Characterisation and investigation of serious thoracic injuries in passenger vehicle rollover crashes

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Characterisation and Investigation of Serious Thoracic Injuries in Passenger Vehicle Rollover Crashes

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Abstract

Passenger vehicle rollover crashes involving a single vehicle occur infrequently; however, when they do the vehicle occupants in these crashes are more likely to sustain serious and fatal injuries compared to other crash modes. The thorax is frequently seriously injured in rollover crashes. Ongoing efforts in the USA and Australia have sought to understand the characteristics and aetiology of these injuries. Despite these efforts, the characteristics and aetiology of thoracic injuries in rollover crashes are still not well understood. It has been hypothesised that these injuries are occurring as a result of occupant flailing within the vehicle during the rollover crash event. Four studies were performed and documented in this thesis to address this identified knowledge gap. Firstly, Flail-space's lateral thoracic impact velocity was validated against existing lateral PMHS thoracic impact tests. The validated velocity was then used as an injury criterion for assessing lateral thoracic injuries resulting from rollover crashes. Secondly, thoracic injuries from real-world vehicle rollover crashes were examined based on occupant seated position and vehicle rollover direction. The results indicated that there is a difference in resultant thoracic injuries based on occupant seated position and rollover direction. Thirdly, correlations between vehicle panel damage and serious thoracic injuries were investigated from real-world rollover crashes. The results indicated that there are associations between vehicle panel damage and serious thoracic injuries. Fourthly, two real-world rollover crash where the driver sustained serious thoracic injuries were analysed using computer simulations to study thoracic injury aetiology and its association with vehicle panel damage, as identified in the third study. Thoracic injuries were then assessed against existing thoracic injury criteria and the lateral thoracic impact velocity criterion from the first study. The results of the analysis indicate two instances in a rollover crash where, indeed, serious thoracic injuries occurred as a result of occupant flailing during the event, thus, confirming the hypothesis.

ORIGINALITY STATEMENT

‘I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at UNSW or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by others, with whom I have worked at UNSW or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.’

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Peer-Reviewed Journal Papers

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Engineering should be performed for the betterment of our environment and those that live within it.

- Tana C. Tan

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Nomenclature

AIS	Abbreviated Injury Scale
ASA	Average Spinal Acceleration
ATD	Anthropomorphic Test Device
AUC	Area Under the Curve
CCIS	Co-operative Crash Injury Study
CFC	Channel Filter Class
CDS	Crashworthiness Data System
CG	Centre of Gravity
CI	Confidence Interval
CIREN	Crash Injury Research Network
deg/s	Degrees per second
EDR	Electronic Data Recorder
EU	European Union
EuroSID	European Side Impact Dummy
FE	Finite Element
FORS	Federal Office of Road Safety
g	gravitational force
GIDAS	German In-Depth Accident Study
IIHS	Insurance Institute for Highway Safety
kg	kilogram
km/h	Kilometres per hour

MAIS	Maximum Abbreviated Injury Scale
MLE	Maximum Likelihood Estimate
MPH	Miles per hour
m/s	metres per second
NASS	National Automotive Sampling System
NCAP	New Car Assessment Program
NFS	Not Further Specified
NHTSA	National Highway Traffic Safety Administration
NSW	New South Wales
NT	Northern Territory
OR	Odds Ratio
PMHS	Post Mortem Human Surrogate
rad/s	Radians per second
ROC	Receiver Operator Characteristic
SAE	Society of Automotive Engineers
SID	Side Impact Dummy
SSF	Static Stability Factor
SUV	Sports Utility Vehicle
UK	United Kingdom
UMTRI	University of Michigan Transportation Research Institute
US	United States
USSID	United States Side Impact Dummy
VC	Viscous Criteria

VIC	Victoria
WorldSID	World harmonised Side Impact Dummy
4WD	Four- Wheel Drive

Abstract

Passenger vehicle rollover crashes involving a single vehicle occur infrequently; however, when they do the vehicle occupants in these crashes are more likely to sustain serious and fatal injuries compared to other crash modes. The thorax is frequently seriously injured in rollover crashes. Ongoing efforts in the USA and Australia have sought to understand the characteristics and aetiology of these injuries. Despite these efforts, the characteristics and aetiology of thoracic injuries in rollover crashes are still not well understood. It has been hypothesised that these injuries are occurring as a result of occupant flailing within the vehicle during the rollover crash event. Four studies were performed and documented in this thesis to address this identified knowledge gap. Firstly, Flail-space's lateral thoracic impact velocity was validated against existing lateral PMHS thoracic impact tests. The validated velocity was then used as an injury criterion for assessing lateral thoracic injuries resulting from rollover crashes. Secondly, thoracic injuries from real-world vehicle rollover crashes were examined based on occupant seated position and vehicle rollover direction. The results indicated that there is a difference in resultant thoracic injuries based on occupant seated position and rollover direction. Thirdly, correlations between vehicle panel damage and serious thoracic injuries were investigated from real-world rollover crashes. The results indicated that there are associations between vehicle panel damage and serious thoracic injuries. Fourthly, two real-world rollover crash where the driver sustained serious thoracic injuries were analysed using computer simulations to study thoracic injury aetiology and its association with vehicle panel damage, as identified in the third study. Thoracic injuries were then assessed against existing thoracic injury criteria and the lateral thoracic impact velocity criterion from the first study. The results of the analysis indicate two instances in a rollover crash where, indeed, serious thoracic injuries occurred as a result of occupant flailing during the event, thus, confirming the hypothesis.

1 Introduction

Road traffic crashes are the eighth leading cause of fatalities worldwide resulting in more than 1.2 million deaths a year. Road crashes especially affect the younger population as they are the leading cause of fatality for young people aged 15 to 29 years.[79] Current trends indicate that road crashes will become the fifth leading cause of fatalities by 2030 unless action is taken to counter this trend.[159, 160]

Road traffic crashes are the second leading cause of unintentional deaths in the United States of America (USA) [22], resulting in approximately 21,000 passenger vehicle fatalities per year [109]. Vehicle rollover crashes are a particular problem. Although they occur infrequently, when they do, they are more likely to result in vehicle occupants sustaining serious or fatal injuries.[12, 46, 126] Rollover crashes have been and continue to be significantly over-represented in fatal passenger vehicle crashes. In 2014, rollover crashes represented only 1.7% of all passenger vehicle crashes yet contributed to just over 32% of all fatalities in the USA.[109] This equates to just over 6,800 fatalities.[109]

The three most common seriously injured body regions in a rollover crash where the occupant is restrained by a seatbelt are the head, thorax and spine.[13, 93, 125, 126] Of these three regions, injuries to the thorax have been and continue to be the least well researched. Although a recent study of passenger vehicle rollover crashes[12] has provided an insight into the epidemiology of serious thoracic injuries resulting from rollover crashes, the aetiology of these injuries is still not understood. As such, the aetiology of thoracic injuries is the focus of this thesis. It is through a better understanding of thoracic injury aetiology that injury mitigating solutions may then be developed.

This thesis has three aims, which are:

1) Develop a potential injury criterion for determining the likelihood of a serious thoracic injury occurring in a rollover crash based on thoracic lateral impact velocity.

2) Determine if the distribution of thoracic injuries and thoracic injury sources differs based on the occupant seated position and rollover direction.

3) Determine if significant rollover vehicle damage and, thus, a marked decrease in vehicle velocity at the moment when the vehicle impacts the ground, is associated with an occupant sustaining thoracic injuries.

The hypothesis of this thesis is that AIS3+ thoracic injuries are occurring when an occupant flails into and impacts vehicle interior components due to a sudden change in vehicle rollover kinematics.

The structure of this thesis has been organised around the aforementioned aims and is presented below:

In Chapter 2, an introduction to the principles of crashworthiness is presented. This is followed by a background on rollover crash epidemiology from the USA, Australia and Europe. Rollover crash vehicle and occupant kinematics are then examined. This is then followed by an analysis of rollover occupant injuries and thoracic injury epidemiology. Finally, areas which require further research in order to better understand the aetiology of thoracic injuries are identified.

In Chapter 3, a brief overview of current injury assessment criteria is presented. The lateral impact velocity from the flail-space model as a potential alternative for thoracic injury assessment is proposed. The lateral component of the flail-space model is then validated against existing Post Mortem Human Surrogate (PMHS) test data. A lateral impact velocity versus resultant thoracic injury model is then developed and presented. From this model, an updated lateral impact velocity for the flail-space model is proposed. This is the first time, to the author's knowledge, that the flail-space lateral impact velocity has been validated. The results from this study are then applied to an investigation of the aetiology of thoracic injuries from a real-world rollover crash in Chapter 6. This is the first time, to the author's knowledge, that the flail-space lateral impact velocity has been applied to investigate thoracic aetiology in a rollover crash.

In Chapter 4, the distribution of thoracic injuries and their sources based on occupant seated positions and vehicle rollover directions are explored using existing rollover crash data. Although previous research has identified the most frequently reported thoracic injuries and their sources, this research is original as thoracic injuries and their sources have now been considered based on occupant seated position and vehicle rollover direction.

In Chapter 5, a case-control study is performed on 224 real-world rollover crashes to determine whether there is an association between vehicle damage and thoracic injuries. Multiple variable logistic regression is performed on the data from these 224 real-world rollover crashes to determine whether rollover crash variables and vehicle damage are associated with an occupant sustaining thoracic injuries. This study is original as it explores potential associations between vehicle damage and thoracic injuries through the use of statistical analysis. The findings from this chapter are then applied to the study documented in Chapter 6.

In Chapter 6, a real-world rollover crash where the driver sustained serious thoracic injuries is reconstructed using computer simulations. This was performed to better understand whether lateral impact velocity from the flail-space model from Chapter 3 can be used as an alternative thoracic injury assessment criterion. The results from the simulation were also used to investigate thoracic injury etiology in rollover crashes. Additionally, simulations also explored whether vehicle damage may be potentially associated with the driver sustaining serious thoracic injuries; thus, drawing on the results from Chapter 5. The study documented in Chapter 6 is also the first time, to the author's knowledge, that a side-impact Anthropomorphic Test Device (ATD) has been used in the reconstruction of a real-world rollover crash using computer simulations.

In Chapter 7, a study was performed which followed on from the findings from Chapter 6. In this study, a real-world rollover crash was reconstructed using computer simulation. The findings from the flail-space model from Chapter 3 was then applied to the vehicle's kinematics obtained from the computer simulation to demonstrate how the findings from Chapter 3 can be used to determine where in the rollover sequence serious thoracic injuries are occurring.

Finally, in Chapter 8, a summary, conclusions and recommendations for future research based on the results and findings from this thesis are presented.

The findings presented in this thesis will guide any future research aimed to further understand serious thoracic injury aetiology resulting from rollover crashes. The findings are significant as they provide an alternative lateral thoracic injury assessment criterion, presents thoracic injuries distribution based on occupant seated position and rollover direction and identifies associations between vehicle rollover environment and vehicle damage and thoracic injuries. Further, the findings also identify ATD kinematics in rollover crashes which has previously not been reported as well as limitations in existing ATDs when used in rollover crash testing for thoracic injury aetiology investigations. These findings will provide valuable information to the ongoing research on thoracic injury aetiology and thoracic injury mitigating devices for rollover crashes.

2 Background & Literature Review

2.1 Introduction

Vehicle crashes can be categorised under four broad crash types: frontal impact, side-impact, rear impact and rollover crashes. Of these four crash types, rollover crashes occur least frequently yet they contribute to a significant and over-representative proportion of occupant injuries. In a rollover crash, the head, neck and thorax are the three most commonly injured body regions.[13, 93, 125, 126] Of these three regions, injury to the thorax is the least well researched and understood and still remains a knowledge gap in regards to their source in a rollover crash. In order to develop effective thoracic injury mitigating devices, a better understanding of the aetiology of thoracic injuries in rollover crashes needs to be developed.

This chapter begins by providing a background to the study of vehicle crashworthiness in Section 2.2. An overview of rollover crash key concepts and the current situation regarding rollover crash statistics in the United States (US), Australia and Europe is then provided in Sections 2.3.1, 2.3.2 and 2.3.3 respectively. This is followed by an overview of vehicle and occupant rollover kinematics in Section 2.4 and 2.5, respectively. Thoracic injuries sustained in rollover crashes and its sources are then presented in Section 2.6.2 and 2.6.3, respectively. This is followed by Section 2.6.4 where potential mechanisms for thoracic injuries during a rollover crash are presented.

Based on the review of the literature, opportunities for developing a better understanding of thoracic injuries in rollover crashes have been identified and are presented in Section 2.6.2, 2.6.3 and 2.6.4. The identified knowledge gaps forms the basis for the research documented in this thesis.

2.2 Crashworthiness Principles

Crashworthiness is defined by the Oxford English Dictionary as, [1]

> *“The quality in an aircraft or motor-vehicle that makes it safer in the event of a crash.”*

The concept of crashworthiness was developed in the early 20th century when Hugh de Haven, then a cadet in the Canadian Royal Flying Corps, was flying in an aircraft which collided with another aircraft in mid-air.[85] Although de Haven survived this mid-air collision the gunner of the other aircraft did not. From this incident, de Haven noted that certain injuries can be prevented through better design of an aircraft's interior.[32, 85] Support that there was a need for a rethink regarding how injuries can be prevented in crashes was demonstrated a few years later when one of de Haven's friends was killed in a car crash.[32] The fatality was attributed to injuries sustained from impact with a sharp steel control knob for the windscreen wipers.[32] Through this event, what de Haven believed was a preventable fatality, he realised that engineers and designers did not understand the concept of safety engineering. His hypothesis was that the interior of a vehicle can be designed to minimise the potential for sustaining an injury in the event of a crash.[32]

In the 1950s, John Stapp, a Colonel in the United States Air Force furthered the work performed by de Haven by securing himself into a rocket propelled sled which was decelerated abruptly from 600 miles per hour with an acceleration exceeding 25 *g*. Although he was blinded temporarily, he suffered no other permanent injuries. Through this experiment, Stapp demonstrated that humans can survive high speed decelerations given the appropriate safety protection.[85]

Over the decades, the concept of safety engineering was developed further, human tolerance to injury was better understood and this translated into safer vehicle design. However, what has not changed is the principle of crashworthiness which was developed originally by de Haven. He demonstrated these principles through an analogy to packaging [32]:

> 1) The package shall not open up and spill its content and should not collapse under expected conditions of force and thereby expose objects inside to damage.
>
> 2) Packaging structures which shield the inner container must not be made of brittle or frail materials; they should resist force by yielding and

absorbing energy applied to the outer container so as to cushion and distribute impact and thereby protect the inner container.

3) Articles contained in the packaging should be held and immobilised inside the outer structure.

4) Wadding, blocks or means for holding an object inside a shipping container must transmit forces to the strongest parts of the contained objects.

These principles are still valid to this day and need to be recognised and used in order to develop safer vehicles. Further, they are particularly relevant in regards to preventing thoracic injuries in rollover crashes

2.3 Rollover Crashes

The vast majority of the published statistical data on rollover crashes come from the US, Australia and Europe. The sections below present key statistics from each of these three regions and also provide a background on key concepts for vehicle rollover crashes for this thesis.

2.3.1 US Statistics

In 2014, a total of 6.06 million police reported passenger vehicle crashes occurred in the US. Of these, rollovers accounted for 102,000 crashes which represent 1.7% of all passenger vehicle crashes.[109] A rollover crash is defined as a crash whereby a vehicle rotates laterally or longitudinally by more than ninety degrees about its longitudinal or lateral axis, respectively, and impacts the ground or another object.

Out of the 6.06 million reported passenger vehicle crashes, there were a total of 21,002 vehicle occupant fatalities. Of these, 6,839 vehicle occupant fatalities occurred in rollover crashes. This represents just over 32% of all vehicle occupant fatalities.[109] That is, rollover crashes contribute to a disproportionate number of passenger vehicle occupant fatalities. This trend has been observed to be consistent over a number of decades [13, 97, 107, 108] and indicates that the protection offered to vehicle occupants in rollover crashes has been inadequate compared to that in other crash types. It is only just recently has there been some attempts to address this issue; albeit, there is still a lot more that can be done, particularly in regards to thoracic injuries.

A limitation of the statistics is the definition of what constitutes a rollover crash. It is recognised that a rollover crash may occur as a single-vehicle crash or in combination with another crash type such frontal, side or rear impact crash. Further, a rollover may occur prior to, during or after a vehicle impacts another object or another vehicle. This result in the inability of crash investigators and researchers to identify which occupant injury can be attributed to the rollover in isolation to other non-rollover confounding impacts. The statistics also do not clearly indicate what percentage of rollover crash fatalities are due to single vehicle rollover crashes. To address this issue, previous research examined US crash data to determine the proportion of vehicle occupant fatalities that occur in single vehicle rollover crashes [34, 39, 148] and found that single vehicle rollovers accounted for more than 80% of all rollovers [39]. Further, 99% of single vehicle rollovers were lateral rollover (i.e., the vehicle rotated about its longitudinal axis) and 73% were initiated by a mechanism known as a trip-over (Figure 2.1). Parenteau *et al*. categorised each of these rollover initiation mechanisms as shown in Table 2.1.[94, 118] Thus, a substantial portion of rollover crash research has focussed on single vehicle tripped rollovers and is also the focus of this current study; albeit, regarding how serious thoracic injuries occur in such events.

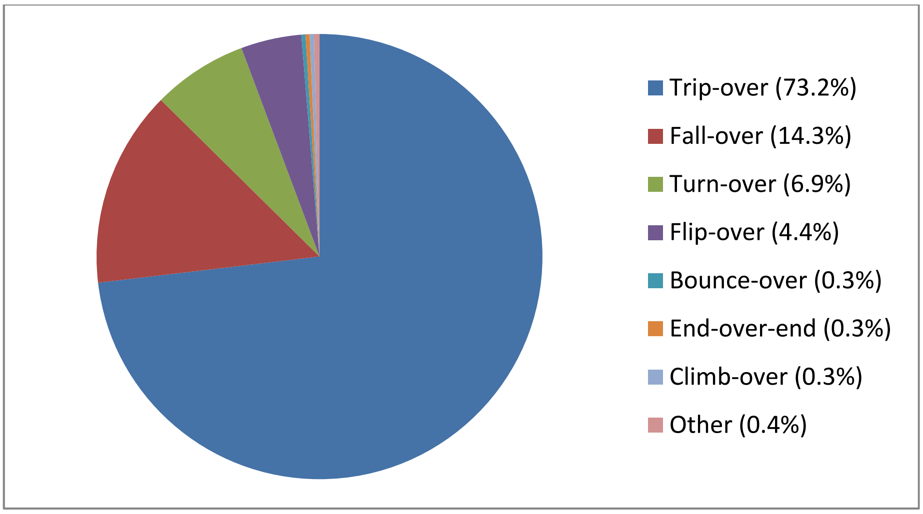
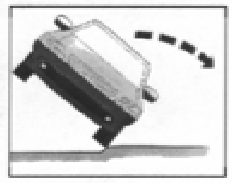
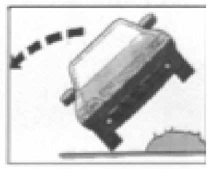
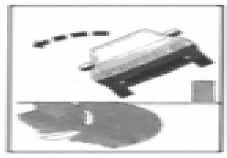
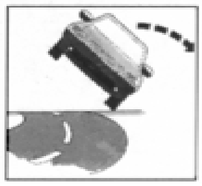
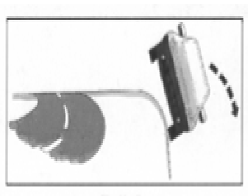


Figure 2.1 Distribution of rollover by initiation mechanism

Table 2.1 Rollover initiation mechanism (Source: Parenteau *et al*., 2003)

Rollover Initiation Mechanism	**Description**	**Diagram**
Trip Over	When the vehicle's lateral motion is suddenly slowed or stopped, inducing a rollover. The opposing force may be produced by a curb, pot hole or pavement/soil dug into by a vehicle's wheels.	
Flip Over	When the vehicle is rotated about its longitudinal axis by a ramp-like object,such as the turned-down end of a guardrail, it may be in a yaw when it comes in contact with the ramp-like object.	
Bounce Over	When a vehicle rebounds off a fixed-object and overturns as a consequence. The rollover must occur in close proximity to the object from which it is deflected.	
Turn Over	When centrifugal forces from a sharp turn or vehicle rotation is resisted by normal surface friction. The surface includes pavement surface and gravel, grass, soil, etc. There is no furrowing, gouging at the point of impact. If the rotation and/or surface friction causes a trip, then the rollover is classified as a turn-over.	
Fall Over	When the surface on which the vehicle is travelling slopes downward in the direction of movement of the vehicle such that the centre of gravity becomes outboard of its wheels.	
Climb Over	When the vehicle climbs up and over an object that is high enough to lift the vehicle completely off the ground. The vehicle must roll on the opposite side from which it approached the object.	

The environment in which rollovers occur has been previously examined. The research evidence indicates that rollover crashes tend to occur on sealed straight roads or on those with a slight bend [12, 39], roads with a high speed limit, [33, 97, 101] and on undivided two-way roads or divided roads with no barriers [97].

Vehicle body type and its association with the probability of a vehicle to be involved in a rollover crash have also been previously examined.[13, 59, 101] Vehicle body type can be divided into two broad categories when studying rollover crashes: passenger car and utility vehicles (Table 2.2). The former category consists of vehicles such as sedans, hatch backs and station wagons. The latter category consists of vehicles such as pickups, sports utility vehicles (SUVs), four-wheel drives (4WD) and vans. Of the two vehicle categories, utility vehicles are involved in rollover crashes more frequently than passenger cars [13, 59, 101] and are over-represented in rollover crashes [13]. This is due to their higher Centre of Gravity (CG) and, thus, greater propensity to rollover. Further, utility vehicle occupants are more likely to be fatally injured compared to those in passenger cars.[107]

Table 2.2 Vehicle categories (Image Source: New South Wales Roads and Maritime Services, 2013)

Category	Examples
Passenger Car	 Sedan

	 Hatch back  Station wagon
Utility Vehicle	 Pickup Truck  Sports utility vehicle  Four-wheel drive

Van

The findings on utility vehicles being more susceptible to rolling over led researchers to develop the concept of Static Stability Factor (SSF) which measures the propensity of a vehicle to roll over.[25] SSF is expressed by the following equation:

$$SSF = \frac{T}{2H} \qquad \text{Equation 2.1}$$

Where T is the vehicle's track width and H is the height of a vehicle's CG (Figure 2.2). SSF is now a widely accepted method of calculating a vehicle's propensity to roll over and has been adopted in 2001 by the National Highway Traffic Safety Administration's (NHTSA) rollover crash rating consumer information program.[100] However, a limitation in SSF is in that it over does not take into consideration the vehicle's dynamic characteristics influenced by the vehicle's suspension, tyres and steering components.[124] As such, the NHTSA now includes a dynamic manoeuvring test which takes into account a vehicle's suspension, tyre and steering characteristics. The result from this test is displayed alongside the SSF rating of a vehicle.[42]

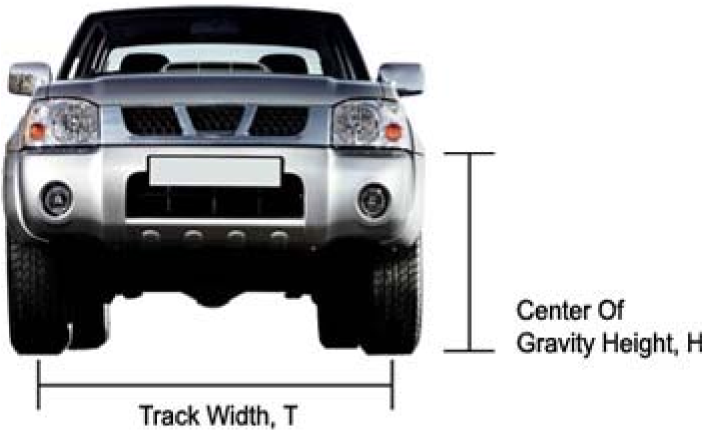


Figure 2.2 Static Stability Factor (SSF) (Source: Center for Injury Research) [23]

It is common practise for researchers analysing rollover crashes to divide a vehicle's rollover kinematics into quarter-turns where one quarter-turn corresponds to the vehicle undergoing a ninety degree rotation about its longitudinal axis. Thus, a vehicle that has undergone one full rotation has undergone four quarter-turns (Figure 2.3). Most rollovers have been observed to undergo less than eight quarter-turns before coming to rest (Figure 2.4). An increase in the number of vehicle quarter-turns is associated with an increase in the likelihood of an occupant sustaining MAIS3+ injuries (Figure 2.4) (See Appendix A).[39] These two key findings are similar to those reported by Eigen [39], Moore *et al*. [93], Conroy *et al*. [27] and Viano *et al*. [153]. A more detailed discussion on injuries and rollover occupant kinematics is presented in Section 2.5.

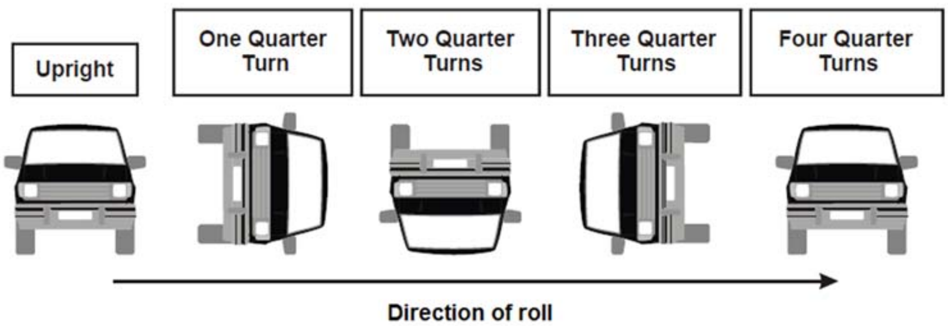


Figure 2.3 Vehicle quarter-turn (Source: NASS-CDS Coding and Editing Manual, 2015)

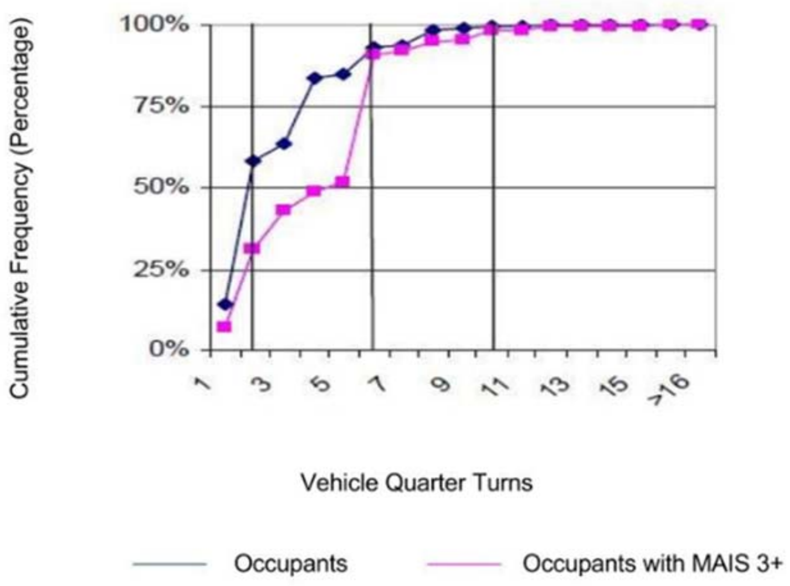


Figure 2.4 Number of vehicle quarter-turn versus occupants and occupants with MAIS3+ injuries (Source: Digges and Eigen, 2004)

A vehicle's seatbelt was designed and developed to reduce the likelihood of an occupant sustaining serious or greater (AIS3+) (See Appendix A) injuries in frontal crashes.[39, 118] Despite this, they have been shown to be somewhat effective in rollover crashes. Firstly, the use of a three-point seatbelt (lap and sash) minimises the likelihood of an occupant from being ejected from the vehicle [13, 153] and, as a result, reduces AIS3+ injuries often associated with an ejection [35, 153]. Secondly, they reduce the likelihood of an injury occurring from impacts with the vehicle interior during a rollover crash although serious thoracic injuries continue to occur.[93] The incorrect use of a seatbelt has been observed to increase the likelihood of an injury occurring [27]; thus, highlighting the importance of the correct use of these safety devices.

Despite their effectiveness in reducing the likelihood of AIS3+ injuries in rollover crashes, the non-use of seatbelts was found to be higher (35%) in rollover crashes than in planar crashes (27%).[39] Other studies have found that three-quarters of occupants fatally injured in a rollover crash were not using seatbelts and two-thirds were completely ejected from the vehicle.[101] The combination of the effectiveness of seatbelts in reducing AIS3+ injuries, highlighted in the previous paragraph, and the findings presented in this paragraph suggests that some of the rollover fatalities in the US can be reduced though the use of seatbelts.

Vehicle rollover direction has been found to be fairly evenly split with 45% occurring to the right and 55% occurring to the left, when viewed from the rear of the vehicle (Figure 2.5).[39] However, a vehicle's roll direction and resultant occupant injury needs to be discussed taking into account to the occupant's seated position in the vehicle. This will be discussed in Section 2.5.

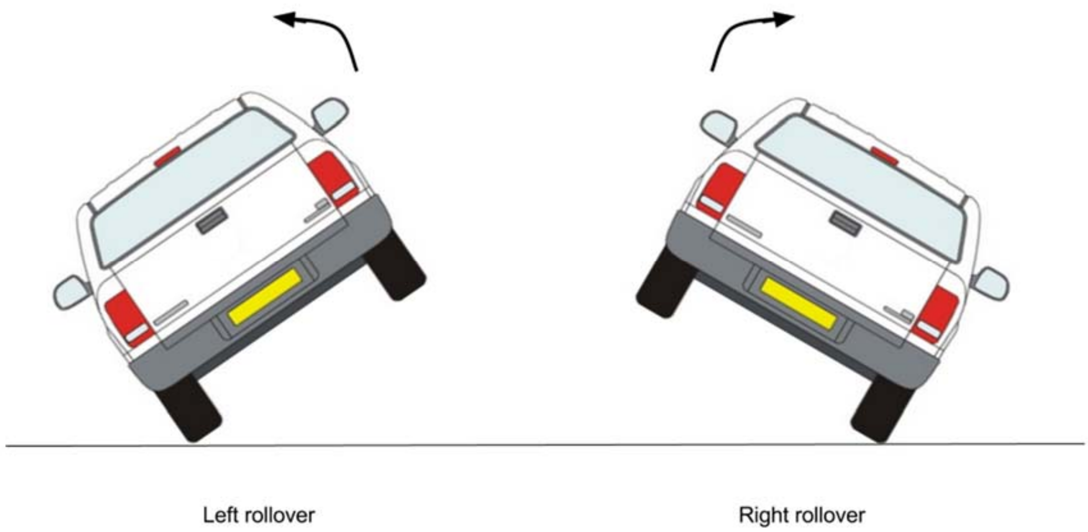


Figure 2.5 Vehicle rollover direction (Image source: ImpactGS)

From a demographic perspective, 73% of the drivers in fatal rollover crashes were male and the average age of the driver was less than 40 years.[97]

2.3.2 Australian Statistics

One of the earliest Australian studies on vehicle rollover crashes was performed in 1988 based on data obtained from the Federal Office of Road Safety (FORS) who found rollover crashes account for 19% of all motor vehicle fatalities in Australia at that point in time.[123] Subsequent studies performed on FORS data from 1988, 1990 and 1992 also found similar fatality rates resulting from rollover crashes (Table 2.3).[55]

Table 2.3 Australian rollover vehicle fatalities (Source: Henderson and Paine, 1997)

Year	Total vehicles crashes with one or more fatalities	Vehicle rollover crashes with one or more fatalities	Vehicle rollover fatality crashes as a percentage of total vehicles with one or more fatalities (%)
1988	2091	320	15.3
1990	1651	236	14.3
1992	1436	215	14.9

A more recent study performed on 2000 to 2007 crash data from New South Wales (NSW), Victoria and the Northern Territory (NT) found single-vehicle rollovers account for 35% of all fatalities from motor vehicle crashes, a figure double that of previous studies. A similar figure of 30% was reported by a study performed on 1996 to 1997 data which was based on rollover crashes in the NT.[145] Both of these reported figures are similar to that of rollover crashes in the US. The increase in the proportion of fatal rollover crashes is likely to be due to the increased proportion of SUVs in the Australian registered vehicle fleet.

A number of similarities exist between Australian and US rollover crash statistics. Firstly, the trip-over was found to be the most frequent rollover initiation method, followed by turn-overs.[43] Secondly, high travel speeds of greater than 95 km/h [43] or on roads with a speed limit of at least 100 km/h were also often associated with rollover crashes [86]. Thirdly, 49% of rollovers occurred on straight roads and a bend in the road was the second most common place for rollovers to occur.[86] Fourthly, most vehicles came to a rest within two full rolls (i.e., eight quarter-turns) (Figure 2.6).[43] Finally, the average age of a fatally injured occupant was found to be 37 years and 74% of rollover fatalities were male.[43]

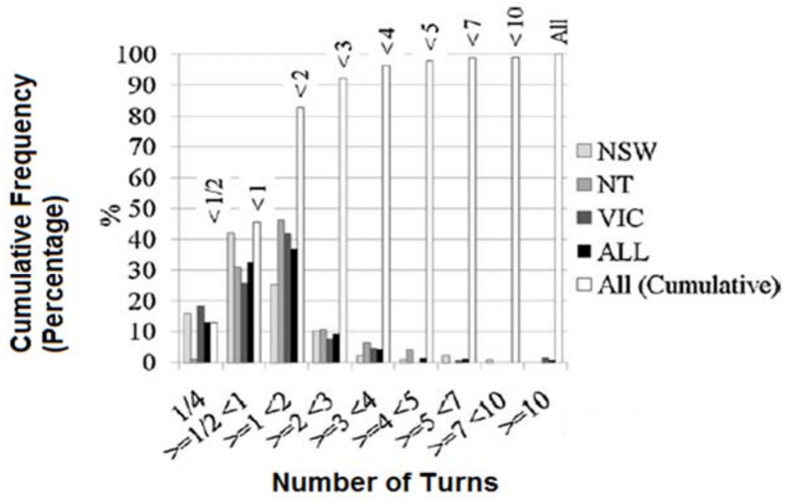


Figure 2.6 Cumulative frequency of vehicle turns in NSW, NT and VIC (Source: Fréchède *et al*., 2010)

The role of seatbelts in minimising serious and fatal injuries in rollover crashes in Australia has also previously been examined. A study in 1997 found that unrestrained occupants were four times more likely to be severely injured than restrained occupants.[55] A more recent study conducted in 2010 found that in fatal rollover crashes, non-restrained occupants were 20 times more likely to be ejected from the vehicle than those restrained by a seatbelt.[43] These findings confirm that the use of a seatbelt can be effective in mitigating AIS3+ injuries in rollover crashes except for AIS3+ thoracic injuries.

2.3.3 European Statistics

Rollover crashes in Europe are not as comprehensively researched in comparison to the US and Australia. (See [30, 53, 113, 115, 117]) Of the research that has been carried out, most are based on United Kingdom (UK) and German studies.

One of the most comprehensive studies into rollover crashes compared US and UK rollover crash data from 1992 to 1996.[117] The US crash data were obtained from the National Automotive Sampling System Crashworthiness Data System (NASS-CDS) (See Appendix B) while UK crash data were obtained from the Co-operative Crash Injury Study (CCIS). In the UK, rollovers accounted for 13% of all crashes and represented about 21% of all seriously injured occupants.[117] A more recent study based on CCIS data from 2002 to 2008 had also reported similar rollover crash statistics.[30]

Similar to the US and Australia, 87% of rollover crashes in the UK occurred when the vehicle was either on a straight road or turning around a bend on a road and 75% occurred on roads with a speed limit of 50 mph (80 km/h) or higher.[117] A further similarity between UK and US rollover statistics is highlighted in the vehicle category most frequently involved in rollover crashes. In the UK, utility vehicles were more likely to be involved in rollovers than passenger cars and constituted 31% of all rollovers compared to 9% for passenger cars.[30]

From an injury perspective, rollover crashes in the UK tend to result in AIS3 injuries to the thorax most frequently.[117] This is in contrast to US rollover crashes where the head most frequently sustains AIS3 injuries.

The use of seatbelts has been previously demonstrated, through US rollover crash statistics, to minimise the likelihood of an occupant in a rollover crash from being fully ejected from the vehicle. However, UK crash statistics indicate that partial ejections still occurred in 83% of rollover crashes and resulted in 89% of partially ejected occupants sustaining an injury.[30] This highlights the need for a better restraint system to be developed to minimise occupant injury in rollover crashes as will be presented in this thesis.

