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Safety for Children in Cars – Focus on Three Point Seatbelts in Emergency Events

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SAFETY FOR CHILDREN IN CARS – FOCUS ON THREE POINT SEATBELTS IN EMERGENCY EVENTS

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ABSTRACT

Child safety in vehicles has improved over time. One of the main factors is due to the increased restraint use by children. Nevertheless, studies show that although children are restrained, injuries still occur indicating that restraint systems have the potential for further improvement. This thesis focuses on emergency events that may precede a crash, and how these events influence the kinematics of child occupants restrained by a three point seatbelt.

Real world data was analyzed and the results identified that a substantial portion of drivers attempted an avoidance maneuver prior to crash. Volunteer tests were carried out to investigate children's motion during emergency braking and steering maneuvers in a passenger vehicle, and the current child crash test dummies were evaluated with respect to child occupants. In addition, a countermeasure was evaluated by activating an electrical reversible seatbelt retractor (pre-pretensioner) prior to run-off road events with child crash test dummies.

The results of the volunteer tests emphasize the need for considering large areas of the vehicle's interior as part of potential head impact surface. Maximum forward excursion is influenced by initial shoulder belt position and type of booster used in the braking events. A steering maneuver is an unstable restraint situation for children in the rear seat and a great variety in lateral displacement and seatbelt position on the shoulder were seen in different restraint configurations. Influencing factors include child age, anthropometry, initial seated posture and initial shoulder belt position on the shoulder. This thesis confirms that children can be exposed to sub-optimal postures due to emergency events. It provides evidence that a pre-pretensioner has considerable potential in maintaining different sizes of rear-seated occupants well restrained.

The braking and steering maneuvers with child volunteers carried out in this thesis provide novel and unique knowledge of possible pre-crash postures of children across a variety of restraint systems in vehicle emergency maneuvers. Test tools are needed to better replicate the real world seated postures and injury causation scenarios. This thesis evaluated the available physical child test tools in low acceleration conditions when exposed to emergency events and highlighted the limitations in capturing child kinematics in emergency events with existing crash test dummies.

Extending previous research, this thesis has resulted in deeper knowledge of how children are affected by emergency events prior to crash, in terms of quantifying the frequency of vehicle maneuvers in real world data, measuring the kinematics of children and child crash test dummies in these scenarios and exploring a possible countermeasure to improve safety. The output has the potential to positively impact child safety in cars through the development of active safety systems, enhanced rear seat restraints, and improved test methods and test tools.

KEYWORDS: Braking, Child safety, Child restraint systems, Crash test dummies, Emergency events, Pre-pretensioners, Run-off road, Steering.

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Isabelle Stockman
Gothenburg, September 2016

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Stockman I, Jakobsson L, (2016) *Pre-crash maneuvers and causation factors of serious motor vehicle crashes involving child passengers*, Submitted.

Contribution: Stockman made the outline of this study. Stockman made the analysis and the presentation of data. The paper was written by Stockman, and reviewed by Jakobsson.

PAPER II

Stockman I, Bohman K, Jakobsson L, Brolin K, (2013) *Kinematics of child volunteers and child anthropomorphic test devices during emergency braking events in real car environment*, Traffic Injury Prevention 14:1, 92-102.

Contribution: Bohman and Stockman made the outline of this study. Stockman made the analysis and the presentation of data. The paper was written by Stockman, and reviewed by all authors.

PAPER III

Bohman K, Stockman I, Jakobsson L, Osvalder AL, Bostrom O, Arbogast K, (2011) *Kinematics and shoulder belt position of child rear seat passengers during vehicle maneuvers,* Annals of Advancement in Automotive Medicine 55, 15-26.

Contribution: Bohman made the outline of the study with support of Stockman and the other authors. Bohman and Stockman made the analysis and the presentation of data. The paper was primarily written by Bohman with substantial contribution by Stockman, and it was reviewed by all authors.

PAPER IV

Stockman I, Bohman K, Jakobsson L, (2013) *Kinematics and shoulder belt position of child anthropomorphic test devices during steering manoeuvres,* Traffic Injury Prevention, 14:8, 797-806.

Contribution: Stockman made the outline of this study with support of Bohman and Jakobsson. Stockman made the analysis and the presentation of data. The paper was written by Stockman, and reviewed by all authors.

PAPER V

Stockman I, Bohman K, Jakobsson L, (2016) *Pre-pretensioner effect on child sized dummies during run-off road events*, Submitted.

Contribution: Stockman, Bohman and Jakobsson made the outline of this study, based on tests performed in a prior research project (led by Bohman). Stockman made the analysis and the presentation of data. The paper was primarily written by Stockman, and partly by Bohman and Jakobsson.

DEFINITIONS AND ABBREVIATIONS

Active HBM	Human Body Model with actively controlled muscles (postural control)
AIS	Abbreviated Injury Scale, a scoring system to determine the severity of single injuries based on the survivability from the injury
ATD	Anthropomorphic Test Device, also called crash test dummy
Belt positioning booster (booster)	Child restraint that elevates the child to better fit the geometry of the vehicle seat belt
Booster cushion	Belt positioning booster without backrest
Emergency event	Critical situations, such as evasive maneuvers, prior to an impact where the vehicle movement is out of the zone of “safe” or “normal” driving
FE	Finite Element
HBM	Human Body Model
Highback booster	Belt positioning booster with backrest
HIII 3y	Child ATD corresponding to an average 3 year old, from the Hybrid III family
HIII 6y	Child ATD corresponding to an average 6 year old, from the Hybrid III family
HIII 10y	Child ATD corresponding to an average 10 year old, from the Hybrid III family
HIII 5th female	ATD corresponding to a fifth percentile female, from the Hybrid III family. The ATD has a similar sitting height and shoulder width as an average 12 year old
Integrated booster cushion	Belt positioning booster built-in to the vehicle
ISOFIX	International standard for universal anchorages and attachments for child restraint systems in passenger cars. In some countries called LATCH or UAS
NASS-CDS	National Automotive Sampling System Crashworthiness Data System, a database of passenger vehicle crashes in USA
NMVCCS	National Motor Vehicle Crash Causation Scenarios
NHTSA	National Highway Traffic Safety Administration, USA
PMHS	Post Mortem Human Subject
Pre-pretensioner	Electrical reversible seatbelt retractor
Q3	Child ATD corresponding to an average 3 year old, from the Q-family

Q6	Child ATD corresponding to an average 6 year old, from the Q-family
Q10	Child ATD corresponding to an average 10 year old, from the Q-family
Submarining	The pelvis slips under the lap part of the seat belt in a crash, and the load is applied to the abdomen instead of the bony pelvis

1. BACKGROUND

Every day, more than 1,000 children and young people under the age of 25 years are killed in road traffic accidents around the world. This age group accounts for over 30 percent of those killed and injured in road traffic accidents (WHO, 2007). Different parts of the world face different challenges and the distribution of road deaths by mode of road user varies. In Europe for example, where child restraint systems are mandatory and restraint usage is relatively high, 32 percent of child traffic fatalities (0-14y) involve children as passengers in cars (WHO, 2008a). In addition to the fatalities, millions of children require hospital care for non-fatal injuries (WHO, 2008b).

In 1997, the Swedish Parliament adopted the road transport safety strategy Vision Zero, meaning that no one should be killed or seriously injured in the Swedish road transport system (Tingvall, 1998). Other nations have been inspired by the Swedish Vision Zero initiative, for example the Netherlands, Canada, Portugal and the United Kingdom. The safety strategy is based on the concept of allowing incidents to occur, however it is essential that they are at a level of violence that is not a threat to life or long-term health (Tingvall, 1997). Vision Zero highlights that the road transport system is an entity, in which components such as roads, vehicles and road users must interact with each other for optimal safety (Trafikverket, 2016).

Child safety in vehicles has improved over the years. One reason is increased restraint use by children (Jakobsson et al. 2005, CHOP, 2007). In addition, child safety in vehicles has also enhanced as a result of implementation of new safety systems and improvement in vehicle crashworthiness, and improvements in road safety in accordance with Vision Zero (Carlsson et al. 2013). Nevertheless, studies show that although children are restrained, injuries still occur (NHTSA, 2005, Bidez et al. 2007, Bohman et al. 2011) indicating that restraint systems have the potential for further improvement.

The head is the most frequently injured body region, regardless of restraint system and crash direction (Durbin et al. 2003, Howard et al. 2004, Arbogast et al. 2004). Head injuries sustained by child occupants restrained in child restraints include both injuries due to contact with the vehicle interior as well as inertial injuries (Arbogast et al. 2005, Jakobsson et al. 2005). Bohman et al. (2011) identified head to front seat back impact as a predominant cause of head injury for rear-seated, seatbelt restrained children, in frontal impacts. They highlighted vehicle emergency maneuvers, prior to impact, as a contributing factor for head injuries, since a lateral inboard motion, for instance, can result in the shoulder belt moving farther out on the shoulder contributing to torso roll out of the shoulder belt during an oblique or frontal impact. Research on how such emergency events influence child occupants is limited.

Substantial advancement in collision avoidance systems has been made over the last decade, such as autonomous braking and steering (Ljung et al. 2015). As such systems are increasing in the vehicle fleet, we will probably see an increase in the frequency of emergency maneuvers, like braking and steering, which will add to current driver initiated emergency events that may occur prior to a crash. This will most likely influence the safety of child passengers and needs to be taken into consideration when developing advanced driver assistance systems and occupant restraints. There is a need to quantify the kinematics of child occupants in response to these evasive maneuvers in order to improve the safety of child occupants in cars.

For the smallest children (aged 0-3), it is a well-established fact that the safest restraint option for optimal protection is rearward facing child seats (Tingvall 1987, Tarrière 1995, Jakobsson et al. 2005, Henary et al. 2007). The rearward facing child seat enhances support to the head and spine in the event of an impact, and distributes the forces over a large part of the body. If a child in a rearward facing child seat is exposed to an emergency event, such as a braking event, prior to crash it will result in the head and spine of the rearward facing child being supported by the seat as a result of the brake. This is not the case for forward facing children, who would be moving forward. To reduce injuries to children in cars, a fundamental step is to ensure the child is properly restrained in a crash. There is a lack of knowledge on how child-to-restraint interaction is influenced by evasive emergency events that may precede a crash. Especially, this knowledge is important for forward facing children using the three point seatbelt as part of their protection.

1.1 CHILD ANATOMY

A child is not a small version of an adult (Figure 1). Growth and development of the human body occurs continuously and is non-uniform, although most body dimensions develop according to predictable trends (Burdi et al. 1969). At birth, the head represents 25 percent, whereas in an adult the head represents approximately 14 percent of the total body length (Burdi et al. 1969). The head of a child is not only proportionally larger and therefore heavier, the face-brain proportions are different and the center of gravity is located higher in a child compared to in an adult (Tarrière, 1995).

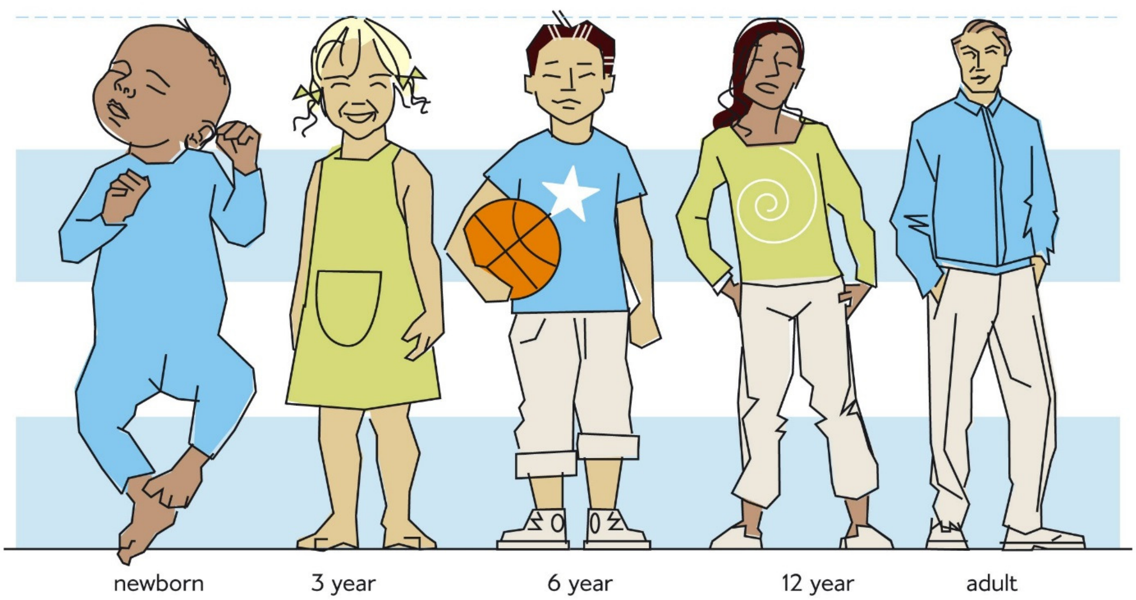

Figure 1 The proportional changes in body segments with age (courtesy of Volvo Cars).

The strength of the neck muscles increases with age and the smaller structure of a child's neck is not strong enough to support the heavy head and to soften violent head movement. At birth, the neck vertebrae consist of bones joined by cartilage (Figure 2). Vertebrae C3-C7 typically fuse during the third year, while the atlas (C1) and the axis (C2) do not complete their joining until age 4-6 (D. Klinich et al. 1996). During early childhood, the facet joints in the upper neck are more horizontal compared to an adults', which increases the risk of partial dislocation even at lower severity levels (D. Klinich et al. 1996).

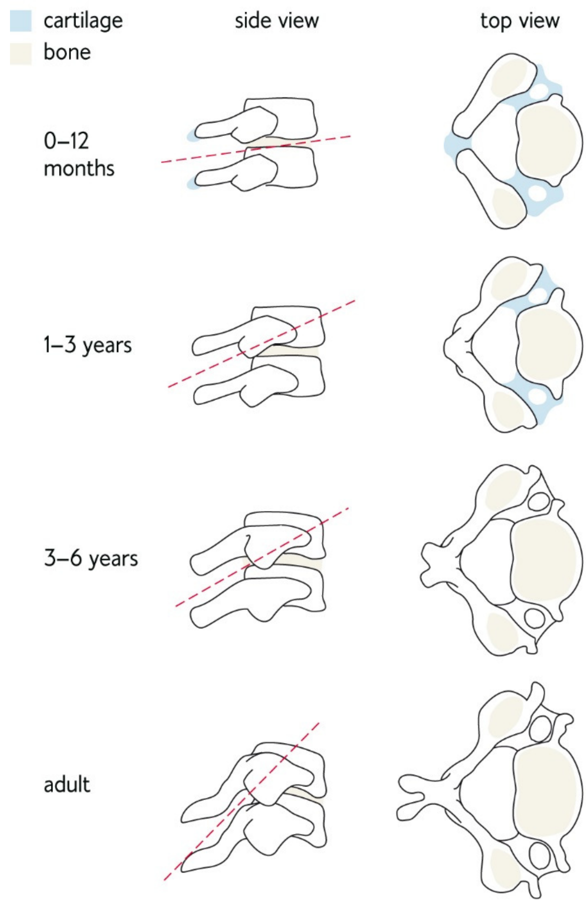

Figure 2 Development of the neck vertebrae (courtesy of Volvo Cars).

