Real life side impact evaluations and model development for virtual prediction of current and future side restraint systems

Project within Trafiksäkerhet och Automatiserade Fordon

Authors: Cecilia Sunnevång,

Date: 151229

Content

FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which half is governmental funding. The background to the investment is that development within road transportation and Swedish automotive industry has big impact for growth. FFI will contribute to the following main goals: Reducing the environmental impact of transport, reducing the number killed and injured in traffic and Strengthening international competitiveness. Currently there are five collaboration programs: **Vehicle Development, Transport Efficiency, Vehicle and Traffic Safety, Energy & Environment and Sustainable Production Technology.**

For more information: www.vinnova.se/ffi

1. Executive summary

This project aimed to, based on real life data, evaluate how occupants are injured in side impacts when they are travelling in a modern, side airbag equipped car. Secondly it also aimed to evaluate the most modern tools for assessment of injuries in side impact using the WorldSID and the THUMS. Thirdly the aim was to develop a generic side impact model reflecting a model vehicle with the possibility to perform population based investigations.

To assess injuries using THUMS the model needed to be validated for side impacts to a greater extent than preciously done. THUMS was compared to previously performed PMHS tests where the PMHS was struck on shoulder, mid and thorax by a linear impactor. By overlays of PMHS and THUMS rigid body parts the kinematics of certain landmarks, as well as force/displacement, was compared between PMHS and THUMS. After modifications to the sternoclavicular joint as well as the scapula attachment to the posterior upper thorax, the THUMS model response were similar to the PMHS.

The real life data analysis, using NASS/CDS, showed a different injury pattern for senior occupants (age>60y) compared to non-senior occupants (10-59y). While the most frequent injuries to the senior occupants were rib fractures, lung injuries and pelvis fractures, the non-senior occupants has a higher frequency of head injuries. It was also found that most side impacts are intersection related and while the severity for non-senior occupants were greater than what is currently tested in consumer rating tests, the senior occupants were injured at severity similar or below current test procedures. Comparing injury outcome for a single driver compared to when there was two occupant present in the vehicle showed a trend of increased risk of thoracic injury and decreased risk of head injury.

To assess injuries in different severities one Swedish accident was reconstructed in the crash lab as well in simulation. This accident was a car-to-car crash in which the target vehicle was hit in the left side by a bullet vehicle. One crash test to evaluate front stiffness, and a series of simulations were performed to achieve a test setup resulting in similar intrusion as in the real accident. The reconstruction test was performed with a still standing passenger car rotated -25 degrees (0 degrees representing full front) impacted with a passenger car at 75 km/h. The physical tests were performed using the WorldSID dummy as driver. In the simulation the car-to-car crash was evaluated using WorldSID and THUMS. The car-to-car crash was also compared to a standard EuroNCAP crash where a mobile deformable barrier impacted the target vehicle at 50 km/h. Both crasehs were run with and without side airbags. Due to model instability injury

prediction using THUMS in the car-to-car crash was not possible. For the EuroNCAP crash both WorldSID and THUMS predicted 0% risk of injury to a 45 year old occupant when the airbag was deployed. Without side airbag the injury risk increased for both WorldSID and THUMS.

As a complement to the simulations using full vehicle models, a simulation study using a simple side impact model was performed. Also in this study a high severity pulse were used and compared to a EuroNCAP pulse. To investigate the occupant response with two front seat occupants the high-speed crash was also investigated using two WorldSID dummies and two THUMS models. Compared to the WorldSID where outboard deflection was highest at the upper part of thorax the THUMS showed the highest outboard loading to the lower part of the thorax. With the THUMS injury risk was also higher for both a non-senior and senior occupant compared to the WorldSID. With two front seat occupants there was no additional loading found due to occupant-to-occupant interaction (as seen in previously performed physical tests or real life data). This might be due to the geometry of the simple side impact model.

By the end of the project the generic side impact model was developed. Due to project end no evaluations using WorldSID was performed but for the THUMS injury prediction of rib fractures was higher using THUMS compared to the risk levels obtained from the real life data.

In conclusion, side impacts are mainly related to intersections and combining improved passive restraint performance with active safety features is needed to improve occupant protection. Especially for the elderly occupants. Although force and deflection response of THUMS were similar to the PMHS response, there is still a need to further understand how to predict injury risk in terms of probability to rib fractures. Other frequent injuries were head injuries, lung injuries, splenic rupture and pelvis fractures. These injuries will need to be addressed to further reduce MAIS2+ injuries sustained in side impacts. Both WorldSID and THUMS lack a valid injury criteria with injury risk functions for addressing pelvis injuries which is the second most frequent injury for all occupants when considering MAIS2+ injuries. To add instrumentation on the WorldSID non-struck side and measure bi-lateral deflection can detect thoracic loading due to occupant-to-occupant interaction.