In Germany 88% of rollovers occurred as the result of a prior collision [114]; thus, substantially differing to that of rollover crashes in the UK, Australia and the US where a majority of rollovers occur as the result of a single-vehicle crash. Despite this difference, there are similarities in German rollover crash statistic to that of the US and Australia. For example, in Germany rollovers were more likely to occur on highways outside city limits, 63% occurred on straight sections of roads, 19.9% occurred on curved roads and 67% occurred on grass, fields, or other soft surfaces. Additionally, utility vehicles were more likely to be involved in a rollover crash compared to passenger cars.[114] And finally, belted occupants were reported to have a lower risk of ejection of 2.4% compared to 31.9% for non-belted occupants.[114]

2.4 Rollover Vehicle Kinematics

Vehicle crash testing has been performed for many decades as it is the best method for obtaining vehicle kinematics during a crash. However, very few rollover crash testing has been performed where the vehicle kinematics are reported. (See [8, 9, 11, 15, 28, 68, 81, 112, 154])

One of the earliest and most comprehensively documented rollover crash tests performed was the Malibu I [112] and Malibu II [11] crash tests. These series of crash tests were performed in the 1980s to study vehicle rollover kinematics and the effects of roof strength on occupant head and neck injuries. Each of the Malibu crash tests involved eight Chevrolet Malibu vehicles – four with standard production roofs and four with strengthened roofs. In Malibu I, Hybrid III 50th percentile ATD were positioned in the front driver and passenger seats and were not restrained. In Malibu II, the ATDs were restrained with the vehicle's standard seatbelts. The rollover crash tests were performed using the dolly rollover test procedure. (See [146]) Orlowski *et al*. [112] and Bahling *et al*. [11] report on the results of these crash tests and the key vehicle kinematics observations from these researchers are presented below.

From the Malibu I tests, vehicle rotational, horizontal (i.e., lateral) and vertical velocities during the rollover crash were investigated.[112] From the investigation, it was observed that the standard vehicle's rotational velocity peaked during the first rollover and subsequently gradually decreased (Figure 2.7). The vehicle's lateral velocity was reported to decrease at a constant rate (Figure 2.8) while the vehicles vertical velocity was reported to oscillate between -1.5 m/s and +2.5 m/s. (Figure 2.9). The vehicle's energy profile was also plotted and observed to closely match that of the vehicle's lateral velocity (Figure 2.10). Further, a comparison of the video of the crash and energy plot was performed from which it was observed that approximately half of the vehicle's energy is lost upon wheel-to-ground contact and the other half was due to vehicle body-to-ground contact. These findings are similar to that reported by Bahling *et al*. [11] from the Malibu II crash tests.

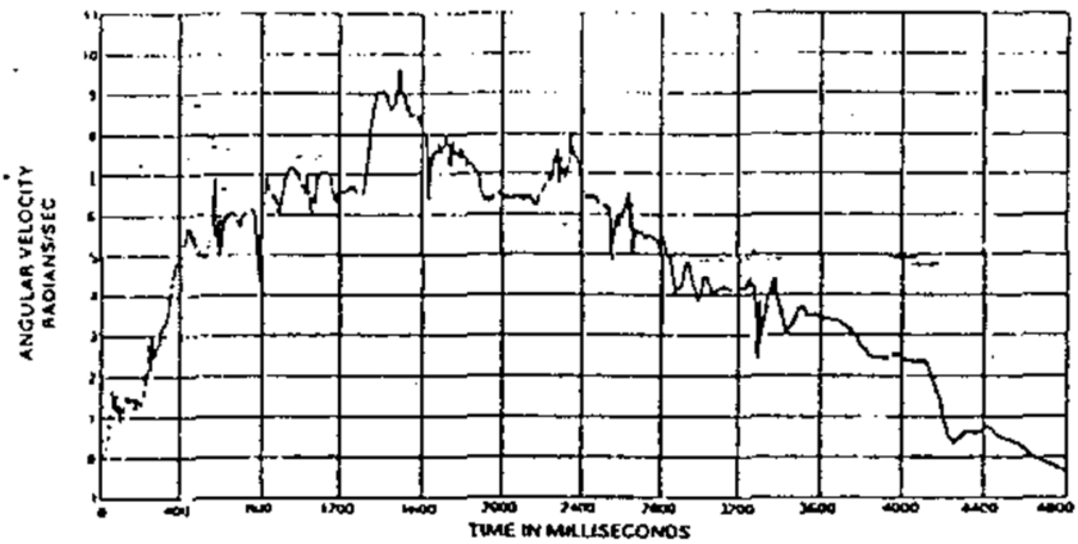


Figure 2.7 Vehicle rotational velocity (Source: Orlowski *et al*., 1985)

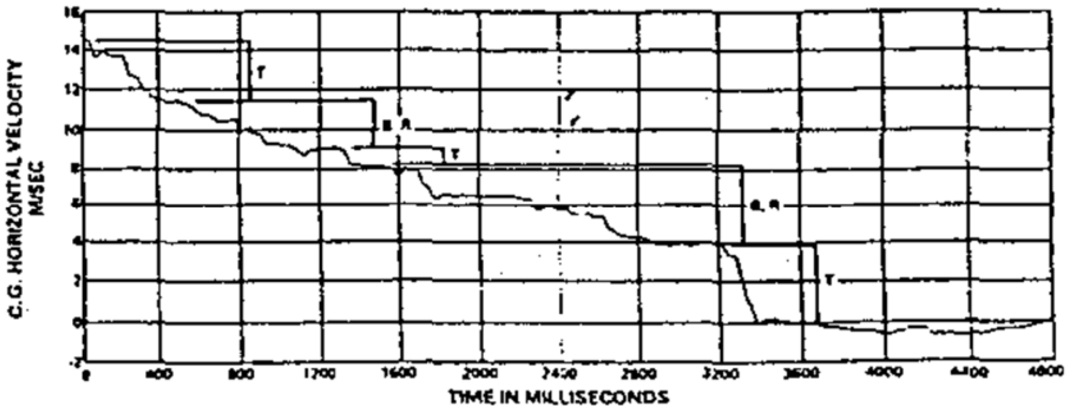


Figure 2.8 Vehicle lateral velocity (Source: Orlowski *et al*., 1985)

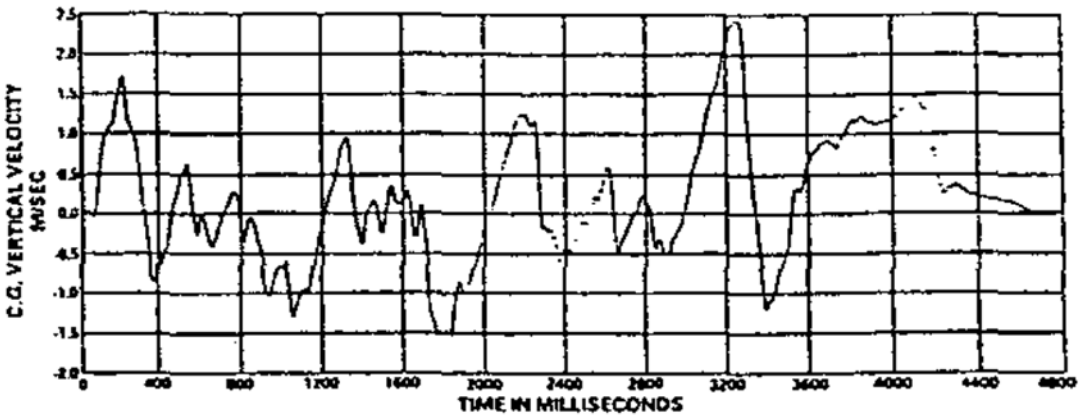


Figure 2.9 Vehicle vertical velocity (Source: Orlowski *et al*., 1985)

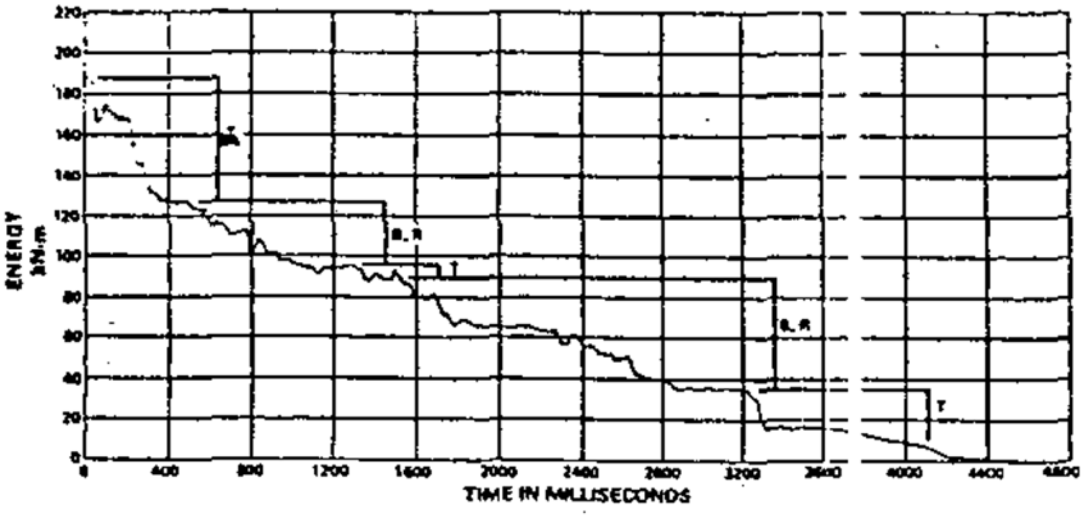


Figure 2.10 Vehicle energy (Source: Orlowski *et al*., 1985)

Since the publication of the Malibu rollover crash test results other researchers have investigated rollover vehicle lateral velocity in more detail to better understand the step-like reductions in a vehicle's lateral velocity highlighted by Orlowski (Figure 2.9).[112] A review of slow motion videos of real-world rally vehicle rollovers by Henderson and Paine [55] provided an insight into this phenomenon:

> *"The actual horizontal velocity profile will be step-like, with the steep portions corresponding to "corner" contacts with the ground"*

This suggests that the vehicle's lateral velocity is reduced markedly when the vehicle's corners (i.e., tyres and roof rails) contacts the ground.

The association between vehicle trip speed and resultant peak angular velocity for tripped rollovers has also been investigated by researchers. A 1990s analysis of previously conducted rollover crash testing found that a vehicle trip velocity of 43.5 km/h and 52.2 km/h resulted in their test vehicles achieving peak angular velocities of 230 deg/s to 390 deg/s, respectively.[29] More recent vehicle rollover crash testing in 2011 found that trip speeds of 19.3 km/h and 48.3 km/h resulted in vehicle peak roll rates of 122 deg/s to 146 deg/s and 237.3 deg/s to 237.4 deg/s, respectively. Higher trip speed appears to result in higher vehicle roll rates.

The Malibu I and Malibu II crash tests had also resulted in researchers studying the association between the number of quarter-turns a vehicle undergoes and the roll distance. This had resulted in the observation of a linear relationship between the number of rollovers a vehicle underwent and the roll distance (Figure 2.11).[65] That is, there is an increase in the vehicle rollover distance as the number of quarter-turns a vehicle undergoes increases.

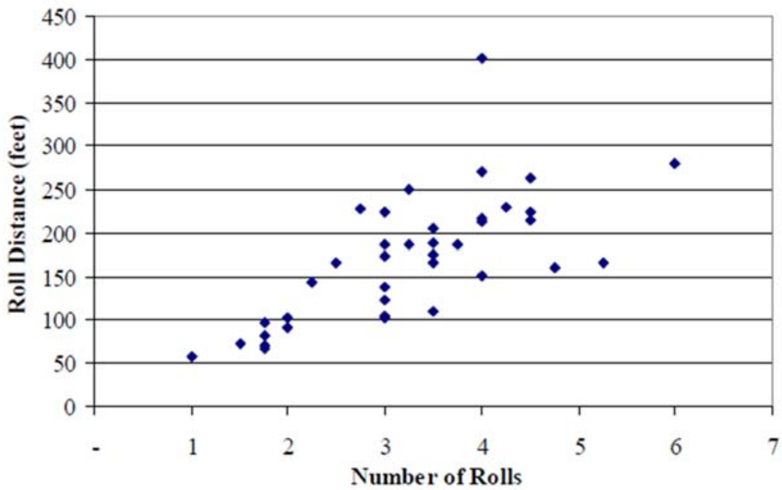


Figure 2.11 Vehicle roll distance versus number of rolls (Source: Jones and Wilson, 2000)

A review of available literature on vehicle kinematics in a rollover crash had led to the concept that vehicle rollover kinematics can be divided into four distinct phases – trip, airborne, sliding and rolling (Figure 2.12).[47] The trip phase consists of the vehicle traversing laterally until its movement is stopped and the vehicle begins to roll over. At this point the vehicle ceases contact with the ground and becomes airborne; thus, commences the second phase, the airborne phase. The vehicle continues in this phase until it makes contact with the ground. At this point it enters the sliding phase where the vehicle slides along the ground until the vehicle's tangential velocity, measured at the point where it contacts the ground, is the same as the vehicle's CG lateral velocity. The final phase, the rolling phase, begins when the vehicle's tangential velocity is approximately equal to the vehicle's CG lateral velocity and the vehicle begins to roll on the ground until it comes to a stop.

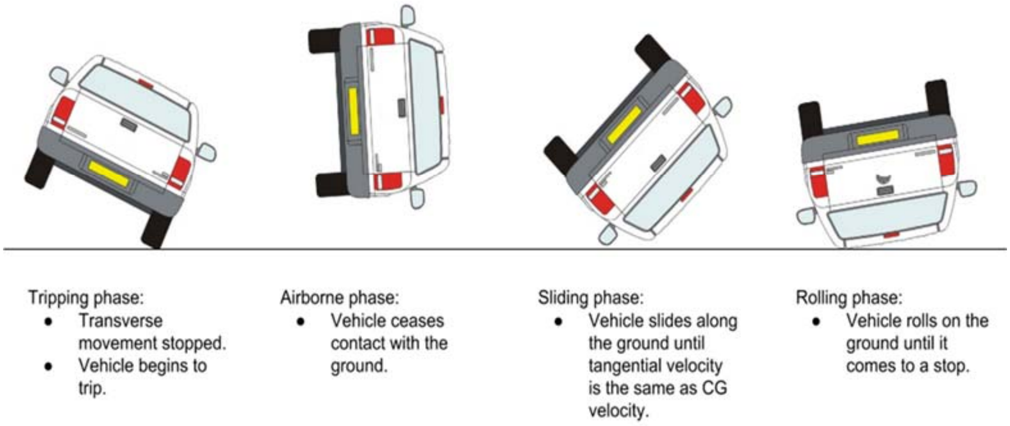


Figure 2.12 Vehicle rollover phases (Image source: ImapactGS)

Funk *et al*. [47] observed that a vehicle's roll rate and translational velocity can be coupled together. They commented that the vehicle's roll rate generally rises monotonically and peaks at the sliding phase before decreasing monotonically at a slower rate than it rose during the rolling phase. The vehicle's translational velocity is noted to be highest at the point of vehicle tripping and decreases, at differing rates, throughout the rollover sequence (Figure 2.13).

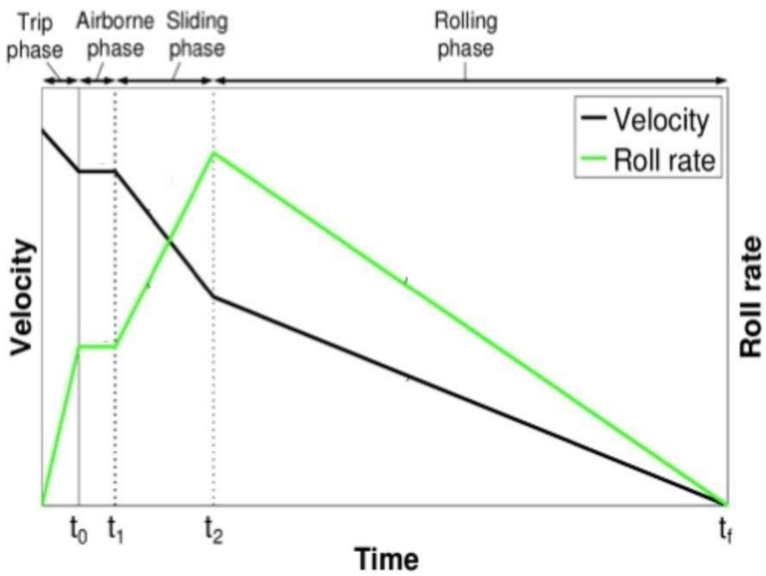


Figure 2.13 Vehicle roll rate and translational velocity during a rollover (Source: Funk *et al*., 2012)

The model developed by Funk *et al*. assumes that the vehicle undergoes a constant deceleration when the vehicle makes contact with the ground and begins the sliding phase and continues to decelerate at a constant rate until the vehicles stops. However; this is not necessarily correct.

Henry *et al*. [56] noted that a vehicle in a rollover crash can make contact with the ground several times during which serious occupant injuries can occur. Specifically, they stated that,

> *"The motion of a rolling vehicle can be characterised as a series of potentially injurious and damaging ground contacts separated by airborne intervals as the vehicle continuously rotates about the roll axis"*

Anderson *et al*. [5] also observed that deformation of the roof panel and supporting pillar damages occurs when the vehicle makes contact with the ground which contributes to a reduction in the rollover rate.

The observations by Henry *et al*. and Anderson *et al*. suggests that as the vehicle makes contact with the ground some of its kinematic energy is dissipated through vehicle structure resulting in vehicle deformation. This reduction in kinematic energy results in a change in vehicle kinematics, specifically, a decrease in vehicle roll rate and translational velocity. Vehicle structural damage as a result of impacts with the ground and its association with occupant injuries will be discussed further in Section 2.6.4.

2.5 Rollover Occupant Kinematics

One of the earliest studies into occupant kinematics in vehicle rollover crashes was performed in 1959.[135] The rollover tests were conducted with seatbelt restrained ATDs in vehicle simulators with the aim of studying occupant kinematics during a rollover. One of the key findings from his research was that the ATD's head contacted the vehicle's roof interior during vehicle inversion despite the use of seatbelts.[135] Following this result, further studies of occupant kinematics in vehicle rollovers were conducted to understand the effects of seatbelt use on injury outcome. (See [11, 16, 57, 62])

Studies have also been performed to better understand occupant kinematics during rollovers (See [57, 92, 120]); however, they are not extensive. From the few studies that have been performed, it has been recognised that occupant kinematics in rollovers are complex.[93, 116, 125] Further, occupant kinematics in a rollover has been observed to be independent of vehicle motion [27, 116]; thus, making it more difficult to study than occupant motion in other crash types. These factors result in occupant kinematics in rollovers hard to generalise and describe.

Despite these difficulties, one of the earliest studies to describe restrained occupants head and torso kinematics in rollovers was performed by in 2001 with the assistance of computer simulations.[116] The study was performed with PC-CRASH, a multi-body three-dimensional dynamic trajectory model, and the observations from the computer simulation resulted in occupant kinematics being divided into three general phases (Figure 2.14):

1) Lateral contact phase – The vehicle is sliding laterally and its lateral velocity rapidly decreases resulting in the vehicle's occupants traversing laterally relative to the vehicle's interior.

2) Roll initiation and air-borne phase – The vehicle trips and begins to rotate resulting in the occupants rotating about the vehicle CG.

3) Ground contact phase – The vehicle rotates beyond the first quarter-turn and impacts the ground. These vehicle-to-ground impacts result in the vehicle occupants contacting vehicle interior components.

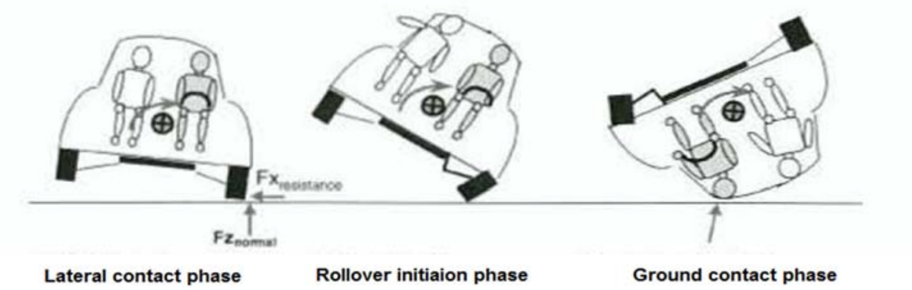


Figure 2.14 Occupant kinematic rollover phases (Source: Parenteau *et al*., 2001)

A marked difference between the near-side (i.e., where the occupant is seated adjacent to the roll direction) and far-side (i.e., where the occupant is seated opposite to the roll direction) occupant kinematics was observed at the beginning of the third phase of the rollover. For near-side occupants, the torso traversed towards the near-side door (i.e., moved outboard) and roof rail (i.e., upwards relative to an upright vehicle) despite the torso remaining within the sash portion of the seatbelt (Figure 2.15). For far-side occupants, the torso was observed to slide out of the seatbelt sash and moved towards the centre console (i.e., moved inboard) and upwards towards the roof rail (i.e., upwards relative to an upright vehicle) (Figure 2.15). The occupants' movement towards the roof rail was also observed by Rechnitzer *et al*. [123], Orloski *et al*., [112] and Bahling [11]. Further, the observation of the torso sliding out of the seatbelt sash demonstrates the inadequacy of current 3-point seatbelts in restraining occupant torsos in a rollover crash.[116]

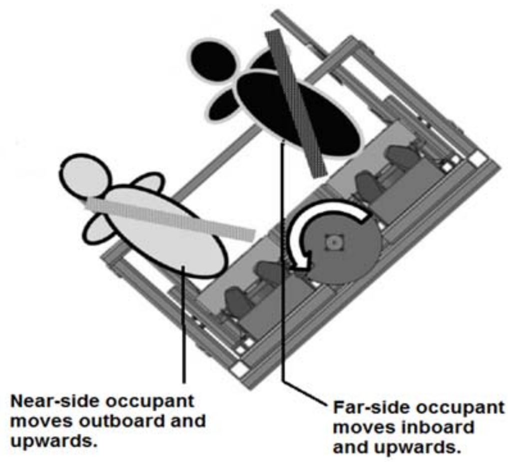


Figure 2.15 Observation of near- and far-side occupant kinematics by Lessley *et al*., 2001 (Source: Lessley *et al*., 2014)

Occupant kinematics in the third phase during the vehicle-to-ground contact was observed to be influenced by vehicle structural deformation, occupant-to-exterior contact and occupant-to-vehicle interior contact.[116] Additionally, it was also observed that the main areas of contact for the near-side driver's head and torso were the front upper A-pillar/header, side rails and B-pillar/roof rail joint.[116]

A vast majority of previously conducted occupant kinematic studies focussed on specific body regions, such as the head and neck. However, very few studies were performed to observe whole body kinematics. One of the few such studies performed recently consisted of a series of tests to characterise whole body kinematics in rollovers through the use of a restrained PMHS placed in a vehicle buck which was then rotated.[78] From the buck rotation tests, the study reported that both near- and far-side occupants move upwards (i.e., out of the seat) and outboard. These observations were similar to that of previous studies [11, 112, 116] which also reported that the occupants upwards excursion was limited through the occupants' contact with the vehicle interior.

A key difference in lateral movement for the far-side occupant in the buck study was observed compared to that of previous studies. In previous studies [91, 116], the far-side occupant was observed to move laterally inboard; thus, allowing the occupant's left shoulder to slip out of the seatbelt's sash (Figure 2.15). This contrasted with the observation from the buck study which reported that the far-side occupant's shoulder moved outboard resulting in it being restrained by the seatbelt's sash (Figure 2.16). This difference in far-side occupant kinematics was attributed to the difference in angular acceleration between the buck study and of previous studies. In the buck study, the angular acceleration was sufficiently high and resulted in centrifugal acceleration moving the occupant outboard. In previous studies, the effect of gravity was greater than centrifugal acceleration which resulted in the occupants moving inboard. That is, the far-side occupant can lean inboard if the angular acceleration is sufficiently low and result in the outboard shoulder slipping away from the seatbelt sash. This subsequently results in the far-side occupant experiencing greater vertical excursion, relative to an upright vehicle, than if the seatbelt sash was still in contact with the outboard shoulder.

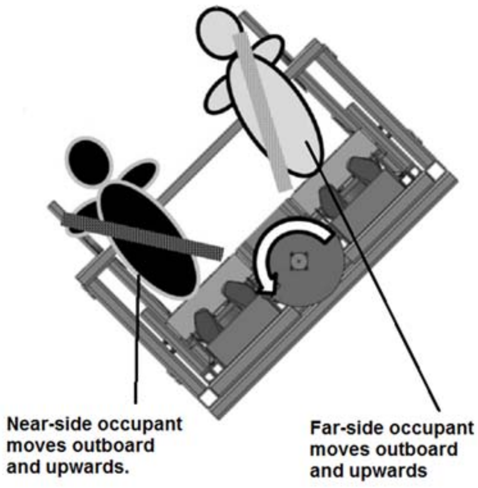


Figure 2.16 Observation of near- and far-side occupant kinematics by Lessley *et al*., 2014 (Source: Lessley *et al*., 2014)

Previous studies have also been performed on rollover crash data to understand if there is a difference in prevalence and injury outcome between near- and far-side occupants. Although left- and right-side rollovers are fairly evenly split [12, 39, 141], a higher proportion of AIS3+ injuries have been observed to occur to occupants in far-side rollovers compared to near-side rollovers [12, 30, 35, 36, 39, 116]. This finding suggests that there may be a difference in kinematics between near- and far-side occupants and supports the observations reported by Moffat *et al*. [91] and Parenteau *et al*. [116] These findings highlight the need to study near- and far-side occupant kinematics separately.

The number of quarter-turns a vehicle is subjected to and its correlation with a vehicle occupant sustaining an injury has also been studied by several researchers.[10, 12, 93, 153] It was found that 50% of vehicles in a rollover completed two or less quarter-turns before coming to a rest while 75% came to a rest within four quarter-turns. These findings are similar to those previously reported by Viano *et al*. [153] and Eigen *et al*. [39] Viano *et al*. [153] also observed that four or less quarter-turn rollover crashes are responsible for 71.4% of near-seated and 64.4% of far-seated occupant fatalities and that occupants are more at risk with an increasing number of vehicle quarter-turns.

A more recent study by Bambach *et al*. [12] plotted the number of AIS3+ injured vehicle occupants against the number of vehicle quarter-turns. They found that nearly half of all AIS3+ injuries occurred between the first and fourth quarter-turn and that the probability of an occupant sustaining an AIS3+ injury increases with the number of vehicle quarter-turns. This finding is similar to those reported by Bedewi *et al*. [13], Digges *et al*. [34] and Moore *et al*. [93]

2.6 Occupant Injuries in Rollover Crashes

2.6.1 Frequently Injured Body Regions in Rollover Crashes

In Section 2.3.1, studies were presented which show that the use of a seatbelt has been associated with a reduced likelihood of an occupant being ejected from a vehicle and also reduce the likelihood of an occupant sustaining AIS3+ injuries in a rollover crash. In this thesis, the discussion with regards to occupant injuries in rollover crashes will focus on studies or statistical analyses which have been performed on seatbelted occupants.

The investigation into rollover injuries and fatalities gained prominence since the NHTSA declared rollover safety a priority in 2003 due to the over-representation of fatalities resulting from rollover crashes.[98] Since then, there have been several studies performed to identify the most frequently injured body regions in rollover crashes.

One of the earliest studies performed to identify frequently injured body regions from crash data was conducted in 2003. The study, based on NASS-CDS data, found that half of all injuries occur to the extremities (i.e., arms and legs).[39] They attributed this to the combined effect of a reduced occupant compartment in the vehicle and flailing extremities. However, for AIS3 injuries, the study found that the thorax most frequently sustained these injuries followed by the abdomen, head and spine.

A similar study performed on UK and US rollover crash data also found that lower and upper extremities are frequently injured in rollover crashes (Figure 2.17). However, when Maximum AIS3+ (MAIS3+) was considered, the thorax was found to be the most frequently injured body region followed by the head and spine (Figure 2.18).

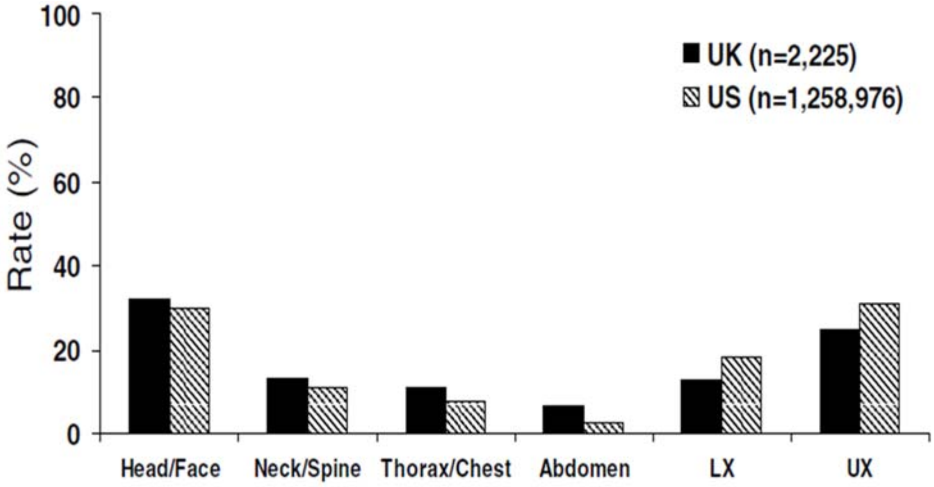


Figure 2.17 Injury distribution (Source: Eigen, 2003)

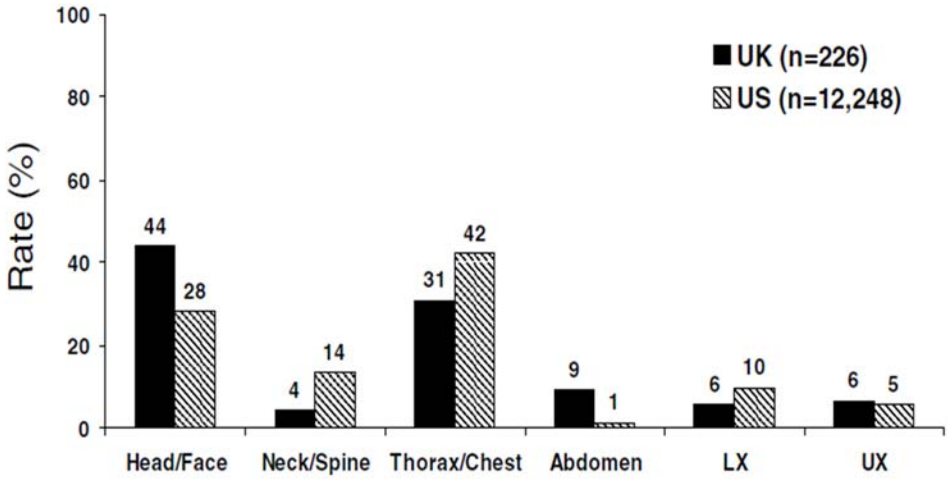


Figure 2.18 MAIS3+ injury distribution (Source: Eigen, 2003)

Other studies have also found that the thorax is the second most frequently seriously injured body region in rollover crashes where the occupant is restrained and contained in the vehicle. [12, 13, 93, 118, 125, 126]

A recent study by Bambach *et al*. [12] analysed NASS-CDS on rollover crash data from 2000 to 2009 and found that one in three rollovers results in an occupant sustaining a serious thoracic injury. Further, they also found that thoracic injury was the maximum severity injury in 84% of rollover crashes.

Although the statistics for Australian rollover crashes are not as comprehensive as those from the US, Fréchède has shown that thoracic injury was the main cause of death in 16% of rollover crashes in Australia.[43]

These findings indicate that the thorax is frequently seriously injured in rollover crashes. Further, when the over-representation of fatalities from rollover crashes is taken into account, these findings also indicate that the thorax is sub-optimally protected.

2.6.2 Thoracic Injuries in Rollover Crashes

The thorax is the area located between the base of the neck superiorly and the diaphragm inferiorly and is enclosed by the rib cage. The thorax cavity is formed by the rib cage which contains and protects organs such as the lungs, heart, trachea, aorta and various nerves (Figure 2.19).

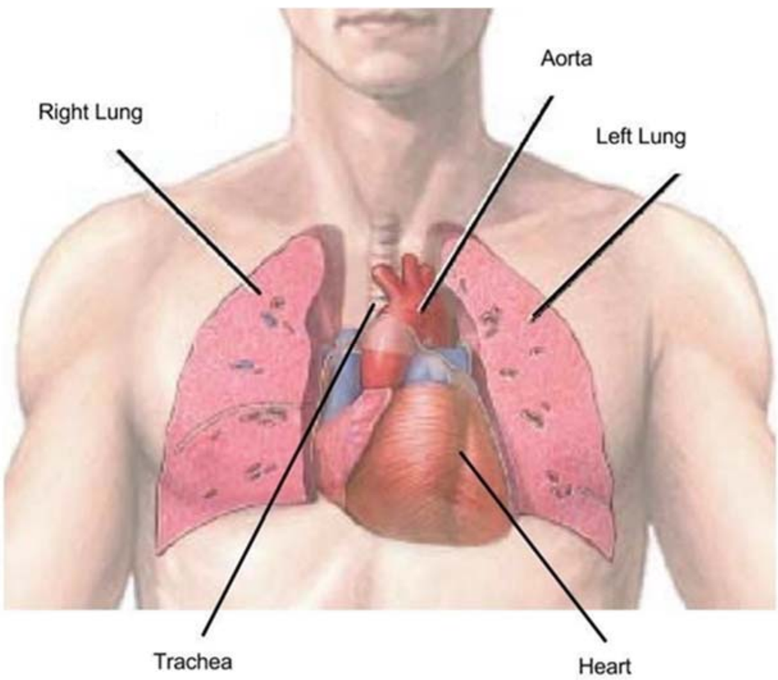


Figure 2.19 Thoracic organs (Source: Northwestern Memorial Hospital)

The thorax contains life sustaining organs, such as the heart and lungs; thus, it is important to prevent or minimise injuries to the thorax during a rollover crash. In order to develop injury mitigation solutions or devices, an understanding of the most frequently seriously injured thoracic organs is required.

One of the most comprehensive and recent study on serious thoracic injuries in rollover crashes for restrained occupants was performed by Bambach *et al*. [12] Their study, based on 2000 to 2009 NASS-CDS data, found that the lungs most frequently sustained AIS3+ injuries followed by the ribs (Figure 2.20). This finding is the same as that of Ridella *et al*.[126] The study by Bambach *et al*. also reported that unilateral lung contusions were the most frequently reported type of lung injury followed by bilateral lung contusions. Similarly, unilateral rib fractures were the most frequently reported rib injury followed by bilateral rib fractures (Figure 2.21). Further, they also noted that in 93% of cases where unilateral lung contusions and rib fractures occurred, the rib fractures were on the same side as the lung contusions. Although this would suggest that unilateral thoracic impact in rollover crashes often results in multiple organ injuries, other studies have reported that thoracic injuries can occur on the side opposite to the impacted side.[164] That is, the reported unilateral injuries may have occurred due to the thorax contacting a vehicle interior component on the opposite side to that of the injured side. Such injuries could also have occurred as a result of impact with an occupant seated adjacent to the flailing occupant.

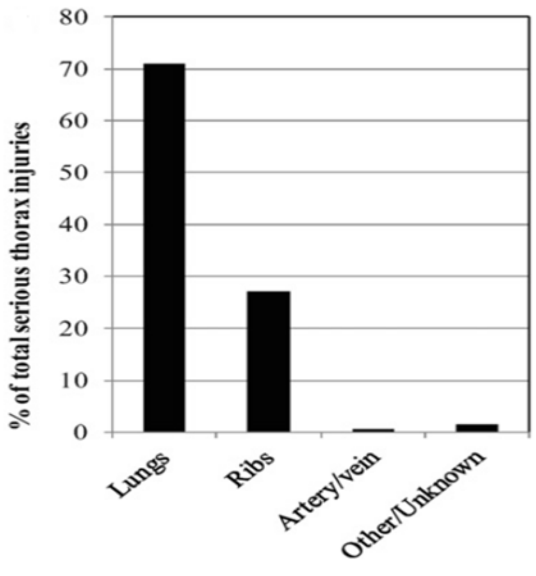


Figure 2.20 Frequently injured thoracic organs (Source: Bambach *et al*., 2013)

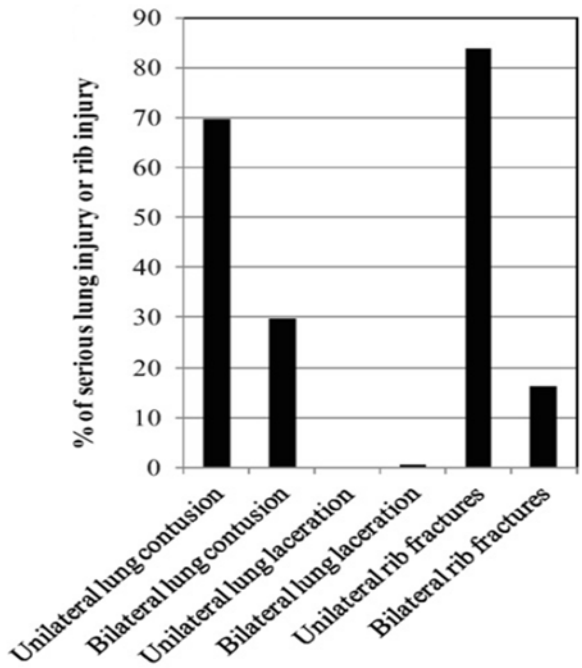


Figure 2.21 Distribution of serious lung and rib injuries (Source: Bambach *et al*., 2013)

Although recent studies have identified the most frequently injured thoracic organs in rollover crashes, what has yet to be considered is whether the difference in occupant kinematics between near- and far-side occupants, as highlighted in Section 2.5, results in different thoracic injuries. This knowledge gap will be explored in Chapter 4.

