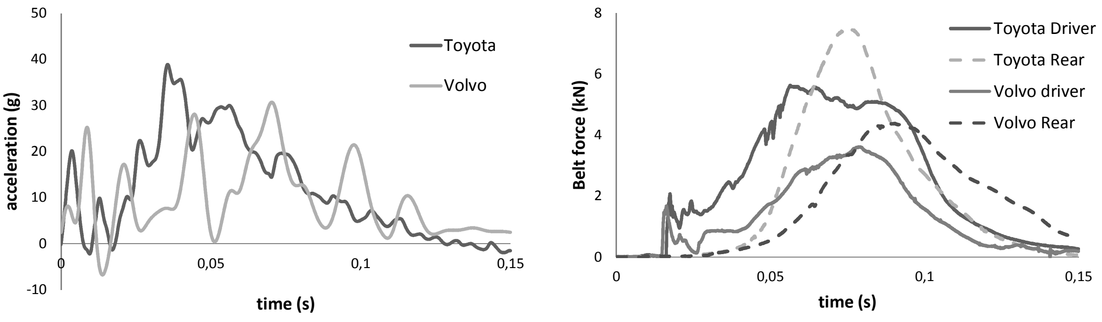
The rating programs and regulatory efforts have shown a positive effect in real life as high-rated vehicles in NCAP programs have had decreased fatality rates for front seat occupants in both frontal and side impacts (Loftis et al. 2011b; Kullgren et al. 2010a). In Europe, a typical 5-star rated vehicle has a wide range of safety features (Table 3). Since the rating programs primarily focus on front-seat safety, benefits to the rear seat have not been seen to the same extent.

Table 3 Overview of standard safety equipment in a typical 5-star-rated vehicle, showed for front and rear seat, respectively.

	Front seat	Rear seat
Seat belt pretensioner	x	
Seat belt load limiter	x	
Frontal airbags	x	
Side airbag (chest)	x	
Side airbag (head)	x	x
Whiplash protection	x	
Steering column	x	
ISOFIX		x
Reinforcement in car structure – side impacts	x	x
Deformable pedals	x	
Seat belt reminders	x	x
Height adjustable seat belts	x	

Historically, rear-seat occupants have had lower injury risks than front-seat occupants (Smith and Cummings 2004, 2006), but recent studies show new trends of rear seats being less safe than the front seat (Esfahani and Digges 2009; Kuppa et al. 2005). This has been attributed to the combination of increased crash pulse severities, (Locey et al. 2012; Swanson et al. 2003) due to stiffer vehicle bodies and poor belt loading management (Bilston et al. 2010; Kent et al. 2007). The stiffer vehicle bodies are a result of designs to reduce intrusion into the vehicle compartment for the front seat occupants. It is not known whether the injury risk for children has increased due to these changes based on real-life data but crash tests have shown higher loadings to rear-seated crash test dummies.

In crash tests the increased loading to the dummy due to increased severity of the crash is measureable. Folksam, Autoliv and Dagens Nyheter (DN 2009; Autoliv 2009) conducted a 40% offset crash test at 64 km/h between a small modern vehicle (Toyota Yaris, model year 2009) and a large older vehicle (Volvo 945, model year 1996), with mid-sized, adult, male crash test dummies (in both driver seats), and a 10-year-old child crash test dummy in the rear seats in each vehicle, restrained on a BPB. Frontal airbags, belt pretensioners and load limiters were activated in the front seat in both vehicles, but such systems were not present in the rear seat. These two vehicles offer the same restraint system to rear seat occupants, even though there is a 13-year difference between models. Deceleration in the small modern vehicle was much higher than in the older larger vehicle (Figure 3), resulting in limited intrusion to the front seat occupant. For the rear seat occupant, high deceleration resulted in almost twice as high a shoulder belt force, lap belt force, head acceleration and chest acceleration to the child dummy in the Toyota compared to the Volvo. Comparing the rear-seated child dummy and the front-seated midsized adult dummy in the Toyota Yaris revealed that the loading to the neck and chest, after normalizing the loading according to FMVSS 208 injury tolerance limits, was twice as high for the child dummy compared to the mid-sized adult dummy. Kuppa et al. (2005) and Tylko and Dalmotas (2005) found similar high loading to the 10-year-old rear-seated, child crash test dummy in crash tests with modern vehicles.



a) **b)**

Figure 3 a) Shows the crash pulse of the small modern vehicle (Toyota) compared to the large older vehicle (Volvo); b) Shows the shoulder belt forces to the driver and to rear seat occupant in the two vehicles (Autoliv 2009).

Generally, child safety has a relatively limited influence on consumer rating scores and is to a minor extent included in safety standards. In particular, the 4-12-year age group is not included at all in any current dynamic vehicle testing, neither in regulation nor consumer rating programs. Overall, these children are “forgotten“ in the legal process of evaluating vehicle safety (Bidez et al. 2007).

1.2 FUTURE GOALS FOR CHILD CAR SAFETY

In 2011, the Decade of Action for Road Safety 2011-2020 was initiated by WHO aiming to stabilize the trend of increasing road traffic injuries and prevent five million road traffic deaths by 2020 in both children and adults. It is based on the following five pillars of activities: road-safety management, safer roads and mobility, safer vehicles, safer road users and post-crash response. The first pillar, “Road-safety management” includes activities to implement road safety conventions. The pillar “Safer road and mobility” highlights the need to improve the road network, especially for vulnerable road users. The safer vehicles category includes improved vehicle safety and mechanisms to accelerate the uptake of new safety technologies as well as the implementation of consumer rating programs in order to inform consumers of the vehicle’s safety performance. Safer road users include activities such as encouraging development and adaption of road safety legislation and increasing public awareness and education of safety “issues”. The last pillar, “Post-Crash”, includes activities to improve the emergency treatment as well as long-term rehabilitation of crash victims (WHO 2011).

Since 2009 in Sweden, traffic injuries have been assessed in terms of the number of fatalities as well as the number of people with traffic injuries resulting in permanent impairment, as a step to fulfill the *Vision Zero* established by the Swedish Parliament in 1997. No one should be killed or seriously injured in the Swedish road transport system, the long term goal of *Vision Zero* (Tingvall 1998). In order to support this effort, the Swedish Transport Administration links traffic safety prevention goals not only to severe injuries reported by the police or injuries classified at higher AIS levels (AIS3-5) but also to impairment outcome. It has been stated that traffic injuries resulting in medical impairment should be reduced by 25% by 2020 (Vägverket 2008). Other nations have been inspired by the Swedish *Vision Zero,* for example, the Netherlands, France, Germany, Portugal and the United Kingdom.

In developing countries, the number of vehicles is increasing rapidly (WHO 2009c), resulting in a conversion of pedestrians and other vulnerable road users to motor vehicle occupants. As this conversion occurs, car safety for children needs to be further considered. Seat belt and CRS use are the basis of child safety in MVCs and, as stated before, their use is generally low in developing countries (Pan et al. 2012; Kulanthayan et al. 2010).

1.2.1 Gaps in child safety research: a summary

While some success has been achieved in reducing fatalities and severe injuries among children in motor vehicle crashes, this success should not lead to complacency. MVCs remain the leading cause of death and long-term consequences for children. However, usage, handling, comfort and function of child restraints need to be improved. This thesis focuses on restrained children (4-12) in the rear seat where complementing child restraint systems are needed. This age group is neglected in legal requirements and consumer rating programs. What is good safety design for adults may not be good safety design for children.

Long-term consequences, as a result of injuries from car crashes, deserve special focus to improve safety for restrained children. An impairing injury will affect the life of a child in many respects: education, social life, work and future economic situation as compared to an adult, who may already be halfway through their lifespan. There is a need to understand long-term consequences for children following injuries in MVCs. There may be other vehicle safety priorities that should be added to today’s priorities, which have been primarily based on the AIS and the reduction of AIS3+ injuries.

To reduce the risk of injuries to restrained children in car crashes, a fundamental step is to ensure that the child is properly restrained. The benefits of belt positioning booster seats as well as their associated misuses have been identified years ago (Durbin et al. 2003). Misuse increases the risk of head injury. Still, the misuse rate of BPBs remains constant (Hummel et al. 2008). Simply having children restrained is not enough; they must also be correctly restrained. Scientific studies need to be undertaken to understand the nature of these misuses as a basis for interventions – for example, educational and/or design-based – to be implemented to reduce these errors.

Furthermore, head injuries are a well-documented problem in MVCs among children. In side impacts, the injury causation scenarios and built-in vehicle countermeasures have been identified (Maltese et al. 2007; Andersson et al. 2012; Bohman et al. 2009). However, head injuries still occur in frontal crashes with seat-belt-restrained children, and thus far standardized vehicle tests in the laboratory have failed to reproduce the problem. This discrepancy warrants attention.

By filling these gaps with data-based knowledge, vehicle safety for rear-seated children restrained by seat belts can be further improved.

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2 AIM

The overall aim of this thesis was to obtain comprehensive knowledge of the real life situation of restrained forward-facing, rear-seated children aged 4-12 in frontal car crashes as a basis for crash safety improvements to reduce long-term consequences.

The specific aims were to:

- Specify the pattern and calculate the risk of permanent medical impairment for children injured in motor vehicle crashes, for different body regions and injury severity levels, through study of injury and crash data (Paper I). Furthermore, impairment outcomes were compared between children and adults.
- Assess the potential misuse of two belt positioning booster designs, vehicle built-in and aftermarket belt-positioning boosters, by conducting experimental studies of children using the restraints (Paper II).
- Identify the injury causation scenarios of restrained, rear-seated children with moderate or more severe (AIS2+) head injuries in frontal impacts including contributing factors to injury, through in-depth studies of such cases (Paper III).
- Study the influence of pre-crash swerving maneuvers on properly restrained children with special reference to their kinematics and shoulder belt position, through controlled human volunteer driving studies (Paper IV).