A child's ribs are generally more elastic and flexible compared to ribs in an adult. Therefore, impact to the thorax will produce large chest wall deflection and reduce the probability of rib fracture, hence, probability of thoracic organ damage from compression increases (Burdi et al. 1969).

A child has a smaller pelvic bone, shorter thigh length and less pronounced iliac wings compared to an adult (Burdi et al. 1969, Tarrière, 1995). At birth, the pelvis is mainly cartilaginous. The ossification occurs gradually in three separate areas until the age of 8 years. The fusion of these three areas is required so that the pelvis becomes a stable ring structure, capable of being loaded; these changes do not occur until puberty (Gray, 2012). With the smaller rib cage and pelvis of the child, the abdominal organs are more exposed than for an adult and can more easily be injured (Burdi et al. 1969).

Generally no gender difference in height, weight and general body proportions were seen in children up to 10-11 years of age (Burdi et al. 1969). The average 12 year old has a similar seated height and shoulder width as a small female (Pheasant and Haslegrave, 2006).

1.2 PROTECTION OF CHILDREN IN CHILD RESTRAINTS

Children's anatomy is different to adults, which is important to take into consideration when developing and designing protection against vehicle impact forces and designing optimal occupant restraint systems (Burdi et al. 1969). Child restraint systems are designed to protect infants and children up to the age of 10-12 years. For the smallest children, the safest restraint option for optimal protection is rearward facing seats (Tingvall 1987, Tarrière 1995, Jakobsson et al. 2005, Henary et al. 2007). The first rearward facing child restraint system was introduced and tested in 1964 with the purpose of enhancing the support for the spine and head in the event of a frontal impact, and to distribute forces over an extended part of the body (Aldman, 1964). At about 4 years of age, when the mass of the head is proportionally less compared to a newborn, and the neck muscles are further developed, the child can be turned facing forward in the vehicle. In Sweden, rearward facing seats are recommended up to the age of 4-5 years. Most other countries advise the transfer of the child at about 1-2 years of age to a forward facing child seat. The rearward facing infant seats, rearward facing child seats and forward facing child seats (Figure 3) are equipped with an integrated belt harness to restrain the child. These seats are attached to the vehicle using the vehicle seatbelt or the international standardized anchorage system ISOFIX.

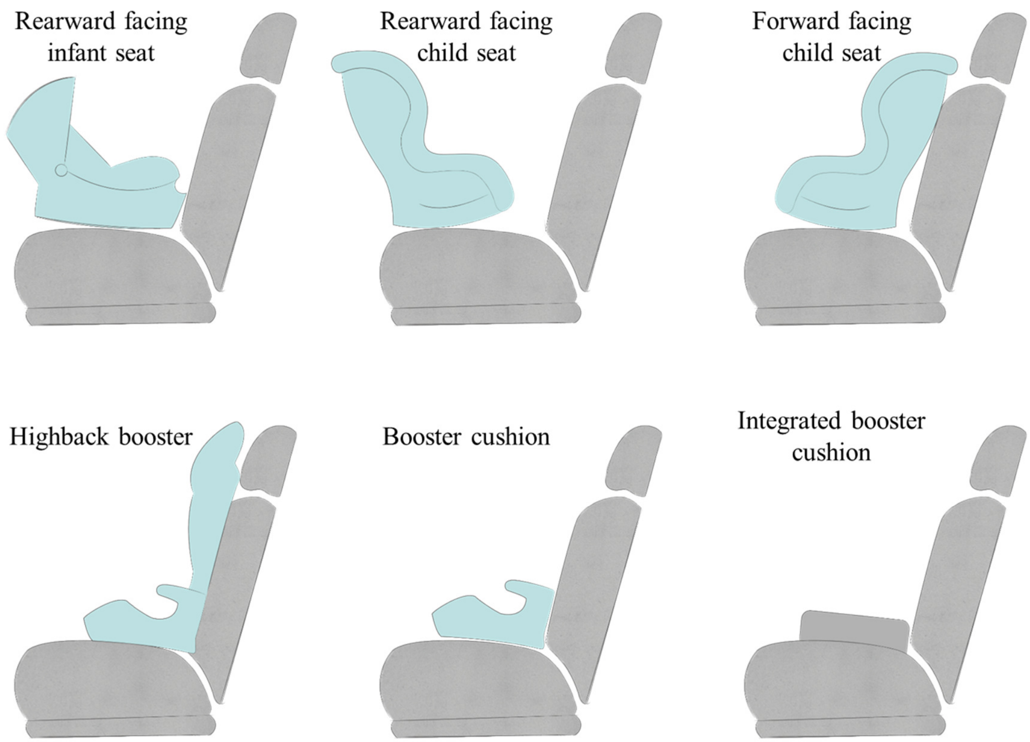

Figure 3 Schematic of the different types of rearward and forward facing child seats and boosters. The various seats and boosters are attached to the vehicle using the vehicle seatbelt or the international standardized anchorage system ISOFIX. The integrated booster cushion is attached directly to the vehicle structure (courtesy of Volvo Cars).

Once the child has outgrown the child seats, the differences between children and adults call for specific adaptions when using vehicle restraints. The iliac spines of the pelvis are important for satisfactory lap belt positioning and reducing risk of belt load into the abdomen (submarining), but are not fully developed until around 10 years of age (Burdi et al. 1969). In the late 1970s belt-positioning booster cushions were introduced as a way to improve belt fit and allow the geometry of the adult seatbelt to function more effectively with respect to the child occupant (Norin et al. 1979). There are three main categories of belt-positioning boosters (Figure 3); highback boosters, booster cushions, and integrated (built-in) booster cushions. A highback booster has a backrest which was initially developed to provide a head restraint for the child (Jakobsson et al. 2012). Over the years, the design of booster backrests has changed and a trend towards fitting large side supports at the level of the torso as well as the head has been noticed. Child restraint system manufacturers emphasize that the reasons for the change, is to provide improved side impact protection (Bendjellal et al. 2009). The backrest can also provide comfort for children by keeping them upright when relaxed or asleep. The boosters are used in conjunction with the vehicle's seatbelt to restrain the child. Recently, some boosters have been equipped with straps or connectors that can be attached to the vehicle ISOFIX anchorages. The purpose of these attachments is to restrain the booster when unoccupied.

Appropriate belt fit is characterized by placing the belt in anatomical regions where the restraint forces can be directed onto the skeleton rather than the soft tissues, i.e., in a frontal impact, the lap belt should engage with the front of the pelvis and the shoulder belt should load the clavicle (Reed et al. 2013). If the lap belt is positioned too high on the abdomen the child may be subjected to submarining, i.e., the pelvis may slide down beneath the lap belt which would apply the loads to the abdominal soft tissue, rather than keeping the body restrained over the strong pelvic bone. Preferably the shoulder belt should be placed on the shoulder, as close to the neck as possible without causing discomfort. Placing the shoulder belt in contact with the neck may lead to misuse such as the child putting the belt behind the back or under the arm. If the belt is too far out on the shoulder, the belt may slide off during an impact. In such cases, the torso may not be properly restrained, leading to excessive head excursion and increased injury risk (Reed et al. 2013).

A belt positioning booster will elevate the child and provide the child with appropriate belt fit and a comfortable leg position while sitting upright. The adjusted geometry will result in a correct lap belt position thus preventing the child from slouching (D. Klinich et al. 1994). Slouching may increase the risk of submarining. Durbin et al. (2003) showed that injuries to the abdomen, spine, and lower extremities, for children 4-7 years old, were nearly eliminated in impacts where children were seated correctly on boosters compared to those restrained by seatbelts only. Children aged 4-8 seated in the rear seat and on a booster were 45 percent less likely to sustain injuries than children in the same age range who were restrained by the vehicle seatbelt only (Arbogast et al. 2009a). No clear evidence of any differences in the safety performance of booster cushions and highback boosters were seen in real world crash data (Arbogast et al. 2009a).

Reed et al. (2013) measured posture and static belt fit for 44 children, aged 5-12, in four highback boosters, one backless booster, and on a vehicle seat without a booster. The children were chosen based on stature and ranged between the reference statures of the HIII 6y and HIII 10y Anthropomorphic Test Devices (ATDs). The boosters differed substantially in how the seatbelts fitted the children. Indeed, the boosters providing the poorest belt fit actually produced a better belt fit than that for the children tested directly on the seat, without a booster. The effect stature had on lap belt fit was statistically significant although interaction between stature and booster type (including no booster) was not found, i.e., children of all sizes experienced fairly similar improvement in the laboratory seatbelt fit on each booster, relative to the no booster condition. The study also highlighted older children restrained by the seatbelt alone and concluded that seatbelt fit improvements when no booster is used should be focused on steeper lap belt angles, shorter seat cushions, and more appropriate D-ring locations.

Integrated booster cushions are available in some cars. An observational laboratory study (Osvalder and Bohman, 2008) of 130 children aged 4-12 was performed to assess potential misuse of booster cushions and to identify whether booster cushion design, children's age or clothing had any effect on the booster cushion performance. The study concluded that an integrated booster had many advantages compared to an accessory booster with regard to both safety and comfort, such as being easy and simple to use which resulted in a significant lower misuse rate.

In Europe, the legal requirements for the height at which a child can transition to using the vehicle belt alone range from 135-150 cm. Swedish law require children to be restrained by an appropriate child restraint system until they reach 135 cm. The dynamic testing and requirements for child restraint systems differ depending on country. Current regulated dynamic test methods to evaluate child restraint systems are limited to sled tests and not based on crashes in real car environments. With the exception of built-in child restraint systems such as the integrated booster cushion all child restraint systems are tested on a generic seat with a simplified seatbelt, not taking any vehicle restraints into account, such as pretensioners, load limiters or airbags.

1.3 CHILDREN'S POSTURES WHEN RIDING IN CARS

To assess the effectiveness of a restraint system, crash tests are in general performed with ATDs positioned according to protocol in a standardized seated posture. As Arbogast et al. (2011) state; the field of naturalistic observation of child occupant postures and seated behavior during riding is an exciting new area of research that crosses many disciplines and may provide valuable data on children's actual positions and posture when riding in vehicles. Naturalistic driving studies have become a common method of evaluating behavior and incidents, as well as normal driving.

Previous research, for example Neale et al. (2005), has primarily focused on adult occupants in the front seat. However, studies exploring seated postures in children during naturalistic riding have begun. A posture study was performed by van Rooij et al. (2005) where 10 children in the age group 1-3 were investigated, in order to study which posture children regularly adopt on longer journeys. The parents were asked to take photos of the child in the child restraint system before, during and after the journey, and to complete a questionnaire. The study found that smaller children adopted a greater variety of postures. A typical posture for older children was to stretch out one of their legs to touch against the front seat, combined with the other leg resting on the knee of the stretched leg. Sitting upright, was the most common posture, however, children often leaned to either side of their child restraint system, resting their heads on the side supports of the child restraint system. Charlton et al. (2010) examined the behavior of children in passenger vehicles, and how children were restrained and seated in their restraint systems, in a study where 12 families were recorded by video camera whenever they rode in their vehicle. The video camera was activated automatically each time the ignition was activated over a period of three weeks. It was found that the children spent approximately 70 percent of the journey time in positions where the body was out of the protective zone defined by the child restraint system structure, or otherwise away from the preferred location within the child restraint system or vehicle restraint system. Andersson et al. (2010) studied children aged 3-6 when positioned on highback boosters in the rear seat while a parent drove the car. The study comprised two different booster designs: one equipped with large head and torso side supports, and one equipped with small head side supports without torso side supports. They found that the design equipped with large side head supports more often resulted in a seated posture without the head and shoulder being in contact with the booster's back, and consequently the head being further away from the seat back. This was probably due to decreased visibility as a result of the large side supports. Shoulder-to-booster back contact was noted during an average of 45 percent of the journey time in the seat equipped with the large head side supports, compared to 75 percent in the seat equipped with the small head supports The percentage of time the subjects spent leaning inwards in the vehicle was limited to approximately 5 percent. Forman et al. (2011)

observed posture and shoulder belt fit among 30 volunteers between 7-14 years old when seated in the rear seat during night time journeys. Each child was appropriately restrained for their height and weight. Ten of the children were seated on a highback booster, ten on a booster cushion without a backrest, and ten were seated directly on the car seat. All children were restrained by the three point seatbelt. They found that the group using the seatbelt exclusively exhibited poor shoulder belt positions during an average of 78 percent of the video frames examined, followed by the booster cushion group (61 percent) and the highback booster group (17 percent). The relative lateral head displacement ranged up to a maximum of 35 cm from the initial position. Jakobsson et al. (2011) identified the seated posture and the shoulder belt positions of six children, 135-150 cm, when seated with and without a booster cushion while riding in the rear seat of a passenger car. The shoulder belt was placed on the mid shoulder for a substantially longer part of the time when seated on the booster cushion, compared to wearing the seatbelt only. Furthermore, greater individual variation in shoulder belt position on the shoulder was seen when restrained by the seatbelt only. When seated on a booster cushion, all children were positioned in a more upright lateral posture to a greater extent of time. When using a seatbelt only, the children changed body posture more frequently, and some children compensated for discomfort by rotating their upper body away from the seatbelt. Osvalder et al. (2013) collected data from video recordings, questionnaires and interviews to analyze seated postures and comfort experience from six children aged 7-9 (131-145 cm) seated on an integrated booster and a highback booster during on-road drives. When seated on the integrated booster the most frequent posture was with the entire back and shoulders against the seat back and the head upright. On the highback booster the shoulders were seldom against the backrest. The most frequent lateral seated posture for both boosters was upright with the seatbelt in contact with the neck or mid-shoulder. Moderate and extreme forward and lateral postures occurred occasionally. They concluded that the seated postures and seatbelt positions were influenced by the children's activities and perceived discomfort during the ride. Arbogast et al. (2016) have monitored 37 child occupants using a Kinect™ sensor to quantify their head position throughout normal, everyday driving trips (582 trips). More variability in head positions was observed for children on boosters compared with children in forward facing child seats with integrated belt harness.

