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Human Body Model with Active Muscles and Detailed Head for Pedestrian Protection
- Prediction of Neck and Head Injuries

Project within: Trafiksäkerhet och automatiserade fordon

Authors: Christer Lundgren, Bengt Pipkorn (Autoliv Development)
                Lotta Jakobsson, Stefan Larsson, Magnus Björklund (Volvo Car
                Corporation)
                Svein Kleiven, Peter Halldin, Victor Strömbäck Alvarez, Madelen
                Fahlstedt (KTH Royal Institute of Technology)

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1. Executive summary

The overall aim of the project was to develop methods and industrial tools to predict head and neck injuries in a biofidelic and detailed manner for car to pedestrian crashes. Specifically, the aim was to improve, validate and use the human body model 'THUMS-KTH head/neck' model (created in a prior research project) by validation against published volunteer and cadaver experiments, and to compare and challenge the model with extended accident reconstruction studies. As part of the project, a mathematical model of a vehicle windscreen was developed and validated, enabling a whole body pedestrian to vehicle front evaluation. In addition physical tests were performed to provide input from a mechanical pedestrian model for which a mathematical counterpart was developed.

Pedestrian accidents are frequent and commonly cause injuries due to the combination of vehicle properties and that the pedestrian is unprotected. Injuries to the head are the most common fatal injury. The resulting head kinematics is a combination of translational and rotational acceleration. The properties of the neck are essential for accurately predicting the kinematic responses of the head. Vehicle properties for pedestrian protection are today mainly evaluated based on sub-system impactor tests, which offer limitations in predicting pedestrian whole-body interaction to the vehicle. Evaluating mechanical and mathematical whole body pedestrian tools and improving an advanced human body model are essential to contribute to real world developments in pedestrian to car crashes.

Within the project, the 'THUMS-KTH head/neck' model has been improved with head skull fracture prediction, updated neck ligament material properties and whole body kinematic validation using published PMHS tests. Accident reconstructions were performed demonstrating the capability of 'THUMS-KTH head/neck' model to predict injuries from real accidents. Evaluation of a new pedestrian protection airbag concept was done, which showed potential to reduce head injury levels to AIS 2 or lower. In addition, the model has been used to evaluate brain strain due to head to windscreen impacts at different locations as well as to the a-pillar of the Volvo S60 car used in the physical tests.

An important part of the project was the development of an advanced analysing tool enabling advanced calculation of head injury risks. The tool 'KTH FE-Model Risk Injury Post Processor (FEMRIPP)' analyses head accelerations, stresses and strains in skull, brain and neck ligaments and creates injury risk curves for concussion. This tool has been used and refined through the project and is a valuable project result to be used together with the model to predict injury risks for all partners; both for research and industrial applications.

Due to lack of functional windscreen models, a detailed state of the art FE-model for windscreen modelling was created within the project, to be able to better predict injuries resulting from head to windscreen impacts. This model was used in the reconstructions

and when comparing mechanical pedestrian crash test dummy, FE-model of mechanical dummy, THUMS-KTH FE-model and EuroNCAP standard head impactor FE-model.

Crash tests were run with a mechanical pedestrian crash test dummy, with the purpose of investigating how different head to windscreen impact locations and how different head impact angles effects brain strain and injury risks. An FE-model of the mechanical dummy was created and validated.

Tests comparing the mechanical pedestrian crash test dummy, the FE counterpart, the 'THUMS-KTH head/neck' model as well as head impactor models have been performed to get knowledge of the similarities and differences in kinematic and injury prediction. This knowledge is important when making reconstructions and developing safety countermeasures. In addition, simulations using the head and leg sub-system impactors have been compared to equivalent situations when using the 'THUMS-KTH head/neck' model to get an insight of how well the EuroNCAP sub-system methods correspond to whole body to vehicle interaction situations.

The tools and methods developed in this project enables rapid development and evaluation of current and new safety systems in a cost and time efficient way. The industrial use will contribute to Swedish automotive and supplier companies to keep their competitive edge in the field of developing safe vehicles and vehicle safety on a global market.

The project has resulted in one PhD thesis, three publications, three master thesis, and two more publications are planned.