2.6.3 Thoracic Injury Sources in Rollover Crashes

In order to design thoracic injury mitigating solutions or devices, there is a need to understand the source of thoracic injuries in rollover crashes with restrained occupants. As such, the study by Bambach *et al*. [12] investigated the sources of thoracic injuries. They reported that the most frequently cited source of AIS3+ thoracic injuries were the door interior followed by the seatbelt, seatback and steering wheel (Figure 2.22). This finding is similar to that found by the author of this thesis.[141] That is, the door was the most common source of AIS3+ thoracic injuries followed by the seatbelt, seatback and steering wheel.

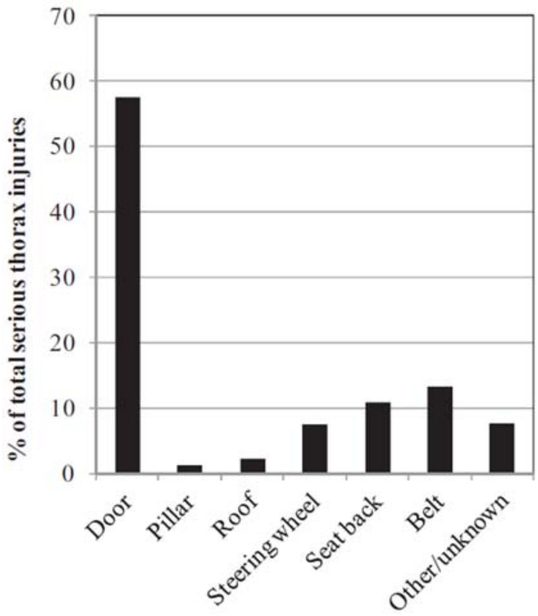


Figure 2.22 Source of AIS3+ thoracic injuries (Source: Bambach *et al*., 2013)

It was initially hypothesised that occupant injuries in rollover crashes resulted from intrusion into the occupant space.[27, 134] Intrusion of the vehicle's door and roof and their implications on thoracic injuries was also questioned by Bambach *et al*.[12] Upon further interrogation of their data, they found that door intrusion was only attributed to 7.4% of AIS3+ thoracic injuries where the door was cited as the source of the injury (Figure 2.23). However, roof intrusion was implicated in over 70% of AIS3+ thoracic injuries where the roof was cited as the source of the injury (Figure 2.23).

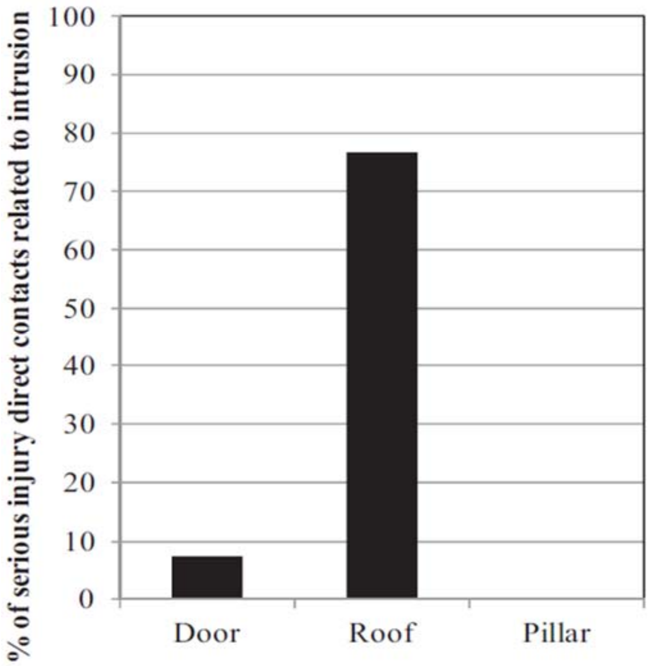


Figure 2.23 Percentage of impacted source of serious thoracic injuries that were directly related to intrusion of the contact source (Source: Bambach *et al*., 2013)

As door intrusion was associated with only 7.4% of all AIS3+ thoracic injuries where the door was the main source of injury, Bambach *et al*. suggested that it is the occupant sliding into and impacting the door interior as the most likely cause of these thoracic injuries. This finding supports Viano *et al*. [148] who postulated that injuries to occupants in a rollover may occur without the vehicle's body intruding into the occupant space.

Although research has been performed to identify sources of thoracic injuries for restrained occupants, the source of thoracic injury based on occupant seated position relative to roll direction has not yet been studied and is, thus, another knowledge gap which this thesis will address. Similar to the discussion on thoracic injuries in Section 2.6.2, the kinematics of near- and far-side occupants differ and needs to be taken into account when discussing sources of thoracic injuries. The source of thoracic injuries based on occupant seated position and rollover direction will be addressed in Chapter 4.

2.6.4 Vehicle Kinematics and Thoracic Injuries

Although studies have been performed which identified frequently seriously injured thoracic organs and the source of these injuries, other studies have focused on developing a better understanding of thoracic injuries and their association with occupant kinematics and vehicle kinematics. Specifically, these studies have sought to find the association between:

1) Occupant seated position and thoracic injuries and

2) The number of vehicle quarter-turn and thoracic injuries.

The association between occupant seated position and resultant AIS3+ injuries was discussed in Section 2.5. Specifically, it was shown through a number of previously conducted studies that far-side occupants have been observed to sustain a greater proportion of AIS3+ injuries than near-side occupants. However, few such studies have been performed with a focus on AIS3+ thoracic injuries. One of the earliest of these studies was performed by Digges *et al*. [35] using 1995 to 2003 NASS-CDS data. Their study found that AIS3+ trunk injuries (i.e., thorax and abdomen) occurred more frequently for near-side occupants although, when all body regions are taken into account, the far-side occupants are more likely to sustain AIS3+ injuries. However, the more recent study by Bambach *et al*. [12] found that far-side occupants were 1.65 times more likely to sustain an AIS3 thoracic injury than a near-side occupant. In both studies, there was an insignificant difference between the number of near- and far-side rollover cases. Thus, the difference in the findings might be a reflection of the different data set used by the two studies.

The study by Bambach *et al*. [12] also explored the association between vehicle quarter-turns and resultant AIS3+ thoracic injuries. Their study found that thoracic injury peaks occurred when the vehicle came to a rest at the second, fourth, sixth and eighth quarter-turn (Figure 2.24). They also observed that the eighth quarter-turn represents only 5% of rollover crashes, however; it constituted 18% of AIS3+ thoracic injuries. Further, they reported that an increase in the number of quarter-turns resulted in an increase in the probability of sustaining an AIS3+ thoracic injury. A finding similar to that reported by Frechede *et al*. [43]

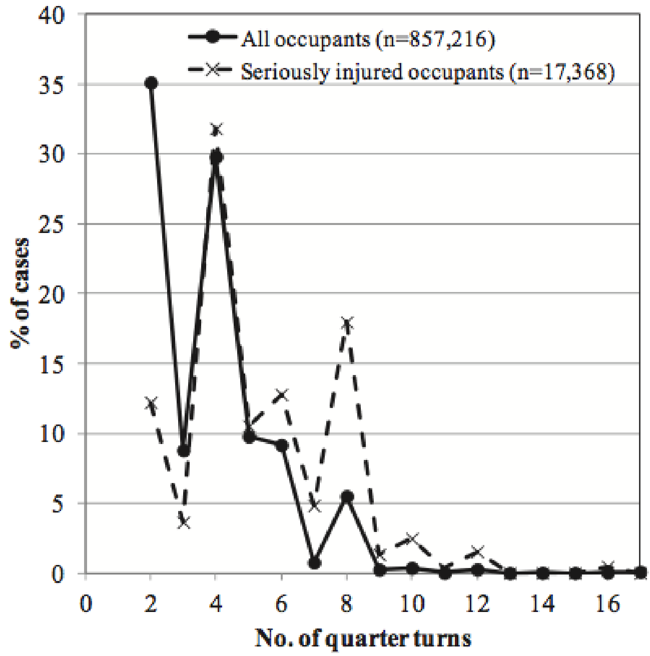


Figure 2.24 AIS3+ thoracic injuries versus number of quarter-turns (Source: Bambach *et al*., 2013)

Bambach *et al*. also sought to find an observable relationship between vehicle crash damage pattern and thoracic injury. However, from their study, an observable pattern could not be established.

Digges *et al*. [37] also attempted to find an association between vehicle crash damage patterns and thoracic injuries. They hypothesised that lateral loading the roof pillars and left front fender during the third and possibly the seventh quarter-tum may be associated with an occupant in a rollover crash sustaining thoracic injuries. However, their study was based on only eight rollover crashes where at least one occupant sustained an AIS3+ thoracic injury; thus, was not sufficiently large to allow a conclusion to be drawn.

The potential for thoracic injury to be associated with vehicle deformation is not a new concept. In Section 2.4, it was noted that Henry *et al*. [56] commented that during a rollover crash, the vehicle makes contact with the ground several times during which serious occupant injuries can occur.

Anderson *et al*. [5] also made similar observations and commented that as the vehicle in a rollover impacts the ground, vehicle deformation occurs which contributes to a change in vehicle kinematics. Further, in Section 2.4 it was highlighted that Henderson and Paine [55] observed that a vehicle's lateral velocity is reduced markedly when the vehicle's tyres and roof rails contact the ground. Thus, it is hypothesised that changes in vehicle kinematics when the vehicle's tyres and roof rail contacts the ground may result in the occupants, if not coupled to the vehicle, impacting against the vehicle's interior. A consistent and clear association between vehicle damage and serious thoracic injuries has yet to be fully established. The possibility that vehicle crash damage may be correlated with an occupant sustaining serious thoracic injuries is explored through a case-control study in Chapter 5.

This literature review has shown that the most frequently AIS3+ injured thoracic organs in a rollover crash have been identified and most common cited sources of thoracic injuries. However, there is a need to correlate this statistical data to occupant kinematics and resultant thoracic injuries. That is, we need to understand the aetiology of thoracic injuries. This will be explored in Chapter 6 through a computer simulation of a real-word rollover crash in which the driver of the vehicle sustained a serious thoracic injury.

2.7 Research Aims and Hypothesis

In section 2.6 it has been highlighted that in order to reduce AIS3+ thoracic injuries in rollover crashes where the occupant is restrained by a seatbelt and contained in the vehicle, there is a need to understand how these injuries are occurring. To achieve this, this thesis has three aims which are:

1) Develop a potential injury criterion for determining the likelihood of a serious thoracic injury occurring in a rollover crash based on thoracic lateral impact velocity.

2) Determine if the distribution of thoracic injuries and thoracic injury sources differs based on the occupant seated position and rollover direction.

3) Determine if significant rollover vehicle damage and, thus, a marked decrease in vehicle velocity at the moment when the vehicle impacts the ground, is associated with an occupant sustaining thoracic injuries.

The hypothesis of this thesis is that AIS3+ thoracic injuries are occurring when an occupant flails into and impacts vehicle interior components due to a sudden change in vehicle rollover kinematics.

The flailing of the occupant into vehicle interior components may occur when the vehicle is right side up (i.e., at the end of the fourth, eighth, etc. quarter-turn) or upside down (i.e., at the end of the second, sixth, tenth, etc. quarter-turn). At these points in the rollover, the occupant's thorax is assumed to be roughly perpendicular to the ground [54, 78] and may not be adequately coupled to the vehicle by the seatbelt. Thus, a sudden change in vehicle kinematics, such as the lateral and roll velocities, may result in the occupant flailing towards and impacting the vehicle's interior.

2.8 Research Structure

2.8.1 Overview of Research Structure

In order to test the aforementioned hypothesis, the following studies were performed:

1) Firstly, a simplified thoracic injury criterion was developed from the flail-space model that was originally developed by Michie in 1981.[90]

2) Secondly, thoracic injuries and sources of injuries were investigated based on occupant seated position and vehicle rollover direction.

3) Thirdly, the association between vehicle damage and thoracic injuries was investigated.

4) Fourthly, two real-world rollover crashes were reconstructed in computer simulations which utilised the results from the first three studies.

The details of each of these studies are presented in the sections below.

2.8.2 Flail-Space Model's Lateral Velocity

Occupants in vehicle rollover crashes are likely to be flailing into and impacting the vehicle's door was highlighted in Section 2.6.4. This occupant kinematics is not dissimilar to a side-impact crash where the vehicle's door intrudes into the occupant space and impacts the occupant's thorax. As such, lateral thoracic injury criteria can be used in assessing the likelihood of an occupant sustaining an injury when they flail into and impact against the vehicle's door and/or other vehicle interior components that are located on either side of the thorax, such as the centre console.

In this study, a brief overview of currently used lateral thoracic injury criteria is presented. Occupant impact velocity, based on the flail-space model, is then presented as a potential alternative for lateral thoracic injury criteria as it simplifies the analyses of occupant kinematics during a rollover crash to determine the source of thoracic injuries. The findings from this study are presented in Chapter 3.

2.8.3 Thoracic Injury and its Sources Based on Occupant Seated Position and Rollover Direction

Studies performed on rollover crashes and resulting thoracic injuries were reviewed in Section 2.6.3. The studies show that the ribs and lungs most frequently sustain AIS3+ injuries. These studies also indicate that the vehicle's door was the most frequently cited source of thoracic injuries. However, as indicated in Section 2.5, near- and far-side occupant kinematics may differ. This suggests that thoracic injuries and the sources of thoracic injuries may differ for near- and far-side occupants. Thus, a limitation of current studies and a knowledge gap, as identified in Section 2.6.3, is that thoracic injuries and thoracic injury sources have not been evaluated from an occupant seated and vehicle rollover direction.

The second study addresses this issue by obtaining NASS-CDS data on rollover crashes where front-seated restrained and contained occupants sustained at least one AIS3+ thoracic injury. The data were then separated into the following four groups: driver near-side rollover, driver far-side rollover, passenger near-side rollover and passenger far-side rollover. Data for each of these four groups were then analysed for thoracic injuries and sources of thoracic injuries. The study methodology and findings from the data analysis from this study are presented in Chapter 4.

2.8.4 The Association between Vehicle Damage and Thoracic Injuries

Vehicle kinematics in a rollover crash was presented in Section 2.4 and it was highlighted that previous researchers have identified that a vehicle's impact with the ground, especially with the vehicle's wheels and roof rails, results in a change in damage to the vehicle and a change in vehicle kinematics. In Section 2.6.4, this change in vehicle kinematics may result in the occupants, if not coupled to the vehicle, impacting the vehicle's interior. As such, it is hypothesised that there is an association between vehicle damage and thoracic injuries.

This hypothesis is explored in Chapter 5 where a case-controlled multiple variable logistic study is performed to determine if there is an association between vehicle damage and AIS3+ thoracic injuries.

2.8.5 Computer Simulation of a Real-World Rollover Crash

In the fourth study, a real-world rollover crash where the driver sustained multiple AIS3+ thoracic injuries, which were attributed to the seatbelt, was reconstructed in a computer simulation. This was performed primarily to study the aetiology of thoracic injuries but also to assess the proposed alternative lateral thoracic injury criterion developed in Chapter 3 and apply the findings from Chapter 4 and Chapter 5.

2.8.6 Application of Flail-Space to Rollover Crash Kinematics

In the fifth study, a real-world rollover crash where the driver sustained AIS3+ injuries pertaining only to the thoracic, which was attributed to contact with the door interior, was reconstructed in a computer simulation. This study was performed to determine if the findings from Chapter 3 can be applied to gross vehicle kinematics to assess for serious thoracic injuries in rollover crashes.

3 Flail-Space Model for Lateral Thoracic Injuries

3.1 Introduction

In this chapter, an alternative approach to existing lateral thoracic injury criteria based on the flail-space model is proposed and its advantages are discussed. Specifically, the advantages are discussed with a focus on identifying potential vehicle interior components which, when impacted upon by an occupant, may result in serious thoracic injuries. In Section 3.2, the flail-space model is introduced and the limitation in applying it for lateral impacts is highlighted. In Section 3.3, the method used for validating the flail-space model for lateral impacts using PMHS test results is presented. This is the first time such work has been performed, that the author is aware of, regarding such validation. In Section 3.4, the results from the validation process are presented. In Section 3.5, a discussion of the results is presented followed by the conclusions and limitations of the study.

3.2 Flail-Space Model

3.2.1 Introduction

ATDs are mechanical surrogates of the human body and are used to assess the performance of vehicle safety systems. Instrumented ATDs are often placed into a vehicle to be crash tested. Data from the instrumented ATD, such as lateral rib deflection in side-impact crash tests, are then obtained and compared to existing injury criteria to determine the likelihood of an occupant sustaining an injury to a particular body region, such as the thorax.

A number of existing injury criteria have been developed for assessing the likelihood of thoracic injuries occurring in side-impact crash testing where an instrumented ATD has been used. They are: rib deflection, upper spinal acceleration, lower spinal acceleration, Average Spinal Acceleration (ASA) and Viscous Criteria (VC). However, these injury criteria cannot be applied in crash tests where an ATD is not used, in the case of roadside barrier crash testing, or not instrumented for side-impact crashes, in the case of the Malibu crash test series. In the latter case, the ATD impact velocity against the vehicle interior can be estimated from the ATD's gross motion obtained from video footage. Thus, it is proposed that an alternative method of estimating the likelihood of lateral thoracic injury in these circumstances, such as occupant impact velocity which based on the flail-space model validated against PHMS tests, can simplify analyses considerably and, thus, be advantageous.

3.2.2 Background

The flail-space model was introduced by Michie in 1981 [90] in order to assess the potential injury risk to an unrestrained occupant during a vehicle road safety barrier crash test, when an ATD is not used or the ATD is not instrumented, for the purpose of minimising the cost of the crash test. In those cases, accelerations from a tri-axial accelerometer placed at the vehicle CG are measured instead, and the impact velocities and ride-down accelerations for front seat occupants within the vehicle are then calculated and compared to 'preferred' and 'maximum' injury reference values. (See [7, 48])

At the time Michie introduced the flail-space model, there was only a 20% seatbelt wearing rate in the USA. A similar seatbelt wearing rate was also reported by Evans *et al*. [41] Hence, Michie based his model on unrestrained occupants.[90]

Prior to the introduction of the flail-space model, Michie reported that the injury risk criterion was based on limiting the vehicle deceleration to no greater than 3*g* laterally and 5*g* longitudinally (1*g* = 9.81 m/s^2), both averaged over 50 ms. Michie expressed concern that this criterion was "overly conservative" on the basis of his assessment of a literature review he carried out in 1981 on human subject testing, animal crash testing, vehicle crash testing and accident data from the 1960s and 1970s from the USA and France. He presented typical long-term acceleration values for both longitudinal and lateral directions on the basis of this review and stated that for both directions an upper limiting value of 20*g* even for pulses of long duration was survivable. He then introduced the flail-space model to better define injury risk on the basis of his findings.

Michie’s flail-space model is founded on the hypothesis that occupant injury occurs during a crash over two distinct phases and that the occupant in a vehicle can be treated as a point mass in space. The first phase occurs when the vehicle impacts an object and starts to decelerate. The impact can be either a frontal impact or a side-impact. The unrestrained occupant continues to move either forwards, for longitudinal crashes, or sideways, for lateral crashes, relative to the vehicle interior. The occupant is also assumed to traverse 0.6 m longitudinally for longitudinal crashes or 0.3 m for lateral crashes before impacting one or more surfaces of the vehicle’s interior and/or the steering wheel with a velocity ‘V’. In the second phase the occupant is assumed to remain in contact with the surface and experiences the same “ridedown” decelerations as the vehicle throughout the remainder of the collision. [90]

From the data Michie analysed, he proposed the ‘preferred’ and ‘maximum’ limits for the occupant impact velocity and the corresponding ridedown acceleration that are presented in Table 3.1. The Manual for Assessment of Safety Hardware (MASH) [7], currently used in the safety evaluation of roadside barriers, continues to use the same flail-space model and associated injury assessment velocity and acceleration values (Table 3.1).

Table 3.1 Flail-space occupant injury risk threshold (Source: Michie, 1981)

	Preferred Value	**Maximum Value**
Longitudinal and Lateral Occupant Impact Velocity (m/s)	9	12
Longitudinal and Lateral Occupant Ridedown Acceleration (*g*)	15	20

3.2.3 Validation

Since the introduction of the flail-space model in 1981, there have been three studies which have related the model to injuries sustained in real world crashes. Ray *et al*.[122] performed ATD buck tests with delta_V ranging from 6.10 m/s to 12.19 m/s. From these tests, they calculated that the likelihood of an occupant sustaining a thoracic injury ranged from 0%, for an occupant impact velocity of 2.35 m/s (corresponding to a delta_V of 6.10 m/s), to 16%, for an occupant impact velocity of 7.59 m/s (corresponding to a delta_V of 12.19 m/s). Ray *et al*. [122] noted that the highest measured occupant impact velocity in the test was 7.59 m/s which is significantly lower than flail-space model's 'maximum' value of 12 m/s. Gabauer and Gabler [49, 50] evaluated the longitudinal component of the flail-space model through data obtained from Electronic Data Recorders (EDR) located in vehicles involved in actual crashes in the USA. They found that an occupant impact velocity of 11.2 m/s and 15.9 m/s for unbelted and belted occupants, respectively corresponded to a 50% likelihood of serious injury in frontal crashes.

To date, a comprehensive review and assessment of the flail-space model for side-impacts has not been published either on the basis of real world crashes and/or PMHS testing.

As the flail-space model is still being used to assess the safety performance of roadside safety barriers and hardware there is a need to determine how well it correlates with actual occupant injuries. In particular, in near- and far-side lateral impacts, where the seatbelt's restraint function may not be as effective as it is in frontal collisions [27] and injury outcomes are severe [74], consideration for performance improvements in roadside barriers is warranted. The flail-space model for lateral impacts can also be applied to the analysis of occupant lateral thoracic injuries in rollover crashes as the lateral motion of the occupant is similar to that in side impact crashes. That is, in a rollover crash, the vehicle's impact with the ground results in the occupant flailing towards and then impacting the vehicle's interior components. This occupant motion follows the two-phase motion described in the flail-space model and can be observed in videos of rollover crash tests conducted by the NHTSA.[103-106] To address the above identified knowledge gap, this study focuses specifically on assessing the potential of using the flail-space model in predicting lateral chest injuries in side-impact crashes though finding a correlation between the occupant's lateral impact velocity and the level of sustained injuries measured using the Abbreviated Injury Scale (AIS).

3.3 Method

3.3.1 Methodology Overview

Four steps were performed in order to validate flail-space model's lateral occupant impact velocity, as described below:

1) Data were obtained from previously conducted PMHS lateral impact tests (i.e., test cases) which reported PMHS impact velocity and thoracic injury AIS level. Filtering of this data was then performed as the tests were conducted with various test methods, impact parameters and PMHSs. That is, the tests were conducted with different test methods (e.g. Heidelberg sled test, pendulum test, dual-sled test, etc.), impact interface (e.g. padded wall with varying padding thickness, non-padded wall, etc.), impact wall type (e.g. flat wall, thorax off-set wall, shoulder off-set wall, etc.) and impact velocity. PMHSs were of different age, mass and sustained different thoracic injuries. This step is described in further detail in Section 3.3.2.

2) The data were then separated into a dependent variable and independent variables and coded in preparation for statistical analysis. This process is described in further detail in Sections 3.3.3.1 and 3.3.3.2 for the dependent variable and the independent variables, respectively.

3) Multiple variable logistic regression analysis was performed to determine the association between the independent variables and thoracic AIS injury level. Specifically, an association was sought between PMHS impact velocity and thoracic injury outcome as measured by the AIS scale. This step is described in further detail in Section 3.3.3.3

4) Single variable logistic regression analysis was then performed to develop a model relating PMHS impact velocity to thoracic injury outcome as measured by the AIS scale. This step is described in further detail in Section 3.3.3.4

3.3.2 Post Mortem Human Surrogate Test Cases

Several series of lateral impact PMHS tests have been performed since the 1970s. The aims of those test series were to study the mechanisms of thoracic injury in side-impacts, develop injury criteria for use with ATDs and establish biomechanical response corridors for biofidelic ATDs. The results from those test series were reported in various papers. In order to identify those papers a formal literature search using Science Direct, Compendex, PubMed and SAE International was undertaken. The following keywords were used in the search field: side-impact, thorax, thoracic, injury, injury criteria, sled, cadaver and PMHS. From the search, a number of papers were retrieved and the references within these papers were then used to locate additional papers relevant to this current study.

The test cases from the papers were then examined to identify lateral impact PMHS studies that specifically related thoracic impact velocity to a thoracic AIS injury level. A total of 178 tests cases were identified which satisfied this criterion.

Filtering was then performed on the 178 test cases based on the test method, impact wall type, impact wall interface, and PMHS arm placement (Figure 3.1). The filters applied on each of the four aforementioned variables are described below.

The test methods used in the test cases consisted of Heidelberg sled tests, dual-sled tests, limited-stroke impactor tests, drop tests and pendulum tests. As the flail-space model requires the occupant to make and remain in contact with the interior of the vehicle during a crash, the Heidelberg sled test, dual-sled test and pendulum tests were included in this current study as they most closely replicate this criterion (Figure 3.1).

The PMHSs in the test cases were impacted against either a rigid or padded surfaces (the impact interface). Padding was used in several of the studies to determine the effect that it had on the resultant injury compared to that of impacting a rigid wall. The padding thickness ranged from 3 inches to 12 inches. The studies also included the door interior of a Volvo and simulated safety research vehicle, both with unspecified padding thicknesses. As this current study evaluated the effect of padding on thoracic injury severity, test cases with all padding thicknesses, the two vehicle door interiors and rigid walls were included in this current study (Figure 3.1).

The impact wall was a padded flat wall, a rigid flat wall or a padded offset wall. Offsets were used in some test cases to understand the effect of a particular body region impacting on the offset prior to that of adjacent body regions. If an offset wall was used, they were located in line with the thorax, abdomen, pelvis or upper leg. As this current study focused on thoracic injuries, only data from padded thoracic offset, padded full wall and rigid full wall tests were included in the model (Figure 3.1). The padded thoracic offset and padded wall types were both classified as a padded interface. That is, no distinction was made between these two walls types. All pendulum tests were noted to have been performed without padding thus the data from these tests were treated as the same as those of sled tests with a rigid wall.

In the test cases, the PMHS's arm was located either at the side of the thorax, taped and placed anteriorly on the PMHS's lap or, in the case of pendulum tests, raised above the head. Although previous studies have found that PMHS arm placement may affect the outcome of lateral thoracic impact tests [24, 69], all three arm positions were included as part of the data set (Figure 3.1). That is, the difference in arm location was not evaluated for its significance in affecting the outcome of thoracic injuries.

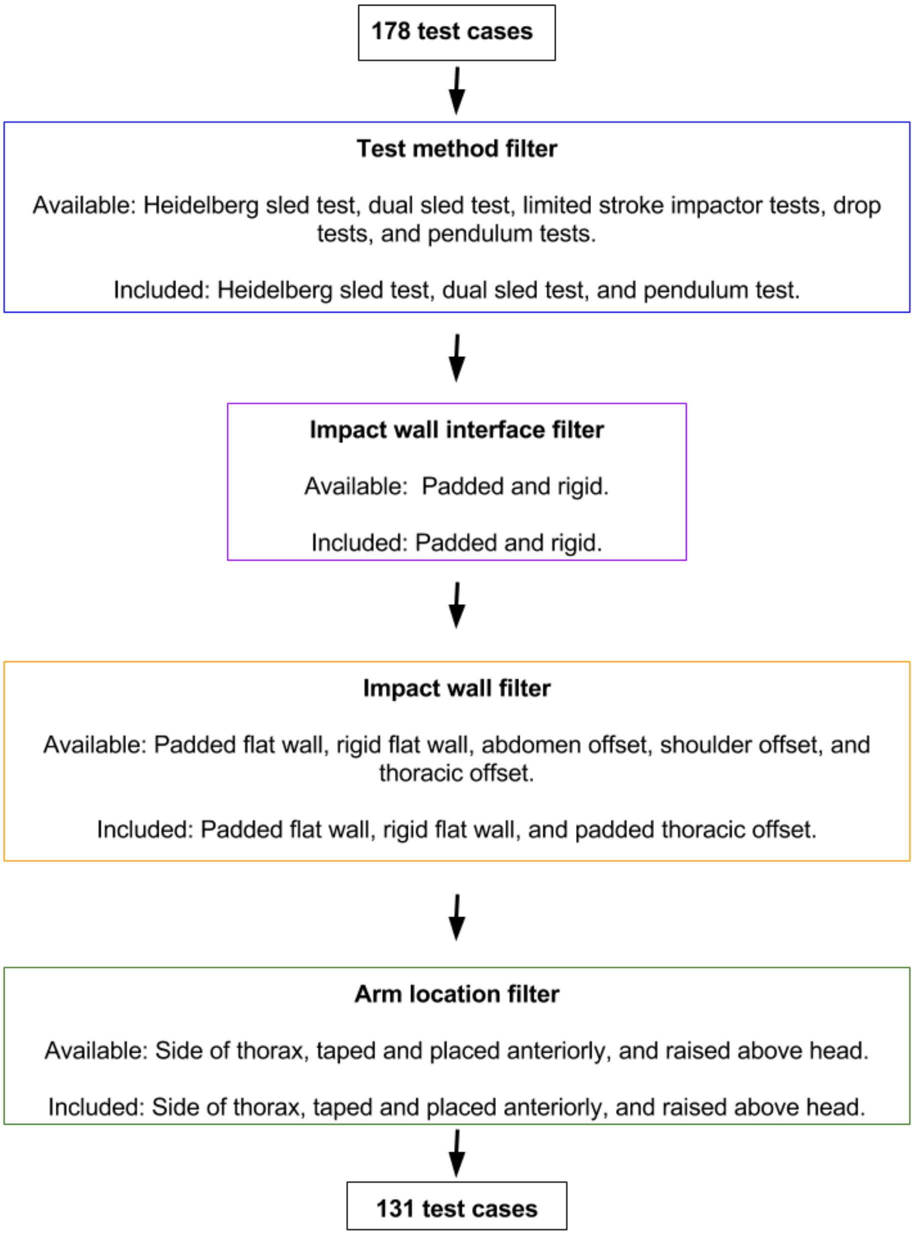


Figure 3.1 Filtering of test cases

It is noted that in some cases a series of PMHS crash tests were performed by one organisation or institution and the results from the tests were analysed and reported in multiple papers. As this current study has collated data from multiple papers there was the potential for test case duplication to occur. Test case duplication was screened for in this current study by cross checking five metrics from one test case against all other test cases. The five metrics used in the cross check were PMHS age, PMHS height, PMHS gender, impact velocity and test number. When an exact match of all five metrics was observed between two test cases, one of the duplicated test cases was removed. This process was repeated until no duplicated test cases were present in the data set.

After filtering for test cases which related lateral thoracic impact velocity to an AIS injury level, test method, impact wall type and impact wall interface, a total of 131 test cases were identified as being suitable for inclusion in this current study (Table 3.2). A full list of all test cases, impact wall interface, test method, impact velocity, PMHS mass, PMHS age and thorax AIS level is provided in Appendix C. A full list of all test cases and resultant thoracic injuries is provided in Appendix D.

Table 3.2 Summary of studies used in this current study.

	Number of Tests	**Test Method**	**Impact Wall Interface**	**Number of AIS 3+ Thoracic Injuries**	**Number of AIS 4+ Thoracic Injuries**
Cavanaugh *et al*., 1993	10	Sled	Rigid and padded	8	8
Kallieris & Mattern, 1986	42	Sled	Rigid and padded	27	15
Kuppa *et al*.,2000	6	Sled	Rigid and padded	0	7
Kuppa *et al*.,2004	25	Sled	Rigid and padded	14	7
Marcus *et al*., 1983	11	Sled	Rigid and padded	8	6
Melvin *et al*.,1976	7	Sled	Rigid and padded	6	5
Pintar *et al*.,1997	5	Sled	Rigid and padded	4	4
Robbins *et al*.,1979	9	Sled and pendulum	Rigid and padded	6	5
Viano *et al*.,1989	16	Pendulum	Rigid	10	5

3.3.3 Statistical Method

3.3.3.1 Dependent Variables

The dependent variable in this study was the thoracic injury severity, as measured with the AIS scale. The thoracic injury severity from the test cases used in this current study ranged from AIS 0 to AIS 6.

In order to assess the association of the independent variables' with an AIS3+ and AIS4+ thoracic injury through the multiple variable logistic regression model, the outcome of the PMHS impact test was coded dichotomously as either 1 for an AIS3+ outcome and 0 otherwise and either 1 for an AIS4+ outcome or 0 otherwise, respectively.

In order to assess the association between thoracic impact velocity and AIS3+ and AIS4+ thoracic injury through the single variable logistic regression model, the outcome of the PMHS impact test was coded dichotomously as 1 for an AIS3+ outcome and 0 otherwise and 1 for an AIS4+ outcome and 0 otherwise, respectively.

3.3.3.2 Independent Variables

The variables that were assessed for their association with an AIS3+ and AIS4+ lateral thoracic injury in the multiple variable logistic regression analysis and are described below.

(a) Impact velocity **-** The velocity at which the PMHS impacted the wall, in sled tests, or the velocity at which the pendulum impacted the PMHS in pendulum tests (Table 3.3). It was treated as a continuous variable for both the multiple variable and single variable logistic regression model. The impact velocity empirical data for padded sled tests, non-padded sled tests and pendulum tests is presented in Table 3.4. Where the impact velocity was reported in kilometres per hour, feet per second or miles per hour, they were converted to metres per second.

Table 3.3 Empirical data on impact velocity for all 131 test cases

Independent Variable	Minimum	Maximum	Mean
Impact Velocity (m/s)	3.62	11.94	8.0

Table 3.4 Empirical data on impact velocity for padded sled tests, non-padded sled tests and pendulum tests.

Test Method	Minimum Velocity (m/s)	Maximum velocity (m/s)	Range (m/s)	Mean (m/s)	Median (m/s)
Padded Sled	4.44	11.94	7.5	8.38	8.88
Non-Padded Sled	6.38	11.94	5.56	8.27	8.82
Pendulum	3.62	10.2	6.58	6.36	6.08

(b) PMHS age - The age of the deceased (Table 3.5).This was included as a variable in the model since it has been identified as a significant variable in studies by Kuppa *et al*. [75, 76] This variable was considered as continuous for the multiple variable logistic regression model.

(c) PMHS mass – The mass of the tested PMHS (Table 3.5). This was included in the model to determine if this independent variable is a significant variable. However, it is noted that previous studies by Kuppa *et al*. [75, 76] have indicated that PMHS mass was not significant in their studies. As with PMHS age, this variable was also treated as a continuous variable for the multiple logistic regression model.

Table 3.5 Empirical data on PMHS age and PMHS mass

Independent Variable	Minimum	Maximum	Mean
PMHS Age (years)	17	86	52
PMHS Mass (kg)	40.8	107.0	68.1

(d) Test method - The test method, sled test and pendulum test, was coded as a dichotomous variable for the multiple variable logistic regression model to determine if the different test method influenced the injury outcome (Table

3.6). For the purpose of dichotomous coding, “0” and “1” were used to indicate sled and pendulum tests, respectively.

Table 3.6 Empirical data on test method

Test Method	Frequency
Sled Test	109
Pendulum Test	22

(e) Impact interface - The effect of the presence or absence of padding on thoracic injury outcome was evaluated in this current study. This variable was dichotomously coded (Table 3.7). For the purpose of dichotomous coding, “0” and “1” were used to indicate unpadded and padded wall impact interfaces, respectively. The effect of padding material, thickness or density was not evaluated in this study due to the limited number of test cases. Further, it is beyond the scope of this study to evaluate the effects different padding thickness on thoracic injury outcome.

Table 3.7 Empirical data on dichotomously coded impact wall interface

Dichotomously Coded Impact Wall Interface	Frequency
Padded Wall	53
Unpadded Wall	78

Independent variables such as PMHS gender and height were obtained from the studies and considered for inclusion in this current study. However, due to the limited number of test cases of 126 and 95 for gender and height, respectively, they were not used in this current study as this would reduce the already limited number of test cases. It is also noted that Kuppa *et al*. [76] have identified that PMHS gender was not a significant variable in predicting thoracic injuries.

The flail-space model specifies both longitudinal and lateral occupant ridedown acceleration limits. As such, acceleration data was also obtained from the studies, however; it was only available for 33 of the 131 test cases.

As such, acceleration was not used for this current study as it would limit the number of test cases available.

In total, there were 131 test cases used in this current study (Table 3.2).

It is noted that in this study pendulum tests constituted only 22 of the 131 tests cases. That is, there are a greater number of sled tests than pendulum tests in the data set. In order to determine if the significant variables from the multiple variable regression analysis with the full data set (i.e., when all 131 test cases were included) is the same as that when only sled tests are present, two multiple variable regression analyses were performed. The first analysis was performed with the full data set and the second with the data set containing only sled tests.

3.3.3.3 Multiple Variable Logistic Regressions Statistical Analysis

SAS Enterprise Guide v5.1 [131] was used for the multiple variable regression analysis. The model is represented by the equation [77]:

$$P(Y = 1 | x) = \pi(x) = \frac{e^{g(x)}}{1 + e^{g(x)}} \qquad \text{Equation 3.1}$$

and the logit, g(x), is represented by the following equation [77]:

$$g(x) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots\ldots + \beta_n x_n \qquad \text{Equation 3.2}$$

where

$$\beta_{0,1,2\ldots n} = \text{parameters}$$

$$x_{0,1,2\ldots n} = \text{predictor variables}$$

The independent variables were evaluated for their significance level for both the AIS3+ and AIS4+ models. Their level of significance was evaluated with the Maximum Likelihood Estimate (MLE) p-value test. Significant independent variables were selected based on having a MLE p-value of less than 0.05.

