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Vehicle Safety

Child Safety in Car Crashes:
A Modeling Approach for Safety System Improvements

by

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ABSTRACT

Traffic related trauma is the most common cause of fatality and severe injury to children in developed countries. The majority of these fatalities and injuries are caused by frontal and side impacts. Researchers agree that the head is the most important body region to protect for all ages of children, while the thorax is equally important for older children. Injury epidemiology has shown that special attention is needed for the 3-year-olds in boosters and the 12-year-olds in seat belts only. The aim of this thesis is to develop mathematical frontal and side impact models and to use them to investigate and define the beneficial characteristics of restraint systems and other crash-related car parameters. It must be emphasized that children are better protected in rear-facing child restraints; they should remain rear-facing for as long as possible. Most children have outgrown the large rear-facing restraints by the age of about 4 years. This work concentrates on injury mitigation for those who have transited to forward-facing restraints.

Models for two load cases were developed and validated. One of them was a frontal impact type, and the other was a near-side impact type. The frontal model was used both for a parameter study, to define beneficial restraint system characteristics for 3-year-olds, and for reconstructing three crashes in order to evaluate the head kinematics of the occupant model. The characteristics of the side impact load case were defined by analyzing real life crashes involving child occupants. The near-side impact model was used for a parameter study to define beneficial restraint system characteristics for 3- and 12-year-olds. It was also used to evaluate and propose improvements to the restraint systems within a range of common sitting positions for 12-year-olds.

The validations carried out here showed that the models developed were suitable tools for conducting comparative studies of injury mitigation systems in both frontal and near-side impacts. The parameter studies showed that several of the restraint systems for adults also reduced the values measured by the child model. In the near-side impact, a curtain airbag, a thorax-pelvis airbag and a seat belt with a pretensioner reduced the head and chest injury measures of the two occupant models. To help mitigate injuries resulting from a frontal impact, the upper belt anchor point should be positioned so that the belt is routed near mid-shoulder (slightly toward the neck) and encloses the shoulder (tight fit). The lap belt anchor points should be positioned to make the lap belt angle as horizontal as possible without inducing submarining. Seat belts with pretensioners and load limiters also reduced the head injury measures for the 3-year-old occupant model.

In side impacts, the results of the evaluation of common sitting positions suggested that extensive outboard, inboard and forward positions should be discouraged, while the restraint systems should be adapted to function with slight inboard, outboard and forward positions. This can be achieved with side supports integrated in the seat back, pre-impact (pre-brake) trigged seat belts, high performance full cell coverage curtain airbags, and/or thorax-pelvis airbags with an extended cover area. These findings are significant contributions to the continuous work of mitigating traffic accident induced injuries and fatalities to children.

Key words: child safety; side impact; frontal impact; near-side; rear seat; evaluations; mathematical simulations; finite elements; rigid body; reconstructions; child seat; belt positioning booster.

LIST OF PUBLICATIONS

This thesis comprises the following scientific papers, referred to by Roman numerals.

I. Johansson, M., Pipkorn, B., Lövsund, P., (2009) Child Safety in Vehicles: Validation of a Mathematical Model and Development of Restraint System Design Guidelines for 3-Year-Olds through Mathematical Simulations. *Traffic Inj Prev.* 10:5; 467–478. Copyright Taylor & Francis, available online at: http://www.tandfonline.com/doi/abs/10.1080/15389580903149243

II. Andersson, M., Pipkorn, B., Lövsund, P., (2012) Evaluation of the Head Kinematics of the Q3 Math Model and a Modified Q3 Math Model by Means of Crash Reconstruction. This is a preprint of an article accepted for publication in the *Traffic Injury Prevention*. Copyright Taylor & Francis, available online at: http://www.tandfonline.com

III. Andersson, M., Arbogast, K., Pipkorn, B., Lövsund, P., (2011) Characteristics of Crashes Involving Injured Children in Side Impacts. *Int J Crashworthiness*. 16:4; 365–373. Copyright Taylor & Francis, available online at: http://www.tandfonline.com/doi/abs/10.1080/13588265.2011.593978

IV. Andersson, M., Pipkorn, B., Lövsund, P., (2011) Parameter Study for Child Injury Mitigation in Near-Side Impacts through FE Simulations. *Traffic Inj Prev*. Online November 2011, not yet in the printed journal. Copyright Taylor & Francis, available online at: http://www.tandfonline.com/doi/abs/10.1080/15389588.2011.637411

V. Andersson, M., Pipkorn, B., Lövsund, P., Rear Seat Child Safety in Near-Side Impacts: A Modeling Study of Common Sitting Positions. This is a preprint of an article submitted for consideration in the *Traffic Injury Prevention,* 2012. Copyright Taylor & Francis, available online at: http://www.tandfonline.com

Division of work

For Papers I, II, IV and V, M. Andersson carried out all of the modeling work, the main part of the analysis, and the main part of the writing.
For Paper III, M. Andersson collected the data from the databases, conducted the main part of the analysis, and wrote the most of the paper.

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DEFINITIONS AND ACRONYMS

AIS	Abbreviated Injury Scale, an anatomical-based scoring system to determine the severity of single injuries based on the survivability of the injury, established by the Association for the Advancement of Automotive Medicine
AS/NZS	Australian/New Zealand Standard
ATD	Anthropmorphic Test Device; crash test dummy
Booster	A child restraint that lifts the child to better fit the geometry of the vehicle's seat belts, seat either with or without backrest
CANDAT	Child ANthropometry DATabase
CRS	Child Restraint System
Curtain airbag	An airbag that deploys from the vehicle's roof rail, to cover the side windows and the upper part of the door, to protect the head
DOE	Design Of Experiments is the statistical term for a method to design the experiment in order to simplify the succeeding statistical analysis.
DOF	Direction Of Force, impact direction defined in clock hours
D-ring	A link attaching and redirecting the seat belt webbing at shoulder height, initially made of a metallic ring shaped like the letter "D"
ECE	Economic Commission for Europe
ECE R44	ECE Regulation for child restraints
EuroNCAP	European New Car Assessment Programme
FEM	Finite Element Method
FMVSS	Federal Motor Vehicle Safety Standard
Folksam	A Swedish insurance company
Full cell coverage	Refers to a type of curtain airbag: the inflated cells cover the whole curtain area
HBB	High Back belt-positioning Booster
HBM	Human Body Model, a mathematical model of a human body
HBM3	A finite element human body model of a 3-year-old child, based on the THUMS 50th percentile adult male model
Hybrid III 3YO	Child ATD corresponding to an average 3-year-old, from the Hybrid III (HIII) series
IBC	Integrated Booster Cushion

IIHS	Insurance Institute for Highway Safety, an organization based in the United States aimed at reducing losses from crashes on US highways
Injury measure	A measure, obtained by an ATD or other occupant model, to assess the load (acceleration, deflection, force, moment or other) applied to specific body parts, correlated to the risk of injury imposed to the corresponding body part of a human.
Kinematic joint	In multibody dynamics a kinematic joint is an object linking two bodies and defining their relative degrees of freedom, i.e. the type of relative motion allowed between the two bodies
Load limiter	A component used to absorb energy in a crash in order to keep the belt force at a controlled and pre-defined level
LS-DYNA	A combined implicit/explicit solver for finite element problems; a code for solving nonlinear transient problems, for example car crashes
MADYMO	MAthematical DYnamic MOdel is a computer program that simulates the dynamic behavior of physical systems; it emphasizes the analysis of vehicle collisions and assesses injuries sustained by passengers
MAIS	Maximum AIS, the maximum of multiple injuries to one person as classified by the AIS
MAIS2+	The maximum injury among all injuries with an injury severity minimum of 2 (moderate injury) and higher
MAIS3+	The maximum injury among all injuries with an injury severity minimum of 3 (serious injury) and higher
NASS-CDS	National Automotive Sampling System Crashworthiness Data System, a database of passenger vehicle crashes mainly used to investigate injury mechanisms to identify potential improvements in vehicle design
Near-side impact	Definition of side impact relative to the sitting position of the occupant; the occupant sits on the struck side of the vehicle
NHTSA	National Highway Traffic Safety Administration, USA
OOP	Out-Of-Position, see definition below
Optimized zone	Defined as the zone where all injury mitigation systems provide their intended functions
ORM	Objective Rating Method, a method to objectively assess the similarity of two signals
Out-of-position	Out-of-position refers to children who are positioned within the volume of the fully expanded airbag during its deployment

Partial cell coverage	Refers to a type of curtain airbag with inflated cells that cover a limited part of the total curtain area adjacent to the head of the ATD in its nominal position
PDOF	Principal Direction of Force, impact direction defined by degrees
Pretensioner	A system used to tighten the belt, during the very first fractions of a second in a crash, to ensure maximum restraint from the belt as early as possible.
Q3	Child ATD corresponding to an average 3-year-old, from the Q series
RB	Rigid Body
Retractor	A component used to feed out and rewind the belt under normal conditions, and to lock it under crash conditions
SID-IIs	A side impact ATD corresponding to a 5^{th} percentile adult female; the LS-DYNA FE model of the SBL-C version (developed by FTSS, User Manual SIDIIs SBL-C, on the homepage of Humanetics) was used in this dissertation
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 pelvis
TNO	Netherlands Organisation for Applied Scientific Research
THUMS	Total HUman Model for Safety, human body model of a 50^{th} percentile adult male
USNCAP	United States New Car Assessment Program
VC	Viscous Criterion, chest injury criterion based on both chest deflection and chest deflection rate

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Marianne Andersson
Göteborg, 2 March 2012

1 INTRODUCTION

1.1 *Injury and fatality to children: Statistics and prevention approaches*

Traffic related trauma is the most common cause of fatality and severe injury to children in developed countries (Bauer and Steiner, 2009; NHTSA, 2010). Most of the traffic related trauma to children occurs when they are passengers in cars in frontal or side impacts, which account for about 50% and 25% of the crashes respectively (Starnes and Eigen, 2002). However, side impacts result in more fatalities than frontal crashes (Partners for Child Passenger Safety, 2008). These facts show that both frontal and side impact injury mitigation should be given priority.

Child safety research started in the 1950s. In 1950, Popular Science published an article (Waltz and George, 1950) discussing ways to make cars safer. It proposed that all occupants (except drivers) should be rear facing. This included a special rear facing seat for children. Somewhat later, inspired by astronaut seats at rocket launches, Bertil Aldman started experimental work. In 1963 he presented a rear facing child seat prototype (Aldman, 1964). Since then, the rear facing child seats have become the given choice to transport infants. In Sweden and other Nordic countries it is recommended that children up to 4 years travel rear facing. At present, the rear facing child restraints for children that weigh more than 13 kg (approximately 1.5 years) are rare outside the Nordic countries, but researchers agree that the rear facing child seats provide state-of-the art safety (Isaksson-Hellman *et al.*, 1997; Henary *et al.*, 2007). Figure 1 shows the injury reduction effects for three types of restraint systems (Isaksson-Hellman *et al.*, 1997). The benefit of the rear facing seats over belt positioning booster seats and the seat belt only is apparent (note that the restraints were used appropriately within each group). Therefore, the primary focus of injury mitigation system improvements for children should be aimed at those who have outgrown the rear facing systems. These children transit initially to belt positioning booster seats and, later on, the seat belt alone.

The latter transition occurs when the children reach a height of 135 to 150 cm. Therefore, the upper size limit for children in child restraint systems corresponds to children between 10 and 12 years old. Hence, the primary size range on which to focus can be translated to 3- to 12-year-olds. The injury rates for children in appropriately used child restraints according to age groups are shown in Figure 2. The injury rate for a given restraint type is higher for the younger children than for the older children (Jakobsson *et al.*, 2005). This indicates that special attention is needed for children at the lower end of the range for which the restraints were designed. These facts indicate that the two transition ages, the 3- to 4-year-olds in boosters and the 10- to 12-year-olds in seat belts only, need special attention.

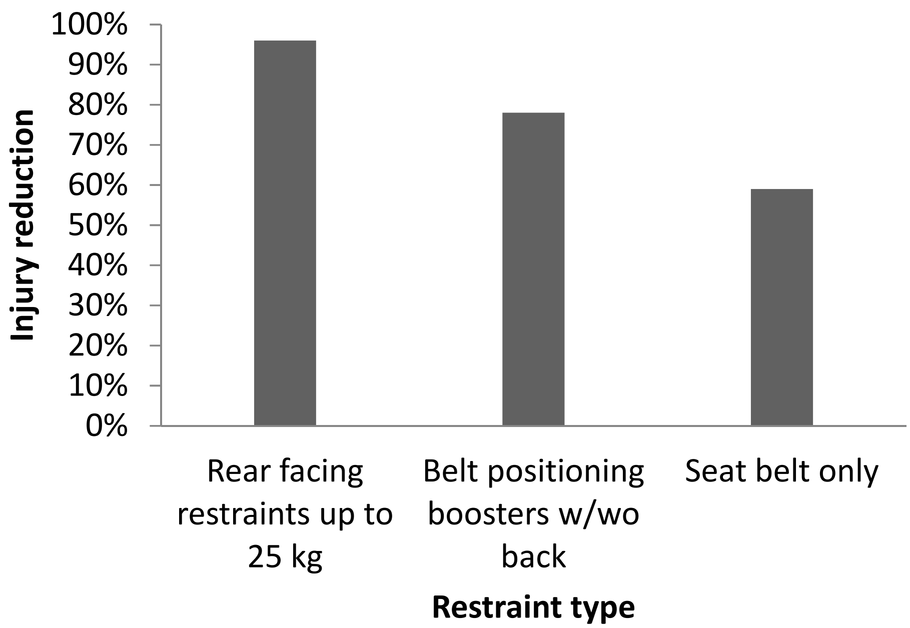

Figure 1. The injury reduction effects for three types of restraint systems, adapted from Isaksson-Hellman *et al.* (1997). All systems were compared with unrestrained. The dataset included all children from 0 to 15 years in the Volvo database (n = 4242 unweighted data), where the earliest accidents are dated 1976.

