THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

in

MACHINE AND VEHICLE SYSTEMS

Child Passenger Kinematics in Emergency Manoeuvres

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Gothenburg, Sweden, 2012

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THESIS FOR LICENTIATE OF ENGINEERING no 2012:18
ISSN 1652-8565

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Chalmers Reproservice
Gothenburg, Sweden 2012

CHILD PASSENGER KINEMATICS IN EMERGENCY MANOEUVRES

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ABSTRACT

In motor vehicle impacts, a child's head is generally the most frequently injured body region, irrespective of impact direction. Head to front seat back impact has been identified as a predominant cause of injury for rear seated, seat belt restrained children, aged 3 – 13, who sustained AIS2+ head injuries in frontal impacts. Previous research highlights vehicle manoeuvres prior to impact as possible contributing factors. Test tools to simulate occupant kinematics during emergency braking and steering manoeuvres would be valuable when investigating different scenarios and restraint systems.

This thesis investigates children's and different Anthropomorphic Test Devices' (ATDs') motion during emergency braking and steering manoeuvres in a passenger vehicle. The kinematic responses of child volunteers during the emergency manoeuvres in different restraint configurations were compared and discussed, and the current child ATDs from the Q-family and the Hybrid III (HIII) family were evaluated with respect to child occupants.

The forward displacement was within the same range during the braking manoeuvres for all tested children, regardless of size and restraint system. All ATDs displayed less forward displacement and head rotation than the child volunteers; the HIII 6 year old on a booster cushion was closest to representing the kinematics of a child of similar age/size in this set-up. Maximum excursion was dependent on the initial seated posture and shoulder belt position on the shoulder. Boosters with a backrest influenced the initial seated posture and thus resulted in the head position being more forward during maximum excursion.

For the steering manoeuvres, the Q ATDs were closer regarding mean values compared to the children, however due to the large variety in lateral displacements of the children, the child performance range covers both the dummy families for the evaluated sizes of 6 and 10 year old ATDs in this set-up.

The braking and steering manoeuvres with child volunteers and ATDs carried out in this thesis provide novel and unique knowledge of possible pre-crash postures of children and currently available ATDs across a variety of restraint systems in vehicle emergency manoeuvres. 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.

Appropriate initial shoulder belt position is important during steering and braking manoeuvres. For real world protection, it is important to take into account the growing child, focusing on and understanding such aspects as initial seated posture, i.e., head position, shoulder belt position and how the child is restrained by the seat belt, as well as the booster design.

KEYWORDS: methods, pre-crash, braking, steering, child volunteers, child restraint systems, child ATD

ACKNOWLEDGEMENTS

This study was carried out at the Division of Vehicle Safety, Department of Applied Mechanics, Chalmers University of Technology in Gothenburg, Sweden, as part of a larger project at SAFER Vehicle and Traffic Safety Centre in conjunction with project partners Saab Automobile AB, Autoliv Development and Volvo Car Corporation. The project was predominantly funded by the Swedish Governmental Agency for Innovation Systems (VINNOVA) within the *Fordonsstrategisk Forsknings och Innovation* (FFI) programme.

This work would not have been possible without the involvement of many people. I would like to thank all of you and especially:

- My supervisors Adjunct Professor Lotta Jakobsson, Associate Professor Karin Brolin and Associate Professor Ola Boström for believing in me, for continuous support and great advice.
- My project colleagues: Katarina Bohman, Mats Svensson, Maria Wimmerstedt, Marianne Andersson, Henrik Svanberg and Kristy Arbogast for valuable team work.
- My colleagues at the Vehicle Safety Division at Chalmers and SAFER for providing information, encouraging discussions and creating a nice working environment.
- The team at Volvo Cars Safety Centre, Autoliv Development, Division of Design and Human Factors at Chalmers and Stora Holm's test track for their great contribution to this work.

♥ My family and friends for all your love, patience and encouragement.

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Bohman K, Stockman I, Jakobsson L, Osvalder AL, Bostrom O, Arbogast KB (2011) *Kinematics and shoulder belt position of child rear seat passengers during vehicle maneuvers,* Annu Proc Ann Adv Automot Med. 2011:55:15-26.

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 and partly by Stockman, and it was reviewed by all authors.

PAPER II

Stockman I, Bohman K, Jakobsson L, (2012) *Kinematics and Shoulder Belt Position of Child Anthropomorphic Test Devices during Steering Manoeuvres,* Submitted to Traffic. Inj. Prev.

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 III

Stockman I, Bohman K, Jakobsson L, Brolin K, (2012) *Kinematics of Child Volunteers and Child Anthropomorphic Test Devices during Emergency Braking Events in Real Car Environment*, accepted for publication in Traffic Inj. Prev.

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.

DEFINITIONS AND ABBREVIATIONS

AIS	Abbreviated Injury Scale, a scoring system to determine the severity of single injuries based on the survivability of the injury
ATD	Anthropomorphic Test Device, also called crash test dummy
Belt positioning booster	A child restraint that elevates the child to better fit the geometry of the vehicle seat belt
CRS	Child Restraint System
FMVSS	Federal Motor Vehicle Safety Standards
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
NASS-CDS	National Automotive Sampling System Crashworthiness Data System, a database of passenger vehicle crashes
MAIS	Maximum Abbreviated Injury Scale, the maximum of multiple injuries to one person as classified by the AIS
MAIS3+	The maximum injury among all injuries with an injury severity minimum of 3 (serious injury) and higher.
PMHS	Post Mortem Human Subjects
Q3	Child ATD corresponding to an average 3 year old, from the Q-family
Q6	Child ATD corresponding to an average 3 year old, from the Q-family
Q10	Child ATD corresponding to an average 3 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. INTRODUCTION

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 account for over 30 percent of those killed and injured in road traffic accidents (WHO, 2007). The distribution of road deaths by mode of road user varies with age, and for children aged 0 – 14 in the WHO European Region, 32 percent occurred in car occupants (WHO, 2008). US data (NASS-CDS) from 1991 – 2005 showed that of all children aged 4 – 12, approximately 67 percent were seated in the rear seat of passenger vehicles or light truck vehicles (Bidez et al. 2007). For the rear seated children, second to rollover accidents, side impacts showed the highest risk to sustain an injury with severity score 3+ according to the Maximum Abbreviated Injury Scale (MAIS3+) (Bidez et al. 2007). Statistics (WHO, 2008) show that road traffic injuries are the most common cause of fatal injuries among children in the European Region where approximately 16,400 children and young people are killed in traffic annually. Road traffic injuries are also the leading cause of traumatic brain and limb injuries, resulting in long-term disability in children (WHO, 2004). In motor vehicle accidents, a child's head is generally the most frequently injured body region, irrespective of impact direction (Durbin et al. 2003, Howard et al. 2004). Traumatic brain injury is the leading cause of traffic related deaths and injuries in high income countries as well as low and middle income countries (WHO, 2007).

The relative protection for belted occupants provided by the rear seat over the front seat has declined in newer vehicle models indicating that rear seat occupant protection has not kept pace with front seat safety system development and improvements (Bilston et al. 2010). There is a great need to focus on safety in the rear seat to enhance knowledge in order to take the right action for reducing injury numbers and severity (Jakobsson et al. 2011b). Methods to evaluate child restraint systems are generally based on sled tests, and not on crashes with complete passenger vehicles, which result in child restraints being developed as independent systems and not integrated as a part of a vehicle (Andersson, 2012). The European New Car Assessment Programme (EuroNCAP) is currently testing child restraints for younger children in complete vehicle testing, however a change in the programme is due in 2015 and it is expected that the Q6 and Q10 will be tested in the rear seat in frontal and side impact tests instead.