3.3.3.4 Single Variable Regression Statistical Analysis

SAS Enterprise Guide v5.1 [131] was also used to develop the single variable logistic regression models for both the AIS3+ and AIS4+ models with impact velocity as the independent variable. The equation for the single variable regression model is [77]:

$$P(Y = 1|\, x) \;=\; \pi\,(x) \;=\; \frac{1}{1 +\; e^{(-a-b\upsilon)}} \qquad \text{Equation 3.3}$$

and the 95% confidence interval (CI) of the single variable model is given by [77]:

$$\text{Upper CI} \;=\; a \;+\; b\upsilon \;+\; \sqrt{\sigma_a^2 +\; 2\sigma_{ab}\upsilon \;+\; \sigma_b^2\;\upsilon^2} \qquad \text{Equation 3.4}$$

and

$$\text{Lower CI} \;=\; a \;+\; b\upsilon \;-\; \sqrt{\sigma_a^2 +\; 2\sigma_{ab}\upsilon \;+\; \sigma_b^2\;\upsilon^2} \qquad \text{Equation 3.5}$$

where

$$\sigma_a^2 \;= \text{Standard error variance}$$

$$\sigma_b^2 = \;\text{Independent variable variance}$$

$$\sigma_{ab} \;= \text{Standard deviations between a and b}$$

$$a \;=\; \text{Intercept}$$

$$b \;=\; \text{Independent variable slope}$$

$$\upsilon \;=\; \text{Independent variable}$$

The Hosmer and Lemeshow Goodness-of-Fit was used to determine the fit of the selected model at a significance level of 0.05.[60] Further, the area under the Receiver Operator Characteristic (ROC) curve was used to determine how well the model is able to predict the likelihood of a serious and severe injury in the AIS3+ and AIS4+ model, respectively. The area under the ROC curve with a value of 0.5 indicates a poor predictive model while values closer to 1.0 indicate a high predictive model. [77]

3.4 Results

3.4.1 Multiple Variable Logistic Regression Model

The results from the multiple variable logistic regression model where all 131 test cases were included indicate that the PMHS mass and test method independent variables were not associated with an AIS3+ thoracic injury outcome. The independent variables that were found to be associated with a PMHS sustaining an AIS3+ thoracic injury (i.e., significant variables) were impact velocity, PMHS age and impact wall interface (Table 3.8).

Table 3.8 AIS3+ independent variables estimates, standard errors and maximum likelihood p-values

Parameter	Variable Class	MLE Ratio Estimate	Standard Error	Odds Ratio Point Estimate	95% CI	p-value
PMHS Mass	Continuous	-0.0010	0.0170	0.990	0.959,1.023	0.5595
Impact Wall Interface	Dichotomous (0 = unpadded, 1 = padded)	0.8200	0.2950	5.264	1.682,16.476	0.0054
Test Method	Dichotomous (0 = sled test, 1 = pendulum test)	0.0598	0.3917	0.974	0.198,4.777	0.8786
Impact Velocity	Continuous	0.9626	0.2056	2.591	1.777,3.778	<0.001
PMHS Age	Continuous	0.0610	0.0160	1.063	1.031,1.097	0.001

For the AIS4+ multiple variable logistic regression model where both sled and pendulum tests were considered (i.e., total of 131 tests), PMHS mass and test method as independent variables were not associated with an AIS4+ thoracic injury outcome (Table 3.9). For this model, impact velocity, PMHS age and impact wall interface were found to be associated with a PMHS sustaining an AIS4+ thoracic injury (Table 3.9).

Table 3.9 AIS4+ independent variables estimates, standard errors and maximum likelihood p-values

Parameter	Variable Class	MLE Ratio Estimate	Standard Error	Odds Ratio Point Estimate	95% CI	p-value
PMHS Mass	Continuous	-0.0100	0.0161	0.993	0.963,1.024	0.6717
Impact Wall Interface	Dichotomous (0 = unpadded, 1 = padded)	0.8290	0.2920	6.336	1.960,20.482	0.0045
Test Method	Dichotomous (0 = sled test, 1 = pendulum test)	0.0816	0.4030	3.032	0.518,17.754	0.8394
Impact	Continuous	1.3730	0.2512	4.081	2.460,6.769	<0.001
PMHS Age	Continuous	0.0794	0.0185	1.084	1.045,1.125	< 0.001

The results of the analysis where only sled tests were included in the data set indicate that the significant variables are the same as that for the full data set (i.e., when all 131 test cases were included) for both the AIS3+ and AIS4+ models (Appendix E). That is, impact wall interface, impact velocity and PMHS age were significant variables in both the AIS3+ and AIS4+ models irrespective of whether pendulum tests were included or excluded from the data set.

3.4.2 Single Variable Logistic Regression Model

From the multiple-regression model, an association between PMHS impact velocity and resultant thoracic injury was found for both the AIS3+ and AIS4+ models. As such, single variable logistic regression models were developed for both AIS3+ and AIS4+ models with PMHS impact velocity as the independent variable.

The model for AIS3+ (Equation 3.6) and AIS4+ (Equation 3.7) thoracic injury risk as a function of impact velocity is presented in Figure 3.2. The former is indicated by the thick solid line with the 95% CI indicated by the thick dashed line and the latter function is indicated by the thin solid line with the 95% CI indicated by the thin dashed lines.

$$p(AIS3+) = \frac{1}{1 + e^{(3.7712-(0.6018\, x\; impact\; velocity)}} \qquad \text{Equation 3.6}$$

$$p(AIS4+) = \frac{1}{1 + e^{(7.1027-(0.8686\, x\; impact\; velocity)}} \qquad \text{Equation 3.7}$$

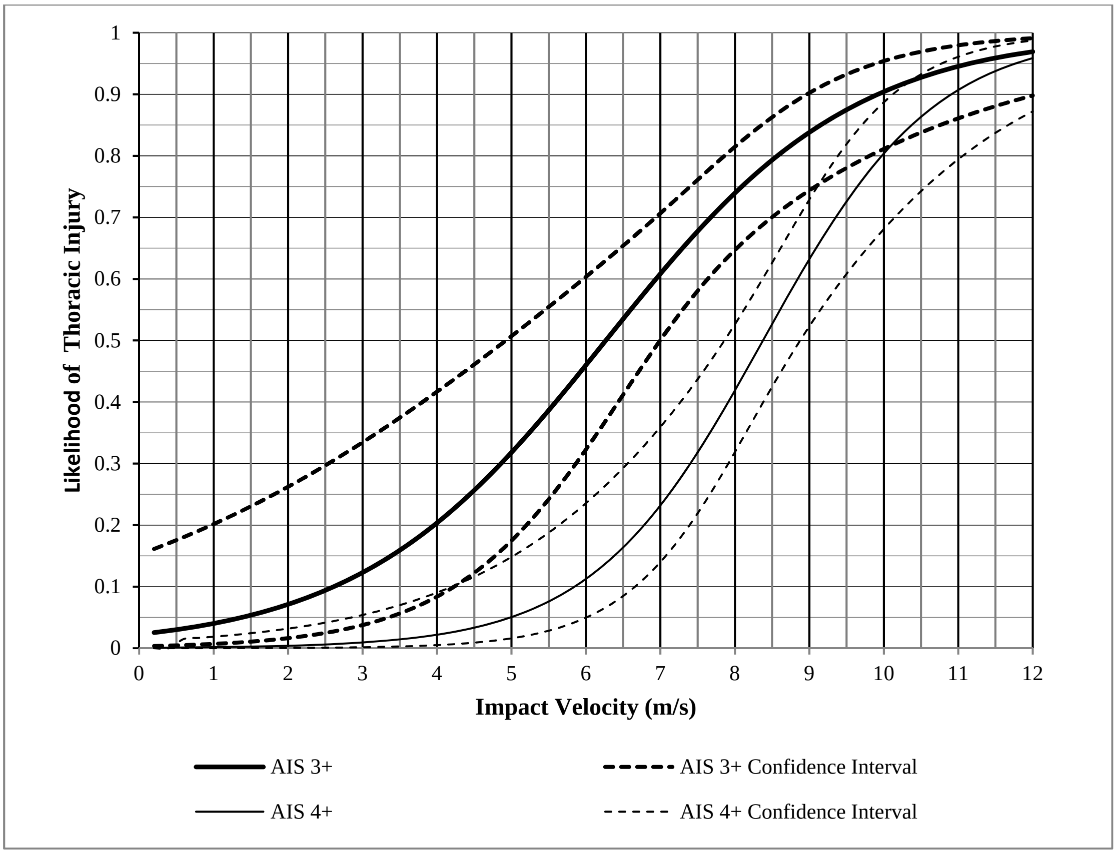


Figure 3.2 AIS3+ and AIS4+ thoracic injury versus impact velocity regression plot

The AIS3+ model indicates that a low likelihood of injury (<10%) exists up to an impact velocity of 2.6 m/s. This risk increases gradually with the impact velocity ranging from 2.6 m/s up to 10 m/s. At velocities higher than 10 m/s, the likelihood of an AIS3+ injury is high (> 90%).

The AIS4+ model indicates that a low likelihood of such injury (<10%) exists up to an impact velocity of 5.6 m/s. The injury risk increases sharply for impact velocities up to 10.8 m/s, beyond which the likelihood of sustaining an AIS4+ injury is high (>90%).

The result of the Hosmer and Lemeshow Goodness-of-Fit Test and the corresponding critical chi-squared p-value are presented in the first and second column in Table 3.10, respectively. The results from this test indicate that the model fits the observations from the test cases well. The Receiver Operator Characteristic (ROC) Area Under the Curve (AUC) is presented in the fourth column of Table 3.10. The results indicate that the AIS3+ and

AIS4+ model have a moderately good and good predictive power, [77] respectively.

Table 3.10 Hosmer and Lemeshow Goodness-of-Fit Test and ROC-AUC results for AIS3+ and AIS4+ single variable logistic regression model

	Hosmer and Lemeshow Goodness-of-fit Test	Critical Chi-Squared p-value	Degrees of Freedom	ROC-AUC
AIS3+ Model	8.9204	15.31	8	0.8459
AIS4+ Model	4.7927	15.31	8	0.7795

3.5 Discussion

3.5.1 Multiple Variable Logistic Regression Model

The PMHS age was found to be associated with a thoracic injury in both the AIS3+ and AIS4+ model. Previous studies [76] had found that PMHS age is a significant variable associated with injury severity, thus the outcome of this study's multiple variable regression models is in line with those previous findings.

This study has not found an association between PMHS mass and likelihood of sustaining AIS3+ thoracic injury despite other studies reporting that obese occupants have an increased likelihood of sustaining AIS3+ thoracic injuries compared to non-obese occupants.[20, 76] However, it has been reported that age has a greater influence than obesity.[20]

Test method was not found to be associated with injury severity. This is likely to be attributed to the over representation of sled tests (n=109) compared to pendulum tests (n=22) in this study. Hence, a conclusion based on the small number of test cases for the test method cannot be made.

In both the AIS3+ and AIS4+ multiple variable logistic regression models, the impact interface was a significant variable. The findings from these models show that a rigid impact interface is associated with PMHSs sustaining a thoracic injury. This finding is similar to the findings by Kallieris *et al*. [67] and

Marcus *et al*. [82] who reported that padding is a contributing factor to the PMHS injury response.

3.5.2 Single Variable Logistic Regression Model

The main finding from this study suggests that the current flail-space model's 'preferred' lateral occupant impact velocity of 9.0 m/s results in an 84% and 67% likelihood of sustaining an AIS3+ and AIS4+ thoracic injury, respectively, and the 'maximum allowable' impact velocity of 12 m/s results in a 97% likelihood of sustaining an AIS3+ or AIS4+ thoracic injury.

The injury likelihood values for the current flail-space 'preferred' and 'maximum allowable' impact velocities are high in comparison to the 50% likelihood of an AIS3+ and 25% likelihood of an AIS4+ thoracic injury values referenced by Kleinberger *et al*. [73] and Viano and Lau [151], respectively.

To determine a proposed impact velocity threshold from the results of this current study, the ROC classification table was used to determine the likelihood of sustaining an AIS3+ injury at a sensitivity level of 90%. A sensitivity level from SAS output of 91.4% was the closest to the desired sensitivity level. This sensitivity level corresponds to a thoracic impact velocity of 6.4 m/s with a corresponding 53% and 18% likelihood of sustaining an AIS3+ and AIS4+ thoracic injury, respectively. These likelihood values are similar to that referenced by Kleinberger *et al*. [73] and Viano and Lau [151]. Further, if occupants are restrained with a seatbelt and supplementary airbags are present in the vehicles, the impact velocity determined using the flail-space model would be conservative in terms of potential injury risk. It is recommended that the 6.4 m/s be set as the 'maximum allowable' occupant impact velocity.

3.5.3 Limitations

This study is not without limitations.

The corresponding acceleration threshold has not been evaluated due to the limited number of test cases reporting acceleration and force. It is recommended that future studies, potentially based on EDR data from vehicles involved in side-impact crashes, are carried out to establish a corresponding acceleration threshold.

A limitation of the single-variable logistic regression model is that only one variable (i.e., PMHS impact velocity) was used. This does not take into account the effect of padding on the impacted surface. The sigmoidal curve in Figure 3.2 would shift to the right if a greater number of padded impactor surface tests were present. This would result in a given impact velocity being less likely to be injurious than in the current model. Conversely, the sigmoidal curve in Figure 3.2 would shift to the left if a greater number of non-padded tests were present. This would result in a given impact velocity being more likely to be injurious than in the current model. Future studies can be directed to exploring how well the model in Figure 3.2 takes into account the effect of padding in vehicle interior components.

This study used data that were pooled from other studies which used different instrumentation, test methods and methods of assessing thoracic injuries. These differences are likely to have affected the overall results of this current study.

The PMHS arm location has been noted to affect the level of injury sustained. If the arm is placed between the impact wall and thorax, the arm dissipates some of the impact energy thus limiting the level of injury sustained by the thorax.[24] In the sled tests, the arm is placed either at the side of the thorax or slightly anterior to the thorax and, thus, its initial position may likely affect the injury outcome.

The age of PMHSs ranged from 17 to 86 with a mean of 52 years. Older PMHSs have an increased likelihood of sustaining an injury compared to that of younger PMHSs given the same impact force.[76, 166] This increased likelihood in sustaining an injury is not necessarily due to greater deformation of the thorax but, rather, due to decrease tolerance of deformation of older subjects.[20] The mean age of the PMHSs in this study is older than that of the average population and, thus, does not accurately reflect that of the average population in the real world. Hence, the consequence of using older PMHSs results would likely result in a conservative model for the mean age population of drivers.

In sled tests, the PMHS was propelled into the impact wall. Differences in contact times have been observed between tests for the pelvis, thorax and shoulder as a result of each test specimen leaning towards or away from the impact wall during the pre-impact phase. In the crash tests used in this current study, it is possible that the shoulder or pelvis may have impacted against the wall prior to the chest resulting in a reduction of the expected chest impact force, despite the impact velocity and wall type (flat or offset) being nominally the same in each test.

The result from this study is applicable to crashes where no intrusion of the occupant space had occurred. It is noted from Chapter 2 that intrusion of the door into the occupant space occurred in only 7.4% of rollover crashes where an AIS3+ thoracic injury had occurred; thus, the results from this study can be applied to a majority of rollover crashes.

The focus of this study is on thoracic injuries resulting from lateral impacts thus the results from the findings cannot be extrapolated and be applied to whole body lateral impacts.

3.6 Conclusions

A total of 178 PMHS side-impact tests cases were obtained from previously conducted studies where the PMHS impact velocity and thoracic AIS injury were reported. These were then filtered for test method, impact wall interface, and location of both impact wall and arm. After filtering, a total of 131 test cases were found to be suitable for inclusion in this study.

Multiple variable logistic regression was first performed to establish the correlation between the independent variables (thorax impact velocity, PMHS mass, impact wall, test method and PMHS age) and the dependent variables (AIS3+ and AIS4+ thorax injury). The results from the analysis indicated that impact velocity, PMHS age and impact wall interface were significant variables for both the AIS3+ and AIS4+ models.

Thorax impact velocity was then used to validate flail-space's 'preferred' and 'maximum allowable' lateral impact velocity criteria of 9 m/s and 12 m/s, respectively (Table 3.1), through two single variable logistic regression models – one each for the AIS3+ and AIS4+ model.

The results from the study indicate that the current flail-space lateral occupant impact velocity of 9 m/s and 12 m/s results in a high likelihood of an occupant sustaining AIS3+ and AIS4+ thoracic injuries. As such, it is proposed that a lower impact velocity of 6.4 m/s should be considered. The 6.4 m/s impact velocity corresponds to a 53% and 18% likelihood of sustaining an AIS3+ and AIS4+ thoracic injury, respectively.

4 Thoracic Injuries based on Occupant Seated Position and Roll Direction

4.1 Introduction

In Section 2.6.3, previous studies that identified the most frequently reported thoracic injury and the sources of these injuries were presented. Specifically, one of the most detailed studies conducted to better understand thoracic injuries in vehicle rollover crashes sustained by restrained and contained occupants was performed by Bambach *et al*. [12] who found that lung contusions were the most frequently reported thoracic injury followed by rib fractures. They also found that the main sources of these injuries were the door interior, seatbelt, seatback and steering wheel. However, recent studies [78] have indicated that near- and far-side occupant kinematics differ from each other. This highlights a need to develop an understanding of thoracic injuries and the sources of these injuries based on the occupant seated position and rollover direction. As such, this study was performed to determine whether thoracic injuries and their sources differ between near- and far-seated occupants.

In Section 4.2, the methodology used for this study is presented. In Section 4.3, the results from the analysis are presented. This is followed by a discussion in Section 4.4 and the conclusions are presented in Section 4.5.

4.2 Method

4.2.1 Rollover Crash Data

Rollover crash data were obtained from the NASS-CDS database for the year 2001 to 2012 inclusive. The data were then queried in SAS Enterprise Guide 5.1 [131] in two stages (Figure 4.1). In the first stage, the data were queried with the following vehicle filters: the vehicle was a passenger car or utility vehicle involved in a single-vehicle tripped rollover crash with at least one quarter-turn rollover or more where the vehicle did not contact another object prior to, during or after rolling over; and no airbags were deployed. In the second stage, the data were queried with the following occupant filters: the occupant was a front seat occupant of 16 years or older; the occupant was restrained and contained in the vehicle; and the occupant sustained at least one AIS3+ thoracic injury.

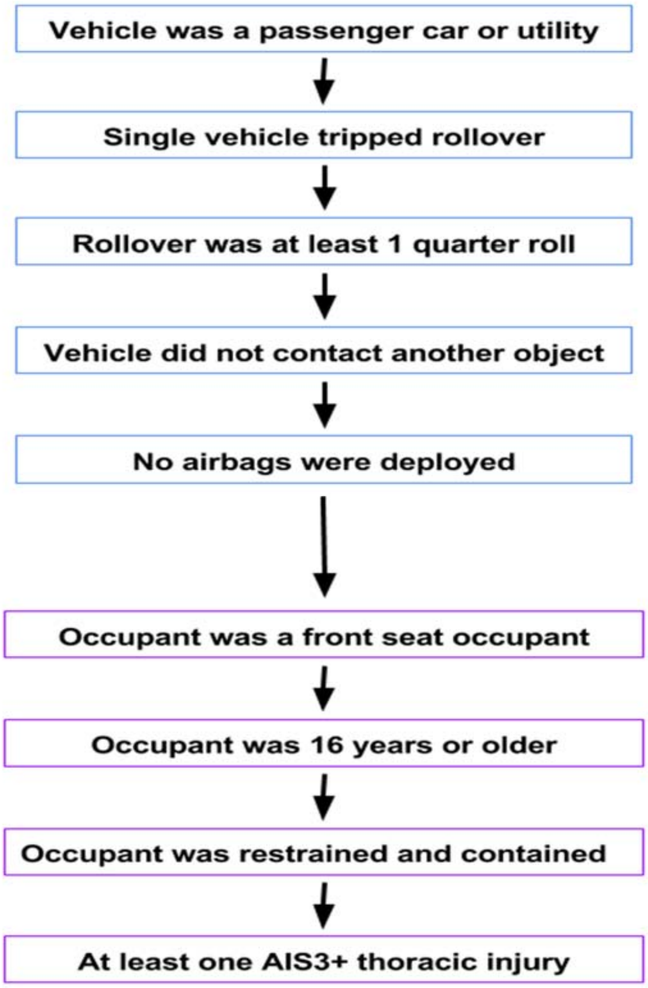


Figure 4.1 Vehicle and occupant filter criteria

Vehicles that had undergone a rollover prior to, during or after impact with another vehicle or object were excluded from this study as it has been shown that these crash types produce different occupant injury patterns to pure rollovers.[35]

After filtering NASS-CDS data with the aforementioned criteria, the query returned 43 cases ($n_{weighted}$ = 4,573). These 43 cases form the data set for this study (Appendix F).

Rollover crashes where an airbag was deployed were also excluded because they introduce a protective effect that might confound the planned investigation of the relationships between sources of injury and injury outcomes for front-seated near- and far-side occupants. Further, a similar query as shown Figure 4.1 was performed; however, the airbag filter was set to include rollover crashes where a side or curtain airbag was deployed. This query returned 1 case; thus, the number of rollover crashes where an airbag was deployed is small compared to the 43 cases where no airbags were deployed.

4.2.2 Empirical Analysis

An empirical analysis of the 43 cases was then performed. Firstly, the data set was evaluated for the distribution of AIS3, AIS4, AIS5 and AIS6 thoracic injuries, the pathology of thoracic injuries and the sources of thoracic injuries. Secondly, the data was divided into the following groups:

1) Driver near-side rollover

2) Driver far-side rollover

3) Passenger near-side rollover

4) Passenger far-side rollover

The pathology of thoracic injuries and the sources of thoracic injuries were then evaluated for each case in the aforementioned groups. It is noted that an occupant in a rollover crash may have sustained multiple AIS3+ thoracic injuries. In these cases, each AIS3+ thoracic injury was considered separately. That is, if an occupant had sustained an AIS3+ rib fracture and an AIS3+ lung contusion, these two injuries are counted in this study as two separate injuries.

4.3 Results

The results from evaluating the data set indicate that 62.8% (n=27) and 37.2% (n=16) of all considered rollover occupants sustained at least one AIS3 and at least one AIS4 thoracic injury, respectively (Figure 4.2). The data set also indicate that lung contusion and rib fractures were the two most common thoracic injuries followed by haemo/pneumothorax and thoracic cavity injury constituting 60.7%, 25.0%, 5.4% and 3.6% of all thoracic injuries, respectively (Figure 4.3).

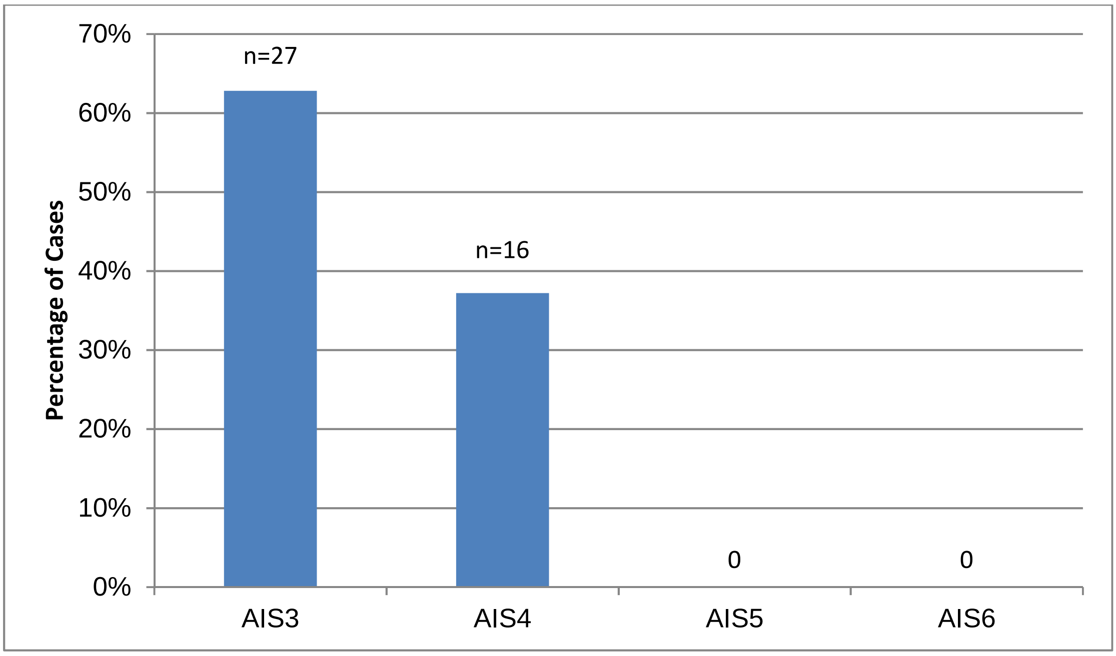


Figure 4.2 Distribution of thoracic injury severity for the considered dataset

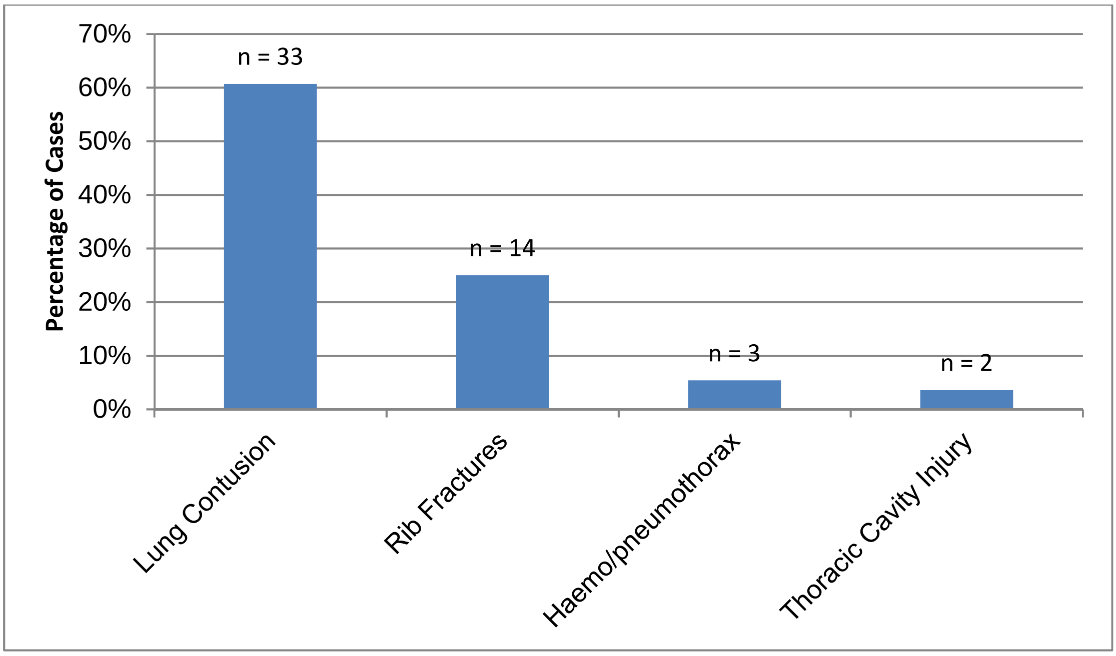


Figure 4.3 Distribution of thoracic injury for the considered data set

When lung contusions and rib fractures were investigated in more detail, unilateral lung contusions occurred most frequently followed by bilateral lung contusions (Figure 4.4). Similarly, this trend was also observed with rib fractures with unilateral rib fractures occurring more frequently than bilateral rib fractures (Figure 4.4).

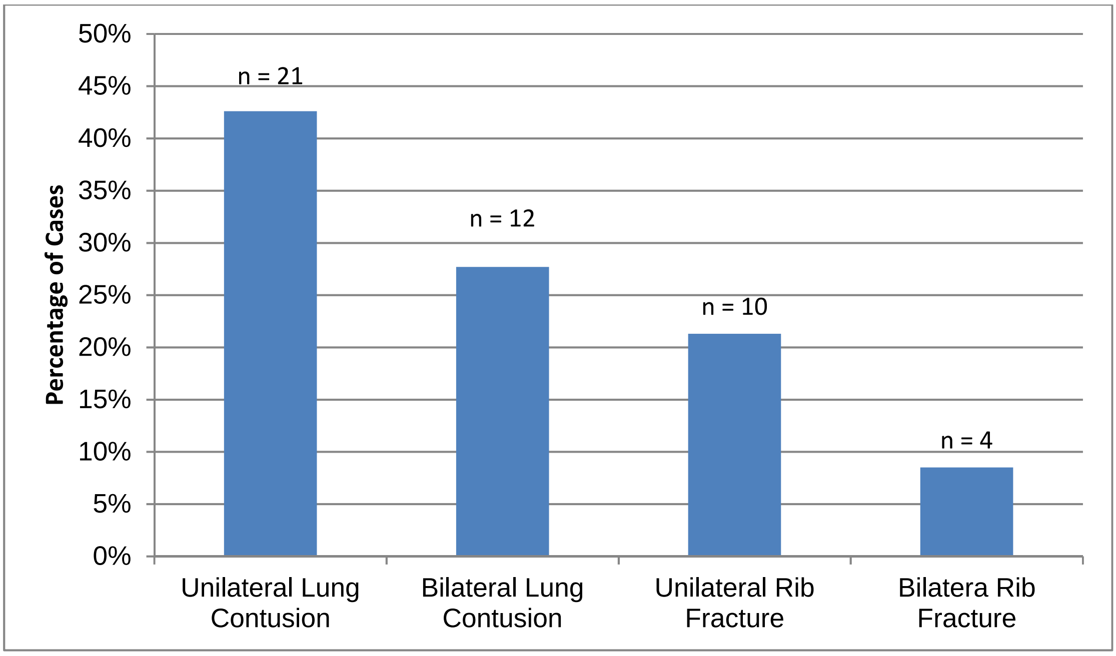


Figure 4.4 Distribution of uni- and bi-lateral lung contusion and rib fractures for the considered dataset

The NASS-CDS crash investigator also codes the source for each injury and whether the injury was related to an intrusion into the occupant space. The most common source of thoracic injury was found to be the vehicle door interior followed by the seatbelt, seatback, steering wheel, centre console and roof that were attributed to 59.7%, 12.3%, 8.8%, 7.0% and 7.0% and 1.8%, respectively (Figure 4.5).

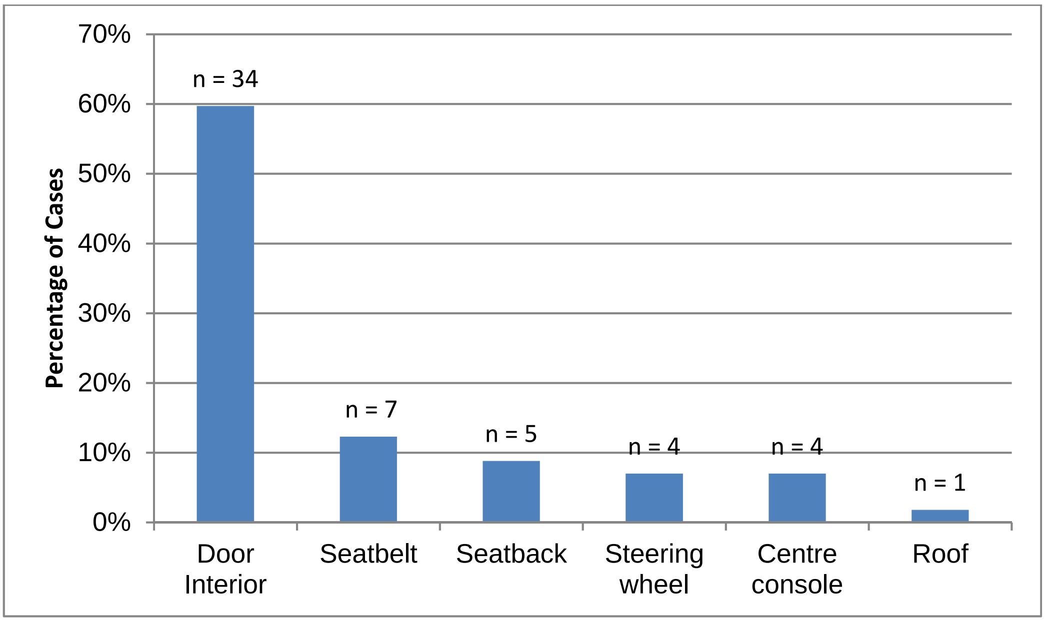


Figure 4.5 Sources of thoracic injuries for the considered dataset

When the results were considered according to occupant seated position, driver near-side rollovers (n=17) and driver far-side rollovers (n=15) were observed to occur most frequently followed by passenger far-side rollovers (n=7) and passenger near-side rollovers (n=4) (Figure 4.6).

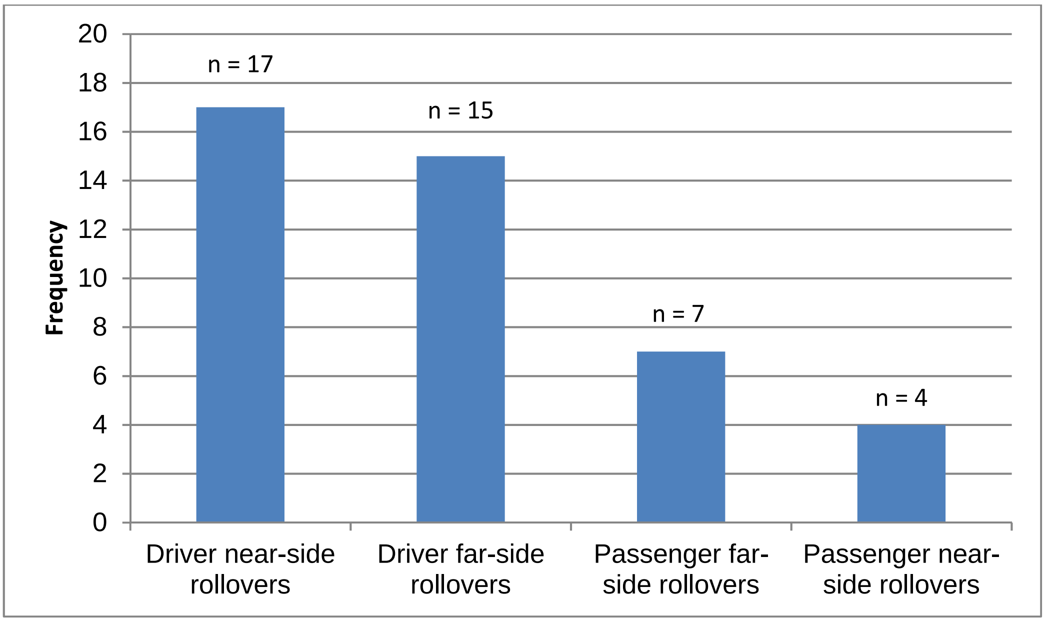


Figure 4.6 Rollovers considered according to occupant seated position for the considered dataset

When injuries were evaluated by occupant seated position, it was observed that there were a total of 20 thoracic injuries recorded for driver far-side rollover, 23 for driver near-side rollovers, 9 for passenger far-side rollovers and 5 for passenger near-side rollovers.

For driver far-side rollovers, the left door interior and seatbelt were the two most common sources of thoracic injury and was attributed to 35% and 30% of thoracic injuries (Figure 4.7). This was in contrast with driver near-side rollovers where the left door interior was attributed to 78% of thoracic injuries; thus making it, by far, the most frequently cited source of thoracic injury (Figure 4.7).

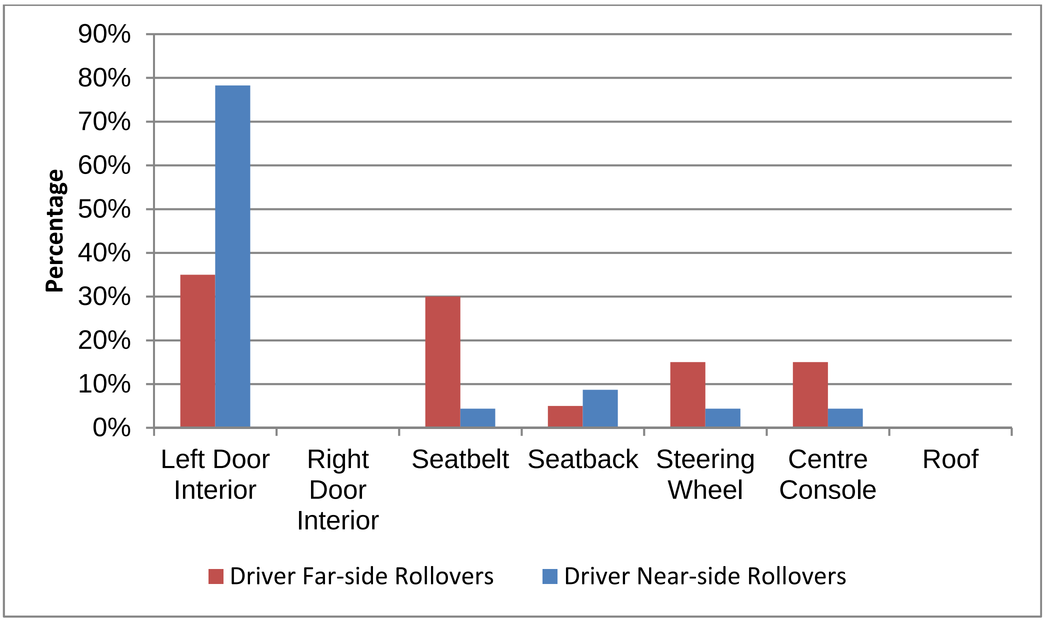


Figure 4.7 Injury sources for driver far-side rollovers and near-side rollovers for the considered dataset

For passenger far-side rollovers, the right door interior was attributed to 77.8% of thoracic injuries thus making it the most commonly coded source of injury (Figure 4.8). For passenger near-side rollovers, the right door interior was attributed to 40% of thoracic injuries. However, it is noted that there was an equal percentage of thoracic injuries that was attributed to unknown sources (Figure 4.8).