2. Background

Legal and rating requirements and tests have driven the improved occupant protection in passenger vehicle side impact. However, there are still a considerable amount of side impacts that generate fatal or serious occupant injuries.

In a previous research project (Dnr: 2009-00507*)* it was found that all car-to-car intersection crashes in Sweden were side impacts. It was also found that the majority of crashes occurred at higher severity than currently tested in consumer rating tests. It was also shown that senior occupants (60 years and above) was overrepresented and that the near-side fatally injured occupant in most cases was accompanied by a passenger. The project also evaluated the new crash test dummy, WorldSID, and its ability to measure crash severity in a wider range than current dummies (ES2). The WorldSID was tested in a number of representative car-to-car crash tests in different crash severities. Occupant injury risk increased with increasing crash severity. Compared to older vehicles, the injury risk in modern vehicles was shown to be significantly lower.

Compared to previous side impact dummies, the WorldSID has a higher score in the biofidelity ranking (the humanlike behaviour) according to NHTSA as well as ISO evaluations. However, using this new dummy in a wider range of impact severities, with modern restraint systems, has evoked questions regarding the validity of the design requirements for crash test dummies

To further investigate the side impact occupant protection in the front seat, both driver and passenger should be taken into consideration. A single near-side or far-side occupant as well as a combination of both for evaluating potential occupant-to-occupant interaction. Furthermore, there is a need for improved knowledge of non-fatal injuries to better understand the mechanisms for serious injuries and injuries leading to medical impairments. For such evaluations, a comparison between the physical WorldSID dummy, the FE model of the WorldSID and a human body models such as the Total HUman Model for Safety (THUMS) is of highest importance to know the opportunities and limitations of each tool.

3. Objective

The aim of the project was to evaluate the state-of-the-art occupant substitute side-impact evaluation tools (mechanical and numerical) and to assess injuries frequently found in real-life-data with the tools. An extended aim was to combine mechanical and numerical accident reconstruction, real life data analysis to develop a generic numerical model as side impact evaluation tool that can be used to develop robust occupant side-impact protection and gain knowledge about the needs for future occupant side-impact protection systems.

4. Project realization

The case-by-case study using NASS/CDS data required more time than anticipated at the beginning of the project. The CAE evaluation also required more time due to model availability and instability. To compare WorldSID and THUMS response in side impact, Autoliv made a larger effort than originally planned for the CAE evaluation, and hence budget was shifted from VCC to Autoliv.

The NASS/CDS database was chosen for the real life data analysis in order to get a large sample with detailed information on injuries and injury sources from side impacts where occupants were injured in modern, side airbag equipped cars. Based on the real life data from NASS/CDS as well as Volvo internal database two crash tests were performed. Occupant loading and injury risk comparisons of WorldSID and THUMS were made in two CAE test series in two crash severities.

4.1 Real life data analysis

4.1.1 NASS/CDS Data

NASS/CDS data between 2000 and 2012 was searched for all side impacts (GAD L&R, all PDOF) with belted occupants in modern vehicles (MY>1999). Rollovers were excluded, and only front seat occupants above 10 years of age were included. Occupants from this sample, seated adjacent to the intruding structure (near-side) and protected by at least one deployed side airbag, were studied case by case.

The data was stratified into senior occupants (60 or older) and non-senior occupants (10-59). Whether the driver was alone or accompanied by a passenger was also investigated (presence of a neighboring occupant).

A total of 7 727 (3 085 656 weighted) occupants in side impacts with a modern target vehicle (MY>1999) and a front seat occupant older than10 (known age) were found in NASS/CDS. Of these occupants; 82% were non-senior, 50% were single drivers (no neighboring occupant) and 46% were males. In 46% of the crashes the occupant was seated far-side, and in the remaining 54% the occupant was seated near-side (adjacent to the intruding structure). Of all side impacts approximately 1 628 (180 493 weighted) occupants sustained at least one AIS2+ or fatal injury and 1 125 (129 462 weighted) of these were near-side seated occupants. In 240 (27 649 weighted) of these cases the target car was equipped with at least one side airbag.

