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Machine and Vehicle Systems

Heavy Vehicle Crash Safety

Improved Thoracic Injury Prediction in Frontal Crash Testing

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An HGV front-to-rear accident as described in the introduction. Image courtesy of Volvo Trucks Accident Research Team

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HEAVY VEHICLE CRASH SAFETY
IMPROVED THORACIC INJURY PREDICTION IN FRONTAL CRASH TESTING

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ABSTRACT

Frontal crashes are regarded as some of the most injurious accidents for Heavy Goods Vehicle (HGV) drivers. One of the leading HGV manufacturers regularly conducts frontal crash testing for occupant safety. The Hybrid III crash test dummy was developed for frontal testing in passenger cars and has become the standard in crash laboratories. This project was initiated to investigate the suitability of the Hybrid III in HGV frontal crash testing. The cab geometries and occupant posture in an HGV differ from passenger cars. The driver chest will thus experience a different loading in a frontal crash. The objective of this thesis was to establish if and how the Hybrid III could be used in frontal HGV crash tests, in particular how to best assess chest injury risk in HGV crash tests with the Hybrid III.

Database analyses of real-world HGV crashes were carried out to establish which injuries to prioritise in the most common and serious crash types. The results confirmed that chest injuries in frontal crashes are a top priority. The chest was the body region with the highest frequency of severe injuries.

The occupant load case was studied in frontal sled crash tests, with a Hybrid III seated in an HGV cab. The chest of the Hybrid III was found to contact the steering wheel rim in all tested configurations. The study concluded that the Hybrid III was able to accurately register chest deflections with the aid of additional instrumentation. Furthermore, the steering wheel rim-to-chest contact was found to be a previously unexplored load case in injury biomechanics, and the need for further biomechanical knowledge regarding this load case became apparent.

A representative HGV frontal crash chest load case was identified. Post Mortem Human Subject (PMHS) testing provided data to confirm the suitability of the Finite Element (FE) Human Body Model (HMB) Total HUman Body Model for Safety (THUMS) as a human surrogate. An FE model of the Hybrid III was validated from physical tests in the representative load case. A simulation test matrix including the THUMS and the FE Hybrid III, was applied to develop a transfer function from the chest response of the Hybrid III to existing injury criteria. The application of the added chest deflection instrumentation and this transfer function enables much improved chest injury assessment with the Hybrid III in frontal HGV crash tests. These results have the potential to facilitate the development of improved HGV occupant safety systems, to reduce the severity of HGV driver injuries, or all-together prevent injuries from occurring. Additional research, including more PMHS testing, is recommended to establish these chest tolerance limits.

KEYWORDS: Accidents, Chest injury, Crash test, Finite Element modelling, Heavy goods vehicle, Hybrid III, Injury assessment, Pendulum test, THUMS

PREFACE

The main part of the work reported in this thesis was carried out at Chalmers University of Technology, at the Department of Applied Mechanics, Division of Vehicle Safety, Injury Prevention Research Group, Gothenburg, Sweden, from 2007-2015, under the supervision of Professor Mats Svensson, Associate Professor Johan Davidsson and Professor Astrid Linder (during 2015).

The work presented in the appended papers of this thesis was primarily funded by the Swedish Vehicle Research Program (PFF) through VINNOVA and AB Volvo. The PMHS tests (Paper III) were funded by Chalmers University of Technology and carried out in collaboration with Graz University of Technology. Partial funding for 2015 was received from the Swedish National Road and Transport Research Institute, VTI.

The simulations were performed on resources at Chalmers Centre for Computational Science and Engineering (C3SE) provided by the Swedish National Infrastructure for Computing (SNIC).

ACKNOWLEDGEMENTS

This study was mainly funded by the Swedish Vehicle Research Programme (PFF) through VINNOVA and AB Volvo. The PMHS tests were funded by Chalmers.

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My co-supervisor, Professor Astrid Linder at VTI, for enabling me to finalise this thesis during my employment at VTI.

Project partners; Stefan Thorn, Fredrik Törnvall and Peter Rundberget at AB Volvo for support and discussions which extended beyond this project.

Many thanks to my colleagues and friends at Chalmers for making the "fika" and lunches more enjoyable; Fredrik, Linus, Weija, Helen, Jan, Mikael, Sunan, Anna, Ulrika, Sogol, Jian-Feng, Aleksandra, Azra, Sarbaz, Emma, Stina, Isabelle, Jonas Ö, Ruth, Manuel, Li, Jan-Ove, András, Ronja, Alexander, Jona, Marianne A, Karin, Jikuang, Rob, Marco, Jonas, Sonja, Marianne H, Petra, Henrik and Mathias.

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I would also like to thank the language editors who have assisted me during my work; Lotta Thörnqvist for her assistance in language editing of the work in my licentiate and Paper V, and Elisabet Agar for the work on Papers I through Paper IV and this thesis.

If you were not mentioned above, you are certainly not forgotten, it was just temporary block and a mistake on my part.

To my family; thank you so much for your love and support!

To my wife Greta, thank you for your love which has sustained and encouraged me to finalise this Thesis.

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LIST OF APPENDED PAPERS

PAPER I

Holmqvist K, Svensson MY, Davidsson J (2015) *Heavy Goods Vehicle Driver Injuries in US and Swedish Accident Data.* Submitted to Accident Analysis & Prevention.

Division of work between authors: Holmqvist made the outline of the study, conducted the database queries and analyses. The paper was written by Holmqvist, edited and reviewed by all authors.

PAPER II

Holmqvist K, Thorn S, Rundberget P, Törnvall F, Svensson MY (2013) *Heavy vehicle frontal sled crash test analysis - chest deflection response in the Hybrid III dummy.* International Journal of Crashworthiness, 18 (2) pp. 126-138.

Division of work between authors: The additional Hybrid III chest instrumentation for the sled tests was suggested by Holmqvist. The sled tests were designed, and carried out by AB Volvo represented by Thorn, Rundberget and Törnvall. The analysis was carried out by Holmqvist. The paper was written by Holmqvist, edited by Svensson and reviewed by all authors.

PAPER III

Holmqvist K, Svensson MY, Davidsson J, Gutsche A, Tomasch E, Darok M, Ravnik D (2016) *Impacts to the chest of PMHSs – Influence of impact location and load distribution on chest response*. Accident Analysis & Prevention, Volume 87, February 2016, PP 148-160, ISSN 0001-4575. In Press.

Division of work between authors: The setup and analysis was designed and carried out by Holmqvist with the assistance of Svensson and Davidsson. The testing was carried out by Holmqvist in cooperation with Gutsche, Tomasch (Graz University of Technology, Graz, Austria) and Darok (Medical University Graz, Graz, Austria). Testing facilities were provided by Ravnik (University of Ljubljana, Ljubljana, Slovenia). The paper was written by Holmqvist and reviewed by all authors.

PAPER IV

Holmqvist K, Svensson MY, Davidsson J (2015) *Evaluation of chest biofidelity of the Total Human Model for Safety in simulated steering wheel impacts.* Submitted to Accident Analysis & Prevention.

Division of work between authors: Simulations and analysis were carried out by Holmqvist. The paper was written by Holmqvist and was reviewed by all authors.

PAPER V

Holmqvist K, Davidsson J, Mendoza-Vazquez M, Rundberget P, Svensson MY, Thorn S, Törnvall F (2014) *Improving Hybrid III Injury Assessment in Steering Wheel Rim to Chest Impacts Using Responses from Finite Element Hybrid III and Human Body Model.* Traffic injury prevention, 15 (2) pp. 196-205.

Division of work between authors: The pendulum testing for FE Hybrid III validation and the simulation setups were designed by Holmqvist. The testing was carried out at Volvo Cars Safety Centre by Holmqvist and AB Volvo, represented by Rundberget, Thorn and Törnvall. The simulations and analysis were carried out by Holmqvist. The refinement and validation work on the THUMS FE HBM was carried out by Mendoza-Vazquez. The paper was written by Holmqvist and reviewed by all authors.

DEFINITIONS AND ABBREVIATIONS

50^{th} %ile average size male	Male anthropometry with a stature of 175 cm and a weight of 78 kg.
3D	Three dimensions; x, y, and z coordinates.
AIS	Abbreviated Injury Scale, injuries are rated based on threat to life, ranging from 1 (slight injury) to 6 (currently untreatable)
ATD	Anthropomorphic Test Device, e.g., the Hybrid III crash test dummy
Bar	Pendulum with a horizontal bar (diameter 30 mm, width 400 mm), designed to represent the loading of a steering wheel rim.
BL	Bar to the Lower impact height
BH	Bar to the Higher impact height
BM	Bar to the Middle impact height
BM*	Bar to the Middle impact height, lower weight, higher impact speed pendulum.
Chest pot	The standard chest deflection sensor of the Hybrid III ATD.
C, C_{max}	Compression criterion, maximum compression criterion. Calculated as chest deflection divided by chest depth.
CDC, TDC	Collision deformation classification, Truck deformation classification
(Critical) Criteria limit	Same as IARV, used in Paper V.
Delta-v	Change in speed.
FE	Finite Element
G	Gravitational acceleration, 1g=9.81 m/s^2
HBM	Human Body Model
HGV	Heavy Goods Vehicle, gross vehicle weight above 3.5 metric tons.
Higher	Impact height on the chest, 50 mm above (superior) 4^{th} intercostal space on a human and between ribs 3-4 on the Hybrid III ATD.
Hub	Circular pendulum with a diameter of 15.3 mm
HM	Hub to the Middle impact height
Hybrid III	ATD, crash test dummy, various sizes exist. In this thesis the 50^{th} %ile average sized male is considered, if nothing else is written.

HyGe sled	Sled crash testing equipment based on acceleration, compared to the conventional retardation based sled test equipment.
IARV	Injury Assessment Reference Value
Lower	Impact height on the chest, 50 mm below (inferior) 4^{th} intercostal space on a human and between ribs 3-4 on the Hybrid III ATD.
LTCCS	Large Truck Crash Causation Study, study on HGV accidents from the US.
MAIS	Maximum AIS, injury with the highest recorded injury severity rating
Middle	Impact height on the chest, 4^{th} intercostal space on a human and between ribs 3-4 on the Hybrid III ATD.
NCAP	New Car Assessment Programme. Independent vehicle safety consumer rating organisations.
NCCF	Normalised Criteria Conversion Factor, factor for converting a Hybrid III criterion response to the corresponding response in the THUMS.
OR	Odds Ratio
ORM	Objective Rating Method
PMHS	Post Mortem Human Subject
RibEye	Chest deflection sensor system, capable of measuring three dimensional deflections at six locations of the Hybrid III ATD.
RibEye-D	Deflection measurement based on a dynamic impact height location (instantaneous steering wheel impact location).
RibEye-S	Deflection measurement based on a static impact height location as indicated by pressure sensitive film on the anterior thorax of the chest.
SD	Standard deviation
STRADA	Swedish Traffic Accident Data Acquisition, Swedish database from police and hospital reported traffic accidents.
THOR	Test device for Human Occupant Restraint, a more advanced and detailed ATD than the Hybrid III.
THUMS	Total Human Model for Safety, FE HBM model.
VC, VC_{max}	Viscous criterion response, maximum viscous criterion response. Product of instantaneous deflection velocity and compression.

Till Tyra och Hugo

I will always take care of your wounds, even though I will never become that kind of Doctor.

1 INTRODUCTION

The US National Highway Traffic Safety Administration (NHTSA, 2014a) reported 5.6 million vehicle accidents in 2013, where 1.7 million accidents had either injurious or fatal outcome for one or more occupants. Passenger car occupants represented approximately 61% and Heavy Goods Vehicle (HGV) occupants 1% in these accidents. The number of killed and injured occupants in passenger cars was 22,912 and 2.134 million, respectively. The corresponding numbers for HGVs were 697 killed and 25,000 injured (NHTSA, 2014b). The ratio between persons killed and injured was thus approximately 1.1% in passenger cars and 2.8% in HGVs.

In Sweden the total number of killed and injured persons in traffic accidents is low compared to other nations. In 2013, there were 260 occupants killed and 2,716 severely injured (TRAFA, 2014a). In each of these categories, about 2% were accounted for by HGV occupants (TRAFA, 2014b). Here, the ratio between injured and killed occupants were 9.3% for passenger cars and 10.2% for HGVs.

In 1997, the Swedish parliament approved the Vision Zero initiative which stipulates that it is not acceptable that any person should be killed or seriously injured in traffic accidents. Since then, many countries have stated similar goals (OECD, 2008, 2014). In this context, all improvements in road safety are important; occupant groups with a relative low share of fatalities and severe injuries, such as HGV drivers, are not excluded.

One of the most injurious HGV accident scenarios is when an HGV strikes the rear of another heavy vehicle (Figure 1). This type of frontal accident commonly results in the driver of the striking vehicle sustaining injuries to the legs, head and chest. Out of these, the chest injuries account for a large part of the more severe injuries (Zinser and Hafner, 2004; Gwehenberger et al., 2002). To prevent injuries, studies need to be undertaken to evaluate the protective capacity in HGVs. Protective systems can be evaluated using crash tests and appropriate tools for injury prediction. In passenger car frontal crash tests, the tool for injury prediction is most commonly the Hybrid III crash test dummy. The issue with respect to HGV safety evaluation is that the Hybrid III was developed with the passenger car occupant in mind, not a driver of an HGV.

The overall aim of this thesis was to evaluate and improve on the capacity of the Hybrid III ATD in assessing thoracic injury risk in frontal HGV crash tests.

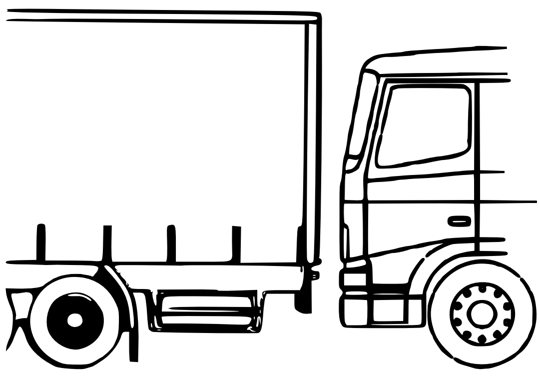

Figure 1. One of the most injurious frontal accident scenarios for HGV drivers, the front-to-rear of another heavy vehicle.

1.1 OCCUPATION WITH HIGH INJURY EXPOSURE

The HGV driver profession is a trade frequently exposed to work related injuries, with a sevenfold risk of dying on the job and more than double the risk of occupational injury or illness compared to the average profession (Saltzman and Belzer, 2007). Consistent findings were reported by The Bureau of Labor Statistics (BLS, 2012), in which the injury and illness incidence rate was reported to be more than double for HGV drivers compared to the average of all occupations. According to the Swedish Work Environment Authority, the risk of occupational injuries (with at least one day off work) among HGV drivers is similar to the US data, where HGV drivers had twice as many reported injuries compared to all occupations (Work Environment Statistics Report 2014:1). Being an HGV driver is a profession where occupational injury or illness causes the highest median number of days off work, with twice as many days off work compared to any other occupation (BLS, 2012). Physical pain and financial hardship are consequences of injuries, which have a high impact on a personal level, but also affect the community.

1.1.1 Work related injuries associated with HGV traffic accidents

Eleven percent of all US HGV injuries and illnesses are associated with roadway incidents (BLS, 2012). In 2012, 5% of work related accidents in Sweden were accounted for by traffic accidents. In 39% of these accidents, the vehicle was an HGV (Work Environment Statistics Short Report 2013:7). Bylund et al. (1997) studied work related injuries related to road trauma. It was found that, in relation to the number of persons employed, the incidence of HGV driver injuries was among the highest. HGV drivers also sustained the highest number of injuries causing impairment and fatalities. A study by Zinser and Hafner (2004) reported that the average period off work for HGV occupants, afflicted with traffic accident injuries, was 260 days. Zaloshnja and Miller (2004) reported that the overall cost per injurious HGV crash was close to three times as high compared to non-injurious crashes. Miller et al. (1999) estimated the cost per passenger mile for occupant victims of combination trucks to be higher than for passenger cars, and it was concluded that one reason may be a lower degree of protection for these occupants compared to passenger car drivers, for example.

1.2 HGV ACCIDENTS AND SEAT BELT USAGE

During 1975-1999 the mileage and number of HGVs on the roads increased and the number of fatal injuries in HGV crashes did not decline much (Lyman and Braver, 2003). The transportation work is likely to continue to increase significantly. Strocko et al. (2014) estimated transportation work on US roads to increase in weight by 40% from 2012 to 2040. Swedish road transports are estimated to increase by 50% (tonne kilometer) from 2014 to 2030 (Trafikverket, 2012). National US accident statistics show that the number of occupant fatalities per traveled kilometer in passenger cars has steadily decreased over the last 20 years, while this trend is not apparent for occupants of HGVs (NHTSA, 2014a) (Figure 2).

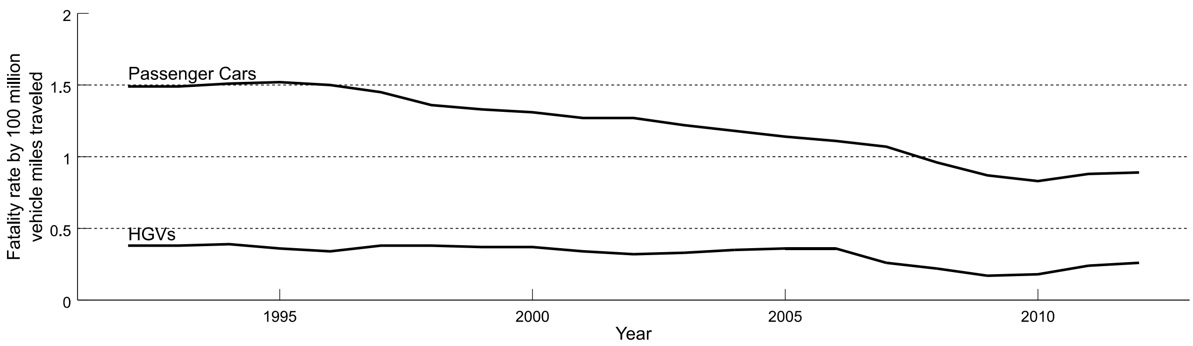

Figure 2. The number of occupants killed annually, per 100 million kilometers traveled, in passenger cars and HGVs in USA from 1992 to 2012 (NHTSA, 2014a).

With regards to HGV accident studies, many studies have focussed on HGV accidents due to the very severe overall accident outcome, i.e., there is a high risk of severe injury for any opponent road user when an HGV is involved (Otte et al., 1989; Chang and Mannering, 1999; Höök and Winstrand, 2002). Moreover, due to the high cost of HGV accidents (Zaloshnja and Miller, 2004), some studies have focussed on HGV accident causation (Höök and Winstrand, 2002; Zhu and Srinivasan, 2011a and 2011b). Several large studies on accident causation have been conducted in the EU project European Truck Accident Causation study (ETAC, European Commission 2008) and in the US project Large Truck Accident Crash Causation Study (LTCCS, FMCSA, 2006).

The results from the ETAC and LTCCS studies were similar, where 85% of the accidents were attributed to human error, and non-adapted speed was given as one of the main causes. Other studies have been conducted to study factors affecting the severity of HGV crashes (Lemp et al., 2011) or HGV driver injuries (Chen and Chen, 2011; Zhu and Srinivasan, 2011a). Lemp et al. (2011) found that an overloaded HGV, use of drugs, and aggressive driver behaviour were factors affecting the crash severity. Chen and Chen (2011) identified that a significant factor in injury severity included drivers who were trapped/extracted and sleeping/fainted. Zhu and Srinivasan (2011a) established driver characteristics such as consumption of alcohol and illegal substances, or driving while fatigued to be important factors. Many of the identified factors suggest that severe accidents and injuries occur at excessive speeds. Despite this, very few studies have reported on crash severity, e.g., impact speed or change in speed (delta-v), in HGV accidents. Gwehenberger et al. (2002) found that 64% of the studied HGV-to-HGV accidents were at closing speed of up to 50 km/h. Simon et al. (2001) reported that the delta-v for HGV-to-HGV accidents was up to 30 km/h in 72% of the cases, and 21-30 km/h being the most common.

