



Rear seat safety – focusing on occupants from 3 years to 5th percentile female in frontal to side impacts



Project within FFI's Traffic Safety Program

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FFI in short

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1. Executive summary

This study presents a broad comprehensive research effort that combined expertise from industry and academia and used various methodologies with applied research directed towards countermeasures. The project included real world crash data analysis, real world on-road driving studies and maneuver studies, and crash testing and simulations, aiming at enhancing the safety of forward facing child occupants (aged 3y to small adults) in the rear seat during frontal to side impacts.

The real world crash data analysis of properly restrained children, originate from European as well as US data. Frontal and side impact crash tests were analyzed using different sizes of crash test dummies in different sitting postures. Side impact parameter studies using FE-models were run. The sitting posture and behavior of 12 children were monitored while riding in the rear seat. Also, the body kinematics and belt position during actual braking and turning maneuvers were studied for 16 rear seat child occupants and for various child crash test dummies.

Real world crash data indicates that several of the injured children in frontal impacts, despite being properly restrained, impacted the vehicle interior structure with their head/face resulting in serious head injuries. Oblique crashes, pre-crash vehicle maneuvers or high crash severity was found contributing reasons for head-to-interior impacts. Crash tests confirm the importance of proper initial belt-fit for best protection. The crash tests also highlight the difficulty in obtaining the kinematics of children using existing crash test dummies and test procedures. The side impact parameter studies indicate that the vehicle's occupant protection systems, such as airbags and seat belt pretensioners, play an important role in protecting children as well.

The results from the on-road driving studies illustrate the variation of sitting postures during riding in the rear seat giving valuable input to the effects of the restraint systems and to how representative the standardized dummy seating positioning procedures are. The results from the maneuver driving studies illustrate the importance of understanding the kinematics of a child relative to the seat belt, and the vehicle, in a pre-crash maneuver situation.

Real world safety of rear seat occupants, especially children, involves evaluation of protection systems beyond standard crash testing scenarios in frontal and side impact conditions. This project explores the complete context of rear seat protection in impact situations, ranging from front to side and directions in between, highlighting the importance of pre-crash postures and behavior.

This research project includes researchers from the industry and universities cooperating with the aim to further improve safety for children (from 3y) to small adults in the rear seat, resulting in a faster process of safety system implementations.

2. Background

Motor vehicle accidents are the leading cause of death or injury to children in several parts of the world (Subramanian, 2005) although the development of protection systems has been significant over the last decades. According to a study in NASS-CDS it was found that 2/3 of the fatally injured 0 – 12 year old children was restrained (McCray et al., 2006).



According to US statistics, 52% of the rear seat occupants are less than 13 years old, 14% are 13 to 15 years, and 34% are older than 15 years (McCray et al., 2006). On average a 12 year old is of similar size as a 5th percentile female, thus by focusing on the children, solutions driven by the data analyses will cover small size adults as well.

Summarizing crash data (NASS-CDS 1991-2005) on rear seated children aged 4-12 years, second to rollover, the highest MAIS3+ injury risk was seen for side impacts situations (Bidez, 2006). However, there were more children injured in frontal impacts, due to the high frequency of frontal impacts compared to other crash direction. Furthermore, several of the injured were restrained, indicating that current restraint systems have potential for further improvements. Thus, there is a need to address protection in both side and frontal impacts for restrained rear seated children, as well as oblique impacts. Also, it is valuable to understand other influencing factors, such as occupant posture and behaviour at impact.