The existing naturalistic driving studies with child occupants highlight that the self-selected postures adopted by the children were not always similar to the ATDs' seated postures when seated according to standardized protocol. Bohman et al. (2010) made a comparison of children's seated postures during on-road driving and the HIII 6y seated positions when seated according to test protocols. They concluded that the children spontaneously chose seated postures with less shoulder contact compared to the ATDs.

1.4 EMERGENCY MANEUVERS AS A CAUSAL FACTOR IN INJURY MECHANISMS

Evasive steering or braking maneuvers prior to impact is an important factor that may affect the injury outcome of all occupants. Bohman et al. (2011) identified head to front seat back impact as a predominant cause of injury for rear-seated, seatbelt restrained children, aged 3-13, who sustained AIS2+ head injuries in frontal impacts. The study highlighted vehicle maneuvers, prior to impact, as a contributing factor for such head injuries. Occupant motion, prior to impact, placed the occupant in a sub-optimal restraint condition allowing the head contact with the side interior and the back of the front seat. In approximately 70 percent of cases, children sustaining head injuries due to head contact with the side interior or the back of the front seat, were exposed to a maneuver prior to the impact.

Such maneuvers are common in the general driving population. McGehee and Carsten (2010) analyzed results from simulator studies and crash data to better understand the driver response by inattentive drivers, immediately prior to a serious vehicle impact. The results indicated that drivers involved in severe impacts generally had a premonition that an impact was imminent, allowing them time to respond by braking and diverting. From collected and analyzed data comprising 860 front impact accidents that had occurred in Japan from 1993-2004, it was concluded that the majority of the drivers had made an evasive braking and/or steering maneuver prior to impact (Ejima et al. 2009). Talmor et al. (2010) studied injured drivers using NASS-CDS data from 1993-2003 and found that braking maneuvers and steering maneuvers occurred in approximately 20-35 percent and 20-25 percent of cases independent of head injury severity, respectively. Hault-Dubrulle et al. (2011) performed a driving simulator study comprising 76 participants. They studied the changes in the driver's position during an emergency situation simulated by a frontal collision with a truck. The typical response to this type of emergency event was for the drivers' to push rearward into the seat and to straighten their arms and brace themselves against the steering wheel, or, to swerve in an attempt to avoid the impacting vehicle.

The kinematic response of adult occupants in low acceleration pre-crash situations, such as severe braking in a real car environment, has been studied in order to increase the understanding of adult occupant motion and behavior due to vehicle motion. Driver reaction to an obstacle thrown in front of the car when driving on a test track, simulating emergency braking has been studied in 13 volunteers (Behr et al. 2010). Occupant kinematics during emergency braking with one volunteer in the passenger seat (Kümpfbeck et al. 1999) and driver behavior in braking and steering maneuvers involving 49 volunteers on a test track (Zuppichini et al. 1997) have been carried out. Several studies have quantified the kinematics of the driver and front seat passenger during braking events in real traffic (Carlsson et al. 2011, Östh et al. 2013, Ólafsdóttir et al. 2013). These studies provide valuable knowledge of adult occupant kinematics during braking. Nonetheless, knowledge of how children are affected during vehicle maneuvers is limited as is data on kinematic behavior of children in emergency situations and consequently more data on the kinematic behavior of children in emergency situations are required.

1.5 TEST TOOLS TO STUDY CHILD KINEMATICS IN EMERGENCY MANEUVERS

Traditionally, ATDs are used to evaluate safety systems in crash loading. The two most recently developed child ATD families are the HIII-family and the Q-family (Figure 4). The Hybrid III series is composed of a 3, 6 and 10 year old child. The Q series represent a 0, 1, 1.5, 3, 6 and 10 year old child. The HIII child ATDs were developed in the US during the 1990s and are based on US child anthropometry data from the 1980s, predominantly relating to the biofidelity of the head, neck and thorax in frontal impacts. The Q-family ATDs are based on anthropometric data from the Child Anthropometry Database (CANDAT) collected from the US, Europe and Japan. The design of the two families of child ATDs also differ. The HIII-family was developed for frontal impacts and out-of-position testing while the Q-family was intended to be a multidirectional dummy, used for both frontal and side impacts, which has influenced their design (Wismans et al. 2008). The Q ATDs have wider and less sloped shoulders, an upward inclination of the chest and a more pronounced abdomen compared to the HIII-family.

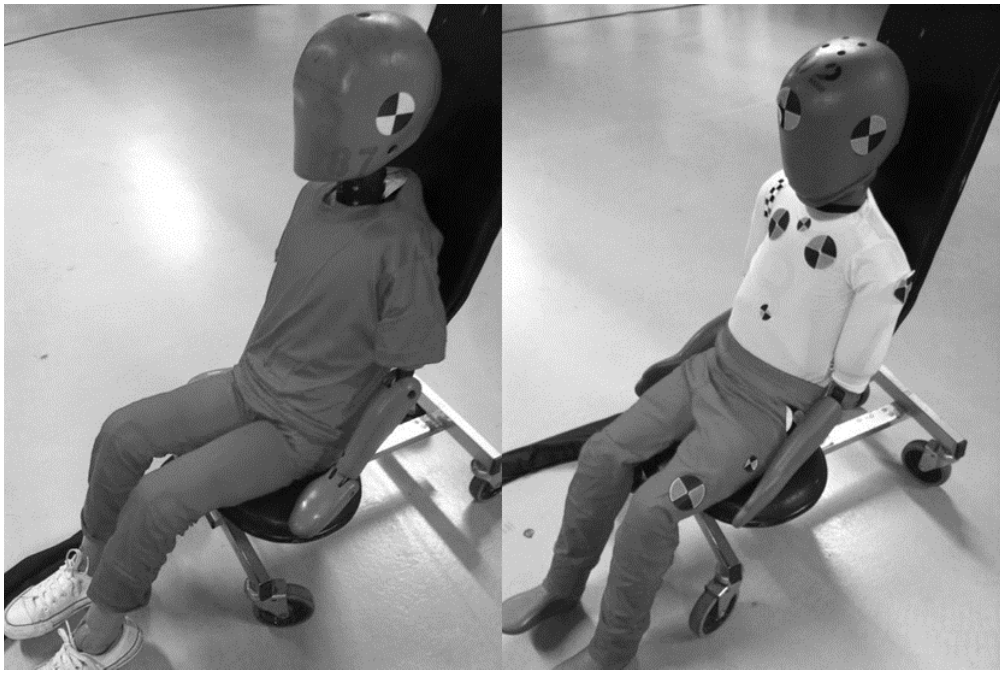

Figure 4 The Hybrid III 6y ATD, left, and Q6 ATD, right.

Several studies have investigated the kinematics of ATDs, volunteers and Post Mortem Human Subjects (PMHSs) in laboratory tests. Beeman et al. (2012) tested male adult volunteers, the HIII 50th percentile male ATD and three male PHMSs in low to moderate speed frontal sled tests. Each volunteer was exposed to two impulses at each severity, one relaxed and one braced prior to the impulse. The forward displacements of relaxed volunteers were greater than those of the ATD at both severities. For braced volunteers the forward displacements of the upper body regions were generally smaller than those of the ATD at both severities. Forward displacements of the relaxed volunteers and PMHSs were fairly similar, with the exception of the head response at both severities, while the forward displacements of the upper body of the PMHSs were generally greater than the responses of the braced volunteers.

Arbogast et al. (2009b) published the kinematics of volunteers, aged 6-40, seated on a lowback padded seat exerted for an average peak deceleration of 3.6g. Seacrist et al. compared the HIII 6y ATD (2010), the HIII 10y, Q6 and Q10 ATDs (2012) to equivalently sized male volunteers from the study by Arbogast et al. (2009b). Furthermore, the HIII 6y ATD was compared to PMHSs of similar size in 10-20g sled tests (Sherwood et al. 2003, Lopez-Valdes et al. 2009). Compared to the volunteers, the HIII 6y and Q6 ATDs exhibited greater seatbelt loads whilst the seat pan shear force was greater for the child volunteers (Seacrist et al. 2010, Seacrist et al. 2012). The HIII 6y exhibited greater head rotation and similar head top and pelvic excursion as the child volunteers, whereas the results for the Q6 were lower for all three parameters. The HIII 10y and Q10 ATDs exhibited reaction loads similar to the volunteers; however, forward displacements and head rotation were significantly reduced compared to in the volunteers. All four ATDs had less forward displacement for C4 and T1 compared to the volunteers. Seacrist et al. (2010, 2012) suggest that increasing the flexibility of the thoracic spine in the ATDs may improve their kinematics. This is also indicated in the study by Sherwood et al (2003) where the neck flexion and thoracic spinal flexion could be seen in the PMHS but not in the HIII 6y ATD.

Lubbe (2010) evaluated differences in kinematic responses between the HIII 6y and Q6 ATDs in a highback booster in three high-speed sled tests. The shoulder belt load was similar for the two ATDs although the chest deflection values differed significantly. This variation was explained by the different seatbelt movements; while the shoulder belt remained in place for the HIII 6y it slid up the thorax of the Q6 until it reached the neck. A possible cause for the difference in seatbelt interaction may be that the Q6 has a more rounded abdomen and slouched posture, as well as an upward inclination of the rib cage which is not the case for the HIII 6y (Lubbe, 2010).

While most ATDs are developed for impacts in one direction, and are therefore limited to either frontal, lateral or rear impacts, detailed numerical Human Body Models (HBMs) can represent the human response to omnidirectional impacts if sufficiently validated. HBMs are becoming increasingly popular and are used to simulate occupant responses both pre-crash and in-crash. The HBMs have the potential advantage over ATDs to simulate anatomical details and predict biofidelic kinematics and injuries at tissue level (Brolin et al. 2015a) via the incorporation of active components that simulate muscle response. HBMs are either Finite Element (FE) or Multi Body (MB) models. The currently available MB models span children of the age of 1.5-15 and the FE models cover ages 3, 6, and 10 (Brolin et al. 2015a). Whole body models are important for future research and currently much research is ongoing. There are FE HBMs of adults that include muscles or an active spine (Cappon et al. 2007, Östh et al. 2015). Brolin et al. (2015b) implemented postural control in the MADYMO human facet occupant model of a 6 year old child. Despite a simplified approach, the HBM with postural control was able to obtain kinematics similar to child volunteers in emergency events. This was not the case in simulations with the same 6 year old model without postural control.

2. AIM

Although an increasing number of children in cars are restrained, injuries still occur indicating that restraint systems have the potential for further improvement. Head injuries in particular, have been identified as the most common body region of injury for child occupants. Vehicle emergency maneuvers prior to crash have been highlighted as a contributing factor for head injuries in restrained children. Advanced driver assistance systems will probably increase the frequency of emergency events, like braking and steering, which will add to the current driver initiated emergency maneuvers that may happen prior to a crash. An emergency maneuver will most likely displace child occupants from an optimal position for restraint performance and thus influence their safety.

The overall aim of this thesis is to understand the influence of factors prior to crash, to enhance child safety in cars. Specifically, the aim is to evaluate child-to-restraint interaction for rear-seated children aged 4-12, restrained by the three point seatbelt during dynamic emergency events. Therefore the following research questions will be discussed:

- Is the frequency of emergency events prior to crash, different for crashes with child occupants compared with crashes not involving children?
- What are the kinematic responses of children in cars during dynamic emergency braking and steering maneuvers?
- Are the current ATDs representative of child occupants in dynamic emergency braking and steering maneuvers?
- Can a seatbelt pre-pretensioner reduce the kinematic responses of occupants during emergency events such as run-off road events?

3. THE CHILD SAFETY PUZZLE

The protection of children in cars is complex and broad. It requires collaborative research to address the knowledge of all parts of the child safety puzzle, as illustrated in Figure 5. Figure 5 is a schematic layout of important areas of knowledge, all important when addressing real world safety for restrained children today. A diverse set of methods must be combined to ensure optimal safety for child occupants. In order to accomplish Vision Zero it is essential to address the area as a whole. Analysis of real world data is necessary to identify and prioritize problems in motor vehicle safety for child occupants. Ideally these problems should be addressed by countermeasures, which if successfully implemented will influence the real world outcome. In order to develop countermeasures, a deeper understanding of the needs is required and evaluation methods for safety assessment reflecting these needs should be developed. Child kinematics is an essential part of the knowledge puzzle as well as for linking real world data to evaluation methods.

To ensure optimal protection in real world crashes the design of restraint systems ensuring that child specific biomechanical principles are followed are recommended. The energy needs to be absorbed effectively in a vehicle crash. The three point seatbelt restricts occupant motion and early coupling between the occupant and the seatbelt is beneficial in terms of energy absorption and the interaction should occur where the body is most durable. Hence, the seatbelt should be placed in anatomical regions where the restraint forces can be directed onto the skeleton rather than soft tissue, i.e., the lap belt should engage with the bony pelvis and the shoulder belt should load the clavicle. To protect real children in real cars it does not suffice to design child restraints to protect an ideally positioned occupant seated according to the standard seating procedures of crash test dummies. Real world safety of rear-seated child occupants, requires evaluation of protection systems beyond standard crash testing. Understanding the kinematics of children in cars is an essential part for addressing this challenge.

The seated postures of child occupants can either be a self-selected posture, or an involuntary posture due to loads from a rapid change in vehicle acceleration. Such sudden change in acceleration can be due to the driver performing an evasive maneuver. It can also happen in a critical situation where a collision avoidance system is activated and the vehicle helps the driver avoid or mitigate a collision. This thesis includes studies of emergency braking maneuvers, emergency steering maneuvers as well as run-off road events. Throughout this thesis, such events are referred to as emergency events to describe critical situations prior to an impact where the vehicle movement is outside the zone of “safe” or “normal” driving.

The present thesis follows the principle research process as described in Figure 5. The research process and the specific areas of studies included in this thesis are highlighted in Figure 5. Based on previous research it has been well established that for the smallest children, the safest restraint option for optimal protection is rearward facing. Therefore this thesis focuses on children aged 4-12 restrained by seatbelts and boosters appropriate for their size. Previous research has highlighted that it is important to focus on head injuries. Furthermore, real world data shows that head injuries still occur in crashes with children wearing child restraints, and thus far standardized vehicle tests in the laboratory with crash test dummies positioned in seated postures for optimal protection have failed to reproduce the problem. Emergency maneuvers prior to crash have been highlighted as possible reasons for head impacts in real world data, although research in this particular field is limited. This thesis aims to understand the influence of factors prior to crash, in order to enhance child safety in cars.