The crashes where the near-side occupant was protected by at least one side airbag and sustaining at least one AIS2+ or fatal injury were selected for a case-by-case study. The case-by-case study was performed to gain a more detailed understanding of occupant injuries in terms of frequency and associations between injuries. For the case-by-case study, a pilot study using a limited sample of cases was performed by the project team to select relevant injuries to the most frequently injured body regions for subsequent notation. As a result, 23 injured body parts were identified as recurring in the pilot cases, and therefore selected for further analysis in all 240 cases. All cases were analyzed by two traffic safety researchers, and the most severe injury according to the Abbreviated Injury Scale (1998 version of AIS) related to the body parts chosen was noted. When all cases were completed a third researcher performed random controls to ascertain that the same injuries had been analyzed.

To evaluate the distribution of impact directions, the angles of the principal direction of force (PDOF) were used. For establishing crash severity, intrusion and delta-v, are commonly used. Depending on vehicle weight and side structure, the same delta-v can result in very different intrusions. For almost 50% of the cases in this study, either delta-v or information regarding intrusion was missing from the NASS/CDS files, making the relationship between injury and crash severity difficult to evaluate. In addition, the accuracy of the estimated NASS/CDS delta-v depends on vehicle type (ex. Passenger car vs. LTV/MPV), structural engagement/overlap, and the level of reconstruction. Because of these different factors delta-v might be underestimated by 5% to 15% (Hampton and Gabler 2010). To have as large a sample size as possible to study injury distribution, all side crashes were included regardless of vehicle and crash type, making delta-v less reliable as a severity measurement, even when noted. To evaluate injuries related to intrusion, deformation close to the occupant is most important. To maintain a consistent measurement, B-pillar intrusion for cases with noted crush profiles was calculated by using deformation measurements available in the NASS-SAS file, and by making some assumptions.

For the validation of the generic side impact model, NASS/CDS based risk curves for rib fracture injuries at levels AIS2+ and AIS3+, were developed using logistic regression. NASS/CDS inclusion criteria were; case years 2000-2014, target vehicle model year newer than 1999, only side crashes with a front seat occupant at the impacted side (near side) and a deployed side airbag and/or an inflatable curtain. This inclusion criteria resulted in a sample size of 626 (207 065 weighted) cases. Covariates in the analysis were total change in velocity, pulse direction, b-pillar deformation and the occupant age. The b-pillar deformation was computed using linear interpolation, based on the measurements in the NASS database.

4.1.2. Volvo Cars' Database

To evaluate the occupant restraint using the WorldSID50% and THUMS in comparison to human response the Volvo Cars' Statistical Accident Database was searched for suitable side-impact cases for reconstruction. Inclusion criteria were the same as for the NASS/CDS data but no detailed analysis was made on the cases. Based on level of details making it feasible to reconstruct, as well as availability of corresponding CAE model, one case was selected to be evaluated using physical tests and simulation. In the selected case, a 19 year-old male lost control of the car (Volvo V70, MY 2011), skidded into opposite lane and was hit on the left side (impact towards driver and rear seat passenger compartment) by a Kia Ceed (MY2008). The impact speed was estimated to approximately 65 km/h. The near-side driver sustained an AIS3 injury to the abdomen and AIS2 injuries to pelvis and lumbar spine. No thoracic injuries were sustained.

4.2 Crash tests

4.2.1 Accident reconstruction

In total, two physical tests were run to reconstruct the selected real-life Volvo car accident. The bullet vehicle was replaced by a Volvo V40, which was within the size of the actual car. In preparation, a CAE study was performed using a Volvo V70 CAE model as target vehicle and a Volvo V40 CAE model as bullet vehicle. In this virtual study, different parameters, such as bullet vehicle mass, impact angle and velocity, were varied in order to match the deformation pattern of the actual vehicles from the accident. Once a satisfactory match was achieved, a physical vehicle crash test was performed in the same settings. In the selected reconstruction set-up, the Volvo V70 was still standing at -25 degree (0 degrees represented pure lateral impact) angle by a V40 in 60 km/h. In the physical reconstruction, the deformation on the struck side did not match the CAE results (nor the real-life car outcome) satisfactory and a second CAE study was performed where bullet front stiffness was correlated to a crash test and speed adjusted. Based on the second CAE study it was decided to run a second physical test, with increased speed of the Volvo V40, while keeping the angle unchanged. In both test the WorldSID male dummy was position (according to the ISO standard) in the driver seat. High speed video captured the event.