Viano et al (2008) reviewed frontal impact cases, obtained from the 1997 – 2005 NASS-CDS, to better understand injury mechanisms of children in the rear seat. Cases were selected from serious to fatal injuries to the head or spine. Included in the review were 28 injured children in 26 frontal impacts. The most common source of injury sustained by the children was contact with the seatback, B-pillar or other structures in front of them (46 percent) or the child seat (21 percent).

Data from The Children's Hospital of Philadelphia shows that protection of children in vehicles has improved as a result of increased restraint use by children (CHOP, 2007). Nevertheless, studies show that although children are restrained, injuries still occur (NHTSA, 2005, Bidez et al. 2007, Bohman et al. 2011) indicating that current restraint systems have the potential for further improvement.

1.1 CHILD ANATOMY

A child is not a small version of an adult (Figure 1). 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 centre of gravity is located higher in a child compared to in an adult (Tarrière, 1995). The strength of the neck muscles increase with age and the smaller structure of a child's neck is not strong enough to support the heavy head and soften violent head movement. At birth, the neck vertebrae consist of bones joined by cartilage. 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 to 6 (D. Klinich et al. 1996). During early childhood, the facet joints in the upper neck are almost horizontal, unlike in adults, which increase the risk of partial dislocation caused by low forces (D. Klinich et al. 1996). 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, however, 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). 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).

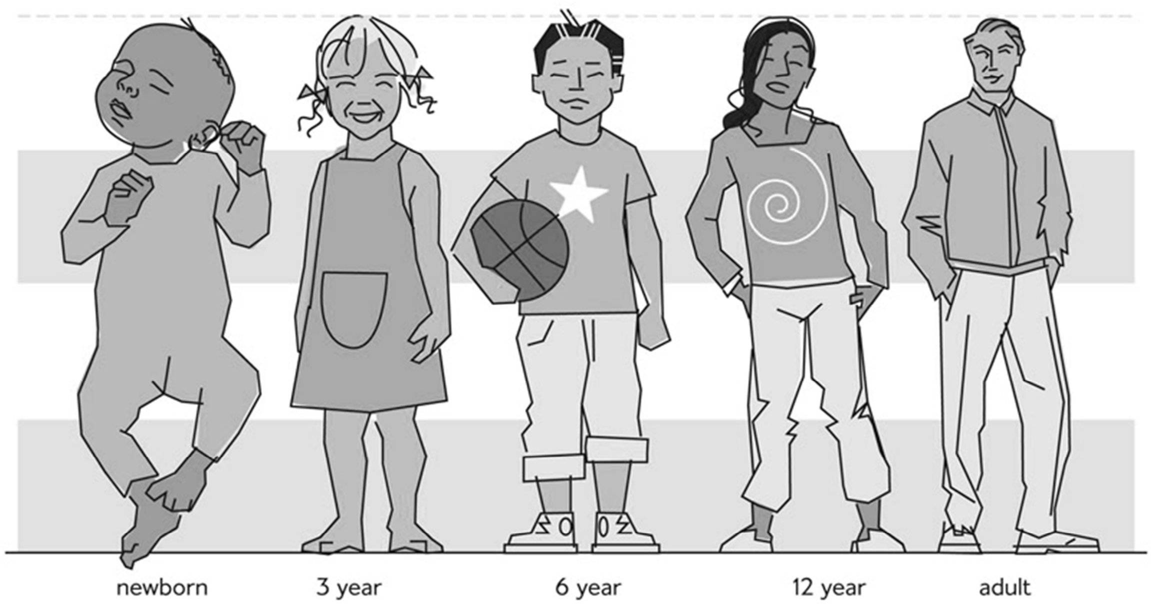

Figure 1 The proportional changes in body segments with age (courtesy of Volvo Car Corporation).

1.2 CHILD RESTRAINT SYSTEMS

The first rearward facing child restraint system was introduced and tested in 1964 (Figure 2) 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). The development of CRSs for vehicles began with this particular rearward facing seat and has been developed over the years to improve protection for children of different sizes and ages (Jakobsson et al. 2005). The different categories of restraint systems can be seen in Figure 3. Forward-facing CRS for children aged 1 – 4 with integrated child harness are very rare in Sweden, and are not included in Figure 3. As mentioned previously, children's anatomy is different to adults, which is important to take into consideration when developing and designing protection against vehicle impact forces and for optimal occupant restraint systems (Burdi et al. 1969). 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). In Sweden, rearward facing seats are recommended up to the age of 3 –

Figure 2 The first rearward facing child restraint developed by Professor Bertil Aldman.

4 years. At about 4 years of age, when the mass of the head is proportionally less and the neck muscles are further developed, the child can be turned facing forward in the vehicle. However, differences between children and adults still exist. The iliac spines of the pelvis are important for satisfactory lap belt positioning and for reducing risk of belt load into the abdomen, but are not fully developed until around 10 years of age (Burdi et al. 1969). Swedish law require children to be restrained by an appropriate child restraint system until they reach 135 cm. Belt positioning boosters are designed to improve belt fit and allow the geometry of the adult seat belt to function more effectively with respect to the child occupant (Norin et al. 1979). Appropriate belt fit is characterised 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. 2012). 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 belt and the body would be restrained through abdominal soft tissue, rather than through applying the loads to the strong pelvic bone. A belt positioning booster will elevate the child and allow the child to have a comfortable leg position while sitting upright and thus preventing the child from slouching (D. Klinich et al. 1994) which may increase the risk of submarining. Preferably the shoulder belt should be placed on the shoulder, as far in as possible without causing discomfort. Placing the shoulder belt too far out on the shoulder 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. 2012).

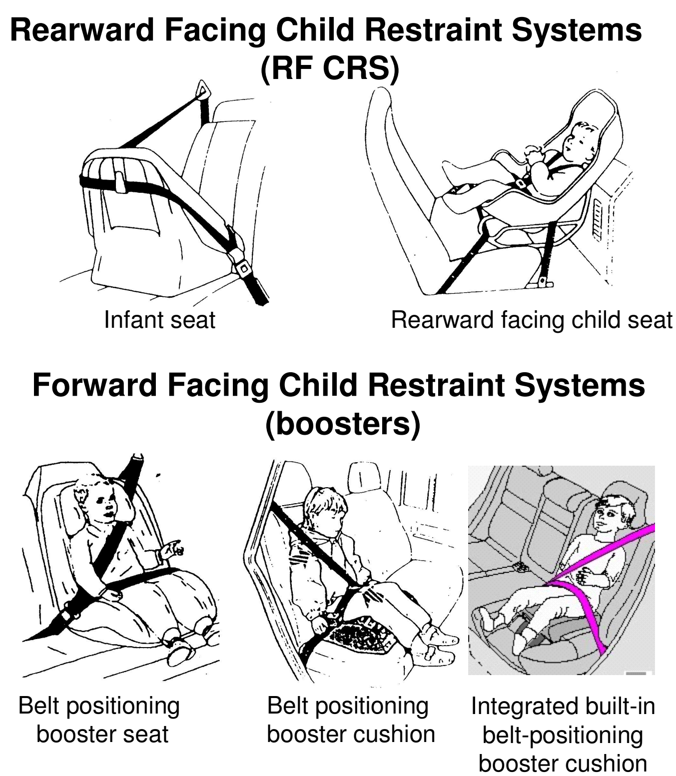

Figure 3 Different types of rearward and forward facing child restraint systems (Jakobsson et al. 2005).