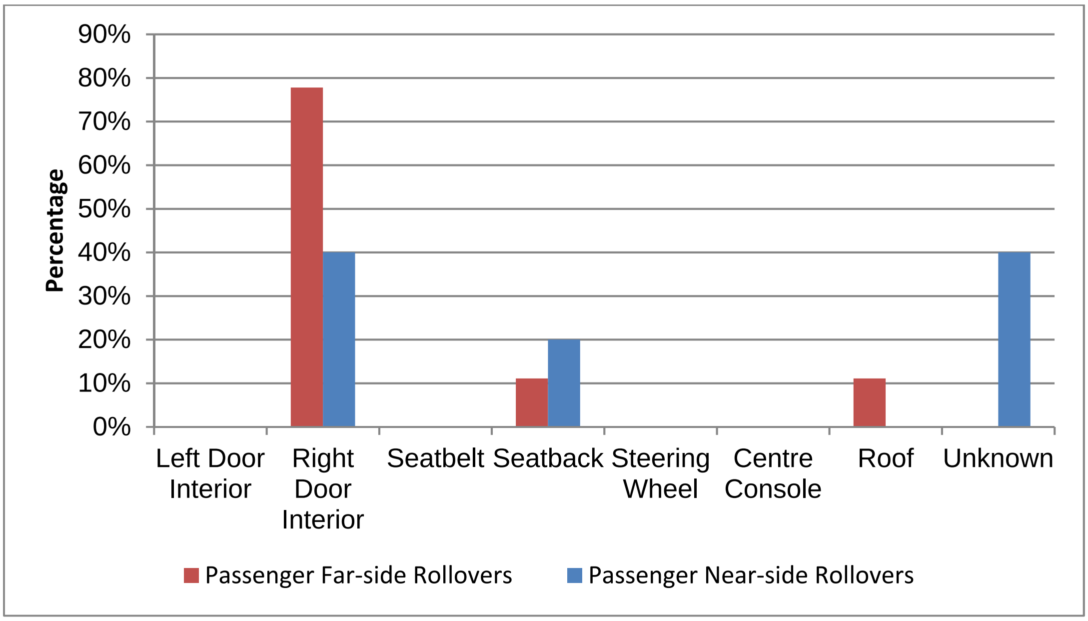


Figure 4.8 Injury sources for passenger far-side rollovers and near-side rollovers for the considered dataset

From all cases of thoracic injuries in this study, only 5.3% of the injuries were attributed to intrusion into the occupant space, which is a finding similar to that of Bambach *et al*.[12]

Thoracic injuries were also considered by pathology and seated position. For driver far-side rollovers bilateral lung contusions, right lung contusion and left lung contusions were the most frequently cited thoracic injuries constituting 30%, 25% and 15% of injuries, respectively (Figure 4.9). For driver near-side rollovers left lung contusions occurred most frequently followed by bilateral lung contusions and left rib fractures constituting 31.8%, 22.7% and 18.2% of thoracic injuries, respectively (Figure 4.9).

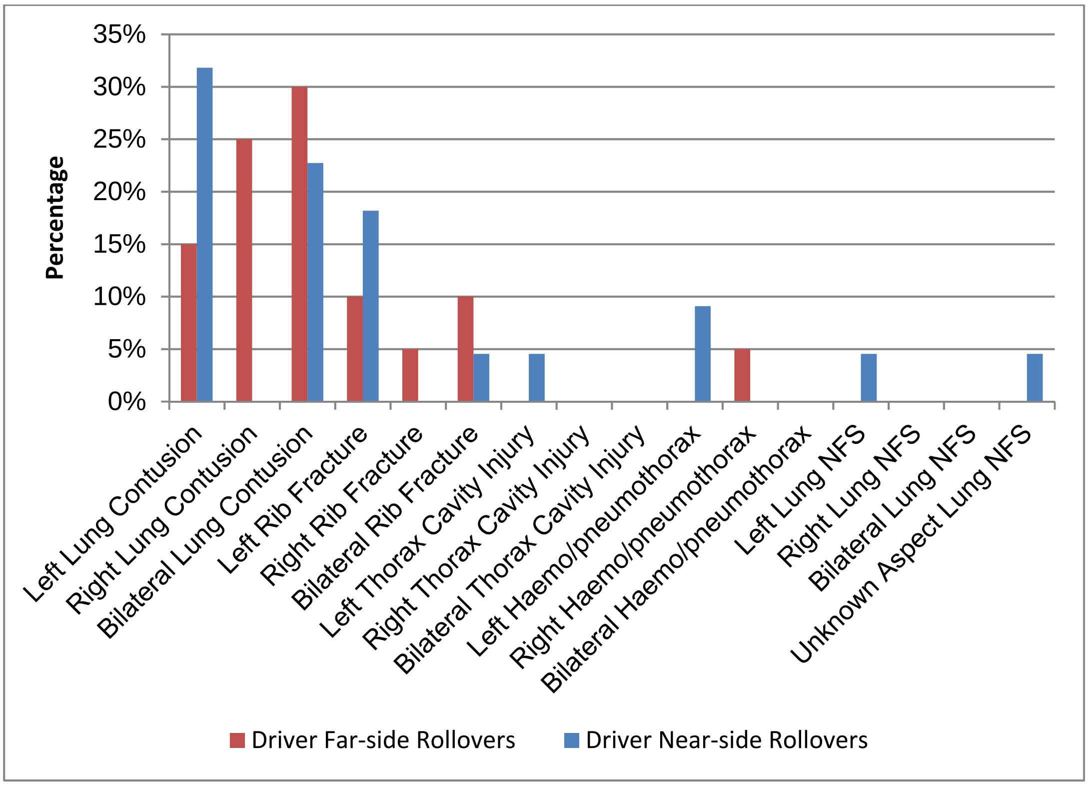


Figure 4.9 Thoracic viscera injured for driver far-side rollovers and near-side rollovers for the considered dataset

For passenger far-side rollovers right lung contusions were the most frequently reported injury followed by right rib fracture, left lung contusion, bilateral lung contusion and bilateral rib fracture constituting 44.4%, 22.2%, 11%, 11% and 11% of thoracic injuries, respectively (Figure 4.10). For passenger near-side rollovers the most frequently reported injury was right lung injury with details which were “Not Further Specified” (NFS) followed by right lung contusion, right rib fracture and left thoracic cavity injury constituting 40%, 20%, 20% and 20%, respectively (Figure 4.10).

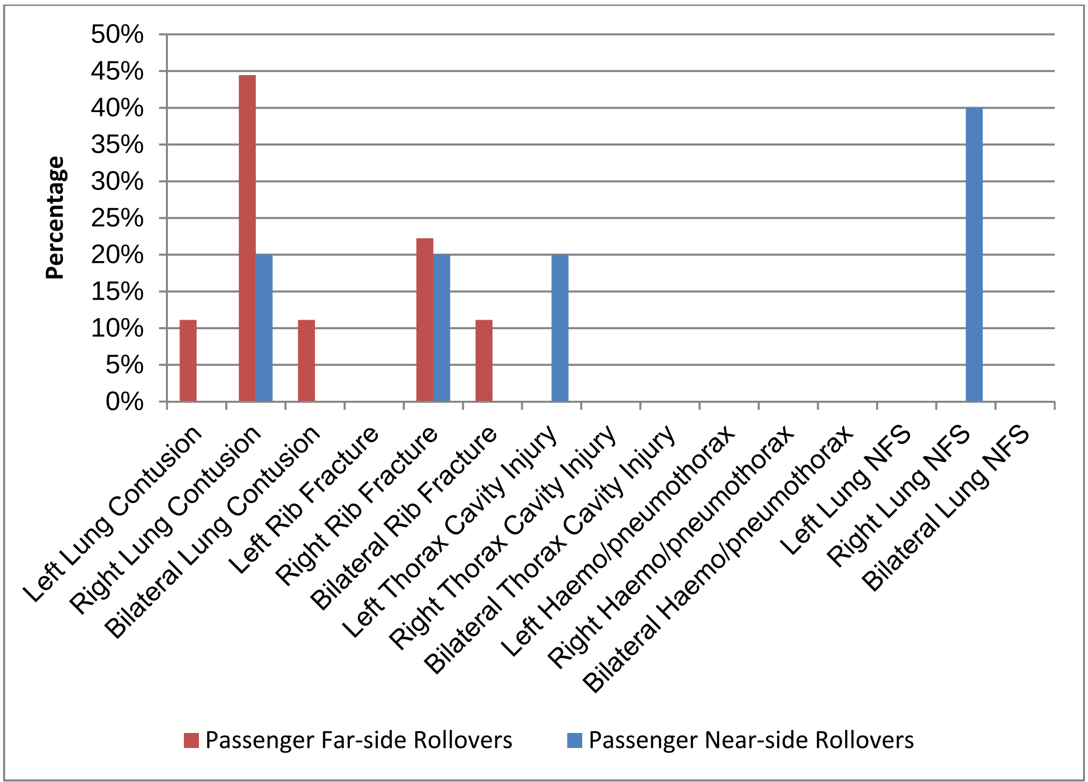


Figure 4.10 Thoracic viscera injured for passenger far-side rollovers and near-side rollovers for the considered dataset

4.4 Discussion

4.4.1 Empirical Analysis

From the analysis of all cases, unilateral lung contusions were the most frequently recorded thoracic injury followed by bilateral lung contusions, unilateral rib fractures and bilateral rib fractures, which is a finding similar to that by Bambach *et al*.[12] For both front seat occupant positions, the door interior was found to be the most frequently coded source of thoracic injury followed by the seatbelt, which is a finding similar to that of Bedewi *et al*. [13] and Parenteau *et al*. [116] However, when this data was considered by occupant seated position and rollover direction, the main sources of thoracic injury and thoracic viscera injured differs.

For driver far-side rollovers, the left door interior was the most frequently coded source of thoracic injury followed by the seatbelt, steering wheel and centre console (Figure 4.7). The sources of driver far-side rollover thoracic injuries is contrasted by that of driver near-side rollover injuries, in which the left door interior is again, by far, the most common source of thoracic injury (Figure 4.7), followed by the seat back. The seatbelt, steering wheel and centre console were not frequently attributed to thoracic injuries for these occupants.

For driver near-side rollovers, left lung contusions, bilateral lung contusions and left rib fractures were the three most frequently occurring thoracic injuries (Figure 4.9). As the left door interior was the most frequently coded source of injury for driver near-side rollovers (Figure 4.7), it is likely that the drivers in these rollovers impacted the left door resulting in left thoracic injuries such as left lung contusions and left rib fractures. The seat back, seatbelt and centre console are the likely sources of right thoracic injuries for drivers in driver near-side rollovers. It is noted from Figure 4.9 that bilateral lung contusions were the second most common thorax injuries for driver near-side rollovers. Thus, for these injuries, right thorax injuries were likely to have been sustained from the seatback, seatbelt and centre console and left thorax injuries from impact with the left door interior. A major limitation in determining the sources of bilateral thoracic injuries is the NASS-CDS data which allows only one source of injury to be attributed to bilateral injury.

The most frequently seriously injured viscera for drivers in driver far-side rollovers were bilateral lung contusions, right lung contusions followed by left lung contusions. As the sources of injuries for these occupants were more evenly divided between the left door interior followed by the seatbelt and the steering wheel and the centre console (Figure 4.7), it is more difficult to reach a similar conclusion in terms of injury mechanism as that for driver near-side rollover.

In contrast to drivers, the right door interior was found to be the most frequent source of thoracic injury for both near- and far-side passengers in rollovers followed by the seatback. Right lung contusion and rib fractures occurred frequently for passenger far-side rollovers and are likely to have occurred from the passenger impacting the right door interior. Left lung contusions for passenger far-side rollovers were likely to have occurred through contact with the seatback as this was the only coded source of injury (Figure 4.8) that is located to the left side of passengers apart from the roof. Due to the small sample size (n=4) for passenger near-side rollovers and that 40% of the sources of thorax injuries were coded as “Unknown”, comments regarding how these injuries may have occurred has not been made for these occupants as the data may not be representative of passenger near-side rollovers. Although there were slightly more cases for passenger far-side rollovers (n=7), it is also not feasible to claim that these cases are a good representation of all passenger far-side rollovers. It is also likely that the low sample numbers for passengers (n=11) also explains why the seatbelt was not coded as a source of injury for passengers while it is quite a common source of injury for drivers (n=32).

This study has also shown that very few passenger vehicles involved in rollover crashes where a front seated occupant has sustained at least one AIS3+ thoracic injury and where a side or curtain airbag has deployed is small. In order to reduce thoracic injuries through injury mitigating devices, such as airbags, it is important to firstly understand where these devices need to be placed for greatest occupant injury protection.

4.4.2 Limitations

The limitations of this study should be noted. Firstly, the NASS-CDS data is a probability sample rather than a census. Secondly, the data is dependent on the investigation and data entry accuracy of the NASS investigators. Thirdly, NASS-CDS also only allows the coding of one source of injury for each injury sustained by an occupant even though a bilateral injury may have occurred. Fourthly, the sample size is small.

4.5 Conclusions

Rollover crash data were obtained from the NASS-CDS database for the year 2001 to 2012 inclusive. Data were then filtered with the following filters: the vehicle was a passenger car or utility vehicle involved in a single-vehicle tripped rollover crash with at least one quarter-turn rollover or more where the vehicle did not contact another object prior to, during or after rolling over; and no airbags were deployed; the occupant was a front seat occupant of 16 years or older; the occupant was restrained and contained in the vehicle and the occupant sustained at least one AIS3+ thoracic injury. This query returned 43 cases.

An empirical analysis was performed on the data to determine the distribution of thoracic injury, sources of thoracic injury and thoracic severity.

The results from the analysis indicated that AIS3 thoracic injuries accounted for a majority of all AIS3+ thoracic injuries. The most common thoracic injury was lung contusion followed by rib fractures. The most common source of thoracic injury, by far, was the door interior followed by the seatbelt and seatback.

The data were then considered according to occupant seated position and vehicle rollover direction. From this, there appear to be differences between thoracic injury sources for driver far-side and driver near-side rollover crashes. The left door interior and seatbelt were the two most commonly and almost equally, coded injury sources for driver far-side rollovers while the left door interior was, by far, the most commonly coded source for driver near-side rollover. Thus, both occupant seat positions need to be considered when developing rollover crash simulation protocols and safety design improvements, such as airbags, because the injury sources are different for both front seat occupant positions (near- and far-sides). Seatbelt injuries were also significantly more prominent in driver far-side rollovers than driver near-side rollovers.

5 Vehicle Damage and Thoracic Injury Correlation

5.1 Introduction

In Section 2.6.3, it was highlighted that previous studies have identified that door intrusion was attributed to only 7.4% of AIS3+ thoracic injuries where the door was coded as the source of the injury.[12] That figure is similar to what has been found in the study presented in Chapter 4. As such, it was proposed by Bambach *et al*. [12] that thoracic injuries are occurring due to the occupant sliding towards and impacting against the door. This suggests that a sudden change in the vehicle kinematics occurs during a rollover that precipitates such an injury causal mechanism.

The change in vehicle kinematics for a vehicle in a pure rollover is likely to occur during ground impact as was found by Anderson *et al*. [5] during an analysis of a real-world rollover crash involving a SUV. From their study, they observed that the SUV's roof impact at a location rearwards of the B-pillar resulted in significant vehicle deformation as well as a sudden decrease in the vehicle roll rate and translational (i.e., lateral) velocity.

Henderson and Paine [55] performed a similar study based on video recordings of rally vehicles involved in rollover crashes. Although those crashes were not necessarily representative of passenger vehicle rollover crashes and the vehicle travel speeds were likely to be higher, the analysis provided an insight into the dynamics of rollover crashes.[55] From their video analysis, they observed that a rollover vehicle's "*horizontal* [i.e., lateral] *velocity profile will be step-like, with the steep portions corresponding to* [vehicle] *'corner' contacts with the ground*." Henry *et al*. [56] also observed that during a rollover crash a vehicle contacts the ground several times at which serious occupant injuries can occur.

The study performed by Bambach *et al*. [12] on thoracic injuries in rollover crashes sought to find a relationship between vehicle damage and thoracic injuries. From their study of vehicle rollover crash damage patterns in which occupants sustained AIS3+ thoracic injuries they observed and commented that,

> *"...typically the side of the vehicle displayed some damage, indicating ground contact. However, a wide variety of vehicle damage occurred, varying from no damage (indicating no ground contact) to significant damage (indicating significant ground contact)."*

However, they were unable to identify observable vehicle damage patterns that corresponded to an occupant sustaining AIS3+ thoracic injuries.

Digges *et al*. [37] extended the study by Bambach *et al*. [12] by examining eight rollover crashes in detail to find an association between vehicle crash damage patterns and thoracic injuries. However, such an association was not found primarily due to the limited number of cases examined. Despite this, they hypothesised from their observations that the *"lateral loading [of] the roof pillars and left front fender during the third and possible seventh quarter-turn may be associated with a driver sustaining an AIS3+ thoracic injury."*

This study extends the work carried out by Digges *et al*. [37] and Bambach *et al*. [12] by determining quantitatively if there is an association between vehicle crash damage patterns and thoracic injuries.

In Section 5.2, the methodology used for this study is presented. In Section 5.3, the results from the analysis are presented. This is followed by a discussion in Section 5.4 and the conclusions are presented in Section 5.5.

5.2 Method

5.2.1 Rollover Crash Data

In order to assess whether vehicle damage is correlated with an occupant sustaining AIS3+ thoracic injury in a rollover crash, a case-control study was performed. The filtered NASS-CDS data set from Chapter 4 was obtained and used as cases in this case-control study. That is, cases consisted of passenger cars or utility vehicles involved in a single-vehicle tripped rollover crash with at least one quarter-turn rollover or more where the front seat occupants were 16 years or older; occupants were restrained and contained in the vehicle; the vehicle did not contact another object prior to, during or after rolling over; no airbags were deployed and the occupant sustained at least one AIS3+ thoracic injury (Figure 5.1).

For controls, the original 2001 to 2012 NASS-CDS data from Chapter 4 were filtered using the same criteria as that for cases; however, in this study occupants were filtered for no thoracic injuries. That is, controls consisted of passenger cars or utility vehicles involved in a single-vehicle tripped rollover crash with at least one quarter-turn rollover or more where the front seat occupants were 16 years or older; occupants were restrained and contained in the vehicle; the vehicle did not contact another object prior to, during or after rolling over; no airbags were deployed and the occupant sustained no thoracic injury (Figure 5.1).

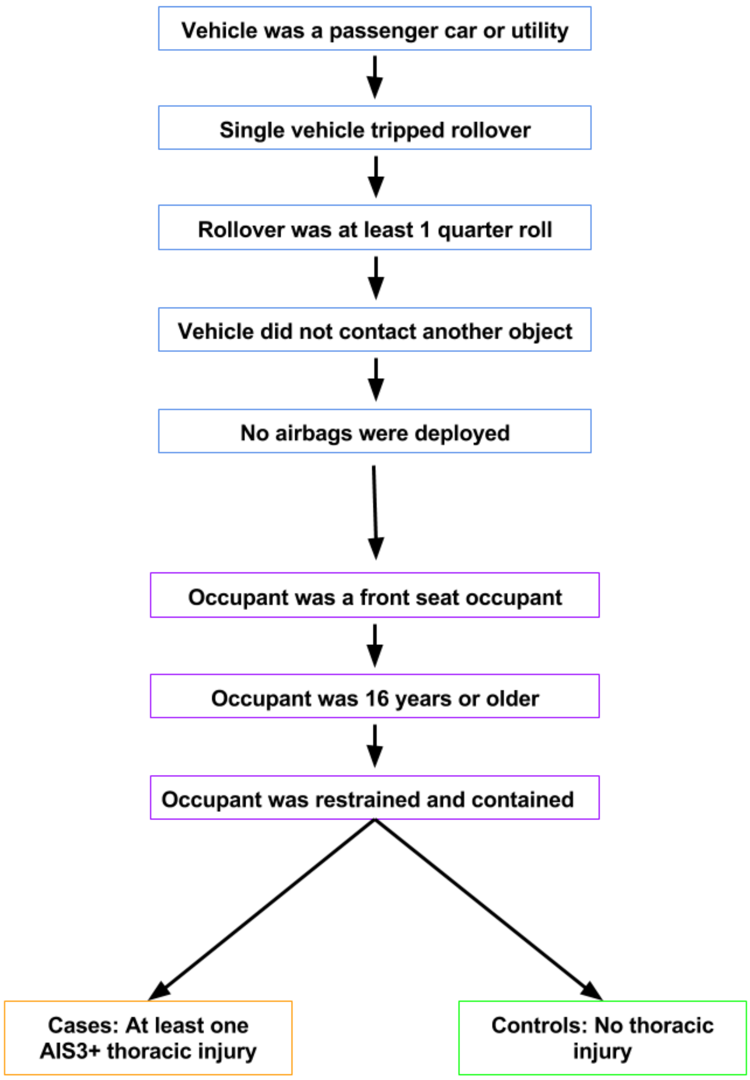
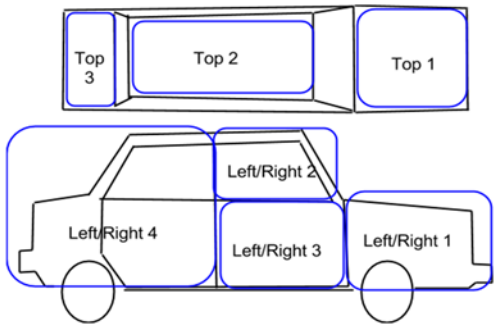
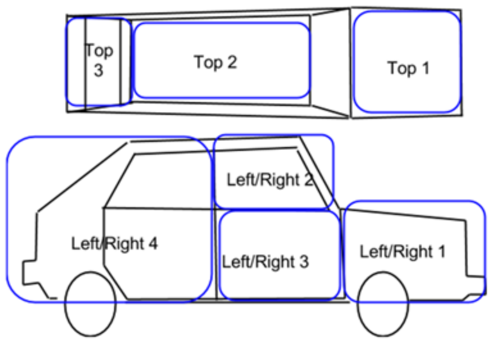
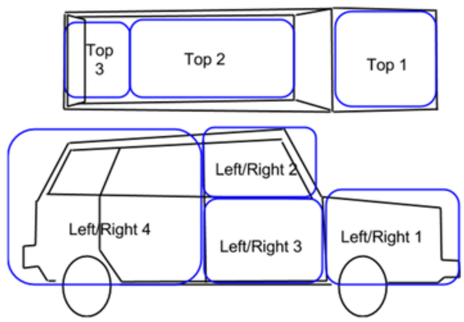
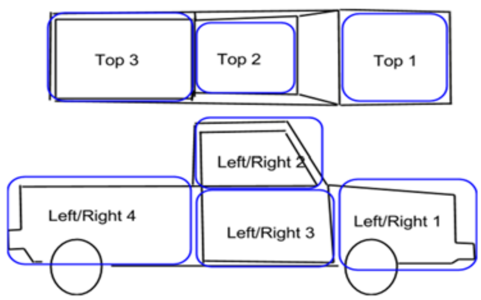


Figure 5.1 Case and control filter

The query returned 43 cases ($n_{weighted}$=4573) and 761 ($n_{weighted}$=325,067) controls. From the 761 controls, 200 were randomly selected for vehicle panel damage coding. This was reduced to 181 ($n_{weighted}$=55,905) controls (Appendix G), thus achieving a ratio of cases to control of 1:4 to 1:5, after filtering out vehicles deemed unsuitable for inclusion in this study. Vehicles were excluded if vehicle panel damage was obscured by plastic sheets used to prevent water infiltration into the vehicle; if the vehicles were cut open and it was unclear if the panels were bent by rescue workers or damaged during the crash; or when vehicles were undergoing repairs when the photos were taken. It is noted that the query for cases originally returned 46 cases; however, 3 were removed due to a lack of suitable photographs. Thus, the number of cases and controls used in this study was 43 and 181, respectively.

5.2.2 Coding of Vehicle External Segment Damage

The panels forming the exterior of each vehicle was divided into eleven segments - four segments on either side of the vehicle and three segments on the top. The segments on the side of the vehicle consisted of the panels forming the front fender, front door upper half including the A-pillar, front door lower half, vehicle side from the B-pillar rearwards. The segments on the top of the vehicle consisted of the panels forming the front bonnet, glasshouse roof from the top of the A-pillar to top of the C-pillar (for sedans and hatch backs) and the area rearwards of the top of the C-pillar (for station wagons, SUVs, 4WDs, vans and pickups) or the trunk lid and hatch (for sedans and hatch backs, respectively) (Figure 5.2). These segments were labelled as Left/Right 1, Left/Right 2, Left/Right 3, Left/Right 4, Top 1, Top 2 and Top 3 respectively for entry into SAS (Figure 5.2).

Category	Class	Vehicle Segments
Passenger Car	**Sedan**	
	Hatch back	
	Station wagon	
Utility Vehicle	**Pickups**	

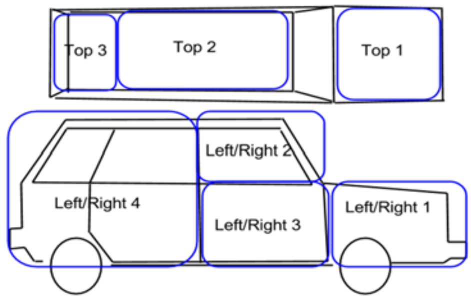
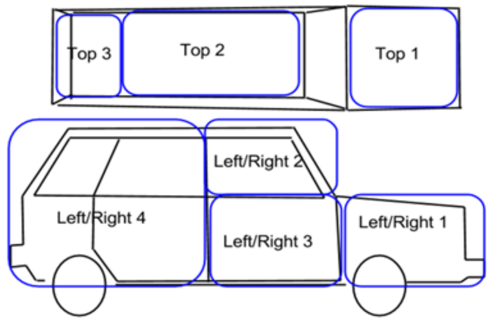
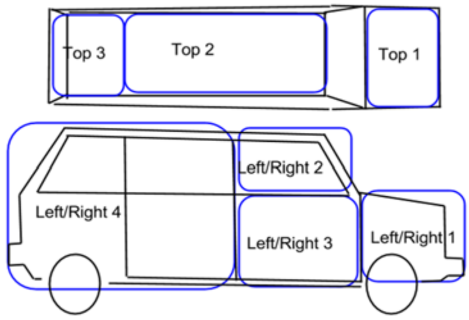
	SUVs	
	4WDs	
	Vans	

Figure 5.2 Each class of vehicle was divided into 11 segments

Photographs of case and control vehicles were obtained and visually examined. Dichotomous coding of vehicle segment damage was performed with segments sustaining either no damage to minor damage, coded as zero, or segments sustaining major damage from vehicle-to-ground contact, coded as one (Appendices F and G). No damage or minor damage is defined as segments which have sustained scratches or small dents from the vehicle-to-ground impact. In this study, it has been assumed that the small dents in the vehicle segments indicate that the energy involved in deforming the segments would be relatively small thus not likely to have altered the vehicle's rollover kinematics significantly. Major damage is defined as segments which have sustained substantial damage to the vehicle's panels and substructure; thus, indicating greater energy dissipation upon vehicle-to-ground impact sufficient to alter the vehicle's kinematics during the rollover. An example of minor and major damage is provided in Figure 5.3. Where it was unclear whether a segment has minor or major damage, a conservative approach was taken and the segment damage was coded as minor.

NASS-CDS Case ID	Example of minor damage	Example of major damage
2002-48-180		
2005-48-248		
2007-50-089		

Figure 5.3 Examples of three case vehicles (Top, middle and bottom row) where vehicle segments have sustained minor damage (left) versus major damage (right)

In the event that two adjacent segments of the vehicle sustained major damaged directly from the vehicle-to-ground impact, both segments would be coded as sustaining major damage. For example, if segment Left 2 and Left 4 sustained major damage from direct ground contact then both of these segments were coded as sustaining major damage. However, if major damage to a segment was purely induced by the deformation of an adjacent segment (i.e., without a direct vehicle-to-ground impact), then only the segment directly damaged from the vehicle-to-ground contact was coded as sustaining major damage and the adjacent segment was coded as sustaining minor damage. An example of this is presented in Figure 5.4. In this example the vehicle's top-half front door (segment Right 2) and roof (segment Top 2) both sustained major damage from vehicle-to-ground contact and caused major damage to the bottom half of the front door (segment Right 3) by pushing down on that segment. Thus, only the first two segments (i.e., segment Right 2 and segment Top 2) were coded as sustaining major damage while the latter (i.e., segment Right 3) was coded as sustaining minor damage.

Figure 5.4 Example of damage induced to one vehicle segment (segment Right 2) from damage to an adjacent segment (segment Right 3)

The weighting allocated to each NASS-CDS case was applied based on various factors such as the crash type, crash severity and crash location, and did not apply to segment damage. That is, two vehicles may have been involved in the same type of crash (e.g. single vehicle rollover) with similar severity and, therefore, are allocated the same weighting value. However, these two vehicles may sustain different vehicle segment damage. For example, one vehicle may roll along a paved surface whereas the other along an unsealed median strip; thus, both vehicles will sustain different crash damage patterns. As such, the weighting does not reflect the resultant damage sustained by the vehicle and was not used in this study. It is also noted that NASS-CDS oversamples more serious crashes thus resulting in the potential for case-control studies to be biased towards the more serious crashes. However, this bias was controlled through the control group which was specifically selected for rollover crashes where no thoracic injuries were sustained by the vehicle occupants. Further, the 1:4 to 1:5 ratio of cases to control also further limits this potential bias.

5.2.3 Empirical Analysis of Cases and Controls

An empirical analysis was performed to determine the mean number of vehicle quarter-turns, the mean age of the occupants, the percentage of utility vehicles versus sedans and the percentage of near- versus far-side rollovers for cases and controls.

5.2.4 Statistical Method

A multiple variable logistic regression model was developed in SAS Enterprise Guide 5.1 [131] to assess the association between the predictor variables and the response variable. The predictor variables for the model consisted of variables from the vehicle, occupant and the crash environment. They were evaluated for inclusion in the model based on the possibility that they may be associated with serious thoracic injury and guided by previous reports. [12, 97] The variables considered for inclusion in the model were: number of vehicle quarter-turn rollovers, occupant age, occupant gender, roll direction relative to the occupant, vehicle class (sedan, hatch back, station wagon, pickups, SUVs, 4WDs and vans), roadway alignment (straight road, left curve or right curve), rollover initiation location (roadway, paved shoulder, unpaved shoulder or roadside/median), surface condition (dry, wet, snow, slush, ice or sand/dirt/oil/gravel) and roadway profile (level, uphill, hill crest, downhill or sag). Other variables such as vehicle travel speed, occupant height, weight and BMI were initially considered for inclusion in this study. However, due to missing observations for several cases, these variables were not included as this would have reduced the number of already limited cases in this study.

The aforementioned variables were classified as either:

- discrete (vehicle quarter-turn rollovers),
- continuous (occupant age),
- dichotomous (occupant gender and roll direction relative to the occupant) or
- polytomous (vehicle class, rollover location, roadway alignment, surface condition and roadway profile).

Due to the small sample size in this study, polytomous variables were classified as dichotomous in the following manner:

- vehicle category was either a utility vehicle or passenger car,
- rollover location was either on the roadway or otherwise,
- roadway alignment was either straight or curved,
- surface condition was either dry or otherwise and
- roadway profile was either level or otherwise.

The response variable was the presence of a serious (AIS3+) thoracic injury, coded as one, or its absence, coded as zero.

The probability of a thoracic injury is modelled for predictor variables $x_i$as [77]:

$$P(Y = 1|x_i) = \pi (x_i) = \frac{e^{\eta_i}}{1 + e^{\eta_i}} \qquad \text{Equation 5.1}$$

And the logit is modelled by the following equation:

$$\eta_i = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \cdots + \beta_n x_{ni} \qquad \text{Equation 5.2}$$

Where β_j are model parameters to be estimated and x_j are predictor variables.

Purposeful Selection was used to determine significant variables associated with serious thoracic injuries that were to be included in the base model (Figure 5.5).[61] The potential variables listed above were initially evaluated at the 20% significance level and at 5% for subsequent models to create the base model. The dichotomously coded segment damage variables were then added to the base model. Non-significant variables (p>0.05) were then removed to create the preliminary main effects model. Variables that were removed from the base model were then individually added to the preliminary main effects model. Significant variables were added to the model and non-significant variables were left out of the model thus resulting in the final main effects model.[18] Additionally, checks for linearity between each continuous variable and the logit was performed.[44, 60]

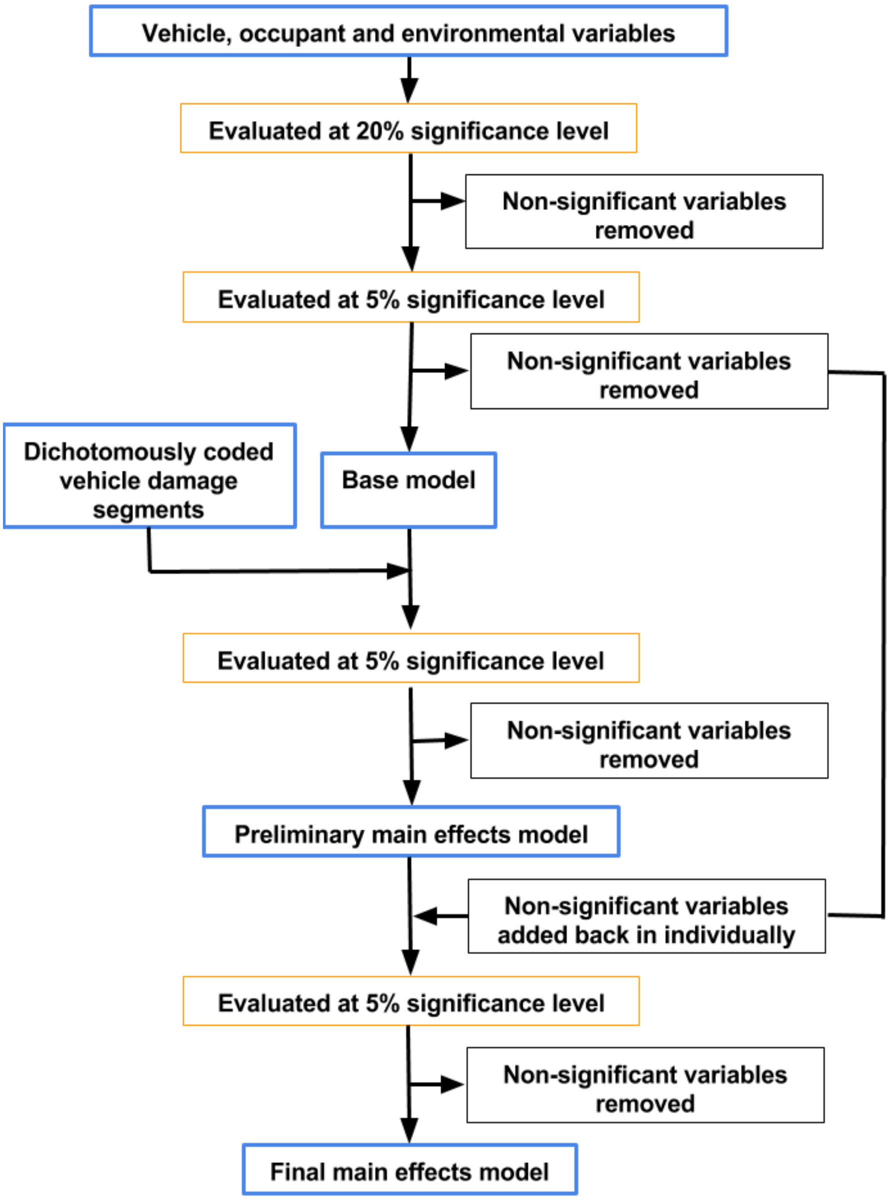


Figure 5.5 Purposeful Selection flow chart

5.3 Results

5.3.1 Empirical Analysis

The results from the empirical analysis of the data indicate that the mean number of quarter-turn rollovers a vehicle underwent was 6.6 and 3.8 for cases and controls, respectively. Most case vehicles were also noted to have undergone eight quarter-turns, which is significantly more than the four quarter-turns most control vehicles had undergone (Figure 5.6).