When looking into HGV accident scenarios; collisions with other vehicles (with or without subsequent HGV rollover), single vehicle accidents resulting in rollover, or collision with roadside objects, occur most frequently. Rollover occurs in about 24% to 54% of all HGV accidents (Campbell et al., 1991; Simon et al., 2001; Gwehenberger et al., 2002; Zinser and Hafner, 2004). From the vehicle opponent types, the highest risk of severe injury outcome for HGV drivers is in a frontal collision against another heavy vehicle. These accidents are estimated to account for between 12% to more than 70% of all fatally and severely injured HGV occupants (Eggelmann, 1987; Horii, 1987; Sukegawa et al., 1998; 2001; Simon et al., 2001; Gwehenberger et al., 2002; Zinser and Hafner, 2004; Hu and Blower, 2013).

HGV accidents involving vehicle rollover frequently result in a severe injury outcome (Eggelmann, 1987; Campbell et al., 1991; Gwehenberger et al., 2002; Svenson et al., 2003; Hu and Blower, 2013). These may have been caused by a single vehicle accident or as a consequence of a vehicle-to-vehicle accident. A large number (30% to 67%) of HGV occupant fatalities and severe injuries originate from accidents where the HGV has run into the rear of another HGV (Horii, 1987; Bylund et al., 1997; Sukegawa et al., 1998; 2001; Simon et al., 2001; Gwehenberger et al., 2002; Zinser and Hafner, 2004; and Wrige 2007). The most severe injuries for HGV drivers are sustained in frontal accidents, hence there is a large potential to protect HGV occupants in these types of accidents is immense (Bylund et al., 1997; Hu and Blower, 2013).

Historically, seat belt usage among HGV drivers has been very low compared to passenger car drivers. The numbers has steadily increased, but are still far from passenger car usage rates. Simon et al. (2001) reported that the HGV driver seat belt usage rate from French research traffic observations was only 1.5%. Gwehenberger et al. (2002) reports that one third of German lorry drivers who participated in a questionnaire, regularly wear a seat belt. In contrast to the HGV drivers, the European Transport Safety Council reported the seat belt usage of passenger car front seat occupants was above 80% for most European countries, and the seat belt usage in France and Germany was above 90% (Achterberg, 2007). The official seat belt usage for HGV drivers in Sweden has risen substantially over the last decade and was at around 60% in 2013, while the passenger car occupant seat belt usage rate for the same year was 96.7% (Larsson et al. 2014, Figure 3). The corresponding seat belt usage rate for the US HGV occupants was estimated to 71%-85% (FMCSA, 2014) and 88% for passenger car occupants in 2013 (NHTSA, 2015). Berg et al. (2001) reported on seat belt usage in German accidents, where 5% to 18% wore a seat belt, depending on HGV size. A Swedish accident study between 2004 and 2006 found a seat belt usage rate of 11% (Nyman and Bylund, 2005). The French truck driver injury study by Charbotel et al. (2003), reported HGV driver belt usage at 14%.

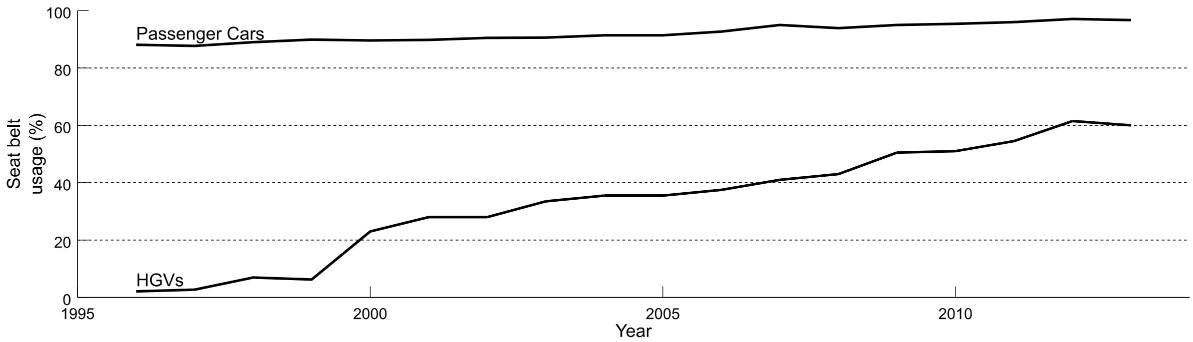

Figure 3. Seat belt usage in Sweden from 1996 to 2013, for passenger cars and HGVs in traffic.

An in-depth study performed by the Swedish Road Administration regarding fatal accidents during 1997 to 2000 involved 27 killed truck drivers, of which only 10 had worn a seat belt. Of the 17 persons not wearing a seat belt, it was estimated that 11 would have survived had they worn a seat belt (Höök and Winstrand 2002). Partly, due to the low HVG driver seat belt usage, Charbotel et al. (2001) showed that the odds of sustaining a more severe injury were higher for HGV drivers than passenger car drivers.

Studies on the efficiency of wearing seat belts in HGV accidents have indicated that the number of fatal and injurious accidents could be reduced by anywhere between 12% to 80% depending on accident configuration and accident severity (Horii, 1987; Campbell et al., 1991; Berg et al., 2001; Simon et al., 2001; Sivak et al,. 2010; Chen and Chen, 2011; Hu and Blower, 2013). Ejections occur in 3% to 34% of the accidents (Campbell et al., 1991; Bylund et al., 1997; Gwehenberger et al., 2002; Hu and Blower, 2013) and are responsible for a large share of the fatal injuries to HGV occupants (Berg et al., 2001). These injuries can be avoided by wearing a seat belt (Hu and Blower, 2013). The seat belts in an HGV perform well with respect to preventing ejection, but less effectively when cab deformations occur (Campbell et al., 1991; Berg et al., 2001). Severe cab deformations may cause the driver to be trapped inside the vehicle and is estimated to occur in 21% to 62% of the accidents (Campbell et al., 1991; Gwehenberger et al., 2002; Zinser and Hafner, 2004). However, the fatality risk is lower for entrapment compared to ejection (Gwehenberger et al., 2002; Berg et al., 2001).

1.3 HGV DRIVER INJURIES

The HGV driver injuries can either be caused by projection, intrusion or ejection. Projection is caused by the movement of the driver into the seat belt or steering wheel, for example, intrusion is caused by cab deformation, where the cab interior parts to move towards the driver. Ejection can be partial or total, which cause the driver to be injured by contacting objects external to the HGV cab. For injured HGV drivers projection is the most common at 61%, followed by intrusion at 25% (Simon et al., 2001). Gwehenberger et al. (2002) found that for about 63% of the severe injuries were sustained while cab intrusion was more than 20 cm and that 34% of the injuries were sustained with an intrusion exceeding 30 cm. For HGV occupants, the most frequently injured body region is the extremities, especially the legs (Bylund et al., 1997; Sukegawa et al., 2001; Charbotel et al., 2003). These injuries may have long term implications (Bylund et al., 1997; Zinser and Hafner, 2004), but are rated low on the Abbreviated Injury Scale (AIS), which means they are rarely life threatening. The more severe injuries are located in the head, thoracic and abdominal regions (Zinser and Hafner, 2004; Gwehenberger et al., 2002) (Figure 4). Bylund et al. (1997) found that MAIS2+ (maximum AIS grade 2 or higher) injuries were more common in occupants of HGVs than in small and medium sized passenger cars. Studies by Gwehenberger et al. (2002) and Sukegawa et al. (1998; 2001) have concluded that thoracic injuries were often caused by contact with the steering wheel of the HGV.

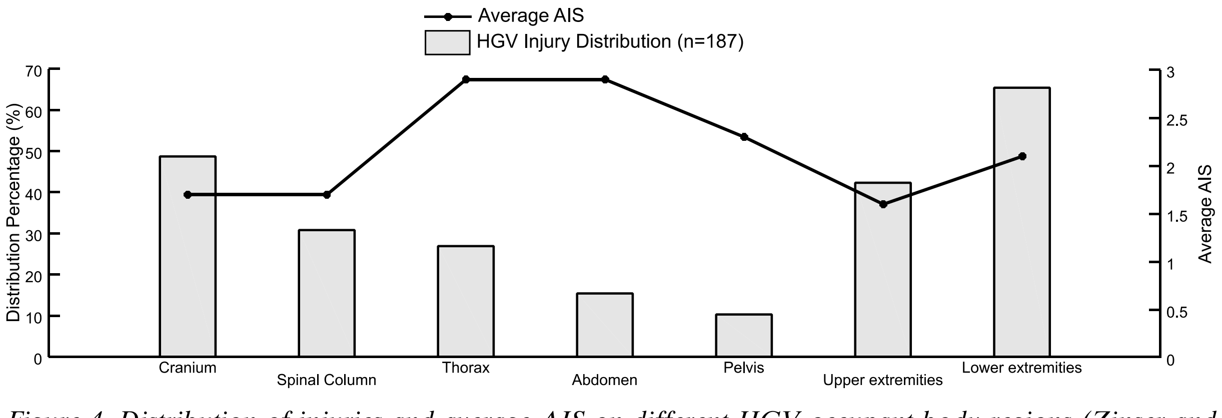

Figure 4. Distribution of injuries and average AIS on different HGV occupant body regions (Zinser and Hafner, 2004).

For belted and unbelted HGV drivers, highly rated AIS injuries or fatal injuries were commonly located in the thoracic region (Sukegawa et al., 2001; Zinser and Hafner, 2004). Therefore, this thesis is focussed on thoracic injuries.

1.4 INJURY CRITERIA AND BIOMECHANICAL RESPONSE OF FRONTAL CHEST IMPACT

Occupant chest injuries in automotive accidents are most commonly arising from blunt loading; resulting in compression, viscous, or inertial loading to the occupant (Nahum and Melvin, 2002). The compression injuries are characterised by a slow deformation rate, commonly associated with skeletal injuries such as rib or sternal fractures. The viscous injuries are characterised by a rapid deformation rate where inertial loading may also be present. Viscous loading is most commonly the cause of injuries to soft tissue such as internal organs. Purely inertial loading may occur with low chest deformation from accelerations to the body, where internal organs are affected by relative movement to the chest wall. Thoracic injuries may also arise from any combination of these loading types. For HGV accidents, where the opponent is another heavy vehicle or stationary object, the crash acceleration pulse can be severe. Combining a range of crash pulse severities with the most common injury causation mechanism in HGVs (Section 1.3); projection and intrusion, the mechanism of thoracic HGV driver injuries can be any combination of the blunt loading types. Therefore, both the amount of chest deflection and the rate of deflection must be taken into account when analysing HGV crash tests. Means of analysing these responses have been developed by application of injury criteria.

1.4.1 Injury criteria

An injury criterion is based on physical measurements, such as spinal acceleration, contact force, chest deflection, etc., obtained in simulated crash tests. The injury criteria can be used to differentiate non-injurious and injurious loading at a given severity. Several injury criteria have then been correlated to probability of injury risk.

The use of criteria such as spinal acceleration is stipulated in the US Federal Motor Vehicle Safety Standards and Regulations (FMVSS 208), and while it is not distinct enough to differentiate between the injuries to the chest, it is considered a measurement of inertial loading for whole body injury severity estimation (Horsch et al., 1991; Kent 2002). Discrepancies and lack of critical values for other criteria have resulted in a limited use of these criteria.

More recent efforts to increase accuracy in estimating chest injury from mechanical ATD measures have been made. This was done to enable differentiation between the contributions from different restraint systems, since injury risk in a human has been shown to be restraint dependent. For the Hybrid III, these issues are further addressed in section 1.6.1.

The equivalent deflection criterion (Deq) was suggested for use with the Hybrid III by Petitjean et al. (2003) to reduce difficulties in differentiating between airbag and seat belt restraint systems in the Hybrid III chest. The method of calculating Deq utilise combinations of the shoulder belt force and mid-sternal deflection to estimate the deflection contribution from the localised seat belt loading to the total chest deflection. The Deq formulation was updated and its predictability enhanced by Trosseille et al. (2013), and age compensated injury risk curves were provided. These risk curves indicated that injury risk could be more accurately determined by the Deq, when evaluating a combination of seat belt and airbag with the Hybrid III.

Song et al. (2011), developed the combined deflection criterion (Dc), to account for asymmetrical chest loading. The Dc takes into account the mid-chest sternal deflection and the difference in right and left chest deflections at the level of the first lumbar vertebra (L1). Similar to the Deq, this criterion was developed to account for the seat belt load, causing the chest to deform in an asymmetrical mode, as well as the distributed load from an airbag.

The Dc criterion was further developed and tuned to predict rib fracture risk in an updated THOR ATD (THORAX demonstrator). The new criterion was referred to as the differential deflection criterion (DcTHOR, Davidsson et al., 2014) and takes data from both the upper and lower pairs (left and right) sensors into account in a similar fashion as Dc.

These recent injury criteria were developed to take into account combinations of forces from seat belt and airbag restraints. For HGVs, this combination of restraints is still not common. The two most commonly used injury criteria for chest injury evaluation in vehicle testing with the Hybrid III ATD are the Compression and Viscous criteria, with the compression criterion also stipulated in FMVSS 208, and both criteria are included for evaluation of passenger cars in the Euro NCAP frontal crash tests (Euro NCAP, 2015).

The maximum compression (C_{max}) is the most commonly used criterion to assess injury risk based on hard tissue injuries, e.g. rib fractures (Kroell et al., 1971; 1974). The maximum compression criterion, as measured in the Hybrid III, has been shown to correlate well with injury risk (Kent et al., 2001a). The compression criterion is defined as the ratio of chest deflection (D(t)) to initial chest depth (D) (Equation 1, Figure 5). The initial chest depth for a Hybrid III 50th %ile male is set to 229 mm. The compression criterion was originally developed with the unrestrained occupant of the 1960s and 1970s in mind, by Kroell et al. (1971; 1974) using the hub shaped impactor, designed to represent the centre hub of a steering wheel. The criterion has since then also been evaluated for, and correlated to, risk of seat belt induced injuries (Horsch et al., 1991; Mertz et al., 1991; Kent et al., 2001a; Kent et al., 2003e).

$$Compression\ Criterion\ (C) = \frac{D(t)}{D} \qquad \text{(Equation 1)}$$

Lau and Viano (1986) and Viano and Lau (1988) found the soft tissues to be loading rate sensitive and developed the viscous criterion (VC). It was found that the maximum product of instantaneous velocity and compression (VC_{max}) correlated well with soft tissue injuries like liver laceration. The VC_{max} is defined as the maximum product of compression and deflection velocity (Equation 2 and Figure 5). For the Hybrid III, a scaling factor is included to account for the internal measures of the chest sensor (Lau and Viano 1986). This factor is 1.3 for the Hybrid III 50th %ile male.

$$Viscous\ Criterion\ (VC) = Scaling\ Factor * \frac{D(t)}{D} * \frac{dD(t)}{dt} \qquad \text{(Equation 2)}$$

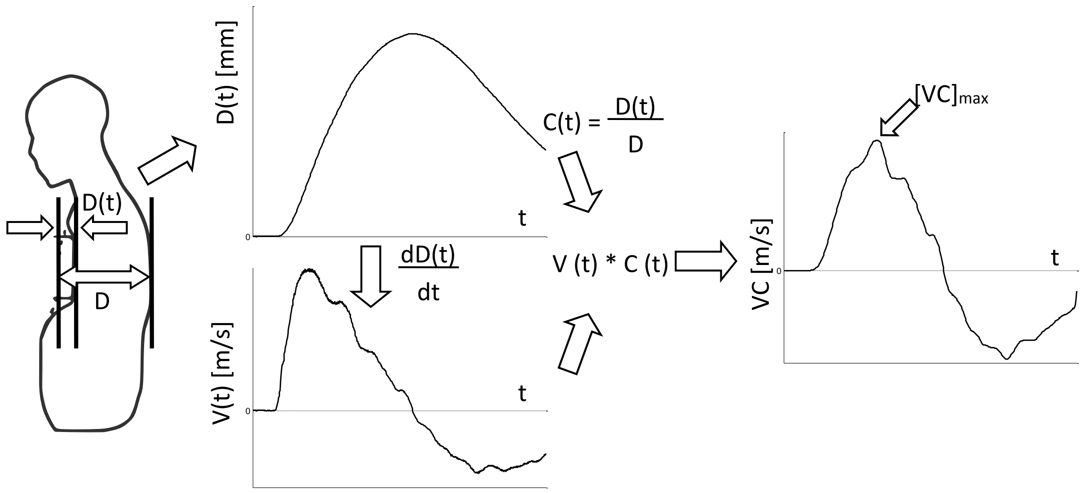

Figure 5. Illustration of the input parameters for the compression (C(t)) and viscous criteria (VC), along with a schematic illustration of how the maximum viscous criteria (VC_{max}) is calculated.

1.5 HGV CRASH TESTING

Real-world accident data analyses have been conducted to find a representative load condition suitable for HGV occupant safety evaluation. Accidents where an HGV strike the rear of another HGV or trailer are reported as a major contributor to HGV occupant fatalities and injuries in Japan, Germany and Western Europe (EU25) (Sukegawa et al., 1998; Gwehenberger et al., 2002; Wrige 2007). The accident data from Japan were sampled during 1995, the German data were sampled from 1992 to 2000 and the Western Europe data were based on the Community Road Accident Database (CARE) and national statistics prior to 2004. In relation to passenger car crash testing, very little information on, or results from, HGV crash tests can be found in the literature.

Volvo has utilised a rigid barrier test at 30 km/h since 1977 (Figure 6, http://www.volvotrucks.com). A similar crash test has been suggested by e.g. Horii (1987) and Sukegawa et al. (1998) where an HGV would impact a flat rigid surface at 32 or 40 km/h. Berg et al. (2001) reports on the results from a frontal crash test of an HGV impacting a simulated rear end of a trailer at 30 km/h. With respect to occupant injury evaluation in HGV crash tests, few studies have been published. Kubiak (1997) conducted frontal HyGe sled tests using a Hybrid III ATD in an HGV cab environment to evaluate the protective effects of wearing a seat belt, with or without an airbag present, on injury criteria. From the selected set of injury criteria, it was found that the combination seat belt and airbag provided the highest degree of overall protection.

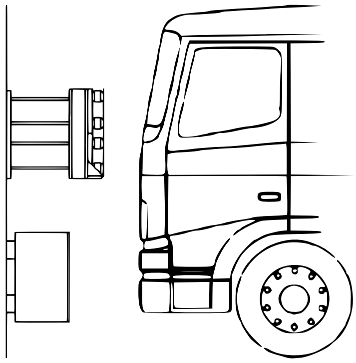

Figure 6. Schematic view of a rigid barrier front-to-rear end crash test.

One of the incentives to study HGV testing, with focus on occupant safety evaluation, is the pronounced differences in the interior driver compartment geometries of HGVs and passenger cars. Examples of geometrical differences, believed to have an effect on the injury outcome of an accident, are the position and orientation of the steering wheel and the seat (Sukegawa et al., 2001), which affects the seated posture of the driver, as illustrated in Figure 7.

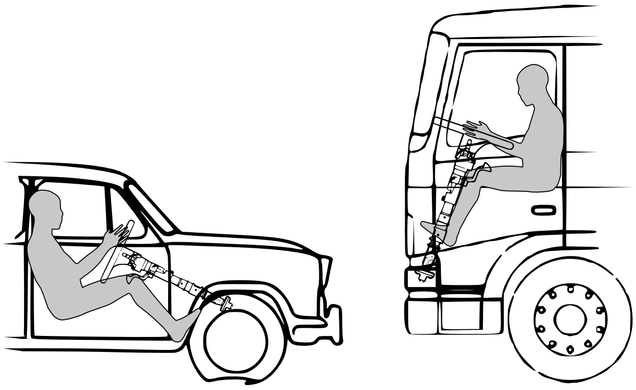

*Figure 7. Illustration of driver compartment geometries for passenger cars (**left**) and HGV (**right**). Differences in position of the seat and steering wheel are believed to have an effect on injury outcome.*

The epidemiological studies concluded that frontal accidents were a major contributor to HGV driver injuries, and that the chest was at high risk of severe injuries. These injuries are believed to originate from steering wheel contacts. The contact may occur as the driver is moving forward, and the contact is possibly intensified by deformation to the cab, forcing the steering wheel to move towards the driver. To study and increase safety and consequently prevent these injuries, a tool for injury evaluation is needed. The most common tool for occupant safety evaluation is the ATD.