The smallest children are optimally protected in a rearward facing seat, where the shell of the child restraint provides the protection of the child's vulnerable neck and head both in frontal and side impact situations, given the child and the seat are restrained (Tingvall 1987, Carlsson et al. 1991, Kamrén et al. 1993, Stalnaker 1993, Tarrière 1995, Isaksson-Hellman et al. 1997, Jakobsson et al. 2005, Henary et al 2007). Rearward facing child restraints up to 3-4 years are available in most countries and have been used as best practice in Sweden from the beginning of child restraints in the 1960:ies. Hence, the focus of the present study is on children older than 4 years old and who are forward facing. Children in the age group 4-8 years have shown great benefits from boosters in frontal impacts (Durbin et al. 2003) and they may also benefit from seat belt technologies such as load limiters and pretensioners (Bohman et al. 2006). Real world data shows that the age group 9-12 year old has higher injury risk than the younger age group (4 - 8 years) (CHOP, 2008). The older age group is not being restrained on boosters as frequently as the younger age group, but still, they are not optimally restrained on the seat only.

Protection of children in cars is the responsibility of several actors. In case of a crash the outcome is related to the interplay of the different protection systems in the car, including the child restraint. In recent years, there has been a strive to provide more pronounced protection built into the child restraint. This influences the acceptance and usability, and thus the usage of the child restraints, posing a potential safety hazard

3. Objective

The overall aim is to further enhance the safety for forward facing occupants (aged 3y to small adults) in the rear seat in the event of frontal to side impacts.

Real world data

- Provide an overview of side impact collisions in terms of crash characteristics, injuries and injury causation
- Provide an overview of frontal impact with focus on severe head injuries: in terms of crash characteristics, injuries and injury causation by in depth case analysis

Real world driving studies

- Increase the knowledge of children's natural sitting behavior during car ride as function of child restraint system and age
- Increase the knowledge of children's kinematics during swerving and braking maneuvers in different child restraint systems

Evaluate existing child ATDs



- Evaluate the kinematics and shoulder belt performance of a number of the existing child crash test dummies in braking and swerving maneuvers, and compare the findings with child volunteers of similar age and size
- Evaluate the frontal and side impact performance of the most recent and oldest child crash test dummy, called Q10
- Compare the crash test dummies' in-crash sitting positions with the children's preferred sitting postures

Crash testing and simulation

- Validate a mathematical simulation model of a complete car in near-side impact and investigate the effects of crash related car parameters
- Evaluate and propose improvements to injury mitigation systems in near-side impacts for six common sitting postures for children

Competence

- Provide a competence sharing platform to the involved partners and create an international network of researchers with ongoing related research.
- Competence dissemination : The project will form part of the PhD-studies of three PhD candidates. These three persons are expected to become a valuable asset to the Swedish vehicle and traffic safety research community in the future. The project will also build up further competence in the involved senior researchers

4. Project realization

This study presents a broad comprehensive research effort that combined expertise from industry and academia at SAFER, Vehicle and Traffic Safety Centre at Chalmers in the joint effort to improve safety in order to reduce the number and severity of injuries of forward facing children (up to small adults) in the rear seat of passenger cars. The project took place during 2009-2012 and a continuation of an additional three years (2013-2015) has started.

The project combined the work of three PhD students (two industrial PhD students and one academic PhD student) and several senior researchers. The project group consisted of researcher from Autoliv, Saab Automobile, Volvo Cars and Chalmers University of Technology and is associated with the Children's Hospital of Philadelphia and Karolinska Institutet. Seminars and workshops were held involving other researchers in the area; for knowledge sharing and for input to the research agenda. Also, the project results were directly fed into standardization activities such as ISO working group on Child Restraints as well as the informal working group on ECE R44 update.

The project contained real world crash data analyses of side and frontal impacts, real world driving studies, and physical and virtual crash testing/simulations, also including a focus on the child crash test dummies in maneuvers. See technical report for more details on the different methods used in the project. The combination of different activities and the close dialogue with other actors in the area, facilitated a comprehensive and real-world-safety based knowledge base for rear seat protection.