3 SUMMARY OF PAPERS

This thesis is based on findings from four studies, described below (see overview in Table 4). The unifying theme of the four studies is rear-seated, forward-facing children aged 4-12 in frontal impacts in cars.

Table 4 Overview of the four studies included in the thesis.

	Study I	Study II	Study III	Study IV
Aim	Specify the pattern and calculate the risk of permanent medical impairment in the event of injury	Assess potential misuse in two different belt positioning booster designs	Identify head injury causation scenarios of restrained children	Study the influence of pre-crash steering maneuvers on child kinematics
Study design	Cohort study	Experimental study	Cohort study	Experimental study
Data	Claim files (Folksam), hospital files, police reports	Observations, structured interviews	In-depth crash cases (NASS-CDS, CIREN)	Video films, vehicle data
Country	Sweden	Sweden	US	Sweden
Number of cases	2619	130	27	16
Age range (years)	0-12	4-12	3-13	4-10
Injuries	Permanent medical impairment (AIS1+), no fatalities	None	AIS2+ head injuries, including fatalities	None
Crash directions	All	-	Frontal	Frontal with pre-crash maneuver
Time period	1998-2010	2007	1996-2008	2010

3.1 PAPER I

In the event of injury the aim of the study was to specify the pattern and risks of injuries resulting in permanent medical impairment among children (0-12) for different body regions and injury severity levels, according to the Abbreviated Injury Scale (AIS).

3.1.1 Method

All car crashes reported to one of the largest insurance companies in Sweden, Folksam, from 1998 to 2010, where at least one child 0-12 years old was injured, were selected. The dataset included 2,070 collisions with 2,619 injured children, which together consisted of 3,704 reported injury diagnoses.

Acute Injury Diagnosis Coding

The children’s injury data was obtained from medical files and/or claim files. All initial diagnoses, including self-reported minor injuries, were classified according to AIS-2005 by a group of five highly experienced AIS-trained persons. Results were presented in groups according to the eleven body regions of AIS-2005, with the exception of “External (Skin) and Thermal Injuries”, which included all lacerations, contusions, abrasions and burns, regardless of location. For all injuries except minor injuries, medical files were collected and stored in the claim files by Folksam.

Permanent Medical Impairment Assessment

One year after injury, Folksam contacted the parents of the injured children to assess their recovery from the injury. If the injured child had not recovered from the injury within 12 months, the injury was assessed by medical specialists according to the guidelines of “Grading Medical Impairment”, used by all Swedish insurance companies (Sveriges Försäkringsförbund 2004). In this process, the injury was given a degree of permanent medical impairment (PMI) between 1% and 99%.

Vehicle occupant and vehicle-related data

Information on restraint use and seating position was most often provided by parents to the doctors or the insurance company. In many cases, this information was missing in the data.

In order to compare child data with adult data, results from a previous study (Malm et al. 2008) were used. Data regarding adults was obtained from the same database as that used for the pediatric data and included 20,848 injured occupants aged 18 or older at the time of the crash and who had initially reported injuries.

3.1.2 Results

Table 5 shows the number of initially reported injuries and those injuries leading to permanent medical impairment, respectively. In all, 80% of initially reported injuries were AIS1 and AIS2 injuries, and the majority were to the body regions “neck” or “External skin and thermal injuries”, while the majority (75%) of the injuries resulting in PMI were to the head and neck. 68% of all injuries resulting in PMI were at an AIS1 level and the neck was the most commonly injured body region at this AIS level. These injuries were all acute neck strain. AIS3+ injuries comprised 1.3% of the reported injuries, with 17% of the injuries leading to PMI, the majority of which were injuries to the head.

In the event of an acute AIS1 injury to the head, the risk of injury resulting in PMI to the head was 3% (95% confidence interval [CI]; 0-10%). Among the reported AIS1 neck injuries, approximately 3% (CI; 2-4%) resulted in permanent medical impairment. For acute injury, there was a 1% risk (CI; 0-4%) of PMI for AIS1 injuries to the thoracic and lumbar spine. Two of ten AIS3 injuries to the lower extremities and pelvis resulted in PMI. One of 23 abdominal injuries (AIS2) resulted in PMI. None of the 40 reported thorax injuries resulted in PMI. Also, 10 of 59 injuries leading to PMIs were of a PMI severity level of 10% or more; 9/10 were AIS3+ head injuries.

Table 5 Number of injuries leading to permanent medical impairment (PMI) and initial injuries (in parentheses) stratified by body region and Abbreviated Injury Scale (AIS) levels. Combinations of body region and AIS level that do not exist in the coding manual are marked as not applicable (n.a.).

Body region	AIS1		AIS2		AIS3		AIS4		AIS5		Total	
	PMI	Initial	PMI	Initial	PMI	Initial	PMI	Initial	PMI	Initial	PMI	Initial
Head	2	(69)	1	(28)	2	(12)	4	(7)	3	(3)	12	(119)
Cervical spine	31	(1223)	0	(4)	1	(1)	0	(0)	0	(0)	32	(1228)
Face	1	(53)	1	(12)	0	(1)	0	(0)	n.a.	n.a.	2	(66)
Upper extremity	0	(19)	3	(28)	0	(1)	0	(0)	n.a.	n.a.	3	(48)
Lower extremity and pelvis	1	(10)	0	(26)	2	(10)	0	(0)	0	(0)	3	(46)
Thorax	0	(8)	0	(17)	0	(15)	0	(0)	0	(0)	0	(40)
Thoracic spine	2	(199)	0	(1)	0	(0)	0	(0)	0	(0)	2	(200)
Abdomen	0	(0)	1	(23)	0	(4)	0	(5)	0	(0)	1	(32)
Lumbar spine	2	(168)	0	(1)	1	(1)	0	(0)	0	(0)	3	(170)
External (skin) and thermal injuries	1	(1747)	0	(8)	0	(0)	0	(0)	0	(0)	1	(1755)
Total	40	(3496)	6	(148)	6	(45)	4	(12)	3	(3)	59	(3704)

Comparing the proportion of injuries resulting in PMI from different body regions for adults and children shows that the head and neck were the most commonly impaired body regions in children (Table 6), while the neck was the primary injured body region among adults (Malm 2008). Few injuries to the abdomen and thorax resulted in PMI for both children and adults.

Table 6 Proportion of injuries leading to permanent medical impairment per body region, for children and adults, respectively.

	Children 0-12 years	Adults *
Head	19%	4%
Cervical Spine	57%	66%
Face	5%	1%
Upper extremities	3%	6%
Lower extremities and pelvis	5%	7%
Thorax	0%	1%
Thoracic spine	3%	4%
Abdomen	3%	0%
Lumbar spine	5%	6%
External (Skin) and thermal injuries	0%	5%

* The data for adults, according to the study by Malm et al. 2008.

Of all impact directions, side impacts resulted in the highest frequency of injuries resulting in PMI to the head, but the difference between crash directions was not statistically significant. AIS1 neck injuries and those leading to PMI, occurred in all crash directions with the highest frequency occurring in frontal and rear-end impacts.

In conclusion, the majority of those injuries leading to PMI were at lower AIS levels. AIS1 neck and AIS1+ head injuries should thus be given priority to prevent and reduce long-term consequences for children.

3.2 PAPER II

The aim was to assess potential misuse of belt positioning booster cushions in an experimental study, and to identify whether booster cushion design, age or clothing had any effect on the extent of misuse.

3.2.1 Method

An experimental study of 130 children took place at the entrance hall of a Science Park in Sweden. Two concepts of belt positioning boosters were evaluated; one integrated booster cushion (IBC) and one aftermarket belt positioning booster (BPB). The cushions were placed on the right rear seat of a Volvo V70 (2004).

Test subjects were children aged 4-12 with prior experience of booster cushions. Some of the younger children did not normally fasten the seat belts themselves, but they were included in the study to observe if the difference in design of the two tested cushions had any effect on misuse by first time users. Each child tested both the IBC and the aftermarket BPB. In addition, children aged 8 to 12 also buckled up without the use of a booster.

Data collection included interviews, observations, photographs, buckling up time, belt slack, stature and sitting height. The structured interviews included questions on type of restraint used, frequency of usage, travelling frequency in cars, and age/sex of the child.

Either IBC or BPB was tested first, at random. Buckling up with the SB was always performed at the end of the session. Observations were made to determine if misuse occurred, and if so, the type of misuse. Severe misuse included shoulder belt incorrectly positioned behind the back, shoulder belt incorrectly positioned under the arm, excessive slack in shoulder or lap belt, and lap belt above one or two guiding loops. Minor misuse included; twisted belts and shoulder belts above the guiding loop (leading to the belt being too close to the neck of short children).

3.2.2 Results

For those 9 years or older, more than 50% always used seat belts. For those 6 years and older, most children buckled up themselves.

Misuse occurred in 4% of the children buckled up on the IBC compared to 77% on the BPB. In the majority of cases at least one severe case of misuse was reported (Figure 4). ‘Placement of the lap belt above one or both guiding loops’ and ‘the shoulder belt above guiding loops’ were the most common types of misuse for BPB. When the children between 8 and 12 years of age used only the seat belt no misuse occurred. None of the younger children (4-6) buckled up correctly on a BPB, however, there were no statistical differences in the frequency of belt routing errors in the younger and older age groups seated on the BPB.