4.2.2. Occupant-to-Occupant interaction

With the objective to evaluate occupant-to-occupant interaction, nine vehicle crash tests performed within a previous project (Dnr: 2009-00507) were used. The tests included a 50th percentile WorldSID male dummy in the near-side (adjacent to the intruding structure) seat and a THOR or ES2 dummy in the far-side (opposite the intruding structure) seat. Due to limited time, the occupant-to-occupant interaction was not evaluated in the previous project.

The near-side seated WorldSID was equipped with 6+6 IR-Traccs (LH and RH) in the thorax/abdomen enabling measurement of bi-lateral deflection. To differentiate deflection caused by the intrusion, and the deflection caused by the neighboring occupant, time history curves were analyzed. The crash tests were performed with different modern vehicles, equipped with thorax side airbags and inflatable curtains, ranging from a compact car to a large sedan, and in different loading conditions such as car-to-car, barrier and pole tests. Lateral delta-v based on vehicle tunnel acceleration and maximum residual intrusion at occupant position were used as a measurement of crash severity to compare injury measurements.

4.3 CAE evaluation using WorldSID & THUMS

4.3.2. CAE in car specific environment

To compare occupant response of WorldSID and THUMS, the two FE models were included in two different load cases (car-to-car in 75 km/h and EuroNCAP barrier) according to the matrix in table 1. The target vehicle was a Volvo V70 and the bullet vehicle was a V40 (car-to-car) and a moving deformable barrier (MDB). To evaluated influence of the side airbag both conditions were run with and without side airbag activation.

Table 1. CAE matrix for WSID and THUMS in car specific model.

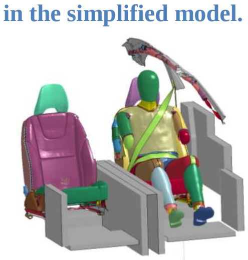
	THUMS	WorldSID
EuroNCAP barrier, std SAB	OK	OK
EuroNCAP barrier, NOSAB	OK	OK
Car-to-Car, 75 km/h, std SAB	Short run	OK
Car-to-Car, 75 km/h, NOSAB	Short run	OK

4.3.3. CAE in simplified model

Due to a delay of the generic model developed by Umeå Univeristy (UMU), an internal Autoliv model was used for comparing the WorldSID and THUMS as a single near-side occupant as well as with a passenger, in low severity (EuroNCAP) and high severity (car-to-car 75 km/h) crashes. Simulation matrix is shown in Table 2.

Table 2. CAE matrix for WSID and THUMS in the simplified model.

Num	Nearside	Farside	Severity
1	WorldSID	-	Low
2	THUMS	-	Low
3	WorldSID	-	High
4	THUMS	-	High
5	WorldSID	WorldSID	High
6	THUMS	THUMS	High



4.4 Validation of THUMS to side impact

The Autoliv Total Human Model for Safety (modified THUMS v1.4) was subjected to localized lateral constant velocity impacts to the upper body. Impact tests previously performed on postmortem human subjects (PMHS) by Subit et al. in 2010 were replicated to evaluate THUMS biofidelity. In these tests, a 75-mm-tall flat probe impacted the thorax at 3 m/s at 3 levels (shoulder, upper chest, and mid-chest) and 3 angles (lateral, +15◦ posterolateral, and −15◦ anterolateral), for a stroke of 72 mm.

Following the THUMS validation, a parametric analysis was performed: the Autoliv THUMS response to a 250-mm impact was evaluated for varying impact levels (shoulder to mid-thorax by 50-mm increments), obliquity (0◦ [pure lateral] to +20◦ [posterior impacts] and to −20◦ [anterior impacts], by 5◦ steps), and impactor pitch (from 0 to 25◦ by 5◦ steps). A total of 139 simulations were run. The impactor force, chest deflection, spine displacement, and spine velocity were calculated for each simulation. For more details see Pipkorn et al. 2014.

4.5 Development of Generic Side Impact Model

The development and validation of the generic model followed closely the method described in Iraeus 2015. The method followed three steps:

1. Create a generic, parameterized finite element (FE) model of a vehicle interior. Define, if available, the related parameter distributions based on NASS/CDS data.
2. Estimate the remaining model parameters using reverse engineering based on IIHS lateral tests.
3. Simulate a population of real-life crashes using the FE model, create risk curves and compare the result to the NASS/CDS risk curves in section 4.1.