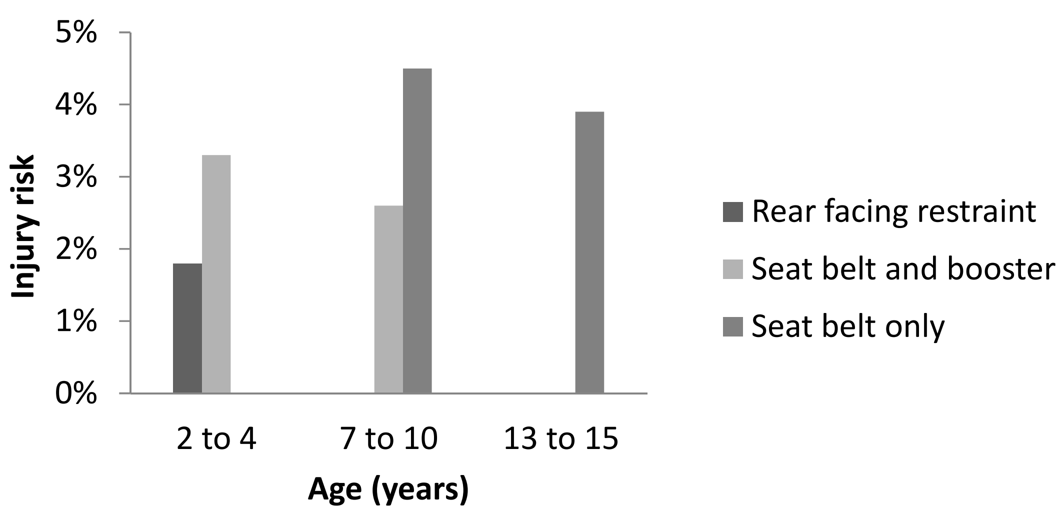

Figure 2. MAIS2+ injury risk by age groups and restraint types (n = 3670) based on Jakobsson *et al.*, 2005.

The safety of cars for adults has been regulated for many years. To some extent, these evaluations have positively influenced the safety of children as well. For example, the restraint systems developed for adults have been shown to reduce real life injury rates even for children. The seat belt is the best example. It has been available in cars since the 1970s; in Sweden it has been mandatory to use it in the front seat since 1975 and in the rear seat since1986. Therefore, there are sufficient amounts of data to calculate its protective effect to approximately 67% (Norin and Carlsson, 1984; Isaksson-Hellman *et al.*, 1997). There are also examples of the opposite, i.e. a negative effect of adult protection systems on child injury; the front passenger frontal airbag has caused fatalities among children positioned within reach of the deploying airbag (McKay and Jolly, 1999). The databases of real life crashes constantly provide information on how injury mitigation systems affect children. This knowledge must be used to further improve the car injury mitigation systems from the perspective of child safety. So far, most child injury mitigation efforts have been aimed at improving the child restraint systems or the child restraint anchorages in vehicles (Bilston *et al.*, 2005; Hu *et al.*, 2008; Kapoor *et al.*, 2008; Hu and Mizuno, 2009; Cui *et al.*, 2012).

Injury epidemiology is nearly unanimous regarding which body region is the most frequently injured; on the AIS2+ level (AAAM, 2012), head injuries dominate in the statistics for all ages of children (Khaewpong *et al.*, 1995; Walsh *et al.*, 1996; Isaksson-Hellman *et al.*, 1997; Langwieder *et al.*, 1999; Arbogast *et al.*, 2001, 2005a, 2005b; Starnes and Eigen, 2002; Orzechowski *et al.*, 2003; Howard *et al.*, 2004; Maltese *et al.*, 2005, 2007; Scullion *et al.* 2008). These publications have shown that the head is the most frequently injured body region, regardless of type of restraint or type of impact. Physicians indicate that head injuries are complicated to treat and for some injury types there are no known treatments (Nance, 2009). These injuries are caused by both impacts and non-impacts (acceleration based, Bohman *et al.*, 2011a). Therefore, injury mitigation should be directed to both reducing the likelihood of impacts and reducing the accelerations that the children are exposed to in a crash.

Other studies have shown that the chest is the second most commonly injured body region (Orzechowski *et al.*, 2003; Bohman *et al.*, 2009). Furthermore, in side impacts the thorax is the most frequently injured body region among children older than 12 years and adults (Bohman *et al.*, 2009). It can be concluded that the head is the most important body region to concentrate on for children up to 12 years, while for older children and adults, the thorax is equally important, especially in side impacts.

1.2 Injury prevention evaluation methods and tools

There are many methods for evaluating the effects of car crashes on occupants. Complete cars instrumented with advanced anthropomorphic test devices (ATDs), which are crashed into different types of barriers, are commonly judged to be the most reliable method. Today, mathematical simulations are becoming more and more common due to their cost and time efficiency. Within injury prevention evaluation, there are two main methods for mathematical simulations: the finite element (FE) method and the rigid body (RB) method. The RB method is fast and accurate for predicting translations and rotations of RBs (and RBs connected by joints) provided there are no major elastic or plastic deformations of them, and that the force-deflection characteristics and the joints between the RBs are known. The FE method computes both elastic and plastic deformations of parts as well as predicting translations and accelerations of the parts. However, the more complex algorithms of the FE method require a greater computation effort. The FE method is needed for side impacts, since the components that interface with the occupants may undergo both elastic and plastic deformation during the impact. In addition, the stiffness of both the occupant and of the components that interface with it must be of the same order of magnitude. The actual deformation is also affected by the interaction with the occupant. On the other hand, frontal impact may be simulated with RB models, since there is almost no deformation to the components that interact with the occupant during the impact, particularly in the rear seat (the FE method can be used also). Therefore, both frontal and side impacts can be evaluated by mathematical simulations, but the computation methods may differ.

In general, the evaluation methods for child safety are not based on crashes of complete cars; current regulated dynamic test methods for child restraint systems are limited to sled tests (ECE R44, FMVSS 225, AS/NZS 1754). These tests do not take any vehicle restraint systems into account. For example, the sled seat is a simplified generic seat, the seat belt is static (no pretensioner and no load limiter) and there are no airbags. As a result, the efforts to improve the injury mitigation systems for children are designed mainly to develop the child restraint as an independent system or to develop the child restraint anchorages. To investigate the protective effect by the vehicle restraint systems on children, other methods are needed. These test methods should be based on a holistic view of the child safety, which integrates vehicle based injury mitigation systems with the traditional child restraints. The IIHS (Insurance Institute for Highway Safety) has taken steps to evaluate the in-car belt fit of belt positioning booster seats. However, this test is a static one. The EuroNCAP (European New Car Assessment Programme) dynamic tests include child restraints and child ATDs in both frontal and side impacts, but the test setup does not yet take into account the car related injury mitigation systems (a change is due in 2015). There is still work to be done to evaluate how the car injury mitigation systems and the child restraint systems can work together to mitigate injuries to children.

To further improve the safety systems for children, the tools used to evaluate the passive safety must be adequate. The child ATDs are important in evaluating the passive safety of children. This also applies to the mathematical models of the ATDs. The child ATDs and mathematical models need to be adequate for emulating children for making real improvements. The two most recently developed child ATD are the Hybrid III (HIII) and the Q series. The basic structures of the 3-, 6- and 10-year-old dummies are similar: rigid skulls with vinyl skin; flexible rubber necks and lumbar spines; thoraxes with rigid spines, supporting ribcage structures; molded foam abdomens; rigid or semi rigid pelvises; and the extremities are vinyl and foam covered steel skeleton parts. The 3-year-olds from the Q and the HIII series are shown in Figure 3 (page 9). Older children (12-year-olds) are similar in size to the small adult females. The 5^{th} percentile adult female ATDs have anthropometry very similar to a 50^{th} percentile 12-year-old regarding stature, sitting height, weight and buttock-knee length; they also take into account the injury mitigation of 12-year-old children (Humanetics Innovative Solutions home page, http://www.humaneticsatd.com/crash-test-dummies/side-impact/sid-iis). The SID-IIs is the most widely used side impact model of the 5th percentile adult female (Figure 3, page 9).

It is expected that the Q ATDs will be included in European regulations and EuroNCAP tests (in 2015), which increases the interest in the performance of the Q-dummies. The anthropometry of the Q ATDs is based on measurements by TNO (Netherlands Organisation for Applied Scientific Research) in 1985 (the CANDAT database). The responses of the ATDs were evaluated according to established response corridors for head drop impact, thorax pendulum impact and lumbar flexion. These response corridors were scaled from the 50th percentile adult male; the scaling was based on anthropometrics and bone modulus (Irwin and Mertz, 1997). Data on the kinematic response of adult humans are gathered through cadaver and volunteer tests, but ethical approvals are rarely issued for such tests on children (only a few tests with child cadavers have been reported, Brun-Cassan et al, 1993). Consequently, there is a distinct difference between the development of adult and child ATDs. Instead, researchers attempt to evaluate, sometimes validate, the child ATDs by comparison with the deduced courses of events in real accidents; data regarding kinematics, injury causes and injury criteria can be obtained by reconstructing real accidents with child ATDs (Klinich *et al.*, 1996; Damm, 2006). A few published studies deal with the evaluation of the HIII 3- and 6-year-old ATDs, or the corresponding mathematical models, relative to real world crashes (Bilston *et al.*, 2007b; Brown *et al.*, 2007; Sherwood *et al.*, 2003), but no such publications regarding the Q ATDs have been found. The study by Sherwood *et al.* (2003) also included a comparison with a cadaver test. The comparison pointed out the difference in head, neck and thorax kinematic responses. The difference was due to the lack of flexibility of the ATD's stiff thoracic spine. In the study, it was shown that the addition of one joint in the thoracic spine improved the correlation of the head and neck kinematics considerably. As the thoracic spine of the Q ATDs have a similar, stiff design, it is likely that they have the same shortcoming in head kinematics. Besides the stiff thorax, other possible shortcomings in the ATDs are mass distribution and geometry. The anthropometry studies on children to date have not measured the weights of 3-year-old children's body parts (body part by body part). However, it is known that bone tissue density differs from fat or lean soft tissue density (Gelander, 2005), and that the proportions of these tissues differ from body part to body part. Hence, there is reason to study the effect of the human mass distribution as compared with the current ATD mass distribution. To do so, such data need to be collected.

In the future, mathematical occupant models are expected to be models of the human body. For example, Toyota has developed the THUMS 50th percentile adult male human body model (HBM) (Iwamoto *et al.*, 2002). Work is being done to make HBMs in other sizes as well, both a small adult female and children of various sizes, but more work is still needed to complete and to further develop these human body models. Mizuno *et al.* (2005) presented a down-sized version of the THUMS 50th adult male; a 3-year-old HBM. This model has the global geometry of a 3-year-old and its material properties correspond to a 3-year-old (downscaled from adult data), while the detailed geometries of bones, organs and tissues still resemble those of an adult. However, this model is the first available HBM of a child; it has been shown to meet the requirements set for the 3-year-old ATDs (Mizuno *et al.*, 2005) and may add valuable data regarding kinematics.

1.3 Sitting behavior of children

Injury mitigation systems are commonly evaluated by tests with an ATD sitting in the nominal position. However, the studies by Andersson *et al.* (2010), Charlton *et al.* (2010) and Jakobsson *et al.* (2011) indicate that children commonly sit in positions other than that in which the ATD normally sits. In addition, many crashes are preceded by some evasive maneuver by the driver, e.g. panic braking or swerving to either the left or the right (Bohman *et al.*, 2011b). As a result, the occupant moves either to the side or forwards (or both) just before the crash. Therefore, there is a need to evaluate injury mitigation systems for positions other than the nominal ATD one. Van Rooij *et al.* (2005) explored the frontal crash safety for 1.5- to 3-year-olds in a forward facing harness seat, in a series of sitting positions, but no such investigations have been conducted for children in side impacts.

The self-selected sitting positions of 12-year-olds were studied by Jakobsson *et al.* (2011) by exploring the sitting behavior while awake, of six 138 to150 cm tall children (8 to 13 years old) seated in the rear of a medium sized passenger car during naturalistic riding. They found that children using only a seat belt most commonly sit with the shoulders against the seat back and with the head against the head rest or upright. Laterally, the children in seat belts were mainly centered in the seat or tilted inboard. Children in sleeping situations, aged 7 to 14 years, were studied by Forman *et al.* (2011). They found that children using only a seat belt were mainly in outboard positions. The outboard positions included a range of positions up to 35 cm (maximum) from the center position. Furthermore, the sitting positions of children during swerving were studied by Bohman *et al.* (2011b). These children were between 135 and 150 cm and they were restrained by the seat belt only. During the swerves, the lateral movement of the sternum was recorded as about 8 cm. In a parallel study, the forward motion of the children was studied during maximum braking events (Stockman, 2011). Preliminary results indicate that the maximum forward excursions were up to 19 cm. Hence, there is enough data to begin the evaluation of injury mitigation in a range of common sitting positions.