2. Background

In the FFI project named "Human Body Model with Active Muscles and Detailed Head for Pedestrian Protection", steps were taken in the area of injury criteria focusing on head injuries where a rough tool was developed to predict risk of concussion and skull fractures. A first step in modelling a detailed windscreen for studying head injuries was taken but an improvement was needed to have a better correlation with experimental test of windscreens in both deformation response and acceleration. A natural continuation was to refine the method to include the probability to sustain a concussion and also to add severe head injuries.

Pedestrian accidents are frequent and commonly cause injuries due to the combination of vehicle properties and that the pedestrian is unprotected. The probability for a pedestrian to be injured or killed is much higher than that for a vehicle occupant; 6.7 % of vehicle-pedestrian impacts in the US were fatal, whereas the corresponding fatality rate for occupants in crashes only was 1.3 % (NHTSA, 2009). For these two reasons pedestrian related fatalities comprise a considerable percentage of total traffic fatalities in industrialized nations: from 11 % in USA (NHTSA, 2009) to nearly 50 % in South Korea

(Youn Y. et al., 2005). In pedestrian accidents the most frequently injured body part is the head followed by the chest (Yang J, 1997 and Otte, 1999).

Injuries to the head are the most common fatal injury in a pedestrian accident. The resulting head kinematics in such an accident is a combination of translational and rotational acceleration. The Head Injury Criteria (HIC) being the only criterion used today to predict head injuries, is insufficient as it only includes translational acceleration and do not take the direction of the impulse into consideration.

Many of the head injuries are due to impact with the windscreen (Mallory, A. et al.,2012). To study head injuries with finite element methods it has been shown that the accuracy of the impacted area are important (Alvarez, et al., 2016). Modelling of windscreens is difficult due to the brittle nature of glass in combination with the elastic layer of laminate in between the two glass layers.

3. Objective

The overall aim of the project was to develop methods and industrial tools to predict head and neck injuries in a biofidelic and detailed manner for car to pedestrian crashes. The focus was on improved kinematics and injury prediction of the pedestrian Human Body Model 'THUMS-KTH head/neck' with the purpose to model humanlike head-to-car contact conditions and to improve the head and neck injury predictability. Specifically, the aim was to improve, validate and use the human body model by validation against published volunteer and PHMS experiments, and to compare and challenge the model with extended accident reconstruction studies.

As part of the project, a mathematical model of a vehicle windscreen was developed and validated, enabling a whole body pedestrian to vehicle front evaluation.

In addition, physical tests were performed with the purpose of creating head impact conditions generating a large span of head injury severities (based on real world data experiences), to provide input to create a mathematical model of the pedestrian crash test dummy and to create a link between mechanical pedestrian dummy, mathematical dummy model, THUMS-KTH model and EuroNCAP head form FE-model.

4. Project realization

4.1 Method

The project was realized through collaboration between Autoliv Development AB (Autoliv), Volvo Car Corporation (VCC) and Royal Institute of Technology (KTH) from January 1st 2014 to December 31st 2016.

The project contains activities in detailed FE model improvements (including the KTH head/neck model, windscreen models and a FE model of a pedestrian crash test dummy), physical whole body to vehicle crash tests as well as simulations reconstructing real world crashes and evaluating different countermeasures evaluating the injury prediction capability of the THUMS-KTH model.

An advanced analysing tool for industrial application has been created, used and refined throughout the project. The tool is a post-processor for analysing head accelerations, stresses and strains in skull, brain and neck ligaments including AIS 1 and AIS 2 risk curves for concussion.

4.1.1. Improvements and Evaluation of THUMS-KTH Model

To improve the fracture prediction capabilities of the KTH head model, a master thesis project was performed (Andersson, 2016). KTH neck model with 1D and 3D neck muscles were compared to THUMS V4.02 and GHBMC neck models through Functional Spinal Unit (FSU) experiments found in the literature, in compression, extension, shear and bending modes.

To determine the level of whole-body biofidelity of the THUMS-KTH (with 1D neck muscles), with focus on head kinematics, simulations of three PMHS tests by (Forman, J.L. et al., 2015a and 2015b) using a vehicle buck were compared.

4.1.2. Windscreen Finite Element Model

As a part of the project, two FE models of windscreen glass were developed: one based on the smeared technique (Timmel, et. al, 2007) ; and one based on the non-local failure model as described by (Pyttel, T., et al., 2011). Both models were evaluated with respect to deformation and acceleration characteristics using data from (Pyttel, T., et al., 2011).