5. Results and deliverables

Real world data

- The analysis of children injured in side impacts highlighted the importance of protecting the head and the thorax of the children (Bohman et al. 2009).
- The characteristics of side impact involving injured children showed that principal direction of force was most frequently between 60° and 75°, the door sill was not engaged in the majority of crashes, the deformation was between 20-30 cm at the child's seating position and the bullet most commonly impacted the rear door of the target vehicle (Andersson et al. 2011)
- The in-depth case analysis of head injured children in frontal impact identified 3 injury causation scenarios; head impact to seat back, side interior or non-contact. Maneuvers and angled frontal impact were important contributing factors (Bohman et al. 2011).
- Real world data indicates that the acceptance of integrated boosters seems to be higher for the older children (8-10), as compared to accessory booster, For total child safety it is important to encourage more integrated systems and to facilitate good and simple booster cushions to attract the older age group of recommended usage and thus increase the overall booster usage rate. (Jakobsson et al. 2009)

Real world driving studies

- Younger children (3 to 6 years) when seated in two different booster seats during ride in a vehicle were sitting more upright in the seat with large side wings compared to the seat with small side wings. This resulted in the head being out of the side wings during the majority of the ride (Andersson et al. 2010).
- For older children (8 to 10 years) the booster helped position the shoulder belt part of the belt at the middle of the shoulder and the sitting postures were more stable as compared to when no booster was used (Jakobsson et al. 2011).
- Swerving maneuvers with 16 child volunteers aged 4 – 12 on a closed circuit test track showed that the children moved laterally inboard the vehicle due to the change in lateral acceleration and the shoulder belt part of the seat belt moved outboard on the child's shoulder to various extents, depending on the size of the child and the type of child restraint (Bohman et al. 2011).
- Braking maneuvers with 16 children aged 4 – 12 on a closed circuit test track showed that the forward displacement was within the same range (150-200mm) for all children regardless of stature and restraint system. However the maximum forward position depended on the initial seated posture and shoulder belt position on the shoulder. Differences could also be seen in the curvature of the neck and spine. Short children exhibited a greater flexion motion of the head whilst a more upright posture at maximum forward position was exhibited by the tall children (Stockman et al. 2013b).

Evaluation of existing child crash test dummies

- The kinematic responses of six child crash test dummies, from the HIII and Q-families, during evasive swerving and emergency braking maneuvers were quantified, focusing on evaluating and comparing the kinematic responses for the dummies to that of children of corresponding sizes (Stockman, 2012, Stockman et al. 2013a, Stockman et al. 2013b).
 - In the swerving maneuver, compared to children, the HIII ATDs were closer with regards to mean values in the initial phase of the maneuver while the Q ATDs



were closer in the end of the ramping phase of the lateral acceleration (Stockman et al. 2013a).

- In the braking maneuvers all ATDs displayed less forward displacement and head rotation than the child volunteers; the HIII 6y on a booster cushion was closest to representing the kinematics of a child of similar age/size in this set-up (Stockman 2012, Stockman et al. 2013b).
- Frontal and side impact tests with the new Q10 dummy showed that the dummy was sensitive to countermeasures in both side and frontal impacts. However, the Q10 was very sensitive to seat belt geometry in frontal impacts (Bohman et al. 2012).
- HIII 6y in-crash sitting positions were found to be more leaned back and within the side wings of the seat with large side wings compared to children's preferred sitting positions. On the booster cushion with small side wings, the HIII 6y had similar position as the children's preferred sitting position (Bohman et al 2010).

Crash testing and simulation

- Validate a mathematical simulation model of a complete car in near-side impact and investigate the effects of crash related car parameters
- Evaluate and propose improvements to injury mitigation systems in near-side impacts for six common sitting positions children
- Head impact tests to seat back evaluated the injury risk of head injury (Arbogast et al. 2012).

Competence

- A competence sharing platform between the involved partners has been established at SAFER center.
- One PhD degree (Chalmers), one Licentiate degree (Chalmers) and one half-time report (Karolinska Institutet) have been finalized.
- Competence dissemination has taken place at numerous conferences and seminars (see publication list)
- Two international workshops have been organized in September 2009 and September 2011 (Arbogast et al. 2011).
- Several presentations to standardization working groups (ISO and ECE R44 update), as well as in dialogue with EuroNCAP.