1.4 Gaps in child safety research: A summary

In Sections 1.1 to 1.3 several gaps in child safety research are highlighted. The following gaps are addressed in this thesis. Injury mitigation for children needs to be further improved for both frontal and side impacts. The two transition ages (3 and 12 years) should be given priority. The head is the most important body region on which to focus for all ages, while for older children there should be an additional focus on the thorax. Moreover, in order to further advance the injury mitigation systems for children, a new approach is needed. The methods for the system evaluations should be based on the characteristics of real life crashes, and should apply a holistic view of child safety that evaluates the car injury mitigation systems and the traditional child restraints together. The methods should also incorporate the most common sitting positions that children adopt while riding in cars. In doing this, the most humanlike tools available should be used.

2 AIMS

The aim of this thesis is to develop and apply tools and methods to investigate and define the beneficial characteristics of injury mitigation systems designed for children in the rear seat, in the most common injury causing impacts, frontal and near-side impacts, with a real life crash safety perspective.

More specifically, the aims are:

- To develop and validate a mathematical model of a frontal impact with an occupant model corresponding to a 3-year-old sitting on an integrated booster seat;
- To develop and validate mathematical models of near-side impacts with occupant models corresponding to a 3-year-old sitting on a backless, belt-positioning booster seat and a 12-year-old sitting directly on the car seat;
- To use the models to investigate and define the beneficial characteristics of the restraint systems and other crash related car parameters.

3 SUMMARY OF PAPERS I – V

To fulfill the aims of the thesis, several studies were conducted. These have been or will be documented in journal papers (a mix of published and submitted). The papers are referenced by Roman numerals in the summary.

3.1 Child Safety in Vehicles: Validation of a Mathematical Model and Development of Restraint System Design Guidelines for 3-Year-Olds through Mathematical Simulations (Paper I)

3.1.1 Aim and Methods

The first objective of this study was to validate a mathematical simulation model of the Q3 ATD, in an integrated, forward-facing booster type restraint in the rear seat; the second is to evaluate restraint parameters to further develop design guidelines for this type of restraint system (for forward facing children, corresponding to the size of the Q3) in frontal impacts.

A mathematical model was developed. It included a Q3 ATD model (the Q3 MADYMO model version 3.2), a seat and a seat belt. The complete model was validated by means of sled tests for frontal test conditions, at two levels of pulse severity (delta v of 50 and 64 km/h respectively). The model was validated with two kinds of seat belts, one with and one without a load limiter and pretensioner. Changes were made to the Q3 math model in order to improve the correlation between the model predictions and the sled test measurements.

The kinematics of the model were validated for displacements of head center of gravity, shoulder joint and knee joint, for lap and shoulder belt forces on the outboard side, and for ATD sensor measurements: head, chest and pelvis accelerations, and chest deflection. The positions of the ATD in the tests and in the mathematical model are shown in Figure 4. The correlation between the model predictions and the physical test results was assessed by computing the ORM (objective rating method) correlation coefficients (Hovenga *et al.*, 2005).

A parameter study was conducted according to factorial design of experiments (DOE). Nine parameters that were assumed to significantly influence the performance of the restraint systems were selected. Six of them were related to the seat belt (such as pretensioner, load limiter, and belt anchor position); two parameters were related to the seat (stiffness and pitch angle); and one was related to the foot support. The "low" and "high" values are given in Table 1.

The ATD measurements for head, chest and pelvis were selected as dependent variables. As noted in the introduction, the head is the top injury risk in several epidemiology studies. Hence, head forward displacement and head resultant acceleration were important to include as dependent variables. In this study, chest resultant acceleration and pelvis resultant acceleration were the responses chosen to estimate injuries to the torso and pelvis. The validated Q3 math model was used in the parameter study.

Table 1. The DOE independent variable levels.

Parameter	LOW (-)	HIGH (+)
Seat stiffness	- 10% of the base model stiffness	40% of the base model stiffness
Seat cushion pitch angle	12˚ with the horizontal	25˚ with the horizontal
Pretensioner (at retractor)	No pretensioner	1.5 kN and 10 cm pull-in
Pretensioner (at belt anchor)	No pretensioner	1.5 kN and 10 cm pull-in
Belt load limiter level	No load limiter (> 6 kN)	3.5 kN
Lap belt angle	24˚	73˚
D-ring x position	Gap between belt and shoulder (loose fit)	Shoulder belt wrapped around the shoulder (tight fit)
D-ring y position	The shoulder belt close to the arm-to-shoulder joint	The shoulder belt close to the neck
Foot support	No foot support	Foot support present

Figure 3. The Hybrid III 3-year-old ATD (left); the Q3 ATD (centre); the SID-IIs 5th percentile adult female ATD (right). (Pictures not to scale)

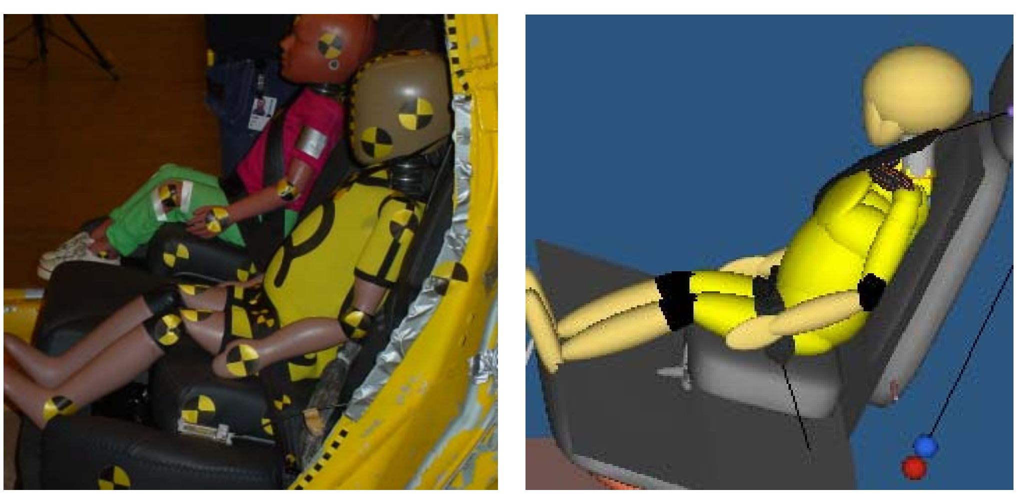

Figure 4. The Q3 ATD in the physical test and in the corresponding mathematical model.

3.1.2 Results

The validation study showed that the mathematical model predicted the ATD kinematics and measurements. In total, 117 ORM coefficients were computed and 97 of them were rated ‘good’. Specifically, 40 of the 42 coefficients for the variables that were used in the subsequent parameters study were rated ‘good’. Based on this, the model was considered adequate to use in a comparative study.

The effects of the Q3 responses for each of the independent parameters were calculated in the parameter study. The effect is the difference between the average response values from the “high” state and from the “low” state. The lap belt angle had the greatest effect on all responses. The resulting head x displacement was 7.8 cm shorter with a lap belt angle of 24˚ from horizontal, when compared with a 73˚ angle from horizontal; it also resulted in a reduction of the head resultant acceleration by 9.8 g. Other significant parameters were the D-ring x and y positions (upper belt anchor) and the seat belt load limiter; tight fit of the seat belt resulted in more favorable ATD responses than when there was a gap between the belt and the chest, and using a load limiter was more favorable than not doing so. Moreover, the retractor pretensioner had positive effects on all of the responses. The anchor pretensioner, foot support and the seat related parameters had marginal or no effect on the head responses.

To decrease the Q3 ATD head acceleration and to limit its head displacement, position the upper belt anchor so that the belt is routed near mid-shoulder (slightly toward the neck) and encloses the shoulder (tight fit). Furthermore, position the lap belt anchors to make the lap belt angle as close to 24˚ as possible without inducing submarining. Finally, a retractor with a pretensioner and load limiter showed some reduction of the measured responses of the Q3.

3.2 Evaluation of the Head Kinematics of the Q3 Math Model and a Modified Q3 Math Model by Means of Crash Reconstruction (Paper II)

3.2.1 Aim and Methods

An objective of this study is to evaluate the head kinematics of the Q3 mathematical model. Another one is to evaluate the effect on head kinematics of: an increase in thoracic spine flexibility; a more humanlike mass distribution; and more humanlike body geometry in the Q3 mathematical model. The evaluations were based on the head kinematics of children deduced from real accidents and on new data of mass distribution and updated body dimensions for 3-year-olds.

Two versions of the Q3 math model were evaluated: one that correlated with the Q3 ATD (also used in Paper I) described in Section 3.1, and another in which the thoracic flexibility and anthropometry were modified. These modifications to the model must not be confused with the modifications made during the validation of the Q3 math model (Section 3.1). The thorax was made more flexible by adding a joint in the thoracic spine. The anthropometry was updated based on new data collected for this study. The anthropometry study was conducted at Queen Silvia Children's Hospital in Göteborg, Sweden. Mass distribution, length and circumference data were collected. The children were sampled by their age and size, approximately corresponding to the size of children in transition between the two ECE R44 Groups I and II (15 to18 kg). The average stature, weight and sitting height were compared with the corresponding data from other more extensive studies to check the validity of the sample. The data was scaled to correspond to an average 3-year-old. The scaled data were used to modify the Q3 model.

The head kinematics of the two Q3 models were evaluated by comparing their responses with the responses of 3-year-old children deduced from real accidents. To do so, data from accidents were collected. The data were used to develop the mathematical vehicle and restraint system models in which the Q3 models were positioned. In total, three accidents involving 3-year-old children with head injuries in frontal impacts were reconstructed. The models were run numerous times, each time with a different setting for each of the variables for which the exact value was not known.

3.2.2 Results

Twenty-six children were included in the anthropometry study. The averaged data and the data that was scaled to correspond to an average 3-year-old are presented in Table 3 (Paper II). When compared with the Q3 ATD data, the main differences were found in the mass distribution of the torso and thighs. However, the total Q3 torso weight differed only slightly from the new anthropometry data. Another difference was identified in the buttock-knee length. In the Q3 math model, it was measured as 29 cm (30.5 cm on the Q3 ATD), while the scaled data from the new anthropometry was 33 cm.

In the first case of the three reconstructed, it was not known whether there was a head impact that caused the head injury. None of the 35 runs with the Q3 showed head impact. The runs with the modified Q3 showed that the head struck the legs in 12 of the 35 runs. Based on the reconstructions of Case I, it was concluded that the two child models reproduced the head kinematics equally well. In the second accident case there was a clear head impact. The impact location was determined to be either the front seat, B-pillar or door trim. The runs with the Q3 did not show any head impacts. The runs with the modified Q3 showed 14 head to leg impacts out of 35. The Q3 did not adequately reproduce Case II in this study. The modified Q3 did not adequately reproduce it either, but improved kinematics was observed. Case III had a definite forehead impact. Seven of the Q3 runs showed impact to the side of the head, mostly with the door trim. The modified Q3 had 14 forehead impacts and 12 other head impacts.

In conclusion, neither of the two child models reproduced the accident cases adequately; however, the modified Q3 showed that a future Q3 ATD with increased thoracic flexibility and updated anthropometry would have the potential to do this. Adequate thoracic spine flexibility cannot be achieved by adding one joint only. Continued work on developing the Q3 thorax should incorporate flexibility along the length of the thoracic spine (continuous or discrete) to allow forward and lateral bending and rotation about its z-axis.

3.3 Characteristics of Crashes Involving Injured Children in Side Impacts: A NASS-CDS Study and a Detailed Case Study (Paper III)

3.3.1 Aim and Methods

The objective of this study is to describe the characteristics of near-side impact crashes in which restrained children, 3 to 13 years old, seated in the rear seats were injured. The impacts included both oblique and perpendicular types with an impact angle of 30–150˚ or 210–330˚. This study included appropriately restrained children only, defined as 3- to 4-year-olds in harness child restraints, 3- to 10-year-olds in booster seats and 3-point safety belts or 8- to 13-year-olds in three-point safety belts. Cases were selected from the NASS-CDS (National Automotive Sampling System Crashworthiness Data System) crashes occurring between 1997 and 2007 (weighted data).

The crash direction of force (DOF, direction defined by clock hours, 1 to 12), principal direction of force (PDOF, direction defined by degrees [˚], 0–360˚), heading angle, horizontal impact location and extent of deformation were described for the whole sample and two subsamples: MAIS2+ or fatal injuries (MAIS2+), and MAIS3+ or fatal injuries (MAIS3+). The definitions are shown in Figure 5.

A more detailed examination of cases was also conducted in order to more precisely describe the horizontal impact location, vertical impact location and intrusion at the child occupant's seating position. The case review was based upon the NASS-CDS study already described, complemented with cases from other databases.

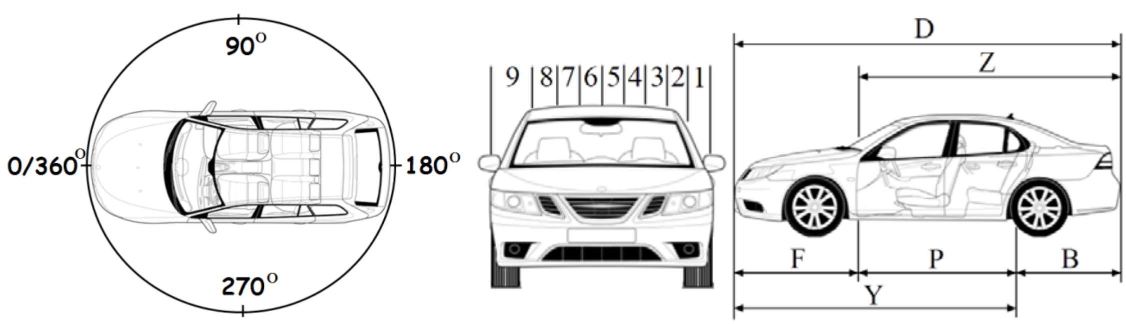

Figure 5. Definition of PDOF in degrees, deformation extent (deformation on left side shown, definition mirrored for deformations on the right side), and horizontal impact location, according to the SAE J224/1 standard (1980).