Paper I analyzed real world data to determine the frequency of emergency events prior to crash for child occupants. To address the problem of head injuries sustained by restrained children it is essential to understand the events leading up to the crash and the effect of these events on child occupant kinematics. To study the kinematic responses of child occupants during evasive maneuvers a repeatable test method had to be developed. This was done in Papers II and III where child volunteers were exposed to evasive braking and steering events. The outcome of Papers II and III highlighted the need of emphasizing emergency events prior to crash and to design countermeasures for improved protection. To objectively evaluate countermeasures, repeatable methods for safety assessment are needed. In Papers II and IV the current available crash test dummies were exposed to the same maneuvers as the child volunteers to assess their effectiveness in replicating child occupant responses. A potential countermeasure for improved protection was addressed in Paper V.

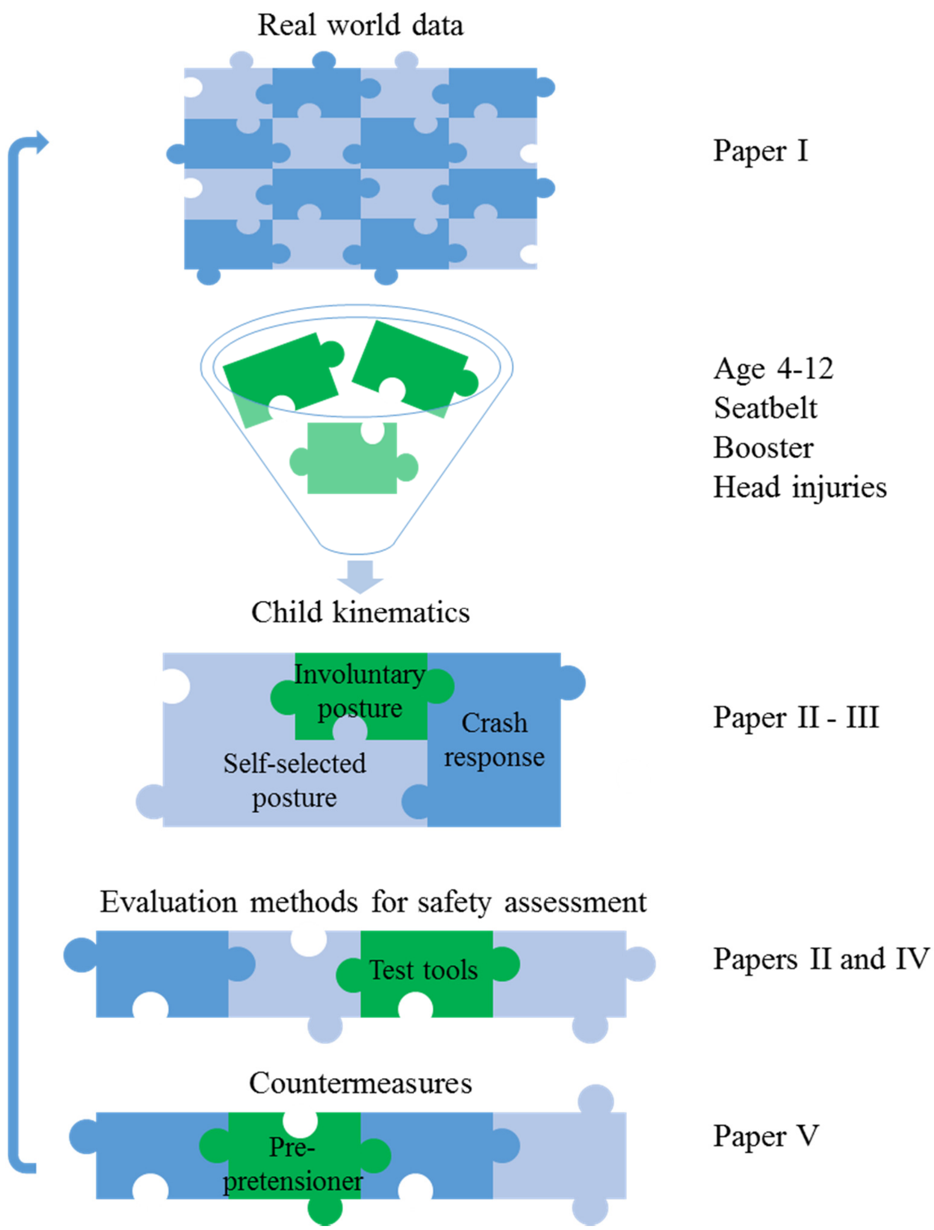

Figure 5 Schematic process of important areas of knowledge, addressing real world safety for restrained children today, illustrated as a research puzzle. Areas addressed in this thesis are *Involuntary posture*, *Test tools* and *Pre-pretensioner*.

4. SUMMARY OF PAPERS

This thesis is based on findings from five studies, described in Table 1, that examine the safety of children in passenger vehicles. Combined, the studies include several methods to enhance child safety by understanding how forward facing children, and current physical test tools, are interacting with the three point seatbelt during emergency events, and the frequency of such events prior to crash.

Papers II and III have been extracted from the same experimental study conducted in 2010 and the same method was used in Paper IV conducted in 2012. Therefore Paper II-IV is discussed together.

Table 1 Overview of the five papers included in this thesis.

	Paper I	Paper II	Paper III	Paper IV	Paper V
Aim	Quantify avoidance maneuvers prior to crash, and specify critical reasons for the pre-crash event among crashes where at least one child aged 0-14 was present as passenger	Quantify and compare the kinematics and shoulder belt position of child volunteers and child ATDs during emergency braking events	Quantify and compare the kinematics and shoulder belt position of child volunteers during emergency steering events	Quantify and compare the kinematics and shoulder belt position of child ATDs during emergency steering events	Investigate seatbelt pre-pretensioner effect on ATDs during run-off road events
Study design	Cohort study	Experimental study	Experimental study	Experimental study	Experimental study
Data	NMVCCS - Nationally representative survey of light vehicle crashes conducted by NHTSA (2005-2007)	Video and vehicle data	Video and vehicle data	Video and vehicle data	Video and vehicle data
Country	US	Sweden	Sweden	Sweden	Sweden
Number of cases	841	46	32	16	17
Age range children (years)	0-14	4-10	4-10	N/A	N/A
ATDs	N/A	Q3, HIII 3y, 6y, 10y	N/A	Q6, Q10, HIII 6y, 10y	Q6, Q10, HIII5th
Emergency event	All	Braking	Steering	Steering	Run-off road

4.1 PAPER I

4.1.1 Background and objective

It is important to have an understanding of the events leading up to a crash in order to prevent a motor vehicle crash from occurring, and to reduce the number of traffic fatalities and injuries. The overall objective of this study was to quantify pre-crash maneuvers and some causation factors of serious motor vehicle crashes involving child passengers. Specifically, using the NMVCCS study to specify and quantify the frequency of avoidance maneuvers prior to crash and critical reasons for the pre-crash event among crashes involving light passenger vehicles where at least one child aged 0-14 was present as passenger. In addition, for the most frequent driver related critical reasons, specify the most frequent crash scenarios (defined as integrated information on a vehicle's movement prior to crash, immediate pre-crash event, and crash configuration). As a point of reference, vehicles with child passengers will be compared with vehicles without passengers (single drivers) and vehicles with only passengers older than 14.

4.1.2 Method

The National Motor Vehicle Crash Causation Survey (NMVCCS) conducted by the National Highway Traffic Safety Administration (NHTSA) between July 2005 and December 2007 was used in this study. The study identified pre-crash factors via investigation of vehicles and crash scenes, and structured on-scene interviews with crash participants. The critical reason for each crash was assigned to a single driver, vehicle or environmental factor. The selected sub-samples for this study included 841 (weighted 308,743) drivers with at least one child passenger, 5,661 (weighted 2,209,082) single drivers, and 1,544 (weighted 537,787) drivers with only passengers older than 14. All drivers were aged 18 and older holding a current and valid driving license at the time of crash.

4.1.3 Results and discussion

Of all drivers in the selected sample, 40 percent (weighted) made an avoidance maneuver prior to crash. The most common avoidance maneuver was braking only, followed by a combination of braking and steering, and steering only (Table 2). Among drivers with at least one child passenger who made a maneuver, 45 percent only applied the brakes, 28 percent applied the brakes and steered, and 22 percent steered only.

Table 2 Frequency of vehicle pre-crash maneuvers, by sub-sample.

	Passenger aged 0-14		**Single driver**		**Only passenger older than 14**	
	UnW N	W %	UnW N	W %	UnW N	W %
Total	841	100	5661	100	1544	100
Maneuver	376	42.6	2284	40.0	595	37.2
Braked	167	45.0	1052	47.1	257	40.3
Steered	57	22.0	333	15.7	84	19.7
Braked and steered	125	27.7	782	33.4	214	35.4
Accelerated	11	2.0	67	1.8	23	2.1
Other	16	3.3	50	2.0	17	2.6

In all three sub-samples, driver error was the single most important critical reason for the event immediately preceding the crash. Of the driver errors, inadequate surveillance was the most common error in all groups followed by internal distraction. While passengers were the most common reason for internal distraction for drivers in the child passenger and driver with only passengers older than 14 sub-samples, single drivers were assigned internal distraction error, mainly due to focusing on other internal objects, retrieving objects from the floor or seat, or adjusting the radio. Drivers with child passengers, who were assigned driver critical error, were involved in 142 crash scenarios of which the top five crash scenarios accounted for 37 percent of the crashes with the most common including *going straight, other vehicle stopped, rear end.* The top five crash scenarios for single drivers and drivers with only passengers older than 14 were similarly drivers with child passengers, with one exception for the single driver sub-sample, although ranking of the crash scenarios was different.

Ideally the data should be contemporary, broad enough to be representative of all crashes on the roads, and provide information on the whole chain of events leading up to the crash as well as detailed information regarding restraint usage and injury severities for all occupants in the car. The data used was collected during 2005-2007 – the only years the NMVCCS study was in operation. Modern vehicles have more active safety systems available, such as autonomous braking, that help the driver in a critical situation. However these advanced driver assistance systems have not yet penetrated significantly within the vehicle fleet and the effects of these advanced technologies are unlikely to strongly influence contemporary crash data. Therefore, using data from 2005-2007 to study crash scenarios is considered representative of the today's circumstance.

Overall, it was found that drivers with child passengers who made a driver critical error in a crash are involved in comparable crash scenarios due to similar critical reasons as single drivers or drivers with only passengers older than 14. These findings suggest that countermeasures designed for one group of drivers may be helpful for other groups of drivers, as well. Enhanced understanding of the events leading up to a crash and the influence of pre-crash factors specifically targeting drivers with children as passengers will likely help drive the development of occupant protection as well as crash avoidance and mitigation technology beneficial for child car occupant safety forward.

4.2 Papers II, III and IV

4.2.1 Background and objective

Head impact to the seat back has been identified as one important injury inducing scenario for restrained children sustaining head injuries, and previous research highlighted vehicle maneuvers prior to impact as a possible contributing factor. The objectives of this study were to quantify, compare and discuss the kinematic response of children (Paper II-III) and child ATDs (Papers II and IV) during emergency maneuvers in different restraint configurations in a passenger vehicle.

4.2.2 Method

A driving study was conducted on a closed circuit test track comprising 16 children, aged 4-10 years old and the six ATDs: the Q3, Q6, Q10, HIII 3y, 6y and 10y ATDs, restrained on the right rear seat of a modern passenger vehicle (Volvo XC70 model year 2010). Shorter children (stature 107-123 cm) and the Q3, Q6, HIII 3y and 6y were restrained on a booster cushion as well as a highback booster. Taller children (stature 135-150 cm) and the Q10 and HIII 10y were restrained on a booster cushion or restrained by three point seatbelts directly on the car seat. The same professional driving instructor drove the test vehicle in all tests. The vehicle data collected included vehicle velocity, acceleration in longitudinal and lateral directions, and brake pressure. Four small video cameras were affixed inside the vehicle providing a front view of the child, a perpendicular lateral view, and two oblique views of the child volunteer. The recording rate was 12.5 frames per second. Vehicle data were synchronized with video data.

Paper II

The brakes of the vehicle was applied to a full stop while traveling at a velocity of 70 km/h. The children were exposed to one braking maneuver in each of the two restraint systems whilst the Q3, HIII 3y, 6y and 10y ATDs were exposed to two braking maneuvers in each restraint system. All maneuvers had a deceleration of 1g. The braking maneuver was identified by simultaneously viewing the vehicle data and the video sequences captured by the four video cameras. The beginning of the braking maneuver was defined as the point in time prior to when the brake pressure began to increase drastically. The ending of the braking maneuver was defined as the point when the longitudinal acceleration returned to level zero. The relevant frames were imported into TEMA v3.12 (Image Systems) in order to track the targets of interest. Forward trajectories for the forehead and external auditory canal (ear) were determined as well as head rotation and shoulder belt force.

Paper III

While traveling at a velocity of 50 km/h, the vehicle was steered sharply to the right at cones on the test track (Figure 6), resulting in inboard motion of the children. The children were exposed to two steering maneuvers in each of the two restraint systems. The time point of a lateral acceleration of 0.2g was used to synchronize all lateral acceleration pulses when calculating the average lateral acceleration. 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. The lateral acceleration pulse and the time points are shown in Figure 6. 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 0.2s after the synchronization time point, i.e., 0.2s after a lateral acceleration of 0.2g, with the purpose of studying the child after they had begun to move laterally, during the ramping in lateral acceleration. T3 was defined as the time at the end of initial ramping in lateral acceleration, which occurred 0.3s after T2. The analysis was based on a gridline consisting of three vertical lines placed along the outboard side of the upper torso, along the inboard side of the upper torso, and a centerline of the two torso lines. Furthermore; a horizontal line was placed perpendicular to the outboard torso line at the level of the top of the left shoulder, and finally a reference line along the vertical centerline of the seat. The following assessments were made for each child in each trial for the three defined time points, T1-T3: shoulder belt position on shoulder, child's lateral position relative 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.