In addition, a windscreen model using the new material model released by LS-Dyna in October 2016 was evaluated. To validate and evaluate the predictive capability of that and the Pyttel model, head impact tests in windscreens were carried out.

4.1.3. Mechanical pedestrian crash test dummy to vehicle impact tests

Five tests using a mechanical crash test pedestrian dummy ('Autoliv pedestrian dummy') impacted by a Volvo S60 car were performed. Head impact conditions generating a large span of different head injury severities (based on real world data experiences) were targeted. The following parameters were varied to achieve this: dummy elevation, the dummy lateral position, head impact locations and impact velocity.

4.1.4. Finite element model of mechanical pedestrian crash test dummy

An FE model of the 'Autoliv pedestrian dummy' was created to provide a link between the physical tests and the THUMS KTH model. This was performed as a master thesis work (El Masoudi, 2015). The model was validated to pedestrian crash impact tests performed at Autoliv in Vårgårda.

4.1.5. Accident reconstructions

Accident reconstructions were performed to evaluate the performance of the THUMS-KTH model's capabilities to reconstruct kinematics and injuries outcome based on real world cases. Four accidents from German In-Depth Accident Study (GIDAS) were reconstructed using a FE buck model and two accidents from Volvo Cars Pedestrian Accident Database (V_PAD) were constructed using a detailed Volvo FE-model.

4.1.6. Comparison THUMS-KTH and impactor sub-system simulations

An evaluation of predicted injuries comparing lower leg and head form simulations to whole body THUMS-KTH simulations was performed as a part of a Master Thesis study (Farkya, P., Cheng, X., 2015) Leg (Flex-PLI impactor) and head form simulations were compared to simulations results using THUMS-KTH impacted by the same vehicle.

4.1.7. Comparison of mechanical dummy, FE-model of mechanical dummy, THUMS-KTH and FE-model of EuroNCAP head impact model

Results from two of the five pedestrian impact tests described above, one 35km/h with 150mm dummy elevation and one 30km/h 200mm dummy elevation, were compared to simulations with the FE-model of the mechanical dummy, THUMS-KTH model and an FE-model of the EuroNCAP adult head form.

4.1.8. Evaluation of Pedestrian Protection Countermeasures

Simulations evaluating the THUMS KTH's model's capability of evaluating pedestrian protection countermeasures were performed, with and without Pedestrian Protection Airbag (PPA). Two different impact locations with a car impact velocity of 40km/h (no breaking after impact) were evaluated; one where THUMS-KTH was standing still in a walking pose so that rear leg was struck first, located at the longitudinal centreline of the car, and the other where the same walking pose was used, but for an off-centreline impact location. The car model was based on a public finite element US Toyota Yaris model, simplified to reduce simulation time, and replaced windscreen to the project developed windscreen.

5. Results and deliverables

The most important results of the project is the further refinement of the THUMS-KTH head/neck model, including the post-processor tool, to enable prediction of head and neck injuries in car to pedestrian impacts. In total 3 peer-review articles (+ additional 2 in process), 3 master theses and one PhD were produced during the project.
The results from the specific sub tasks are summarized below.

5.1 Results

5.1.1. Improvements and evaluation of THUMS-KTH

Head skull fracture prediction was added, providing additional injury prediction. The fracture prediction is somewhat limited in terms of fracture propagation and type of fracture, due to coarse mesh. Neck ligaments material properties were adjusted to better match the test corridors for translational and angular displacement.

5.1.2. Windscreen finite element model

Results from simulations show that the non-local failure is able to predict both head acceleration and windscreen deformation. The effect on brain strain measured by THUMS-KTH is described in (Alvarez AS, et al.,2013).
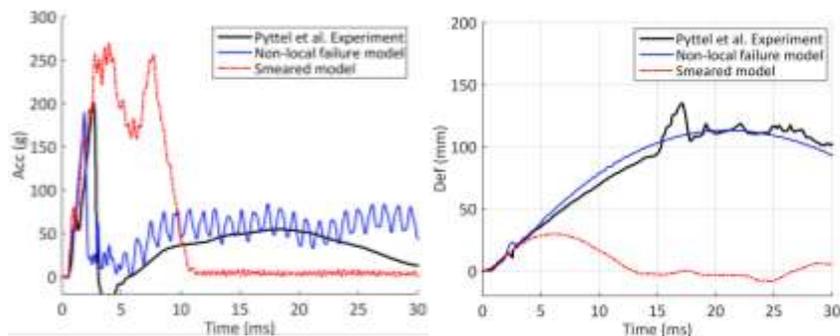
Figure 1: Acceleration from head impactor (left) and deformations at the centre of plate (right) presented for 4.8 kg 10 m/s. The experiment from (Pyttel et al., 2011) is drawn in solid black, the two models used in the current study are presented in solid blue and dashed red.