5.1 Delivery to FFI-goals

- The protection principles in frontal to side impacts are used of the participants in the project and also other, in order to develop restraint system and input for balancing new vehicle subsystems requirements.
- Input to Swedish standpoint for the design of side impact tests (guidelines), used as input to discussions within ISO, ECE R44 update and worldwide lobby activities. Also, other Swedish standpoints in various child safety topics has been discussed and forwarded to the rest of Swedish child safety community. Results have been used to inform EuroNCAP about the performance of the Q10 dummy.
- Competence development for all involved, the PhD students as well as the other representatives of the project partners. The project members have had regular meetings and have discussed various safety topics related to children. These



meetings have supported the work of the PhD students as well as enhanced child safety competence for each project partner representative. The international workshops and seminars together with the discussions within the project group has contributed to competence development for partners and external companies/organizations involved in traffic safety.

- The involvement of Chalmers in this project has resulted in development of an academic resource in child safety, which is available for future work together with the industry and for education activities within the University. It has also started the development an independent competence platform for national and international discussions and competence sharing.
- The visiting researcher has led to an extended network to the University of Philadelphia and the researchers at the Children's Hospital of Philadelphia (CHOP) for the partners in the project. The PhD students have visited the researchers at CHOP.
- Spinn-off effects:
 - As a consequence, the project partners are, through SAFER, part of a joint association agreement between SAFER and CHOP, including it's associated organization C-ChiP. The project partners have become involved in a research project together with CHOP.
 - Chalmers and Autoliv has also joined a research project together with Monash University, covering field operational tests with children.
 - Volvo, Autoliv and Chalmers have started up a new FFI project "New belt geometires" (diare nr 2010-02846) as a spin-off effect of the results from the current project.

6. Dissemination and publications

During the project, Marianne Andersson has finalized her doctoral thesis. Isabelle Stockman has finished her licentiate exam. Katarina Bohman has accomplished her half-time report at Karolinska Institutet, which corresponds to a licentiate level.

The project has resulted in 13 peer-reviewed articles, 6 articles published at various conferences, see publication list below.

6.1 Knowledge and results dissemination

Two international workshops have been arranged during the project. In 2009, the workshop "Child occupant protection" took place and it included 12 international child safety researchers from Sweden and USA. The first day was a seminar, which open to the public. The researchers, both in the project group as well as the invited researchers, presented the latest news of child safety. The two following days, there was a closed workshop, in which the ongoing research and future needs of research was discussed.



In 2011, the second workshop took place with the title "Setting the future agenda for child passenger safety". This time 20 international child safety researchers from Sweden, USA, Canada, France, Spain and Australia participated, including expert within the field of biomechanics, behavioral safety scientists, child restraint manufactures, epidemiologists, government researchers, physicians, safety researchers, system suppliers, vehicle manufactures. The final result of the workshop was published and presented at the 9th International Conference on Protection of Children in Cars, Munich, 2011. This publication has already been referred to by other child researchers over the world.

The research project has been a land mark in setting a future agenda for child safety. With relatively small resources, this has been achieved thanks to , the strategic choice of leading-edge and good-in-timing research studies together and a tight network of leading researcher from all over the world. Thanks to this, a quick dissemination of the ongoing research as well as mandate for being part of leading the way in heading out the prioritized direction of child safety was accomplished.

Besides the international workshops and presentation at international confereces, several seminar and presentations at national level, spreading the results from the project have been taken place. In these seminars, representatives from the "riksdag", "kommuner", "landsting", car industry, suppliers, research institutes, students, journalists, insurance companies etc have participated.