The vehicle interior FE model was based on the model developed in Iraeus 2015, although updated for lateral impacts. The geometry of the original model was based on an average of 14 modern vehicles. The updates of the model in this project included adding a seat backrest, side airbags (seat mounted and inflatable curtain) and a detailed modelling of the side structure dynamic intrusion, see left subfigure in Figure 1. The lateral intrusion, was prescribed using a coarse grid, see right subfigure in Figure 1. In a subsequent step the intrusion of the underlying FE model was interpolated from this grid. This provided the possibility to model the intrusion of any crash test or real life crash, which have been measured post-crash. Several of the model properties were parameterized, e.g. passenger distance to the side structure, the height of the armrest, the size and pressure of the side airbag as well as pulse parameters like change in velocity and peak lateral intrusion. In total 21 parameters was defined.

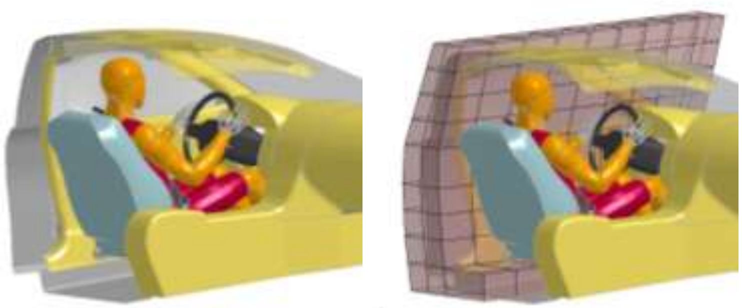


Figure 1. The updated generic side impact FE model, including the Autoliv THUMS human FE model (left) and the same model but with the coarse grid boundary condition (right) overlaid.

To model real life crashes, all of the 21 parameters must be described as statistical distributions based on real life data. Many of the parameters was estimated from the NASS/CDS analysis in section 4.1. However, some of the pulse parameters, i.e. the pulse shape and the pulse duration could only be analyzed for a subset (n=59) of the NASS/CDS cases, for which event data recorder (EDR) data was available. Using these cases the variation in pulse shape was analyzed by using eigenvalue analysis.

For some other parameters, e.g. airbag properties, which are not available in NASS/CDS, the parameter distributions had to be estimated using reverse engineering of IIHS side impact crash tests. This means that the IIHS tests were modelled including the SID2s crash test dummy, and the properties of the airbag were tuned until the simulation model results matched the physical test results.

A large number of simulations, in this case 500 simulations, were performed. For each simulation the FE model parameter settings were sampled from the previously derived statistical distributions. This procedure is also called a stochastic simulation or a Monte Carlo simulation. For each of the 500 simulations the risk of rib fracture was computed based on the strain in the cortical bone.

The final step, the validation of the model, was carried out by creating risk curves based on the simulation data set, and comparing these risk curves with the risk curves derived using the NASS/CDS data in section 4.1.

5. Results and deliverables

5.1 Real life data

NASS/CDS analysis

The most typical crash occurred either at an intersection or in a left turn where the striking vehicle impacted the target vehicle at a 60 to 70 degree angle, resulting in a moderate change of velocity (delta-v) and intrusion at the B-pillar. The head, thorax and pelvis were the most frequent body regions with rib fracture the most frequent specific injury. A majority of the head injuries included brain injuries without skull fracture, and non-senior rather than senior occupants had a higher frequency of head injuries on the whole. In approximately 50% of the cases there was a neighboring occupant present that might influence injury outcome.

The relative risk of injury, using odds ratio calculation, for cases where a side airbag protecting the head deployed, showed a 17% risk reduction for head injuries for the near-side occupant when accompanied by a neighboring occupant. On the other hand, comparing cases when the side airbag protecting the thorax was deployed, the risk of thoracic injury was approximately 24% higher for the near-side occupant with a neighboring occupant present.

The odds ratio calculation showed a trend of reduced risk of head injury, and an increased risk of thoracic injury, for the near-side occupant with a neighboring occupant present. Possible explanations for these trends is the “nut-cracker effect” where the near-side occupant is squeezed between the intruding structure and the neighboring occupant, preventing the head from secondary impacts but increasing loading to the thorax, causing a higher number of fractures. For more details see Sunnevång et al. 2015a.

5.2 Crash tests

5.2.1. Accident Reconstruction

At impact speed 60 km/h (the first reconstruction), the dummy measurements to head, shoulder and thorax were very low. Pubic force measurement resulted in the body region with highest injury risk prediction of1% AIS2+ (for a 45 year old occupant). The crash severity was judged to be similar to the severity of a consumer rating test as performed by IIHS. At the higher impact speed 75 km/h (second reconstruction), dummy measurements were substantially higher. Even though HIC was low, the BrIC predicted a 30% risk of AIS3+ head injury. The thorax deflection predicted a 10% risk of AIS3+ injury and pubic force 10% risk of AIS2+ injury.