The additional comparison between the non-local failure and *MAT_280 shows a slight improvement of curve shape for the *MAT_280 material model. Both models predicts the

windscreen deformation similar the first 20ms.
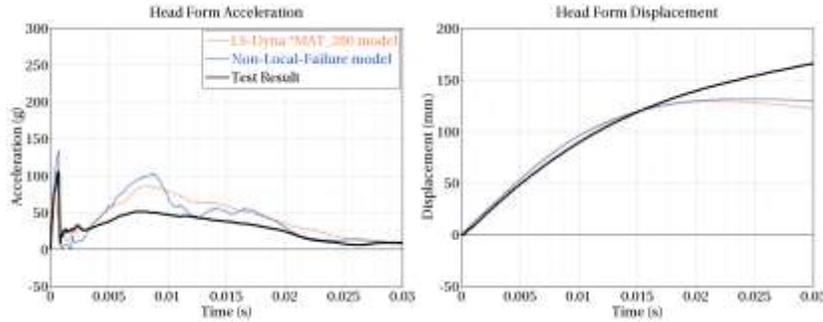
Figure 2: Comparison of head to windscreen impact tests (4.53kg, 11.1m/s) to non-local failure model and LS-Dyna
*MAT_280.

5.1.3. Mechanical pedestrian crash test dummy to vehicle impact tests

Head acceleration signals from the five tests were recorded and used as input to simulations with THUMS-KTH model. The simulations showed strain values corresponding to injury levels AIS 0-5. The global injury measurements, HIC and BrIC, and simulated local injury measurements, brain strain, show different trends and probability of injury.
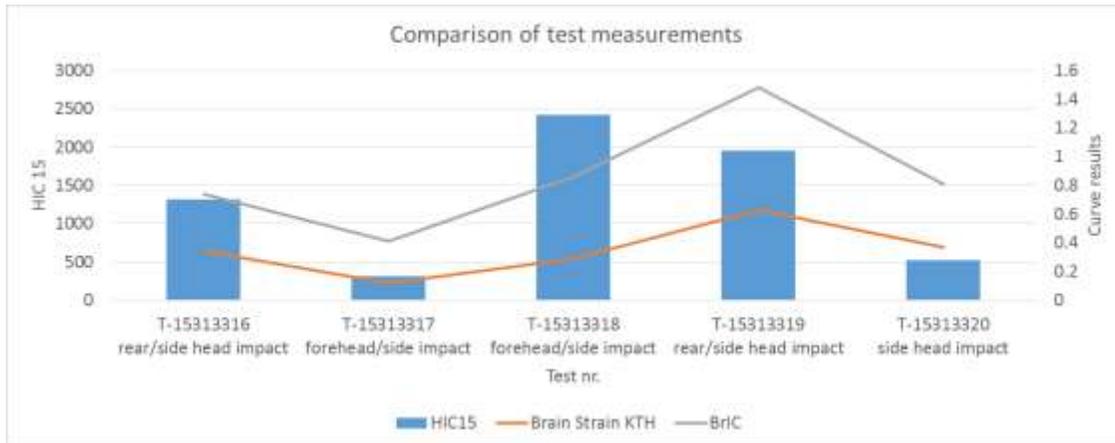
Figure 3: Comparison between global, HIC and BrIC and local, brain strain injury parameters.

5.1.4. A FE-model of Autoliv mechanical dummy

The model has been used in simulations to estimate impact locations before the physical tests and later it was compared to test results. The FE-model showed different impact location and head acceleration compared to the mechanical dummy. The comparison shows that this model has potential to be a valuable tool when developing new safety products.