1.5.1 ATDs for frontal crash test

Currently, the most frequently used tool for injury prediction in frontal automotive crash testing is the Hybrid III ATD (Figure 8, Foster et al., 1977). The Hybrid III was originally developed for passenger car occupant injury prediction. The chest of the Hybrid III was developed and validated using a circular pendulum that impacted the centre of the chest, designed to mimic the load from a steering wheel hub (Kroell et al., 1971; 1974; Neathery 1974). Chest injury risk curves for belted occupants have been developed using the Hybrid III by replicating real-world passenger car accidents and analysing Hybrid III chest deflection sensor measurements (Mertz et al., 1991).

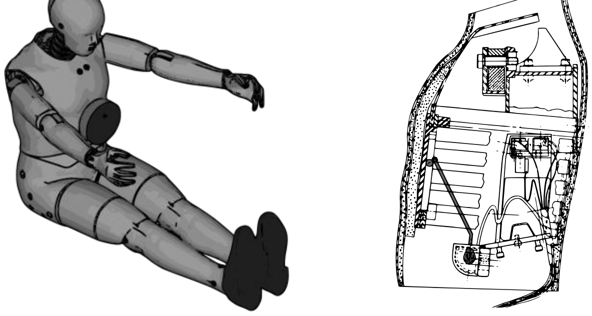

*Figure 8. To the **left**; the Hybrid III ATD in chest calibration posture. Distribution of the circular pendulum is indicated in figure (Left). Figure to the **right** shows a midsagittal section of the Hybrid III torso, anterior side of the torso facing left. In the figure, sections of the ribs are visible, as well as the chest deflection sensor with the transducer arm coupled to the sternal plate.*

This ATD is standardised for use in passenger car regulatory testing with proven repeatability and reproducibility (Foster et al., 1977); moreover, it is widely available and well known in crash test laboratories. The chest of the Hybrid III is constructed from six ribs attached to the rigid thoracic spine on the posterior side, and on the anterior side the ribs are joined by a polyurethane bib to a stiff plastic sternal plate with an aluminum bracket. The standard chest deflection sensor consists of a rotary potentiometer with a transducer arm with a ball point. The ball is sliding in a groove in the plastic sternal plate. As the sternum is deformed posteriorly towards the spine the transducer arm is rotated and the angle from the potentiometer is recalculated into sternal chest deflection (Figure 8).

A more recent ATD, the Test device for Human Occupant Restraint (THOR), has shown to be more humanlike than the Hybrid III in many aspects (Nusholtz et al., 1997; Rudd et al., 2000; Shaw et al., 2002; Vezin et al., 2002; Shaw et al., 2004; Sunnevång et al., 2014), but is also more complex and sensitive (Xu et al., 2000a, 2000b; Petitjean et al., 2002). The THOR ATD will be a worthy successor to the Hybrid III in the near future, although the availability of this ATD is currently limited and heavy vehicle safety researchers have little or no experience of using it. With these points in mind, only the Hybrid III ATD will be considered for the remainder of this thesis.

HGV tests with the Hybrid III ATD have been conducted in Japan, which confirmed chest contact with the steering wheel, and is believed to be a load case peculiar to HGV accidents (Sukegawa et al., 1998). In an effort to understand steering wheel loading to the chest, strain gauges were mounted on the ribs of the Hybrid III (Sukegawa et al., 2001). The strain gauges were mounted bilaterally on the 1^{st}, 3^{rd} and 6^{th} rib to measure the deflections of the chest at multiple points. These measurements were compared to the internal chest deflection sensor of the Hybrid III. A horizontal rigid bar impactor was used to simulate chest to steering wheel rim impact at different heights. The results showed that the strain gauges provided a different response compared to the internal chest sensor of the Hybrid III.

Other studies have employed impact testing using a steering wheel, however, no one has replicated the loading pattern specific to HGV frontal impacts, where the chest is affected.

1.6 ATD BIOMECHANICAL EVALUATION

ATDs or combinations of ATDs and other human surrogates, such as PMHSs, have been utilised to assess frontal impacts with steering wheel-to-chest interaction (Morgan et al., 1987; Begeman et al., 1990; Shaw et al., 2004) (Figure 9). These setups were designed to reproduce the situation in a passenger car and as a result, the loading of the steering wheel rim was to the abdominal area and, where applicable, the chest was loaded by the steering wheel centre hub. The results showed that the capacity to detect and evaluate injuries in the abdominal area of the Hybrid III were poor. The THOR performance was better due to a more human-like construction of the torso (Shaw et al., 2004).

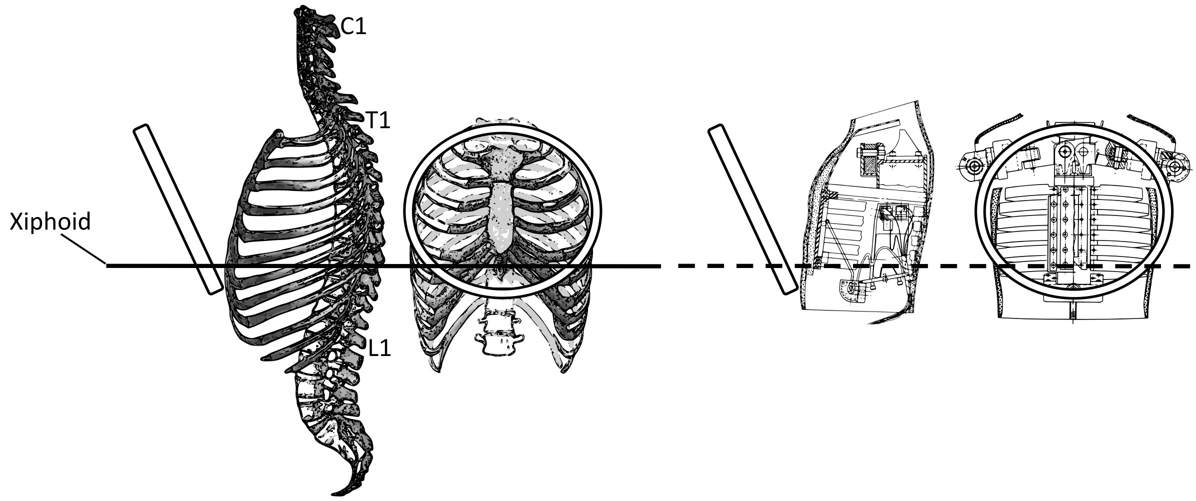

Figure 9. Schematic examples of location and orientation of impact by the steering wheel rim. Location of the xiphoid process is indicated in the figure. Images of human ribs and spine adapted from Gray (1918).

In addition to steering wheel loading, many other loading conditions have been employed. Kent et al. (2001a) analysed sled tests where the chests of PMHSs and the Hybrid III were loaded using seat belt and/or airbag restraint systems. The normalised deflection (Compression criterion) of the Hybrid III chest proved to correlate best with PMHS chest injuries.

In 2002, Kent et al. studied the viscoelastic properties of the Hybrid III chest in a number of loading conditions using a diagonal belt load, hub load, and distributed load (Figure 10). The same tests were subsequently repeated using PMHSs (Kent et al., 2004). The tests were elaborated to different test specifications to test the influence of soft tissue on the chest (Kent et al., 2008a). It was concluded that the Neathery (1974) corridors developed in the chest loading setup of Kroell et al. (1971; 1974), are necessary but not adequate requirements for ATDs, or computational models, which are designed for this kind of restraint evaluation. It was suggested that a similar methodology of testing using different loading conditions would provide a more robust assessment of biofidelity, to assure compatibility with different restraint conditions.

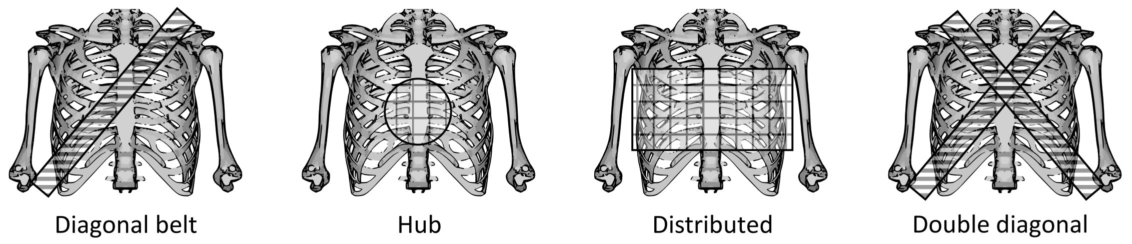

Figure 10. Schematic view of the loading distributions used by Kent et al. 2002 and 2008a.

The torso of the Hybrid III ATD has been shown to be sensitive to differences in loading device, such as different seat belt routing, seat belts with and without load limiting systems, airbags, steering wheel or any combinations of these. The sensitivity is closely linked to the function of the standard chest deflection sensor, and the design of the Hybrid III torso (Matsuoka et al., 1989; Horsch et al., 1991; Vezin et al., 2002; Kent et al., 2003a; 2003b; 2003c).

In efforts to resolve these issues, a number of studies have suggested improvements to the Hybrid III torso. These have included changes to the design of the ATD, i.e., adding retrofit parts, such as additional ribs (Matsuoka et al., 1989), but more commonly they involve new sensors. Rouhana et al. (1990; 2001), Ishiyama et al. (1994) and Rath et al. (2005) investigated the possibility of fitting an abdominal part with sensors for abdominal injury prediction to the Hybrid III. For the thorax, so called chest bands which register the transverse sectioned profile of the human thorax under loading, has been used extensively (Cesari and Bouquet 1994). These have also been complemented by external string potentiometers at various locations while comparing the chest properties of the Hybrid III to PMHSs in stationary tests (Cesari and Bouquet 1994). Internal string potentiometers to register the chest deflection have also been extensively utilised (Nusholtz et al., 1997; Shaw et al., 1999; Butcher et al., 2001; Kent et al., 2003d; Shaw et al., 2005). Shaw et al. (1999) used contact sensitive Fuji Film to register the impact location on the Hybrid III thorax. A few sensor systems are commercially available for purchase with, or as retrofit parts of, the Hybrid III. Rouhana et al. (2002) and Petitjean et al. (2002) evaluated a system called IR-TRACC and Yoganandan et al. (2009) have evaluated the performance of RibEye™ by Boxboro Systems, LLC (Boxborough, MA, USA), both are examples of multi-location and multi-dimension chest deflection measurement systems. In the absence of a standardised abdominal measurement system due to limitations in the current Hybrid III ATD, the focus of this thesis was narrowed down to thoracic injuries.

1.6.1 Sensitivity of the Hybrid III chest with respect to loading

The Hybrid III is sensitive to shoulder belt routing (Matsouka et al., 1989) as the position of the belt may cause it to either slide on the lateral side of the chest or get caught on the bottom rib. The resulting seat belt positions affect the chest, and chest deflection characteristics.

Deflection in the Hybrid III and the human chest is affected when considering a setup with the circular pendulum in contrast to e.g. a shoulder seat belt setup. The maximum tolerable load of a human is higher for the seat belt setup, when the load is shared between the chest and the shoulder (Horsch et al. 1991). The chest compression in seat belt setups may still be an objective measure if a relationship of the compression to injury is appropriately determined. This relationship was determined by Mertz et al. (1991) for belted passenger car occupants by replicating accidents for which the injury outcome was known, using the Hybrid III. For the hub type tests 30% to 40% chest compression corresponds to an AIS2 to AIS4 injury severity (Kroell et al., 1974). In the belted occupants, a 21% chest compression, as measured by a Hybrid III dummy, corresponded to an AIS3+ injury (Mertz et al., 1991).

The Hybrid III has been shown to be sensitive to both rate of deflection and loading distribution (Kent et al., 2002). Kent et al. (2003e) showed that for hub, seat belt, air bag or combined seat belt and air bag, the C_{max} measured on PMHSs will adequately predict the injury risk. The C_{max} measured by the Hybrid III using different restraint conditions, does not directly relate to injury risk (Kent et al., 2003b). This necessitates different criteria tolerance levels for different restraints/loading conditions. This is demonstrated in Figure 11, where risk curves of studies with the Hybrid III and PMHSs are plotted. Even though the risk curves for the Hybrid III and the PMHSs are plotted with respect to slightly different injury probability (AIS3+ for the Hybrid III, and more than 6 rib fractures for the PMHS), the spread of the curves indicate that the criterion response of the Hybrid III is very much dependent on the restraint system.

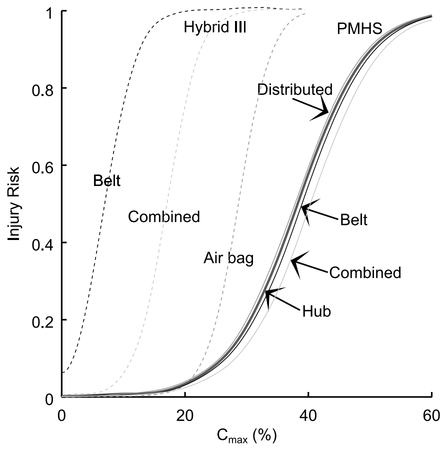

Figure 11. Risk curves demonstrating sensitivity of the Hybrid III and PMHS chest to different restraints/loading devices with respect to the C_{max} criterion. The Hybrid III are represented by dashed curves, and show the probability of an AIS 3+ injury with respect to different loading (Kent et al., 2003b). The PMHS curves are represented by solid curves, and show the probability of more than 6 rib fractures (Kent et al., 2003e).

1.7 NUMERICAL MODELS OF THE HUMAN

Numerical modelling has brought great possibilities to the field of vehicle safety development and assessment. Detailed FE models of mechanical ATDs, such as the Hybrid III, exist and can be used in a virtual development environment of vehicle safety systems. In addition to mechanical ATD models, FE HBMs have been developed. These are numerical representations of the human body, which have a more accurate representation of the human body structures than mechanical ATDs, for example, do. In principle it is possible to include any structure, soft or hard tissues, in FE models. In these models, material data from biological testing such as rib bending tests (Kimpara et al. 2003; Charpail et al. 2005; Li et al., 2010; Kindig et al., 2011) or coupon testing (Kemper et al., 2005; Subit et al., 2011), has been utilised. The FE HBMs allow for the study of specific load cases where injury evaluation is possible, not only by means of injury criteria, but also at element level where strain and stress can be studied. This allow for more detailed evaluation of safety system performances, and can complement both physical and numerical testing using mechanical ATDs.

A few full body HBMs exist, e.g. HUMOS2 (Robin, 2001), GHBMC (Park et al., 2013) and THUMS (Iwamoto et al., 2002). The THUMS is a commercially available model for corporate and academic research purposes.

1.7.1 THUMS

Iwamoto et al. (2002; 2003) reports that the seated, 50^{th} %ile male occupant FE model THUMS (Figure 12) was generated using the anthropometric specifications by Robbins et al. (1983), and has a final stature of 175 cm and a mass of 77 kg. This version of the model comprise 60 000 nodes and 83 500 elements.

Figure 12. The THUMS HBM. Soft tissue has been removed from the left side of the body for illustration purposes. The version illustrated here is the THUMS v3.0 with refined thorax (Pipkorn and Mroz, 2008; Mroz et al., 2010 and Mendoza-Vazquez, 2012).

The chest of this THUMS version was validated for frontal and lateral hub-type impacts (Furusu et al., 2001; Iwamoto et al., 2002; Oshita et al., 2002). Frontal steering wheel tests performed in accordance to the tests by Nusholtz et al. (1988) was also reported by Oshita et al. (2002). The global response of the THUMS was considered good or adequate for these loading conditions.

The THUMS v3.0 model has been further developed and comprise about 150 000 elements and 110 000 nodes. This model was adjusted to further improve on the numerical stability and match to biomechanical data by means of rib cage mesh refinement and material property adjustments (Pipkorn and Mroz, 2008; Mroz et al., 2010 and Mendoza-Vazquez, 2012). Extensive validation has been conducted (Mendoza-Vazquez, 2012) against the PMHS sled tests of Shaw et al. (2009) and the PMHS table top tests by Kent et al. (2004, 2008a). The refined model showed significant improvements in biofidelity, and the responses were predominantly within the PMHS response corridors (Mendoza-Vazquez et al., 2013). Even though the model comprise a large number of elements, the internal organs of the model are lumped together, which allow for a more computer resource efficient design, without affecting global chest response. This model was utilised in the studies within this thesis. With respect to the global chest response validity, the refined THUMS FE HBM is considered state-of-the-art.

1.8 CHEST BIOMECHANICS VALIDATION DATA

In addition to the above mentioned PMHS tests paired with the Hybrid III (section 1.6), many other biomechanical studies using PMHSs, other biological models, such as swine, and volunteers have been conducted. These were performed to study the human chest response to external loading both in dynamic and quasi-static testing environments. The most common setups to test dynamic responses of the thorax have been sled tests (e.g. Salzar et al., 2013; Shaw et al., 2009; Kent et al., 2001b; Kallieris et al., 1998 etc.), table top tests (e.g. Lessley et al., 2010; Salzar et al., 2009; Kent et al., 2003d; Cesari and Bouquet, 1990 etc.), pendulum or impactor tests, conducted with and without spine fixation (e.g. Lebarbé and Petit, 2012; Vezin and Berthet, 2009; Yoganandan et al., 1997; Kroell et al., 1971 etc.). Setups to quasi-statically test responses can be table top tests (e.g. Arbogast et al., 2006; Cavanaugh et al., 1988 etc.) or fixed spine tests (e.g. Kindig et al., 2010 etc.). Moreover, the human chest response has not only been characterised in pure frontal loading, but also in lateral and oblique tests (e.g. Trosseille et al., 2008; Yoganandan et al., 2008; Maltese et al., 2002; Yoganandan et al., 1997 etc.).

Despite this extensive characterisation of the biomechanics of the human chest, none is representative of the load case thought to be peculiar to the HGV driver; the steering wheel rim-to-chest.

1.8.1 Factors contributing to chest injuries

Studies have also been conducted to study the effects of parameters such as age (Zhou et al., 1996; Agnew et al., 2013; 2014; Johannesen and Müller, 2013), sex (Kimpara et al., 2003) and muscle activation (Kemper et al., 2011) on injury tolerance and chest response. The elderly have been shown to be at a significantly higher risk of sustaining rib fractures at similar C_{max} as younger subjects (Kent et al., 2003e; 2008b). Kimpara et al. (2003) found that the female chest is less stiff compared to the male chest. Kemper et al. (2011) showed that bracing during low velocity impacts has the potential to decrease chest compression significantly. Anthropometric variables such as Body Mass Index (BMI) have also been studied to find correlation to injury risk (Poulard et al., 2013; Carter et al., 2014). However, the effect of BMI on thoracic injury is yet unclear and has been stated to be of less importance than e.g. age (Carter et al., 2014). Many studies include full PMHS tests as well as component and tissue testing where detailed analyses have been conducted (Nahum and Melvin, 2002). The results from the tissue tests have been used to develop material models suitable for numerical modelling.

1.9 HGV SAFETY REQUIREMENT ENFORCEMENTS

There are currently no legislated or consumer information HGV crash tests in which the occupant injury risk is evaluated. Existing requirements for HGVs are structural demands for cab integrity and occupant survival space, tested by means of quasi-static loading to assure sufficient cab strength and residual space to prevent the driver being trapped or injured from cab deformation (ECE R29; VVFS1994:22). Safety system requirements such as seat belts (FMVSS 571:208) and underrun protection providing safety for other road users are in place (ECE-93; ECE-58; ECE-73). Seat belt use for HGV occupants was legislated in 1999 in Sweden and in the European countries through the EEC Directive 2003/20/EC amending 91/671/EEC in 2003. The US federal regulation 49 code §392.16, from 1970 amended in 1995, stipulate that seat belts fitted in commercial vehicles must be worn while driving.