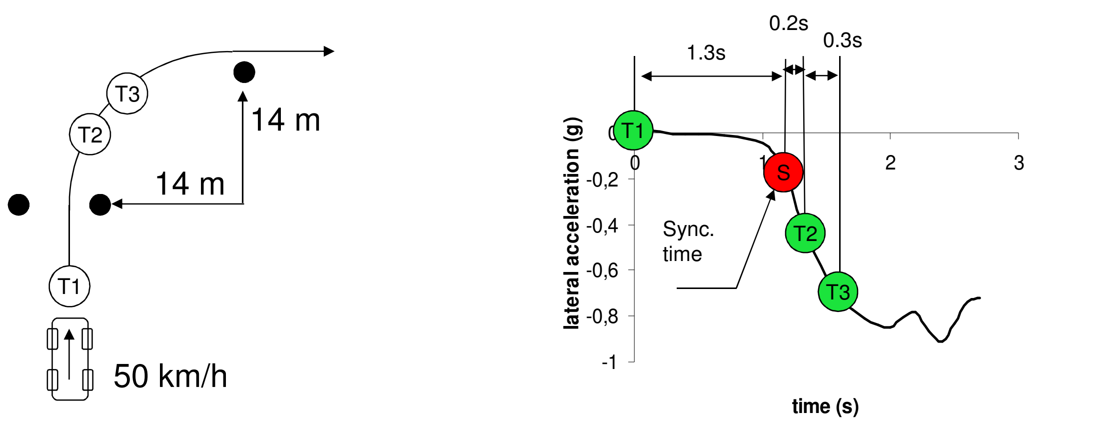

Figure 6 Left: a sketch of the turn. The dots represent cones placed on the test track. T1, T2 and T3 were time points used in the analysis. Right: The average lateral acceleration and three time points at which occupant kinematics were analyzed.

Paper IV

While traveling at a velocity of 50 km/h, the vehicle was steered sharply to the right at cones on the test track. The Q6, Q10, HIII 6y and 10y ATDs were exposed to two steering maneuvers in each restraint system. The event was identified by simultaneously viewing the vehicle data and the video sequences captured by the four video cameras. The beginning of the event was defined as the point in time 0.5s prior to a lateral acceleration of 0.2g. The ending of the event was defined as the point the vehicle passed the last cone on the track and exited the curve. The frames capturing the event were imported into TEMA v3.12 (Image Systems) in order to track the targets of interest. Lateral inboard motion of the forehead and upper sternum was determined as well as the torso tilting angle and shoulder belt movement on the shoulder.

4.2.3 Results

Paper II

A total of 40 trials were analyzed. Child volunteers had greater maximum forward displacement of the head and greater head rotation compared to the ATDs (Figure 7). The forward displacement was within the same range for all children regardless of stature and restraint system. However, the maximum forward position depended on the initial seated posture and shoulder belt position on the shoulder. The average maximum displacement for children ranged from 165-210 mm and 155-195 mm for the forehead and ear target, respectively. Corresponding values for the ATDs were 55-165 mm and 50-160 mm.

Figure 7 Maximum forward displacement of a child from the shorter group (top left), child from the taller group (top right), the HIII 6y (bottom left) and the HIII 10y (bottom right).

The shorter children exhibited a greater flexion motion of the neck and moved forward and downward whilst a more upright posture at maximum forward position was exhibited by the taller children. All ATDs displayed less forward displacement and head rotation than the child volunteers; the HIII 6y on a booster cushion was closest to representing the kinematics of a child of similar age/size in this setup. The change in head angle was greater for shorter children than taller children. The shoulder belt force was within the same range for shorter children when restrained on a booster cushion as when restrained on a highback booster. For taller children, the shoulder belt force was greater when restrained on a booster cushion compared to being restrained by seatbelts directly on the car seat.

Paper III

A great variety of responses were seen in different child volunteers (Figure 8). The children moved approximately 100 mm laterally, regardless of stature or restraint system. Depending on the initial seated posture and size of the child, different shoulder belt positions was observed. The shoulder belt slipped off the shoulder in almost 67 percent of the trials for the shorter children restrained by a booster cushion. The shoulder belt was kept on the shoulder when the shorter children were restrained by a highback booster, although half of the trials resulted in the shoulder belt being positioned far out on the shoulder. For the taller children no belt slip-off occurred. In the taller group, the distance the shoulder belt moved relative 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 taller children were restrained by seatbelt only. Taller children seated on a booster cushion demonstrated a shoulder belt position far out on the shoulder as a result of the steering maneuver.

Figure 8 A child from the group of shorter children on a booster cushion, left, and a child from the group of taller children on a booster cushion, right.

Paper IV

Results for the ATDs were presented as mean values plus/minus the difference of maximum and minimum value of the two trials in each restraint system. For comparison with the child data from Paper III, the results were presented at the time points T2 and T3, presented in Paper III, as well as at maximum inboard position. All ATDs started to move approximately at the same point in time corresponding to a vehicle lateral acceleration of just below 0.2g. There was a small lateral shift inboard for all ATDs before the tilting of the upper body occurred. The

ATDs reached their maximum inboard position approximately when the ramping phase of the lateral acceleration was finished and the plateau was reached. All HIII ATDs showed greater inboard displacement when compared to their Q-family counterpart. Positions of the Q6, HIII 6y, and a representative child from the short group and the Q10, HIII 10y, and a representative child from the tall group on a BC, respectively, are shown in Figures 9 and 10 with respect to initial position and position at T2 and at T3. As can be seen in Figure 9, the Q6 and HIII 6y ATDs had less inboard displacement compared to the child volunteer at T2, whereas at T3 the HIII 6y had moved further inboard compared to the child. The Q6 had the shoulder belt far out on the shoulder at T3 and the HIII 6y and the child had shoulder belt slip-off. As can be seen in Figure 10, the Q10 showed less inboard displacement at T3 compared to the child volunteer, whereas the HIII 10y had greater displacement.

Figure 9 Position of the Q6 (top), HIII 6y (middle) and child from the short stature group (bottom) on a booster cushion. From left to right: initial position, position at T2, and position at T3.

Figure 10 Position of the Q10 (top), HIII 10y (middle) and child from the tall stature group (bottom) on a booster cushion. From left to right: initial position, position at T2, and position at T3.

4.2.4 Discussion of results

Paper IV provides valuable knowledge on how representative the current ATDs are of replicating potential pre-crash postures of children, as a result of a vehicle emergency steering maneuver, for a variety of restraint systems and child ATD sizes. During emergency steering maneuvers all ATDs tended to fall inboard, to different degrees, depending on their anatomy and the initial position of the seatbelt. Children, on the other hand, were generally able to control their movement and attempted to return to their initial seated position (Paper III). A steering maneuver can be a complex and unstable restraint situation for occupants in the rear seat and substantial variation were seen between child volunteers. The question of which ATD better replicates the behavior of children exposed to steering maneuvers still remains open. As shown in Paper IV, this depends on the focus of the comparison and on what phase of the maneuver is of interest. Compared to the children, the HIII ATDs were closer with regard to mean values in the initial phase of the maneuver, whereas the Q ATDs were closer in the end of the ramping phase of the lateral acceleration. Due to the large variety in lateral displacements for the children, the child performance range covers both the dummy families for the evaluated sizes of 6 and 10 year old ATDs.

The method of analysis was improved between the analysis of the child volunteers (Paper III) and the ATDs (Paper IV) during the steering maneuver. For the steering maneuvers comprising child volunteers (Paper III), the lateral inboard movement and shoulder belt position on the shoulder, were quantified at three distinct time points by using a gridline system. For the steering maneuvers comprising the ATDs (Paper IV), all frames during the maneuver were tracked using tracking software and the corresponding assessments were performed. By using tracking software, the method of analysis is more reliable, less dependent on the user, and human error and qualitative analysis is reduced. The assessments are more repeatable as well as more quantitative. In Paper IV, when comparing the results of the two methods of analysis for the steering maneuvers, it was evident that the final results were similar.

One factor influencing the results of Paper II-III was that the children were not given specific instructions regarding how to sit and behave inside the vehicle, resulting in differences in the initial seated posture and head position among the test subjects. The children knew the drive would include steering and braking maneuvers, but were not told exactly when the maneuvers would take place. A relaxed child would better simulate a real life situation, i.e., the results would be more realistic if the child is not prepared for quick and unexpected maneuvers. It was determined that the youngest children, aged 4-5 years, may have had difficulties understanding instructions of what was expected of them during the test. Had they been instructed to be relaxed, the outcome may have been the opposite since they may then have focused on their bodies and the imminent maneuvers. Each child was exposed to three braking events and four steering events. All children started with a braking event as a test event. After that, one braking and two steering events per restraint configuration was conducted in a randomized order. The method was repeatable with regard to vehicle acceleration and movement during the test due to the very skilled professional driver. The repetitions for each child volunteer were few, which is a limitation. No difference was seen in the results between the first and last trials in Paper II-III, indicating that the children did not seem to adapt and learn from previous test situations. However, it is possible that the children became familiar with the process and did adapt although this did not affect the kinematic measurements.

Despite some individual differences in belt fitting at the time of the braking maneuver or steering maneuver, the children and ATDs were restrained with the shoulder belt over the shoulder, the belt tightened to reduce potential slack and the lap belt was positioned under the guiding loops of the boosters. In reality, a large proportion of misuse (incorrect use of restraint systems) occur among children restrained on a booster cushion (NHTSA, 2004), however such positions have not been included here.

The assessment system used in Paper II-IV included vehicle data and video data from four cameras enabling a connection between occupant kinematic responses and vehicle motion. The lowest sampling frequency in the assessment system was for the cameras which had a sampling rate of 12.5 frames per second. Video data and vehicle data was viewed simultaneously. The vehicle data was used to define the beginning and end of the maneuvers as well as the points in time where the kinematic responses of the occupants were compared. Since the vehicle data had a higher sampling frequency than the video data, only the vehicle data points, where a corresponding frame existed, were shown. This resulted in that the frame closest to the defined starting point and analysis point (T2, T3) was chosen. For the steering event this affected the lateral inboard displacement due to small variations in the lateral acceleration at the time points T2 and T3. The average lateral accelerations with standard deviation at time points T2 and T3 for the tests with ATDs (Paper IV) were $0.43g \pm 0.05$ and $0.72g \pm 0.03$, respectively. For the tests including child volunteers (Paper III), the corresponding accelerations were 0.51g ± 0.07 and 0.77g ± 0.04. The differences in acceleration levels at T2 and T3 were not statistically significant. For the braking maneuver, this had an effect on the time from the beginning of the maneuver, defined as the point in time prior to when the brake pressure drastically increased, until the occupant began to move forward and reached maximum forward position. The children started to move forward approximately 0.2s after the brake pressure was increased. During the braking event the children's torso moved forward until sufficiently restrained by the shoulder belt. Maximum forward displacement occurred for the children's head approximately 0.5s after the initial braking event, and the children stayed in this position for approximately 2s before the rebound phase began. Using a higher sampling frequency, the point in time when the forward motion of the children started would have produced a more precise measurement although it only had minor effect on the maximum forward displacement, the main results and conclusions.

Ideally the gender selection would have been equal, however anthropometry data of children in this age group who have not reached puberty show no gender difference (Pheasant and Haslegrave, 2006).

In summary, the braking and steering maneuvers with child volunteers and ATDs carried out in Paper II, III and IV provide novel and unique knowledge of possible postures of children and currently available ATDs across a variety of restraint systems in vehicle emergency maneuvers. The test methods and methods of analysis were repeatable and the results offer input to safety system development, ATD design as well as test method development.

4.3 PAPER V

4.3.1 Background and objective

Run-off road events are another frequent emergency pre-crash maneuver that can result in severe consequences. Several potential injury causing mechanisms are seen during the diverse types of events. Real world data shows that different types of environment, ditch types and whether multiple events occur, may be important contributing factors to occupant injury. While countermeasures addressing front seat occupants have been presented, studies on the rear seat occupant retention in situations such as a run-off road event are lacking. The aim of the study was to investigate the seatbelt pre-pretensioner effect on rear-seated ATDs during run-off road events.

4.3.2 Method

The study was carried out using two test setups; a rig test with a vehicle rear seat mounted on a multi-axial robot simulating a road departure event into a side-ditch (Figure 11), and a test setup with a passenger car entering a side ditch with a grass slope, driving inside the ditch, and returning back to the road from the ditch. Three different ATDs were used. The Q6 and Q10 were seated on an integrated booster cushion and the HIII 5th female was positioned directly on the seat. The seatbelt retractor was equipped with an electrical reversible retractor (pre-pretensioner) with three force level settings: low, medium and high. In addition, reference tests without activation of the pre-pretensioner were run as well.

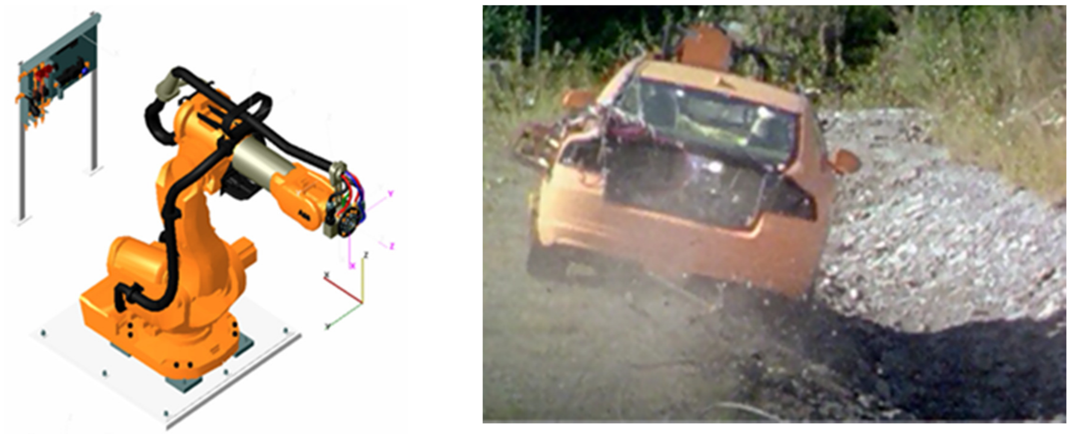

Figure 11 Robot used for the road departure rig test (left). Road departure test programmed into the robot rig (right).

In the rig test, in total eight test configurations were run, including a variation of ATD sizes, two different pre-pretension forces in addition to no pre-pretension. One test configuration; the HIII 5th female with the pre-pretension inactivated, was repeated three times, in order to investigate the repeatability of the test setup. In total, 10 tests were conducted. Three high speed cameras were used providing a front and side view of the complete test rig, and a top view of the belt retractor and shoulder of the ATD. The recording rate was 250 frames per second. The front view camera was used to quantify the lateral motion of the head of the ATDs relative to the starting position centralized in the seat. The relevant frames were imported into TEMA v3.5-012 (Image Systems) in order to track the forehead target to determine maximum lateral head motion during the event. In addition, the kinematic responses and the shoulder belt position on the shoulder and upper body were analyzed.