5.1.5. Accident reconstructions

Accident reconstruction is one of the most important tasks that the THUMS-KTH model should be used for. Four reconstructions using a vehicle buck and two reconstructions using a detailed vehicle model of real world cases were made with THUMS-KTH. These provided evidence of the capabilities of using the THUMS-KTH model in whole body reconstructions. The reduction from the initial goal of 24 was due to the difficulty to find relevant input data and that whole body kinematic validation was more time consuming than expected. This is a first step and more cases (including a variety of situations, including impact points, gait positions, injury types etc) should be included in order to draw conclusions on the prediction capabilities of the model.

5.1.6. Comparison THUMS-KTH and impactors

These simulations, using the head and leg sub-system impactors and 'THUMS-KTH head/neck' model gave an insight of how well the EuroNCAP sub-system methods correspond to whole body to vehicle interaction situations. The results show that the lower extremities injuries predicted by Flex-PLI and THUMS do not correlate while head linear accelerations as predicted by THUMS-KTH and head impactor were in correlation to each other in terms of trend and behaviour of acceleration during impact.

5.1.7. Comparison of mechanical dummy, FE-model of mechanical dummy, THUMS-KTH and FE-model of EuroNCAP head impact model

The comparison of the different pedestrian substitutes and the EuroNCAP head form showed differences in impact location, timing, velocity and head acceleration. The most striking difference is the neck behaviour where THUMS-KTH is much more flexible and is considered to be most human like. The differences found in this comparison forms a knowledge base and a link between the mechanical dummy, FE-dummy, THUMS-KTH and EuroNCAP head form model.

5.1.8. Evaluation of Pedestrian Protection Countermeasures

The evaluation of full body pedestrian protection airbag using THUMS-KTH and the post-processor FEMRIPP shows strong potential to reduce the risk of sustaining a head injury from severe to AIS 2 level or lower.

Figure 4: Three different PPA-concepts evaluated with THUMS-KTH and FEMRIPP.

Pedestrian Model		THUMS_KTH	THUMS_KTH
Position		Y0	Y0
Impacted leg		rear leg	rear leg
Pedestrian walking speed		0 km/h	0 km/h
Injury Mitigation System		PPA v 41	No PPA
HIC15		77	1231
Risk for AIS 2 (HIC)	%	2	97
BrIC		0.61	1.59
Risk for AIS 2 (BrIC)	%	63	100
Maximum Principle Strain Corpus Calossum		0.16	0.75
Risk for concussion	%	31.4	100
Maximum Principle Strain Brain		0.22	0.75
Maximum Stress Scull	MPa	50.3	76.5
Neck ligament rupture	Y/N	N	N

Table 1: Results from simulations with and without the right PPA in Figure 4.

5.1.9. KTH FE-Model Risk of Injury Post Processor (FEMRIPP)

An advanced analysing tool for industrial application has been created, used and refined throughout the project. It is a post-processor for analysing head accelerations, stresses and strains in skull, brain and neck ligaments including AIS 1 and AIS 2 risk curves for concussion.

5.2 Delivery to FFI Goals

This project mainly contributes to the FFI zero injured or killed in traffic goal through creating refined and detailed mathematical models together with a post-processor to evaluate the risk for head and neck injuries for pedestrians impacted by passenger cars. Head injuries are the most frequent as well as severe injuries sustained by pedestrians when impacted by passenger vehicles. The advanced virtual tools from this project will enable evaluation and development of protective systems, such as the new airbag concepts, which was positively evaluated within this project.

The advanced virtual tools enable not only development of state of the art protective systems they also enable the development of them in a cost effective way. This contributes to secure competitiveness of Swedish automotive and supplier companies and to remain at the leading edge in developing safe cars and safety systems for vulnerable road users.

6. Dissemination and publications

6.1 Knowledge and results dissemination

There are many initiatives world-wide focused on human body models, improving their biofidelity and injury prediction capabilities, which can benefit from the results of this project. Specifically, the results from this project form an important pillar in the SAFER HBM competence area.

The project resulted in several peer-review articles, three master theses and one PhD. Project partners have presented results and knowledge at international meetings and conferences.

6.2 Publications

PhD thesis:
Madelen Fahlstedt. *Numerical Accident Reconstructions, A Biomechanical Tool to Understand and Prevent Head Injuries.* Doctoral Thesis, KTH Royal Institute of Technology, School of Technology and Health, Neuronic Engineering. ISBN 978-91-7595-512-4.