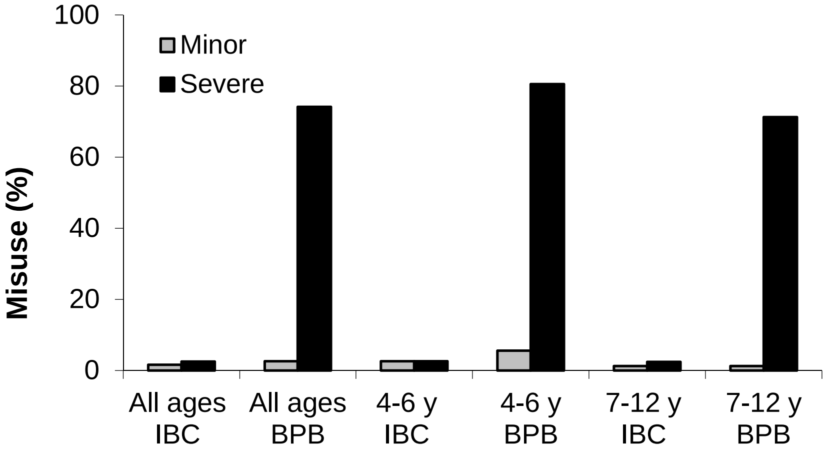


Figure 4 Minor and severe misuse when buckling up on IBC and BPB respectively, shown for all children aged 4-12 years and for two different age groups, among children in an experimental study in a car.

There was about half the slack in the shoulder belt compared to the lap belt for the IBC and SB. When restrained on the BPB, there was approximately the same amount of slack in both the shoulder and lap belts. There was on average twice as much slack in the lap belt for the children with winter jackets compared to those without.

Buckling time was significantly longer for BPB than for IBC. The younger children (4-6) needed more time to buckle up compared to the older children. When buckling up with the IBC and SB there was only a small difference in time for the older children.

In general, the younger children (4-6) found the BPB difficult to use. Most children found the IBC easy to use, especially children older than 7 years of age. 40% of the 130 children preferred the IBC, followed by 30% preferring SB only, 21% the BPB and 9% thought the IBC and BPB were equally good. From about 8 years of age, the children favored only a seat belt.

In conclusion, with the limited usage details provided to the children, a booster cushion integrated in the vehicle resulted in a misuse level of 4% compared to 77% for an aftermarket belt positioning booster.

3.3 PAPER III

The aim was to investigate the AIS2+ head injury causation scenarios for rear-seated, seat belt restrained children (3-13) in frontal impacts.

3.3.1 Method

Extensive crash investigations of cases were analyzed from two NHTSA databases: the Crash Injury Research and Engineering Network (CIREN) 1996-2008 and the

National Automotive Sampling System Crashworthiness Data System (NASS-CDS) 1997-2008. The inclusion criteria were frontal impacts including PDOF (principal direction of force) of 11, 12 and 1 o'clock, and rear-seated, three-point belt-restrained children (with or without a BPB) 3-13 years old with an AIS2+ head injury. Cases with an unknown injury source, those with misuse of the seat belt, and multiple impacts in which the head injury source could not be attributed to the frontal impact, were excluded.

In this study, 27 cases were analyzed and the AIS2+ head injuries were coded using the CIREN BioTab method developed by Schneider et al. (2011). The BioTab approach to analyzing occupant injuries in a crash allows the researcher to attribute one or more injury causation scenarios (ICS) to each injury. Each ICS includes all the factors that the researcher believes essential to the occurrence of the injury. Such factors are delta-velocity (DV), PDOF, occupant initial position, restraint system, restraint geometry, vehicle maneuvers prior to impact, evidence of contact points, and minor injuries to the case occupant confirming contact. Each ICS includes “involved physical components” (structures external to the occupant) representing those structures that contacted occupants, e.g. vehicle interior, other occupants, or the restraint system. Hereafter, the involved physical component is described as the contact source.

As part of the analysis for this study, an experienced crash investigator, blinded to the injury outcome in the case, re-analyzed the PDOF by simulating each case using PC-crash (version 8.1, Dr Steffan Datentechnik, Linz, Austria). The influence of the PDOF and maneuvers prior to impact on the occupant kinematics were identified and recorded.

3.3.2 Results

Expected kinematics of the occupant with respect to the PDOF and seating position resulted in 41% of the case occupants moving outboard (towards the door/window of the vehicle) from their initial seating position, 26% inboard (towards the middle of the vehicle), and 30% straight ahead.

In 70% of the cases, there were maneuvers and/or small crash events occurring prior the main frontal impact. The maneuvers may have caused the occupants to move from their initial position depending on the seating position relative to the maneuver.

There were 19 cases with MAIS2 head injuries and 8 cases with MAIS3+ head injuries, including two fatalities. Overall, there were 80 AIS2+ injuries to all body regions, and 34 were to the head. Thorax, abdomen and upper extremities were other commonly AIS2+ injured body regions. The most severe head injuries (AIS3+) included diffuse axonal injuries, subdural hematoma, subarachnoid hemorrhage and cerebrum contusion. These case occupants had typically more than one injury to the head. A majority of the AIS2 head injuries were consciousness-related, which was typically the only head injury.

Three main injury causation scenarios were identified in the 27 cases including head contact with seat back in front of the rear-seated occupant (10 cases), head contact with side interior (7 cases), and 9 cases with no evidence of head contact. There was a single case in which the head injury was due to head contact with loose objects in the vehicle (Table 7).

Table 7 An overview of cases of restrained children who had been in car accidents leading to head injuries, showing the contact source, age, maximum Abbreviated Injury Scale (MAIS) score for the head, principal direction of force (PDOF), occupant kinematics due to steering maneuver (inboard or outboard) and braking.

Contact source	Age (years)	MAIS head	PDOF	Maneuver	Braking
Seat back	9	2	i	i	b
Seat back	10	2	i	i	
Seat back	7	2		i	
Seat back	7	2	i		b
Seat back	7	2	o		
Seat back	8	2	o	o	
Seat back	8	2	o	o	
Seat back	7	5	i	i	
Seat back	12	5	i		b
Seat back	11	5		i	
Side interior	9	2	o	o	
Side interior	11	2	o	o	
Side interior	11	2	o	o	
Side interior	10	2	o		b
Side interior	7	2	o	i	
Side interior	4	2	o		
Side interior	13	3	o	o	
No evidence of contact	13	2		i	b
No evidence of contact	10	2			
No evidence of contact	3	2			b
No evidence of contact	8	2			b
No evidence of contact	9	2	i		
No evidence of contact	11	3	o		
No evidence of contact	4	4	o		b
No evidence of contact	4	4			
No evidence of contact	11	5	i		
Object	5	2			

i=inboard motion, o=outboard motion, b=braking present.

In 5 of 10 seat back contacts, a combination of pre-crash maneuvers and the specific crash direction influenced the occupant to move inboard enabling torso rollout of the shoulder belt. Five of the cases were accompanied by severe injuries to other body regions (AIS3+), most commonly the thorax and spine.

In this study, the definition “side interior contact” included contact to side window, window sill, door/side interior and pillar. In all side-interior contacts (7 cases), the PDOF, and in most cases also the pre-crash maneuvers, influenced the occupant to move laterally towards the side interior. None of the cases had severe injuries to body regions other than the head. In one case the occupant had an AIS3 head injury; in the other cases occupants had AIS2 head injuries.

Cases were deemed as “no evidence of head contact” if there were 1) no skull or facial fractures, 2) no minor injuries such as contusions or abrasions to the head or face, and 3) no physical evidence of head/face contact. The average delta-velocity of these 9 cases was 54 km/h. Five cases were accompanied by severe injuries to the chest and/or spine (AIS3+).

In conclusion, three injury causation scenarios were identified in head injuries to restrained rear seat occupants including contact with the seat back in front, contact with the side interior or no evidence of any head contact. In these scenarios, maneuvers prior to impact, angled principal direction of force or high crash severity were recognized as contributing factors.

3.4 PAPER IV

The aim was to study the influence of pre-crash swerving maneuvers on properly restrained children with special reference to their kinematics and shoulder belt position.

3.4.1 Method

A study was conducted with 16 children aged 4-10, restrained in the right rear seat of a modern passenger vehicle and tested on a closed circuit test track. The children were divided equally into two groups, one group of short children (105 – 125 cm) and one group of tall children (135 – 150 cm). The short children were tested in two different restraints: belt positioning booster, and high-back belt positioning booster. The tall children were also tested in two different restraints: belt positioning booster, and directly on the vehicle seat. All test subjects were restrained by the seat belt included as standard equipment in the test vehicle. A professional driving instructor drove the test vehicle at 50 km/h, repeatedly making sharp turns to the right, resulting in inboard motion of the children. The children were exposed to two steering maneuvers in each of the two restraint systems. Four video cameras were fitted inside the vehicle monitoring the child and relevant vehicle data was also collected. The time of a lateral acceleration of 0.2g was used to synchronize all lateral acceleration pulses.

The child’s posture and shoulder belt position were determined at each of the three designated times (T1, T2, and T3) based on recorded video frames. T1 was defined as the time for the reference position of the child in each trial just before the maneuver had begun. T2 was defined as 0.2 seconds (s) after the synchronization time point, i.e. 0.2s after a lateral acceleration of 0.2g, with the purpose of studying the children after they had begun to move laterally, and during the ramping at lateral acceleration. T3 was defined as the time at the end of initial ramping in lateral acceleration, which occurred 0.3s after T2. The following assessments were made for each child in each trial for the three defined time points: shoulder belt position on the shoulder, child’s lateral position in relation to the seat, and the angle of the child’s torso relative to the center of the seat. These measurements were used for determining the child's kinematics. The shoulder belt position on the abdomen was divided into three categories: low, middle and high.

3.4.2 Results

The children moved approximately 10 cm laterally during the steering maneuver, for all heights and restraint systems. Depending on the initial seated posture and size of the child, this resulted in different shoulder belt positions. The shoulder belt slipped off the shoulder in two-thirds of the trials for the short children restrained by a belt positioning booster. The shoulder belt was kept on the shoulder when the short children were restrained by a high-back booster seat, but half the trials resulted in the shoulder belt being positioned far out on the shoulder. The short children supported themselves in 17 of 30 of the trials by holding on to the guiding loops of the BPB.