3.3.2 Results

The NASS-CDS study

In total, 75,473 children (weighted) met the sampling criteria for the NASS-CDS study. Forty percent of the children were female, and 74 % of the children were between 9 and 13 years old. Of those children, 3,164 (4%) had an MAIS2+ or fatal injury, and 865 (1%) had an MAIS3+ or fatal injury.

The majority of the crashes had a DOF that was either 2 or 10 o'clock, and a PDOF between 60 and 90˚ or 300 to 330˚ included. Further, 62 percent of the crashes in the sample are of Extent 1 or 2, while all of the MAIS3+ injuries occurred in crashes of Extent 3 or greater. Eighty-nine percent of the MAIS2+ injuries occurred in crashes of Extent 2 or 3.

Crashes with the heading angle between 31 and 90˚ accounted for 67% of those resulting in MAIS2+ injuries and 87% of those resulting in MAIS3+ injuries. Specifically, 69 % of the MAIS3+ injuries occurred in crashes with a heading angle of 61 to 90˚. The F, Y and Z impacts (Figure 5) were more frequent than P and B impacts among all crashes. The D impacts were rare. Among the crashes that result in MAIS2+ injuries, the P impact (to the occupant compartment, between the A and C pillars) was the most frequent, followed by F and Z. The passenger compartment was involved in 73% of the crashes resulting in MAIS2+ injuries. The Z impacts, from the A pillar rearward, were most frequent among the crashes resulting in MAIS3+ injuries, while no MAIS3+ injuries occurred in F, P or B impacts.

The detailed case study

There were 16 cases in total that matched the case selection criteria for the detailed study. The rear door (adjacent to the child) was impacted in all of the 16 selected cases except one. The front door was impacted in 10 cases. The B-pillar was impacted in 11 of the cases, and the C-pillar in 9 cases. The bullet overlapped two pillars in 11 cases: A and B in 6 cases, and B and C in 5, however only slight overlap with the C-pillar occurred in 2 of those 5. A, B and C were overlapped in one case, but in this case there was only a minor overlap with the C-pillar. The sill, which is an important structure in side impacts, was not engaged in 11 of the 16 cases (Photographs in Appendix A).

3.4 Parameter Study for Child Injury Mitigation in Near-Side Impacts through FE Simulations (Paper IV)

3.4.1 Aim and Methods

The objectives of this study are to validate a mathematical simulation model of a complete car in a near-side impact with the SID-IIs ATD seated in the rear seat on the side that was struck, and to investigate the effects, of crash-related car parameters, on values of head and chest injury assessment measures for 3- and 12-year-old children in near-side impacts.

Finite element (FE) simulation was used for this study. The basic model consisted of a midsize 4-door sedan. The validity of the vehicle model was shown by comparing response data, from two full vehicle crash tests, with the response data from the corresponding computed crashes. The crash tests were the IIHS deformable barrier side impact test and the USNCAP test. The responses compared were the intrusion (in the vehicle reference system) and global velocity (in the ground reference system) for selected points. The selected points were at the waist height of the vehicle (common head impact height for children of various ages, Maltese *et al.*, 2007), and they were distributed along the length of the struck side of the target vehicle. Accelerometers were attached to the vehicle and their signals were used to calculate the intrusions and intrusion velocities of the vehicles. The head resultant accelerations and the maximum of all peak rib deflections of the SID-IIs (shoulder, thorax and abdominal ribs) were also compared to show the validity of the occupant model inside a complete vehicle model. This vehicle model included a seat belt without a pretensioner, a head airbag (curtain type, mounted at the roof rail), and a thorax-pelvis airbag (mounted in the seat bolster). The similarities of the physical tests and the mathematical simulations were quantified with the objective rating method (ORM) coefficients (Hovenga *et al.*, 2005).

The parameter study was a full factorial design of experiment (DOE) at two levels (Box *et al.*, 1978). Five car parameters (independent variables), which were assumed to significantly influence the performance of the vehicle in a side impact, were selected for the DOE. The car parameters were: target vehicle mass; side structure stiffness; side head airbag; side thorax-pelvis airbag; and seat belt pretensioner. The parameters and their respective 'high' and 'low' values are shown in Table 2. The vehicle model that was validated (Section 3.4) was also used as the basic model in the parameter study. The SID-IIs 5th percentile adult female ATD and the HBM3 (Human Body Model of a 3-year-old, down scaled version of the THUMS 50th percentile adult male, Mizuno *et al.*, 2005) finite element models were used for the parametric investigation. These models were chosen to represent 3- and 12-year-old children. The models were positioned one at a time in the rear seat of the vehicle, where the 3-year-old was sitting on a backless belt positioning booster (backless booster). Dependent variables included were: resultant head linear acceleration, resultant head rotational acceleration, chest VC (viscous criterion), rib deflection, and relative velocity at head impact. The chest measurements were only considered for the SID-IIs.

Table 2. The DOE independent variable levels. The levels that were part of the validated vehicle model are marked by an asterisk (*).

	Independent variable	HIGH (+)	LOW (-)
A	Vehicle mass	1700 kg *	1100 kg
B	Side structure stiffness	Extra high strength	High strength
C	Seat belt pretensioner	120 mm	0 mm *
D	Thorax-pelvis airbag	Yes *	No
E	Head airbag (curtain)	Yes *	No

The side impact load case in the parameter study was defined to correspond to the findings of Paper III (Section 3.3). In the parameter study, the IIHS impact barrier was used as the bullet. The barrier impact location on the target vehicle was set to overlap the A-pillar, front door, B-pillar and most of the rear door, but not to overlap the sill or the lower C-pillar (b, Figure 6). At impact, the angle between the longitudinal axes of the target vehicle and the barrier was 90˚ (known as the heading angle), i.e. the same as in the IIHS load case. The direction of travel of the striking barrier had an angle of 70˚ to the longitudinal axis of the stationary vehicle struck. These impact settings resulted in an intrusion profile with a maximum at the mid height of the B-pillar. The velocity of the barrier was then adjusted to result in an intrusion similar to the median intrusion of 26 cm reported in Paper III. In the parameter study, the velocity of the barrier was set to 60 km/h, which resulted in a maximum dynamic intrusion of 25 cm. The corresponding intrusion was 18 cm in the IIHS load case and 6 cm in the USNCAP load case.

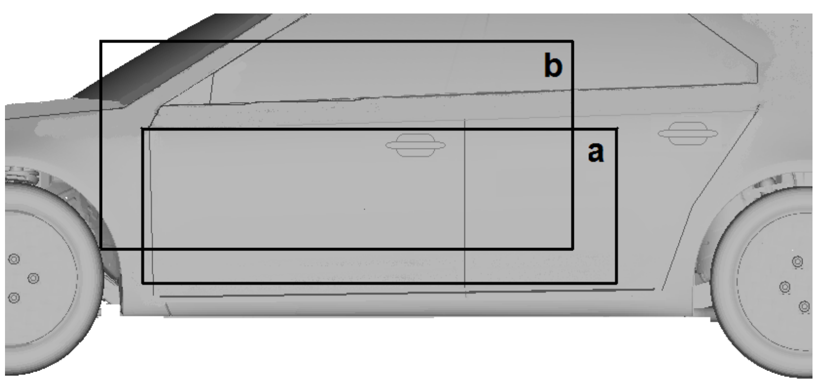

Figure 6. The side of the vehicle. The squares represent the barrier contours relative to the side just before contact (a = USNCAP barrier and b = Child LC barrier).

3.4.2 Results

Model validation

The validation of the vehicle model showed that the simulation model corresponded adequately to the physical vehicle in general, with regard to the point intrusion, the global velocity, and the head acceleration. All global velocity ORM coefficients were rated 'good', i.e. higher than 0.65, except the phase coefficient for one point (Point III on the B-pillar) in both of the load cases. All intrusion ORM coefficients were rated 'good' except: magnitude, phase and shape in Point I of the USNCAP load case; shape in Point III of the USNCAP load case; and magnitude and shape in Point IV of the IIHS load case (46 out of 54 were 'good'). The signals with ORM coefficients less than 0.65 are shown in Appendix B. The ORM may underestimate the similarity when the signals have several local maxima, minima, or both, which was the situation here (Figures A to D in Appendix B). Despite low ORM coefficients, the signal correlation was considered adequate for the parameter study.

Furthermore, the ORM coefficients for the resultant head acceleration were all above 0.66; the magnitude coefficients were 0.80. This shows that the SID-IIs head acceleration is a reliable measure. (Note: the Roman numerals referred to in this section should not be confused with the numbering of the studies in this thesis).

The parameter study

The head airbag had the greatest effect on the head measurements for both of the occupant models. On average, it reduced the peak head linear acceleration by 54 g for the HBM3 and 78 g for the SID-IIs. The seat belt had the second greatest effect on the head measurements; the peak head linear accelerations were reduced on average by 39 g (HBM3) and 44 g (SID-IIs). The 'extra high stiffness' side structure increased the SID-IIs head acceleration, while it had marginal effect on the HBM3. Vehicle mass had a marginal effect on SID-IIs head accelerations, while the lower vehicle mass caused 18 g higher head acceleration for HBM3 and the greatest rotational acceleration. The thorax-pelvis airbag, the vehicle mass and the seat belt pretensioner affected the chest measurements the most. The presence of a thorax-pelvis airbag, high vehicle mass and a seat belt pretensioner all reduced the chest VC and peak rib deflection in the SID-IIs.

The peak intrusion of the C-pillar was increased by the high vehicle mass and the extra high structure stiffness. Similarly, the peak intrusion of the rear end of the window sill was increased by the high vehicle mass; however, it decreased with the extra high structure stiffness. The high vehicle mass also reduced the peak global velocity. Here, the peak intrusions and global velocities were extracted from the time interval during which there was interaction between the occupant and the vehicle. The SID-IIs had earlier interaction than the HBM3; the interval with head interaction for the SID-IIs was 45–64 ms, while it was 60–80 ms for the HBM3. The reason for the difference was mainly the initial distance between the occupant and the side struck; the smaller occupant had a greater gap to the side.

3.5 *Rear Seat Child Safety in Near-Side Impacts: A Modeling Study of Common Sitting Positions (Paper V)*

3.5.1 Aim and Methods

The purpose of this study was to evaluate and propose improvements to the injury mitigation systems, in near-side impacts, for six common sitting positions of 12-year-olds.

The vehicle model that was described in Section 3.4 was used to conduct this study. The SID-IIs was chosen to represent 12-year-old children; it was positioned in the rear seat and restrained by the seat belt only (no belt positioning booster seat). Six common sitting positions were selected for the SID-IIs this study. The selection was based on the findings of Jakobsson *et al.* (2011), Forman *et al.* (2011), Bohman *et al.* (2011b) and Stockman (2011). Thus, the six sitting positions covered the common ones of children, awake and sleeping, during normal riding as well as the positions of children during swerving and braking (pre-impact evasive maneuvers).

The vehicle model was subjected to two types of side impacts. One of these was according to the USNCAP side impact test protocol. The barrier represents a midsize passenger car. In this test the barrier had a speed of 62 km/h and it struck the target vehicle at an angle of 63˚ to the longitudinal axis of the vehicle (i.e. a crabbed impact). This resulted in a maximum dynamic intrusion of approximately 6 cm at the mid height of the B-pillar. This load case is henceforth called the 'USNCAP'. The other side impact was designed according to findings regarding the most common impact characteristics of side impacts where children are injured (Paper III). Here, the barrier of the IIHS side impact test was used. It represents a truck or an SUV. The longitudinal impact location on the target vehicle was set to overlap the A-pillar, the front door, the B-pillar and most of the rear door, but not to overlap the sill or the lower C-pillar (Figure 6). The speed of the barrier was 60 km/h; it had an angle of 70˚ to the longitudinal axis of the vehicle struck (crabbed). This resulted in a maximum dynamic intrusion of approximately 25 cm at the mid height of the B-pillar. This load case (LC) is henceforth called 'Child LC'.

3.5.2 Results

The occupant model interacted differently with the airbags depending on the initial position. The most obvious differences in the interactions with the airbags were seen between the two most outboard (OB2 and OB3) sitting positions and all other positions; the curtain airbag deployed between the ATD and the side of the vehicle in all runs except for the OB2 and OB3 runs. Furthermore, the thorax-pelvis airbag overlapped the torso in the lateral projection in the nominal ATD and inboard (IB) positions, while parts of the torso were not fully overlapped in the OB and braking positions. Note that the theoretical thorax-pelvis airbag position shown (Paper V, Table 1) did not match the resulting position in the simulations in the OB cases. The reason was that the OB SID-IIs interacted with the thorax-pelvis airbag during the deployment. The IB position resulted in higher relative velocity between the ATD and the vehicle's side just before they impacted, which pushed the curtain airbag over the window sill.

In general, the outboard and the inboard positions had the highest head accelerations and HIC, in both load cases, while the centered positions (ATD and braking) had the lowest. The highest chest deflections and VCs were observed for the outboard and braking positions, while the lowest were seen in the ATD and inboard positions. The inboard positions resulted in higher levels due mainly to the increased relative velocity between the ATD and the side of the vehicle at impact. Animations of the inboard runs suggest that the curtain airbag needs to be designed so that the occupant does not push the curtain out through the window, thus exposing the window sill to potential head impacts. The outboard positions resulted in unfavorable airbag positioning. Thus, the injury mitigation effects of the airbags were significantly reduced. In the braking position, the occupant was more exposed to the relatively greater intrusion near the B-pillar (compared with the C-pillar). These results suggest that, in side impacts, extensive outboard, inboard and braking positions should be discouraged; the restraint systems should be adapted to function with slightly inboard, outboard and forward positions. This can be achieved with side supports integrated in the seat back, pre-impact (pre-brake) trigged seat belts, high performance full cell coverage curtain airbags, and/or thorax-pelvis airbags with extended cover area.