The test setup with a vehicle driving into a side ditch with a grass slope, driving in the ditch, and driving up from the ditch was conducted at a closed test track. The test track sequence was programmed into the steering robot. The seatbelt retractor was activated when the vehicle started to drive off the road and down into the side-ditch. In total nine tests were run, including a variation of ATD sizes, two different pre-pretension forces in addition to no pre-pretension. A camera was mounted inside the vehicle facing the left outboard rear seat, where the ATDs were placed. With the objective of evaluating the shoulder belt position relative to the ATD shoulder during the inboard movement at the end of the event, the video was analyzed to determine maximum inboard lateral motion of the head of the ATD. No effort was made to quantify the exact positions.

4.3.3 Results and discussion

In the road departure rig tests, head displacement for each ATD was reduced when the pre-pretensioner was activated compared to tests when it was inactivated (Figure 12). Maximum inboard displacement occurred earlier in the event, for all ATDs, when the pre-pretensioner was activated. Shoulder belt slip-off occurred for the Q6 and Q10 in tests where the pre-pretensioner was inactivated. Although the belt did not slip off the shoulder of the HIII 5th female in any of the tests, when the pre-pretensioner was inactivated, it did settle further out on the shoulder compared with tests with the pre-pretensioner activated. During run-off road driving in a side-ditch test setup, maximum inboard displacement occurred when driving back up from the ditch. Maximum inboard displacement was reduced in tests where the pre-pretensioner was activated compared to tests in which it was inactivated

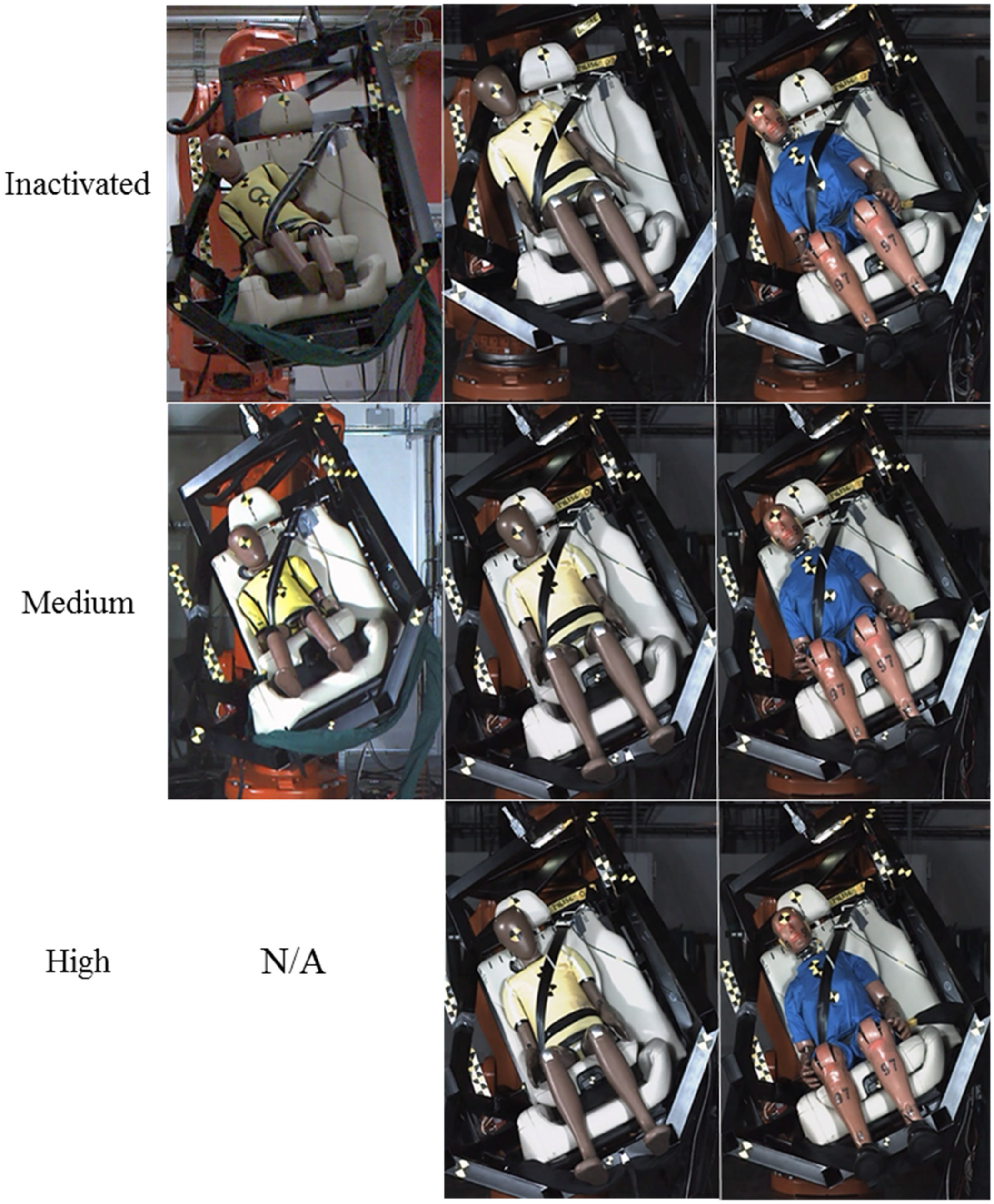

Figure 12 From left to right: Maximum inboard position of the Q6, Q10 and HIII 5th female with the pre-pretensioner inactivated (top) and pre-pretensioner activation of medium force (middle) and high (bottom). The Q6 was not tested with the high pre-pretensioner force (bottom left).

This study provides data on the kinematics of ATDs during complex events and evaluates the influence of a potential countermeasure. It provides evidence that the pre-pretensioner has a substantial potential in maintaining different sizes of rear-seated occupants well restrained. The test setups developed and used in this study are unique and provide possibilities to evaluate occupant kinematics in complex events. Although the ATDs are not developed for this purpose, the design of the test setups and the method of analysis are believed to be within their capacity.

In the simulated run-off road tests, the activation of the pre-pretensioner resulted in reduced lateral excursion of the Q6, Q10 and HIII 5^{th} female due to the shoulder belt remaining on the shoulder, and by retaining the torso. The results provide new insights in the potential benefits of a pre-pretensioner to reduce kinematic responses during complex run-off road events in helping maintain the shoulder belt on the shoulder. This study addresses the potential of countermeasures improving real world protection of children in rear seats, and provides a wider perspective including the influence of pre-crash kinematics. In addition, it emphasizes child occupant protection as an integrated system, comprising vehicle restraints and child restraints.

5. GENERAL DISCUSSION

The focus of this thesis was to understand the influence of factors prior to crash to quantify the kinematic response of child occupants and child crash test dummies during emergency events preceding a crash, in order to provide knowledge for improving child safety. Enhanced knowledge is needed to make appropriate decisions when designing new test tools, improved evaluation methods for safety assessment, and future countermeasures. The outputs of this thesis are real world data analysis, kinematic responses of child volunteers and ATDs in vehicle emergency events, and evaluation of an advanced countermeasure – improved seatbelt design.

Analyzing real world data is important to increase the protection of children in cars since such data includes real world situations with actual child occupants and drivers in real vehicles. Through analysis of real world data, Paper I identified that a substantial portion of drivers attempted an avoidance maneuver prior to crash. Paper II-III confirms that children can be in sub-optimal postures due to emergency events that may place them at risk for head injuries in a crash. The seated postures of child occupants can either be an involuntary posture due to rapid motion of the vehicle as in Paper II-III, or a self-selected posture (Jakobsson et al. 2011, Osvalder et al. 2013), influenced by children's activities and distractions, as well as perceived discomfort, including booster and seatbelt positions.

Today, advancement in vehicle safety is driven through testing of ATDs in a single, standardized posture centralized in the seat. Generally, this is not representative of the seated posture of most real children (Paper II-III, Andersson et al. 2010, Jakobsson et al. 2011, Osvalder et al. 2013). Sub-optimal restraint situations for children exposed to emergency maneuvers were identified in Paper II-III. A possible solution to address the sub-optimal postures due to emergency events (Paper II-III) was tested in Paper V where a seatbelt pre-pretensioner was activated prior to run-off road events with child ATDs. The results were promising in keeping the seatbelt on the shoulder during the event.

It is important to protect children by minimizing the risk of them getting in to potentially dangerous positions and by protecting them, should they for whatever reason, still find themselves in a sub-optimal position. As real world crashes are complex and diverse, one sub-optimal position may not be dangerous while another may be very dangerous. It is essential to increase the knowledge of children's seated postures and kinematics during car rides in order to enhance the safety for children in cars. Existing test methods need to be improved to better reflect real world conditions, hence realistic seated postures simulating real children in real cars need to be incorporated in future evaluations. Furthermore, test tools are needed to better replicate real world injury causation scenarios. Papers II and IV evaluated the available physical child sized test tools in low acceleration conditions when exposed to emergency events and highlighted the difficulties capturing child kinematics in emergency events with existing ATDs.

This thesis provides further understanding of how the child-to-restraint interaction alters during emergency maneuvers prior to crash, the influence of seated postures, vehicle geometry, as well as vehicle motion, on occupant posture. The findings of this thesis also highlight that in order to best protect children in a crash, it is crucial to consider how child kinematics are affected by emergency events prior to crash.

While this thesis has addressed some pieces of the child safety puzzle as presented in Figure 5, it is essential to connect these pieces to other pieces aiming for overall safety for children in cars. Especially, important pieces of the puzzle that would contribute to this thesis are those linking the child kinematic responses in emergency events to consequences and injury risk in a crash. The relation between the prevalence of sub-optimal postures and how dangerous such postures would potentially become in the event of a crash, is an example of areas that should be further investigated as a complement to current knowledge on child kinematics in emergency events. Test tools to capture kinematics of child occupants must be improved to capture child kinematic responses in emergency events as well as different types of crash situations. This will likely include HBM development due to the challenges of pre-crash and in-crash kinematics for physical test tools. Developing such test tools would provide the opportunity to investigate further types of countermeasures besides the pre-pretensioner, enabling impact on real world safety benefit for children.

5.1 METHODOLOGICAL REFLECTIONS

A variety of complementary methods were used in this thesis including real world crash data, kinematic studies of child volunteers and ATDs in a real car environment, and laboratory tests with ATDs. There are several aspects of these methodological approaches that advance previous work.

Real world data reflects a variety of crash circumstances and provides information on the relative safety of cars. To understand how emergency events prior to crash affect child occupants in a crash it is important to combine information of the variety of events leading up to a crash and reasons for their occurrence, as well as information regarding injuries and occupant injury severity. It is necessary to obtain detailed information of the injuries to fully comprehend how these injuries occur. The piece connecting the series of events leading up to a crash, and injury severity together with injury mechanism, is currently missing from literature. A combination of real world data, volunteer and crash tests, as well as numerical simulations would help fill this gap. This thesis objectively provides measurements of how vehicle motion during emergency events affects the seated posture and belt geometry of forward facing child occupants restrained by three point seatbelts.

Real world data from naturalistic driving studies comprising children have presented data on the seated postures children naturally adopt when traveling in passenger vehicles. Through recorded video data or photos, their different seated postures were categorized according to pre-defined postures, and the duration of each posture was determined (van Rooij et al. 2005, Charlton et al. 2010, Andersson et al. 2010, Jakobsson et al. 2011, Osvalder et al. 2013). In the study by Forman et al. (2011) the lateral distance the forehead moved was determined using software, while the shoulder belt position was qualitatively described using three pre-defined shoulder belt positions. Arbogast et al. (2016) contributes with a method to quantitatively determine the postures of children in a large amount of data. The findings in these studies are valuable and give increased knowledge on how different restraint systems affect seated posture and what effect, if any, distractions such as talking to someone in the front seat or seeing something interesting outside the vehicle, has on the behavior. However, vehicle data was not recorded in van Rooij et al. (2005), Charlton et al. (2010), Andersson et al. (2010), Jakobsson et al. (2011), Osvalder et al. (2013) and it remains unknown how posture is related to vehicle movement, such as rapid changes in acceleration due to an emergency braking or steering event. In Paper II-IV, vehicle data and video data were recorded simultaneously to enable a direct relation between the measured variables and the vehicle interior. This relationship is important when designing advanced driver assistance systems as well as occupant protection technologies.

While one advantage of the test setup in Paper II-IV was that vehicle data and video data were recorded simultaneously, it is a limitation that a test track study is not fully naturalistic. In order to capture enough emergency events to be able to draw any conclusions a significant amount of trips must be collected. Future large naturalistic driving studies should focus on drivers as well as passengers. A majority of the large existing naturalistic driving studies were designed with the purpose of studying driver behavior and did not install video cameras observing other potential occupants in the vehicle. Even when the passenger seat and rear seat are visible, the data cannot be published due to the lack of consent from the passengers.

In addition, a limitation of Paper II-IV is that one vehicle model and two boosters were used in the evaluation. Rear seat design including seatbelt and seat geometry is likely to influence the forward and lateral motion of the occupant during maneuvers. Similarly, only one seat geometry was evaluated in Paper V. As presented by Reed et al. (2009, 2013) the differences in lap belt and shoulder belt fit among boosters are relatively large which may result in different combinations of vehicles and boosters producing contradicting results. Different belt geometries were evaluated briefly, by using a variety of restraint systems (i.e., booster cushion, highback booster, integrated booster cushion), although further studies are required for a more comprehensive view.

Furthermore, the occupant tools used in Paper V are ATDs developed for crash testing, have inherent limitations when used in situations such as in this study. Although not developed for evasive maneuvers, the analysis of the tests conducted for Paper V stays within the capacity of the ATDs as shown in Paper IV, due to the design of the test setups and the method of analysis.