For the tall children, no belt slip off occurred. In the tall group, the distance the shoulder belt moved in relation to the shoulder was the same, regardless of restraint system. However, the initial position of the shoulder belt was closer to the neck when the tall children were restrained by only the seat belt. Tall children seated on a belt positioning booster experienced a shoulder belt position far out on the shoulder during the turn. The tall children supported themselves in only 3 of 24 trials by holding on to the guiding loops of the BPB.

The shoulder belt position on the abdomen did not vary during maneuvers. The short children had a low shoulder belt position on the abdomen in 28 of 30 trials. The tall children, on the other hand, had a high position in 10 of 24 trials and a low position in 12 of 24 trials.

In conclusion, maneuvers prior to impact may position children in a non-optimal inboard position with the shoulder belt far out on the shoulder or completely off.

4 GENERAL DISCUSSION

In developed countries, child fatalities and injuries in motor vehicle crashes (MVCs) have decreased over the years due to improved vehicle safety, increased child restraint usage, increased information to parents and improved road designs. However, the priority to improve child safety remains.

In forming the background of this thesis, specific research areas were identified as important in reducing the burden of injury. The focus of this thesis was to provide knowledge to improve child safety in vehicles when restraint systems are used. Misuse, injuries leading to long-term consequences, and better understanding injury-causing scenarios with restrained children in car crashes, were highlighted as research areas of priority.

Study I highlighted the importance of looking beyond the moderate and severe injuries (AIS2+) and also consider injuries resulting in long-term consequences for children. Head and neck injuries with permanent impairment were identified as priorities in child safety to reduce the burden of trauma to children injured in motor vehicle crashes.

Belt positioning boosters (BPB) are a common safety feature for older children (4-10). Information campaigns and law enforcement have increased the use of belt positioning boosters without reducing the potential for misuse. Study II demonstrated the potential of misuse reduction by integrating the booster cushions into the vehicle.

The greatest proportion of injuries and fatalities to children occur in frontal impacts. Furthermore, head trauma accounts for the most severe injuries in the short-term as well as in the long-term. Study III presented new information on how restrained children sustain head injuries in frontal impacts, by identifying three injury causation scenarios and contributing factors.

In Study IV, steering maneuvers, a key contributing factor for head injuries in frontal collisions due to seat back contact, were further investigated. Unstable restraint situations for children exposed to the steering maneuvers were identified.

The knowledge gained in this thesis is based on data from developed countries, but can be directly applied to developing countries, which can learn and accelerate their advancement towards improved child safety in cars. This thesis addresses activities in 2 of the 5 pillars identified by WHO (2011) in the Decade of Action for Road Safety, namely safer vehicles and safer road users, in terms of child injury prevention and implementation of child safety.

4.1 INJURIES WITH LONG-TERM CONSEQUENCES

Study I showed two major findings: the head and neck were the most vulnerable body regions, and the majority of injuries resulting in permanent medical impairment were at AIS1 or AIS2 levels.

An early study by Tingvall (1987) used Folksam insurance data (1976-1980) to study injured children (0-14) in car crashes. In the event of injury, 4 of 653 children had sustained impairment of 10% or more. In Study I of this thesis, 10 of 2619 children had an injury resulting in a PMI of 10% or more. Several confounding factors may have influenced the risk of impairment as a result of injury, and there is no clear evidence. Improved treatment by ambulance triage as well as rehabilitation over the years may have reduced the risk of injuries resulting in PMI.

4.1.1 Neck injuries

Acute severe injuries to the spine are rare in motor vehicle crashes (Kuppa 2005), but are associated with a high mortality rate and a high risk of long-term consequences (Platzer et al. 2007). There has been limited focus on AIS1 neck injuries to children, since traditional epidemiology studies focus on acute injuries at an AIS2+ level. Research on adults with AIS1 neck injuries (often referred to as Whiplash Associated Disorder (WAD) in the literature) has been conducted for decades, since about 16% of all AIS1 neck injuries among adults result in long-term consequences (Malm et al. 2008). Countermeasures to reduce the incidence of AIS1 neck injuries for adults have been successfully developed (Kullgren and Krafft 2010b). Conversely, there has been limited focus on AIS1 neck injuries for passengers in the rear seat, and for children in particular. However, a few studies (Agran et al. 1987; Boyd et al. 2002; Hadfield et al. 1998) reported that children (0-16) may also sustain AIS1 neck injuries with persisting symptoms for at least some months. Tingvall (1987) never highlighted AIS1 neck injuries as a problem 25 years ago, since that study only included injuries resulting in PMI of 10% or more. At that time, WAD in adults was already acknowledged.

In Study I, almost all children with AIS1 neck injuries resulting in PMI were six years or older, which was in line with previous studies (Agran et al. 1987; Boyd et al. 2002). This age dependency suggests anatomic differences contributing to the injury resulting in PMI, or that results were influenced by younger children’s ability to express the pain associated with WAD compared to older children.

The Task Force of Neck Pain and Its Associated Disorders reviewed 1203 scientific papers and identified specific deficiencies in the current literature. WAD in children was identified as one of the primary research areas warranting attention, including epidemiology, risk of WAD, screening criteria, risk factors and preventive measures (Carroll et al. 2009). Study I confirmed these priorities by identifying AIS1 neck injuries resulting in PMI as a new priority in vehicle safety for children.

4.1.2 Head injuries

The majority (82%) of AIS3+ injuries resulting in PMI were head injuries. Also, most injuries leading to severe impairment were head injuries. Previous research has shown that traumatic brain injury often results in persistent neurological problems.

This thesis has revealed that head injuries leading to PMI also occurred at AIS1 levels. AIS1 injuries to the head, consisting of many MTBIs, implied a 3% risk of PMI (Study I), excluding all external skin and thermal injuries to the head. Barlow et al. (2010) showed that 11% of children 3 months after MTBI had post-concussion syndrome, which resulted in poorer performance at school for months, and 1 year after the injury 2% still suffered from post-concussion syndrome. In other trauma research areas, MTBI in children has been found to be underreported (Meridith 2012), thus suggesting that these are conservative estimates.

Study I also showed that children had a higher proportion of long-term injuries to the head (19%) in relation to other body regions, compared to adults (4%). When comparing the distribution of moderate to severe injuries (AIS2+ and AIS3+) to rear-seated children and adults, the most common injury sustained by children (0-15 years) was to the head, while the primary injured body region for adults was the thorax (Kuppa et al. 2005).

Therefore, in line with other studies (Tingvall 1987; Arbogast et al. 2004; Durbin et al.2003; Howard et al. 2004), Study I identified the head as the body region to be given highest priority in terms of most severe injuries, both acutely and in the context of injuries resulting in PMI. However, the entire spectrum of head injury severity needs to be included, since injuries resulting in PMI were found at all AIS levels.

4.1.3 Other body regions

In Study I, none of the thoracic injuries resulted in PMI. Among children and adolescents, lung contusion and pneumothorax are common thoracic injuries, while rib fractures occur infrequently (Arbogast et al. 2012a). Children (0-17) generally show good recovery from lung contusions and long-term consequences are rare (Haxhija et al. 2004).

In study I, only 1 of 31 (3%) abdominal injuries resulted in PMI. Due to the low number of injuries, the risk of PMI as a result of an injury could not be determined at various AIS levels for this body region. In the literature, children’s abdominal injuries have a good prognosis if the acute injury is treated properly (Gaines and Ford 2002).

The majority of the initial AIS1 injuries to the lumbar and thoracic spine were strain rarely resulting in PMI. A larger dataset is needed to draw any further conclusions as to the risk of PMI to the lumbar and thoracic spine at other AIS injury levels. More severe (AIS4+) injuries to the cervical, thoracic and lumbar spine virtually always result in PMI.

Comparing children with adults, it was seen that both adults and children have a low risk of PMI due to abdominal and thoracic injuries. Adults had a 35% to 50% risk of PMI as result of AIS2+ injuries to the upper and lower extremities. In contrast, few injuries to the extremities resulted in PMI in the children. Similar differences between adults and children were seen in the lumbar and thoracic spine.

Overall, there were few injuries to other body regions, besides the neck and head, resulting in PMI in children.

The proportions of injuries resulting in PMI per body region differs between children and adults, and needs to be considered when developing safety in the rear seat, since all sizes of occupants should be protected.

4.2 CHILD OCCUPANTS IN VEHICLES

Regulatory and consumer rating testing are designed to represent severe real-life crashes. Crash dummies are to be properly restrained and positioned according to the crash protocols, centered in the seat, with their backs in contact entirely against the seat back. The crash dummy is to be correctly restrained by proper belt routing and snug seat belt fit. During the ride towards the barrier, the dummy stays in position.

In a real-life situation, there may be misuse of the restraint and belt slack as a result of clothing layers, and the child self-donning the seat belt (Study II) (Figure 5). During riding, the child may be in a user-selected position that differs from a crash test dummy's pre-crash position (Bohman et al. 2010; Andersson et al. 2010; Charlton et al. 2010; Jakobsson et al. 2011). Activities, e.g. playing with electronic devices, may influence the child to a more forward leaning position compared to a crash test dummy (Osvalder et al. 2013). There may be pre-crash events such as braking and steering putting the child in non-optimal restraint situations (Study IV, Stockman et al. 2013). The real-life restraint situations can, and most likely do, differ significantly from the proper and well-defined crash positions of the crash test dummy's situation in the laboratory environment (Bohman et al. 2010).

Figure 5 An example of a real-life position and posture of a restrained child from Study II.