Belt positioning boosters can have a backrest which was initially developed to ensure a head restraint for the child and place the shoulder belt in an optimal position on the child’s shoulder and across the chest (Jakobsson et al. 2011b). 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 emphasise that the reasons for the change, is to provide improved side impact protection and to provide protection and comfort for children by keeping them upright when relaxed or asleep (Jakobsson et al. 2011b). Integrated (built-in) belt positioning boosters 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 regards to both safety and comfort, such as being easy and simple to use which resulted in a significant lower misuse rate.

Durbin et al. (2003) showed that injuries to the abdomen and spine, associated with improperly fitted seat belts for children 4 – 7 years old, were nearly eliminated in impacts where children were seated correctly on boosters compared to those restrained by seat belts 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 seat belt only (Arbogast et al. 2009b).

Reed et al. (2012) 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 ATDs. The boosters differed substantially in how the seat belts 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 seat belt fit in each booster, relative to the no booster condition. The study also highlighted older children restrained by seat belt alone and concluded that seat belt fit improvements should be focused on steeper lap belt angles, shorter seat cushions, and more appropriate D-ring locations.

1.3 SELF-SELECTED POSTURE WHEN RIDING IN VEHICLES

To assess the effectiveness of a restraint system, crash tests are performed with ATDs positioned in according to protocol in a standardised seated posture. As Arbogast et al. (2011) state; the field of naturalistic observation of child occupant postures and seated behaviour 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 behaviour 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, recently 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 (CRS) 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 CRS, resting their heads on the wings of the CRS. Charlton et al. (2010) examined the behaviour of children in passenger vehicles, and how children are restrained and seated in their restraint systems, in a study where 12 families were recorded by video cameras whenever they rode in their vehicle. The video camera was activated automatically each time the ignition key was activated over a period of 3 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 CRS structure, or otherwise away from the preferred location within the CRS or vehicle restraint system. Andersson et al. (2010) studied children aged 3 – 6 when positioned in 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, resulting in the head being further away from the seat back. 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 restrained by a three-point seat belt and appropriate CRS for their height and weight. Ten of the children were seated on a highback booster seat, ten on a booster cushion without a backrest, and ten were seated directly on the car seat. They found that the group using the seat belt exclusively exhibited poor 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 seat group (17 percent). The relative lateral head displacement ranged up to a maximum of 35 cm from the initial position. Jakobsson et al. (2011a) identified the seated posture and the shoulder belt positions of 6 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 the most part of the time when using the booster cushion, compared to the seat belt only. Furthermore, greater individual variation in shoulder belt position on the shoulder was seen when restrained by the seat belt only. When seated on a booster cushion, all children were positioned in a more upright lateral postures to a greater extent of time. However, when using a seat belt only, the children changed body posture more frequently, and some children compensated for discomfort by rotating their upper body away from the seat belt.

1.4 PRE-CRASH MANOEUVRES IN VEHICLES

McGehee and Carsten (2010) analysed 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 preview that an impact was imminent, allowing them time to respond by braking and diverting. From collected and analysed 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 manoeuvre 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 manoeuvres and steering manoeuvres occurred in approximately 20 – 35 percent and 20 – 25 percent of the cases independent on 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 to attempt to avoid the impacting vehicle. Evasive steering or braking manoeuvres 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, seat belt restrained children, aged 3 – 13, who sustained AIS2+ head injuries in frontal impacts. The study highlighted vehicle manoeuvres, 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 manoeuvre prior to the impact.

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 behaviour due to vehicle motion. Driver reaction to an obstacle thrown on the car trajectory 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 on the passenger seat (Kümpfbeck et al. 1999) and driver behaviour in braking and steering manoeuvres involving 49 volunteers on a test track (Zuppichini et al. 1997) have been carried out. Carlsson et al. (2011) quantified the kinematics of the driver and passenger during braking events in real traffic. These studies provide valuable knowledge of adult occupant kinematics during braking. Nonetheless, knowledge of how children are affected during vehicle manoeuvres is limited and data on kinematic behaviour of children in pre-crash situations is lacking.

1.5 TEST TOOLS

The two most recently developed child ATD families are the HIII-family and the Q-family (Figure 4). The HIII child ATDs were developed in the US during the 1990's and are based on US child anthropometry data from the 1980's, 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 US, Europe and Japan. The Q ATDs include requirements for the abdomen and pelvis in front and side impacts. The design of the above two families of child ATDs also differ. The HIII-family was developed for frontal impacts while the Q-family was developed intended for use in 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.

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. (2009a) 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. (2009a). 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 seat belt 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. The authors 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.

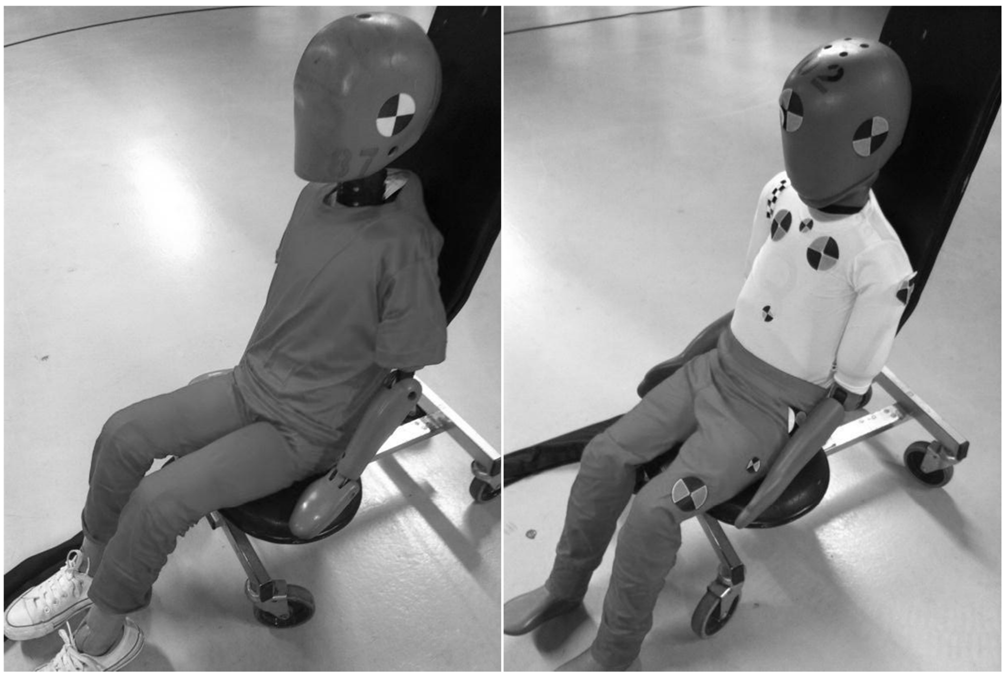

Figure 4 The Hybrid III 6y ATD, left, and Q6 ATD, right.