Peer-reviewed articles:
Victor S. Alvarez, Peter Halldin, Svein Kleiven. *The Influence of Neck Muscle Tonus and Posture on Brain Tissue Strain in Pedestrian Head Impacts.* Stapp Car Crash Journal 2014

Victor S. Alvarez, Svein Kleiven. *Importance of Windscreen Modelling Approach for Head Injury Prediction.* IRCOBI 2016

Madelen Fahlstedt, Peter Halldin, Svein Kleiven. *Comparison of Multibody and Finite Element Human Body Models in Pedestrian Accidents with the Focus on Head Kinematics.* Traffic Injury Prevention 2016

Master theses:
Solayman El Masoudi, *Finite Element Modelling of a Pedestrian Impact Dummy*, KTH Royal Institute of Technology, School of Technology and Health, 2015.

Frida Andersson, *Finite Element Modelling of Skull Fractures, Improvements of the skull fracture prediction for the KTH FE head model*, KTH Royal Institute of Technology, School of Technology and Health, 2016.

Pradeep Farkya, XiaoXiao Cheng, *Assessment of injuries to the lower leg and head of pedestrians in vehicle-to-pedestrians collisions through FE simulations*, Department of Applied Mechanics, Chalmers University of Technology, 2015.

Publications in process:
Madelen Fahlstedt, Victor S. Alvarez, Svein Kleiven. *Detailed Pedestrian Accident Reconstructions Using a Validated FE-model*

Victor S. Alvarez, Madelen Fahlstedt, Svein Kleiven. *Implications of Reducing Boundary Conditions and Velocity components in Pedestrian Accident Reconstructions*

7. Conclusions and future research

7.1 Conclusions

The project has delivered methods and industrial tools for head and neck injury prediction. This was addressed by an improved pedestrian human body model, THUMS-KTH, with added skull fracture prediction, improved neck kinematic and whole body kinematic. An advanced user friendly analysing post-processor tool, FEMRIPP, was created and used throughout the project enabling detailed analyses in an efficient way.

The THUMS-KTH model was used for accident reconstructions where its capability was proven for both kinematic and injury prediction.

A detailed mathematical windscreen model was created and used in the accident reconstructions and the evaluation and development of a new pedestrian protection airbag.

A link between physical tests and simulations has been created by comparing the mechanical pedestrian dummy impact tests with the FE-model of the mechanical dummy, the THUMS-KTH and EuroNCAP adult head form FE-model.

7.2 Future Research

Head injuries are common in car to pedestrian accidents but the available head injury criteria are insufficient to capture real world injuries since they either measure only translational accelerations or only angular velocities. The industry needs better injury criteria and tools to create safety systems with better protective capabilities. With a strain based injury criteria both translational and rotational loads are taken into account.

A common injury for occupants in frontal crashes is WAD (Whiplash Associated Disorder) type neck injuries that do not possess any life threatening risk but can cause long term consequences for the individual and high costs for the society. This type of injury cannot be predicted with the tools available today.

With autonomous cars soon being a reality the acceptance to get injured in a crash, whether it is a pedestrian or occupant will likely be reduced. Therefore injury criteria and tools that address low severity injuries are needed by the industry.

In NHTSA's Federal Automated Vehicles Policy it is stated that simulations can be used in combination with physical tests to demonstrate expected performance of a highly automated vehicle (HAV). The industry therefor need to develop methods and models to show that the mathematical models correspond to reality.

Today's protective systems will likely need to be developed to address higher demands from legal and rating requirements to stay on the competitive edge. New inventions to address the challenges with expected different seating positions in autonomous cars need to be analysed and evaluated with state of the art numerical tools to be time and cost effective.

To contribute to safer traffic environment and to minimize the risk of injuries and fatalities in the event of a crash, better and more refined analysis tools that are able to measure stresses and strains that the human body is exposed to are needed to better understand different injury mechanism and to address the right counter measures.

8. Participating parties and contact person

Autoliv Development AB:	Volvo Car Corporation:	Kungliga Tekniska Högskolan:
Christer Lundgren (contact person), christer.lundgren@autoliv.com Bengt Pipkorn	Lotta Jakobsson, Stefan Larsson, Magnus Björklund	Svein Kleiven, Peter Halldin, Victor Strömbäck Alvarez, Madelen Fahlstedt

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