HGV cab strength, restraint systems and steering control systems recommendations have been issued by the Society of Automotive Engineers (SAE), in which certain dynamic and quasi-static testing are described (SAE J2418 through J2426). These SAE recommendations also incorporate injury response analysis using an ATD, where response evaluation and limits have been adopted from passenger car crash testing. The purpose of SAE recommendations are to establish standardised testing procedures for crash testing. HGV manufacturers may also have internal requirements related to ATD response in crash tests.

2 AIMS

The overall aim of this thesis was to evaluate and improve on the capacity of the Hybrid III ATD in assessing thoracic injury risk in frontal HGV crash tests. This was accomplished by conducting a set of studies, summarised in the bullet points below:

- Study of real world accident data to verify that the HGV frontal impact scenario is relevant, and establish a priority on injury prevention
- Analyse the chest load conditions and the suitability of the Hybrid III ATD in frontal HGV crash tests
- Evaluate Hybrid III chest deflection sensor systems, and make recommendations
- Generate biological evaluation data for the steering wheel rim-to-chest load case
- Improve on the chest injury risk assessment of the Hybrid III ATD in HGV frontal crash testing

3 SUMMARY OF PAPERS

3.1 SUMMARY PAPER I

The primary objective of this study was to characterise accident types and driver injuries to establish some fundamental requirements for Anthropomorphic Test Devices (ATDs) for use in Heavy Goods Vehicle (HGV) crash testing. A secondary aim was to compare real-world accident data to a specific HGV crash test configuration, the front-to-rear so called trailer back test. Two databases containing both HGV accident and driver injury data were identified.

The Large Truck Crash Causation Study (LTCCS) database contains HGV accident data samples from the USA with weighting factors to represent national accident statistics, and the Swedish Traffic Accident Data Acquisition (STRADA) database contains Swedish traffic accidents. Selection criteria based on occupant type and vehicle body type, drivers and HGVs, were used to extract data for analysis. These samples were studied with respect to injuries sustained by HGV drivers. The severity, body region, and structure type defined by the second digit in the abbreviated injury scale (AIS, Table 1) was used to characterise these injuries. Accident type, accident frequency, and injury distribution were identified and odds ratio was calculated to assess association between; injury severity and body regions, and effect of belt use on injury severity.

Table 1. Structure type and short descriptions as defined by the AIS code.

Second digit of the AIS code	**Injured structure**	**Short description of structures of the Thoracic region**
1	Whole Area	External, i.e. skin, injuries without internal injuries or massive thoracic injuries
2	Vessels	Injuries to arteries and veins of the thorax
3	Nerves	Injuries to the vagus nerve
4	Organs (incl. Muscles/Ligaments)	Injury to organ and tissue contained within the skeletal thorax.
5	Skeletal (incl. Joints)	Rib cage, sternal and chest wall injuries, including costal cartilage injuries.
6	Loss of Consciousness (Head only)	Not applicable for thoracic injuries.

The database queries resulted in 62 200 injured drivers in the weighted representation of USA accidents and 1 328 injured drivers involved in Swedish accidents. The crash direction, identified in the US database, was mainly frontal or non-horizontal (typically rollover), and both databases showed that up to 54% of the frontal vehicle-to-vehicle cases involved at least one other HGV.

All body regions were afflicted with injuries, but as the injury severity grade increased, the frequency of thoracic injuries was the highest (Figure 13). The serious thoracic injuries were mostly confined to organ- and/or the skeletal structures, as defined by the AIS code. Injuries to drivers not wearing the seat belt were significantly associated with a higher severity, compared to drivers who wore the seat belt.

HGV drivers were most commonly male with an average stature close to an average sized male, however the weight of the driver was high, being closer to that of a 95th %ile male.

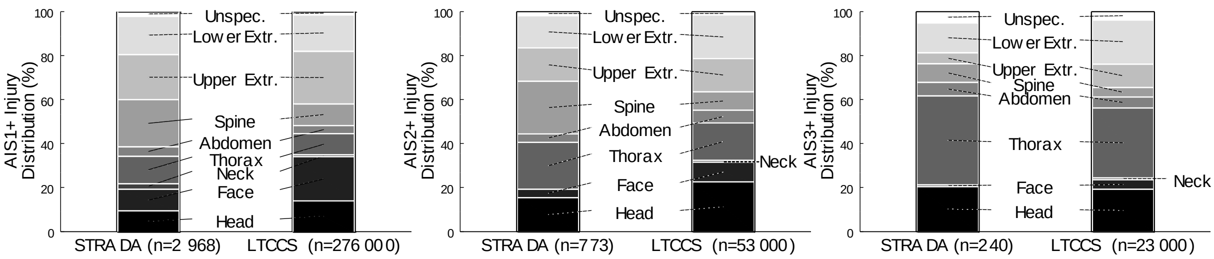

Figure 13. Distribution of injuries of AIS1+ (Left), AIS2+ (Middle) and AIS3+ (Right) on the 9 body regions from all accidents, as defined by the AIS.

This study concludes that one of the most common HGV injury sustaining accident configurations were frontal collisions, second only to non-horizontal loading direction. The findings were in accordance with earlier published results, and suggest that a frontal impact test, as proposed by Horii (1987), Sukegawa et al. (1998) and Berg et al. (2001), is important for HGV occupant safety evaluation. It is difficult to draw a conclusion for non-horizontal crashes due to the lack of data to determine an appropriate test condition for this type of crash test. The thorax was the body region with the strongest association to high severity grade injuries, compared to any other body region. The most severe injury of the thorax for an HGV driver was commonly to the skeletal or organ body structure type. It is common for these injuries to be of similar severity in both structures, i.e., a concomitant with severe injury to the skeletal structure is a similarly severe injury to the organ structure, or vice versa. It can be concluded that a frontal HGV crash test would require chest injury risk assessment. This would typically be achieved by including an appropriately instrumented ATD and suitable injury assessment reference values (IARVs).

3.2 SUMMARY PAPER II

The Paper I results confirmed that the frontal accident scenario was an important configuration to study. In this Paper, the aim was to study the performance of the Hybrid III dummy chest based on responses with respect to the load conditions in heavy goods vehicle (HGV) frontal crashes, while using the standard and extended instrumentation for the Hybrid III chest. This was conducted by means of analysing HGV sled crash tests. The results were also compared to the reference load case from which the Hybrid III chest was developed, the perpendicular impact of a 23.4kg, circular pendulum to the chest.

In total, eight HGV front-to-trailer back type sled tests were performed. The impact velocity was set to 30 km/h with an average peak acceleration of 289 m/s^2. The sled was equipped with a truck cab with the relevant components and an intrusion device for reproducing cab deformation. The driver position was occupied by a Hybrid III ATD, restrained by different combinations of restraint and safety systems. The safety systems used were seat belt, with and without pre-tensioner, and steering wheel mounted airbag. The Hybrid III was fitted with two chest deformation measurement systems; the standard potentiometer sensor and the RibEye® system which record chest deflections in three dimensions at six locations of the chest (Figure 14). The steering wheel rim contact location on the chest was established by using the impression on a pressure sensitive Fuji Film (Figure 14), as well as video data. The two methods of acquiring steering wheel rim chest contact location, allowed for two approaches of calculating chest deflection using the RibEye system, first from the static location of the pressure film and secondly from the dynamic location from the video and sensor data. These were referred to as RibEye-S (Static) and RibEye-D (Dynamic) and these were calculated in addition to the mid-sternal deflection measurement of the standard chest sensor.

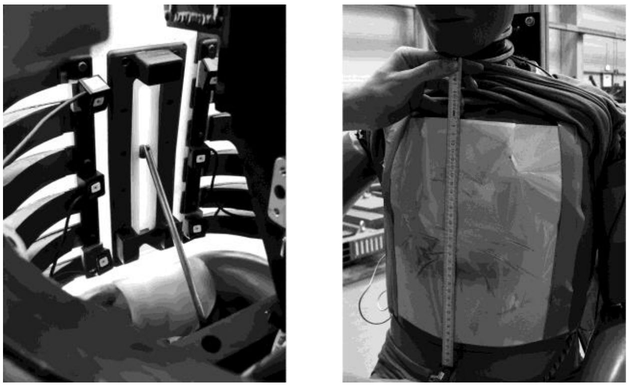

*Figure 14. The **left** picture shows the RibEye sternal instrumentation as seen mounted in the Hybrid III chest. The RibEye system consists of six LEDs, which are optically sampled in three dimensions relative to the thoracic spine. The RibEye method of measuring allow for the standard chest sensor to be used simultaneously. The **right** picture shows the pressure sensitive film, which was attached to the anterior chest of the Hybrid III.*

The results show that steering wheel rim-to-chest contact occurred in all tests, regardless of which combination of safety systems were used, and that the contact was the major contributor to chest deflection. The standard chest deflection sensor and the two additional methods of acquiring chest deflection show different chest responses (Figure 15), due to that the location of impact rarely coincided with the standard sensor single point of measurement. The use of the RibEye-D method also allowed for classification of failed chest deflection measurement, e.g., when the steering wheel impact location was cranial to the Hybrid III rib cage, where no injury assessment instrumentation is available.

When compared to the reference Hybrid III dummy test, i.e., the 153 mm circular pendulum impacting perpendicularly to the middle of the chest at a velocity of 3 m/s to 6.7 m/s, the results in the load case identified in this study were different. The results indicated a narrower load distribution contacting the chest at an angle at varying locations. Moreover, the loading occurred at higher initial impact velocities and at angled impact directions.

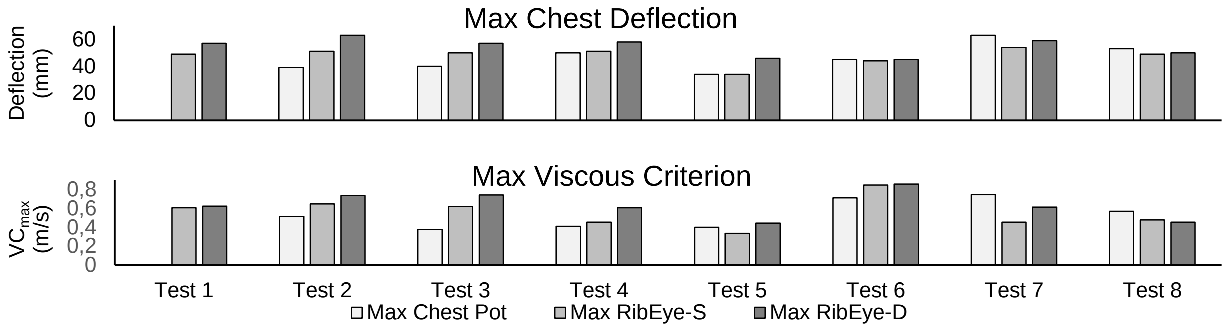

Figure 15. ***Top*** *graph shows the maximum chest deflection as calculated using the three different methods for all eight sled tests. The* ***bottom*** *graph shows the corresponding* VC_{max} *of the corresponding tests. In Test 1, the Chest Pot sensor failed.*

It was concluded that steering wheel rim contact was the major contributor to chest deflection. The Hybrid III chest deformation consists of anterior/posterior compression and upward deflection of the sternal plate. The Hybrid III single location measurement of the standard chest deflection sensor data is not reliable in this load case, when combined with sternal plate rotations (Figure 16). In contrast to the standard sensor, the RibEye system is able to register deflections at multiple locations on the sternal plate, which allow for the sternal plate motion to be uniquely determined. By determining the Hybrid III and steering wheel motions from e.g. a video, accurate steering wheel contact detection can be achieved. These combinations allow for full assessment of the chest deflection at the point of chest contact in the Hybrid III dummy. New biomechanical data is needed to adapt the injury risk assessment to the load cases common in HGV frontal collisions.

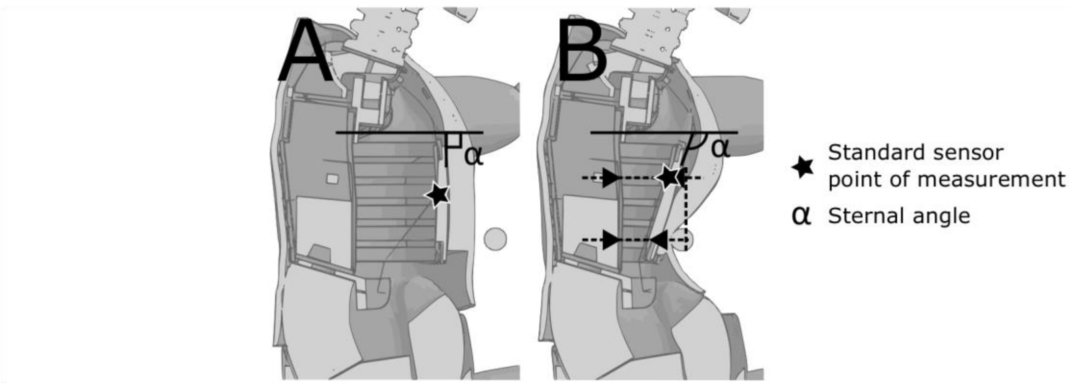

Figure 16. The validity of the standard chest sensor is dependent on the load distribution and location of the loading. ***A)*** *A midsagittaly sectioned Hybrid III chest indicating sternal angle and standard sensor point of measurement prior to chest loading.* ***B)*** *The Hybrid III loaded by a narrow object, such as a steering wheel rim, to the lower part of the chest. Here, the deflection at point of contact and the value measured by the standard sensor are different.*

3.3 SUMMARY PAPER III

In Paper II it was found that chest contact is a core issue in the frontal HGV crash test condition, and new instrumentation for the Hybrid III and test setup was suggested. However, a lack of biomechanical data was identified. The aim of this study was to investigate the responses of the human chest in simulated steering wheel rim impacts. To determine how the chest responses change with load distribution and location, pendulum impacts to the chest tests of Post Mortem Human Subjects (PMHSs) were carried out.

Two male PMHSs were exposed to rigid pendulum impacts using either a straight, horizontal bar-shaped front (bar), representing a steering wheel, or a traditional flat circular shape (hub). In total, ten tests were carried out. The hub pendulum (mass 23.4 kg, velocity 2.4 m/s) was designated to strike the middle of the chest at the height of the 4th intercostal space; this condition served as a reference to other studies. The bar-shaped pendulum (mass 25.8 kg, velocity 2.4 m/s) was directed at the fourth intercostal space and at various heights of the chest, spanning approximately 120 mm around the fourth intercostal space. One bar impact was conducted using a lower pendulum mass and a higher initial velocity (mass 9.6 kg, velocity 3.73 m/s) to assess the effect of loading velocity. The energy of the pendulum at chest impact was set below a level estimated to cause rib fracture. Analysis of the tests was conducted by using accelerometer data and high speed video tracking (Figure 17).

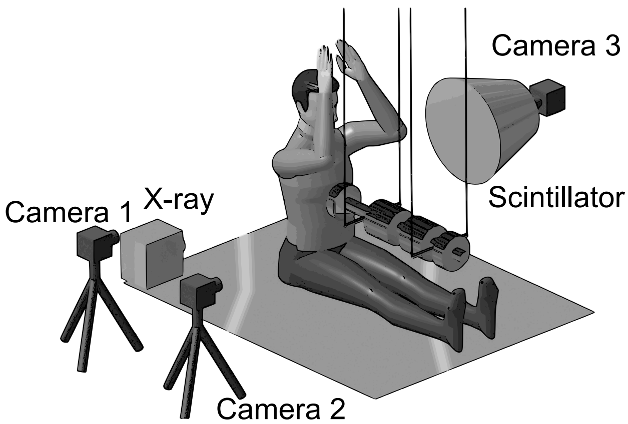

Figure 17. Pendulum test setup. The arms of the PMHS were raised to allow for video clearance. The PMHS was suspended in a seated, upright position by an electromagnet which was set to release upon impact. The image shows the pendulum with a hub shaped impactor, but the tests were also conducted with a straight horizontal bar.

The resulting chest deflection responses were scaled to match those of an average size male subject; impacted by a 23.4 kg impactor at a velocity of 2.4 m/s. From these scaled deflection responses, chest compression and viscous response were calculated and their maxima (C_{max} and VC_{max}, respectively) were evaluated with respect to differences in the pendulum front shapes and impact heights.

The results showed that the bar impacts produced consistently lesser scaled chest compressions than the hub; the Middle bar responses were around 90 % of the hub responses (Figure 18A). A superior bar impact resulted in lesser chest compression; the average response was 86 % of the Middle bar response. For inferior bar impacts, the chest compression response was 116 % of the chest compression in the middle. The high speed bar impacts provided a chest compression of 88 % of that in low speed impacts, very likely an effect of the damping properties of the chest (Figure 18B). The scaled deflection responses showed good agreement with previously published responses, which also indicates that the compression criterion response was similar.

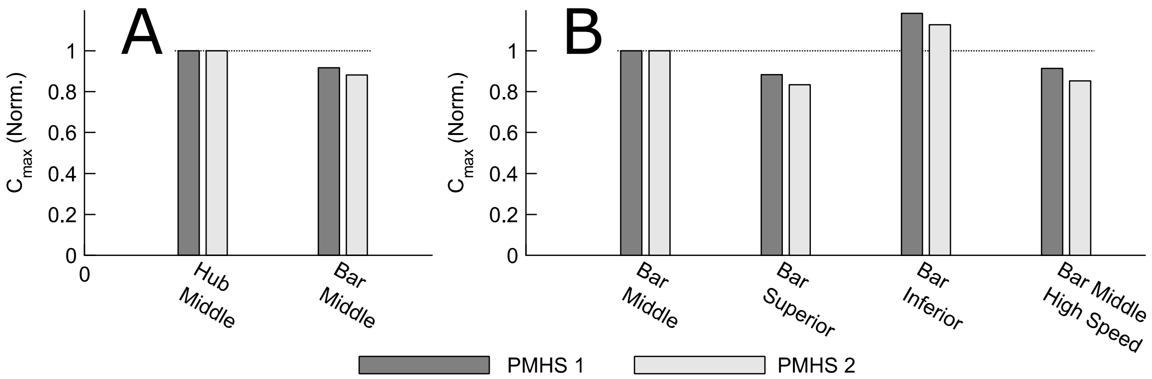

*Figure 18. The two left pairs of bars **(A)** show the normalised C_{max} indicating the difference between a Hub and a Bar to the middle impact height. The four right pairs of bars **(B)** show the differences when using a bar to different locations, C_{max} is normalised to the bar in the middle impact height.*

The study concludes that the impact from the bar shaped pendulum provides lower chest criteria responses compared to the hub. Furthermore, the responses are dependent on the impact height on the chest. Inertial and viscous effects of the upper body affect the responses. The results can be used to assess the responses of human substitutes such as Anthropomorphic Test Devices (ATDs) and Finite Element Human Body Models (FE HBMs).

3.4 SUMMARY PAPER IV

The aim of the Paper IV study was to evaluate the chest response of the average sized male Total Human body Model for Safety (THUMS) Human Body Model (HBM) to simulated steering wheel impacts. This was conducted by replicating all the individual Post Mortem Human Subject (PMHS) tests of the Paper III study in a Finite Element (FE) environment (Table 2). In addition to the replicated PMHS tests, a series of impacts to the THUMS at the nominal impact heights were conducted. In accordance with Paper III, the pendulum front was equipped with a circular front shape (hub, Figure 19A), or straight horizontal bar (bar, Figure 19B). The hub was used as a reference to previous studies of chest impacts, and the bar represented the steering wheel rim load pattern.