Lubbe (2010) evaluated differences in kinematic responses between the HIII 6y and Q6 ATDs in a highback booster seat 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 seat belt 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 seat belt 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).

2. AIMS

The main aim of this thesis is to develop methods to obtain better understanding of children's motion during emergency manoeuvres in a passenger vehicle. Moreover, this thesis will compare and discuss the kinematic responses of child volunteers during emergency manoeuvres in different restraint configurations, and evaluate how well current child ATDs represent child occupants.

The specific aims are to:

- Develop methods for data collection, studying and quantifying the kinematics of child occupants during evasive vehicle steering manoeuvres with a focus on the child's lateral movement and seat belt position relative to the shoulder.
- Develop methods for data collection, collecting data, studying and quantifying the kinematics of child occupants during emergency braking manoeuvres and to produce a data set that can be used for validation of different test tools in emergency braking situations.
- Quantify the kinematic responses of six child ATDs during evasive steering and emergency braking manoeuvres, focusing on evaluating and comparing the kinematic responses for the ATDs to that of children of corresponding sizes.

3. SUMMARY OF PAPERS

3.1 SUMMARY OF PAPER I

Head impact to the seat back has been identified as one important injury inducing scenario for seat belt restrained children sustaining head injuries, and previous research highlighted vehicle manoeuvres prior to impact as a possible contributing factor. The aim was to quantify the inboard motion and kinematics of child occupants during evasive steering manoeuvres focusing on the child's lateral movement and seat belt position relative to the child's shoulder.

A study was conducted on a closed circuit test track comprising 16 children aged 4 – 12, restrained in the right rear seat of a modern passenger vehicle. The children were recruited into two groups, one group of short children (stature 105 – 125 cm) and one group of tall children (stature 135 – 150 cm). The short children were tested in two different restraints: booster cushion, and highback booster seat. The tall children were also tested in two different restraints: booster cushion, and directly on the vehicle seat. All test subjects were restrained by the seat belt included as standard equipment in the test vehicle. A professional driving instructor drove the test vehicle at 50 km/h, repeatedly making sharp turns to the right, resulting in inboard motion of the children. The children were exposed to two steering manoeuvres in each of the two restraint systems. Four video cameras were fitted inside the vehicle monitoring the child and relevant vehicle data were also collected. The time point of a lateral acceleration of 0.2g was used to synchronise 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. T1 was defined as the time for the reference position of the child in each trial just before the manoeuvre had begun. T2 was defined as 0.2s after the synchronisation 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 and 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 centre of the seat. These measurements were used for determining the child's kinematics.

A steering manoeuvre is an unstable restraint situation for children in the rear seat, and a great variety of responses were seen in different child volunteers. This data provides valuable knowledge on possible pre-impact postures of children as a result of vehicle steering manoeuvres for a variety of restraint systems. The children moved approximately 100 mm laterally, regardless of stature or restraint system. Depending on the initial seated posture and size of the child, this resulted in different shoulder belt positions. The shoulder belt slipped off the shoulder in almost 67 percent of the trials for the short children restrained by a booster cushion. The shoulder belt was kept on the shoulder when the short children were restrained by a highback booster seat, but half of the trials resulted in the shoulder belt being positioned far out on the shoulder. For the tall children no belt slip off occurred. In the tall 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 tall children were restrained by seat belt only. Tall children seated on a booster cushion demonstrated a shoulder belt position far out on the shoulder during the turn.

3.2 SUMMARY OF PAPER II

The aim of this study was to present, compare and discuss the kinematic response of ATDs during emergency steering manoeuvres in different restraint configurations in a passenger vehicle. Furthermore, the ATDs were compared to the results collected from child volunteers in the same test setup, presented in Paper I.

A driving study was conducted on a closed circuit test track comprising 6 ATDs: the Q3, Q6, Q10, HIII 3y, 6y and 10y ATDs restrained on the right rear seat of a modern passenger vehicle. The same professional driving instructor used in the study comprising child volunteers (Paper I and Paper III) drove the test vehicle. While travelling at a velocity of 50 km/h, the vehicle was steered sharply to the right at cones on the test track. The ATDs were exposed to two steering manoeuvres in each restraint system. The Q3, Q6, HIII 3y and 6y were restrained on a booster cushion as well as a highback booster seat. The Q10 and HIII 10y were restrained on a booster cushion or restrained by three-point belts directly on the car seat. Vehicle data was collected and synchronised with video data. The event was identified by simultaneously viewing the 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.

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, the results were presented at the time points T2 and T3, presented in Paper I, 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. The shoulder belt slipped off the shoulder for all ATDs when restrained on a booster cushion, as well as for the HIII 3y when on a highback booster seat. This occurred already before T2, i.e., before a lateral acceleration of 0.55g±0.05 (mean±SD).

Previous research identified vehicle steering manoeuvres prior to frontal impact as a contributing factor to head injuries caused by seat back contact for restrained children. This study 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 manoeuvre, for a variety of restraint systems and ATD sizes. During emergency steering manoeuvres all ATDs tended to fall inboard, to different degrees, depending on their anatomy and where the seat belt was positioned. Children, on the other hand, were generally able to control their movement and attempted to return to their initial seated position. A steering manoeuvre can be a complex and unstable restraint situation for occupants in the rear seat and great variation were seen between child volunteers. Compared to the children, the Q ATDs were closer regarding mean values, however due to the large variety in lateral displacements of the children, the child performance range covers both the dummy families for the evaluated sizes of 6 and 10 y ATDs. Generally, the Q-family was better restrained by the shoulder belt due to having wider shoulders and a more pronounced abdomen compared to the corresponding HIII ATD.

3.3 SUMMARY OF PAPER III

The aim of this study was to present, compare and discuss the kinematic response of children and child ATDs during emergency braking manoeuvres in different restraint configurations in a passenger vehicle.

A driving study was conducted on a closed circuit test track comprising 16 children, aged 4 – 12 years old and the Q3, HIII 3y, 6y and 10y ATDs restrained on the right rear seat of a modern passenger vehicle. The children were exposed to one braking manoeuvre in each of the two restraint systems whilst the ATDs were exposed to two braking manoeuvres in each restraint system. All manoeuvres had a deceleration of 1.0g. Short children (stature 107 – 123 cm) and the Q3, HIII 3y and 6y were restrained on a booster cushion as well as a highback booster seat. Tall children (stature 135 –150 cm) and HIII 10y were restrained on a booster cushion or restrained by three point belts directly on the car seat. Vehicle data was collected and synchronised with video data. The braking manoeuvre was identified by simultaneously viewing the data and the video sequences captured by the four video cameras. The beginning of the braking manoeuvre was defined as the point in time prior to when the brake pressure started to increase drastically. The ending of the braking manoeuvre 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.

A total of 40 trials were analysed. Child volunteers had greater maximum forward displacement of the head and greater head rotation compared to the ATDs. 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. Short children moved forward and downward while it was more common for tall children to demonstrate a forward and slightly upward motion. The ATDs moved forward and back again with minimal changes in the z-direction. The change in head angle was greater for short children than tall children and shoulder belt force was within the same range for short children when restrained on a booster cushion or highback booster seat. For tall children, the shoulder belt force was greater when restrained on a booster cushion compared to being restrained by seat belts directly on the car seat.