4.2.1 Misuse

Belt positioning boosters are often misused (O'Neil et al. 2009). Such misuse may reduce the safety benefit and therefore contribute to injury or even fatality (Gotschall et al.1997; Skjerven-Martinsen et al. 2011; Bilston et al. 2007b). Study III showed the importance of minimizing the risk of head contact in frontal collisions. Therefore, misuse conditions contributing to increased head excursion deserve special attention. Study II showed increased belt slack, which may have resulted in a higher risk of head injury as a result of larger head excursion. Study II showed that many children (39%) forgot to put the shoulder belt under the guiding loop, resulting in the shoulder belt being close to the neck. This is not severe misuse, but reduced comfort, due to chafing of the neck, and may result in the child putting the belt behind the back or under the arm. In an observational study (O'Neil et al. 2009), shoulder belt behind the back or under the arm was seen in 19% of all children restrained on BPB. This makes the torso restraint ineffective and increases the risk of the head impacting the vehicle interior (Bilston et al. 2007b).

Laws and law enforcement have proven beneficial in increasing the use of CRS including belt-positioning boosters, but have not reduced the problem of misuse (Koppel et al. 2013; APSI 2011). Information campaigns have been frequently launched in different countries. However, misuse of belt-positioning boosters remained at the same levels for decades (Hummel et al. 2008). The need for information is continual with new generations of parents in need of instruction.

Positive long-term effects of information campaigns have been shown, but also questioned (Ebel et al. 2003; O’Neill et al. 2002). The optimal solution would be the elimination of the need for such detailed information by intuitive handling when restraining children in vehicles.

The development of BPB has recently focused extensively on side impact protection. Comparing booster design from the 1980s to a BPB of a recent model, the side head and thorax supports are more pronounced. The design of the seat cushion and the principle of guiding loops, however, has remained the same resulting in consistent problems with belt routing under the guiding loops. Belt routing under the guiding loops is needed to ensure that the BPB is attached to the vehicle to guide the lap belt into the correct position over the child’s thigh, while avoiding loading to the abdomen. However, the guiding loops are also a major source of misuse, as is incorrect lap and shoulder belt routing, which contributes to excessive belt slack.

In Study II, two different designs were compared, the integrated booster cushion and an aftermarket belt-positioning booster. The conventional aftermarket BPB had a misuse level of 77%, which is higher than on-road observational studies, which vary between 40-65% (Willis et al. 2006; O’Neil et al. 2009). This difference is probably explained by the fact that children donned the belt themselves with no adults present to correct belt routing. However, an integrated booster cushion in the vehicle resulted in a misuse level of only 4%, without any specific training to the children in correct handling. Intuitive handling eliminated major misuse issues with belt routing of the guiding loops. No other study has documented such a decrease in misuse.

Misuse may not only occur during handling (Study II), but it may also occur during actual usage during drive. The child may reach for something and not correct the shoulder belt afterwards (Andersson et al. 2010). Comfort issues, such as the belt chafing the neck, may result in the child removing the belt from the shoulder (Jakobsson et al. 2011). Both aspects need to be considered to keep the misuse of BPB at a minimum.

4.2.2 Head injury causation in frontal impacts

Being of the utmost priority it is important to understand how restrained children sustain head injuries so that restraints can be further optimized to reduce these injuries. In the retrospective in-depth case study (Study III) of restrained children (4-12) sustaining AIS2+ head injuries in frontal impacts, three injury causation scenarios were identified including head contact with the seat back in front of the occupant, head contact with side interior, and no evidence of head contact. Arbogast et al. (2012b) also identified head contact with the seat back in front of the occupant and B-pillar contact as the majority of contact points to restrained, rear-seated children (0-15) with AIS2+ head injuries. In Study III, there was a single case in which the head injury was due to head contact with an unstrapped object. Skjerven-Martinsen et al. (2011) identified loose objects as contributing to severe injuries or fatalities in children (0-15) in a Norwegian study.

No evidence of head contact

The concept of AIS2+ head injuries occurring without contact to the head has been greatly debated, although many of the discussions have been based on adult data analyses (Yoganandan et al. 2010; Yoganandan et al. 2009; Margulies et al. 1990). However, based on the following information, it was concluded that injuries showing no evidence of contact was an important subset of the cases in Study III. The case occupants without evidence of head contact were well restrained by the seatbelt, supported by documented contusions to the neck, torso, and abdomen due to webbing loading, but no minor injuries, such as contusions, abrasions or lacerations to the head or face. Also, associated injuries to the thorax, spine, and shoulder were indicative of seat-belt loading. Several head injuries without evidence of head contact could be associated with injury mechanisms such as neck tension and neck flexion/tension injury, contributing to the hypothesis of no head contact.

Furthermore, these cases of injured children without evidence of head contact were also characterized by such high crash severity that their injuries could have been solely due to high head deceleration.

The findings suggest that increased energy management (e.g. belt pretensioners and load limiters) is needed for the rear seat.

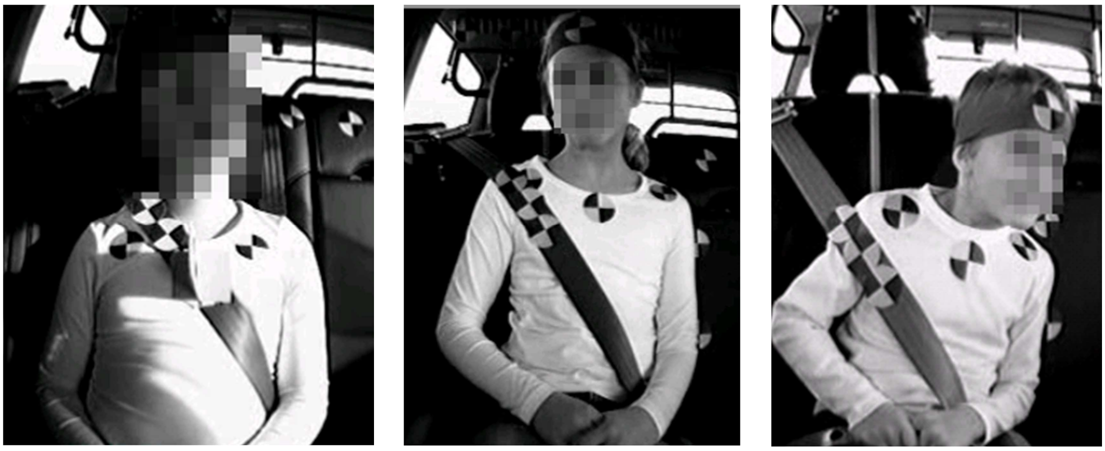
Occupant kinematics prior to and during impact

In study III, the majority of cases of head injury had a PDOF of 10° or 20°, thus influencing occupant kinematics either inboard or outboard of the vehicle to some extent. In addition, in a majority of cases with head contact, maneuvers were common before impact. These events were estimated to have an influence on the child’s position prior to impact. An inboard motion causes a suboptimal position of the belt further out on the shoulder. Such positions lead to the child being poorly restrained during the steering maneuver, causing an increased risk of rolling out of the shoulder belt on impact. Bidez and Syson (2001) also identified torso rollout in oblique frontal crashes, with seat-belt-restrained child crash test dummies in the rear seat.

Study III further documented that 6 of 7 case occupants with head injuries due to contact with the side interior sustained injuries of an AIS2 level, while one case had an AIS3 injury. The force associated with lateral contact was probably limited whereby most head velocity was characterized by a frontal component. Crash tests of small overlap crashes have demonstrated lateral or oblique movement of the front seat occupant (Boström and Kruse 2011), similar to what is suggested having occurred in rear-seat cases reviewed in Study III. These findings suggest side impact protection is needed in frontal impacts as well.

4.2.3 Children in vehicle maneuvers

Study III identified steering maneuvers as a contributing factor to head injuries due to seat back contact, since an inboard motion of the occupant may place the shoulder belt further out on the shoulder, resulting in suboptimal restraint of the torso. The results of Study IV, which utilized controlled steering maneuvers with properly restrained child volunteers in the rear seat, showed unstable restraint to the child (Figure 6).



a) **b)** **c)**

Figure 6 Occupant kinematics during steering maneuvers. a) Shows the shoulder belt remaining on the shoulder, b) Shows the shoulder belt far out on the shoulder, and c) shows the shoulder belt off the shoulder (From Study IV).

The short children were more prone to sliding out of the belt immediately due to the fact that their stature resulted in shoulder belts having a lesser “grabbing” effect on the shoulder compared to the tall children. There was also a difference in how the shoulder belt surrounded the lower torso and abdomen, depending on the age of the child and restraint system. The children had the lower shoulder belt on the lower abdomen in most trials, while the tall children often had a high shoulder belt position on the abdomen when restrained only by the seat belt (Figure 6a), and the high abdominal position may restrict lateral movement by supporting the lower torso. These findings emphasize the influence of belt geometry on restraint of the children in steering maneuvers. The differences in kinematics between short and tall children may also be related to parameters such as anthropometric differences, muscle activity, muscle response and muscle maturity, or a combination of all of the above.

Overall, Study IV shows unstable restraint situation, during steering maneuvers, with the torso belt positioned far out on the shoulder in numerous scenarios. To improve child safety, the restraint system must maintain contact with the clavicle even pre-crash, such as during evasive steering maneuvers prior to impact.

In a parallel study, children aged 4-12 were exposed to emergency braking (Stockman et al. 2013). The maximum forward head displacement varied between 155 and 210 millimeters. The farther out the shoulder belt was initially positioned on the shoulder, the greater the forward displacement of the head, indicating less optimal restraint situation. The braking maneuver put the child’s head in a more forward position closer to impacting interior structures such as the seat back and b-pillar. Previous studies documented head contact with the B-pillar, as one of the injury causation scenarios (Bohman et al. 2009; Andersson et al. 2011), and the forward position obtained from emergency braking may increase the risk of head injury in subsequent side impacts, since the head will be outside the side wings of the booster. If contact with the vehicle side interior does occur, an inflatable curtain may not protect the contact area.

In conclusion, pre-crash maneuvers highlight the need for an adequate restraint system which keeps the child properly restrained.