The second test was more similar to the real life car deformation pattern outcome. It was also the one with highest pelvis loading, which more likely reflected the injuries sustained by the occupant. However, no head or thoracic injuries were found in the real life case, although a risk was predicted by the reconstruction.

5.2.2. Occupant-to-Occupant Interaction

In the nine vehicle crash tests, thoracic loading induced by the intruding structure as well as from the far-side occupant varied due to the size and structural performance of the car as well as the severity of the crash. Peak deflection on the thoracic outboard side occurred during the first 50 ms of the event. Between 70 to 150 ms, loading induced by the neighboring occupant occurred and resulted in an inboard side peak deflection and viscous criterion response. In the tests where the target vehicle lateral delta-v was below 30 km/h and intrusion less than 200 mm, deflections were low on both the outboard (20-40mm) and inboard side (10-15 mm). At higher crash severities, delta-v 35 km/h and above as well as intrusions larger than 350 mm, the inboard deflections (caused by interaction to the far-side occupant) were of the same magnitude, or even higher (30-70 mm) than the outboard deflections (30-50 mm).

A WorldSID male dummy equipped with bilateral IR-Traccs can detect loading to the thorax from a neighboring occupant making injury risk assessment feasible for this type of loading. At crash severities resulting in a delta-v above 35 km/h and intrusions larger than 350 mm, both the inboard deflection and VC resulted in high risks of AIS3+ injury, especially for a senior occupant. For more details see Sunnevång et al. 2015b.

5.3 CAE evaluation using WorldSID & THUMS

The set-up for the second reconstruction test (Volvo V40 into Volvo V70 at 35 degree angle in 75 km/h), were run using both WorldSID and THUMS. The WorldSID FE model showed similar responses as the physical dummy in the physical test. For the THUMS model, the run did not complete making the injury prediction unreliable.

To investigate the influence of the side airbag the crash was also simulated without airbag (but all other parameters similar). In the car-to-car test, peak values for the WorldSID were similar for the run without side airbag indicating that the bag bottoms our when the crash severity is higher than what the airbag is designed for (e.g. consumer rating procedures). Unfortunately the simulation did not run a sufficient time for THUMS to predict injury risk in the car-to-car test.

In the comparison of WorldSID and THUMS in the EuroNCAP test, the WorldSID measurements showed 0% risk of injury for all body regions and so did the THUMS (for rib fractures). Removing the side airbag in the EuroNCAP simulation resulted in 10% risk of thoracic injury for a 45 year old occupant. THUMS predicted 73% risk of three or more rib fractures in the EuroNCAP without side airbag.

5.3.2. THUMS versus WorldSID50% in simplified model

In the simplified model the WorldSID rib deflection in the low speed crash resulted in 1% risk of AIS3+ injury for a 45 year old occupant and 12% risk for a 67 year old occupant.

For THUMS as a single near-side occupant in the low severity crash pulse, the predicted risk of three or more rib fractures was 78% and 92% respectively. Maximum strain occurred in the lower part of thorax while deflection measured in the WorldSID was found in the upper part of thorax. For the THUMS strain on the inboard side of the thorax down to the buckle was high indicating loading from the diagonal belt. At the higher severity the THUMS predicted 100% risk of three or more rib fractures with loading pattern similar as in the lower velocity. The WorldSID AIS3+ thoracic injury risk increased to 17% and 65% respectively for a 45 and 67 year old occupant.

In the simulation with two occupants, the WorldSID as passenger do contact the near-side occupant but the measurements failed to provide useful data due to a model error. For the THUMS additional strain was found on the inboard side of the thorax at mid height.

5.4 Validation of THUMS to side impact

After adding muscle elements to improve scapula attachment, increasing the stiffness in the joint between clavicle and sternum, the Autoliv THUMS biofidelity was found acceptable. Overall, the predictions from the model were in good agreement with the PMHS results. The worst ratings were observed for the anterolateral impacts.

For the parametric analysis, maximum chest deflection (MCD) and maximum spine displacement (MSD) were found to consistently follow opposite trends with increasing obliquity. This trend was level dependent, with greater MCD (lower MSD) for the higher impact levels. However, the spine velocity for the 250-mm impactor stroke followed an independent trend that could not be linked to MCD or MSD. This suggests that the spine velocity, which can be used as a proxy for the thorax kinetic energy, needs to be included in the design parameters of countermeasures for side impact protection.