In a severe braking manoeuvre children moved forward by up to 200 mm. 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. Differences were also seen in the curvature of the neck and spine. Short children exhibited a greater flexion motion of the head whilst a more upright posture at maximum forward position was exhibited by the tall 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 set-up.

4. EMERGENCY BRAKING WITH THE Q6 AND Q10 ATDS

The Q6 and Q10 ATDs were tested in equivalent test setup conditions as in Paper III adopting the same method of analysis. However different weather conditions resulted in small changes in longitudinal acceleration (Figure 5). The Q6 was restrained on a booster cushion as well as on a highback booster seat, while the Q10 was restrained on a booster cushion or restrained by the three-point belt directly on the car seat. The ATDs when tested on a highback booster seat or a booster cushion were positioned based on the FMVSS 213 protocol. The same principal procedure was used for the HIII 10y when restrained by seat belt only. The ATD was placed centrally on the vehicle seat and positioned similarly to the FMVSS 213 protocol for ATDs on a booster cushion.

The ATDs were exposed to two braking manoeuvres in each restraint system. Forward trajectories for the forehead and the lateral head target (ear), located at the centre of gravity, as well as head rotation, were determined. Results are presented as mean values of the two trials and compared with the HIII 6y and HIII 10y ATDs in each restraint system.

There were small differences in the initial position of the targets due to differences in seated height between the ATDs of similar size, as well as differences in initial seated posture. The Q6, Q10 and HIII 6y ATDs had an initial seated posture including seat back contact for both shoulder and head, while the HIII 10y when seated on a booster cushion, did not make contact between the head and the head restraint.

The mean peak deceleration for the two test series are shown in Figure 5. There was a variation in the vehicle longitudinal acceleration and the time to reach the plateau between the additional braking tests for the Q6 and the Q10 compared to previously performed tests with children and ATDs (Paper III). In the present tests the maximum deceleration of all analysed braking events was 1.06g. The peak mean deceleration was 0.9g with a standard deviation of 0.09g. The duration of the entire deceleration period was 2.9s. In the tests presented in Paper III, the maximum deceleration of all analysed braking events was 1.2g. The peak mean deceleration was 1.0g with a standard deviation of 0.08g. The duration of the entire deceleration period was 2.4s. The difference in mean peak deceleration was assumed to have minimal effect on the results. Due to the extended time to reach the peak plateau no data on displacement over time is presented.

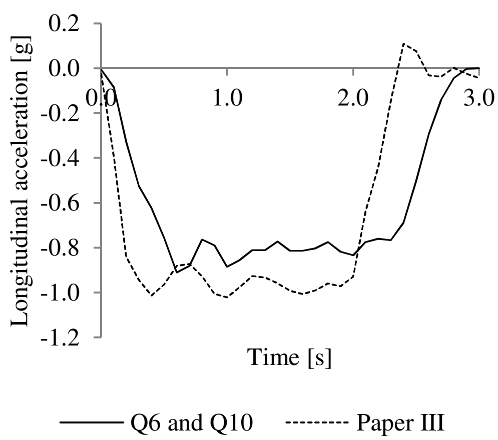

Figure 5 The average longitudinal acceleration for the two brake manoeuver test series. Time zero is defined as the point where brake pressure increased drastically.

The delta displacement for the ear and forehead targets were computed in the x and z-direction as the change from initial position to maximum displacement, and are presented, together with peak head rotation for Q6, HIII 6y, Q10 and HIII 10y in Table 1. The ear target was not visible for the ATDs when seated on a highback booster seat due to the side wings obstructing the view. Consequently, the head rotation was not measured in experiments when both head targets were not visible.

The Q6, HIII 6y and HIII 10y showed greater forward displacement when seated on a booster cushion compared to a highback booster seat and restrained by seat belt only, respectively. The Q10 showed the opposite results.

All the ATDs were exposed to a flexion rotation motion (defined as positive head angle).

Table 1 Peak head rotation and delta displacement for ear and forehead targets in the x and z direction as the change from initial position to maximum displacement for the Q6, HIII 6y, Q10 and HIII 10y ATDs. N/A: Not Applicable.

		Forward displacement				
		Ear [mm]		**Forehead [mm]**		**Peak head**
		x-dir	z-dir	x-dir	z-dir	**rotation [°]**
Highback booster seat	**Q6**	N/A	N/A	60	10	N/A
	HIII 6y	N/A	N/A	95	-20	N/A
Booster cushion	**Q6**	85	25	90	10	9
	HIII 6y	160	30	165	-30	39
	Q10	50	15	50	5	7
	HIII 10y	70	40	75	5	11
Seat belt only	**Q10**	75	10	80	10	14
	HIII 10y	50	10	55	10	5

The trajectories in x and z-direction for the ear and forehead target motions are shown in Figure 6-9 divided into groups based on size and restraint system. The origin was used as a reference value. It can be seen that the HIII 6y moved forward and downward while it was more common for the other ATDs to demonstrate a forward and slightly upward motion.

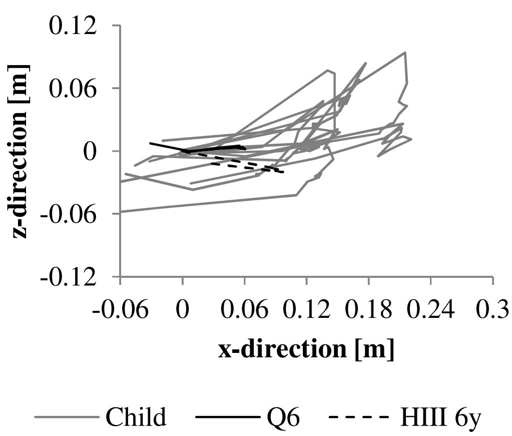

Figure 6 Trajectories for forehead target for Q6, HIII 6y and children (grey) on highback booster seat.

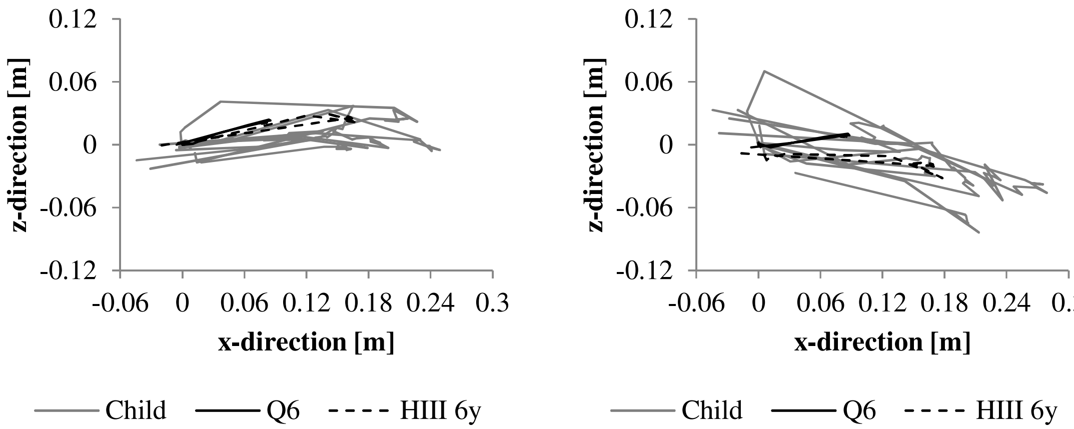

Figure 7 Trajectories for Q6, HIII 6y and children (grey) on booster cushion. Ear target to the left and forehead target to the right.