4 GENERAL DISCUSSION

Traffic accidents are the leading cause of serious injury and death to children in a large part of the world, including Europe and the USA (Bauer and Steiner, 2009; NHTSA, 2010). Actions can be taken to reduce the consequences of accidents within three main phases: pre-crash, crash, and post-crash. This thesis concentrates on the crash phase and on the passive safety or injury mitigation systems. To make real improvements to the injury mitigation systems, one has to take into account the real life safety perspective. Improvement as such is often described as cyclic work (known as the Deming cycle) and is illustrated here in Figure 7. Generally, improvements are initiated by gathering information about a situation or problem. From the crash safety perspective, valuable knowledge can be gained by studying real crashes (Figure 7). This thesis provides new information about the kinematics of children in real crashes (Paper II) and improves our knowledge of the nature of crashes involving children (Paper III). This information was used as input to evaluate a child ATD and to develop design guidelines for child injury mitigation systems for both frontal and side impacts (Papers I, IV and V). Figure 7 shows where the studies fit into the cycle of improvements.

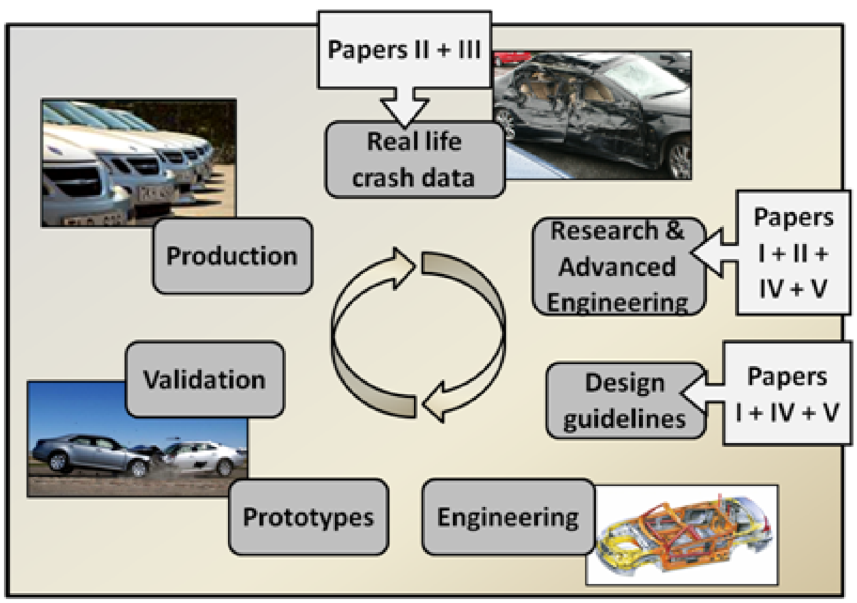

Figure 7. The cycle of continuous improvements applied to real life crash safety (based on the Deming cycle), and how the work of this thesis relates to it.

4.1 Methods

Crash safety evaluations are traditionally conducted with ATDs. The Q-series of child ATDs is expected to be used in both consumer tests and in regulatory tests in the near future. The research in Papers I and II, which deal with 3-year-olds in frontal crashes, was conducted with a model of the Q3. The Q3 was developed for frontal and side impacts (van Ratingen *et al.*, 1997). It was shown to fulfill the requirements set for ATDs (van Ratingen *et al.*, 1997). However, the accident reconstructions in Paper II revealed areas of improvement needed for the Q3; suggestions were made for improving its head kinematics (Paper II). Despite this, the improvements suggested are not expected to alter the conclusions of Paper I, because that study did not incorporate any lateral pulse component. Bearing the findings of Paper II in mind, a human body model was chosen to represent 3-year-olds in the side impact evaluation: the THUMS model scaled to the 3-year-old size (HBM3). The HBM3 was developed by Mizuno *et al.* (2005). Another reason for choosing the HBM3 was that, in the future, there will be a great potential to improve the occupant crash safety by using human body models as a complement to the ATDs. Models of humans will enable more detailed analysis of the body when it is loaded and even facilitate identifying local injuries, which ATDs do not. By using the HBM3 and disseminating the results, more information about this model will be made available and help to improve child human body models. The HBM3, as it is, needs further development before it is capable of predicting specific injuries; for example to correct the child geometries and the compositions of organs, bones, cartilage and other tissues. Here, it was used in the same way as an ATD. Unfortunately, there were no available human body models of a 12-year-old child. In the side impact studies, the 12-year-olds were represented by the SID-IIs. This ATD has very similar anthropometry to a 50th percentile 12-year-old and it is a widely used side impact ATD.

The thesis work evaluated the protective effects of several injury mitigation systems for children by means of mathematical simulations. The simulation-based studies could also have been conducted by physical testing with the corresponding ATDs (the HBM3 excluded). Physical tests with ATDs may have provided appropriate repeatability (although less than mathematical simulations) and would have given results similar to those of the mathematical simulations, but at a greater cost in both materials and work hours. Moreover, mathematical simulations have additional advantages over physical tests: they enable the use of child human body models; they make it possible to measure accelerations, velocities and displacements anywhere; and they facilitate making a detailed analysis of the results because the models can be cut, rotated, studied part by part.

The assumption of similar results is based on the model validations conducted in Papers I and IV. The frontal model validation showed ‘good’ correlation between the physical tests and the mathematical model (Paper I) according to the objective rating method (ORM) described by Hovenga *et al.* (2005). This validation was based on occupant responses and seat belt forces. The validation of the side impact model was based on occupant responses and deformation of the side of the car at points adjacent to the rear seat (Paper IV). The ORM coefficients for the side impact model were rated ‘good’ regarding all occupant responses. However, 8 of the 54

ORM coefficients regarding deformation were not rated 'good'. The signals for those coefficients are shown in Appendix B. The ORM may underestimate the similarity when the signals have several local maxima, minima, or both, which happened here. Visual judgment indicates that, despite the low rating, the signals correlate well for seven of those eight coefficients (Figures A, C, D and E, Appendix B). The remaining coefficient concerns the point close to the occupant's head (Figure B). There, the model over predicted the intrusion by approximately 30 mm in the last 5 ms of the simulation run. This was considered acceptable for the parameter study.

The parameter studies (Papers I and IV) were conducted according to the full factorial design of experiments (DOE) method, at two levels (Box *et al.*, 1978). This method is well documented and can be used either as a full factorial DOE (all combinations of parameter values are tested) or as a reduced factorial DOE in order to minimize the number of experiments. For the full factorial DOEs, this method provided primarily a clear overview of the relative effect of each of the parameters for the selected dependent variables and of possible interaction effects. Alternatively, the results could have been presented for each of the experiments conducted (as in the studies by for example Forman *et al.*, 2008; Arbogast *et al.*, 2009a), but small effects and interaction effects would have been harder to identify.

Paper III reviewed the crash circumstances for appropriately restrained children aged 3 to 13 years in near-side impacts. This study was the first to focus on defining the nature of near-side impact crashes with the goal to verify and enhance test procedures for this impact direction. The majority of the characteristics were described according to the variables defined in NASS-CDS, while the detailed vertical and horizontal impact locations were described based on thorough studies of photographs of the deformations in the cars. Among the crashes studied that resulted in AIS2+ injuries, the bullet vehicle generally struck the target vehicle on the rear door and on one of the two adjacent pillars. Most often, it struck the B-pillar. It was less common that the bullet vehicle overlapped both of the adjacent pillars. The bullet vehicle structure did not overlap the target vehicle sill in two thirds of the cases. There seemed to be two reasons for the lack of overlap: either the bullet vehicle was taller, with a bumper or crash structure that was higher than the sill of the target vehicle, or the bullet vehicle elevated from the ground just before the impact with the target, due to some unevenness of the road (e.g. traffic islands). The sill is an important crash structure in side impacts: if it is not engaged, there is less resistance to deformation of the vehicle and to intrusion into the occupant compartment. This should be taken into account in child injury mitigation system evaluations. A similar investigation of crash characteristics was conducted by Rattenbury *et al.* (2001). Their study was based on crashes with occupants between 13 and 64 years old, and the findings were similar. They also recommended that cars should be tested with less involvement of the sill and C-pillar structures. Their results indicate that the findings in Paper III are relevant despite the relatively smaller sample of crashes investigated.

4.2 Injury mitigation

As stated in the introduction, injury mitigation for children should mainly aim to reduce the likelihood of head impacts and to limit the inertial loads to the head that child occupants experience in crash. Therefore, this thesis concentrates on investigating methods to reduce the measured values of a selection of head injury measurements. For older children (aged 12) there was an additional focus on thoracic injuries. In the injury mitigation studies presented here, children of two ages were chosen: 3- and 12-year-olds. These occupant sizes were represented by two ATDs and a human body model. There was no emphasis on the measured absolute values; for the 3-year-old occupant models, there were no definite Injury Assessment Reference Values (IARVs), and hence only relative values were considered relevant.

4.2.1 Three-year-olds

It has to be emphasized that children are better protected in rear-facing child restraints; they should remain rear-facing for as long as possible. However, most children have outgrown the large rear-facing restraints by the age of about 4 years. This thesis concentrates on injury mitigation for those that have transited to forward-facing restraints. Papers I, II and IV deal with injury mitigation for 3-year-olds, seated on backless belt positioning booster seats, in frontal and near-side impact crashes. These studies suggested that in a frontal impact, head displacement and head accelerations can be reduced by implementing a seat belt with pretensioner and load limiter functions (Papers I and II). These results are in accordance with those for the HIII 6-year-old in two similar test setups (van Rooij *et al.*, 2003; Forman *et al.*, 2008). The seat belt pretensioner was also effective in reducing head accelerations in near-side impacts (Paper IV). However, the kinematics of the head and neck seen in the animations suggested that the lateral translation of the torso needs to be controlled to avoid potential lateral loads to the neck. A thorax-pelvis airbag has the potential to control the lateral translation, which can also be controlled by a torso side support integrated either in a belt positioning booster seat or in the vehicle seat (Paper IV).

The curtain and thorax-pelvis airbags were also shown to have the potential to reduce the injury measures for 3-year-old children. At present there is no drive, either by regulatory tests or by consumer tests, to design these airbags for 3-year-olds. The curtain airbag was the most effective parameter of all those investigated in Paper IV. The geometrical overlap was shown to be adequate (approximately 3 cm below eye-level), but any decrease in the overlap may reduce the protective effect significantly. It is recommended that the overlap be increased to gain a safety margin. In Paper IV, the curtain airbag had the greatest effect; however the control volume approach used did not appropriately reflect the airbag positioning, in that the computed curtain jiggled more than the physical curtain. Therefore, the protective effect of the curtain may have been underestimated. Some test runs with the particle-method airbag formulation showed a less jiggly computed curtain. It seems that the particle formulation is preferable for this type of load case. The curtain formulated with the control volume method might have been less jiggly with other parameter settings, but this was not tested.

Furthermore, it was found (Paper IV) that the pressure of the thorax-pelvis airbag used in the study was too low to have any effect on the 3-year-old due to its small size. This airbag also had an inadequate geometrical overlap, in the oblique load case, with regard to head injury, in that part of the head missed the airbag. This finding is likely to apply to many of the thorax-pelvis airbags in vehicles on the market today. The conclusion drawn by Arbogast and Kallan (2007a), that there is no increase (or decrease) in injury risk for children up to nine years of age exposed to a deploying thorax-pelvis airbag, may be interpreted to mean that the airbags neither caused nor mitigated injuries. With this interpretation, their findings are in line with those in Paper IV. The thorax-pelvis airbag in this study was intentionally tuned to obtain a deployment that minimizes harm to out-of-position children. Additional simulation runs (Paper IV) indicated that an HBB with an extra deep torso side support in combination with the thorax-pelvis airbag, or a thorax-pelvis airbag with increased pressure, may help to mitigate head injury. The increase in airbag pressure was achieved by reducing the airbag ventilation. It is likely that reduced ventilation can be implemented without jeopardizing out-of-position children; however, thorax-pelvis airbag requirements regarding out-of-position occupants and occupant injury mitigation (all occupants) need to be carefully balanced. Moreover, the geometry of the thorax-pelvis airbag should be designed to overlap the 3-year-old occupant, even in oblique crashes, to help mitigate injuries.

From an acceleration and head forward displacement point of view, the safety belt should be positioned close to the neck (Paper I). However, such a position must be balanced with the potential increase in neck injury rate due to direct belt-neck interaction, and possible discomfort of the safety belt webbing edge rubbing the neck. It is known that the shoulder belt is frequently routed under the arm (10%) or behind the back (9%) possibly due to discomfort (O'Neil *et al.*, 2009). Such misuse may cause serious injury in the event of a crash. Bearing this in mind, improved practice would be to route the belt adjacent to the neck, with a suitable clearance to avoid contact. In practice, this would correspond to a near mid-shoulder position. Therefore, the seat belt geometry at the shoulder should ensure that the belt is routed near the mid shoulder, slightly towards the neck. It should also provide a tight fit around the shoulder (Paper I).