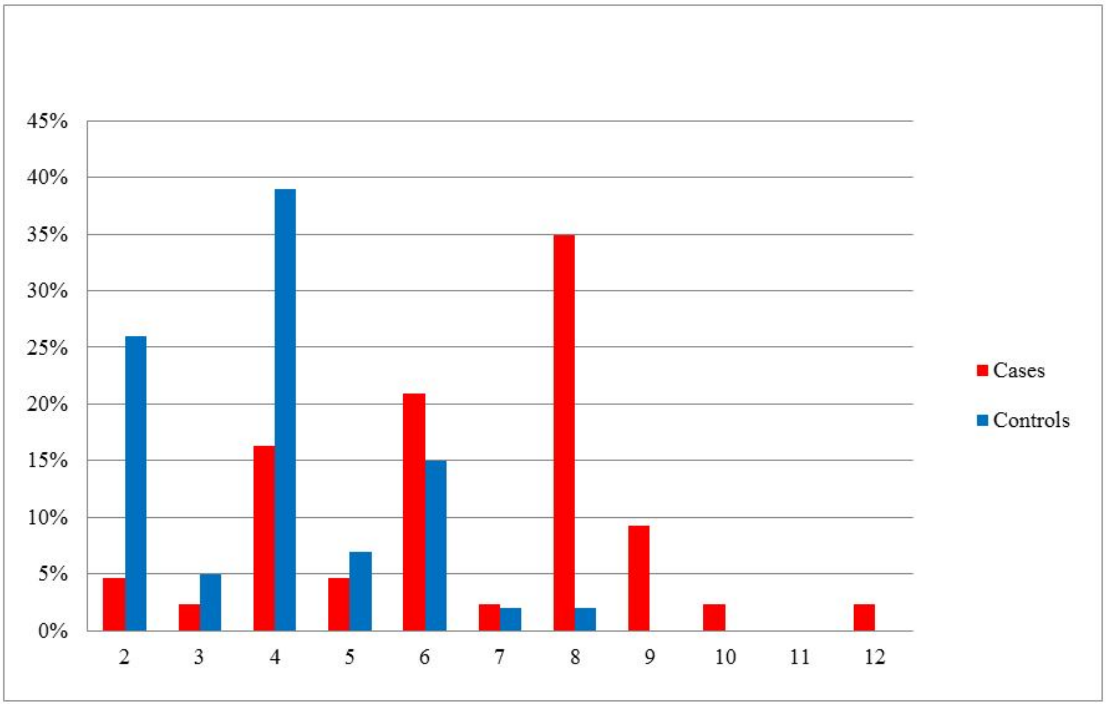


Figure 5.6 Number of vehicle quarter-turn for cases and controls

The median age of a case occupant was 38 years old while that of the control occupant was 32 years old. Thus, the age difference between cases and controls was small although notable.

For cases, utility vehicles constituted 86.0% of all vehicles and passenger cars constituted the remainder 14.0% (Table 5.1). For controls, utility vehicles constituted 64.1% of the vehicles in the controls, which is significantly less than that of the cases; whereas sedans constituted 35.9%, which is significantly more than that of the cases (Table 5.1).

For cases, near-side and far-side rollovers were almost evenly split at 49.0% and 51.0%, respectively (Table 5.1). The almost even split between near- and far-side rollovers is also noted for controls, with 56.4% of occupants having undergone near-side rollovers and 43.6% having undergone a far-side rollover (Table 5.1).

Cases were observed to have occurred on a dry surface more frequently than controls, whereas controls occurred on a level roadway more frequently than cases (Table 5.1). There were significantly less differences between cases and controls for the following dichotomous variables: paved roadway surface, straight roadway and rollover off roadway (Table 5.1).

Table 5.1 Empirical results for dichotomous variables in cases and controls

Dichotomous Variable	Percentage of Cases	Percentage of Controls
Drivers	74.4%	91.2%
Near-side rollovers	49.0%	56.4%
Male	53.5%	46.4%
Vehicle was a utility vehicle	86.0%	64.1%
Dry surface	86.0%	62.4%
Level roadway	74.4%	83.4%
Paved roadway surface	100.0%	93.4%
Straight roadway	65.1%	66.9%
Rollover off roadway	81.4%	85.6%

5.3.2 Multiple Variable Logistic Regression

The base model from the logistic regression analysis included the following variables: number of vehicle quarter-turn rollovers, dichotomously coded rollover location (off roadway, coded as 1, versus on road way, coded as 0), dichotomously coded vehicle category (utility vehicle, coded as 1, versus passenger cars, coded as 0) and dichotomously coded surface condition (dry, coded as 1, or otherwise, coded as 0). The results from this analysis are presented in Table 5.2.

The dichotomously coded segment damage variables were then added to the base model and all non-significant segment damage variables removed; thus, resulting in the final model (Table 5.3). It is noted that the dichotomously coded surface condition was removed from the final model since it was insignificant (p=0.416, OR=1.67). Additionally, segment Left 2 damage was kept in the final model even though its p-value of 0.058 was higher than the statistical significance level of 0.05. However, segment Left 2 odds ratio point estimate of 2.45 was high and, thus, the damage for this segment was deemed to be an important variable.[110]

The final model consisted of the following variables: number of vehicle quarter-turn rollovers, dichotomously coded rollover location (off roadway versus on road way), dichotomously coded vehicle category (utility vehicle versus passenger car), damage to segments Left 4, Right 2 and Left 2 (Table 5.3). The odds ratio of serious thoracic injuries for segment damage is visually presented in Figure 5.7.

Additionally, to obtain the odds ratio of sustaining serious thoracic injuries given a particular segment damage, all segment damage variables were added to the model consisting of the number of vehicle quarter-turn rollovers, dichotomously coded rollover location and dichotomously coded vehicle class. The results are presented in Table 5.4.

Table 5.2 Logistic regression results for thoracic injury (AIS3+) and base model covariates

Variable	MLE Ratio estimate	Standard Error	Odds Ratio Point Estimate	95% CI	p-value
Increase in one quarter-turn rollover	0.81	1.40	2.26	1.70,2.95	<0.001
Rollover off roadway	1.22	0.61	3.40	1.03,11.13	0.043
Utility vehicle	1.59	0.59	4.91	1.55,15.51	0.007
Dry surface	1.13	0.56	3.10	1.04,9.24	0.042

Table 5.3 Logistic regression results for thoracic injury (AIS3+) and final model covariates

Variable	MLE Ratio estimate	Standard Error	Odds Ratio Point Estimate	95% CI	p-value
Increase in one quarter-turn rollover	0.74	0.15	2.09	1.57,2.78	<0.001
Rollover off roadway	1.36	0.64	3.90	1.11,13.72	0.034
Utility vehicle	1.31	0.64	3.71	1.06,12.93	0.040
Segment Left 4	1.21	0.48	3.35	1.30,8.62	0.012
Segment Right 2	1.30	0.50	3.68	1.37,9.86	0.010
Segment Left 2	0.89	0.47	2.46	0.97,6.22	0.058

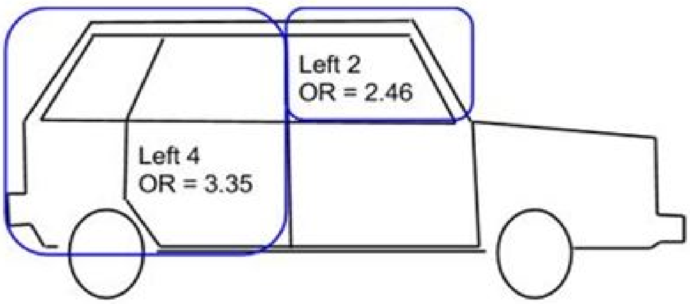
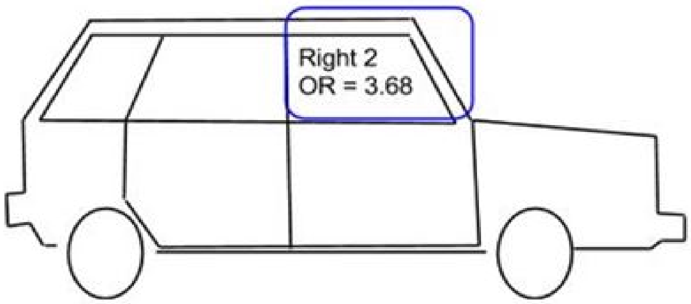
Vehicle Plane	Odds Ratio for Each Vehicle Segment
Left	
Right	

Figure 5.7 Odds ratio of sustaining a serious thoracic injury for a particular damaged segment

Table 5.4 Logistic regression results for thoracic injury (AIS3+) with base model covariates and all segment damage covariates

Variable	**MLE Ratio estimate**	**Standard Error**	**Odds Ratio Point Estimate**	**95% CI**	**p-value**
Increase in one quarter-turn rollover	0.78	0.16	2.19	1.60,2.98	<0.001
Rollover off roadway	1.18	0.68	3.25	0.86,12.27	0.082
Utility vehicle	1.35	0.69	3.88	1.01,14.85	0.048
Segment Left 1	-0.06	0.54	0.94	0.33,2.72	0.910
Segment Left 2	1.10	0.54	3.01	1.05,8.62	0.040
Segment Left 3	0.20	1.21	1.22	0.11,13.21	0.870
Segment Left 4	1.06	0.52	2.90	1.05,7.98	0.039
Segment Right 1	0.53	0.57	1.70	0.56,5.18	0.347
Segment Right 2	1.03	0.58	2.79	0.90,8.67	0.076
Segment Right 3	-0.68	0.98	0.51	0.08,3.46	0.489
Segment Right 4	0.26	0.57	1.30	0.43,3.95	0.642
Segment Top 1	0.94	0.59	2.55	0.81,8.06	0.110
Segment Top 2	-0.74	0.91	0.48	0.08,2.82	0.416
Segment Top 3	0.28	1.34	1.32	0.10,18.51	0.833

5.4 Discussion

5.4.1 Empirical Analysis

From the empirical analysis, case vehicles experienced a mean of 6.6 quarter-turn rollovers with most undergoing eight quarter-turn rollovers. These figures are higher than those of control vehicles which experienced a mean of 3.8 quarter-turn rollovers with most undergoing four quarter-turn rollovers. The higher mean number of quarter-turn rollovers experienced by cases compared to that of controls suggests that there is a higher level of energy involved in rollovers with thoracic injuries compared to those without thoracic injuries.

The small difference in the median age of occupants in this study between the cases and controls, i.e., 38 years and 32 years respectively, was not likely to have affected the outcome of this study.

Utility vehicles constitute 86% of the type of vehicles in cases, which is substantially higher than the 64.1% in the control group. This may reflect the greater potential of utility vehicles to roll due to their higher centre of gravity compared to sedans. This finding is similar to those by previous studies.[26, 101, 123]

Eighty-six percent of cases were observed to occur on a dry surface which is significantly more than the 62.4% in the control group, a similar finding to that of Bambach *et al*.[12] This would suggest that surfaces with a higher friction co-efficient may be associated with greater trip speed and/or greater deceleration during vehicle-to-ground contact resulting in a more severe rollover event.[12]

5.4.2 Multiple Variable Logistic Regression

The results from the multiple variable logistic regression model indicates that the following are associated with a front seat occupant sustaining a serious thoracic injury: the number of vehicle quarter-turn rollovers; the vehicle is a utility vehicle; the rollover occurred off the roadway; and major damage occurred at segment Left 4, Right 2 and Left 2.

An increase of one quarter-turn rollover is associated with a 2.09 times increase in the odds of an occupant sustaining a serious thoracic injury, a finding similar to that from previous studies.[12, 93, 153] This increase in odds ratio is likely due to the higher velocity or crash energy and the corresponding higher likelihood for occupants to impact the vehicle interior.

This study also shows that occupants in a utility vehicle are subjected to a 3.71 increase in the odds of sustaining serious thoracic injury compared to occupants in a passenger vehicle, confirming the findings of a previous study by Bambach *et al*.[12] It is suggested that this is most likely due to the geometrically higher aspect ratios of utility vehicles compared to passenger cars resulting in a higher deceleration rate as the vehicle rolls.

Rollovers that are initiated off the roadway, that is, on the shoulder or the median, are 3.90 times more likely to result in a front seat occupant sustaining a serious thoracic injury than rollovers that were initiated on the roadway. This is most likely due to the higher friction forces that occur when a vehicle furrows into a soft surface [3, 155] resulting in a higher deceleration than when the vehicle tripped on a stiffer paved surface.

Intuitively, an increase in occupant age would be associated with an increased probability of sustaining an injury in a rollover crash. However, it was found not to be a significant variable in this study and is likely to be due to the small sample size and the fact that age was entered into the model as a continuous variable. However, entering age into the model as an interval categorical variable did not affect the outcome of the model. Previous studies [12, 30, 116] have found that rollover direction was associated with an increased probability of sustaining an injury. However, in this study an association between vehicle rollover direction and thoracic injury was not found. This is similar to findings by Bedewi *et al*. [13], Conroy *et al*. [27] and Viano and Parenteau [153].

Damage to segments Right 2 and Left 2 is associated with a 3.68 and 2.46 increase in the odds of sustaining a thoracic injury, respectively. An explanation of the vehicle kinematics resulting in damage to these segments and a discussion on the possible relationship between damage to these segments and thoracic injury are provided in the following subsections.

5.4.2.1 Damage to Segment Right 2 and Thoracic Injuries

A vehicle in a clockwise rollover, as viewed from the rear, may sustain damage to segment Right 2 as it impacts the ground upon entering the 2nd, 6th and 10th quarter-turn rollover (Figure 5.8), noting that most rollovers do not exceed 12 quarter-turns.[12] Previous studies have indicated that, if the centrifugal acceleration is sufficiently high at those points in the rollover, the occupants are pushed outboards towards the door.[78] However, if the centrifugal acceleration is not sufficiently high to push the occupants outboard as the vehicle's Right 2 segment impacts the ground, the driver and passenger, who are located approximately horizontal relative to the ground [54], may flail towards and impact against the centre console and right door interior, respectively, under the influence of inertia loading predominantly created by rotational deceleration. That is, inertia loading exerts a greater influence on the occupants than centrifugal acceleration.

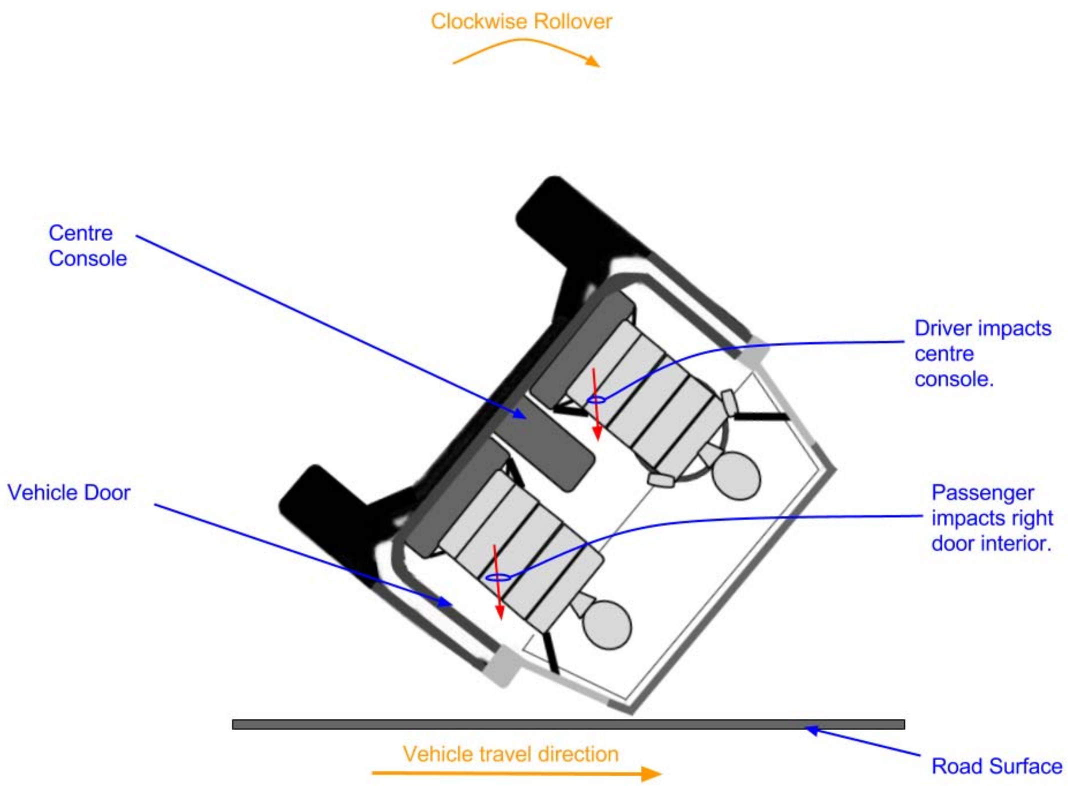


Figure 5.8 Vehicle in a clockwise rollover impacting the ground at segment Right 2 resulting in the driver and passenger impacting the centre console and right door interior, respectively

In a counter-clockwise rollover a vehicle may sustain damage to segment Right 2 as it enters the 3rd, 7th and 11th quarter-turn (Figure 5.9). At the start of the 3rd quarter-turn, the vehicle may be subjected to significant lateral deceleration. If the occupants are not adequately coupled to the vehicle by the seatbelt, they are likely to move relative to the vehicle.[27, 39, 167] That is, considering the ground as the frame of reference, the vehicle is decelerating while the occupants continue to traverse laterally at a speed faster than the vehicle due to their inertia. This may result in the driver and front seat passenger flailing towards and impacting against the centre console and right door interior, respectively.

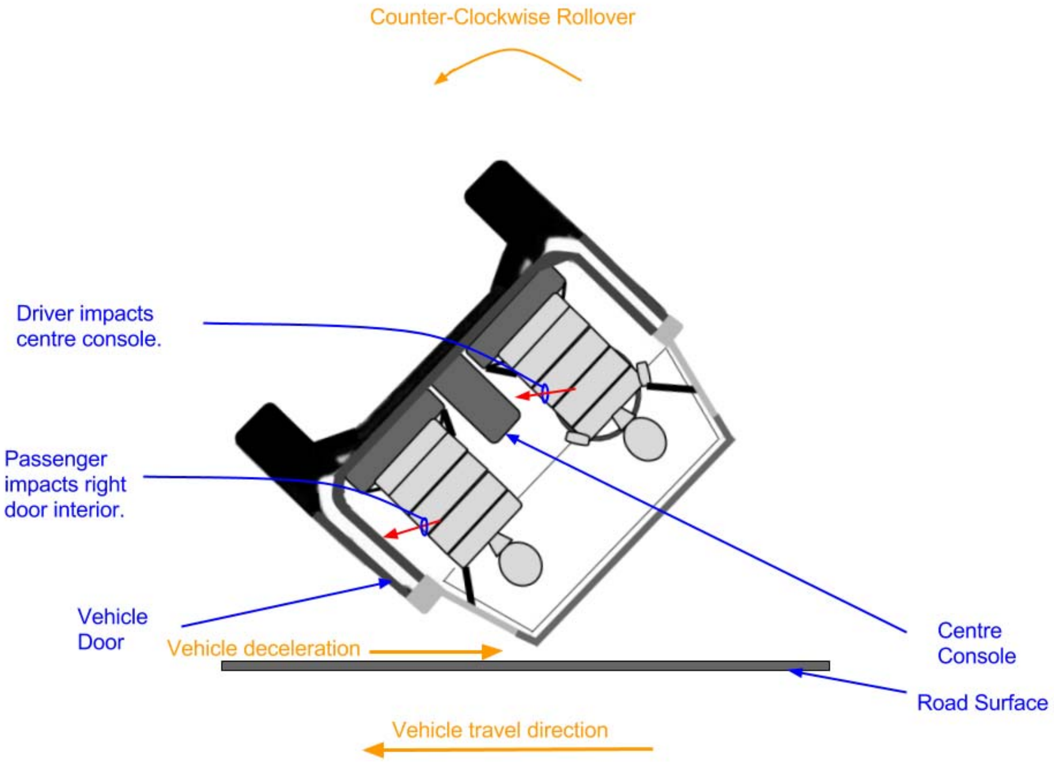


Figure 5.9 Vehicle in a counter-clockwise rollover impacting the ground at segment Right 2 resulting in the driver and passenger impacting the centre console right door interior, respectively

As with clockwise rollovers, the occupant's position is less clear once the vehicle rotates beyond four quarter-turns; thus, comments have not been made on potential injury mechanisms when a vehicle rotates beyond four quarter-turns.

5.4.2.2 Damage to Segment Left 2 and Thoracic Injuries

A vehicle in a counter-clockwise rollover, as viewed from the rear, may sustain damage to segment Left 2 (Figure 5.10) as it impacts the ground when it enters the 2nd, 6th and 10th quarter-turn rollover. Similar to the discussion in Section 5.4.2.1 to segment Right 2 damage in clockwise rollovers, if the centrifugal acceleration is sufficiently high in the rollover the occupants are pushed outboards towards the door.[78] However, if the centrifugal acceleration is not sufficiently high to push the occupants outboard the driver and passenger, who are located approximately horizontal relative to the ground [54], may flail towards and impact against the driver's door interior and centre console, respectively, under the influence of inertia caused by rotational deceleration.

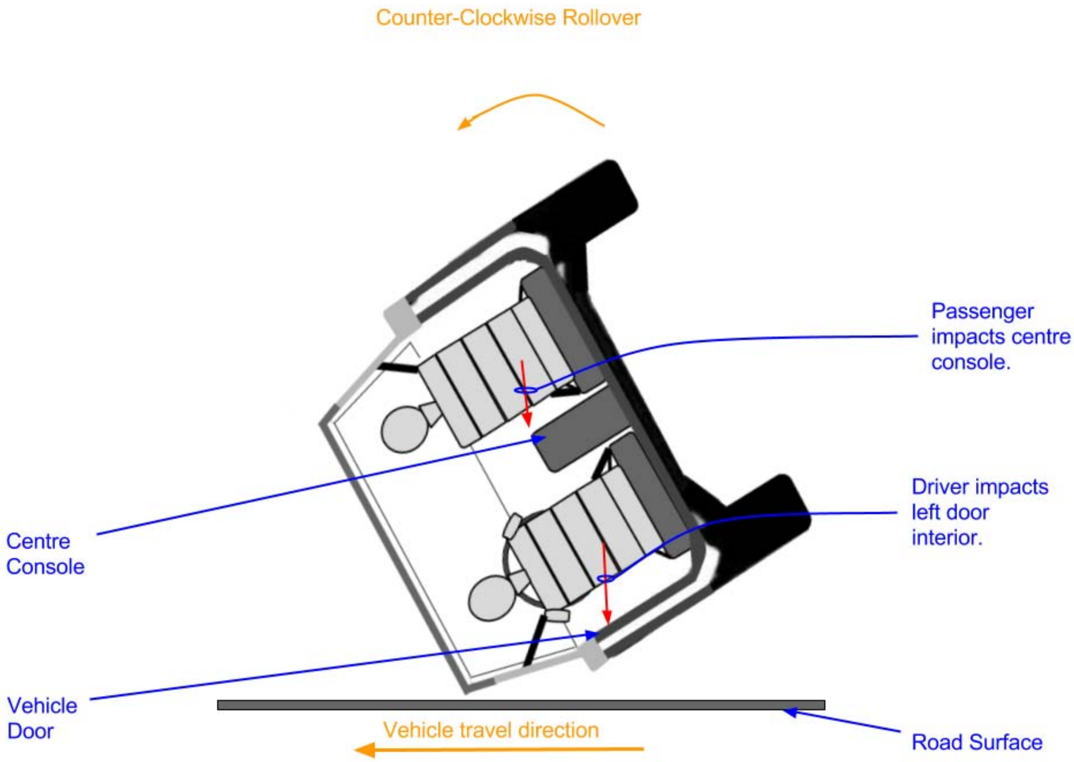


Figure 5.10 Vehicle in a counter-clockwise rollover impacting the ground at segment Left 2 resulting in the driver and passenger impacting the centre and right door interior, respectively

Similar to the discussion in Section 5.4.2.1 on Right 2 damage in counter-clockwise rollovers, a vehicle in a clockwise rollover may sustain damage to segment Left 2 as it impacts the ground upon entering the 3rd, 7th and 11th quarter-turn rollover (Figure 5.11). At the start of the 3rd quarter-turn rollover the vehicle may be subjected to significant lateral deceleration. If the restrained occupants are not adequately coupled to the vehicle by the seatbelt they are likely to move independently to the vehicle.[27, 39, 167] That is, with the ground as the frame of reference, the vehicle is decelerating while the occupants continue to traverse laterally at the vehicle's pre-impact speed. This may result in the driver and front seat passenger flailing towards and impacting against the driver's door interior and centre console, respectively.

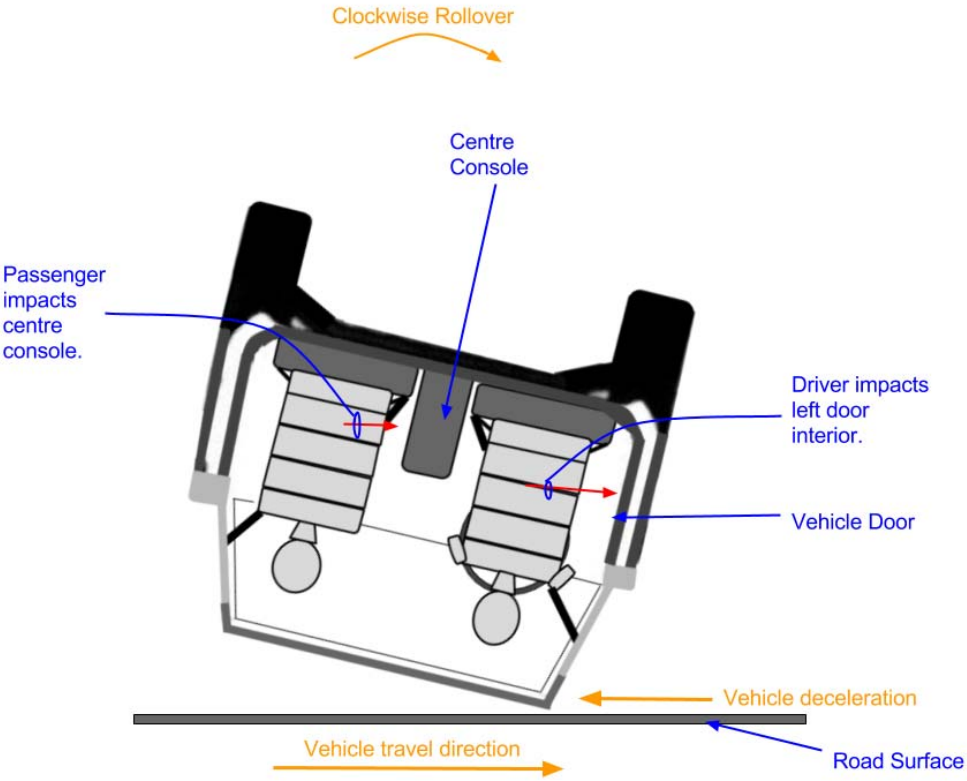


Figure 5.11 Vehicle in a clockwise rollover impacting the ground at segment Left 2 resulting in the driver and passenger impacting the left door interior and centre console, respectively

It is noted that the occupant’s position is less clear once the vehicle rotates beyond four quarter-turns; thus, comments have not been made on potential injury mechanisms when a vehicle rotates beyond four quarter-turns.

5.4.2.3 Damage to Segment Left 4 and Thoracic Injuries

Damage to segment Left 4 was found to be associated with serious thoracic injury (OR=3.35). The vehicle kinematics and damage mechanism is similar to that which results in damage to segment Left 2. However, it is likely that the vehicle would have a negative pitch, as defined by the Society of Automotive Engineers (SAE) sign convention for vehicles, thus allowing the rear of the vehicle to contact the ground as it enters the 2nd, 6th and 10th quarter-turn rollover, for counter-clockwise rotations, and as the vehicle enters the 3rd, 7th and 11th quarter-turn rollover for clockwise rotations.

The potential of thoracic injuries occurring as segment Left 4 contacts the ground is the same as that with segment Left 2; thus, will not be repeated here.

It is interesting to note that damage to the rear right of the vehicle rearwards of the B-pillar, that is, segment Right 4, is not associated with thoracic injury even though there is an almost equal distribution of near- and far-side rollover configurations for both drivers and occupants. This is likely to be due to the small number of cases and, to a lesser extent, controls.

In the cases described above only the occupant's vertical velocity or lateral velocity, relative to the ground, were considered. The vehicle and occupant are being subjected to lateral velocity, vertical velocity and rotational velocity relative to the ground. Thus, changes in these velocities have the potential to influence occupant-to-vehicle interior interactions. However, taking these velocities into account requires a more complex analysis and was not within the scope of this study.

5.4.3 Limitations

The limitations of this study should be noted and are divided into three main categories: statistical data, vehicle damage coding and regression analysis.

From a statistical data perspective, it is noted that the NASS-CDS data is a probability sample rather than a census and the data is dependent on the investigation and data entry accuracy of the NASS investigators. Secondly, sampling bias may be present in the randomly selected controls. Thirdly, the number of cases in this study is small; thus, limits statistical power. Fourthly, occupant height and weight were not included as variables in the analysis as this would reduce the already limited number of cases available for this study. Fifthly, NASS-CDS weighting was not used which may result in a potential bias towards more serious crashes despite controlling for this using a 1:4 to 1:5 cases to control ratio.

From a vehicle damage coding perspective, it is noted that the coding of vehicle segment damage is subjective and is based on residual deformation only. Sheet metal strength varies from one vehicle model to another. Thus, two different vehicle models subjected to the same impact force may deform differently. Secondly, major damage reflects both impact energy and structural strength. Thus, if a vehicle-to-ground impact occurs on a relatively rigid structure of the vehicle, such as the B-pillar, the structure may deform less than if the impact occurred on a less rigid component of the vehicle, such as a door panel. As such, this may confound the results of this study. Similarly, the deformation will also be less if the vehicle structure strikes soft ground compared to a hard bitumen or concrete surface.

Finally, it is also important to note that the regression model establishes associations between the predictor variables and response variable. However it does not imply causality.

5.5 Conclusions

Coding of vehicle panel damage was carried out for a total of 224 vehicles involved in tripped rollover crashes to assess what association, if any, exists between vehicle panel damage, vehicle, occupant and the crash environment variables and serious (AIS3+) thoracic injury. It was found that vehicle quarter-turn rollovers, rollovers involving utility vehicles, rollovers occurring off the roadway, damage to the vehicle rearwards of the left B-pillar (segment Left 4), damage to the top-half of the right front door (segment Right 2) and damage to the top-half of the left front door (segment Left 2), were associated with serious thoracic injury in rollover crashes.

The logistic regression model indicates damage to the left rear of the vehicle rearwards of the B-pillar and damage to the top-half of the right front door and left front door are associated with an increased probability of sustaining thoracic injuries. It is hypothesised that damage to either of these areas during a rollover crash indicates rotational and/or lateral deceleration, which in turn, results in a sudden decrease in vehicle velocity relative to the occupant. This then causes the occupant to impact interior components of the vehicle, because of flailing of the torso, which in turn results in a thoracic injury.

6 Rollover Crash Reconstruction for Thoracic Injury Aetiology Investigation

6.1 Introduction

Previous research on thoracic injuries resulting from rollover crashes have predominantly focused on statistical analysis of existing crash data [12, 13, 101] with limited studies conducted with computer simulations.[139] The statistical studies have identified the most common thoracic organ injured and sources of thoracic injury in rollover crashes. However, the aetiology of thoracic injuries in rollover crashes is still not well understood.[12] As such, a real-world rollover crash in which an occupant had sustained AIS3+ thoracic injuries was reconstructed using computer simulations. The aim of this reconstruction, which is documented in this chapter, is to:

- apply the findings from Chapter 3 on occupant impact velocity,
- develop a better understanding of the aetiology of thoracic injuries in a rollover crash especially in light of the findings in Chapter 4 on frequently injured thoracic organs and the sources of thoracic injuries and
- understand how vehicle segment damage, as identified in Chapter 5, may be associated with an occupant sustaining an AIS3+ thoracic injury.

In Section 6.2, an overview of side impact ATDs is introduced along with thorax side-impact injury criteria. In Section 6.3, the methodology is presented. In Section 6.4 the results of the study is presented and is followed by a discussion of the results in Section 6.5. In Section 6.6, an additional simulation was performed based on the discussion from Section 6.5. In Section 6.7, the conclusions from this study are presented.

6.2 Injury Assessment using Anthropomorphic Test Devices

When an injury occurs, tissues are loaded and deformed beyond a recoverable limit, the injury tolerance level, resulting in damage to anatomical structures and altering their normal function. ATDs, also referred to as crash test dummies, are human surrogates which have been designed to simulate human body responses to injury using instrumentation that measures displacements and decelerations in controlled impact crash testing. Further, they have been specifically designed to respond to particular injury mechanisms and measure various injury criteria. These measurements can then be used to determine if injury tolerance levels are exceeded. The design of ATDs have relied on extensive data gathered from PMHS testing, animal testing and human volunteers to develop correlations between ATD response to mechanical loading and human injury risk.

Although ATDs have been extensively validated against PMHSs, animals and human volunteers, they have some limitations [88]:

- They are not perfectly biofidelic and can only approximate human response for specific injury mechanisms
- The reproduction of impact conditions is subjective
- ATDs replicate selected discrete sizes and mass of the human body, thus they are not representative of the entire spectrum of human beings.

6.2.1 Side-Impact Anthropomorphic Test Devices

A number of side-impact ATDs have been developed by government agencies and the automotive industry to facilitate vehicle side impact testing and for research purposes. These dummies were developed to measure the likelihood of an occupant sustaining injuries in side impact crashes. The three most common side impact ATDs which are available both as real-world ATDs and Finite Element (FE) models are the USSID, EuroSID-2re and the WorldSID.

These three ATDs differ in their thorax construction and their instrumentation, details of which are presented in the sections below. It is noted that the ATD's local coordinate system follows the SAE standard definition with positive x-axis pointing anteriorly, positive y-axis pointing laterally to the right and positive z-axis pointing caudally.[130]

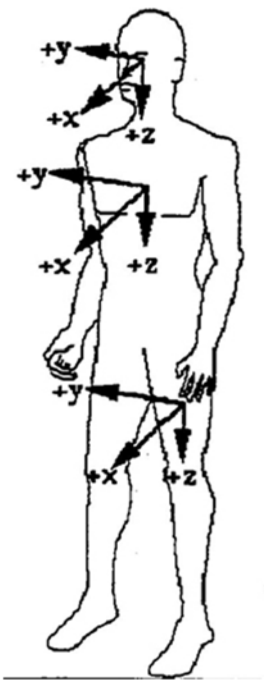


Figure 6.1 ATD coordinate system (Source: SAE, 2014)

6.2.1.1 US Side Impact Dummy

The US Side Impact Dummy (USSID) was developed in 1979 by the University of Michigan Transportation Research Institute (UMTRI) and NHTSA. The ATD is a Hybrid II ATD modified for side impact testing. The thorax of the USSID has five interconnected ribs which are connected to the spine at the back of the ATD and the movement is influenced by one spring damper (Figure 6.2). The USSID instrumentation channels are detailed in Table 6.1

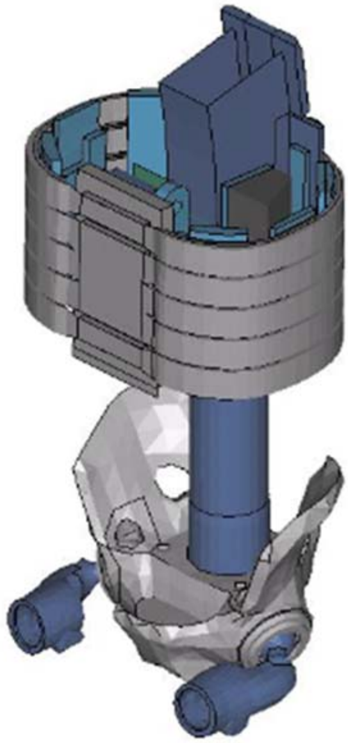


Figure 6.2 USSID thorax (Source: Schuster, 2004)

Table 6.1 USSID instrumentation (Source: Schuster, 2004)

Region	Measurements	Number of Channels	Component
Head	Head acceleration	1	y-axis
Thorax	Upper left rib acceleration	1	y-axis
	Lower left rib acceleration	1	y-axis
	Rib deflection	2	y-axis
Spine	Upper spine	1	y-axis
	Lower spine	1	y-axis
Pelvis	Pelvis acceleration	1	y-axis

6.2.1.2 EuroSID-2re

The European Side Impact Dummy (EuroSID-1) was a joint developed in 1986 by a consortium of European organisations and the EuroSID-2re is the latest iteration of the EuroSID ATD series. The EuroSID-2re thorax consists of three ribs each with its own spring damper system resulting in the ribs being able to move independently from each other. As with the USSID the ribs deflect laterally. The EuroSID-2re instrumentation channels are detailed in Table 6.2.