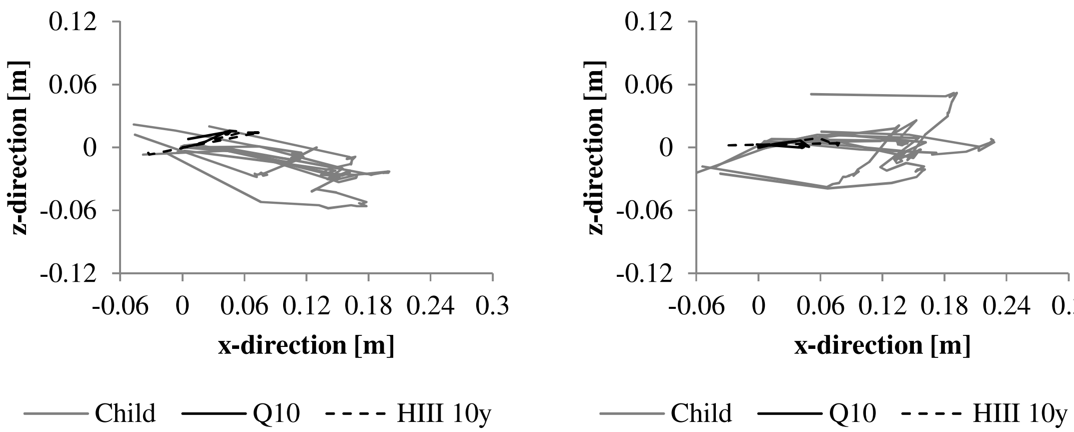

Figure 8 Trajectories for Q10, HIII 10y and children (grey) on booster cushion. Ear target to the left and forehead target to the right.

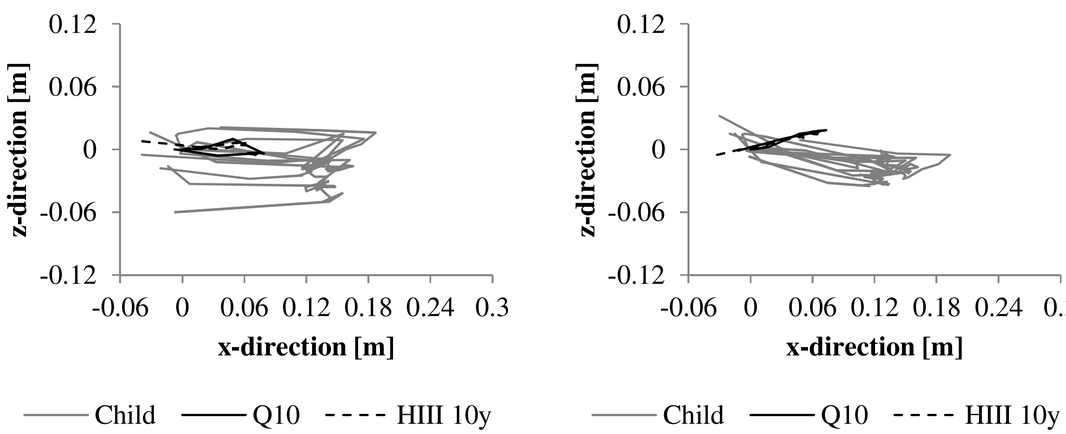

Figure 9 Trajectories for Q10, HIII 10y and children (grey) restrained by seat belt only. Ear target to the left and forehead target to the right.

As can be seen in Figures 6–9, there was a distinct difference in the motion pattern between the Q6 and HIII 6y while the Q10 and HIII 10 showed similar trajectories. Similar findings were presented by Seacrist et al. (2012).

This data complements the data in Paper III providing valuable knowledge on potential pre-crash postures of ATDs as a result of a vehicle emergency braking manoeuvre for a variety of restraint systems and sizes.

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 set-up (Paper III).

5. GENERAL DISCUSSION

Methods in this thesis were developed to study children's and ATDs' kinematics during emergency vehicle manoeuvres such as evasive braking and steering manoeuvres. Test procedures, data collection and analyses were performed. For optimal protection during an impact, the seat belt position on the lap and shoulder, and how the child is restrained by the belt are important factors and present a particular challenge when developing future restraints.

The methods can be used to quantify occupant behaviour and kinematics in vehicles caused by vehicle accelerations. Moreover, the data sets produced in this thesis comprising the kinematic behaviour of child volunteers and child ATDs from the Q and HIII families may be used to improve and validate existing and new test tools for low acceleration manoeuvres such as different pre-crash situations.

5.1 METHOD AND ANALYSES

Repeatable test performance was achieved by placing cones on the test track to indicate the point for steering and braking manoeuvres to begin, as well as by utilising the same vehicle and professional driver throughout all studies. Using an actual vehicle environment throughout the tests was an advantage and enabled a direct relation between the measured variables and the vehicle interior.

To study the behaviour, seated posture and kinematic response of occupants in real car environments poses certain assessment challenges, compared to in laboratory testing environments. The space inside the passenger compartment is limited. Researchers expect the volunteers to behave as naturally as possible, i.e., the assessment equipment should preferably be discrete as to not influence or affect the volunteer, in order to increase the usability of the collected data. In a laboratory environment it is reasonable to assume that the participants are more aware of being observed and this may affect their behaviour.

One factor influencing the results of the studies in this thesis 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 manoeuvres, but were not told exactly when the manoeuvres 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 manoeuvres. It was determined that the youngest children, aged 4 – 5 years, may have difficulties understanding instructions of what was expected of them during the test. Had they been instructed to be relaxed, the opposite may have been the outcome since they may then have focused on their bodies and the imminent manoeuvres. No difference was seen in the results between the first and last trials 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 but this did not affect the kinematic measurements.

Rear seat design including belt and seat geometry is likely to influence the forward and lateral motion of the occupant during the manoeuvres. A limitation of the studies in this thesis is that one vehicle model and two belt positioning boosters and seat models were used in the evaluation. As presented by Reed et al. (2009, 2012) the differences in lap belt and shoulder belt fit among boosters are relatively large which may result in different 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 seat), although further studies are required for a more comprehensive view.

Although there were some individual differences in belt fitting at the time of the braking manoeuvre or steering manoeuvre, 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. In reality, a large proportion of misuse (incorrect use of restraint systems) occur among children restrained by a booster cushion (NHTSA, 2004), however such positions were not included here. It is known that there are considerable differences between the self-selected posture children adapt and the postures recommended for standardised sitting instructions (Reed et al. 2006). The studies in this thesis confirm this conclusion.

The assessment system used in this thesis included vehicle and video data from four cameras enabling communication between vehicle and occupant. The occupants' displacements, both lateral and longitudinal, were in the centre of the camera view. The distortion effect introduced by the use of wide-angle lenses was less than 2 percent in the area where the motion occurred. 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 ending of the manoeuvers 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 acceleration with standard deviation at the time points T2 and T3 for the present tests was 0.55g±0.05 and 0.72g±0.03, respectively. The maximum inboard displacement was not affected. For the braking manoeuver, this had an effect on the time from the beginning of the manoeuver, 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 0.2 s 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 0.5 s after the initial braking event, and the children stayed in this position for approximately 2 s 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 more precise records although it only had minor effect on the maximum forward displacement, the main results and conclusions.