The parametric analysis reveals a trade-off between the deformation of the chest (and therefore the risk of rib fracture) and the lateral translation of the spine: reducing the maximum chest deflection comes at the cost of increasing the occupant lateral displacement. The trade-off between MCD and MSD is location dependent, which suggests that an optimum point of loading on the chest for the action of a safety system can be found. For more details see Pipkorn et al. 2014.

5.5 Generic Side Impact Model

A comparison of the risk curves based on real life NASS/CDS data and corresponding risk curves based on the results of the generic side impact model is presented in Figure 2. The left subfigure shows the risk curves for a 30 years old occupant and the right for a 70 year old occupant. The simulation based risk curve (dashed line) overestimated the risk for rib fracture.

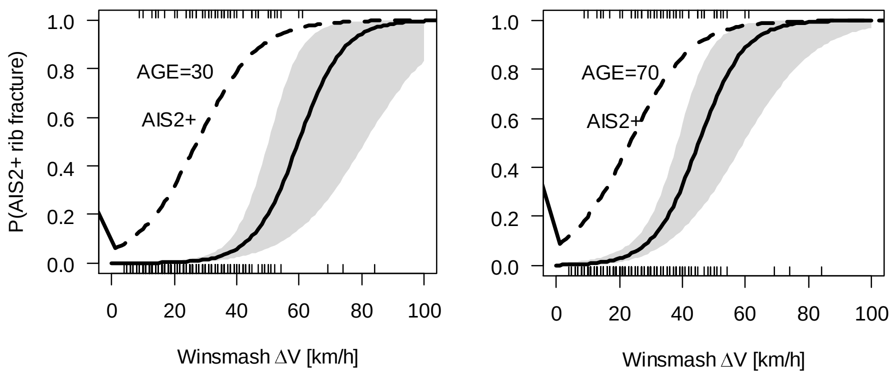


Figure 2. Comparison of NASS/CDS risk curves presented using the solid line (gray area represents 95% confidence bands) and FE simulation-based risk curve presented using the dashed line. The curves are presented as conditional risk curves for discrete values of the variable age (AGE) at injury severity level AIS2+.

The results were similar to the results for frontal impacts analyzed in Iraeus 2015. Some of the difference between the NASS/CDS risk curves and the simulation results were probably an effect of the simplified modelling of age effects in the current version of the Autoliv THUMS FE model. However, this did not explain all of the difference.

To study benefit of design changes, a regression model can be created by using all simulation model parameters. After removing non-significant parameters, the resulting regression model can be seen in Table 1. The "estimate" column shows the effect on the LOG-odds, of changing the parameter one unit. For example, this model suggests that moving the occupant 10 mm closer to the side structure increases the log-odds by 10*0.023=0.23, which thus will increase the risk of injury. In the same way the effect of other design changes, in term of risk of injury in real life crash scenarios, can be evaluated using the model.

Table 1. Results of the logistic regression analysis of the stochastic simulation study. The table presents the significant co-variates to the log-odds of risk of rib fractures at severity level AIS2+

	Estimate	**Std. Error**	**Signif. level**
(Intercept)	-9.35	0.63	***
Side structure distance	0.023	0.007	**
Pulse shape parameter EV1	-0.23	0.035	***
Door friction	-5.46	1.10	***
Pulse duration	-0.072	0.005	***
Side airbag time to fire	0.007	0.003	**
Side airbag ΔWidth	0.013	0.003	***
Principle direction of force (PDOF)	-0.032	0.003	***
Change in velocity (dV)	0.37	0.01	***
Magnitude of side intrusion	0.044	0.001	***
Age of occupant	0.035	0.003	***

5.3 Delivery to FFI-goals

Using the CAE WorldSID male and the THUMS in back to back comparison has resulted in a deeper understanding of potentials and limitations for each of the tools available for occupant protection. This is of high importance addressing design of future collision mitigation systems and advanced restraint systems, enabling reduction of injured occupants in traffic.

The real life data analysis concluded that brain injuries (without skull fractures), rib fractures, lung injuries and pelvic fractures should be further assessed to reduce injuries sustained in side impacts. With increased active safety systems better preventing high severity crashes in the future, side airbag performance in intersection crashes, especially for senior occupants, will gain importance. To further reduce the injury risk to senior occupants, dummy biofidelity and injury criteria matching future crash modes must be ascertained. As a complement to physical tests, evaluations using human body modelling is needed to ensure good occupant protection in a wider range of crashes. However, that require further development of injury criteria, and corresponding injury risk curves, to the THUMS (or other human body model).