The results from the project feeds directly into vehicle design through the participating car manufacturer and restraint manufacture. Also, the research has been influenced by the ongoing international dialogue on future standards and rating methods developments. The research results from this project have been used within the discussions at ISO and ECE R44 working groups (especially side impact method and compatibility evaluation for booster) as well as towards EuroNCAP update (especially Q10 performance). These dialogues have both influence the direction of some of the project parts (especially the driving studies) and been valuable contributions for driving the international child safety work forward, thus a two-way 'drivers of change'.

Seminar presentations:

Katarina Bohman, "Barns säkerhet i bil har blivit eftersatt", Tylösand, September 9, 2012.

Isabelle Stockman, "Rear Seat Safety for Children – Driving Studies and the Needs for Real Life Posture Data", Field Data and Impact Biomechanics - a joint seminar between the SAFER competence areas Field Data and Biomechanics, February 23rd, 2012.

Lotta Jakobsson, Smarta Fordon och smarta system, Konferens 'Barn, Liv och Trafik', NTF Väst, Göteborg, 7 Mars 2012.

Lotta Jakobsson, 'Hur tåliga är barn', NTF Väst, Den ömtåliga människan, Seminarie Göteborg, 10 Maj, 2012.

Isabelle Stockman, Lotta Jakobsson, Samverkan och demonstration – vägen till gröna, säkra och effektiva transporter! Seminarium Chalmers styrkeområde Transport, Göteborg 8 september 2011

Isabelle Stockman, "Rear Seat Safety for Children – Driving Studies", SAFER Biomechanics Competence Area, May 27th, 2011.



6.2 Publications

Doctoral thesis:

Marianne Andersson "Child Safety in Car Crashes - A car and child seat system approach", Chalmers University of Technology, 30th of March, 2012.

Licentiate thesis:

Isabelle Stockman "Child Passenger Kinematics in Emergency Manoeuvres", Chalmers University of Technology, 15th of October, 2012.

Peer reviewed publications (sorted after date):

Stockman I, Bohman K, Jakobsson L, Kinematics and Shoulder Belt Position of Child Anthropomorphic Test Devices during Steering Manoeuvres, Traffic Injury Prevention, (In press), 2013a.

Stockman I, Bohman K, Jakobsson L, Brodin K, "Kinematics of Child Volunteers and Child Anthropomorphic Test Devices during Emergency Braking Events in Real Car Environment", Traffic Injury Prevention 2013b;14(1).

Andersson M, Pipkorn B, Lövsund P, 'Rear seat child safety in near-side impacts a modeling study of common sitting positions', Traffic Injury Prevention, (In Press) 2013.

Andersson M, Pipkorn B, Lövsund P, 'Evaluation of the head kinematics of the Q3 math model and a modified Q3 model by means of crash reconstruction', Traffic Inj Prev. 2012 Nov;13(6):600-11

Arbogast KB, Maltese MR, Locey C, Bohman K, " Headform Impact Tests to Assess Energy Management of Seat Back Contact Points Associated with Head Injury for Pediatric Occupants" . SAE 2012-01-0561. 2012.

Andersson M, Pipkorn B, Lövsund P, 'Parameter study for child injury mitigation in near-side impacts through FE simulations', Traffic Inj Prev. 2012;13(2):182-92.

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

Bohman K, Arbogast K, Boström O, (2010) Head injury causation scenarios for belted, rear-seated children in frontal impact, Traffic Inj Prev. 2011 Feb;12(1):62-70.

Jakobsson L, Bohman K, Stockman I, Andersson M, Osvalder AL. Older Children's Sitting Postures when Riding in the Rear Seat. International IRCOBI Conference on The Biomechanics of Impact, 2011.



Andersson M, Bohman K, Osvalder AL., Effect of Booster Seat Design on Children's Choice of Seating Positions During Naturalistic Riding. *Ann Adv Automot Med.* 2010;54:171-80.

Bohman K, Rosén E, Sunnevang C, Boström O. (2009) Rear seat occupant thorax protection in near side impacts. *Annu Proc Assoc Adv Automot Med.* 2009 Oct;53:3-12.