5.2 CHILD KINEMATICS IN EMERGENCY MANEUVERS PRIOR TO CRASH

Several studies have highlighted that drivers usually have a premonition of impending critical situations and try to brake or steer to avoid a potential crash (Ejima et al. 2009, Talmor et al. 2010, McGehee and Carsten 2010, Hault-Dubrulle et al. 2011). The findings from Paper I show that two out of five drivers made a maneuver before crash. However, despite an avoidance maneuver they were all involved in a crash. This suggests that the maneuver did not influence the course of events, or the braking and steering inputs from the drivers were not sufficient, and that drivers could possibly have benefitted from advanced driver assistance systems. It is likely that we will see an increasing amount of autonomous braking and steering in the future, which will add to the current manual braking and steering events. A successful maneuver that results in avoiding a crash is the best alternative, however this thesis emphasize the importance of understanding the consequences of a maneuver that would possibly put the occupant in a sub-optimal position. If the driver attempts to avoid the crash by making an avoidance maneuver, but is still involved in a crash, that avoidance maneuver may in reality put the child in a sub-optimal position with sub-optimal belt geometry (Paper II-III), which may in fact increase the risk of children being subject to more severe injuries in a crash compared to children who are seated similarly to the ATDs when positioned according to test protocol.

For children who experienced shoulder belt slip-off during the steering maneuver (Paper III) the shoulder belt slipped off early in the maneuver sequence. From the video analysis it was obvious that the design of the crash pulse (acceleration vs time), the slope of the pulse and especially the start of the pulse, affect occupant kinematics to a greater extent than the peak acceleration values later in the maneuver. We tested this hypothesis in Brolin, Stockman et al. (2015b) where postural control was implemented in the MADYMO human facet occupant model of a 6 year old child using feedback controlled torque actuators. Control parameters were tuned and the active HBM was compared to experimental data from Paper II-III. It was shown that the shape of the acceleration pulse highly influences the peak head displacements of the active HBM. Although limited, this study shows the importance of developing active HBMs of children to use when evaluating autonomous safety systems. Even though the study was small and further research is needed to address this issue; the aspect of the design of the acceleration pulse needs to be considered when autonomous safety systems are designed.

The different restraint systems affected the maximum forward displacement relative to the vehicle in the braking maneuvers, (Figure 13). When the backrest was fitted (highback booster), the children began and ended in a position further forward compared to when seated on the booster cushion. The maximum forward head position was considerably further forward than the side supports of a highback booster will cover. In line with the findings by Reed et al. (2006), when the children were elevated by the booster cushion, the initial position of the head was further rearwards compared to when seated directly on the seat,. Taller children displayed a forward displacement within the same range irrespective of restraint system (booster cushion vs seat belt only); hence a more rearward initial position produces a less maximum forward position relative to the vehicle. This may be of importance in a potential subsequent impact scenario.

Figure 13 Schematic plot representing trajectories for forehead targets for child volunteers. From darker to lighter grey, the areas represent: taller children on booster cushion, taller children restrained by seatbelt only, shorter children on highback booster and shorter children on booster cushion (Paper II).

For the taller children, a high shoulder belt position on the abdomen was seen, when restrained by seatbelt only (Figure 14). The high abdominal position of the shoulder belt may help retain the occupant and restrict lateral movement by supporting the lower torso.

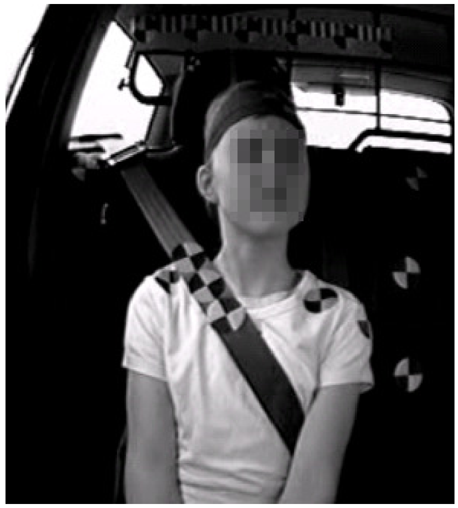

Figure 14 Example of a high shoulder belt position on the abdomen for a taller child when restrained by seatbelt only (Paper II-III).

In Paper III, a high shoulder belt position on the abdomen did also lead to a shoulder belt position close to the neck, hence the shoulder belt had a greater distance to slide before an eventual slip-off (Figure 14). For shorter children in the steering maneuvers, the lower torso/abdomen was restrained better by the shoulder belt in the highback booster than on the booster cushion. Due to the back of the highback booster, the children were seated further forward on the cushion part and there was no or only a small gap between the lower torso/abdomen and the shoulder belt. When the backrest was removed, less of the lower part of the shoulder belt was in contact with the lower torso of the child. This was possibly due to the child being able to sit further back on the booster cushion and the guiding loops positioned the belt as when the backrest was fitted (Figure 15). For taller children, when on a booster cushion, this gap was not as pronounced (Figure 15). The group of taller children had wider shoulders and greater chest depth compared to the group of shorter children, resulting in a different interface between the shoulder belt and the torso, i.e., a greater part of the shoulder belt webbing was in contact with the child's body for the taller children compared to the shorter.

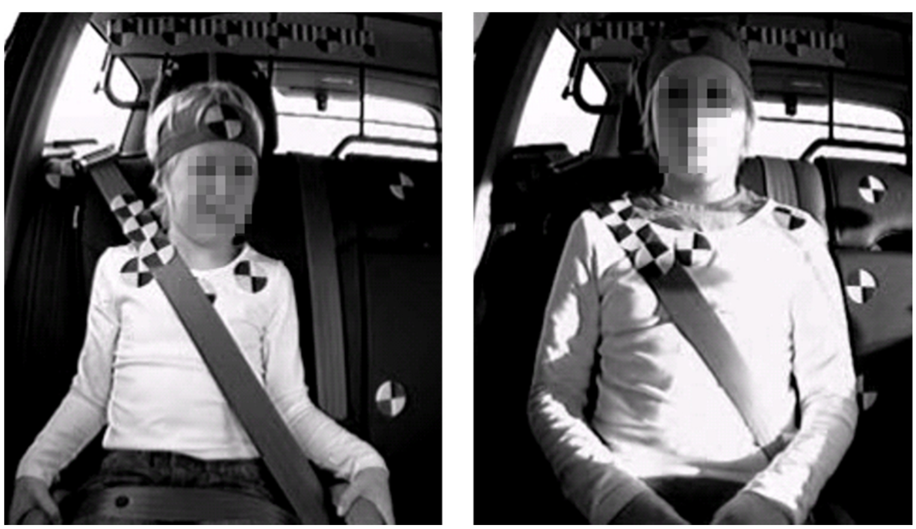

Figure 15 A child from the group of shorter children on a booster cushion, left, and a child from the group of taller children on a booster cushion, right (Paper II-III).

A good initial shoulder belt position is important during braking. Paper II showed that if the shoulder belt was positioned mid-shoulder or close to the neck on the child occupant prior to the braking event, it is feasible the shoulder belt position would be maintained throughout the full braking sequence. However, the results indicated that the further out the shoulder belt was positioned on the shoulder, the greater the forward displacement distance, indicating a less stable restraint situation. In Paper III, the shoulder belt moved further out on the shoulder during the steering event and slipped off the shoulder in some configurations. Only two trials resulted in the shoulder belt slipping off the shoulder when restrained on the booster cushion in the braking events (Paper II). In one trial the belt slipped off the shoulder during the beginning of the braking event although the torso was still retained effectively by the seatbelt. In the second trial the belt slipped off momentarily before the braking event and moved further down the upper arm during the braking event resulting in a greater maximum forward displacement. These two child volunteers displayed the greatest and second greatest forward displacement in the study, reaching more than 100 mm further forward than trials where the belt stayed on the shoulder, hence being at an increased risk of exposure to potential head impact during a subsequent crash event.

When the initial position of the shoulder belt was close to the neck, it reduced the likelihood of it slipping further out on the shoulder during the steering maneuver. When the children, regardless of size, were restrained on a booster cushion, the shoulder belt was positioned below the inboard booster guiding loop in accordance to the instruction manual. Had the shoulder belt been guided above the inboard guiding loop it would have resulted in an initial belt position closer to the neck. However, shoulder belt-neck contact may result in the child experiencing discomfort which would be associated with other negative consequences such as an increased risk of misuse, for instance placing the shoulder belt under the arm or behind the back.

During the steering maneuver the taller children often moved the outboard shoulder upward and/or forward in order to maintain the shoulder belt on the shoulder (Paper III). The difference in kinematics between the group of taller and shorter children indicates a need to further investigate the shoulder belt restraint effect on children of different sizes. Future studies should include a selection of children of different sizes, as well as different belt geometries for better quantification of how emergency braking and steering maneuvers affect children, and establish what the important factors influencing the outcome are. Other interesting parameters, which may influence the shoulder belt slip-off seen in shorter children on a booster cushion (Paper III), are differences between different stature groups in: muscle recruitment/muscle maturity, and belt geometries and booster design, and anthropometry/anatomical differences. If children of different ages and stature are equally restrained by the seatbelt, the results will be less affected by how the child is restrained by the seatbelt and it would be possible to study how children engage their muscles to retain the belt on the shoulder.

5.3 EVALUATION OF AVAILABLE TEST TOOLS

The ATDs used in this thesis have not been designed specifically for the loading conditions presented here. Nevertheless, the ATDs tested in this thesis are currently the only available physical child ATDs, and the feasibility of the ATDs to reflect the kinematic responses of children at such low acceleration levels has been evaluated as a part of this thesis.

The existing ATDs are designed for use in impact situations, seated in a standardized position in accordance to protocol. On-road driving studies (van Rooij et al. 2005, Andersson et al. 2010, Charlton et al. 2010, Jakobsson et al. 2011), resulted in the children adopting several different postures and positions not corresponding to the standardized seated posture by the ATDs when positioned in accordance to protocol, although it is the ATDs' seated posture that the development and evaluation of new restraint systems is based on. Papers II and III show that child occupants adopt a variety of seated postures when exposed to emergency maneuvers, thus the need for applicable test tools that can be located in appropriate pre-crash postures and then tested in vehicle impacts, is apparent.

Are the current ATDs representative of child occupants in dynamic emergency braking and steering maneuvers? The capacity of the ATDs to replicate the kinematic responses of child occupants is limited due to the ATDs being too stiff and due to their obvious lack of muscle response. However, the ATDs can still be used in some load cases when the test setup, the time duration, and the focus of comparison with child occupants lies within their capacity. Based on the findings of this thesis the ATDs can be used as a loading device for the seatbelt and booster, when the shoulder belt is on the shoulder. However, they are limited when out of the protective zone offered by the restraint. In addition, the ATDs are not suitable for determining realistic child responses or to determine where the head is. The challenges include occupant kinematics to be predicted for a longer period of time and the influence of muscle activation in non-impact situations.

The kinematic response and rotation of the ATDs' head during emergency braking maneuvers have been quantified in Paper II. The forward displacement values were generally less for the ATDs than for the children. The HIII 6y on a booster cushion was the ATD most closely representing the forward displacement of a child of similar size. This is in line with the findings of Seacrist et al. (2010, 2012). Previous studies have highlighted the problem of the lack of thoracic spine flexibility in the HIII 6y (Sherwood et al. 2003, Seacrist et al. 2010), Q6 (Seacrist et al. 2012), the HIII 10y (Ash et al. 2009) and Q10 (Seacrist et al. 2012). To reduce head injuries to child occupants it is important to restrict head motion, hence restrict the motion of the upper torso. For real world safety it is important that the ATDs' are improved with a focus on accurate child kinematics in order to replicate the kinematics resulting in head impacts in a more realistic way.

In addition to the lack of thoracic spine flexibility, the ATDs need to be improved with focus on accurate interaction with the seatbelt. During the steering maneuvers in Paper IV, depending on where the seatbelt was positioned and the anatomy of the ATD, the ATDs fell inboard to various extents, whereas the children were in control of themselves and tended to try to return to their initial position. Great variation in conduct was noticed in the child volunteers. The question of which ATD better replicates the behavior of children exposed to emergency maneuvers still remains open. It depends on the focus of the comparison and on what phase of the maneuver is of interest. Compared to the children, the HIII ATDs were closer with regard to mean values in the initial phase of the steering maneuver, whereas the Q ATDs were closer in the end of the ramping phase of the lateral acceleration. Due to the large variety in lateral displacements for the children, the child performance range covers both the dummy families for the evaluated sizes of 6 and 10 year old ATDs.

The differences in design may affect the interaction between the torso of the ATD and the seatbelt. The shoulders of the Q-family are wider and their abdomen is more pronounced compared to the corresponding HIII ATD. Thus, the interface differences between the ATDs' torso/abdomen and the shoulder belt might have helped to maintain them in a more upright position. As an example, the Q6 has an upward inclination of the ribcage, a more rounded abdomen, and slouched posture compared to the HIII 6y where the ribcage is more flat and the ribs horizontally oriented (Lubbe, 2010). The design of the shoulders and the shoulder width of the Q and HIII-families are different. The Q-family was developed with the intention of use in both frontal and side impacts which has influenced their design (Wismans et al. 2008). To restrict the motion of the upper torso it is important to ensure the shoulder belt stays on the shoulder. The design of the shoulders of the ATDs are most likely of importance for the shoulder belt-to-shoulder interaction. Other studies have shown high sensitivity of chest deflection to belt geometry in crash tests with the Q10 (Bohman and Sunnevång 2012, Tylko and Bussières 2012) and Q6 (Lubbe 2010).

While this thesis has evaluated the response of ATDs in emergency events, Bilston et al. (2007) studied the ATDs when positioned in a non-standardized seated posture during a crash test to simulate real world cases in sub-optimal postures. They identified problems with the biofidelity of the ATDs' dynamic responses and the ability to position the ATDs in realistic pre-crash postures due to the stiffness of the ATDs' torsos and necks. It is challenging to design physical test tools able to capture pre-crash and in-crash kinematics as current designs already show limitations in capturing in-crash kinematics.

It is evident that test tools to evaluate situations where an emergency maneuver is followed by an impact is required, hence, it is crucial to develop new physical and numerical test tools for low acceleration maneuvers. To this end HBMs are promising test tools. To study on-road driving and involuntary child seated postures during emergency and pre-crash events, it is necessary to implement muscle activity in the HBMs. Child FE HBMs can be enhanced similarly to the adult (Östh et al. 2015) and child models (Brolin et al. 2015b) which have been implemented with active muscle response to analyze emergency events. Once a model validated for emergency events followed by crash is available, it can provide valuable information for impact situations where an emergency maneuver is present. Numerical simulations could serve as valuable input for understanding the consequences of critical sub-optimal postures in children. It would then be possible to evaluate the consequences of pre-crash positions, and performing parameter studies to evaluate different countermeasures and their impact on injury outcome in child occupants, would become viable.