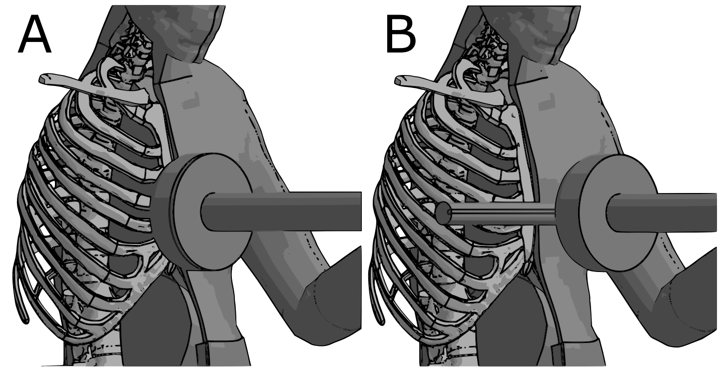

*Figure 19. The THUMS model in the hub pendulum **(A)** setup, and the setup with the bar front shape added to the pendulum **(B)**. Right arm and soft tissues were removed for visibility and illustration purposes.*

The mass of the pendulum was 23.4 kg, and was used to impact the chest of the THUMS at 2.4 m/s. The hub pendulum was directed at the height of the fourth intercostal space (hub middle, HM). The rigid bar impacts were directed at three heights of the chest, the 4th intercostal space (bar middle, BM) and 50 mm above (bar higher, BH) and 50 mm below (bar lower, BL). A second bar impact to the middle height was conducted with a 9.6 kg pendulum at 3.73 m/s (bar middle high speed, BM*) to study the effect of initial impact velocity on the chest response.

Table 2. Test replication matrix. Test name abbreviations and setup parameters.

Test Abbreviatio	Test Description	Pendulum mass (kg)	Velocity (m/s)	PMHS 1 Impact Height	PMHS 2 Impact Height	THUMS nominal Impact Height
HM	Hub Middle Location	23.4	-2.4	3.9	23.5	0
BM	Bar Middle Location	23.4	-2.4	-3.8	29.7	0
BH	Bar Higher Location	23.4	-2.4	14.2	67.3	50
BL	Bar Lower Location	23.4	-2.4	-48.8	-41.9	-50
BM*	Bar Middle Location, High Speed	9.6	-3.73	3.1	18.4	0

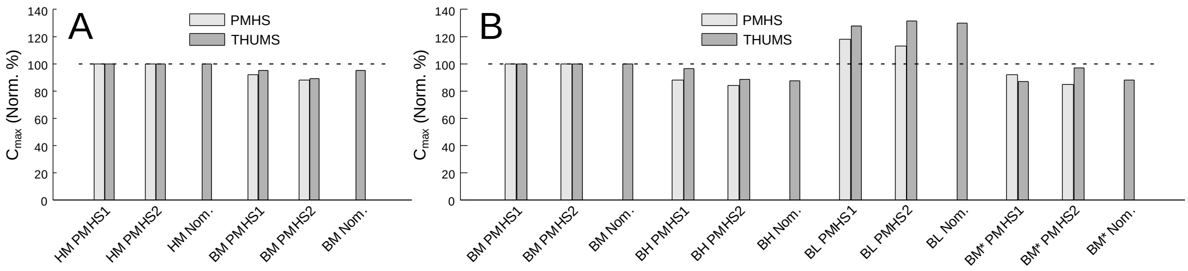

Figure 20. C_{max} responses normalised against either the hub middle (HM) ***(A)*** *for the response difference with respect to impacting shape, or against the bar middle (BM) impact* ***(B)*** *for distinguishing the effect of different impact heights and impact speeds. Light grey bars are the PMHS response results from the Paper III study and the dark grey bars are the respective replicated PMHS tests or nominal test responses of the THUMS from the current study.*

The results consist of comparisons of responses with respect to differences in the impactor shape (Figure 20A) and impact height (Figure 20B) in the THUMS and the corresponding results from the PMHS tests. The three bar shape pendulum impacts to the middle chest (BM) of the THUMS was determined to cause an average of 93% of the hub C_{max} at the middle impact height (HM), very similar to the average of 90% in the PMHS results (Figure 20A). The bar impacts to the upper part of the chest (BH) showed lower average C_{max} (THUMS - 91%, PMHS - 86%) relative to BM, while the impacts to the lower chest (BL) showed higher average C_{max} (THUMS - 130%, PMHS - 115%) relative to BM. The results from the higher speed BM* tests showed an average C_{max} of 88% in the PMHSs and 91% in the THUMS (Figure 20B). The response differences were similar in the THUMS and the PMHSs, and the results showed that the THUMS was satisfactory in predicting the human intra-subject thoracic response in the steering wheel rim-to-chest load case.

3.5 SUMMARY PAPER V

The main aim of this study was to improve the injury risk assessments in steering wheel rim-to-chest impacts when using the Hybrid III crash test dummy in frontal heavy goods vehicle (HGV) crash tests. The biofidelity of the Total Human Model for Safety (THUMS) chest in steering wheel rim impacts was shown to be satisfactory in Paper IV. Here, the THUMS was used as a substitute for the human body, and in this way a large set of test cases could be simulated. Correction factors for chest injury criteria were calculated as the chest injury parameter ratios between a finite element (FE) model of the Hybrid III and the THUMS. These factors are proposed to be used to compensate Hybrid III measurements in HGV crash tests where steering wheel rim-to-chest impacts occur.

The two impactor shapes utilised in the Paper III and Paper IV studies were used; the circular hub and the long, thin horizontal bar. Preceding the main study, efforts were made to validate the FE-Hybrid III in the specific load case of the horizontal bar (Figure 21). This was carried out by conducting pendulum test using a physical Hybrid III ATD, equipped the RibEye chest deflection sensor system as suggested in Paper II, and objectively comparing the responses to the FE Hybrid III in an identical setup using the Objective Rating Method (ORM).

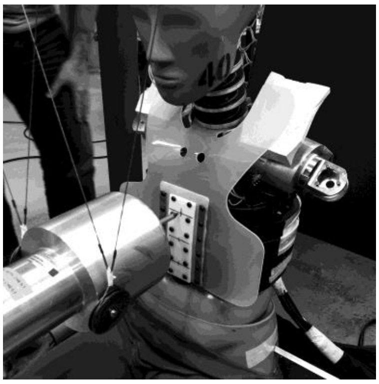

Figure 21. Setting the impact heights for the Hybrid III pendulum test, which were used to validate the response of the FE-Hybrid III. The validation was carried out using the hub and bar shaped impactors at 4.3 and 6.7 m/s, at three impact heights. The ORM was used for objective evaluation and in total 180 parameters from 12 tests and 12 simulations were used in the comparison.

In the main study, chest impacts at velocities ranging from 3.0 m/s to 6.0 m/s were simulated at three impact heights. A ratio between FE-Hybrid III and THUMS chest injury parameters, maximum chest compression (C_{max}) and maximum viscous criterion (VC_{max}) were calculated for the different chest impact conditions to form a set of correction factors. The definition of the correction factor is based on the assumption that the response from a circular hub impact to the middle of the chest is well characterized from previous studies and that injury risk assessment values are independent of impact height. The current Injury Assessment Reference Values (IARVs) for these chest injury criteria were used as a basis to develop correction factors that compensate the limitations in biofidelity of the Hybrid III, in steering wheel rim-to-chest impacts. In this study these factors are denominated Normalised Criteria Conversion Factors (NCCF).

The FE Hybrid III reproduced the response of the physical ATD well and was considered valid for the given impact conditions. The results showed that the hub and bar impactors produced considerably higher C_{max} and VC_{max} responses in the THUMS compared to the FE Hybrid III. The correction factor for the responses of the FE Hybrid

III, showed that the criteria responses for the bar impactor were consistently overestimated, due to different responses of the hub and bar in the THUMS compared to the Hybrid III. The chest response of the THUMS was lower for the bar impacts compared to the hub, while the Hybrid III chest results were the opposite. Ratios based on Hybrid III and THUMS responses, are shown in Table 3. These factors can be used to estimate C_{max} and VC_{max} values when the Hybrid III is used in crash tests for which steering wheel rim-to-chest interaction occur.

Table 3. The calculated Normalised Criteria Conversion Factors (NCCF) and recalculated injury criteria IARVs for use with the Hybrid III in steering wheel rim-to-chest impacts.

	NCCF C_{max}	**NCCF VC_{max}**	**Recalculated IARV C_{max} (50 mm)**	**Recalculated IARV VC_{max} (1.0 m/s)**
Higher	0.84	0.87	60	1.2
Middle	0.91	0.91	55	1.1
Lower	0.93	0.86	54	1.2

From this study it was concluded that bar impacts caused higher chest deflection compared to hub impacts in the FE Hybrid III, although contrary results were obtained with the more humanlike THUMS. Correction factors that can be used to correct the Hybrid III chest responses were developed. Higher injury criteria IARVs for steering wheel impacts to the Hybrid III are acceptable.

4 DISCUSSION

A literature study indicated a potential, and a need, for improved passive safety for HGV drivers in frontal collisions. HGV drivers in frontal crashes have shown a high frequency of sustaining severe injuries to the chest area (Zinser and Hafner, 2004). The present project was initiated by AB Volvo and Chalmers University of Technology, under the framework of the Swedish Vehicle Research Program (PFF) through VINNOVA, to evaluate the requirements and suitability of using the Hybrid III ATD in frontal HGV crash testing. To establish the validity of an ATD in a new load case is an extensive process. The work conducted within the scope of this thesis, was designed to provide answers and guidance to push the knowledge on HGV crash testing for occupant safety a bit further.

The Paper I study verified high frequency of severe injuries to the chest and partially verified that steering wheel rim contact is a cause of these injuries in frontal impacts. In Paper II this type of chest contact occurred in every frontal crash test. Therefore, steering wheel rim contact resulting in chest injuries should be given high priority in HGV safety. The Paper I study confirmed earlier findings in the literature, that a front-to-rear accident scenario is suitable for improving real life HGV driver safety.

Crash tests include ATDs to evaluate occupant loading and assessment of injury risk. The Hybrid III is the only regulatory ATD for frontal impact crash tests, ready to be used on short term (Figure 22A). Therefore, within the framework of this thesis only the Hybrid III ATD was considered. It was evaluated with respect to the HGV load case (steering wheel rim-to-chest) in Paper II. In the Paper II study it was shown that the Hybrid III was able to detect and distinguish the localised deflections from a steering wheel rim with the aid of additional sensors and camera instrumentation. The FE model of the Hybrid III was evaluated and found to replicate the responses of the physical ATD (Paper V).

In addition to FE models of the Hybrid III ATD, there are models of the human body that can be used to investigate occupant response and interaction with protection systems. In this thesis the THUMS FE HBM was found to be state-of-the-art (Figure 22C). In general, HBMs are intended to be better representations of the human, with more accurate geometries and properties than the ATDs. The Paper IV study verified the suitability of using the THUMS model in the selected load case. Before the THUMS could be verified, a new set of PMHS response data was obtained in Paper III. In Paper V, the response of the Hybrid III was compared to that of the THUMS. Conversion factors were developed to transfer Hybrid III responses to humanlike THUMS responses in steering wheel rim-to-chest impacts at various sternum heights.

Kent et al. (2001a) suggested that any lack of ATD biofidelity in a specific load case, should not be considered a disqualifier for the ATD if it is still possible to interpret the recorded measure in a specific load case into a plausible injury outcome, when compared to relevant human response data. Bearing this in mind, the Paper V study was conducted to establish the means to interpret the response of the Hybrid III ATD in the HGV load case.

Other ATDs may prove to preform even better, with an extended range of use in e.g. oblique crashes, such as the more recently developed THOR ATD (Figure 22B) which will likely become a more relevant ATD in the near future. However, the availability and experience of the THOR in crash test laboratories are still low. It will be possible to use a similar approach, to which has been used in this thesis, to evaluate other ATDs in the HGV load case.

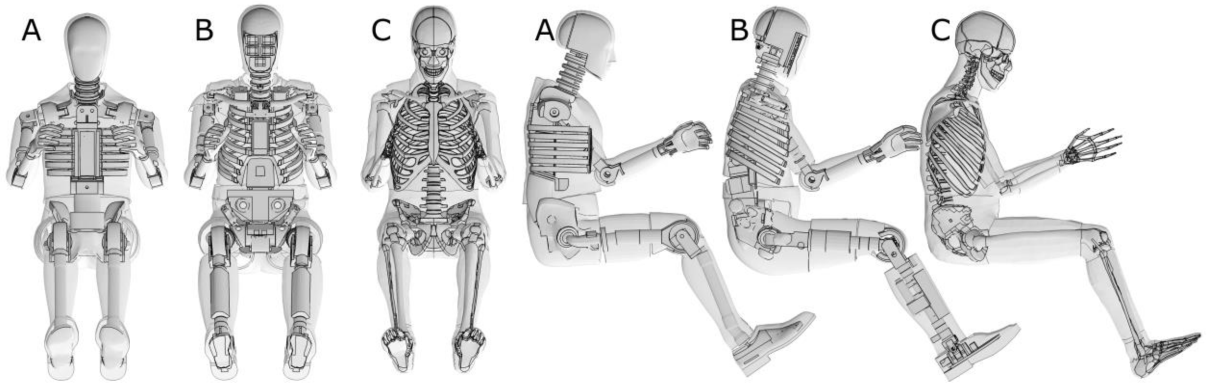

*Figure 22. Frontal and side views of FE models of the Hybrid III ATD **(A)**, THOR ATD **(B)** and the THUMS HBM **(C)**. External covering parts and soft tissue are semi-transparent to illustrate the underlying structures and skeletal representations in each model.*

4.1 REAL WORLD ACCIDENTS AND CRASH TESTING

4.1.1 Accident scenarios

In Paper I it was found that a significant part of the injurious accidents were within 15 degrees of full frontal (Figure 23). About 40% of all accidents were vehicle-to-vehicle accidents and included at least one other HGV in 40% of the cases. This means that about 16% of all injurious HGV accidents were accidents with other HGVs. This type of accident has been recognised as one of the most injurious accidents, accounting for between 20% and 67% of all severely or fatally injured HGV drivers (Bylund et al., 1997; Sukegawa et al., 2001; Simon et al., 2001; Gwehenberger et al., 2002; Zinser and Hafner, 2004; and Wrige 2007). Using the 30 km/h frontal rigid barrier crash test would, in addition to the HGV front-to-trailer back it represents, also address the occupant loading in other accidents, such as single vehicle crashes into roadside objects or accidents with other vehicles. Generally, HGV-to-passenger car accidents are less severe for the HGV driver, although they occur more frequently. One conclusion from the Paper I study was that previously designed tests replicating HGV-to-HGV accidents is still an appropriate and important method for HGV occupant safety testing.

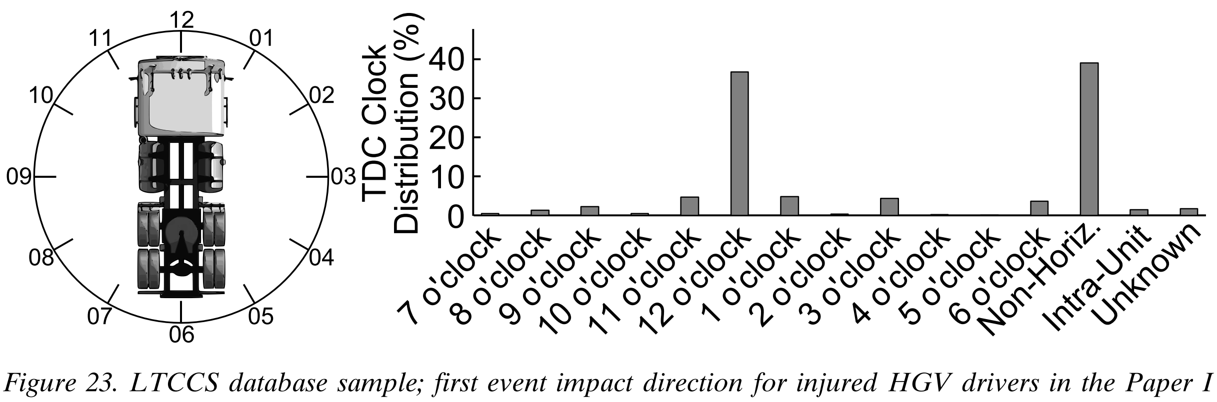

Figure 23. LTCCS database sample; first event impact direction for injured HGV drivers in the Paper I study.

4.1.2 HGV driver injuries and injury mechanisms

The HGV driver injuries in Paper I, graded AIS2+ and AIS3+, were most frequently located in the thoracic region. This confirmed the findings of earlier studies (Sukegawa et al., 2001; Zinser and Hafner, 2004). However, many injuries of similar severity were also located in the head region. These injuries are also of importance, and there are measures which can be taken to decrease head injuries, such as steering wheel- or curtain airbags. Passenger cars and light vehicles in the US are required to be equipped with airbags (Hinch et al., 2001) and passenger car manufacturers and NCAP consumer rating organisations, have promoted passenger car airbags worldwide. Passenger car accident data thus contain plenty of information regarding these devices. In contrast, very few HGVs in the databases utilised in Paper I, were equipped with airbags. Consequently, it was not possible to conduct proper analysis on the effect of airbags in Paper I. Some studies have shown that the effectiveness of a steering wheel mounted airbag in passenger cars and HGVs is low in preventing non-specified driver injury compared to the effectiveness of the seat belt (Hu and Blower, 2013). Studies have shown that for passenger cars, the airbag is efficient in reducing the severity of head and facial injuries (Huère et al., 2001), and that the thoracic injury severity is reduced by distributing the load. To the best knowledge of the author, there are however no studies conducted showing the efficiency of airbags to prevent injuries to any specific body region in HGV accidents. HGV airbags may turn out to be very effective in preventing e.g. head injuries, but may be less effective in protecting e.g. the thorax, resulting in the low effectiveness found in literature (Hu and Blower, 2013) in general. This type of study will only be possible as the number of HGVs equipped with an airbag increase, and are included in accident databases. In Paper II, it was not possible to distinguish the effect of an airbag on Hybrid III chest deflection. The combination of the steering wheel movement towards the horizontal plane, short crash pulse duration, and the distribution of the airbag in relation to the steering wheel rim diameter resulted in only minor interaction with the Hybrid III chest.

The seat belt is the most important passive safety system in vehicles. The study in Paper I showed a significant decrease in chest injuries in belted drivers, and these findings are widely supported in literature. In Paper II, the effect on maximum chest deflection in the Hybrid III ATD from seat belt use could not be distinguished. This result may possibly due to the low number of tests, where only one out of the eight sled tests employed an unbelted Hybrid III. In the Paper II study, only the primary impact (to the steering wheel) was analysed. In an HGV accident, subsequent injurious impacts of an unrestrained driver would probably be prevented by seat belt use.

About 5%-10% of the HGV drivers in Paper I who sustained thoracic AIS2+ injuries did so while wearing the seat belt. In comparison, all eight crash tests in Paper II showed contact of the ATD thorax to the steering wheel which indicated possible injury. It was not possible to make a direct comparison of the crash tests to any real world accident from the databases since crash severity information was insufficient in the database, lacking information such as delta-v. The only parameter on any speed, which was available in some cases, is the posted speed limit for the specific section of road where the accident occurred. However, this parameter is not a measure of crash severity. There are some differences between the results in Paper II and the injury findings in Paper I in that the stated sources of the thoracic injuries in Paper I is not solely attributed to the steering wheel, but also commonly the right and left side cab interior surfaces. This difference may be due to any number of factors. The sled crash tests are simplified and the crash pulse is only distinguishable in the immediate line of travel, while there are additional factors involved in a real world accident. The statistics in Paper I is based on the first event in the HGV crash, but sequent injurious events may have followed. The decision to focus on the first event was made since the database material does not distinguish which event gave rise to any specific injury. Moreover, there are other factors affecting the outcome in an accident such as driver anthropometry, posture or how the driver adjusts the seat and steering wheel. Influences from the driver anthropometry may also affect the seat belt interaction and efficiency. The injured drivers in the Paper I study were shown to have an average weight well above the weight of the 50^{th} %ile male, closer to the weight of a 95^{th} %ile male. These factors should be put in contrast to the sled crash tests where a 50^{th} %ile male ATD was positioned accurately with the seat and steering wheel adjusted very similarly for all tests.

The identification of differences between occupant loading and how injuries are sustained in real world accidents compared to frontal crash tests, are important for future studies. Focus on all events in an accident is desirable to distinguish between injuries from the primary event and subsequent events. The study of other common injury sources, other than the steering wheel such as the right and left side interior, may require the use of an ATD with better biofidelity and instrumentation in oblique loading directions, such as the previously mentioned THOR ATD.