Naturalistic driving studies comprising children have presented data on which positions children naturally adopt when travelling in passenger vehicles. Through recorded video data or photos, their different seated postures were categorised according to pre-defined postures and positions, and the duration of each posture was determined (van Rooij et al. 2005, Charlton et al. 2011, Andersson et al. 2010, Jakobsson et al. 2011a). 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. 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 behaviour. However, vehicle data was not recorded and it is unknown how posture is related to vehicle movement. In this thesis vehicle data and video data has been recorded continuously which enabled a direct relation between the measured variables and the vehicle interior. The children were exposed to evasive braking and steering manoeuvres that differs from normal driving situations but nevertheless might arise in an emergency situation when the driver tries to avoid a potential impact. The methods presented in this thesis provide basis for gaining increased knowledge on children's behaviour in vehicles and quantification of their kinematic responses in relation to vehicle movement and acceleration forces. Volvo Cars in Gothenburg collected vehicle data and video data from 100 passenger vehicles during one year. Four cameras providing forward and rearward view out of the vehicle, a view of the pedals and the driver's feet movement and a view of the driver's face and upper torso were installed (Dozza et al. 2012). By combining naturalistic driving studies with the manoeuver studies presented in this thesis it was evident that it would be advantageous in future driving studies to equip the rear seat with video cameras and collect vehicle data during on-road driving.

The method of analysis was developed between the analysis of the child volunteers (Paper I) and the ATDs (Paper II) during the steering manoeuvre. For the steering manoeuvres comprising child volunteers (Paper I), 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 manoeuvres comprising the ATDs (Paper II), all frames during the manoeuvre 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 declining. The assessments are more repeatable and they are more quantitative. In Paper II, when comparing the results of the two methods of analysis for the steering manoeuvres, it was evident that the final results were similar.

5.2 CHILDRENS RESPONSE TO VEHICLE MANOEUVRES

In the steering manoeuvers (Paper I), the shoulder belt slipped off the shoulder in the majority of turns for the shorter children when seated on a booster cushion, while the belt remained on the shoulder when seated on a highback booster seat. Among tall children, the shoulder belt moved further laterally on the shoulder, in half of the turns. Tall children have wider shoulders by approximately 3 cm on each side, thus providing a larger anatomical surface for the shoulder belt to rest on before it slipped off.

The short children were well restrained by the highback booster seat in the steering manoeuvres although, during the steering manoeuvers the highback booster seat and the children moved sideways and tilted laterally. Furthermore, the children also moved sideways within the side support of the highback booster seat, however, the shoulder belt stayed on the shoulder due to the upper guiding loop, and the side wings supported the children's torso. Still, some children (38 percent) ended up with the shoulder belt far out on the shoulder. It is, however, unknown how the highback booster seat protects the child in an impact when the shoulder belt is positioned far out on the shoulder.

For the tall children the relative distance the shoulder belt moved on the shoulder, was independent of restraint system. 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 manoeuvre. When the children, regardless of size, were restrained on a booster cushion, the shoulder belt was positioned under the inboard guiding loop according to the instructions in the manual. A shoulder belt guided above the inboard guiding loop would have resulted in an initial belt position closer to the neck. However, shoulder belt/neck contact may result in discomfort to the child and therefore have other negative consequences such as an increased risk of misuse.

For short children in the steering manoeuvres, the lower torso/abdomen was restrained better by the shoulder belt in the highback booster seat than on the booster cushion. Due to the back of the booster seat, 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 of the booster cushion was removed the short children were not restrained as well on the booster cushion. This was possibly due to the child being able to sit further back on the booster seat and the guiding loops positioned the belt as when the backrest was fitted (Figure 10). For tall children, when on a booster cushion, this gap was not as pronounced (Figure 10). Tall children have wider shoulders and greater chest depth compared to short children resulting in 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 tall children compared to the short. The shoulder belt restrained the tall children better than the short children on the shoulder as well as the abdomen when on a booster cushion or seated directly on the seat.

Figure 10 A child from the group of short children on a booster cushion, left, and a child from the group of tall children on a booster cushion, right.

Visual inspection showed that the lap belt fit was changed when the short children were on a booster cushion compared to a highback booster seat. The lap belt rested flatter on the upper thighs and was less angled when the backrest was removed. This is in line with the findings by Reed et al. (2009) where static belt assessments were performed by measuring the belt position on pelvis.

During the steering manoeuvre the tall children often moved the outboard shoulder upward and/or forward in order to maintain the shoulder belt on the shoulder (Paper I). It is possible that the upward shoulder movement identified in the tall children is only one out of many factors contributing to the shoulder belt not slipping off their shoulders. There was a difference in how the shoulder belt enveloped the lower torso and abdomen, as mentioned previously. All children, when seated on belt positioning boosters always had the shoulder belt guided under the inboard guiding loop resulting in a shoulder belt position on the lower abdomen in most trials. For the tall children when restrained by seat belt only, a high shoulder belt position on the abdomen was seen. The high abdominal position may restrict lateral movement by supporting the lower torso. The differences in kinematics between short and tall children may be related to parameters such as anthropometric differences, muscle activity, muscle response and muscle maturity, or a combination of the above.

The variation in maximum forward displacement between the short children was greater when restrained on a booster cushion compared to a highback booster seat during the braking manoeuvers (Paper III). The results indicate that tall children displayed forward displacement within the same range, irrespective of the restraint system evaluated. However, the spread in forward displacement was slightly greater when restrained on a booster cushion. This was predominantly due to differences in shoulder belt position on the shoulder during the braking manoeuvre. The further out the shoulder belt was positioned on the shoulder, the greater the forward displacement distance, indicating a less stable restraint situation.

In the braking manoeuvers, the short children moved forward and downward while it was more common for the tall children to demonstrate a forward and slightly upward motion. For the short children in general, the ear target showed a more horizontal forward motion while the forehead target showed a downward motion. For the tall children, both ear and forehead targets displayed a horizontal forward motion irrespective of restraint system.

Furthermore, the different restraint systems affected the maximum forward displacement relative to the vehicle, in the braking manoeuvres. When the backrest was fitted, the children started and ended in a position further forward compared to when on booster cushion. The maximum forward head position was considerably further forward than the side supports of a highback booster seat will cover. 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, in line with the findings by Reed et al. (2006). As mentioned in the previous section, tall children displayed a forward displacement within the same range irrespective of restraint system; hence a more rearward starting position produces a less maximum forward position relative to the vehicle. This may be important in a potential subsequent impact scenario.

5.3 ATDS COMPARED TO CHILDREN

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

As restraint systems are becoming more effective in protecting occupants in an impact and active safety systems are increasingly being fitted in passenger vehicles, appropriate test tools are required to investigate further, situations where an impact is preceded by an emergency manoeuvre. The existing ATDs are designed for being used in impact situations, seated in a standardised 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. 2011a), resulted in the children adopting several different postures and positions not corresponding to the standardised seated posture by the ATDs when positioned in accordance to protocol, although it is the ATD's seated posture that the development and evaluation of new restraint systems is based on. The studies presented in this thesis show that child occupants adopt a variety of seated positions when exposed to emergency manoeuvres, thus the need for applicable test tools that can be located in appropriate pre-crash positions and then tested in vehicle impacts, is apparent.