4.3 INJURY PREVENTION

From a vehicle restraint point of view, injury prevention includes four main areas to further advance the child's safety: attitude, handling, comfort and safety. These components mainly refer to the first two phases, pre-crash and in-crash, in Haddon's matrix, with a focus on human, vehicle, and equipment factors.

Reasons for non-use of BPB have been identified, including the perception of BPB as childish (Bohman et al. 2007; Jakobsson et al. 2007; Bingham et al. 2006). Consequently, it is important to design a BPB attractive to both the child (the user) and the adult (the buyer), to ensure usage or change attitudes.

Handling of the restraint system should be easy, fast, and minimize the likelihood of errors. An optimal BPB design allows children to handle the BPB correctly without help from an adult, and without extensive information or instruction. Study II showed that this is possible for children as young as 6 years of age.

Once the restraint system is in place, it should be comfortable. The comfort of the belt on the shoulder helps to avoid the child putting the belt behind the back or under the arm, compromising safety. Finally, in a crash, the restraint system should provide adequate protection for the child.

4.3.1 Built-in design

The definition of built-in design for children in the rear seat incorporates the idea of the vehicle providing complete protection with no required aftermarket equipment.

Once a child outgrows their harness-based restraint at about the age of 4, the child must be restrained by the vehicle seat belt, adapted to ensure proper seat belt fit. Currently, that adaptation is generally provided via an aftermarket belt positioning booster cushion, but there is only a limited focus on vehicle design to provide this protection for the child. One option is the integrated booster cushion (IBC), designed for a specific vehicle. An IBC leads to increased use since it is always available, provides easy handling (Study II, Bohman et al. 2007), appeals to older children (Jakobsson et al. 2007) and demonstrates increased comfort since vehicle belt geometry is developed along with the IBC, thus minimizing belt chafing of the neck. Intuitive handling results in a low misuse risk (Study II).

IBCs offer safety benefits as well, as they are designed together with the vehicle belts with optimal geometry and performance characteristics adapted to the vehicle. Preliminary results show the use of an IBC with a pretensioner to improve performance, as the pretensioner tightens the belt more efficiently with an IBC compared to an aftermarket BPB. Belt routing around guiding loops and associated friction upon tightening can be avoided. Reduced belt slack results in limited head excursion and a lower risk of head impact to the vehicle interior. In addition, an IBC is attached to the vehicle, insuring a correct centralized position on the vehicle seat. Its placement is not affected by the child leaving or entering the vehicle (Bohman et al. 2007). By eliminating the seat back of a high-back BPB, the head is 6-8 cm farther away from the front seat back, reducing the risk of impacting the head. The absence of side wings minimizes the need for children to lean forward to see through the window, resulting in a more reclined position, away from possible impact surfaces in a frontal impact (Andersson et al. 2010).

IBCs are available as options in only a few types of cars, and currently no car manufacturer offers IBC as standard equipment. As a result, their penetration into the vehicle fleet has been limited, and IBCs may not be available for the family buying a second-hand vehicle. This may particularly affect children in families with lower socioeconomic status, a group prone to increased risk of traffic injury. Furthermore, WHO (2013) highlights the need to achieve high usage of CRSs not originally installed in vehicles. Vehicle safety principles state that adults need not buy supplementary safety equipment, as their safety is included in the vehicle. Children should be provided this benefit as well.

From about 10-12 years of age, children should be properly restrained in the vehicle without BPB, according to governmental recommendations (Trafikverket 2012; NHTSA 2011b). Special attention should be paid to lap-belt geometry and seat cushion length. Seat cushion length is commonly longer than the length of the adolescent femur (Huang and Reed 2006, Bilston and Sagar 2007a), and children as tall as 145 cm, the height of an average 11-year-old child (Pheasant and Haslegrave 2006), still cannot be seated comfortably without slouching (Reed et al. 2013). In a driving study of older children, 135 cm or taller, seated directly on the seat bench, occupants were slouched for up to 16% of the time (Jakobsson et al. 2011). In the rear seat, the middle position could be designed to fit older (9-12) children by reducing the seat cushion length. The seat could still be used by other occupants, but taller occupants may experience reduced comfort due to the shorter seat bench.

In general, improved vehicle structures in modern vehicles have reduced intrusion into the vehicle compartment in MVCs. The improved car structures have resulted in more severe crash pulses (in terms of deceleration of the occupant) and energy management (belt pretensioners and load limiters) has been addressed in the front seat but not to the same extent as in the rear seat. Recent studies have shown that pretensioners and load limiters are beneficial for crash test dummies and adult post mortem human subjects in the rear seat, both in terms of improved kinematics and reduced risk of injuries to the neck and thorax in frontal impacts (Forman et al. 2009; Forman et al. 2008; Lopez-Valdez et al. 2010). Pretensioners and load limiters may be beneficial for children in real life as well. In study I, AIS 1 neck injuries resulting in PMI were identified in the child occupants. In previous studies, Bohman et al. (2000) and Kullgren et al. (2000) have shown that AIS1 neck injuries to drivers in frontal impacts can be reduced by introducing pretensioners, load limiters and airbags, thereby limiting shoulder belt force to minimize loading to the neck. These findings may be relevant for children as well, but needs further investigation. Further studies are also needed to investigate necessary compromises when choosing load limiter levels for different sized occupants in the rear seat.

Both Study I and Study III highlighted the importance of protecting the head from contact with the side interior. Contact with the side interior of the vehicle, including door, window and B-pillar was identified (Study III) and those findings have been confirmed in other studies (Arbogast et al. 2012b; Maltese et al. 2007; Andersson et al. 2011; Viano and Parenteau 2008b). High-back BPBs currently on the market have pronounced side wings and are often marketed as providing side impact protection, yet the theoretical side impact benefit of high-back BPBs have not been realized in field data (Arbogast et al. 2005) or laboratory testing (Bohman and Sunnevang 2012).

However, side supports provide a beneficial function in supporting the child when sleeping (Forman et al. 2011). Side impact protection provided by the vehicle, such as thorax side airbags and inflatable curtains, have shown benefits to adults and small women (Loftis et al. 2011b; Bohman et al. 2009) and could be beneficial to children as well (Bohman and Sunnevang 2012).

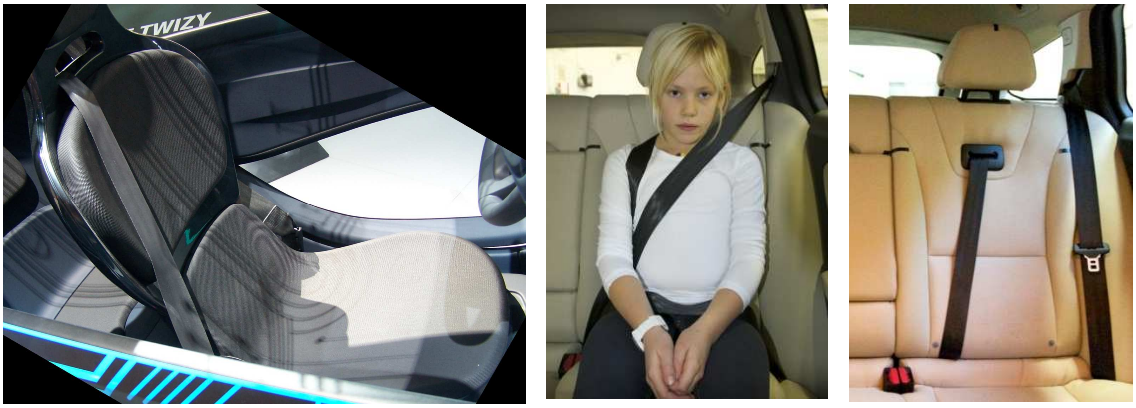
4.3.2 Restraint systems in maneuver situations

Driving studies (Andersson et al. 2010; Jakobsson et al. 2011; Forman et al. 2011; Bohman et al. 2010; Osvalder et al. 2013) highlighted that user positions are not always equivalent to in-crash positions but still represent part of the spectrum of “normal” positions. Study IV showed possible occupant positions due to steering maneuvers. A restraint system should protect the child taking into account natural occupant positions and possible occupant positions due to pre-crash maneuvers.

The challenge is in keeping the child well-restrained throughout all pre-crash events. Study IV showed that the shoulder belt assured a correct position on the shoulder for smaller children restrained on high-back BPBs, although the entire BPB tilted inboards. However, preliminary results showed that a tilted pre-position of a high-back BPB in a frontal sled test resulted in the shoulder belt guiding loop for the BPB being broken and the shoulder belt sliding off the shoulder. This is because the shoulder belt guiding loop is a comfort loop not designed to withstand significant loading in a crash. It is possible that ISOFIX would have kept the high-back BPB in a centralized position during the maneuver.

A possible countermeasure to maintain the shoulder belt on the shoulder in a pre-crash maneuver would be a pre-pretensioner, which is a reversible system where the belt is pretensioned at a lower force level, compared to the pyrotechnical pretensioner activated in a crash. The pre-pretensioner tightens the shoulder belt during pre-crash events. However, good initial belt geometry is important if it is to benefit from the pre-pretensioner. The shoulder belt must anchor on the mid-clavicle in order to reduce the movement of the occupant. Initial studies have shown such benefits of pre-pretensioner to drivers (Sander et al. 2009).