Almost all thoracic AIS2+ injuries were rib cage fractures and/or organ injuries, such as lung contusions or pneumo- hemothorax. Combinations of these injury types were present for about 40% of the HGV drivers. This combination of injured structure types indicate that reducing or preventing skeletal injuries would have a positive effect on the organ injuries due to the stability of the thorax being maintained (Viano and Lau, 1988) which would reduce the risk of injuries such as hemothorax and other injuries that can be caused by fractured rib penetration. (Nahum and Melvin, 2002).

Skeletal injuries are most commonly assessed using chest deflection and associated injury criteria such as the C_{max} (Section 1.4.1) However, not all injuries were combination injuries and the remaining 60% of the organ injuries were not associated with skeletal injuries. Soft tissue and organs have been found to be loading rate sensitive and detection of such injuries can be addressed by utilising the VC_{max} criterion (Section 1.4.1). The ATD to be used in frontal HGV crash testing must thus be sensitive to accurately distinguishing these criteria.

4.2 THE LOAD CASE AND THE MEANS TO EVALUATE IT USING THE HYBRID III

An objective in this thesis was to study the suitability of the Hybrid III ATD to assess chest injury risk in frontal HGV crash tests. Originally, the Hybrid III ATD was developed for frontal passenger car crash testing. The chest was developed and validated for loads from the steering wheel hub for unbelted car drivers. The design of the chest and its sensors allows it to register deflection as a function of time, and the responses for hub and seat belt loads have been correlated to injury risk using injury criteria (Kroell et al., 1971; 1974; Viano, 1978; Mertz et al., 1991). However, the question was if the Hybrid III chest would also be able to accurately register localised loads, such as the loading from a steering wheel rim.

The 30 km/h delta-v, front-to-rear HGV crash test approach used in Paper II was aimed at one of the most common injurious conditions found in accident statistics. Tests using these impact conditions are already employed by HGV manufacturers, such as the Volvo Barrier Test, and are commonly referred to as trailer back tests. For the Paper II study, this test was simplified into a sled setup with an intrusion device which simulated cab deformation (Figure 24).

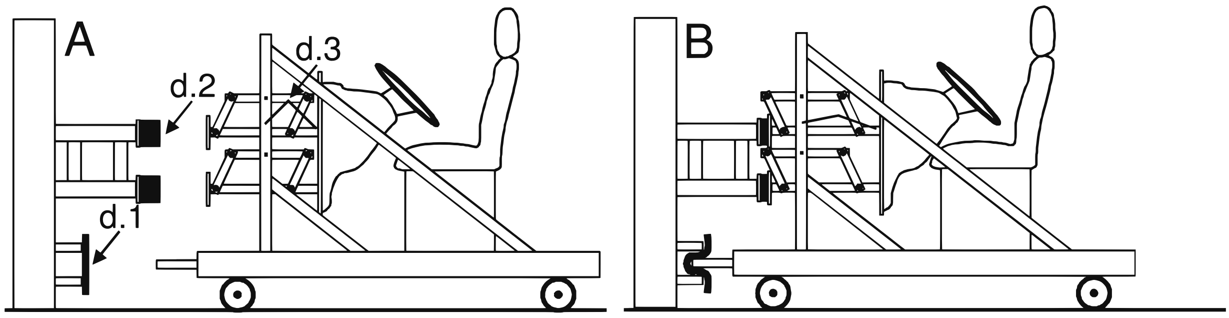

Figure 24. Metal band brake sled with an intrusion device, utilised in the Paper II study. ***Figure A*** *shows the sled and barrier before impact with the metal band brake (d.1), deformable elements for instrument panel intrusion device (d.2) and the intrusion stroke limiter (d.3).* ***Figure B*** *illustrates the post-impact appearance. Note: during testing a Hybrid III ATD was seated in the HGV seat and different seat belt systems, some in combination with an airbag, were employed.*

A study from the literature review (Sukegawa et al., 2001) and a pre-study (Holmqvist et al., 2009), indicated the need for more detailed chest deflection measurements in the Hybrid III ATD, when dealing with steering wheel rim-to-chest interaction. The pre-study was conducted by employing multiple pendulum impacts on an FE-Hybrid III model using a hub and a horizontal bar, to mimic the load distribution of a steering wheel hub and rim, at the level of each rib (Holmqvist et al., 2009). Therefore, the Hybrid III ATD used in the Paper II study was equipped with the six point, 3D RibEye® chest deflection measurement system. The RibEye system allowed for the extra channels of data to be sampled while also being able to record deflection from the standard Hybrid III chest sensor. The study by Holmqvist et al. (2009) also indicated that it may be advantageous to record the accurate point of contact. A pressure sensitive film was added to the anterior side of the ATD chest, just beneath the thin cotton t-shirt of the ATD. This method allowed for distinguishing the contact surface and approximating the location where the highest pressure was applied, but was unable to give time dependent information on location of the steering wheel rim.

The method of calculating steering wheel rim-to-chest contact location which was concluded to be the most appropriate and accurate method available for this test series, was extracted from tracking of laterally recorded high speed video. Here, the ATD and steering wheel rim was tracked, and the point of contact was calculated as a function of time. This method was deemed accurate but not very efficient, since it would not be possible to track objects without accurate high speed video tracking, which is difficult inside the cab during full scale crash testing. Additional non-invasive methods of acquiring the necessary measures, without video tracking, were suggested in Paper II. The approach of calculating chest deflection at the instantaneous point of steering wheel rim-to-chest contact resulted in a different output response compared to the standard sensor, in some tests the response was higher and some tests the response was lower. A secondary effect of calculating the point of contact on the chest was that in some tests, it was found that the steering wheel rim had moved close to the boundary of, or outside, the measurable area i.e. cranial to the top rib of the Hybrid III ribcage. A response from a similar test measured by the standard chest deflection sensor could easily have been rated as a good result, while in reality it may have caused severe injuries. Another advantage of using the RibEye system is that it can be used when the standard sensor fails, and even with up to three of the six sensors of the RibEye failing, the results were considered accurate. In one of the sled tests (Test 1, Paper II) and one of the pendulum tests to the chest of the Hybrid III in Paper V, the standard chest sensor failed. In the pendulum test, the transducer arm was detached from the sternal plate. This is believed to have been caused by the sternal rotation from the localised loading of the steering wheel substitute to the lower chest, and it is possible that this can occur in full scale testing as well.

The main conclusion from the Paper II study was that the Hybrid III ATD is able to distinguish the localised loading from a steering wheel rim but additional instrumentation was necessary. The average load case derived from the sled tests in Paper II, was found to be significantly different to the standard calibration pendulum test (Figure 25A). The load case was corresponding to the Hybrid III ATD striking the steering wheel rim at an angle of about 10 degrees from the horizontal plane, due to Hybrid III upper body forward rotation (Figure 25B).

From the Paper II results, a simplified load case was developed for use in the Paper III, IV and V studies. This was conducted by limiting the number of parameters from the steering wheel rim-to-chest load case to promote repeatability and reproducibility. The simplified load case was designed for laboratory studies, where a pendulum could be employed. The new load case was based on an ATD chest calibration setup where the impacting surface of the pendulum was replaced by a rigid, horizontal bar, to mimic the load distribution of the steering wheel rim, similar to the impactor used by Sukegawa et al. (2001). This approach was used to separate the properties of the steering wheel rim from the response of the chest. The impact locations for the load case were based on the inferior-superior extent of the Hybrid III rib cage (Figure 25C).

Moreover, since it was concluded that the load case is significantly different from the standard calibration pendulum test, there was a question regarding the biofidelity of the Hybrid III chest for the new load case. The design of the Hybrid III chest is biofidelic in its response to hub impacts at the middle chest, but the biofidelity of the response at other impact locations of the chest are unknown.

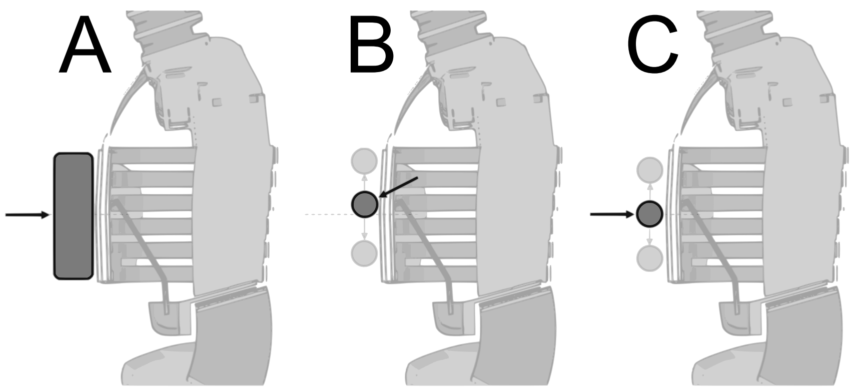

Figure 25. Illustrations of load cases of the Hybrid III ATD. ***A)*** *Chest calibration load case, where the hub impacts the middle chest.* ***B)*** *Average HGV load case of the Paper II study, where the Hybrid III strikes the steering wheel rim at an angle at different heights of the chest.* ***C)*** *Simplified load case, where a rigid bar strikes at three heights of the Hybrid III chest. The arrows in each figure indicate the direction of motion of the loading object. In A) the loading object is the hub, in B) the loading object is the Hybrid III itself, and in C) the loading object is the simulated steering wheel rim.*

To study the implications of the new load case, FE modelling was implemented, included in the Paper V publication. An FE Hybrid III ATD model together with the FE HBM THUMS representing the human, was exposed to a set of impacts utilising the simplified load case setup using a pendulum with a front shape of a rigid horizontal bar, designed to mimic the load distribution of the steering wheel rim (Figure 25C). Since this load case is new to biomechanics research, both the FE Hybrid III and the THUMS needed evaluation to establish that the responses are representative of their physical counterparts. This motivated the sub-study in Paper V where results from pendulum testing of the Hybrid III and corresponding simulations with the FE Hybrid III were compared; and the Paper IV study where the PMHS testing from Paper III was compared to corresponding THUMS simulations.

4.2.1 Acquisition of biomechanical chest response data from PMHS tests

In the Paper III study PMHS chest impact tests were carried out. The study originated in a need to complement biomechanical data for evaluation of steering wheel rim-to-chest impacts, and to acquire data for evaluation of the THUMS model. In a potentially injurious setup the PMHS is assumed to be the best available model of the human. A representative model of the human is necessary for development of advanced ATD technology and sophisticated material and geometrical modelling of HBMs in FE environments. The use of PMHSs in the acquisition of response data representative of the living human is not without downsides, since the properties of tissue and joints change after death and the PMHS lack muscle tone, pulmonary and arterial system pressures etc. However, Viano et al. (1977) studied chest force-deflection responses in live and sacrificed pigs, and concluded that the general characteristics were similar. Kent et al. (2004a) found muscle tensing effects to be negligible when chest deflection exceeds 20% of total chest depth. Arbogast et al. (2006) studied chest force-displacement during cardiopulmonary resuscitation (CPR) of relaxed (unconscious) patients in relation to chest responses of PMHSs subjected to the hub-type load. The results were inconclusive, but there was a tendency of a stiffer response by the PMHSs. Kemper et al. (2011), conducted low velocity (10 km/h delta-v, 5 g acceleration) sled crash tests with volunteers in a relaxed and tensed state and found that it was possible to eliminate chest compression from seat belt loads, by pre-impact bracing. These conclusions indicates that the global response of the PMHS chest can be considered representative of the human in a relaxed state or at higher severity crashes, but may not be representative while bracing in low severity crashes.

In Paper III, a study was conducted using five pendulum impact tests to the chests of two PMHSs in an upright seated position. The use of two PMHSs was very limited, and the purpose was to establish the intra-subject response differences with respect to impact load distribution and impact location. The contact force and chest deflection was sampled for each test and was subsequently scaled to match those of a 50^{th} %ile male subject. The method used for scaling was the same as has been used by e.g. Lebarbé and Petit (2012) while developing the suggested new chest response corridors for the standard hub impact (Kroell et al., 1971). One of the objectives of this thesis is to be able to assess chest injuries using the Hybrid III, therefore, two of the most commonly used injury criteria were calculated from the scaled responses; the maximum of the Compression and Viscous criteria, C_{max} and VC_{max}. The Paper III study method necessitated multiple impacts to each PMHS, and in an effort to minimise the potential effect fractures would have on chest response, the impact velocity was adapted to an energy level which was estimated to be below the point when rib fracture first occur.

Unfortunately, impact speed and energy are not the sole factors involved in fractures and the autopsy revealed multiple fractures at different locations. The fractures were not detected in between tests since detailed examination or radiographic screening was not conducted. The autopsies revealed significantly different fracture patterns in the two PMHSs, while the test results from these subjects revealed comparable scaled intra-subject chest response variations. The conclusion from this is that the fractures did not significantly affect the response of the chests, which has also been hypothesized in other studies (Yoganandan et al., 2004; Kent et al., 2004b; Shaw et al., 2007). The scaling method applied to calculate the response of a 50^{th} %ile male subject was considered to work well for subsequent calculation of the C_{max} criterion. It was discussed in Paper III that calculation of VC_{max} from scaled responses may work poorly using this scaling method, since damping effects would not be taken into account.

For the Paper III and Paper IV studies, impact responses using the steering wheel rim substitute, the rigid horizontal bar pendulum (bar), was studied in relation to the response from the standard hub pendulum (Kroell et al., 1971). This was done to establish the response difference from the load distributions, where the human response in hub pendulum impacts is well characterised from previous studies. By relating the bar to the hub responses at the same impact location, it was possible to eliminate some of the subject-to-subject variations, e.g. overall chest stiffness. It was not feasible to physically compare the PMHSs responses with any previously constructed chest impact response corridors, since the required impact energy (23.4 kg hub impactor at 4.3 m/s or 6.7 m/s) would very likely have resulted in multiple fractures, although scaled responses to the 4.3 m/s level were shown to be reasonable. The THUMS showed to comply with both the 4.3 m/s and 6.7 m/s response corridors. Moreover, the two PMHSs were elderly subjects while the THUMS is designed to represent a younger subject. It is well known that chest properties change with age (Zhou et al., 1996), which may affect the results. The results from the Paper III study revealed that the scaled intra-subject responses between the two PMHSs were similar. The bar provided lower chest criteria responses (both C_{max} and VC_{max}) compared to the hub at the middle impact location, and bar responses increased as the impact point was lowered. The results were thus indicating softer chest properties in the inferior part and stiffer in the superior part, compared to the middle part. These results are consistent with findings by Cavanaugh et al. (1988), which found that the upper sternum provided the highest stiffness and the lower sternum the lowest.

4.2.2 Evaluation of the THUMS chest response

The Paper IV study design was based on the resulting parameters from the Paper III study, where the impact heights from each respective PMHS hub and bar test was matched in the FE setups (Figure 26).

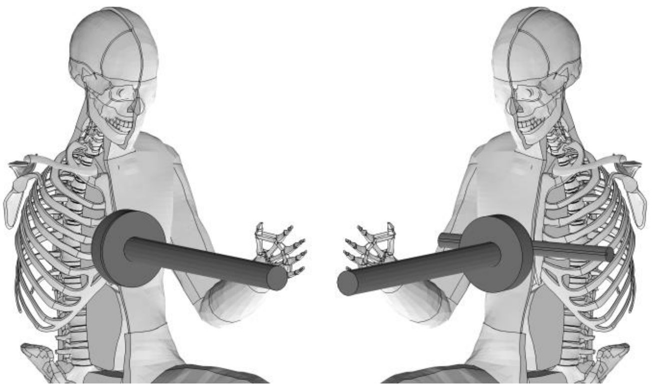

Figure 26. Illustration of the FE setup of the replicated PMHS test using the THUMS model. The left picture illustrate the hub impact condition and the right picture the bar impact condition, both at the middle chest. Soft tissue and arm was are removed from one side for illustration purposes only.

The responses of the THUMS were scaled towards the same subject size and setup parameters as the PMHSs, using the scaling method from Paper III. This scaling was conducted even though the THUMS has already been assigned the properties of a 50^{th} %ile human, because answers to some questions regarding the scaling method e.g. the chest depth or effective chest mass of a 50^{th} %ile human, 50 mm above or below the 4^{th} intercostal space, were still outstanding. Historically, these parameters have been extracted based on statistics of a large set of subjects or tests (Lebarbé and Petit, 2010), which was not possible for the Paper III study. A potential alternative method for scaling the PMHS responses can be to carry out the replicated FE-modelling with the THUMS, and utilise the resulting parameters for the scaling of PMHS data. This approach is investigated in Appendix A.

Only two PMHSs were used in this study, which limits the amount of available data, and may be inadequate for detailed validation of ATDs or HBMs for the current load case. The results do however indicate that the THUMS provides similar trends with reasonable response amplitudes making it applicable in HGV frontal crash safety assessment. The THUMS is thus also useful in evaluation of the Hybrid III response as conducted in Paper V. In principle it would be possible to directly compare the Hybrid III to the PMHS data, however, this would only allow for determining the correlation between PMHSs and Hybrid III in the specifically tested setups. To broaden the study the THUMS was used in place of a substantial number of PMHS tests required.

4.3 THE HYBRID III AS A TOOL TO ASSESS CHEST INJURY IN HGV CRASH TESTS

4.3.1 Evaluation of the Hybrid III chest response

The evaluation of the Hybrid III ATD chest to steering wheel rim impacts in Paper V was conducted in a similar manner as the Paper III and Paper IV studies, utilising a pendulum setup with a hub and a rigid horizontal bar to simulate a steering wheel rim. Prior to evaluation of the injury risk assessment capacity of the FE Hybrid III ATD, using the THUMS, the model was evaluated against a physical ATD. Since the steering wheel rim-to-chest load case is not a standardised test, it was necessary to verify that the FE Hybrid III would reproduce the response of its physical counterpart and vice versa.

Therefore, a set of pendulum tests to the chest of the Hybrid III was conducted in an ATD chest calibration rig, and subsequently replicated in an FE environment. The tests were conducted for three impact locations, middle chest and 50 mm above and below, using the hub and the bar pendulum front shapes. These were tested at two impact velocities, 4.3 m/s and 6.7 m/s. The response of the FE model was evaluated using the objective rating method (ORM, Hovenga et al., 2005), which is able to take into account peak value responses and also the shape of response time-history curves. The FE model was compared to the Hybrid III with respect to the time-histories of contact force, compression criterion and viscous criterion as well as the peak values thereof. Similarly to the sled setup in Paper II, the Hybrid III was equipped with the six location 3D RibEye chest deflection sensor system, which allowed for calculation of the deflection at centre point of impact. The criteria were calculated from both the standard chest deflection sensor as well as from the RibEye, all of which were included in the comparison analysis, totalling 180 parameters from all 12 tests. The results revealed that the FE Hybrid III was able to accurately predict the response of the physical Hybrid III, receiving an overall complete score of 81% from the ORM analysis. This should be compared to the score acquired from comparing the same parameters from two replicated standard chest calibration pendulum tests to the middle of the chest of the physical ATD, which resulted in a 95% ORM score. The FE Hybrid III model was therefore regarded as robust and representative of the physical ATD for the steering wheel rim load cases.

4.3.2 Injury risk assessment using the Hybrid III in steering wheel rim-to-chest impacts

The testing and simulations in Paper III, Paper IV and Paper V showed that the THUMS and Hybrid III FE models are credible representations of the human and a Hybrid III ATD, respectively. These models were employed in the main study in Paper V aiming to establish suggestions on how to interpret the Hybrid III responses in an HGV load case where steering wheel-to-chest interaction occurs, with respect to prediction of injury risk. FE modelling facilitated the simulation of a large number of tests at minimum effort and cost, as the environment and input parameters could easily be controlled and changed.

The response data in Paper V, showed a clear difference between the HBM and ATD models. For instance, in the hub impact responses, the amount of chest compression in the Hybrid III was roughly half of that registered in the THUMS, for any of the impact velocities, which ranged from 3 m/s to 6 m/s. PMHS hub pendulum impacts have been the most important method for evaluating chest response, and both models have been validated against these. However, since the Hybrid III was developed from the Kroell et al. (1971; 1974) PMHS tests and Neathery (1974) chest response corridors, a slightly different view on how to treat PMHS response data emerged, which resulted in the reanalysed PMHS response corridors of Lebarbé and Petit (2012). The THUMS model used in Paper V was tuned and validated (Mendoza-Vazquez, 2014) to match these corridors rather than the preceding Neathery (1974) corridors.