The case-by-case study of side airbag equipped vehicles provided a thorough understanding of injuries sustained in a side impact and also the pre-crash conditions. Although different from US road design many of the conclusions from the real life data analysis can be used to improve occupant protection in a side crash with respect to vehicle, occupant and infrastructure.

Using WorldSID for evaluating occupant protection has resulted in an advance for occupant safety design to EuoNCAP 2015 and future USNCAP which both will use this dummy for side impact evaluation. The results in this project has resulted in driving the implementation of advanced dummies, helping to drive the safety development in a larger context than among the project partners only.

The generic model, developed within the project, can be used for injury prediction as well as restraint system evaluation both with the THUMS and with the WorldSID. Using the model can provide insight of the occupant protection for crash characteristics beyond legal requirements and consumer tests.

6. Dissemination and publications

6.1 Knowledge and results dissemination

This project has increased knowledge of the side impact characteristics, the injury outcome on the field, the tools available for injury assessment and the level of injury risk measured by WorldSID and THUMS in low and higher crash severities. The results obtained in this project will be used in the FFI project Injury Prediction for Human Body Models - Part 3 as well as for product development. During the course of this project results have been used for product development for EuroNCAP 2015 and also to influence the future USNCAP.

6.2 Publications

Pipkorn B, Subit D, Donlon JP, Sunnevång C. *A Computational Biomechanical Analysis to Assess the Trade-off Between Chest Deflection and Spine Translation in Side Impact*. AAAM 2014 and Traffic Inj Prev 15: Supl, S231-S237

Sunnevång C, Sui B, Lindkvist M, Krafft M. *Census study of real-life near-side crashes with modern side airbag-equipped vehicles in the United States.* ESV 2015 and Traffic Inj Prev 2015;16 Suppl 1:S117-24

Sunnevång C, Pipkorn B. Boström O. *Assessment of Bilateral Thoracic Loading on the Near-Side Occupant Due to Occupant-to-Occupant Interaction in Vehicle Crash Tests.* AAAM 2015 and Traffic Inj Prev 2015 Oct;16 Suppl 2:S217-23

Lindkvist M, Kjaer C, Sunnevång C. *Side Collision Induced Pelvis Fractures in Modern Cars*. AAAM 2014 and Traffic Inj Prev, 15:sup1, S270-S277

Thesis work:

Johansson Eric, 2015. *Pelvic Injury Criterion for Lateral Impact in a in Finite Element Human Body Model. Master Thesis*, Department of Applied Mechanics, Division of Vehicle Safety

7. Conclusions and future research

Side impacts are mainly related to intersections and combining improved passive restraint performance with active safety features is needed to improve occupant protection. Especially for the elderly occupants.

Although force and deflection response of THUMS exposed to lateral localized impacts were similar to the PMHS response, there is still a need to further understand how to predict injury risk in terms of probability to rib fractures. Other frequent injuries were head injuries without skull fracture, lung injuries, splenic rupture and pelvis fractures. These injuries will need to be addressed to further reduce MAIS2+ injuries sustained in side impacts in the future.

Both WorldSID and THUMS lack a valid injury criteria with injury risk functions for addressing pelvis injuries which is the second most frequent injury for all occupants when considering MAIS2+ injuries.

To add instrumentation on the WorldSID50% non-struck side and measure bi-lateral deflection can detect thoracic loading due to occupant-to-occupant interaction.

8. Participating parties and contact person

Autoliv Development AB:

Cecilia Sunnevång, cecilia.sunnevang@autoliv.com
Bengt Pipkorn, bengt.pipkorn@autoliv.com
Krystoffer Mroz, krystoffer.mroz@autoliv.com
Christian Forsberg, christian.forsberg@autoliv.com

Volvo Car Corporation:

Hampus Grimmemyr, hampus.grimmemyr@volvocars.com

Ulf Lechelt, ulf.lechelt@volvocars.com

Umeå University:

Mats Lindkvist, mats.lindkvist@umu.se

Johan Iraeus, johan.iraeus@afconsult.com

9. References:

Iraeus, J. *"Stochastic finite element simulations of real life frontal crashes: With emphasis on chest injury mechanisms in near-side oblique loading conditions",* PhD Dissertation (Comprehensive summary), 2015, Umeå University