These recommendations are in line with contemporary national recommendations (NHTSA, 2012; the Swedish Transport Administration, 2012). However, these measures have positive effects in real life only when the child remains in a position where the shoulder belt is in its intended position. To achieve this position, the backless booster seat, in combination with the most common design of vehicle rear seats (flat seat back), may not be adequate. The torso side supports that can be used to control lateral translation in a crash may also have a primary function to maintain the child in the optimized zone at all times. The optimized zone is here defined as the zone in which all injury mitigation systems provide their intended functions. Child restraint manufacturers claim that the side supports of high back belt positioning booster seats (HBB) are designed for the purpose of doing this. However, a complementary study conducted by Andersson *et al.* (2010) pointed out some sub-optimizations with these side supports. In general, the torso side supports are combined with large head side supports. Figure 8 shows the typical design of such HBBs. Andersson *et al.* (2010) found that the large head side supports induced sitting positions that were forward of the optimized zone. In these forward positions, the child had limited use for the torso side supports.

Future work should be aimed at finding the "golden mean" for the torso and head side supports, so that the children choose to stay within the optimized zone while they benefit from the supports both during sleep and in a crash. With an optimized design of the side supports, three important goals may be achieved: the child remains with the shoulder belt in the intended position; the head remains in the optimized zone where the head airbag provides impact protection; and the torso side support improves the function of the thorax-pelvis airbag. The child restraint manufacturers (e.g. Britax and Maxi-Cosi) also claim on their homepages that the side supports of HBBs mitigate injury in side impacts. There is not yet any evidence that these side supports have any protective effect in real life with the current design; research has shown that there is no difference between protective effect of HBBs and backless boosters (Arbogast *et al.*, 2009b).

Further, Papers I and II showed that head accelerations could be reduced by positioning the lap belt anchors to make the lap belt angle as horizontal as possible (in Paper I it was 24˚ to the horizontal). The reason for this is that the more horizontal the lap belt is, the smaller the amount of downward movement of the occupant's pelvis into the seat cushion will be (theoretically, a truly horizontal belt would not pull in any z-direction). The downward movement causes slack in the seat belt which allows forward movement of the pelvis. This effect is evidently reduced with a perfectly rigid seat, but this does not exist in the real world.

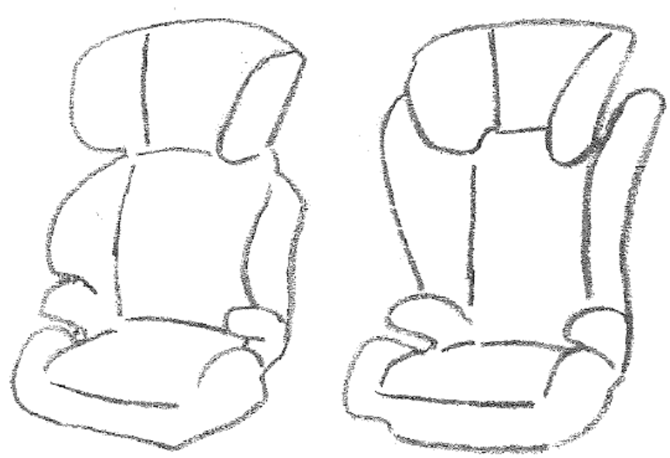

Figure 8. Two typical designs of contemporary high back belt positioning booster seats.

Seat belt slack delays the time of seat belt engagement with the occupant, thereby delaying the ride down with the vehicle crash pulse. This frequently results in a higher peak in the accelerations experienced by the occupant once the seat belt engages. It is important, however, that submarining is not induced by excessively horizontal lap belt angles. Studies show that a horizontal lap belt angle is not recommended from a submarining point of view (Adomeit and Heger, 1975; Arbogast *et al.*, 2007b; Reed *et al.*, 2009). Reed *et al.* (2009) claimed that vertical lap belt angles help to keep the lap belt on the pelvis in a crash; this is true provided the seat cushion is stiff enough to prevent the child from translating downwards into the cushion with subsequent slack in the lap belt. Adomeit and Heger (1975) described a method to prevent submarining for adults and suggested that the foam of the seat cushion forward of the lower pelvis should enforce upward movement of the H-point instead of downward. Although adult and child pelvises differ in geometry and material properties (Gray, 1918: the hip bone of a newborn is partly cartilaginous; it is gradually ossified from birth to adulthood), this suggestion may work for children as well.

However, submarining of children was shown to often be caused by poor initial lap belt positioning, i.e. the lap belt routed on the abdomen before the crash (Arbogast *et al.*, 2007b). For example, seat cushions that are longer than the children's thighs can induce slouching (Huang and Reed, 2006; Bilston and Sagar, 2007a), which can lead to poor lap belt positions (Reed *et al.*, 2009). A method to assess the lap belt fit was described by Reed *et al.* (2009). This method is mainly aimed at rating belt positioning boosters for lap and shoulder belt fit by measuring the belt position on the pelvis and shoulder, respectively. The rating is based on correct use of the booster. Unfortunately, several studies indicate that the lap belt guides of boosters are often misused (Osvalder and Bohman, 2008; O'Neil *et al.*, 2009).

Therefore, based on a synthesis of the findings in Paper I and other studies, the following measures are recommended: position the belt anchors so that the lap belt angle is as close to 24˚ as possible (accounting for regulation and other occupant sizes); select a belt positioning booster seat that rules out lap belt guide misuse and that provides good lap belt fit according to the method by Reed *et al.* (2009); and make sure that the combination of car seat cushion and booster seat prevents downward movement and is short enough to prevent slouching.

The vehicle mass had a significant effect for the HBM3 head measurements. The higher head accelerations of the HBM3, in the low mass vehicle, imply that injury mitigation systems designed for 3-year-olds, such as the head airbag, the thorax-pelvis airbag and the seat belt pretensioner, are even more important in light weight cars.

4.2.2 Twelve-year-olds

Papers IV and V comprehend injury mitigation for 12-year-olds seated on the vehicle's seat in near-side impacts. These studies evaluate the effects of the vehicle injury mitigation systems in both the nominal ATD position and five other common sitting positions. Investigations of the injury mitigation effects in common sitting positions, besides the nominal ATD position, are essential to find the means to provide improved and robust safety for child occupants in real life. To date, no other similar studies have been found.

The head and thorax-pelvis airbags were shown to have the potential to reduce injury measures for 12-year-olds, provided the airbag properties, such as geometry and pressure, are designed to include this occupant size also (Paper IV). Currently, the FMVSS 214 side impact protection regulation includes the 5th percentile adult female ATD in the rear seat. Hence, it is likely that the curtain airbags and thorax-pelvis airbags in today's vehicles mitigate injury for older children as well. Furthermore, Paper IV showed that the seat belt pretensioner was effective in reducing injury measures even in side impacts. For the SID-IIs the pretentioner prevented both forward and lateral movement of the upper body. It also coupled the occupant to the vehicle early, which reduced the relative velocity of the occupant to that of the vehicle at impact.

Before a crash in real life, many drivers make evasive maneuvers (Bohman *et al.*, 2011a) which cause children to be either inboard or outboard at the moment of crash. Paper V investigated the inboard position among others. Relative to the occupant in the nominal ATD position, the one in the inboard position struck the side of the vehicle later and further forward (due to the forward component of the load case), and gained higher relative velocity. Although the injury measures were kept at a low level, the additional velocity of the occupant, in combination with the more forward position, pushed the lower edge of the curtain airbag over the window sill and out through the window opening. Thereby, the window sill was exposed to potential head impact. There were no head impacts with the window sill in this study. However, Sherwood *et al.* (2003) showed that the downward head movement of the HIII 6-year-old was less than that of a PMHS. The HIII 6-year-old has a rigid spine, as does the SID-IIs. There could have been head impacts, if the SID-IIs had had a more biofidelic thoracic flexibility. Therefore, positions that are far inboard should be discouraged for better safety in a crash, unless the airbags are designed or tuned to be robust also with higher lateral loads. However, the primary goal should be to keep the occupant in or close to the center of the seat in order to control the relative velocity between the occupant and the vehicle side. It is suggested that the side supports be integrated with the rear seat.

It has been observed that children adopt sleeping positions close to the side of a vehicle (Forman *et al.*, 2011). However, the injury reduction effects of the airbags were lower for occupants in both sleeping positions and far outboard positions after swerving, since the occupant was in the deployment zones of the airbags during deployment (Paper V). Specifically, the sleeping position revealed insufficient curtain airbag positioning. In the future, car manufacturers should consider that child occupants (adults as well) may sleep and provide an environment that allows sleeping outside of the deployment zone.

Braking maneuvers are also common before a crash and the effect of the injury mitigation systems on occupants in positions caused by braking need to be considered. In this context it should be mentioned that some sitting positions identified as common among 3- to 6-year-old children in HBBs with large head side supports (Andersson *et al.*, 2010) are similar to the braking position. Paper V showed that the occupant is more exposed to intrusion in the braking position, since the intrusion increases from the C-pillar to the B-pillar. In addition, there is less overlap between the occupant and the current designs of the thorax-pelvis airbags in the braking position. Moreover, the most common designs of the curtain airbags (partial cell coverage) have no inflated cells that overlap the occupant in braking positions. Paper V showed that the full cell coverage curtain provided better protection for the occupants in the braking position. Nevertheless, a system that ensures that the occupant is in the optimized zone (near the nominal ATD position) would provide more robust injury mitigation. Injury mitigation systems must give adequate protection in a range of sitting positions, not just the nominal ATD position, in order to provide a robust real life safety effect. The development of the restraint systems for a range of sitting positions should be combined with the development of features that generate a more limited set of sitting positions. It should be feasible to achieve an optimized zone by working from both ends simultaneously.

Today, the European strategy seems to be that children as old as 12 years should use HBBs to keep them upright and in the optimized zone. A study of children in evasive maneuvers (Bohman *et al.*, 2011b) showed that children translate laterally during swerves. Their study did not include 12-year-olds in HBBs, but investigated the lateral movement of 8- to 10-year-olds in backless boosters and seat belt only, as well as 4- to 6-year-olds in HBBs and backless boosters. They did not observe any difference in lateral movement due to restraint type. This could be an indicator that a HBB may not prevent undesirable lateral movements of 12-year-old either. It is known, however, that the usage rate of HBBs among 12-year-olds is low, and that the acceptance rate among older children (>8 years) of HBBs is significantly lower than that of backless boosters (Jakobsson *et al.*, 2009). Hence, it is likely that the usage rate of HBBs among 12-year-olds will remain low; other systems are needed to keep 12-year-olds upright and in the optimized zone.

The stiffness of the side structure selected in Paper IV had a major effect on the linear head acceleration of the SID-IIs. The values measured by the SID-IIs were higher with the 'extra high stiffness'. This effect may be explained by studying the intrusion and global velocity of the vehicle C-pillar and window sill; the 'extra high stiffness' reduced the intrusion at the window sill, while it increased the intrusion at the C-pillar. The intrusion at the C-pillar thus correlated with the SID-IIs head injury measures. The preferred stiffness of the side structure of a vehicle is therefore a balance between intrusion at the C-pillar and at the window sill, bearing in mind that window sill intrusion negatively affects the head injury risk for younger children.

In the course of the work conducted for this thesis, it has become clear that frontal and near-side impacts have common characteristics. Both impact categories have components in the x and the y directions (forward and lateral in the vehicle reference system); only the relative magnitudes differ. Therefore, the injury causation scenarios and injury mechanisms identified in frontal crashes are also to be found in side ones and vice versa. An important example of this is head injuries due to striking the side of the vehicle (Bohman *et al.*, 2011a; Maltese *et al.*, 2007; Lindquist *et al.*, 2006). The studies by Bohman *et al.* (2011a) and Lindquist *et al.* (2006, adults only) both presented real life cases in which there had been head impacts with the side of the car in frontal crashes. It can be assumed that a curtain airbag positioned to cover the impacted areas has the potential to mitigate such head injuries (Bohman *et al.*, 2011a). Furthermore, the seat belt pretensioner reduced the head injury measures in both frontal and near-side crashes (Papers I, II and IV). Thus, the injury mitigation systems that were developed for one crash type also have benefits in the other.

The anthropometry study (Paper II) was conducted on a sample of children whose average standing height, sitting height and weight corresponded well to those of children in previous studies (Albertsson-Wikland *et al.*, 2002; Fredriks *et al.*, 2005). For that reason, it was assumed that the other measurements also represented the average of the whole population. The mass distribution measurements were new and valuable for simulations of dynamic events. The average stature and weight of 3-year-old children correspond well to those of the Q3. However, differences were identified in the mass distribution for the torso and the thighs; mass should be moved from the pelvis to the thighs, abdomen and thorax. The main geometrical difference between the Q3 and the anthropometry of children presented here is the length of the thighs. Although this is unlikely to affect the head kinematics, it should be taken into account in future dummy updates for improved anthropometry.

Other findings of the thesis work include, and underline, the lack of thoracic flexibility of child ATDs (here the Q3) and their ability to adequately predict head impact with the vehicle side in frontal crashes with a lateral component (Paper II). In high severity frontal crashes, the Q3 model predicted head impact adequately. However, in frontal oblique crashes, the Q3 model did not sufficiently predict the head impacts. The modified Q3 model predicted the location of the head impacts better than the Q3 model did. Paper II indicated that greater flexibility of the thorax and redistributed mass made a positive difference. It was natural to add the flexibility to the Q3's rigid thoracic spine as the human spine is not rigid. These findings regarding thoracic flexibility support those of Sherwood *et al.* (2003), who made a similar study with the HIII 6-year-old. Future changes implemented in the Q3 ATD need further investigation of the stiffness magnitude and tuning of all joints to keep the chest deflection response while improving the head kinematics. Furthermore, one joint may not be enough to achieve the flexibility; continued work on developing the Q3 thorax should incorporate flexibility along the length of the thoracic spine (continuous or discrete) to allow bending (forward and lateral) and rotation about its z-axis. As a result of such evolution of the Q3 ATD, the torso structure of the Q3 MADYMO model may need to be redesigned to achieve proper thoracic spine flexibility.