For the hub impactor loading, it was hypothesized that identical impacts to each of the two models would imply the same injury risk. Kent et al. (2003e) wrote that C_{max}, measured on the human (PMHS) chest is an objective criterion for assessing injury risk from different loading distributions and locations, while this is not the case in the Hybrid III. The Paper IV evaluation of the THUMS indicated that it is representative of PMHSs in its response, therefore the injury criteria was also considered to be accurate for assessment of injury risk in any loading condition for the THUMS HBM. From here, it was necessary to find the means to have the Hybrid III reflect the response of the THUMS with respect to load distribution and impact location. This was conducted by studying the individual and combined relations of responses with respect to impactor shape and impact location for each model. This was similar to how the intra-subject response evaluation of the THUMS was conducted in the Paper IV study from the data in Paper III. Here, the intra-subject responses of the Hybrid III and the THUMS were put in relation to each other in order to relay the response in the Hybrid III, to correspond with responses in a human being. The relation between the ATD model and HBM response was denominated the Normalised Criteria Conversion Factor (NCCF). For each impact velocity the relation was calculated to account for differences in properties, such as damping, in the Hybrid III chest and the THUMS. The reliability of the NCCF is very much dependent on the reliability of the models used. The development of an accurate prediction of the human response from any specific test in the Hybrid III will require identical setups and output parameters from both models adding an extra burden on analysis. The aims of this thesis include developing a method of using the Hybrid III ATD to assess injury risk in frontal HGV crash testing. Therefore, the NCCF was used to shift the current criteria IARVs developed for passenger cars to suit the frontal HGV impact situations.

4.4 ADJUSTING THE HYBRID III IARV'S FOR STEERING WHEEL RIM-TO-CHEST IMPACTS

The approach to shift the IARVs for use with the Hybrid III ATD was conducted for two of the most commonly used injury criteria with the Hybrid III ATD, the C_{max} and VC_{max} criteria. Common IARVs for the Hybrid III in e.g. Euro NCAP frontal tests are 22% C_{max} (50 mm deflection, Mertz et al. 1991) and 1 m/s VC_{max} (Lau and Viano, 1986; Euro NCAP, 2015). The test matrix included four impact velocities from 3 m/s to 6 m/s in 1 m/s increments. These velocities were not enough to produce responses exceeding the Hybrid III IARVs in all cases. For instance, only two out of the three bar impacts managed to reach the IARV for NCCF corrected C_{max}, and the VC_{max} IARV was not reached for any of the NCCF corrected responses. To estimate the NCCF at the IARVs extrapolation of the NCCF and criteria responses was required. Another option, or a complement, for conducting extrapolation could have been to adjust impactor mass and velocity to reach the IARV. While a higher impact velocity was possible for the Hybrid III tests, it was not so for the THUMS, where there was a risk of the chest bottoming out onto the anterior spine for higher velocities at the current pendulum mass. This would result in erroneously assessing the same injury risk for the THUMS at higher criteria responses for the Hybrid III. A second possibility would be to lower the mass of the pendulum while increasing velocity, which may work well since the underlying properties of the Hybrid III and the THUMS chest are different. The Hybrid III chest response is primarily inertial, while the human (THUMS) response is primarily viscous (Kent et al., 2002). This implies that the response of the THUMS would be stiffer than the Hybrid III at higher velocities which can be seen in the response results of Paper V. In Paper V the C_{max} results from the THUMS are increasing at a decreasing rate of compression with increased pendulum velocity, while the responses of the Hybrid III are showing linear trends or an increase at an increased rate with increased pendulum velocity (Figure 27).

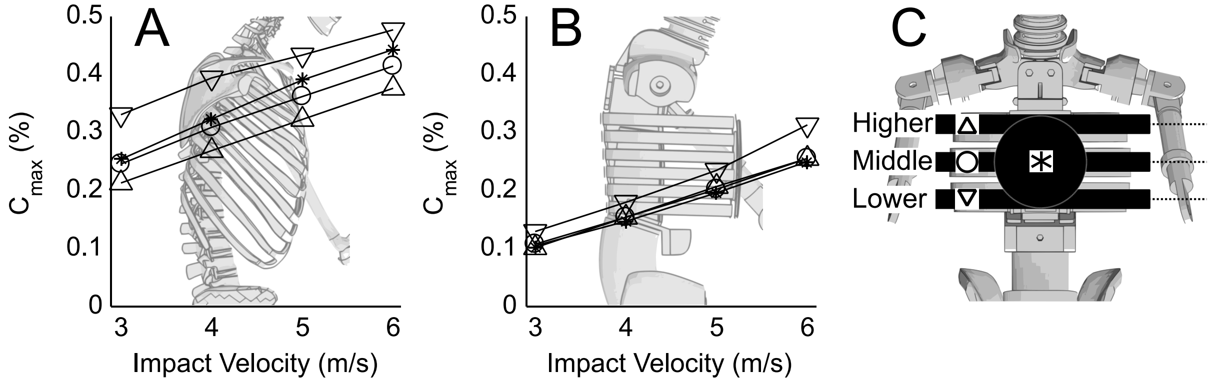

*Figure 27. C_{max} criterion responses of the THUMS **(A)**, and Hybrid III **(B)**. Legend and load distribution explanation in **(C)**. The THUMS responses are indicating a decrement trend with the increase in impact velocity, while the Hybrid III responses are increasing as the impact velocity increase.*

However, lowering the pendulum mass would reduce the applicability of the results to the frontal HGV barrier test, where the actual load case was not primarily that of the steering wheel striking the ATD, but the chest of the ATD striking the steering wheel (Paper II). Here, the established effective mass of the 50^{th} %ile human chest was close to 30 kg, which was used for the scaling process of the PMHSs in Paper III.

4.4.1 Implications of PMHS and THUMS stiffness differences on Hybrid III response interpretation

The difference in the THUMS and the PMHSs chest stiffness does not significantly impact the interpretation of the recalculated Hybrid III IARVs as has been showed in Paper V, Appendix A. There are two reasons for this; firstly, the overall stiffness does not have much effect, compared to the difference in stiffness with respect to load distribution (hub or bar) and location (high, middle or low). Secondly, if the stiffness differences detected in Paper IV, between the PMHSs and the THUMS in the Higher and Lower impact locations, are representative then the IARV would still be increased for the Hybrid III ATD. The effect of stiffness variation was studied in Paper V, Appendix A, and the most similar permutation of stiffness differences in this study is Permutation 26, where the upper chest response was increased and the lower chest response was decreased. Considering that the actual difference in normalised compression (compared to the bar at middle location) was 86% versus 91% in the PMHS and THUMS respectively, the THUMS compression response would be 5.4% lower at the Higher location compared to the PMHSs. The corresponding numbers for the Lower location was 116% for the PMHSs and 130% for the THUMS, which results in the THUMS compression response being 10.8% higher compared to the PMHSs. Moreover, by including all the identified relative difference in stiffness from the hub to all bar impacts of the PMHSs to the THUMS, the IARV for the Hybrid III will be affected. This would result in a 53.1 mm C_{max} IARVs for bar impacts at the Middle, 56.2 mm for the Higher and 65.5 mm for the Lower impact location, compared to the original IARVs associated with a hub load to the middle of the chest, which is 50 mm chest deflection. The VC_{max} was concluded to work poorly with the current scaling method, and therefore it is not considered here, but would be affected in a similar manner, given any difference in response between PMHSs and the THUMS. These results are dependent on the assumption that the relative differences in stiffness between the THUMS and the PMHSs are the same, regardless of impact velocity. The stiffness differences can change if the viscous properties of the THUMS and PMHS chests do not match. This will require further studies.

Table 4. Recalculated IARVs for the chest deflection for steering wheel impacts to the chest of the Hybrid III based on THUMS stiffness variations, conducted by increasing or decreasing criteria responses of the THUMS by 5%. ***Original Paper V*** *designates the result from the study, the* ***Mean*** *is the average from the stiffness variation study (Paper V Appendix A, with the standard deviations), and the* ***Outcome Paper IV****, is the result by applying the resulting differences from the PMHS to the THUMS in the Paper IV study. (See Paper V, Appendix A, for more details)*

	Hybrid III chest deflection (mm)		
	Higher	Middle	Lower
Original Paper V	59.8	54.8	53.6
Mean	59.9	54.8	53.6
Mean +1 SD	62.5	54.8	58.0
Mean -1 SD	57.2	54.8	49.3
Outcome Paper IV	56.2	53.1	65.5

4.5 LIMITATIONS

4.5.1 Thesis scope restrictions

The work in this thesis was limited to the applications available in the Hybrid III ATD for HGV crash testing. The Hybrid III ATD was designed to represent the human in full frontal crashes. Standard instrumentation for thoracic injury prediction in this particular ATD is a single point measurement of the sternum motion towards the spine. These circumstances result in a number of related limitations of the evaluation method presented in this thesis, one being restriction in impact direction. Another limitation is the restriction in possible biomechanical response measurements which can be acquired from this ATD. The first limitation could have been addressed by further development of the Hybrid III or by adopting the more advanced THOR ATD. However, these options were beyond the scope of this thesis. Limitations in the biomechanical measurement sensors of the Hybrid III were addressed by using commercially available techniques and solutions. The evaluation method presented in this thesis had to be pragmatic and suitable to be used with the Hybrid III ATD for the specific HGV crash test.

4.5.2 Limitations of the included studies

There are a number of limitations to the studies included in this thesis, which may need to be addressed through further research in the future. Below, some of the more important limitations are summarised.

Paper I.

The registered course of events during the HGV crash events were not detailed enough to establish that the observed injuries included in the analysis occurred during the frontal crash, or if they arose during subsequent events. It is therefore possible that some of the injuries were not caused by the first, frontal event, but in a subsequent event with in oblique or lateral force direction. Even so, it does not change the fact that thoracic injuries are of great importance in frontal HGV crashes. Differences in sampling methodologies between the two databases also imposed limitations to the study, as some variables were not directly comparable, or altogether lacked a corresponding variable in the other database. For some of the variables, transcoding was applied to make the variables comparable in the two datasets. While it was not possible to test the validity of the transcoding, the contents of the variables used for transcoding suggests that the method would be accurate enough to study trends. Hence, the conclusions that were conveyed in in Paper I, that a frontal HGV test is of importance and that the chest is frequently at great risk of injury, is still valid. Consequently, this finding implies that the ATD used in HGV frontal crash tests must be able to assess these chest injuries, to promote the development and design of HGV safety systems.

Paper II.

The sled crash test is a simplification of a full scale barrier test, which in turn is a reproduction of common real-world accidents. Therefore, the sled tests carried out in Paper II are not completely representative of real-world accidents. For instance, the crash pulse is applied only in the frontal longitudinal direction and pitching effects from wheels and suspension are not included. The driver kinematics and seat belt interaction may be affected by these parameters, altering the steering wheel rim contact to the chest. During testing, a pressure sensitive plastic film was added beneath the cotton t-shirt of the standard Hybrid III ATD, to allow for registration of the point chest contact to the steering wheel. This film may have decreased the friction and contributed to more sliding of the steering wheel rim. The limitations in this study are not considered significant enough to change the conclusions in Paper II or the test method presented in this thesis, since they are based on the results from a sled setup, which is very similar to the HGV test setup used in the design of restraints. These limitations do, however, call for future work in which the Hybrid III should be fitted with the suggested additional chest deflection sensors that allow for a more advanced steering wheel rim-to-chest analysis and injury risk assessment.

Paper III.

Applying multiple impacts to each of only two PMHSs, especially with the occurrence of rib fractures, are two major limitations to this study as the rib fractures complicate the interpretation of the responses. In case an impact produces a rib fracture, the response in subsequent impacts to the same rib cage may be affected. The fracture patterns were different in the two PMHSs, yet the scaled intra-subject responses were comparable, indicating that the possible stiffness reduction produced by the different fractures was small and did not influence the test method that is presented in this thesis in general. The effect of varying the chest stiffness is further discussed in section 4.2.1. The limitations need to be taken into consideration and are therefore addressed again in the section on future work.

The setup in this study, was designed to replicate the load case which was identified in the Paper II study. However, some simplifications were made to increase the repeatability of the test conditions. While the occupant motion into the steering wheel rim was found to be non-horizontal in the Paper II study, all PMHS tests were carried out by an anterior horizontal bar pendulum setup constrained to move perpendicular to the chest front wall. Moreover, the impact energy was decreased to a much lower level. The simplifications in the test setup decreased the similarities to the original load case, although the impact locations and impacting front shape provided the means to reach the main objective of the study. This was to evaluate the responses of the human chest and to provide data suitable for assessing the biofidelity of the THUMS chest, for the current simplified load case, in the subsequent Paper IV study. The data provided from the PMHS tests is very limited and it is possible that the responses from two subjects were outliers, i.e., significantly different from the average human. However, by applying the scaling method to scale responses towards a 4.3 m/s pendulum impact, it was possible to compare the responses to the 4.3 m/s response corridor by Lebarbé and Petit (2012) (Figure 13 in Paper III). Here, it was found that the responses of the two PMHSs in the Paper III study were likely not due to an outlier, which further increases the validity of the analysis, and usefulness for subsequent evaluation of the THUMS.

To compare the responses of the two PMHSs, the responses were scaled to the 50th %ile male subject size. It was necessary to make some assumptions about the chest properties of the scaled subjects for this scaling technique. It also required specific properties of the 50th %ile male to have been previously established, such as the effective chest mass and chest depth. These measures can be considered to be constant for any specific impact location on the chest of the 50th %ile male, where these properties during an impact to the middle chest can be estimated to be known from previous studies. However, the variation of impact location in the Paper III setup rendered these properties uncertain. An alternative approach to using only 50th %ile parameters for scaling was tested in Appendix A, where the effective mass and chest depth scaling parameters were extracted from the replicated PMHS simulations using the THUMS from the Paper IV study. The results from the Appendix A study showed that the change in scaling parameters did have an effect on the responses, but not enough to change the conclusions from the Paper III study. The change in scaling parameters also indicates reasonable robustness of the results.

The definition for the timing of initial pendulum-to-chest contact was based on a specific level of registered contact force (30N). The appropriateness of this approach was not investigated, and changing the definition of initial contact may affect the chest deflection results to a minor degree.

Paper IV.

The comparison of the responses of the PMHSs to the THUMS model was necessary to establish if the THUMS would be a reasonable human surrogate in the simplified HGV load cases. This comparison consisted of the results from the two PMHSs in the five setups used in Paper III, and were used to study the intra-subject response variation to changes in impactor shape and impact location of the THUMS. The anthropometry and material properties of the PMHS and the THUMS are different. The THUMS is modelled to represent those of the 50th %ile male at around 30-40 years of age. For the PMHSs, the anthropometry deviated somewhat and the ages were 65 and 80 years. Scaling was applied to deal with anthropometric differences. The underlying skeletal and soft tissue structures were similar between the PMHSs and the THUMS and by basing the comparison on the intra-subject response differences, i.e., by only studying the relation of any response to another response from the same subject, some of the issues related to age could be reduced.

The evaluation of the THUMS was only conducted for the relatively low energy impacts of the PMHS study, which is a limitation of the evaluation. This was, on one hand, a necessary limitation when applying repetitive impacts to the same subject due to the potential effect of rib fractures. On the other hand, it was assumed that the target of future restraint system design would be to drastically reduce the risk of rib fracture, and thus it would be essential that ATD biofidelity had been evaluated at load levels close to the limit where rib fractures begin to occur. Another assumption was that if the responses of the THUMS matched the PMHSs for the low energy impacts, then the odds that the THUMS would provide an appropriate response would be favourable also for higher energy impacts. Moreover, the THUMS has been shown in Paper V to adequately match the Lebarbé and Petit (2012) chest response corridors at the 4.3 m/s and 6.7 m/s.

The limitations in using the scaling method in Paper III are also present in the Paper IV study. Similarly to the Paper III results, the effect from a slight change in the scaling parameters was checked in Appendix A and found to have little effect on the results, and did not to change the conclusions from the study.

Paper V.

The intra-subject response comparison of the THUMS to the PMHSs in Paper IV was considered reasonable and the FE Hybrid III model was considered to replicate the responses of a physical Hybrid III well in the current study. However, the analysis showed that the match between models and physical counterparts was not perfect, and there may be some variability of the responses in a physical Hybrid III that were not captured in this evaluation. The use of two models which reproduce the responses of their physical counterparts to a certain level is another limitation to this study, which introduced some uncertainties. To increase the quantitative confidence in the proposed method, further future investigations are recommended.

In the Paper IV study, the responses of the THUMS chest were shown to have a slightly different stiffness distribution compared to the PMHSs tested in the Paper III study. The Higher impact location was softer and the Lower impact location was stiffer in the PMHSs. This can potentially affect the main result in this study. However, by introducing the difference in stiffness in a similar manner as in the variation study in Paper V, Appendix A, it was possible to evaluate the difference in response between the THUMS and the PMHSs (Appendix A). The results showed that the conclusions were not affected (section 4.4.1).

Moreover, altering the parameters used for scaling of the PMHS and THUMS responses during the evaluation of the THUMS, provided slight changes in stiffness differences. A small study on the effect of scaling parameters on the main result of the Paper V study was explored in Appendix A of this thesis. The results showed that, even though the scaling parameters did have a small effect on the final results, it did not change the conclusions. This implies that there is a robustness in the recalculation of the IARVs for the Hybrid III while exposed to steering wheel rim-to-chest impacts.

Applying a simplified load case may have implications on the real-life injury risk, since all aspects of the load case with the angled impact direction of a deformable steering wheel as described in Paper II, was not studied. It may be advantageous, or even necessary, to study the load case in more detail in the future, as the ATDs become more advanced and the injury criteria are further developed. However, limitations in the Hybrid III and the currently used injury criteria which today assess injury risk using anterior-posterior deflection of the chest, the method for recalculating IARVs, can provide HGV crash test engineers with an understanding of the tolerance levels for the Hybrid III in this load case. Moreover, the additional sensors which were suggested for use when conducting HGV crash tests with the Hybrid III, provide the tools for detection and interpretation of the Hybrid III chest deflection responses. Erroneous interpretation of the responses may have severe consequences for HGV driver safety.

4.6 FUTURE WORK

Below follow some suggestions on the need to address some of the limitations that arose in the studies, as well as other future potential focus areas for HGV driver safety.

The results from Paper I showed that the most common HGV accident scenario involve rollover, which are potentially very injurious. Much would be gained by preventing this type of accident or in deed designing safety systems able to reduce the injurious effects from such accidents.

Head injuries were shown to be the second most occurring of all accidents in Paper I, and also frequently reached high AIS severity grades. Therefore, it is crucial to study the causation mechanism behind these injuries to be able to address them in future crash testing and crash safety development.

There was a high occurrence of low severity lower limb injuries in the Paper I study. Previous studies have indicated that HGV drivers who are injured in accidents suffer long term consequences with long periods off work (Bylund et al., 1997; Zinser and Hafner, 2004), not only from sustaining life threatening injuries, but also from low severity injuries (as rated by the AIS). Some drivers are forced to end their HGV driver careers prematurely due to impairment sustained in HGV accidents. There is a need to address these issues in future studies.

In order to analyse HGV accidents more efficiently more detailed databases, preferably containing reconstructions or EDR-data (Electronic Data Recorder) for parameters such as crash severity is required. Making accident sampling more continuous would also be preferred, possibly by including the HGV in the vehicles that are eligible for sampling ("CDS applicable vehicles", currently only passenger cars, light trucks and vans) in the US National Automotive Sampling System – Crashworthiness Data System (NASS-CDS) sampling. The Swedish database STRADA includes continuous HGV sampling, but the methodology may need adjustment to better suit the HGV, by including variable categories for e.g. rollovers. It would also be advantageous for accident investigation methodologies to be harmonised, which would facilitate combining data in a common analysis more easily.