Another possible countermeasure to prevent the occupant slipping out of the belt would be to add an extra shoulder belt coming from the opposite shoulder to the normal three-point belt. In rally racing, five- or six-point belts, which restrain shoulders and buckle between the legs, are used to increase the effectiveness of the restraint system to restrict the movement of the occupant. From a handling perspective, however, a five- or six-point belt might not be desirable in daily driving. Another possible solution would be to add a two-point belt restraining the opposite shoulder, a so-called rucksack. This solution can be found in the Renault Twizy (Figure 7a). An additional shoulder belt (rucksack) has been shown effective for front seat adult occupants in frontal, far-side impact and rollover studies (Boström et al. 2008; Boström et al. 2013). Similar countermeasures could possibly be used to improve the safety of the rear-seated occupants.



a) b) c)

Figure 7 a) Renault Twizy with extra rucksack belt (Courtesy of Autoliv France). b) Shows a prototype of a rucksack belt in the rear seat with a child occupant in a midsized vehicle (Autoliv 2013). c) Shows a prototype of a rucksack belt in the rear seat in a midsized vehicle (Autoliv 2013).

Another possible solution is to add the additional two-point belt across the chest, in a criss-cross pattern (Figure 8b). Another version of this type of four-point belt system has been evaluated and shown beneficial to front seat adult occupants in frontal impacts to reduce thoracic loading (Rouhana et al. 2006, see Figure 8a).

a) b) c)

Figure 8 a) A four-point belt system presented by Ford (Courtesy of Ford). b) Shows a prototype of a five-point belt system (criss-cross pattern) with a child occupant in the rear seat of a midsized vehicle (Autoliv 2013). c) Shows a prototype of a five-point belt system in the rear seat of a midsized vehicle (Autoliv 2013).

4.4 IMPLEMENTATION OF IMPROVED CHILD SAFETY

Regulatory testing differs significantly from real life crashes. There can be a great variability in the occupant's position, occupant's clothing, belt positioning and tightness, impact velocity, vehicle acceleration, principal direction of force, and pre-crash events. To further improve child safety and ensure a "tolerant" restraint system, the restraint system must provide protection in real life events that, thus far, have not been replicated in existing vehicle test methods.

4.4.1 Test methods must reflect real-life conditions

Tylko and Bussières (2012a) showed that a BPB, approved by US regulations, demonstrates poor performance in a full vehicle frontal rigid barrier test. Another study evaluated a highly rated ISOFIX BPB in full vehicle frontal rigid barrier tests and demonstrated poor performance due to submarining, due to the interaction between the vehicle seat and the BPB (Tylko and Bussières 2012b). Regulatory approval is based on a dynamic sled test with a child crash test dummy positioned on a BPB on a rigid test bench restrained by a pre-tensioned seat belt without a retractor. Since BPBs rely on the vehicle seat belt to provide restraint, BPBs must be designed and tested dynamically together with the vehicle to ensure good safety performance.

Natural occupant positions must be included in test methods. Evaluations should not be limited to optimally position crash test dummies with the belt slack removed. For example, a consumer rating test could include a child crash test dummy in the rear seat and one out of a range of e.g. 4 different sitting postures. Thus, the vehicle manufacturer must evaluate all seating positions to ensure proper performance, although only one will be included in the final rating test. Belt slack in the lap and shoulder belt should always be included in tests and legal requirements, as in real-life there is always a certain amount of slack in the seat belt (Study II).

Study IV has shown unstable restraint situation for children during steering maneuvers. Implementing a real maneuver in a sled test or in a complete vehicle test is a challenge, but the dummy can be pre-positioned to represent their post-maneuver posture. Restraint performance in maneuvers can also be evaluated separately, by only evaluating the maneuver and not the actual impact condition.

In conclusion, a consumer rating program should promote vehicle integrated booster cushions more than what is currently the case in EuroNCAP, since benefits are shown in attitude, handling, comfort and safety.

4.4.2 Rating and legislation

Rating programs, which have improved front-seat safety, play an important role in the consumer’s choice of vehicle. When the IIHS introduced a new test representing small-overlap crashes, the Volvo S60 received a high rating and increased sales by 40% over a short period of time (Cicchino 2013).

The 4-12 age group is not included in dynamic vehicle testing; neither in regulatory nor consumer rating programs. These children have been “forgotten“ in the legal process of certifying vehicles. Japan and China’s NCAP have included a small female crash test dummy in the rear seat during frontal impacts. In side-impact rating programs, only IIHS includes a rear-seated small female crash test dummy. It is unjustifiable that first row safety is comprehensively evaluated, but not rear row. EuroNCAP will revise the test protocol in 2015 for both frontal and side impact tests (EuroNCAP 2009). The child crash test dummies, Q6 and Q10, are suggested to be included in the rear seat in the revision 2015.

This thesis implies that all full vehicle testing, legal requirements and consumer rating testing should include two rear-seated child crash test dummies restrained by the vehicle. US data shows that 69% of rear seat occupants are 14 years or younger

(Kent et al. 2007) and the rear seat is recommended for children (Durbin 2011). It is proposed that one of the child crash test dummies be seated on a BPB and restrained by the vehicle restraint system, in order to evaluate the rear seat restraint system as well interaction between the BPB and vehicle restraint system. The other seat position should be designed for a 10-year-old crash test dummy, restrained by the vehicle seat belt alone with no BPB. This is because 10-year-old children in real life are rarely seated on BPBs and are therefore only protected by the vehicle restraint system. A potential drawback of not having an adult occupant, for example a midsized male in the rear seat test protocol, could be that the restraint system in terms of load limiting levels would be optimized for the child dummies. However, there are currently technical solutions that can adapt the load limiter level to different sizes of occupants. No choice is needed as to which type of occupant is best protected by a load limiter in the rear seat.

Consumer rating organizations have a responsibility to use adequate test methods and tools. When a family buys a 5-star rated vehicle, they assume that the rating applies to all seating positions in the vehicle. This is not presently the case. The average consumer is not a biomechanical expert and relies on comprehensive consumer information and regulatory testing to guide them in making vehicle choices. Thus, it is recommended to include child crash test dummies in the rear seat when evaluating vehicle restraint systems.

4.5 METHODOLOGICAL CONSIDERATIONS

Study I

Investigating long-term consequences to injured children in MVCs requires access to databases that include complete detailed medical records encompassing not only the acute medical care immediately following the crash but also follow-up medical information. Folksam covers a large part of insured vehicles in Sweden, and their claim files of children in MVCs include extensive medical information extending beyond the initial event, since children are followed up 1 year after the accident. Any long-term consequences are systematically assessed according to the “Grading Medical Impairment” method. This is an established method used by all insurance companies in Sweden. The claim files also include crash information.

Study II

Misuse is often investigated in observational studies, for example by investigators standing outside daycare centers or by observations of CRS use in vehicles in traffic. This approach is limited however as some aspects of misuse are subtle and can only be detected by hands-on evaluation of the CRS. In Study II, two specific designs of BPBs were compared. IBCs are rarely found in vehicles so that observations in real traffic were therefore not a practical method. It is also important to study children in real life rather than interview the child as to how they think they would perform a particular action. Usability studies show that people do not perform a task in the same way they imagine they would (Nielsen 1993). Besides, few children have tried IBCs and would consequently have no experience of buckling up on IBCs. Therefore, a vehicle was parked at an entrance to a museum, with good access to children. The children were asked to put on the belt as if going for a real drive.

Study III

In order to investigate how restrained children are injured in frontal impacts, databases with in-depth crash information and associated medical data are needed. These requirements limit Study III to a few accessible databases. CIREN and NASS-CDS were used in Study III. The researchers excluded two other available in-depth databases, (GIDAS) and (CCIS) due a limited number of cases fulfilling the selection criteria. There may be other in-depth databases at vehicle manufacturers and other research groups, but these databases were not publically accessible to the authors of Study III.

Study IV

Studying pre-crash maneuver effects on child kinematics requires a method for simulating real life events and access to properly restrained child volunteers or child models (physical or numerical) validated for pre-crash events. Naturalistic driving studies have become a useful method of studying driver behavior that reflects real life events. However, such an approach results in an extremely low likelihood of capturing pre-crash events such as hard braking or swerving with a properly restrained child in the rear seat. Experimental tests with child crash test dummies, numerical simulations with human body child models or finite element child models are common methods for evaluating the effect of impacts in injury prevention. However, pre-crash events are different from crash events and recent studies show that neither child crash test dummies nor numerical child models have good correlation with child volunteers in these scenarios (Stockman et al. 2013; Gras and Brolin 2013).

An evaluation method with child volunteers was developed by conducting steering maneuvers on a closed circuit test track, to ensure safety to volunteers, repeatability of the maneuver, and access to child volunteers.

4.6 LIMITATIONS OF THE METHODS

There are several limitations to the studies. The most frequent were the size of the dataset. Study I could have included the risk of PMI as a result of an injury to all AIS/body regions with a larger dataset, as was done in Malm et al. (2008) for adults. However, for many combinations of body regions and AIS levels, the limited number of cases resulted in wide confidence intervals. However, the most important findings were clear, giving the conclusion that the neck AIS1 and head AIS1+ injuries had to be prioritized.

Study I was based on claim files, including medical files, police reports and communication between the child’s caretaker and insurance company. Medical files include high quality injury data. However, the data on belt usage, seating position and specific restraint were not well documented. Improved documentation of these parameters would allow studying their influence on the risk of PMI as a result of injury. It is desirable in future studies and databases to collect and document this information. However, the aim of Study I was to study the relationship between a given injury and the risk of injury resulting in PMI.

There are different ways of measuring long-term consequences, and in Study I a predictive method was used measuring impairment outcome, since it is a nationally accepted and consensus-based method by medical specialists. However, there are various aspects of loss of health where, for instance, normal activities or individual circumstances are not included and might have influenced results.

Study II included children visiting a science museum because of the accessibility of volunteers. This dataset is not necessarily representative of all Swedish children. The children in this study were more likely to come from middle and high income families known to have a higher usage of BPBs. Still, this subset of children was generally familiar with the typical aftermarket BPB, but still showed high misuse of this type of BPB. In contrast, children not familiar with the integrated booster cushion still buckled up properly.