5.4 Implications of Results for Restraint and Vehicle Design

A seatbelt needs to protect and keep the child properly restrained in a variety of situations, ensuring that the restraint interaction is optimal during self-selected as well as involuntary seated postures during normal on-road driving and emergency events. This is challenging. For optimal protection it is important to restrain the clavicle, throughout the pre-crash phase as well as throughout the crash, ascertaining optimal belt geometry and guide the seatbelt as smoothly and efficiently as possible, in a straight path.

In the course of the work conducted for this thesis however, it has become evident that the seated postures adopted by children when riding in cars do not always correspond to how ATDs are positioned and restraints are tested in crash tests. Children will naturally move and their seated postures are influenced by the design of restraint systems, perceived discomfort, activity and riding conditions such as time of the day and duration of the trip. Furthermore, the seated postures for children are influenced by size and body shape, parameters that are of importance in order to understand how the anthropometry of a child will influence the interaction with the restraint.

In order to gain insight into the child occupants' lateral movement and shoulder belt position, children across a range of statures were studied for the steering maneuvers (Paper III) in several restraint systems. For shorter children the highback booster showed potential for maintaining the shoulder belt on the shoulder. However, it is not known whether the highback booster will have the ability to continue to keep the shoulder belt in position during a frontal impact, when seat and child are in such a tilted position. Preliminary sled tests (Bohman, 2013) showed that a laterally tilted highback booster in a frontal sled test resulted in breakage of the shoulder belt guiding loop for the highback booster and the shoulder belt slipping off the shoulder. The design of current shoulder belt guiding loops is for comfort, it is not designed to withstand significant loading in a crash. The strength of the backrest, including guiding loops, in this type of tilted situation is not addressed in any tests or guidelines.

The design of booster backrests has changed over the years and a trend towards fitting large side supports at the level of the torso as well as the head has increased. In Papers II, III and IV the booster cushion was identical to the highback booster, aside from the backrest having been removed. In this study the benefit of the booster backrest, with respect to seatbelt geometry, was that the children were seated further forward, hence it decreased the booster cushion length, beneficial for the shorter children (Papers II and III) due to a greater part of the shoulder belt being in contact with the body of the child. Forman et al. (2011) further highlighted that the backrest provides support while sleeping. This was seen in Osvalder et al. (2013) too. The same study also highlighted that most children disliked the torso side supports of the highback booster; they created a restrained and confined feeling and prevented them from looking out through the side window. Objective results from video analysis of the seated postures confirmed this (Osvalder et al. 2013).

The highback booster influence initial seated posture and thus result in a further forward head position during maximum excursion. Figure 13 shows the area of the children's head trajectories during the braking maneuvers. The differences in trajectories were influenced by the size of the child as well as the restraint system used, including the initial seated posture. In case of a subsequent side impact, any of these head positions resulting from the braking event would be a potential position at impact. Maltese et al. (2007) identified evidence of a variety of head impact locations for restrained children (4-15 years) in side impacts. This is in line with the findings in this thesis, where the maximum forward head position was considerably further forward than the side supports of a highback booster would cover (Figure 16).

Figure 16 Maximum forward head position of a child on a highback booster during an emergency braking maneuver (Paper II).

For the emergency braking maneuvers (Paper II) the results provide insight into possible injury causing mechanisms and measures for protection. The results emphasize the need for considering a large area of the vehicle's side interior as part of potential head impact surface, and thus urgent to develop with regard to child protection. The findings have the potential to help improve the understanding of side impact protection for children, emphasizing the importance of the characteristics of the vehicle's side interior protection and the capacity of the restraints to keep the child in a favorable position. Osvalder et al. (2013) identified that playing with electronic devices during normal on-road driving often resulted in a concentrated forward flexed seated posture with the head leaning forward and low frequency in posture changes (Figure 17). This posture is very similar to the forward positions due to the braking event in Paper II. The child's self-selected or involuntary posture indicates the need of covering large areas, in order to reduce the risk of head injuries to children. This can be achieved through the design of the side structure and the inflatable curtain.

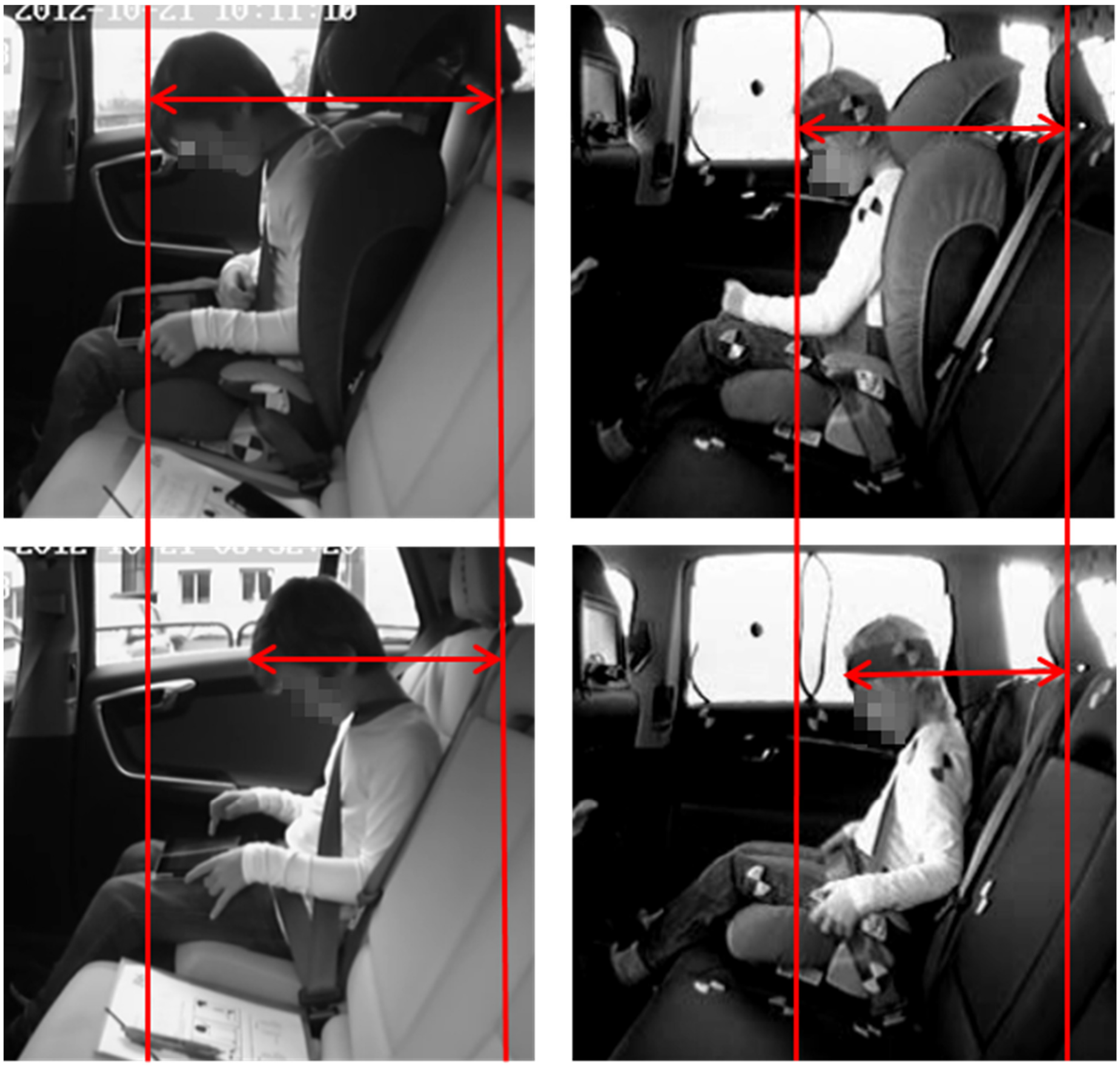

Figure 17 Self-selected seated posture during on-road driving (left) from Osvalder et al. (2013), and seated posture due to braking maneuver in Paper II (right).

Forward head motion can also be limited by restricting the forward motion of the torso. Pre-pretensioning of the seatbelt before an emergency braking event resulted in decreased forward displacements in drivers and adult front seat passengers (Östh et al. 2013, Ólafsdóttir et al. 2013). Arbogast et al. (2012) identified significantly reduced lateral displacement in low-speed side and oblique sled tests with volunteers by early engagement of the torso with the shoulder belt due to the pre-pretensioner. Douglas et al. (2007) exposed adult volunteers and ATDs to a lateral force of 1g to characterize factors influencing occupant-to-seatbelt interaction in a far-side impact. They observed that the likelihood of the shoulder engaging the seatbelt was increased when the D-ring was moved rearward and the pretension of the seatbelt was increased. Their results also highlighted that the occupant-to-seatbelt interaction is dependent on occupant anthropometry. Furthermore, torso shape and shoulder depth highly influences how well the torso is restrained by the shoulder belt in a far-side impact. Paper V provides new insights into the potential benefits of a pre-pretensioner to retain rear seat occupants in emergency run-off road events. The overall effect is influenced by several aspects such as initial seatbelt geometry and shoulder belt position throughout the event, seat geometry and body size of the occupant.

Potentially, guiding loops of boosters can reduce the positive effect of the pre-pretensioner due to unnecessary friction between the booster cushion and the seatbelt. By designing the rear seat and restraints as one system with respect to child occupants the design can be optimized to best protect child occupants. Built-in child restraint systems, such as integrated booster cushions, are designed in conjunction with the three point seatbelt and can provide optimal seatbelt geometry adapted to a specific vehicle. The two-stage booster cushion provides optimal belt fit for a broad range of sizes of forward facing children (Jakobsson et al. 2007). Child occupants should also benefit from vehicle safety systems provided for adults.

An additional belt may provide a further solution to ensure the child is properly restrained, with the seatbelt on the shoulder. It has been shown that an additional shoulder belt has the potential to improve restraint effectiveness in front seat adult occupants in far-side impacts, rollovers and frontal impacts (Boström et al. 2008, Boström et al. 2013). Osvalder et al. (2015) studied the attitude of child and adult passengers and how they experienced the comfort of extra seatbelts during on-road driving in the rear seat of a passenger car. Two different seatbelt systems were tested, consisting of the standard three point seatbelt together with an additional two point seatbelt. Perceived safety benefit and experienced comfort were the most determinant factors for the positive attitude toward the extra seatbelts, factors important for a system to be successful and correctly used by the occupants.

Comfort is an important factor to take into consideration for optimal safety for children in cars (Bohman, 2013). Discomfort caused by the seatbelt close to the neck may result in the child rotating the upper body to move the belt further out on the shoulder (Jakobsson et al. 2011), or putting the shoulder belt behind their back. The findings in Bohman et al. (2007) show that children wanted to use booster cushions for safety and comfort reasons, but perceived the use of booster cushions as childish. Misuse was detected for most children using the accessory booster cushion as compared with misuse being almost eliminated when restrained in the integrated version. This was supported by Osvalder and Bohman (2008) and they concluded that misuse of boosters can be reduced by designing restraint systems that are simple, comfortable and intuitive in design.

Child occupants may also benefit from foot support both for stability in emergency events and for comfort reasons during normal driving. The child volunteers in Papers II and III were too short to use their feet for support during the maneuvers. Children occasionally stretched out one of their legs to find support against the back of the front seat or by putting the right foot on the sill and the left foot on the center panel in front of the middle seat position in the rear seat during normal driving (Jakobsson et al. 2011, Osvalder et al. 2013). Providing foot support designed for the needs of children will likely increase the chance of adopting a good posture.

To further improve the safety for children in cars, it is essential to develop countermeasures based on real world data, and if successfully implemented they will influence the real world outcome. Several pieces of the child safety puzzle (Figure 5) must be combined to ensure optimal safety for child occupants. In order to develop countermeasures, a deeper understanding of the needs is required and evaluation methods for safety assessment reflecting these needs should be developed.

6. CONCLUSIONS

This thesis focuses on emergency events that may precede a crash, and how these events influence the kinematics of child occupants restrained by the three point seatbelt.

This research revealed that a substantial portion of drivers attempted an avoidance maneuver prior to crash. The most common avoidance maneuver was braking only, followed by a combination of braking and steering, and steering only. No difference was seen in the frequency of emergency events prior to crash for vehicles with child occupants compared with vehicles without child occupants. Autonomous technology in vehicles will increase the frequency of these events and such advanced driver assistance systems should be designed in conjunction with integrated safety systems in the vehicle to optimally protect child occupants.

In the braking events of 1g, the children moved forward up to 0.2 m when restrained optimally. Highback boosters influenced initial seated posture and thus resulted in a further forward head position during maximum excursion. The forward motion was large enough to position the head of the child in front of the side supports for the booster. The forward displacement due to braking event will reduce the distance to potential head impact areas in case of a subsequent frontal impact. The results emphasize the need for considering large areas of the vehicle's interior as part of potential head impact surface.

In the steering maneuvers, the children moved approximately 0.1 m laterally. A steering maneuver is an unstable restraint situation for children in the rear seat, and a great variety in lateral displacement and seatbelt positions on the shoulder was seen in different conditions. Influencing factors include child age, anthropometry, initial seated posture, and initial shoulder belt position on shoulder. Steering maneuvers prior to crash may position children in a sub-optimal inboard position with the shoulder belt far out on the shoulder or completely off.

This thesis evaluated the available ATDs in low acceleration conditions when exposed to emergency maneuvers and highlighted the limitations in capturing child kinematics. It was seen that the ATDs can be used as a loading device for the seatbelt and booster; however they are not suitable for determining realistic child responses or to determine where the head is, due to the rigid spine.

In run-off road events a pre-pretensioning of the three point seatbelt resulted in reduced lateral head excursion of the ATDs. This was due to the shoulder belt remaining on the shoulder, which was a combination of tightening of the seatbelt and that the lower torso was supported by the shoulder belt.

In addition to involuntary factors, such as maneuvers, the child's seated posture when potentially exposed to a crash is influenced by self-selected factors. Children of different ages and body sizes need to be taken into account and factors such as how the child is restrained by the seatbelt, and the effect of the booster design are important. Appropriate initial seatbelt position to ensure the upper torso remains restrained despite emergency events before crash is important for enhanced safety for children in cars.

How to best protect child occupants when riding in cars is a broad and complex question that covers several areas of research and requires a variety of methods of investigation. This thesis complements previous research and has specifically resulted in deeper knowledge of the effect of emergency events prior to crash on children in terms of accident data, kinematics of children and child ATDs as well as evaluation of a possible countermeasure. The output has potential to positively impact child safety in cars through the development of active safety systems, enhanced rear seat restraints, and improved test methods and test tools.

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