Full scale testing should be carried out to establish potential drawbacks in sled testing, specifically with respect to driver kinematics. In Paper II, the accuracy of the method of using a plastic pressure sensitive film to register contact location, was established to be second to the method of continuously calculating the location. For future similar studies, the plastic pressure film should be omitted. Contact point registration accuracy could possibly be increased and streamlined by incorporating digital pressure sensors on the ribs or the sternal plate of the Hybrid III in combination with inertial motion tracking sensors on the ATD, which are able to operate without lateral high speed video cameras for tracking. High speed video recording inside the HGV cab is also very impractical in full scale testing.

The chest load case, consisting of the rigid horizontal bar to impact the chest in a perpendicular manner, was a simplification to achieve a robust test setup. Further studies to investigate the importance of this simplification are recommended. The load case also disregarded the angled impact which was identified in Paper II. Moreover, although the load distribution from a rigid horizontal bar may be similar to a physical steering wheel rim, it is not perfect. There are modes of deformation for a steering wheel which may influence the outcome in some cases. The degree of in-plane deformation (from the circular shape) of the steering wheel rim is one factor. A study by Holmqvist in 2010, where a generic steering wheel was impacted by an HMB and an FE Hybrid III model, indicated that the mode of deformation of a steering wheel may depend on the angle at initial contact to the chest, and also that the response may differ if it was loaded by a chest from a Hybrid III ATD or an HBM. This may also have implications on the impact location, and how the results acquired by the ATD should be interpreted. For instance, the anatomy of the human chest may offer a stronger resistance to steering wheel sliding than the chest of the ATD. The Hybrid III has been shown to have a high degree of coupling between the ribs and similar regional stiffness (Shaw et al., 2005), while this is not so for the human (Shaw et al., 2007), which would influence the contact location on the chest. Moreover, the mechanism behind rib fractures may be affected by the angle at which the force is applied to the chest, resulting in fractures from bending and/or torsion. Future studies focusing on these issues could be conducted by means of virtual testing.

Additional PMHS tests are recommended as a basis to increase confidence in simulations. Further such test data would give the opportunity to make more robust evaluations of the HBM and ATD models. The two PMHS tests conducted in Paper III provided some insight to the suitability of the THUMS in the specific load case. However, for a more conclusive evaluation, more details regarding steering wheel rim-to-chest interaction and the human responses are needed. There may also be a need to study the influence of spinal stiffness on the chest deformation characteristics, especially for the narrow load case which the steering wheel rim-to-chest represent. The spine of the THUMS is designed to maintain its posture, and may therefore be too stiff (Östh et al., 2012).

If a test setup similar to the one in Paper III is applied, it would be advantageous to accurately record any fractures during or between tests and to be able to investigate factors such as Bone Mineral Density (BMD) for each PMHS. There may also be a need to test other Hybrid III ATDs to establish if the resulting match, between the physical and FE Hybrid III, is affected by physical ATD variations and if it is necessary to improve on the validity of the Hybrid III FE model. There are also alternative methods to the Objective Rating Method (ORM), such as the Correlation and Analysis method (CORA), while evaluating the match between tests, although the CORA method was not explored during this work. The validity of both the FE Hybrid III model and the HBM will have an effect on the validity of the NCCF and the subsequent recalculated IARVs.

In the future it would be beneficial to find criteria that have the ability to resolve lower severity injuries, and utilise ATDs that are able to assess these. The ultimate aim in occupant safety should be to prevent all injuries, and therefore we must also be able to predict these. The low energy impacts to the chests of PMHS in Paper III, can be an appropriate level where a future ATD should be sensitive in assessing injury risk. The current IARVs are extracted from injury risk curves with large confidence intervals, which may provide somewhat low accuracy in predicting injuries. It may also be necessary to study the effect of different anthropometries on injury risk.

Furthermore, an increased number of PMHS tests would provide the means to study the reliability of the scaling method used in the current work, where some additional assumptions on the properties of the 50^{th} %ile male chest, such as chest depth and effective mass for the non-middle impact locations, were necessary. It is also possible to explore other, more recently developed, methods of scaling such as the deformation energy approach described by Donnelly et al. (2014).

Full scale or sled equivalent FE simulations of HGV cab and a Hybrid III ATD compared to an HBM will provide more information on steering wheel rim-to-chest interaction. Here, it would also be possible to employ an HBM and ATD which are more representative of the HGV driver anthropometry. In Paper I the drivers were found to be heavier than the average sized male. Studies have found that obese passenger car occupants are at risk of sustaining more severe injuries to e.g. the abdomen in some accident configurations (Pal et al., 2014; Ida et al., 2013). Moreover, obese HGV drivers have a higher accident risk (Anderson et al., 2012) and obesity can have implications on seat belt efficiency, by introducing more slack into the system (Reed et al., 2013). These issues also need further studies.

Furthermore, the Paper I study showed that the right and left side interior surfaces of HGV cabs were frequently stated as the point of contact giving rise to thoracic injury. This indicates that the real world accident scenarios may include a lateral component to the frontal loading, or a sequent event which causes the driver to make an oblique movement. The Hybrid III ATD was designed for pure frontal accidents, while future frontal crash test ATD candidates, such as the THOR, will be more apt in resolving oblique loading. It may also be desirable to investigate whether the design of the trailer-back crash test needs to be updated to include the variability of real-world accidents.

The approach used in this thesis is not restricted to establishing a relationship between the human and the Hybrid III ATD with respect to the two selected injury criteria, the C_{max} and the VC_{max}, but may also be applicable to various other injury criteria and ATDs. The relationships between the human and ATD also has the potential to be improved as the HBMs are continuously being refined in many aspects.

5 CONCLUSIONS

The aim of this thesis was to evaluate and improve on the capacity of the Hybrid III ATD in assessing thoracic injury risk in frontal HGV crash tests. The results from the database study on accidents indicate that the front-to-rear end impact of the HGV is an essential load case and an appropriate method of evaluating HGV driver safety. The results also confirm that thoracic injuries should be prioritised due to high occurrence and severity.

Sled test analyses indicated that the major contributor to chest deflection was contact to the steering wheel rim. It was demonstrated how the instrumentation in an HGV crash test may be extended to allow for the Hybrid III ATD to accurately resolve the chest response from steering wheel rim loading. A minimum requirement for the Hybrid III, is that the deflection at the top and bottom of the sternal plate is sampled and that the instantaneous point of contact of the steering wheel rim to the chest is registered. The measurement from the standard chest deflection sensor in the Hybrid III ATD is insufficient and may cause an erroneous estimation of chest deflection at the point of impact.

Unique PMHS chest impact data was produced for evaluation of steering wheel rim-to-chest loading for HBMs and ATDs. This data was applied to THUMS, which was shown to adequately reproduce the overall, and intra-subject, response variations of human chest, as represented by PMHSs. The results showed that the human offered a stiffer response to a bar-shaped impactor at the cranial part of the chest and softer response in the caudal part of the chest. The comparison in responses between the hub-shaped impactor and the bar-shaped impactor indicated that the human has a greater resistance to chest deflection for the bar-shaped impactor. This was opposite for the Hybrid III ATD.

The utilisation of the THUMS to evaluate the responses of the Hybrid III showed that higher IARVs for the ATD may be applied to represent the injury risk to the human in steering wheel rim-to-chest impacts. This is mainly an effect of the inverse response difference between hub-shaped and bar-shaped impactors of the human and the Hybrid III.

The present study used PMHS and ATD testing in combination with HBM and ATD simulation to develop a transfer function to convert the proposed detailed Hybrid III ATD chest deflection data into predicted chest deflection of a human HGV driver.

The presented process to develop such a transfer function shows a feasible chain of methods to develop a transfer function to transform ATD output into improved predictions of human chest response. It is however strongly recommended that the current work is complemented with additional PMHS test data as well as more elaborate evaluations of the assumptions made in the different steps of this chain. This would be a requirement in case this type of instrumentation and transfer function would be considered for standardisation or regulation.

More studies are needed for the complete picture of HGV driver safety evaluation in crash testing. However, the step from just using a Hybrid III ATD, which was designed for passenger car safety evaluation, in the new load case that the HGV frontal crash test represent, this thesis provide a leap forward in the understanding of what factors needs to be taken into account when the Hybrid III is used for HGV driver safety evaluation.

APPENDIX A. EFFECT OF SCALING PROPERTIES ON RESPONSES AND IARVS

One concern in the studies in this thesis is the scaling method (Mertz, 1984; Viano, 1989) used to account for differences in test parameters and anthropometries in Paper III and Paper IV. For the scaling of impacts to the middle chest, the 50^{th} %ile male size parameters are considered to be known, where the effective chest mass is set to 28.5 kg (Lebarbé and Petit, 2010) and the chest depth is set to 229 mm. However, uncertainties as to how these measures are affected when the impact height is changed have arisen. Ultimately, the scaling may have a potential effect on the NCCF, and subsequent IARV, results in Paper V. The purpose of this appendix was to study the effect of changing these parameters which was conducted based on the THUMS being designed to represent the 50^{th} %ile male size, and use the calculated resulting parameters from replicated simulations of each PMHS test. From these, the chest effective mass and depth, can be used to scale the response of each PMHS test in Paper III individually. In this study, the nominal velocity of 2.4 m/s and impactor mass of 23.4 kg was used for scaling. The results from the new scaling parameters have been compared to the results from Paper III. Only the C_{max} criterion was considered here, since the scaling method was considered to work poorly with the VC_{max} criterion in Paper III.

The chest depth was the distance from the impactor centre to the corresponding point on the posterior chest at time of initial contact (t0). The effective mass of the body (m_2) was calculated using the "Conservation of momentum and energy" method (Horsch and Patrick, 1976), which require the input from impactor Contact Force (F), Chest Deflection (x), Impactor Mass (m_1) and the Impactor initial Velocity (v_0).

The initial sum of momentum is conserved after impact

$$m_1 * v_{1_0} + m_2 * v_{2_0} = m_1 * v_1 + m_2 * v_2 \quad \text{(Eq.1)}$$

Where $v_{1_0} = initial\ impactor\ velocity$ And $v_{2_0} = initial\ body\ velocity$

Given the initial conditions of the setup ($v_{1_0} = v_0;\ v_{2_0} = 0$);

$$m_1 * v_0 = m_1 * v_1 + m_2 * v_2 \quad \text{(Eq.2)}$$

At the point of maximum deflection the velocity of the impactor and the body are identical ($v_1 = v_2$).

$$m_1 * v_0 = v_1(m_1 + m_2) \quad \text{(Eq.3)}$$

$$v_1 = \frac{m_1 * v_0}{(m_1 + m_2)} \quad \text{(Eq.4)}$$

Conservation of energy:

Energy of impactor initial to impact is equal to the sum of kinetic energy of impactor and body and the deflection energy (E_d) of the chest.

$$\frac{m_1 * v_0^2}{2} = \frac{m_1 * v_1^2}{2} + \frac{m_2 * v_2^2}{2} + E_d \quad \text{(Eq.5)}$$

At the time of maximum chest deflection the deformation energy is:

$$E_d = \int_{x=0}^{x_{max}} F * \mathrm{d}x \quad \text{(Eq.6)}$$

Solving Eq.5 for the effective mass of the body (m_2) results in

$$m_2 = \frac{2*E_d*m_1}{m_1*v_0^2 - 2*E_d} \quad \text{(Eq.7)}$$

Table A1. Test abbreviations and descriptions

Test Abbreviation	Test Description
HM	Hub Middle Location
BM	Bar Middle Location
BH	Bar Higher Location
BL	Bar Lower Location
BM*	Bar Middle Location, High Speed

Applying results from the Paper IV simulation study to the results of Paper III

The results from the replicated simulation of the PMHS tests provide the following results for the effective chest mass and chest depth (Table A2).

Table A2. Resulting effective mass and chest depth based on replicated simulations of the PMHS tests using the THUMS. Test configuration abbreviations are in accordance with Table A1.

Test configuration	Replicated test	Effective mass (kg)	Chest depth (m)
HM	THUMS PMHS 1	29.9	0.232
HM	THUMS PMHS 2	27.2	0.231
BM	THUMS PMHS 1	33.3	0.232
BM	THUMS PMHS 2	32.6	0.230
BH	THUMS PMHS 1	35.1	0.232
BH	THUMS PMHS 2	26.0	0.219
BL	THUMS PMHS 1	29.8	0.233
BL	THUMS PMHS 2	35.5	0.232
BM*	THUMS PMHS 1	36.1	0.232
BM*	THUMS PMHS 2	34.2	0.231

The calculated C_{max} from the re-scaled responses provided difference of up to 6% from the originally scaled responses using the same 50th %ile parameters for chest mass and chest depth (Table A3)

Table A3. Responses from the PMHS tests. Non-scaled C_{max}, the C_{max} calculated using the 50th %ile parameters, and the C_{max} calculated from scaled responses using the THUMS resulting effective mass and chest depth.

Test configuration	Test subject	Original Cmax	Original Scaled Cmax	Re-scaled Cmax	Ratio
HM	PMHS 1	0.156	0.259	0.257	99%
HM	PMHS 2	0.188	0.254	0.250	99%
BM	PMHS 1	0.123	0.238	0.245	103%
BM	PMHS 2	0.222	0.224	0.227	102%
BH	PMHS 1	0.087	0.210	0.217	103%
BH	PMHS 2	0.142	0.187	0.193	103%
BL	PMHS 1	0.153	0.282	0.298	106%
BL	PMHS 2	0.207	0.253	0.268	106%
BM*	PMHS 1	0.100	0.218	0.229	105%
BM*	PMHS 2	0.202	0.191	0.198	103%

Impact of the results on the conclusions of Paper III and Paper IV

The impact of re-scaling the responses using the calculated parameters from the THUMS simulations is small. The largest effect is identified for the BL configurations where the average difference to the BM was 120% in contrast to the 116% using the original scaling method. Overall, the intra-subject responses were in concordance with the previous results, showing a stiffer response for the BH impacts and a softer response for the BL impacts in comparison to the BM. The difference of the BM to the HM was similar at 93% compared to 90% using the 50th %ile parameters (Table A4).

Table A4. Normalised responses of the PMHS tests using original scaling and re-scaled using THUMS parameters.

Test configuration	Test subject	Original scaling responses			Re-scaled responses		
		Normalised to HM	Normalised to BM	Average	Normalised to HM	Normalised to BM	Average
HM	PMHS 1	100%			100%		
HM	PMHS 2	100%			100%		
BM	PMHS 1	92%	100%		95%	100%	
BM	PMHS 2	88%	100%	90%	91%	100%	93%
BH	PMHS 1		88%			88%	
BH	PMHS 2		84%	86%		85%	87%
BL	PMHS 1		118%			122%	
BL	PMHS 2		113%	116%		118%	120%
BM*	PMHS 1		92%			93%	
BM*	PMHS 2		85%	88%		87%	90%

Applying results from the Paper IV simulation study to the results of Paper IV

As stated in the Paper IV study, the THUMS responses were also scaled to the 50th %ile male size. Therefore the same approach was conducted for the simulation results. When scaling the THUMS responses towards the acquired results from the THUMS simulations, the resulting scaling parameter are equal to 1 (no scaling), with the exception of the BM* responses which were scaled with respect to initial velocity. Comparing these results we found that the largest difference was at the BH for the PMHS 2, which was 8% higher using the re-scaled (or non-scaled) compared to the response scaled to the 50th %ile male size (Table A5).

Table A5. Responses from the THUMS replicate simulations. Non-scaled C_{max}, the C_{max} calculated using the 50th %ile male size parameters, and the C_{max} calculated from scaled responses using the THUMS resulting effective mass and chest depth. Ratio is the ratio of the Original scaled to response the Re-Scaled response.

Test configuration	Replicated test	Original Cmax	Original Scaled Cmax	Re-scaled Cmax	Ratio
HM	THUMS PMHS 1	0.207	0.211	0.207	98%
HM	THUMS PMHS 2	0.205	0.210	0.205	98%
HM	THUMS nominal	0.211	0.210	0.211	100%
BM	THUMS PMHS 1	0.205	0.201	0.205	102%
BM	THUMS PMHS 2	0.189	0.187	0.189	101%
BM	THUMS nominal	0.202	0.200	0.202	101%
BH	THUMS PMHS 1	0.197	0.194	0.197	102%
BH	THUMS PMHS 2	0.179	0.166	0.179	108%
BH	THUMS nominal	0.182	0.175	0.182	104%
BL	THUMS PMHS 1	0.268	0.257	0.268	104%
BL	THUMS PMHS 2	0.258	0.246	0.258	105%
BL	THUMS nominal	0.270	0.260	0.270	104%
BM*	THUMS PMHS 1	0.206	0.175	0.182	104%
BM*	THUMS PMHS 2	0.212	0.182	0.186	102%
BM*	THUMS nominal	0.206	0.176	0.180	102%

Similar to the re-scaled responses of the PMHSs, the results from the THUMS simulations do not significantly affect the results, nor do they change the conclusions from Paper IV. The intra-subject responses are still consistent in that the BH provides a stiffer response and the BL responses are softer (Table A6).

Table A6. Normalised responses of the THUMS simulations using original scaling and re-scaled towards THUMS parameters.

Test configuration	Replicated test	Original scaling responses			Re-scaled responses		
		Normalised to HM	Normalised to BM	Average	Normalised to HM	Normalised to BM	Average
HM	THUMS	100%			100%		
HM	THUMS	100%			100%		
HM	THUMS	100%			100%		
BM	THUMS	95%	100%		99%	100%	
BM	THUMS	89%	100%		92%	100%	
BM	THUMS	95%	100%	93%	96%	100%	96%
BH	THUMS		96%			96%	
BH	THUMS		89%			95%	
BH	THUMS		87%	91%		90%	94%
BL	THUMS		128%			131%	
BL	THUMS		131%			136%	
BL	THUMS		130%	130%		133%	133%
BM*	THUMS		87%			89%	
BM*	THUMS		97%			98%	
BM*	THUMS		88%	91%		89%	92%

The stiffness difference in the Paper IV study, using the 50th %ile male size parameters, showed that the average of the ratio of BH to BM of the PMHSs was 86% compared to 91% for the THUMS. The average of the ratio of BL to BM of the PMHSs was 116% compared to 130% for the THUMS. The difference in HM to BM was on average 90% for the PMHSs and 93% for the THUMS. When re-scaling, using the THUMS resulting parameters, the BH to BM ratio was 87% for the PMHSs and 94% for the THUMS and the BL to BM was 120% for the PMHSs and 133 for the THUMS. The HM to BM ratio was 93% for the PMHSs and 96% for the THUMS.

Influence of re-scaled results on the Paper V results

In section 4.4.1 of the thesis, the implication of stiffness differences between the PMHSs and the THUMS was explored. There, the stiffness was found to be 5.4% softer for the BH impact condition and 10.8% stiffer for the BL impact condition compared to the BM. The difference in stiffness for the HM and BM was 3.4% softer for the PMHSs than the THUMS. The results were shown not to affect the conclusion of Paper V. By using the re-scaled responses, the stiffness was found to be 7.5% softer for the BH impact condition and 10.2% stiffer for the BL impact condition compared to the BM impact condition. The difference in stiffness for the HM and BM was 2.8% softer for the PMHSs than the THUMS.

*Table A7. Recalculated IARVs for the chest deflection for steering wheel impacts to the chest of the Hybrid III based on THUMS stiffness variations, conducted by increasing or decreasing criteria responses of the THUMS by 5%. **Original Paper V** designate the result from the study, the **Mean** is the average from the stiffness variation study (Paper V Appendix A, with the standard deviations), and the **Outcome Paper IV**, is the result by applying the resulting differences from the PMHS to the THUMS in the Paper IV study. The **Re-scaled outcome** is the results of applying the parameters from the THUMS replicate simulations to extract stiffness differences to the PMHSs (See Paper V, Appendix A, for more details on the original variation study).*

	Hybrid III chest deflection (mm)		
	Higher	Middle	Lower
Original Paper V	59.8	54.8	53.6
Mean	59.9	54.8	53.6
Mean +1 SD	62.5	54.8	58.0
Mean -1 SD	57.2	54.8	49.3
Outcome Paper IV	56.2	53.1	65.5
Re-scaled outcome	55.6	53.4	64.3

Conclusion

Using the resulting THUMS effective mass and chest depth parameters from the replicated PMHS tests have very little effect on the recalculated IARVs, although they are not included within the standard deviations from the original Paper V, Appendix A, variation study.

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