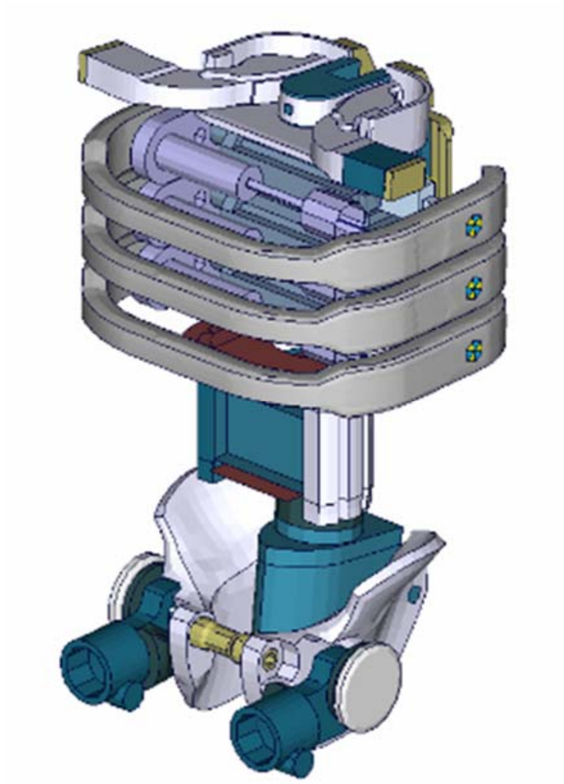


Figure 6.3 EuroSID-2re thorax (Source: Schuster, 2004)

Table 6.2 EuroSID-2re instrumentation (Source: Schuster, 2004)

Region	Measurements	Number of Channels	Component
Head	Head acceleration	3	x-,y- and z-axis
Neck	Upper neck force	1	y-axis
	Upper neck moment	1	x-axis moment
	Lower neck force	1	y-axis
	Lower neck moment	1	x-axis moment
Shoulder	Shoulder force	2	x- and y-axis
Thorax	Upper rib acceleration	1	y-axis
	Middle rib acceleration	1	y-axis
	Lower rib acceleration	1	y-axis
	Upper rib deflection	1	y-axis
	Middle rib deflection	1	y-axis
	Lower rib deflection	1	y-axis

Abdomen	Abdominal force front	1	y-axis
	Abdominal force middle	1	y-axis
	Abdominal force back	1	y-axis
Spine	Upper spine acceleration	1	y-axis
	Lower spine acceleration	1	y-axis
Pelvis	Pelvis acceleration	3	x-,y- and z-axis
	Pelvis force	1	y-axis
Femur	Femur force left	1	y-axis
	Femur moment left	1	x-axis moment
	Femur force right	1	y-axis
	Femur moment right	1	x-axis moment

6.2.1.3 WorldSID

The World Side Impact Dummy (WorldSID) was developed in 1997 under the WorldSID task group. The ATD was developed to provide improved biofidelity compared to current side impact ATDs. The ATD was also developed to harmonise side impact ATDs through the elimination of different side impact ATDs that are used throughout the world.

The WorldSID thorax consists of three ribs that form the thorax and two ribs that form the abdomen (Figure 6.4). Similar to the EuroSID-2re, each rib is individually connected to its own damper system. The WorldSID instrumentation channels are detailed in Table 6.3.

Figure 6.4 WorldSID thorax (Source: Stahlschmidt, 2009)

Table 6.3 WorldSID instrumentation (Source: Stahlschmidt, 2009)

Region	Measurements	Number of Channels	Component
Head	Head acceleration	3	x-,y- and z-axis
Neck	Neck force	6	x-,y- and z-axis
	Neck moments		x-,y- and z-moments
Shoulder	Shoulder acceleration	3	x-,y- and z-axis
	Shoulder force	3	x-,y- and z-axis
Thorax	Upper rib acceleration	3	x-,y- and z-axis
	Middle rib acceleration	3	x-,y- and z-axis
	Lower rib acceleration	3	x-,y- and z-axis
	Upper rib deflection	1	y-axis
	Middle rib deflection	1	y-axis
	Lower rib deflection	1	y-axis
Abdomen	Upper abdomen acceleration	3	x-,y- and z-axis
	Lower abdomen acceleration	3	x-,y- and z-axis
Spine	Upper spine acceleration	3	x-,y- and z-axis
	Middle spine acceleration	3	x-,y- and z-axis
	Lower spine acceleration	3	x-,y- and z-axis
	Lumbar force	3	x-,y- and z-axis
	Lumbar moments	3	x-,y- and z-moments
Pelvis	Pelvis acceleration	3	x-,y- and z-axis
	Sacro-iliac force right	3	x-,y- and z-axis
	Sacro-iliac force left	3	x-,y- and z-axis
Femur	Femur neck force right	1	y-axis
	Femur neck force left	1	y-axis
	Femur force right	1	z-axis
	Femur force left	1	z-axis
Knee	Knee outboard force right	1	y-axis
	Knee outboard force left	1	y-axis
	Knee inboard force right	1	y-axis
	Knee inboard force left	1	y-axis

6.2.2 Injury Criteria

Injury criteria are determined from a set of physical parameters which has been correlated to injury severity for the body, region or tissue.[157] There are several thoracic injury criteria which have been developed and used to predict the level of injury that a vehicle occupant in a crash may receive given a certain displacement, force, moment and/or acceleration. Some of these injury criteria have been correlated to ATD responses such as rib deflection, spinal acceleration, ASA and VC. This enables ATD measured responses in crash testing to be related to potential injury risk levels in humans.

6.2.2.1 Rib deflection

Force-deflection data of the thorax in tests with PMHS was studied by Tarriere *et al*. [143] in the 1970s. In that study, the thorax compression was found to correlate well with thoracic injury resulting in it being adopted by the European Union (EU) as a an injury criteria for vehicle side impact crash testing.[75] More recently, these results have been correlated to the EuroSID-2re rib deflection response by Kuppa [75] and the probability of an AIS3+ thoracic injury is given by the equation:

$$p(AIS3+) = \frac{1}{1+e^{(2.0975-(0.0482\ x\ maximum\ rib\ deflection))}} \quad \text{Equation 6.1}$$

6.2.2.2 Upper and Lower Spinal Acceleration

Upper and lower spinal accelerations have been used for thoracic injury assessment and was developed by Kuppa *et al*. [76] through their study of 34 PMHS side impact-tests. Their study had found that upper spinal acceleration was found to be a good indicator of injury severity and, to a lesser extent, lower spinal acceleration. Further, upper and lower spinal acceleration results from the PMHS tests have been correlated to the EuroSID-2re response by Kuppa.[75] The probability of an AIS3+ thoracic injury is given by the equations for upper and lower spinal acceleration, respectively [75]:

$$p(AIS3+) = \frac{1}{1+e^{(1.56-(0.0366\ x\ maximum\ upper\ spine\ acceleration))}} \quad \text{Equation 6.2}$$

$$p(AIS3+) = \frac{1}{1+e^{((1.991-0.0254\ x\ maximum\ lower\ spine\ acceleration))}} \quad \text{Equation 6.3}$$

6.2.2.3 ASA-10

ASA was developed by Cavanaugh *et al*. [21] as an acceleration based criterion to predicting thorax injuries in side impacts and is based on 17 PMHS side impact-tests performed in 1993. It is obtained by filtering the lower spine acceleration with a 300Hz Butterworth filter, integrating this acceleration pulse to obtain spinal velocity and then taking the slope of the spinal velocity between specified ranges of minimum and maximum spine velocity. In the case of ASA-10, the slope is taken between 10% and 90% of the peak spine velocity. Cavanaugh *et al*. observed that this reflected the rate of change of energy that is transferred to the thorax and, thus, the spine. The equation for ASA is given by the following formula [21]:

$$ASA = \frac{mass}{mass_{std}} x \ \frac{\Delta\, v}{\Delta\, t} \qquad \text{Equation 6.4}$$

Where;

mass = mass of the subject or 75 kg for an ATD

$mass_{std}$ = 75 kg

Δv = change in velocity

Δt = change in time

ASA has been found to provide good probability of predicting thoracic injury using the equation [75]:

$$p(AIS3+) = \frac{1}{1 + e^{(2.1633 - (0.0469\, x\, ASA))}} \qquad \text{Equation 6.5}$$

6.2.2.4 Viscous Criteria

Viscous Criteria was developed by Viano and Lau [151] to take into account both the velocity of deformation and chest compression. It is the maximum of the momentary product of the thorax deformation speed and thorax deformation and is represented by the following formula [151]:

$$VC = V(t) x\ C(t) \qquad \text{Equation 6.6}$$

Where;

$V(t)$ = instantaneous velocity of deformation

$C(t)$ = normalised instantaneous compression

Unlike the aforementioned thoracic injury criteria, an AIS3+ probability curve for VC has not yet been developed for the EuroSID-2re ATD. However, a VC of 1 m/s equates to a 50% probability of an AIS3+ thoracic injury for PMHSs and previous evaluations have also correlated a VC of 1 m/s to a 50% probability of an AIS3+ thoracic injury in the EuroSID-1 ATD.[150] Although the EuroSID-1 and EuroSID-2re have different responses, the results from Viano *et al*. provide an indication of the probability of a thoracic injury occurring using measurements from the EuroSID-2re.

6.3 Method

6.3.1 Selection of a Rollover Crash Case

In Chapter 4, 43 rollover crash cases in which an occupant had sustained at least one AIS3+ thoracic injury were identified and obtained from the NASS-CDS database. From those 43 cases, further filtering was performed in order to select a suitable case to be reconstructed in a computer simulation for this study. The additional filters applied were:

- the rollover crash was four or less vehicle quarter-turns,
- the vehicle was a 2nd (1995 to 2001) or 3rd (2002 to 2005) generation Ford Explorer and
- the vehicle sustained major damage, as described in Chapter 5, to the segments identified as being associated with a vehicle occupant sustaining an AIS3+ thoracic injury.

The first additional criterion was applied to allow easier identification of where in the rollover phase a thoracic injury may have occurred. The second additional criterion was applied because computer models of these utility vehicles are available. The third additional criterion was applied to develop an understanding as to how segment damage is related to an occupant sustaining an AIS3+ thoracic injury.

From the filtering of the NASS-CDS data, only one case satisfied all the aforementioned criteria, namely – case number 2006-41-176.

From a thoracic injury perspective, it was preferable that an AIS3+ thoracic injury was attributed to the door interior as it has been identified as one of the most frequently cited sources of thoracic injury for rollover crashes.[12, 141] However, the AIS3+ thoracic injuries sustained by the occupant in case number 2006-41-176 were attributed to the seatbelt rather than the door interior. Despite this, it was decided to proceed with this rollover crash case as it would provide an insight into rollover vehicle occupant thoracic injury aetiology.

6.3.2 Rollover Crash Case Description

The vehicle involved in case number 2006-41-176 was a 1996 2nd generation 3-door Ford Explorer. The vehicle, according to the NASS-CDS case report, was negotiating a curve at an estimated travel speed of 72 km/h when it tripped and underwent a driver far-side four quarter-turn rollover over an estimated ten metre distance.

Three occupants were seated in the vehicle at the time of the crash. One occupant was located in the driver’s seat, one in the front passenger’s seat and one in the second row right seat. Only the driver, who was 38 years old at the time of the crash with unspecified height and weight, was documented to have sustained injuries from the crash (Table 6.4). The driver’s AIS3+ injuries pertained only to the thorax and consisted of bilateral lung contusion and bilateral rib cage fractures with a greater number of rib fractures on the right side than the left side (Table 6.5).

Table 6.4 Summary of driver's AIS <3 injuries

Body Region	Injury	Aspect	AIS	Source	Confidence Level
Head	Facial skin lacerations	Superior/ Upper	1	Flying glass	Possible
Head	Facial skin abrasion	Superior/ Upper	1	Roof left side rail	Possible
Thorax & Abdomen	Back skin contusion	Right	1	Seat back	Probable
Thorax & Abdomen	Chest skin contusion	Central	1	Belt restraint webbing/buckle	Possible
Thorax & Abdomen	Chest skin abrasion	Central	1	Belt restraint webbing/buckle	Possible
Thorax & Abdomen	Abdomen skin contusion	Left	1	Belt restraint webbing/buckle	Possible
Thorax & Abdomen	Abdomen skin abrasion	Central	1	Belt restraint webbing/buckle	Possible
Thorax & Abdomen	Myocardium contusion	(Not specified)	1	Belt restraint webbing/buckle	Possible
Lower Extremity	Lower extremity contusion	Bilateral	1	Knee bolster	Possible
Lower Extremity	Lower leg abrasion	Bilateral	1	Knee bolster	Probable

Table 6.5 Summary of driver's AIS3+ injuries

Body Region	Injury	Aspect	AIS	Source	Confidence
Thorax	Rib cage fracture (2-3 ribs) with bilateral hemo-/pneumothorax. More rib fractures on the right than left thorax.	Bilateral	3	Belt restraint webbing/buckle	Possible
Thorax	Lung contusion	Bilateral	4	Belt restraint webbing/buckle	Possible

The confidence level in Table 6.4 and Table 6.5 indicates the NASS-CDS investigator’s level of confidence that a component was contacted by an occupant, based on witness marks observed during the vehicle inspection, is rated on a scale. This scale consists of four confidence levels – unknown, possible, probable and certain (Table 6.6).

Table 6.6 NASS-CDS Confidence Level Description

Confidence Level	Description
Certain	Is coded when, based on visible physical evidence, it has been established beyond doubt or question that the component was contacted by an occupant.
Probable	Is coded when, in all likelihood, an occupant contacted the component, although the evidence is insufficient to be absolutely sure.
Possible	Is coded when there is more evidence for than against; however, there is room for doubt due to the lack of substantiating physical evidence.
Unknown	Is coded when it is unknown whether the component listed as a contact point was contacted by an occupant or some type of induced or post-crash damage.

6.3.3 Computer Simulations

Full-scale crash testing with an instrumented ATD is expensive. The availability of powerful computers and reliable simulation software has provided the capabilities for crash testing to be simulated in detail in a more cost effective manner. Similar to full-scale crash testing, computer simulations provides loads and kinematic outputs from the ATD.

However, there are a number of drawbacks with computer simulations. Firstly, ATD computer models need to be validated against real-world ATDs. Secondly, the reliability of the simulations is limited by the computer simulation algorithms. Thirdly, higher levels of simulation accuracy and detail require increased computing power and/or model run time. Fourthly, computer model instability increases with longer simulations and complex models.

6.3.4 Crash Modelling

A combined computer modelling approach was performed to reconstruct the rollover crash. In the first part of the computer modelling PC-CRASH [31], a multi-body three-dimensional model, was used to model the vehicle's trajectory to obtain the vehicle's kinematics at the point of trip. (Figure 6.5). In the second part of the crash modelling, LS-DYNA, a non-linear finite element solver, was used to simulate the vehicle's and occupant's kinematics from the point of trip to the point of rest (Figure 6.5).

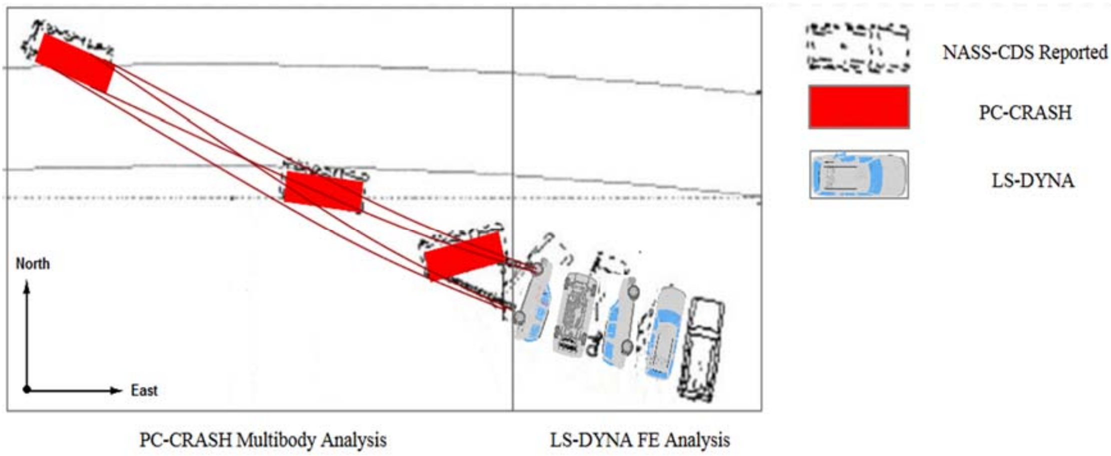


Figure 6.5 Overlay of PC-CRASH, LS-DYNA simulations and NASS-CDS scene diagram

For the purpose of this study, the point of trip was defined as the point where the vehicle had rotated by ninety degrees about its longitudinal axis. The vehicle's kinematics at the point of trip is presented in Table 6.8.

This combined approach of reconstructing a vehicle rollover crash takes advantage of the strengths of each modelling approach. That is, PC-CRASH is able to model the vehicle's trajectory with low computational time and LS-DYNA is able to accurately calculate the vehicle's and occupant's deformations during the impact, although this comes at a significantly greater computational cost.[83] The details of the PC-CRASH and LS-DYNA modelling are described in the sections below.

6.3.4.1 PC-CRASH Modelling

The reconstruction in PC-CRASH was guided by commonly used reconstruction techniques [156] and vehicle characteristics during rollover crashes.[4, 28, 38, 65, 81, 138]

In order to reconstruct the roadway geometry where the crash occurred, NASS-CDS scene diagrams and scene photographs were obtained and used in conjunction with roadway design guidelines.[2]

The vehicle's dimensions, inertial properties and suspension are variables that influence a vehicle's trajectory and rollover kinematics. As such, these properties for the Ford Explorer were obtained from existing literature and applied to the vehicle model.[17, 58]

Similarly, vehicle tyre properties also affect a vehicle's trajectory and rollover kinematics. Thus, the vehicle's tyre properties were obtained from published data and applied to the simulation via the "*easy tyre*" model option in PC-CRASH.[45, 71] This option models a realistic non-linear relationship between the tyre's lateral force and lateral slip angle and applies it to the PC-CRASH model.

The vehicle model was then located upstream of tyre marks and an initial velocity was applied based on the NASS-CDS reported vehicle travel speed of 72 km/h, the reported rollover distance of ten metres and four quarter-turns the vehicle underwent during the rollover phase and the effective deceleration rates.[4, 6, 81]

Steering and acceleration input was then applied based on the reported vehicle trajectory and this was guided by available literature on realistic driver response.[19, 65, 72, 111]

Friction polygons were used to define friction between the vehicle and the ground during the rollover phase and as guided by existing literature.[6, 45, 65, 155]

The aforementioned parameters were adjusted until the vehicle's trajectory from loss of control to the vehicle coming to rest matched as closely as possible the yaw marks, trip point, quarter-turns and rollover distance as documented in the NASS-CDS case report (Figure 6.5).

6.3.4.2 LS-DYNA Modelling

A FE model of the 3rd generation Ford Explorer is publically available which was validated against full-scale front and side-impact tests as well as quasi-static roof strength tests.[96, 140] This model was previously modified to match the roof strength of the 2nd generation Ford Explorer [83] which was then used in this study.

Two ballasts of 75 kg were added to represent the mass of the front seat occupant and rear seat occupant. This mass is similar to that of most 50th percentile ATDs.

A global system was defined with the positive x-, y- and z-axis pointing east, north and up (out of the page) (Figure 6.5), respectively. The vehicle's local coordinate system followed the SAE standard definition with positive x-axis pointing forward of the vehicle along the longitudinal axis, positive y-axis pointing to the right of the vehicle along the transverse axis and positive z-axis pointing downwards of the vehicle along the vertical axis of the vehicle (Figure 6.6).[130]

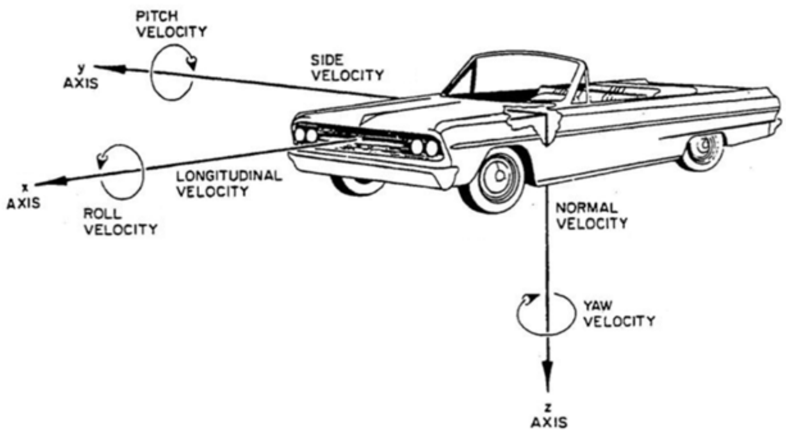


Figure 6.6 SAE vehicle coordinate system (Source: SAE, 2014)

It is also noted that the vehicle's linear velocity and roll rate was filtered with SAE Channel Filter Class (CFC) 60.[8, 130]

The reconstructed rollover was assessed for accuracy qualitatively and quantitatively. Quantitative assessments were performed by comparing vehicle intrusion and rollover distance to the values documented in the NASS-

CDS case report. A qualitative assessment was performed by comparing FE vehicle damage to the photos of the actual vehicle in the NASS-CDS case report.

6.3.5 Side Impact Anthropomorphic Test Device Selection

One of the main criteria in the selection of an appropriate FE ATD was its capability of measuring lateral thoracic loading since the driver sustained AIS3+ bilateral thoracic injuries in the case that was reconstructed.

The ATDs considered were the USSID, EuroSID-2re and WorldSID. The EuroSID-2re is currently used in the USA side impact tests due to its improved biofidelity compared to the USSID ATD [99, 162] and has improved response and is more sensitive to oblique impact tests compared to previous EuroSID ATDs.[158] Although the WorldSID has been shown to be more biofidelic than the EuroSID-2re [161, 165] it does not have as an extensive injury criteria and associated injury risk curves for lateral thoracic impacts compared to the EuroSID-2re.[75] That is why the EuroSID-2re [80] ATD was selected for use in this study.

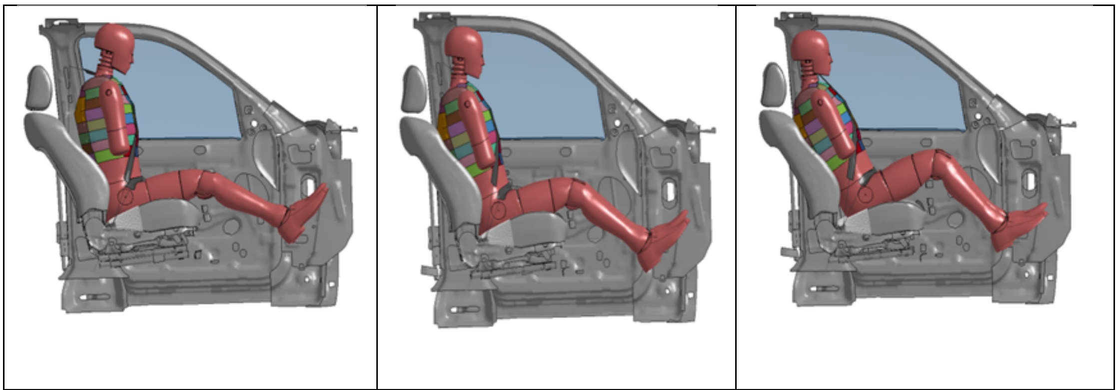
It is noted that in the NASS-CDS case report, the driver's bilateral thoracic injuries were attributed to the seatbelt. From a review of currently available literature, no side-impact ATDs have been designed to measure lateral thoracic injury due to seatbelt contact. Thus, it is plausible that the EuroSID-2re may not measure injurious lateral thoracic loads from the seatbelt. Further, the NASS-CDS case report states that the seatbelt was a "possible" rather than "certain" cause of the driver's bilateral thoracic injuries. As such, these injuries may have resulted from impact with other vehicle interior components such as the door interior or centre console.

6.3.6 ATD Positioning

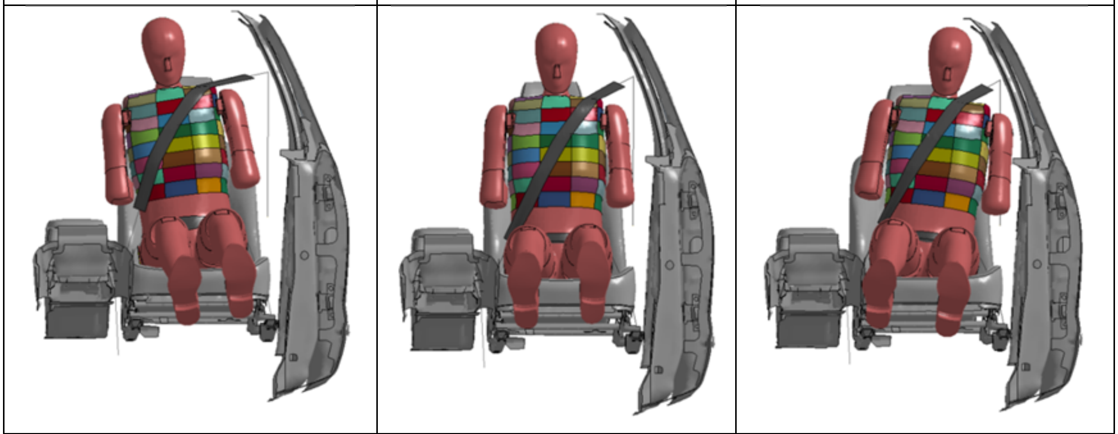
The driver seat was located mid-track and the B-pillar D-ring was positioned in the "full up" position as documented in the NASS-CDS case report. The posture of the ATD in the driver's seat of the Ford Explorer FE model was guided by previous studies.[144, 168] That is, the anterior-posterior recline and lateral lean angles of the EuroSID-2re, relative to the vertical axis, were based on the anterior-posterior recline and lateral lean angles of PHMSs and ATDs from the studies performed by Lessley *et al*. [78] and Zhang *et al*. [168] when their buck, which represented a vehicle, was rotated by 90 degrees. In this study, the ATD was positioned in nine different postures (Table 6.7). In all postures, the ATD's back and gluteus maximus contacted the seatback and seat base, respectively. The images in Figure 6.7 shows the ATD's anterior-posterior recline and lateral lean angles, respectively. For ease of reference and clarity, the nine postures are titled Position 1 to Position 9 henceforth (Table 6.7).

Table 6.7 ATD target positions

ATD Posture Title	**Anterior-Posterior Lean Angle (deg)**	**Lateral Lean Angle (deg)**
Position 1	-11.0	-7.5
Position 2	-11.0	0.0
Position 3	-11.0	+7.5
Position 4	-21.0	-7.5
Position 5	-21.0	0.0
Position 6	-21.0	+7.5
Position 7	-31.0	-7.5
Position 8	-31.0	0.0
Position 9	-31.0	+7.5



-11 degrees recline.	**-21 degrees recline.**	**-31 degrees recline.**



+7.5 degrees lateral lean.	**0.0 degrees lateral lean.**	**-7.5 degree lateral lean.**

Figure 6.7 ATD anterior-posterior recline angles relative to the vertical axis (top) and ATD lateral lean angles relative to the vertical axis (bottom)

In all nine simulations, the seatbelt was located firmly across the thorax and the lap of the ATD. The seatbelt retractor was locked as the vehicle had rotated by more than fifteen degrees at the initial time in the simulations.[102] Although previous studies have indicated that the seatbelt retractor can unlock during a rollover [40, 89, 121], taking this into account was beyond the scope of this study.

6.3.7 Thoracic Injury Assessment

The ATD kinematics from each completed simulation was examined and the points of impact between the ATD's thorax and vehicle interior components were identified. The following injury criteria were used to evaluate the probability of an AIS3+ thoracic injury occurring from thoracic to vehicle interior impact: rib deflection, upper spinal acceleration, lower spinal acceleration, ASA-10 and VC. These injury criteria, with the exception of VC, were chosen as injury risk curves are available which correlate acceleration and rib displacement measurements obtained from the EuroSID-2re to PMHS injury outcomes.[75] Further, these injury criteria have been shown to be sound predictors of lateral thoracic injuries in previous studies.[75] In addition to the aforementioned injury criteria, lateral thoracic impact velocity, thorax force and seatbelt axial force were also measured and the method used to obtain these additional metrics is presented in Sections 6.3.7.1, 6.3.7.2 and 6.3.7.3, respectively.

The coordinate system used in this study was the SAE ATD local system.[130] Although the EuroSID-2re used in this study was instrumented for left thoracic impacts, spinal acceleration measurements were also obtained for right side impacts as this provides an indication as to whether any right side impacts may be injurious.

Spinal acceleration was filtered with SAE CFC180 filter [130], except for ASA-10 where a Butterworth (BW) 300 filter was applied [21]. Deflections were filtered with SAE CFC600 filter.[130] SAE J211 [130] does not specify the CFC for forces and velocities; thus, SAE CFC600 filter was applied for forces [165] and SAE CFC180 filter was applied for velocities.[14]

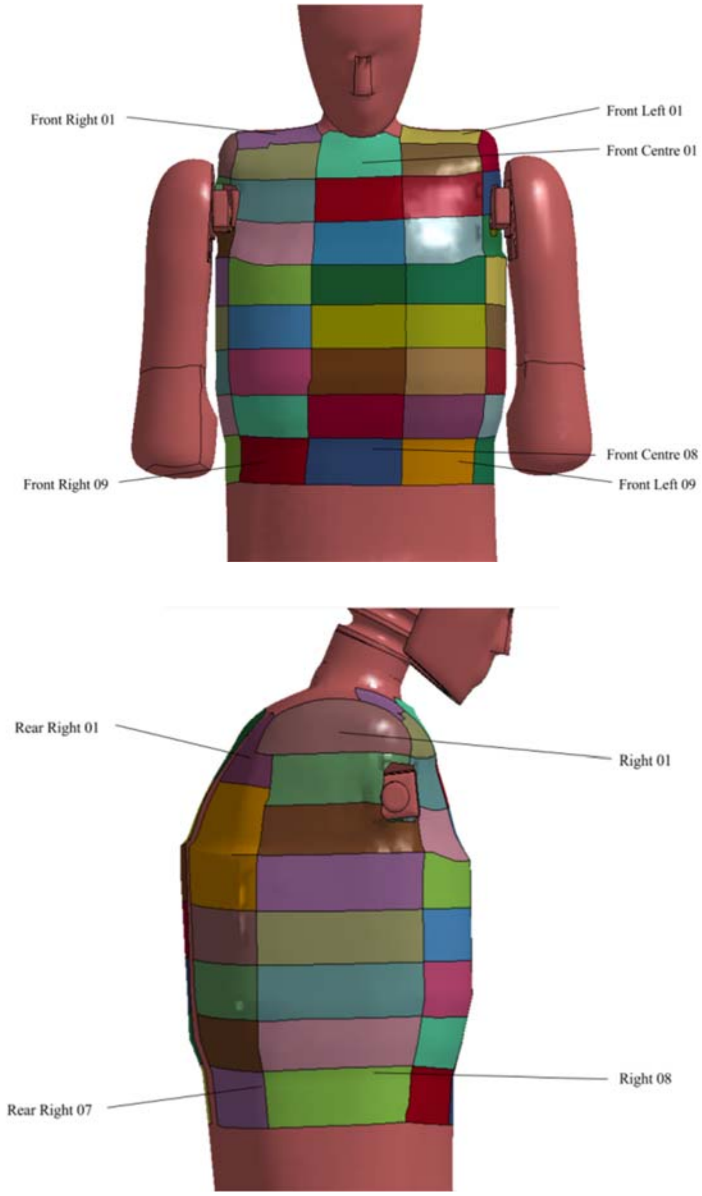
6.3.7.1 Lateral Thoracic Impact Velocity

The assessment for potential AIS3+ thoracic injury was based on the results for the lateral thoracic impact velocity [142] that were previously described in Chapter 3. The lateral thorax impact velocity was measured by tracking targeted nodes on the side of the ATD's thorax along the Y-axis of a local coordinate system relative to the ATD.

To identify the node or nodes which were subjected to peak lateral velocity during the rollover simulation, an initial screening was performed to identify the areas where the thorax had deformed upon impact with the vehicle interior components. The node located closest to the centre of each deformed area was then identified. This node and eight adjacent nodes were selected, thus forming a 3x3 node matrix. The time history of the y-axis lateral velocity from each of these nine nodes was then plotted and the node with the peak lateral velocity was identified. The peak lateral velocity was then correlated to the probability of an occupant sustaining an AIS3+ thoracic injury through the injury risk curves previously described in Chapter 3.

6.3.7.2 Thorax Force

The thorax was divided into 56 segments (Figure 6.8) and the resultant contact force on each segment was obtained. The ATD kinematics from each rollover simulation was analysed and thoracic deformations due to contact with the seatbelt or impact against vehicle interior components were identified. A time history of the resultant force for each of the deformed thoracic segment was then plotted and peak resultant force identified.



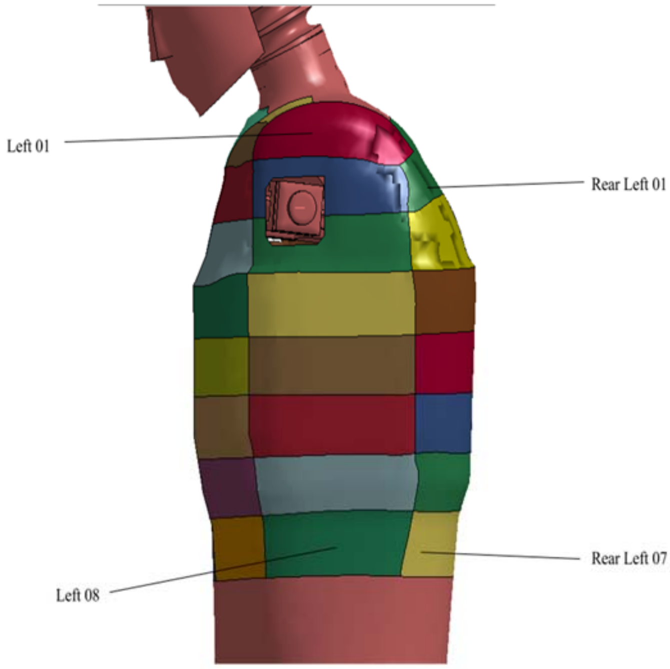


Figure 6.8 Segments defined to measure thorax impact forces.

6.3.7.3 Seatbelt Axial Force

Seatbelt axial force was also measured during each simulation. The axial forces were measured at the lap belt's left and right end and bottom and top of the sash. The peak axial force from each of these four locations was obtained from the time history plots.

6.4 Results

The results from the multibody simulation are presented first. This is followed by the qualitative and quantitative results from the FE vehicle simulation and finally the quantitative results from the FE ATD.

6.4.1 Vehicle Kinematics

6.4.1.1 Multibody Simulation

The vehicle kinematics at the point of trip from the PC-CRASH simulation is presented in Table 6.8.

Table 6.8 Vehicle kinematics at the point of trip

Roll (deg)	90.00
Pitch (deg)	4.50
Yaw (deg)	32.06
Roll rate (deg/s)	152.41
Pitch rate (deg/s)	68.75
Yaw rate (deg/s)	-4.01
Horizontal velocity (km/h)	27.75
Vertical velocity (km/h)	-0.67

6.4.1.2 FE Vehicle Simulation

The trip conditions obtained from the PC-CRASH simulations and used in the FE analysis resulted in a four quarter-turn rollover over a distance of eight metres. Plots of the vehicle velocity along global X-axis and the vehicle roll rate and roll angle are presented in Figure 6.9, Figure 6.11 and Figure 6.12, respectively. Figure 6.9 also indicates the time during which the vehicle is in the 2nd, 3rd and 4th quarter-turns. The vehicle and ATD figures at the start of the point of trip (0 ms) and at the end of the 2nd (700 ms), 3rd (1400 ms) and 4th (2450 ms) quarter-turn are presented in Figure 6.10.