The lack of thoracic flexibility may be a contributor to the question of why there is limited difference in the resulting kinematics and injury measures of side impacts with and without a forward component. Important child side impact test methods have chosen not to include any forward component (future ECE R44, EuroNCAP). As a result, there will not be any drive to improve ATDs to realistically predict the head motion. Without test methods that mimic real accidents and without ATDs that correctly predict head kinematics, many real life safety improvements will develop slowly or not at all. The real life improvements to injury mitigation systems must thus come from elsewhere. Besides the projected regulatory tests and consumer tests, there must be parallel work to develop omni-directionally, biofidelically validated human body models. These models must also be subjected to realistic crash conditions to further develop the injury mitigation systems. Ideally there will be a holistic view of injury mitigation systems that combines child restraints and vehicle safety systems to achieve optimal safety.

5 CONCLUSIONS

The validations carried out for this thesis showed that the vehicle models developed were suitable tools for conducting comparative studies of injury mitigation systems in both frontal and near-side impacts. Moreover, the mathematical occupant models can predict trends for injury assessments. However, the ATDs need to be improved regarding their ability to correctly predict the head kinematics in all directions. A rigid thorax contributes to incorrect head kinematics, especially in oblique frontal crashes.

The forward component of side impacts and the lateral component of frontal impacts are frequently present in real life crashes; it was found necessary to take them into account in evaluations of child injury mitigation systems. Also, the structural overlap found among real life, side impact crashes has to be reflected in the setup of load cases for injury mitigation system development. In most side impact crashes that resulted in AIS2+ or fatal injuries, the bullet vehicle struck the rear door and the B-pillar, but not the C-pillar. The car sill was not engaged. The resulting intrusion at the position of the child was about 25 cm.

The main conclusions regarding injury mitigation in the nominal ATD position are listed below.

- Curtain airbags, thorax-pelvis airbags, seat belts with pretensioners and load limiters reduce head injury measures of occupant models corresponding to 3- and 12-year-olds in both frontal and near-side impacts.
- Inflated cells are needed where the heads of occupants may strike the car interior. The forward component in near-side crashes causes impacts to the curtain both forward and below the nominal head positions projected in the lateral direction. Specifically, the lower edges of the curtain airbag cells need to cover the main part of the booster seated 3-year-old's head in the y projection.
- The pressure in the thorax-pelvis airbags also needs to be designed to restrain the 3-year-old.
- The lateral translation of the small occupants in near-side impacts needs to be controlled, if the seat belt has a pretensioner, to avoid direct loads to the neck by the seat belt. The translation can be controlled by a thorax-pelvis airbag or by a torso side support.
- In frontal impacts, the 3-year-old's head injury measures are reduced when the upper belt anchor is positioned so that the belt is routed near mid-shoulder and encloses the shoulder, and the lap belt anchors are positioned to make the lap belt angle as horizontal as possible without inducing submarining.
- Light vehicles require interior restraint systems of higher performance than those needed for heavy vehicles, to achieve the same level of injury measures for a given side structure.

In order to provide a robust, real life, safety effect, the injury mitigation systems must also provide adequate protection in a range of sitting positions, i.e. not just the nominal ATD position. Features that generate a more limited set of sitting positions need to be developed; the restraint systems need to be designed to mitigate injury in the residual range of sitting positions.

The outboard and inboard positions resulted in the highest head injury measures. This suggests that, in near-side impacts, these positions should be discouraged. The extensively outboard positions resulted in unfavorable airbag positioning. The inboard and the braking positions resulted in head strikes further forward of the nominal one; the curtain airbags need inflated cells at all locations of head strike.

The studies presented in this thesis are significant contributions to the continuous work of mitigating traffic accident induced injuries and fatalities to children.

REFERENCES

AAAM. (2012). The Abbreviated Injury Scale. Available at http://www.aaam1.org/ais/. Accessed February 20, 2012.

Adomeit, D., Heger, A. (1975). Motion Sequence Criteria and Design Proposals for Restraint Devices in order to Avoid Unfavourable Biomechanic Conditions and Submarining. 19th Stapp Car Crash Conference, San Diego, California, USA.

Albertsson-Wikland, K., Luo, Z. C., Niklasson, A., Karlberg, J. (2002). Swedish population-based longitudinal reference values from birth to 18 years of age for height, weight and head circumference. Acta Paediatrica. 91: 739–754.

Aldman, B. (1964). A Protective Seat for Children: Experiments with a Safety Seat for Children between One and Six. 8th Stapp Car Crash Conference, Detroit, Michigan, USA.

Andersson, M., Bohman, K., Osvalder, A.-L. (2010). Effect of booster seat design on children's choice of seating positions during naturalistic riding. 54th AAAM Conference, Las Vegas, Nevada, USA, October 17–20, 2010.

Arbogast, K., Ghati, Y., Menon, R.A., Tylko, S., Tamborra, N., Morgan, R.M. (2005a). Field investigation of child restraints in side impact crashes. Traffic Inj Prev. 6: 351–360.

Arbogast, K., Jermakian, J., Ghati, Y. (2009a). Abdominal injuries in belt positioning booster seats. 53rd AAAM Conference, Baltimore, Maryland, USA.

Arbogast, K., Jermakian, J., Ghati, Y., Smith, R., Maltese, M., Menon, R. (2005b). Predictors and patterns of pediatric head injury in motor vehicle crashes. IRCOBI Conference, Prague, Czech Republic, September 21–23, 2005.

Arbogast, K., Jermakian, J., Kallan, M., Durbin, D. (2009b) Effectiveness of Belt Positioning Booster Seats: An Updated Assessment. Pediatrics. 124: 1281–1286.

Arbogast, K., Kallan, M. (2007a). The exposure of children to deploying side air bags: An initial field assessment. 51st AAAM Conference, Melbourne, Victoria, Australia.

Arbogast, K., Kent, R., Menon, R., Ghati, Y., Durbin, D., Rouhana, S. (2007b). Mechanisms of abdominal organ injury in seat belt-restrained children. J Trauma. 62: 1473–1480.

Arbogast, K., Moll, E., Morris, S., Anderko, R., Durbin, D., Winston, F. (2001). Factors Influencing Pediatric Injury in Side Impact Collisions. J Trauma. 51: 469–477.

Bauer, R., Steiner, M. (2009). Injuries in the European Union – Statistics summary 2005–2007. ISBN: 978-3-7070-0096-2. Available at http://ec.europa.eu/health/healthy_environments/docs/2009-idb-report_screen.pdf. Accessed March 1, 2012.

Bilston, L. E., Brown, J., Kelly, P. (2005). Improved protection for children in forward-facing restraints during side impacts. Traffic Inj Prev. 6(2): 135–146

Bilston, L., Sagar, N. (2007a). Geometry of rear seats and child restraints compared to child anthropometry. Stapp Car Crash Journal. 51: 275–298.

Bilston, L., Yuen, M., Brown, J. (2007b). Reconstruction of Crashes Involving Injured Child Occupants: The Risk of Serious Injuries Associated with Sub-Optimal Restraint Use May Be Reduced by Better Controlling Occupant Kinematics. Traffic Inj Prev. 8: 47–61.

Bohman, K., Arbogast, K., Boström, O. (2011a). Head Injury Causation Scenarios for Belted, Rear-Seated Children in Frontal Impacts. Traffic Inj Prev. 12(1): 62–70.

Bohman, K., Rosén, E., Sunnevång, C., Boström, O. (2009). Rear seat occupant thorax protection in near side impacts. 53rd AAAM Conference, Baltimore, Maryland, USA, October 5–7.

Bohman, K., Stockman, I., Jakobsson, L., Osvalder, A.-L., Boström, O., Arbogast, K. (2011b). Kinematics and shoulder belt position of child rear seat passengers during vehicle maneuvers. 55th AAAM Conference, Paris, France.

Box, G. E. P., Hunter, W. G., Hunter, J. S. (1978). Statistics for Experimenters. John Wiley & Sons, New York.

Britax homepage. http://www.britax.co.uk/car-seats/highback-booster-campaign , http://www.britax.co.uk/news/kid-car-seats-with-sict. Accessed February 20, 2012.

Brown, J., Bilston, L. (2007). High back booster seats: In the field and in the laboratory. 20th Enhanced Safety of Vehicles Conference, Lyon, France.

Brun-Cassan, F., Page, M., Pincemaille, Y., Kallieris, D., Tarriere, C. (1993). Comparative study of restrained child dummies and cadavers in experimental crashes. SAE Technical Paper 933105, doi:10.4271/933105.

Charlton, J., Koppel, S., Kopinathan, C., Taranto, D. (2010). How Do Children Really Behave in Restraint Systems while Travelling in Cars? 54th AAAM Conference, Las Vegas, Nevada, USA.

Cui, Y., Yamaguchi, M., Mizuno, K., Tanaka, Y., Yoshida, R. (2012). FE analysis of child occupant kinematics in CRS in side oblique impact. Int J of Crashworthiness. Available online January 11, 2012, at: http://www.tandfonline.com/doi/abs/10.1080/13588265.2011.648515.

Damm, R. (2006). Physical reconstructions. Child Project Dissemination Workshop, Berlin, Germany, May, 30–31, 2006.

EuroNCAP homepage. Available at http://www.euroncap.com/home.aspx. Accessed March 1, 2012.

Forman, J., Michaelson, J., Kent, R., Kuppa, S., Boström, O. (2008). Occupant restraint in the rear seat: ATD responses to standard and pre-tensioning, force-limiting belt restraints. 52nd AAAM Conference, San Diego, California, USA.

Forman, J. L., Segui-Gomez, M., Ash, J. H., Lopez-Valdes, F. J. (2011). Child posture and shoulder belt fit during extended night-time traveling: An in-transit observational study. 55th AAAM Conference, Paris, France.

Fredriks, A. M., van Buuren, S., van Heel, W. J. M., Dijkman-Neerincx, R. H. M., Verloove-Vanhorick, S. P., Wit, J. M. (2005). Nationwide age references for sitting height, leg length, and sitting height/height ratio, and their diagnostic value for disproportionate growth disorders. Archives of Disease in Childhood. 90: 807–812.

Gelander, L. (2005). Pediatrician at Växthuset at Drottning Silvias barn och ungdomssjukhus. Specialized in children's growth. Personal communication, June 16, 2005.

Gray, H. (1918). Anatomy of the Human Body. The Hip Bone. Bartleby. 20th Edition, edited by Lewis, W. H. Available at: http://www.bartleby.com/107/57.html. Accessed on March 1, 2012.

Henary, B., Sherwood, C. P., Crandall, J. R., Kent, R. W., Vaca, F. E., Arbogast, K. B., Bull, M. J. (2007). Car Safety Seats for Children: Rear Facing for Best Protection. Inj Prev. 13: 398–402.

Hovenga, P. E., Spit, H. H., Uijldert, M., Dalenoort, A. M. (2005). Improved Prediction of Hybrid-III Injury Values Using Advanced Multibody Techniques and Objective Rating. SAE World Congress, Detroit, Michigan, USA, April 11, 2005. SAE Technical Paper 2005-01-1307, doi:10.4271/2005-01-1307.

Howard, A., Rothman, L., Moses McKeag, A., Pazmino-Canizares, J., Monk, B., Comeu, J. L., Mills, D., Blazeski, S., Hale, I., German, A. (2004). Children in side-impact motor vehicle crashes: Seating positions and injury mechanisms. Journal of Trauma. 56(6):1276–1285.

Hu, J., Mizuno, K. (2009). The kinematic behaviour and responses of Hybrid III 3YO dummy and child human FE model in ISOFIX CRS in frontal impact. Int J of Crashworthiness. 14(4): 391–404

Hu, J., Mizuno, K., Tanaka, E. (2008). Occupant responses in child restraint systems in side impact tests. Int J Vehicle Safety. 3(1).

Huang, S., Reed, M. (2006). Comparison of Child Body Dimensions with Rear Seat Geometry. SAE World Congress, Detroit, Michigan, USA, April, 2006. SAE Technical Paper 2006-01-1142, doi:10.4271/2006-01-1142.

Humanetics Innovative Solutions homepage. SID-IIs Small Side Impact Dummy. http://www.humaneticsatd.com/crash-test-dummies/side-impact/sid-iis. Accessed February 29, 2012.

Irwin, A., Mertz, H. (1997). Biomechanical Bases for the CRABI and Hybrid III Child Dummies. SAE Technical Paper 973317, doi:10.4271/973317.

Isaksson-Hellman, I., Jakobsson, L., Gustavsson, C., Norin, H. (1997). Trends and Effects of Child Restraint Systems Based on Volvo's Swedish Accident Database. SAE Technical Paper 973299, 1997, doi:10.4271/973299.

Iwamoto, M., Kisanuki, Y., Watanabe, I., Furusu, K., Miki, K., Hasegawa, J. (2002). Development of a Finite Element Model of the Total HUman Model for Safety

(THUMS) and Application to Injury Reconstruction. IRCOBI Conference, Munich, Germany, September 18–20, 2002.

Jakobsson, L., Bohman, K., Stockman, I., Andersson, M., Osvalder, A.-L. (2011). Older Children's Sitting Postures when Riding in the Rear Seat. IRCOBI Conference, Krakow, Poland, September 14–16, 2011.