Lopez-Valdes FJ, Forman J, Kent R, Bostrom O, Segui-Gomez M. A comparison between a child-size PMHS and the Hybrid III 6 YO in a sled frontal impact. *Ann Adv Automot Med.* 2009 Oct;53:237-46.

Lopez-Valdes F, Forman J, Ash J, Kindig M, Lamp J, Kent R, Bohman K, Bostrom O (2009) The frontal-impact response of a booster-seated child-size PMHS, International IRCOBI Conference on the Biomechanics of Impact, 2009.

Osvalder AL, Bohman K. (2008) Misuse of booster cushions - an observation study of children's performance during buckling up. *Annu Proc Assoc Adv Automot Med.* 2008 Oct;52:49-58.

Non peer-reviewed conference publications:

Bohman K, Sunnevang C, Q10 child dummy performance in side and frontal sled tests, 10th International Conference on Protection of Children in Cars, Munich, 2012.

Jakobsson L, Lechelt U, Walkhed E, The balance of vehicle and child seat protection for the older children in child Restraints, 10th International Conference on Protection of Children in Cars, Munich, 2012.

Jakobsson L, Bohman K, Andersson M, Stockman I, Boström O, Svensson M, Svanberg H, Wimmerstedt M, Arbogast KB, Rear seat safety in frontal to side impacts – focusing on occupants from 3yrs to small adults, The 22nd International Technical Conference on the Enhanced Safety of Vehicles Conference (ESV) in Washington, USA, 2011.

Arbogast K, Bostrom O, Jakobsson L, Fildes B, 'Setting the future agenda for child passenger safety', 9th International Conference on Protection of Children in Cars, Munich, 2011.

Jakobsson L, Bohman K, Stockman I, Child Kinematics in the Rear Seat during Driving Manoeuvres, 9th International Conference on Protection of Children in Cars, Munich, 2011.

Bohman K, Andersson M, Osvalder AL. "A comparison of children's sitting postures during drive and HIII 6y seating positions – in two different highback booster cushions", 8th International Conference of Children's protection in Cars, Munich, 2010.

Jakobsson L, Isaksson-Hellman I, Lindman M. Positive trend of proper restraint usage injury reduction for children aged 4-12. 7th Int. Conf. Protection of children in cars, Munich Germany, Dec 2009



7. Conclusions and future research

The real world crash data indicates that several of the injured children, despite being properly restrained, impacted the vehicle interior structure with their head/face resulting in serious injury. This was attributed to oblique crashes, pre-crash vehicle maneuvers or initial poor belt fit.

Crash tests confirmed the importance of proper initial belt-fit for best protection. The crash tests also highlighted the difficulty in obtaining the real world kinematics and head impact locations using existing crash test dummies and test procedures. The parametric side impact simulation studies indicated that the vehicle's occupant protection systems, such as airbags and seat belt pretensioners, play an important role in protecting children as well.

The results from the on-road driving studies illustrate the variation of sitting postures during riding in the rear seat giving valuable input to how representative the standardized dummy seating positioning procedures are. The braking and swerving maneuvers with child volunteers and ATDs provide unique knowledge of possible pre-crash postures of children and currently available ATDs across a variety of restraint systems in vehicle emergency maneuvers. The results offer valuable input to safety system development, ATD design as well as test method development. Appropriate initial shoulder belt position is important during maneuvers. For real world protection, one needs to take into account the growing child, focusing and understanding such aspects as initial seated posture, i.e., head position, shoulder belt position and how the child is restrained by the seat belt, as well as the booster design.

The results help to drive the rear seat safety development in frontal to side impacts by providing knowledge and by identifying important tasks for the research agenda.

A continuation, from 2013 to 2015, is already started. The project partners include Chalmers University, Volvo Cars and Autoliv. This second part will continue the work, including focus on crash test dummy – restraint interaction during crash and parameter studies on pre-crash situations providing input to future protection principles also including pre-crash aspects.

8. Participating parties and contact person

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