During the steering manoeuvres, depending on where the seat belt 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 come back to their initial position. All HIII ATDs showed greater inboard displacement of the upper sternum at T2 and T3 when compared to their Q-family counterpart. Compared to the children, the Q ATDs are closer regarding mean values, however due to the large variety in lateral displacements seen in the children; the child performance range covers both the dummy families for the evaluated sizes of 6 and 10y ATDs. Hence, based on this study, it is difficult to conclude which ATD family are best at representing child volunteers in lateral inboard displacement during a steering manoeuvre.

Generally, the Q-family was better restrained by the shoulder belt due to having wider shoulders and a more pronounced abdomen compared to the corresponding HIII ATD. Thus, the differences in interface between the ATDs' torso/abdomen and the shoulder belt might also have helped to maintain them in a more upright position. The differences in design may affect the interaction between the torso of the ATD and the seat belt. 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 Q6 and HIII 6y have a shoulder width of 305 mm and 267 mm respectively whilst an average 6 year old child has a shoulder width of 285 mm (Pheasant, 2006). The Q10 and the HIII 10y have a shoulder width of 338 mm and 314 mm respectively whilst an average 10 year old boy has a shoulder width of 335 mm (Pheasant, 2006). The Q-family was developed with the intention of being used in both frontal and side impacts which has influenced their design (Wismans et al. 2008).

The kinematic response and rotation of the ATDs' heads during emergency braking manoeuvres have been quantified in this thesis. The forward displacement values were generally shorter 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 age. 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) and the HIII 10y (Ash et al. 2009) and Q10 (Seacrist et al. 2012). In a braking manoeuvres the stiffness of the ATDs plays a more important role than the effect of the seat belt position, regardless of whether the shoulder belt is initially positioned far out on the shoulder as the forward displacement of the ATDs was still less than for child volunteers.

5.4 IMPLICATIONS OF SAFETY IMPROVEMENTS

The results from the studies presented in this thesis can be considered as a first step towards establishing a method of how to gain better understanding of child kinematics during different vehicle emergency manoeuvres. It is believed to contribute to evaluation and potentially creation of objective and repeatable test tools for the purpose of simulating the position of a child occupant affected by an emergency steering and/or braking manoeuvre, prior to an impact.

Children across a range of statures were studied for the steering manoeuvres in several restraint systems in order to gain insight into the child occupants' lateral movement and seat belt position. For shorter children the highback booster seat showed potential for maintaining the shoulder belt on the shoulder. However, it is not known whether the highback booster seat 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 pre-crash position.

For the emergency braking manoeuvres the results are valuable and provide significant insight into possible injury mechanisms and measures for protection. The results emphasise the need for considering a large area of the vehicle's side interior as part of potential head impact surface, and thus important to develop with regards to child protection. The findings has the potential to help improve the understanding of side impact protection for children, incorporating not only the sides of a child restraint system but also the characteristics of the vehicle's side interior protection and capacity for keeping the child in a favourable position.

Figure 11 Schematic plot representing trajectories for forehead targets for child volunteers. From darker to lighter grey, the coloured areas represent: tall children on booster cushion, tall children restrained by seat belt only, short children on highback booster seat and short children on booster cushion.

Figure 11 shows the area of head trajectories of the children during the braking manoeuvres. 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 could 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 a highback booster seat would cover (Figure 12).

Figure 12 Maximum forward head position of a child on a highback booster seat during an emergency braking manoeuvre.

6. CONCLUSIONS

The braking and steering manoeuvres with child volunteers and crash test dummies (ATDs) carried out in this thesis provide valuable and unique knowledge of possible pre-crash postures of children and currently available ATDs across a variety of restraint systems in vehicle emergency manoeuvres. The test methods and methods of analysis were repeatable and the results offer valuable input to safety system development, ATD design as well as test method development.

The main conclusions regarding emergency braking manoeuvres are listed below:

- The forward displacement was within the same range for all children regardless of stature and restraint system.
- Maximum excursion was dependent on the initial seated posture and shoulder belt position on the shoulder. Boosters with backrest influenced initial seated posture and thus resulted in a further forward head position during maximum excursion.
- Short children exhibited a greater flexion motion of the head whilst a more upright posture at maximum forward position was exhibited by the tall 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 set-up.

The main conclusions regarding emergency steering manoeuvres are listed below:

- Steering manoeuvre can be an unstable restraint situation for children in the rear seat.
- The children moved approximately 100 mm laterally, regardless of stature or restraint system.
- The shoulder belt slipped off the shoulder in almost 67 percent of the trials for the short children restrained on a booster cushion.
- For the tall children, belt slip off did not occur. However; tall children seated on a booster cushion demonstrated a shoulder belt position far out on the shoulder during the steering manoeuvre.
- Compared to the children, the Q ATDs were closer regarding mean values, however due to the large variety in lateral displacements for the children, the child performance range covered both the dummy families for the evaluated sizes of 6 and 10 y ATDs in this set-up.

Appropriate initial shoulder belt position is important during steering and braking manoeuvres. For real world protection, one needs to take into account the growing child, focusing and understanding such aspects as initial seated posture, i.e., head position, shoulder belt position and how the child is restrained by the seat belt, as well as the booster design.

7. FUTURE WORK

The difference in kinematics between the group of tall and short 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 manoeuvres affect children, and what the important factors influencing the outcome are.

Other interesting parameters, which may influence the shoulder belt slip off seen in short children on a booster cushion, are differences between different stature groups in:

- muscle recruitment/muscle maturity, and/or
- belt geometries and booster design, and/or
- anthropometry/anatomical differences

It is apparent that working test tools are needed to test situations where an emergency pre-crash manoeuvre is followed by an impact, hence, new test tools for low g manoeuvres need to be developed. However, in the meantime a working test method for low g manoeuvres comprising the existing physical ATDs needs to be designed. The data can be used as a validation set for physical ATDs, numerical ATD models or child-sized human body models in various restraint configurations and shoulder belt positions. The development of an active child model to reproduce pre-crash events such as braking and steering manoeuvres would be valuable.

A multibody model can be used as an introduction into analysing the kinematic responses. Based on the results presented in this thesis it can be assumed that older/tall children are in a more stable restraint situation in emergency braking and steering manoeuvres than younger/short children. This is most likely due to anatomical differences in combination with muscle properties and maturity. Short children (4 – 6 years old) are in an unstable restraint situation during pre-crash manoeuvres and need more support from the restraint systems. The first focus should therefore be on this age range.

Once a model can be validated for pre-crash manoeuvres it can provide valuable information for impact situations where an emergency manoeuvre is present. Numerical simulations, varying manoeuvres, ramping and acceleration, belt geometries and booster design could serve as valuable input in understanding critical pre-crash postures in children. The consequences of pre-crash positions should then be evaluated and it would be viable to perform parameter studies to evaluate different countermeasures and their impact on the outcome.

If children of different age and stature are equally restrained by the seat belt, the results will not be affected by how the child is restrained by the belt and it is possible to study how children use their muscles to retain the belt on the shoulder.

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