Jakobsson, L., Isaksson-Hellman, I., Lindman, M. (2009). Positive trend of proper restraint usage – Injury reduction for children aged 4–12. 7th Protection of Children in Cars Conference, Munich, Germany.

Jakobsson, L., Isaksson-Hellman, I., Lundell, B. (2005). Safety for the growing child: Experiences from Swedish accident data. 19th Enhanced Safety of Vehicles Conference, Washington, District of Columbia, USA.

Kapoor, T., Altenhof, W., Tot, M., Zhang, W., Howard, A., Rasico, J., Zhu, F., Mizuno, K. (2008). Load Limiting Behavior in CRS Tether Anchors as a Method to Mitigate Head and Neck Injuries Sustained by Children in Frontal Crash. Traffic Inj Prev. 9: 243–255, DOI: 10.1080/15389580801975210.

Khaewpong, N., Nguyen, T., Bents, F., Eichelberger, M., Gotschall, C., Morrissey, R. (1995). Injury Severity in Restrained Children in Motor Vehicle Crashes. SAE Technical Paper 952711, doi:10.4271/952711.

Klinich, K. D., Saul, R. A., Auguste, G., Backaitis, S., Kleinberger, M. (1996). Techniques for Developing Child Dummy Protection Reference Values. NHTSA Report No. 74-14 N97, Item 069. Available at: http://www.nhtsa.gov/DOT/NHTSA/NRD/Multimedia/PDFs/Biomechanics%20&%20Trauma/kid.pdf. Accessed March 1, 2012.

Langwieder, K., Hummel, T., Finkbeiner, F. (1999). Injury risks of children in cars depending on the type of restraint. 43rd AAAM Conference, Sitges, Spain.

Lindquist, M. O., Hall, A. R., Björnstig, U. L. (2006). Kinematics of belted fatalities in frontal collisions: A new approach in deep studies of injury mechanisms. J Trauma. 6: 1506–1516.

Maltese, M., Chen, I., Arbogast, K. (2005). Effect of increased rear row occupancy on injury to seat belt restrained children in side impact crashes. 49th AAAM Conference. Boston, Massachusetts, USA.

Maltese, M., Locey, C., Jermakian, J., Nance, M., Arbogast, K. (2007). Injury causation scenarios in belt-restrained nearside child occupants. Stapp Car Crash Journal, 51:299–311.

Maxi-Cosi homepage. http://www.maxi-cosi.com/us-en/products/car-seats/booster/rodi-xr.aspx. Accessed February 20, 2012.

McKay, M. P., Jolly, B. T. (1999). A retrospective review of air bag deaths. Academic Emergency Medicine. 6(7): 708–714.

Mizuno, K., Iwata, K., Deguchi, T., Ikami, T., Kubota, M. (2005). Development of a Three-Year-Old Child FE Model. Traffic Inj Prev. 2005;6:361-271.

Nance, M. (2009). Child physician at the Children's Hospital of Philadelphia, Philadelphia, PA, USA. Personal communication, October 9, 2009.

NHTSA. (2012). Child Passenger Safety recommendations, available at: http://www.nhtsa.gov/Safety/CPS. Accessed February 20, 2012.

NHTSA. (2010). Traffic Safety Facts: 2009 Data – Children. NHTSA's National Center for Statistics and Analysis. DOT HS 811 387.

Norin, H., Carlsson, G. (1984). Seat Belt Usage in Sweden and Its Injury Reducing Effect. SAE Technical Paper 840194, doi:10.4271/840194.

O'Neil, J., Dawn, M., Daniels, D. M., Talty, J. L., Bulla, M. J. (2009). Seat belt misuse among children transported in belt-positioning booster seats. Accident Anal Prev. 41: 425–429.

Orzechowski, K., Edgerton, E., Bulas, D. I., McLaughlin, P. M., Eichelberger, M. R. (2003). Patterns of Injury to Restrained Children in Side Impact Motor Vehicle Crashes: The Side Impact Syndrome. Journal of Trauma. 54(6):1094–1101.

Osvalder, A.-L., Bohman, K. (2008). Misuse of booster cushions – An observation study of children's performance during buckling up. 52nd AAAM Conference, San Diego, California, USA.

Partners for Child Passenger Safety. (2008). Fact and Trend Report 2008. Available at www.chop.edu/carseat. Accessed October 10, 2010.

Ratingen van, M., Twisk, D., Schrooten, M., Reusenberg, M., Barnes, A., Platten, G. (1997). Biomechanically Based Design and Performance Targets for a 3-Year-Old Child Crash Dummy for Frontal and Side Impact. SAE Technical Paper 973316, doi:10.4271/973316.

Reed, M. P., Ebert-Hamilton, S. M., Sherwood, C. P., Klinich, K. D., Manary, M. A. (2009). Evaluation of the Static Belt Fit Provided by Belt-Positioning Booster Seats. Accident Anal Prev. 41: 598–607.

Rooij van, L., Harkema, C., de Lange, R., de Jager, K., Bosch-Rekveldt, M., Mooi, H. (2005). Child poses in child restraint systems related to injury potential: Investigations by virtual testing. 19th Enhanced Safety of Vehicles Conference, Washington, District of Columbia, USA. Available at: http://www-nrd.nhtsa.dot.gov/pdf/esv/esv19/05-0373-O.pdf.

Rooij van, L., Sherwood, C., Crandall, J., Orzechowski, K., Eichelberger, M. (2003). The effects of vehicle seat belt parameters on the injury risk for children in booster seats. SAE Technical Paper 2003-01-0500, doi:10.4271/2003-01-0500.

SAE Recommended Practice J224/1. (1980). Collision Deformation Classification. Society of Automotive Engineers, Warrendale, PA.

Scullion, P., Morgan, R., Nagabhushana, V., Digges, K., Kan, C. D., Park, S., Bae, H. (2008). Side Impact Risk for 7–13 Year Old Children. SAE Technical Paper 2008-01-0192, doi:10.4271/2008-01-0192.

Sherwood, C. P., Shaw, C. G., Rooij van, L., Kent, R. W., Crandall, J. R., Orzechowski, K. M., Eichelberger, M. R., Kallieris, D. (2003). Prediction of Cervical Spine Injury Risk for the 6-Year-Old Child in Frontal Crashes. Traffic Inj Prev. 4: 206–213.

Starnes, M., Eigen, A. M. (2002). Fatalities and Injuries to 0–8 Year Old Passenger Vehicle Occupants based on Impact Attributes. NHTSA, report no: DOT HS 809 410. Available at: http://www-nrd.nhtsa.dot.gov/Pubs/809-410.PDF.

Stockman, I. (2011). Researcher at Chalmers University of Technology, Göteborg, Sweden. Personal communication, October 31, 2011.

Swedish Transport Administration (Trafikverket). Swedish recommendations for booster seat use, in Swedish. Available at: http://www.trafikverket.se/Privat/Trafiksakerhet/Din-sakerhet-pa-vagen/Sakerhet-i-bil/Barn-i-bil/Baltesstolkudde/. Accessed January 20, 2012.

Walsh, M., Kelleher-Walsh, B. and McCullough, C. (1996). A Study of Motor Vehicle Accidents Involving Children. 40th Stapp Car Crash Conference, Albuquerque, New Mexico, USA.

Waltz, J., George H. (1950). Making the death seat safer. Popular Science. July: 82–90.

APPENDIX A

Complementary photographs of the case study cars in Paper III

Examples without direct sill involvement: Cases 5, 8, 9, 10 and 14.

Case 5. No sill involvement

Case 8. The sill was pulled up by the B-pillar but was not directly involved.

Case 9. No sill involvement

Case 10. No sill involvement

Case 14. No sill involvement

Example with slight sill involvement:

Case 3. Slight sill involvement

APPENDIX B

Complementary information for Paper IV: Signals with ORM coefficients below 0.65

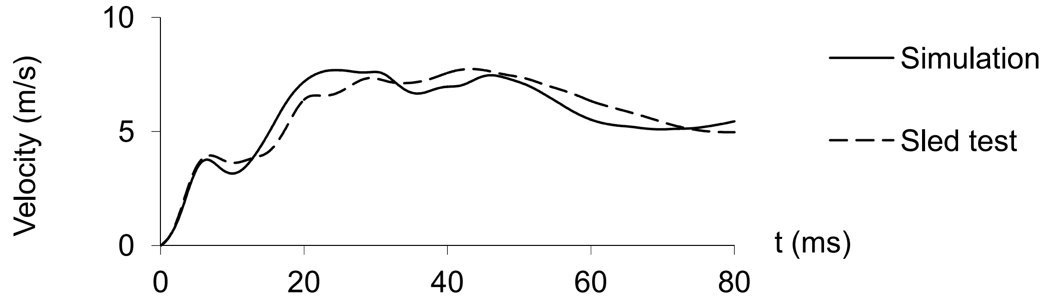

Figure A. IIHS global velocity Point III: Phase 0.57

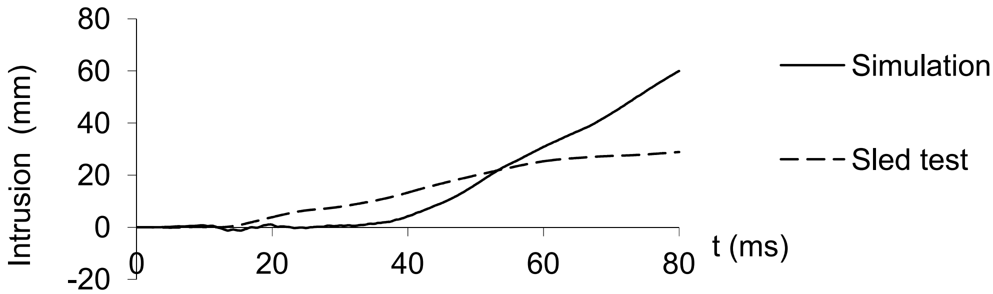

Figure B. IIHS intrusion Point IV: Magnitude 0.48; Shape 0.53

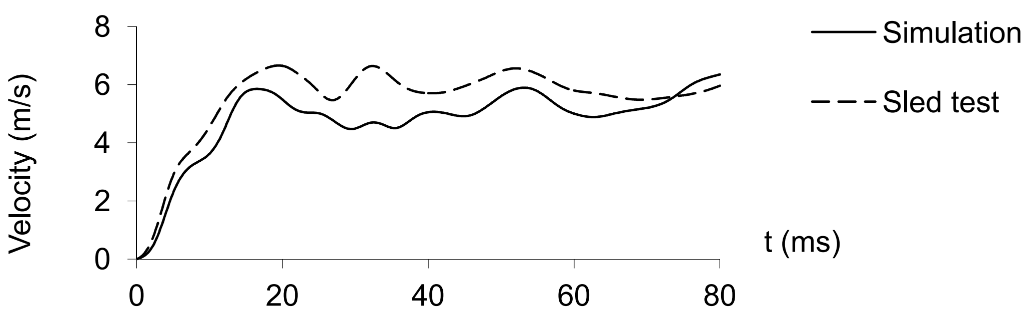

Figure C. USNCAP global velocity Point III: Phase 0.25

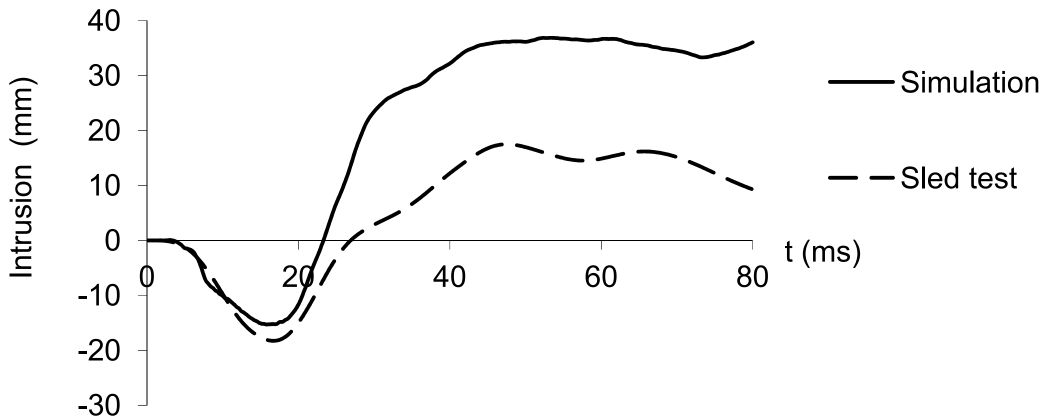

Figure D. USNCAP intrusion Point I: Magnitude 0.00; Phase 0.31; Shape 0.39

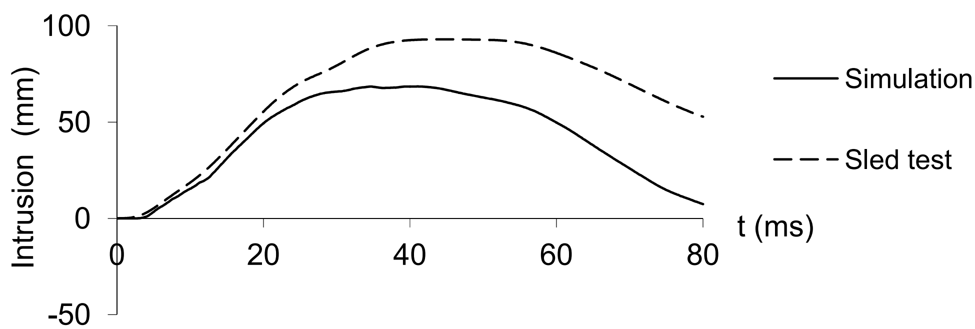

Figure E. USNCAP intrusion Point III: Shape 0.60