Study II focused on the ability of the child to correctly restrain her/himself, and did not evaluate how misuse could be reduced if parents were allowed to adjust the restraint, which may or may not be the case in an everyday situation. However, a BPB should be user-friendly so that a child can correctly use it on her/his own. Furthermore, the environment may have influenced the child in different ways; either in that the child tried to do their best to buckle up correctly since they were being observed by adults unfamiliar to the child, or they were indifferent about buckling up correctly since they knew they were not going for a real drive. Nevertheless, the test leader instructed the children to buckle up as if they were going for a real drive.

Study III would have benefitted from larger datasets since the influence of age and stature could have been further explored. Other possible contributing factors such as seat belt geometry, clearance distance to the seat back in front of the occupant, and the child's initial position were difficult to examine in a retrospective review of cases. In some cases this information was available, but in some it was not recorded. Still, Study III clearly showed the influence of pre-crash maneuvers as contributing factors. The study was limited by not including AIS1 head injuries, but preventing AIS2+ injuries will most likely benefit those with AIS1 head injuries as well.

Study I and Study III both included analyses of earlier data which lead to fewer new vehicle models. Thus, results may not fully reflect the modern vehicle fleet which may have an increased crash severity due to stiffer vehicle bodies, and therefore result in increased loading to the rear occupant than those studied. As these vehicles increase in the fleet, acute and long-term injury risk to rear seat occupants may increase. Future research should continue to monitor this trend.

Study IV evaluated only one type of maneuver in only one vehicle in a controlled testing environment. Occupants were aware that certain maneuvers and braking events would take place during the testing but were not told exactly when the turns would take place. No correlation was found between measurements (such as the shoulder belt off the shoulder) and the order of the trials. Belt geometry is essential in this type of study, and vehicles with other child restraints may have resulted in different outcomes. However, different belt geometries were evaluated by using different child restraint systems (i.e. BPB, high-back BPB).

This thesis has not presented results based on gender differences. There was an equal distribution of boys and girls in all datasets used in the studies. The datasets used in Study I to Study IV were too small to draw any conclusions regarding differences in gender. However, the anthropometrical differences between boys and girls in the age group 4-12 were small, suggesting limited gender effect in that aspect. Among adults, gender differences have been seen concerning the risk of long-term consequences as a result of AIS1 neck injury (Krafft et al. 1997), suggesting that gender effect should be monitored in children as well.

Study I was limited to children sustaining permanent medical impairment as a result of an injury in a motor vehicle crash. Children born with an impairment were not included.

The studies in this thesis are based on data from developed countries and did not include data from developing countries. However, it is my belief that the knowledge gained from this thesis can be directly applied in developing countries.

5 CONCLUSIONS

This thesis has resulted in increased knowledge of real life situations for restrained, rear-seated children aged 4-12 in motor vehicle crashes. This knowledge can serve as basis for future safety improvements, aimed at reducing long-term health consequences. Overall, the head and neck were identified as prioritized body regions for injury reduction. Also, the importance of preventing injuries of all severities was highlighted. Injury causation scenarios were identified for head injured children in frontal impacts. Evasive steering maneuvers prior to impact may result in an unstable restraint situation for the child and thereby contribute to head injuries. Misuse of belt positioning booster cushions can be significantly reduced by designing an intuitive booster cushion integrated in the vehicle.

The main conclusions are listed below:

- The patterns of injuries resulting in permanent medical impairment are different for children and adults, therefore, safety priorities for children need to be based on pediatric data.
- The vast majority of injuries with higher degree of permanent impairment were severe injuries to the head. The most frequent injuries leading to permanent impairment were minor injuries to the neck and head. Hence, these injuries must be prioritized in developing crash safety strategies to reduce long-term health consequences for children.
- Belt positioning boosters can be designed to ensure correct belt handling by the child, without needing support from parents/adults or targeted education.
- Protection in oblique frontal impacts and frontal impacts with pre-crash steering maneuvers needs to be addressed to reduce the risk of head injuries to restrained children. Therefore, “tolerant” restraint systems need to be developed to ensure the torso remains restrained despite pre-crash events and oblique impacts.

6 RECOMMENDATIONS

To further improve child safety in cars, it is essential to continue to advance the areas of biomechanical research, countermeasure and test procedure development and implementation.

- Biomechanical research
  - Further research is needed on AIS1 neck injuries to children in order to understand injury mechanisms, injury criteria and injury thresholds. Research should include development of countermeasures, child test methods, and the evaluation of child crash test dummy biofidelity. In addition, it is necessary to continue to monitor the prevalence of AIS1 neck injury resulting in permanent medical impairment to children and adults in countries throughout the world.
  - Define injury criteria and injury thresholds for mild traumatic brain injuries. Monitor MTBI prevalence in children in MVCs.
  - Improve child vehicle-crash databases by improving the data quality regarding restraint and user position. Larger datasets are also needed, obtainable by pooling datasets.
  - Study the prevalence of misuse in naturalistic driving studies.
- Countermeasures
  - Belt positioning boosters should be built-in to the vehicle thereby eliminating the need for guiding loops, contributing to high misuse.
  - Restraint systems in the rear seat need to be designed to protect children in actual user positions that occur during normal driving and pre-crash driving.
  - Develop countermeasures to reduce the risk of AIS1+ head injuries resulting in permanent medical impairment.
  - Develop and implement rear seat restraint systems that manage increased crash energy.
- Test methods
  - Incentivize vehicle manufacturers to accelerate safety improvements for children in their vehicles. To do so, an assessment of child safety for those 4-12-years-olds needs to be included in consumer rating programs and legal requirements.
  - Include a pre-crash position or pre-crash maneuver prior to impact in restraint evaluation tests in order to evaluate the “tolerance” of the restraint.
  - Besides crash safety aspects, attitude, handling and comfort need to be considered by including usability studies when developing restraint systems for children to ensure proper usage.
  - Child models, mechanical and numerical, needs to be evaluated and improved, with a focus on accurate kinematics and interaction with the seat belt, in order to replicate the kinematics resulting in head impacts in a more realistic way.

7 ACKNOWLEDGEMENTS

This thesis was financially supported by Autoliv and Fordonsstrategisk Forskning och Innovation (FFI). I would like to express my sincere gratitude and appreciation to everyone who has helped and supported me throughout my PhD studies. A special thanks to:

Jan Olsson, my manager, for giving me the opportunity to carry out this work.

Maria Krafft, my supervisor, for your continuous support, enthusiasm, discussions, for always being there, and for your guidance throughout my research.

Ola Boström, my co-supervisor, for your never-ending enthusiasm and for always making me look at the findings from a different point of view.

Anders Kullgren, my co-supervisor, for your firm support, especially at the start of this journey, for your guidance and stimulating discussions.

Kristy Arbogast, my co-supervisor, for always being there with thoughtful advice, guidance and support, despite being on the other side of the Atlantic.

Kristina Alexanderson, my co-supervisor, for taking me under your wings when the situation changed at Karolinska Institutet and for great support, guidance and feedback.

Anna Nilsson-Ehle, SAFER, my mentor, for being there when needed.

My closest colleagues at Autoliv; Rikard Fredriksson and Cecilia Sunnevång, for your constant support, stimulating discussions, constructive criticism of the thesis, and for always reminding me of the goal: “När blir det fest..?”

My other colleagues at Autoliv Research; Yngve Håland, my unofficial mentor, for hiring me (once upon a time) and introducing me to this research area, for your thoughtful advice and encouragement. Benny Nilsson, Erik Rosén, Ulrich Sander, Johan Karlsson and Torbjörn Andersson, for your generous support and sharing of your knowledge and experience. Lena Ljunggren – for always lending a helping hand in practical issues. Mikael Enänger, Torgny Bengtsson, Ambjörn Olovson – for your support in all experimental tests and for your patience with my never-ending test matrix. To all other colleagues at Autoliv, for all their encouragement, inspiring discussions and contributions to create a stimulating atmosphere at work.

The SAFER “Småfolks” (Small people) project team; Isabelle Stockman, Lotta Jakobsson, Mats Svensson, Anna Carlsson, Maria Wimmerstedt and former team members Marianne Andersson, Henrik Svanberg and Magnus Holmquist. Teamwork with you is stimulating, inspiring and fun.

Anna-Lisa Osvalder, for great collaboration in Study II, Study IV and in many other studies we have carried out together, and for valuable input to the thesis.

Anders Lie and Anna Anund, for constructive criticism and valuable input in how to improve the thesis.

Helena Stigson, for great cooperation in Study I and for valuable feedback on the thesis.

Åke Nygren for constructive criticism and valuable advice.

Mark Rosenfeld, for excellent language editing of the thesis and all the studies.

Colleagues at Chalmers, SAFER and Karolinska Institutet, for creating inspiring atmospheres and interesting discussions.

Colleagues at Folksam; Anders Ydenius, Josefin Lundin, Sigrun Malm and Anita Malmqvist for your dedicated support in Study I.

Maria Eriksson, for your excellent support with the data collection in Study II.

Thomas Alfredsson, Torsten Freyhall, Lars-Ola Bligård, Håkan Gustafson, Samuel Borgen and Jordanka Kovaceva, for your support in Study IV.

All the children in the studies, for your participation.

My friends outside the academic world, for supporting me with your enthusiastic encouragement. Anna, for reminding me of the horses, when I needed to revitalize. Linda, for your company on our refreshing evening walks, and for patiently listening to my never-ending research talk. Special thanks to Sara and Sara, for your support and belief in me.

My family; Mats, Kicki, Sofie, Ola, Erik and Lina, for your constant love, support and encouragement.

My parents, Hans and Anita, for all your love and support, practical help and for giving me your time, when I had too little.

Mathias, Emma and Oscar – my beloved children – for helping me design future child restraint system. For showing me what is important in life. Most of all - You are my everything!

Stéphane, for your love, support and patience, knowing you were by my side to give me the energy to finish this thesis. Endless love.

Katarina Bohman

April, 2013.

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