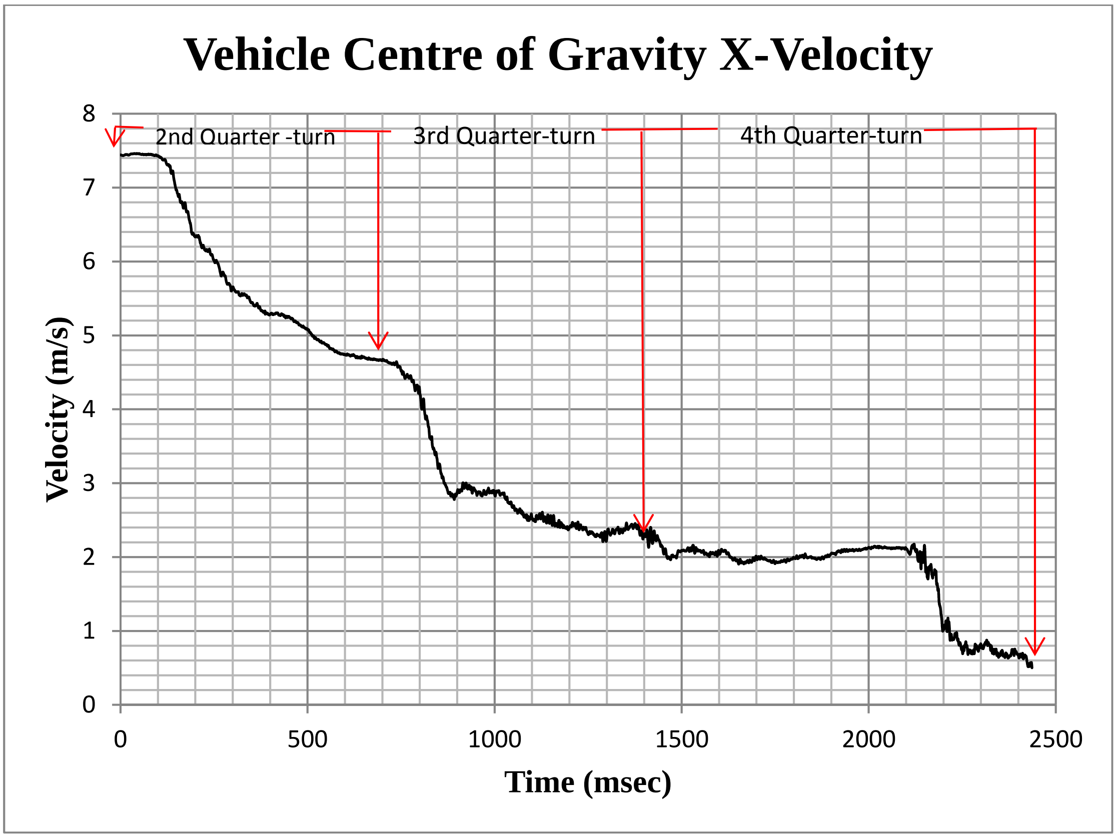


Figure 6.9 Vehicle centre of gravity x-velocity

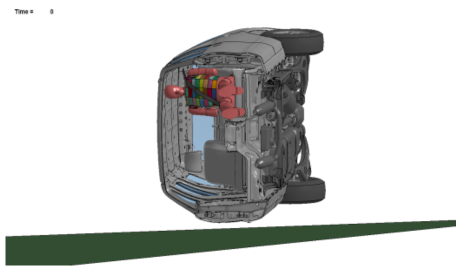
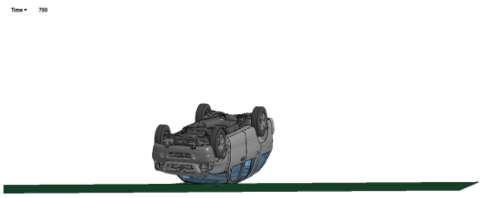
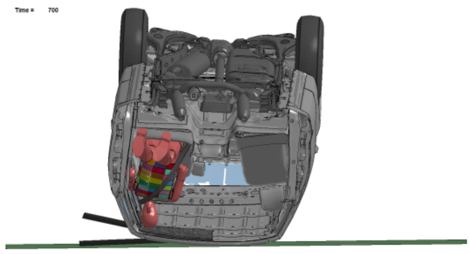
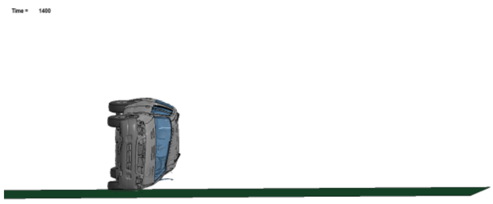
Time (ms)	Vehicle Figure	ATD and Vehicle Section Figure
0		
700		
1400		
2450		

Figure 6.10 Vehicle and ATD figures from rollover sequence

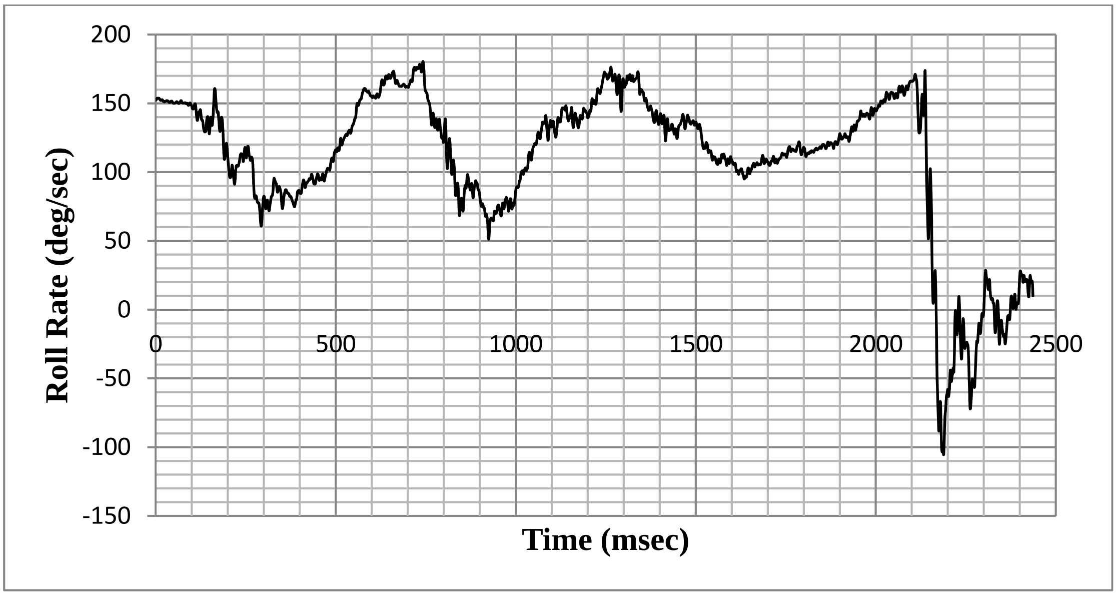


Figure 6.11 Vehicle centre of gravity roll rate (relative to vehicle x-axis)

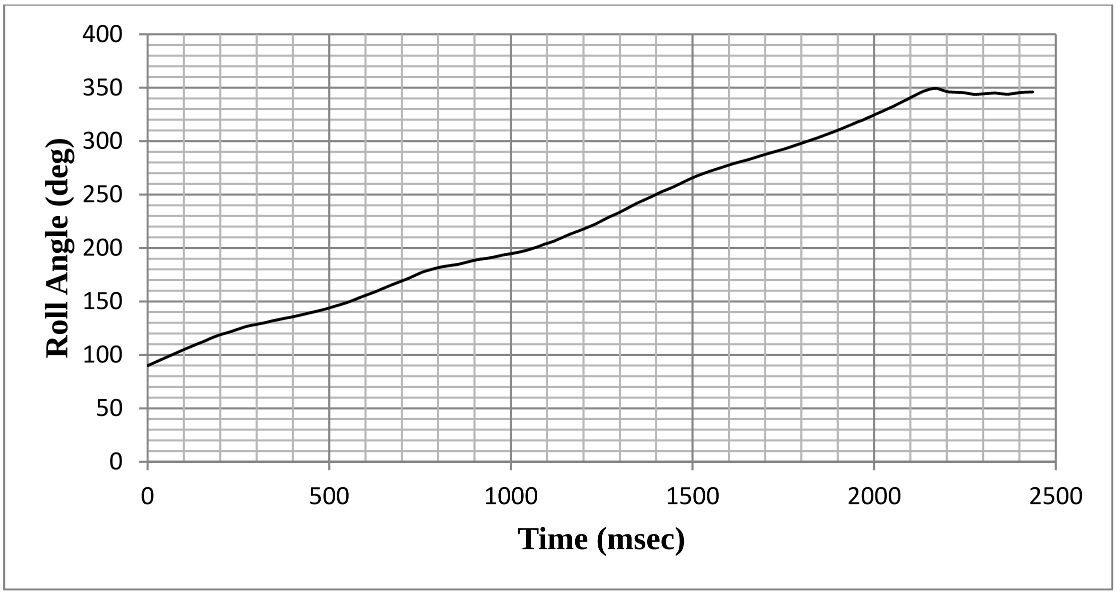


Figure 6.12 Vehicle roll angle

It is noted that apart from the vehicle skid marks, trip point and the vehicle's final position, no other details were available from the NASS-CDS scene diagrams for comparison with the reconstructed trajectory. However, the key impact points between the FE vehicle model and the ground surface could be compared to the NASS-CDS case vehicle photos (Figure 6.13a & Figure 6.13b).

In the FE simulation, the location and direction of the damage pattern of the right A-pillar, which was the first part of the vehicle structure to contact the ground, correlated well with those of the case vehicle (Figure 6.13a). The subsequent impact occurred at the left A-pillar and left B-pillar (Figure 6.13b). Corresponding photos from the case vehicle are also presented in Figure 6.13a and Figure 6.13b.

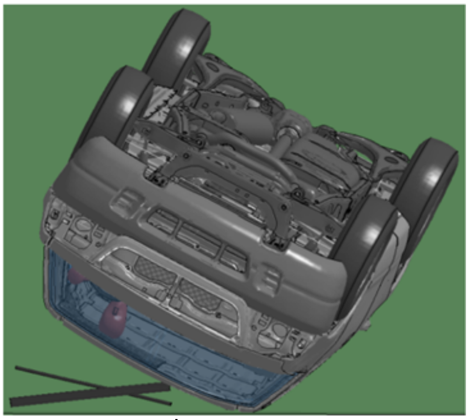
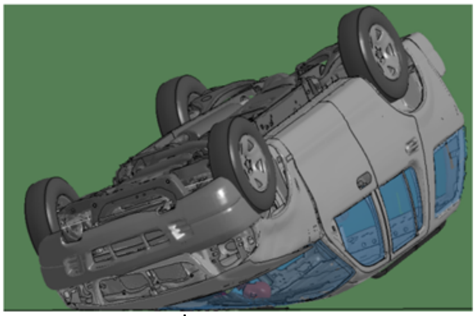
	FE Model	**Actual Vehicle**
Figure 6.13a	 **2nd quarter-turn.**	
Figure 6.13b	 **3rd quarter-turn**	

Figure 6.13: FE vehicle model during key ground impacts (left) with corresponding vehicle damage

A quantitative assessment of the vehicle damage was performed by comparing the NASS-CDS reported intrusion and crush direction to the corresponding intrusion and crush direction from the FE model (Table 6.9). The time history plots of the vehicles A-pillar and B-pillar deformation are presented in Appendix H and Appendix I, respectively.

Table 6.9 Comparison of NASS-CDS Reported Vehicle Intrusion and FE Model Measured Intrusion

Intruded Component	Crush Direction	NASS-CDS Reported Intrusion (cm)	FE Model Measured Intrusion (cm)
Left A-Pillar	Vertical	10	11.8
Left B-Pillar	Vertical	5	3.4

A comparison of the roof damage between the case vehicle and FE model is presented in Figure 6.14

Figure 6.14 Comparison of roof damage between the FE model (left) and case vehicle (right)

6.4.2 ATD Kinematics and Dynamics

Of nine simulations that were performed for this current study only four ran to completion. The other five simulations terminated due to unresolvable EuroSID-2re instabilities. The simulations which ran to completion were with the ATD in Position 1, 2, 5 and 8 (Table 6.7 and Figure 6.7).

In all four simulations, the only significant thorax to vehicle interior impact was with the centre console which occurred during the vehicle's 4^{th} quarter-turn as the vehicle's right wheels contacted the ground (2,100 ms to 2,400 ms). This wheel-to-ground contact resulted in the dummy traversing from outboard to inboard and the right thorax impacting the centre console. This impact with the centre console (Figure 6.15) became a focus of this investigation.

At no other instance during the rollover was the lateral part of the thorax observed to neither have impacted with vehicle interior components nor deform due to the seatbelt. However, it was observed that there was potential for the left thorax to impact the vehicle interior at the 2^{nd} to 3^{rd} quarter-turn (550 ms to 1,150 ms). This instance in the rollover was also a focus for this investigation.

Quarter-turn	Vehicle	ATD
2nd quarter-turn (650 ms)		
4th quarter-turn (2,250 ms)		
Note: Figures have been righted for clarify		

Figure 6.15 Vehicle position at the 2nd and 4th quarter-turn (left) and corresponding ATD posture (right)(ATD originally in Position 2).

6.4.2.1 Rib deflection

The maximum rib deflections are presented in Table 6.10 along with the corresponding time and probability of an AIS3+ thoracic injury, as calculated from equation 6.1. A time-history plot of the rib deflection is provided in Appendix J.

Table 6.10 Rib deflection

ATD Position	Rib	Maximum Deflection (mm)	Time of Peak Deflection (ms)	Vehicle Quarter-turn	Probability of AIS3+ Lateral Thoracic Injury
1	Upper Rib	1.05	1099	3rd	0.10
	Middle Rib	2.01	1132	3rd	0.12
	Lower Rib	1.82	1129	3rd	0.12
2	Upper Rib	1.85	834	3rd	0.12
	Middle Rib	1.86	637	2nd	0.12
	Lower Rib	1.96	632	2nd	0.12
5	Upper Rib	2.73	580	2nd	0.13
	Middle Rib	2.51	582	2nd	0.12
	Lower Rib	2.17	210	2nd	0.12
8	Upper Rib	1.43	755	3rd	0.12
	Middle Rib	0.48	204	2nd	0.11
	Lower Rib	1.44	204	2nd	0.12

6.4.2.2 Upper and Lower Spinal Acceleration

The peak upper and lower spinal accelerations when the ATD contacted the left vehicle interior and impacted the centre console are presented in Table 6.11 and Table 6.12, respectively. It is noted that the probability of an AIS3+ upper and lower lateral thoracic injury was calculated with Equation 6.2 and 6.3, respectively. A time history plot of the upper and lower spinal acceleration for each ATD position is presented in Appendix K and Appendix L, respectively.

Table 6.11 Upper spinal acceleration results

ATD Position	Peak Upper Spinal Acceleration (*g*)	Time of Peak Acceleration (ms)	Vehicle Quarter-turn	Probability of AIS3+ Lateral Thoracic Injury
Position 1	5.14	1099	3rd	0.20
	-4.44	2261	4th	0.19
Position 2	4.64	751	3rd	0.19
	-5.99	2286	4th	0.21
Position 5	3.72	573	2nd	0.19
	-5.39	2270	4th	0.20
Position 8	5.79	774	3rd	0.20
	-5.77	2228	4th	0.21

Table 6.12 Lower spinal acceleration results

ATD Position	Peak Lower Spinal Acceleration (*g*)	Time of Peak Acceleration (ms)	Vehicle Quarter-turn	Probability of AIS3+ Lateral Thoracic Injury
Position 1	8.48	824	3rd	0.15
	-6.47	2289	4th	0.14
Position 2	10.48	843	3rd	0.15
	-9.40	2276	4th	0.15
Position 5	3.42	856	3rd	0.13
	-9.27	2241	4th	0.15
Position 8	11.28	862	3rd	0.15
	-7.63	2289	4th	0.14

6.4.2.3 ASA-10

ASA-10 results are presented below (Table 6.13) with time history plots presented in Appendix M. It is noted that the probability of an AIS3+ lateral thoracic injury was calculated with Equation 6.5.

Table 6.13 ASA-10 results

ATD Position	Start time of Pulse	End Time of Pulse	ASA (*g*)	Vehicle Quarter-turn	Probability of AIS3+ Lateral Thoracic Injury
Position 1	818	857	6.89	3rd	0.14
	1985	2147	0.57	4th	0.11
Position 2	831	858	8.44	3rd	0.15
	1895	2177	0.56	4th	0.11
Position 5	-	-	-	-	-
	1814	2151	0.46	4th	0.11
Position 8	857	873	9.31	3rd	0.15
	1978	2155	0.66	4th	0.11

6.4.2.4 Viscous Criteria

The result from the VC analysis is presented in Table 6.14 and the time history plots are presented in Appendix N. It is noted that the VC was calculated with Equation 6.6.

Table 6.14 Viscous criteria results

ATD Position	Rib	VC (m/s)	Time (ms)	Vehicle Quarter-turn
Position 1	**Upper Rib**	0.0005	782	3rd
	Middle Rib	0.0013	1129	3rd
	Lower Rib	0.0018	1095	3rd
Position 2	**Upper Rib**	0.0007	830	3rd
	Middle Rib	0.0004	632	2nd
	Lower Rib	0.0002	578	2nd
Position 5	**Upper Rib**	0.0013	575	2nd
	Middle Rib	0.0009	576	2nd
	Lower Rib	0.0004	204	2nd
Position 8	**Upper Rib**	0.0004	750	3rd
	Middle Rib	0.0001	197	2nd
	Lower Rib	0.0104	2235	4th

6.4.2.5 Thorax Lateral Impact Velocity

The peak of the thorax lateral impact velocity from each simulation is presented in Table 6.15. Figure 6.16 indicates the location of the Node IDs that are referenced in the table. A time history plot of impact velocity for these nodes is presented in Appendix O.

Table 6.15 Lateral thorax impact velocity

ATD Position	Node ID	Peak Lateral Thorax Impact Velocity (m/s)	Time of Peak Impact Velocity (ms)	Vehicle Quarter-turn	Probability of AIS3+ Lateral Thoracic Injury
Position 1	380839	-4.95	2271	4th	0.31
Position 2	380823	-3.66	2326	4th	0.17
Position 5	380870	-3.31	2266	4th	0.14
Position 8	381218	-3.14	2285	4th	0.13

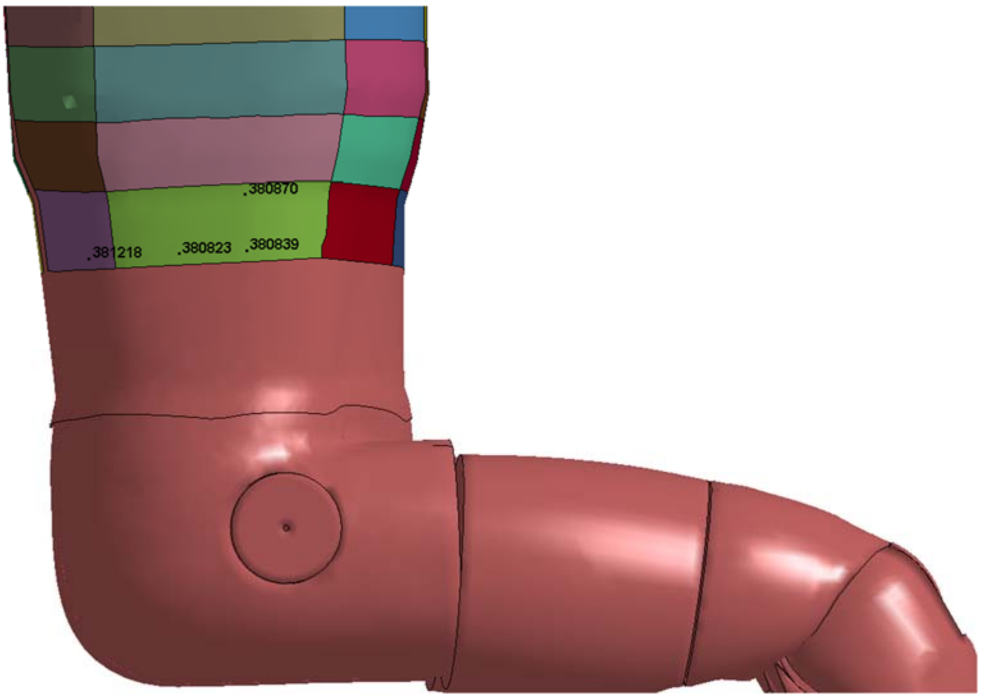


Figure 6.16 Location of node IDs referenced in Table 6.15

6.4.2.6 Thorax Force

The peak resultant force from the four simulations is presented in Table 6.16 and the peak resultant force from the thorax to centre console impact is presented in Table 6.17. A time history plot of the resultant thoracic force for each of the thorax segment that is referred to in Table 6.16 and Table 6.17 is presented in Appendix P. The time history plot of all thorax segments which were observed to have been deformed upon contact with vehicle interior components or the seatbelt in the simulation is presented in Appendix Q.

Table 6.16 Peak thoracic force and pressure

ATD Position	Thorax Segment	Peak Force (kN)	Time of Peak Force (ms)
Position 1	Front Right 05	0.27	827
Position 2	Front Left 01	0.19	847
Position 5	Rear Right 05	0.15	2264
Position 8	Rear Right 07	0.64	2291

Table 6.17 Peak thoracic force and pressure from right thorax to centre console impact

ATD Position	Thorax Segment	Peak Force (kN)	Time of Peak Force (ms)
Position 1	Right Side 06	0.19	2303
Position 2	Right Side 06	0.10	2254
Position 5	Right Side 06	0.08	2256
Position 8	Right Side 07	0.53	2271

6.4.3 Seatbelt axial force.

The peak seatbelt axial forces from the four simulations are presented in Table 6.18 and Table 6.19 for the lap and sash belt, respectively. A time history plot of seatbelt axial force is presented in Appendix R.

Table 6.18 Peak Lap Belt Axial Forces

ATD Position	Left Lap Belt Peak Force (kN)	Time of Peak Force (ms)	Vehicle Quarter-turn	Right Lap Belt Peak Force (kN)	Time of Peak Force (ms)	Vehicle Quarter-turn
Position 1	2.38	817	3rd	1.13	193	2nd
Position 2	2.74	827	3rd	2.74	827	3rd
Position 5	2.28	2289	4th	2.28	2289	4th
Position 8	2.39	850	3rd	2.39	850	3rd

Table 6.19 Peak Sash Belt Axial Forces

ATD Position	Sash Bottom Peak Force (kN)	Time of Peak Force (ms)	Vehicle Quarter-turn	Sash Top Peak Force (kN)	Time of Peak Force (ms)	Vehicle Quarter-turn
Position 1	1.05	198	2nd	1.18	201	2nd
Position 2	0.95	189	2nd	0.95	194	2nd
Position 5	1.15	192	2nd	1.23	195	2nd
Position 8	1.33	875	3rd	1.24	876	3rd

6.5 Discussion

6.5.1 Vehicle Kinematics

The FE simulation resulted in the vehicle rollover occurring over a distance of eight metres. This was two metres shorter than that reported in the NASS-CDS case report of ten metres. A number of variables were altered in order to increase the roll distance which included increasing and decreasing the vehicle-to-ground friction coefficient, increasing the vehicle’s roll rate and increasing the vehicle’s transverse velocity. However, it was not possible to increase the roll distance from eight metres to ten metres without a resulting increase in vehicle quarter-turns. However, from the analysis of vehicle intrusion (Table 6.9), it is noted that the FE model’s left A and B-pillar intrusion is similar to that reported by NASS-CDS in both magnitude and direction.

6.5.2 ATD Kinematics and Dynamics

The results from rib deflection, upper and lower spinal acceleration, ASA-10 and VC indicate a low probability that an AIS3+ lateral thoracic injury had occurred. However, impact velocity indicates that an AIS3+ thoracic injury may have occurred during the 4th quarter-turn and is discussed below.

In all four simulations, the right thorax impacted the centre console between 2,200 ms and 2,400 ms. Of the four ATD positions, the ATD in Position 1 was subjected to the highest lateral thoracic impact velocity of 4.95 m/s when the ATD impacted the centre console (Figure 6.17). This impact velocity corresponds to a probability of an AIS3+ thoracic injury of 0.31 (Figure 3.2). This indicates that the driver's AIS3+ thoracic injury is likely to have occurred due to contact with the centre console, a finding similar to that by Tahan *et al*. [139] Previous studies by Robbins *et al*. [128] found that a blunt lateral thorax impact velocity of 4.2 m/s resulted in PMHSs sustaining between two rib fractures (AIS2) and seven rib fractures (AIS4) while Viano *et al*. found that blunt lateral thoracic impacts of 3.62 m/s was sufficient to result in a PMHS sustaining two rib fractures (AIS2).[149] These reported injuries are similar to that sustained by the driver despite the impact velocities being lower than that in the reconstruction. Further, it is also noted that a significant decrease in the vehicle's lateral velocity between 2,150 ms to 2,250 ms (Figure 6.9) was also observed to have occurred when the ATD impacts the centre console which suggests that a significant decrease in lateral velocity may be associated with an occupant sustaining a lateral thoracic injury, thus, confirming the hypothesis stated in Section 2.7. That is, the injury is occurring as a result of the occupant flailing into and impacting the vehicle interior components.

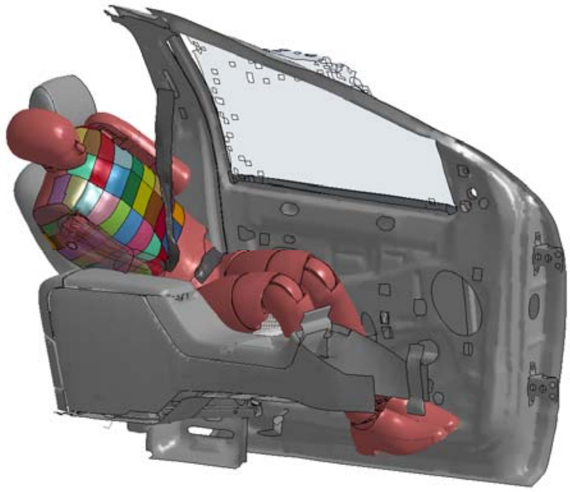


Figure 6.17 Position 1 - ATD impacting the centre console at 2,300 ms

A significant decrease in the vehicle's lateral velocity was also observed to have occurred between 700 ms and 900 ms (Figure 6.9). This corresponded with a peak in maximum rib deflection for the ATD in Position 2 (upper rib) and ATD in Position 8 (upper rib). From the video analysis, the ATD is seen to be flailing towards the driver's door at this instance (Figure 6.18). Although the observed rib deflections were low and is likely to be the result of the thorax impacting the ATD's arm rather than the driver's door interior, this observation indicates a possibility that thoracic injury may be associated with a decrease in the vehicle's lateral velocity. That is, as the vehicle's lateral velocity decreases significantly from vehicle roof-to-ground impact the occupant continues to travel at the vehicle's pre-impact velocity. This difference in vehicle and occupant velocity results in the occupant impacting against the vehicle interior components. Additionally, it is also observed that at this instance in the rollover sequence, the driver's door top-half sustains significant damage from the vehicle-to-ground impact. The resultant damage to the door correlates with the findings from Chapter 5 where damage to segment Left 2 (i.e., driver's door top-half) was found to be associated with an occupant sustaining AIS3+ thoracic injury.

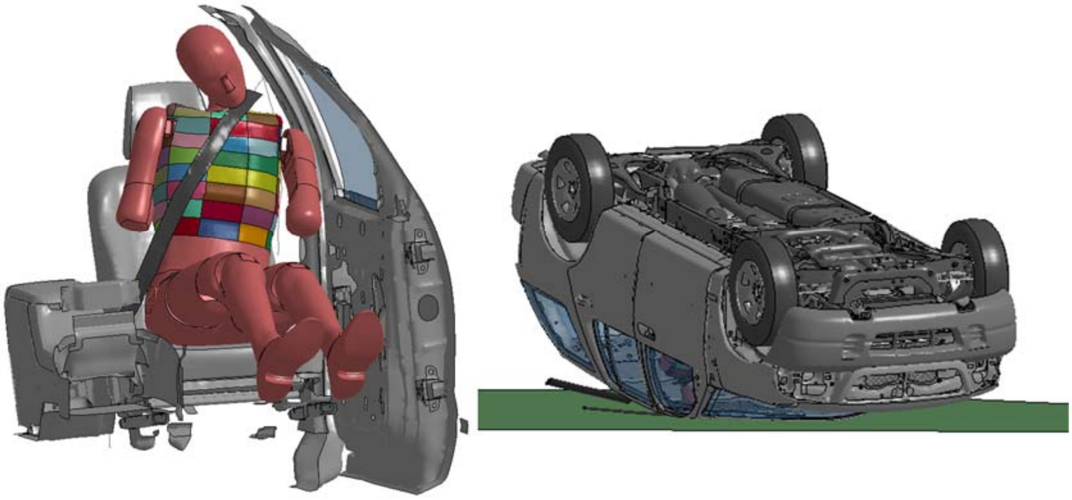


Figure 6.18 Position 2 - ATD flailing towards driver door interior (left) and corresponding vehicle position (right)

The results from Chapter 4 indicate that the driver's door interior is the most frequently cited source of injury for driver far-side rollover crashes. Although the ATD thorax had not impacted the driver's door interior in the simulations, the overall ATD kinematics does indicate that this may occur under certain conditions, such as a higher vehicle lateral velocity, and where the occupant arm is not positioned between the thorax and driver's door interior.

From the lateral thoracic impact velocity plots in Appendix O, it is noted that peak lateral thoracic impact velocities of up to 6.4 m/s were observed. However, this was due to the ATD head and left shoulder impacting the vehicle's roof rail interior and left door interior, respectively, resulting in the lower right thorax registering this peak in velocity (Figure 6.19) rather than the thorax actually impacting vehicle interior.

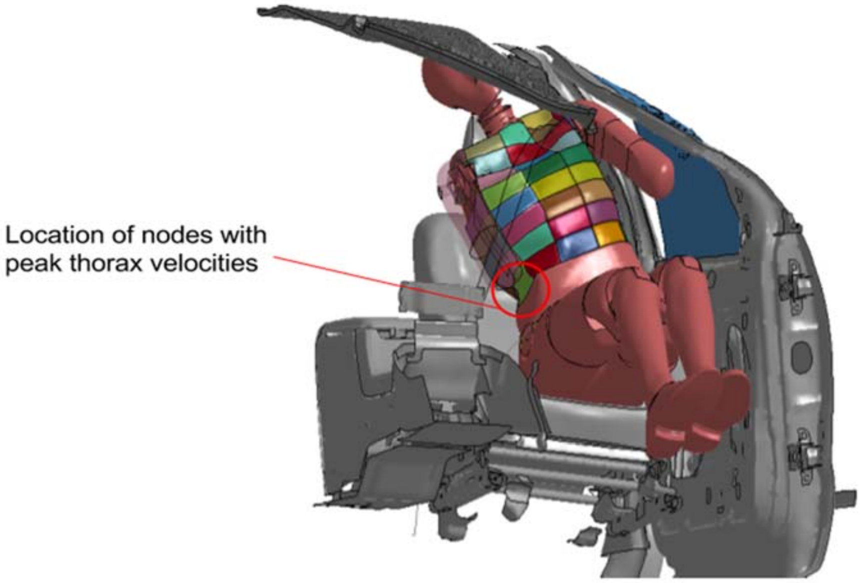


Figure 6.19 Position 2 - ATD left shoulder and head impacting vehicle interior components

It was also observed that a change in ATD lateral lean angle of 7.5 degrees from Position 1 to Position 2 resulted in a decrease in maximum observed lateral thoracic impact velocity from 4.95 m/s to 3.66 m/s and that the nodes that registered these velocities are located on the Right 08 thorax segment (Figure 6.8). These impact velocity values correspond to a probability of an AIS3+ lateral thoracic injury of 0.31 and 0.17 (Figure 3.2), respectively. This result suggests that the probability of an occupant sustaining a thoracic injury during a rollover is sensitive to the ATD position at the point of trip.

The highest thoracic resultant force for impacts not involving the centre console was 0.27 kN which occurred at 826 ms for the ATD at initial Position 1. This force was due to the seatbelt pressing against the thorax's Front Right 05 thorax segment (Figure 6.20). However, this force is substantially lower than those required to result in a thoracic injury.[132]

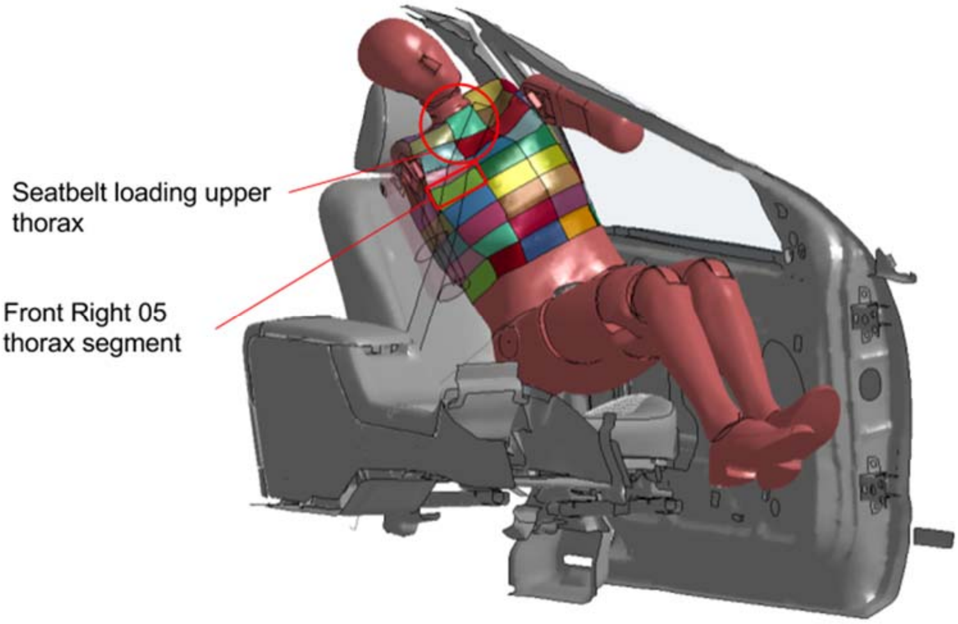


Figure 6.20 Position 1 - Seatbelt loading right side of thorax

The highest thoracic resultant force due to the impact with the centre console was observed to be 0.53 kN at 2,270 ms (Figure 6.21). Existing literature indicate that a lateral thoracic force of 7.4 kN and 10.2 kN results in an AIS0 and AIS3+ lateral thoracic injury, respectively.[132, 143] Other studies estimated that a 5.5 kN lateral impact force results in a 25% probability of an AIS4+ thoracic injury.[132, 152] The observed force of 0.53 kN is less than the reported injurious forces. Thus, lateral thoracic injury was not likely to have occurred due to the thorax's impact with the centre console. However, force may not be a suitable criterion for thoracic injuries as it does not take into account the viscous nature of the thorax nor does it take into account the area to which the force is applied.[132]

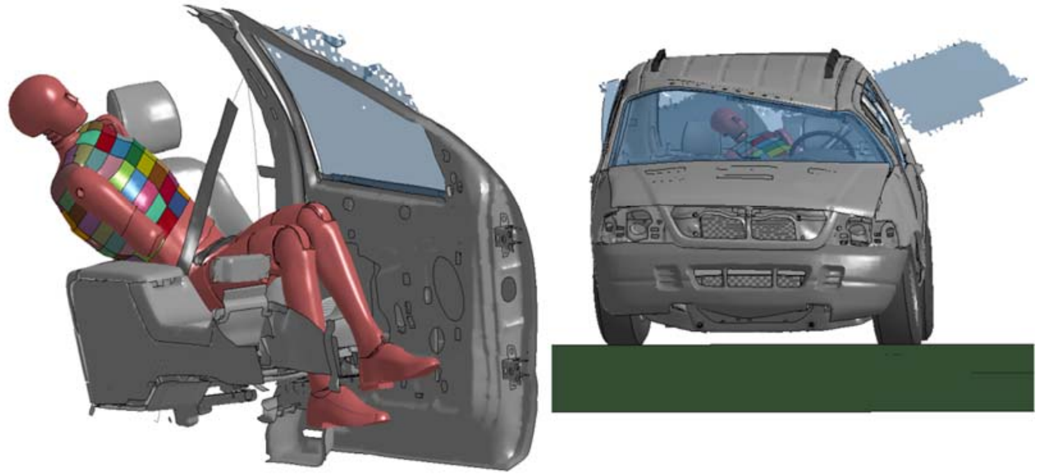


Figure 6.21 Position 8 - ATD with the right thorax impacting the centre console at 2,300 ms (left) and corresponding vehicle position (right).

The maximum lap belt axial forces were observed to be between 2.28 kN and 2.74 kN and occurred during the 2nd to 3rd vehicle quarter-turn. The maximum observed axial force from this study are noted to be approximately three times higher than those measured in previous studies.[16] These observed higher axial belt forces is a reflection of the ATD pelvis moving upwards (i.e., away from the seat cushion) and towards the door and is restrained by the lap belt (Figure 6.22). However, when the ATD was in Position 5, the maximum lap belts axial force occurred during the 4th vehicle quarter-turn (Figure 6.23). This peak load was due to the lap belt being sufficiently taut thus restraining the ATD as the right wheels impact the ground which resulted in the ATD traversing and pivoting inboard.

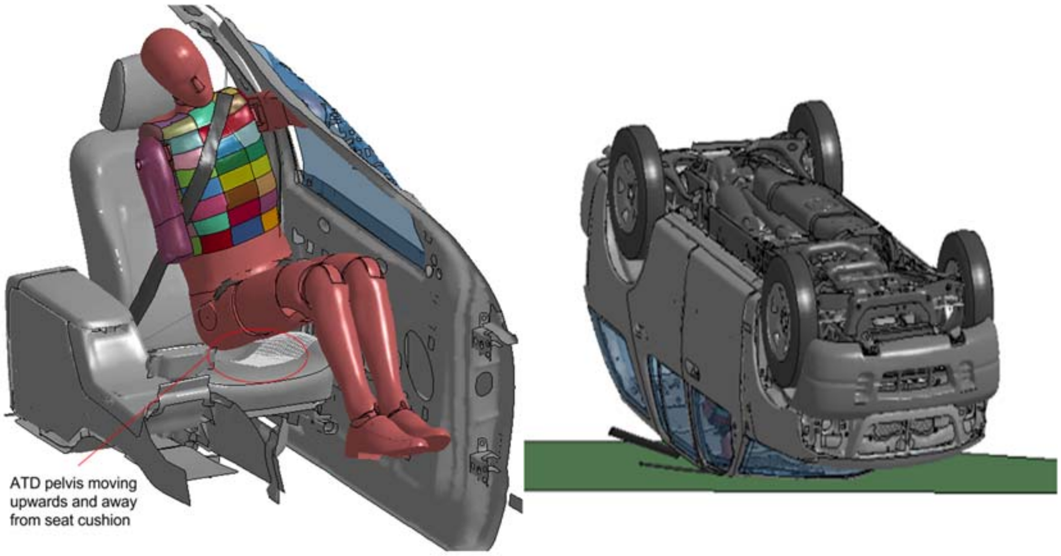


Figure 6.22 Position 2 – ATD restrained by lap belt at end of 2nd quarter-turn (left) and corresponding vehicle position (right)

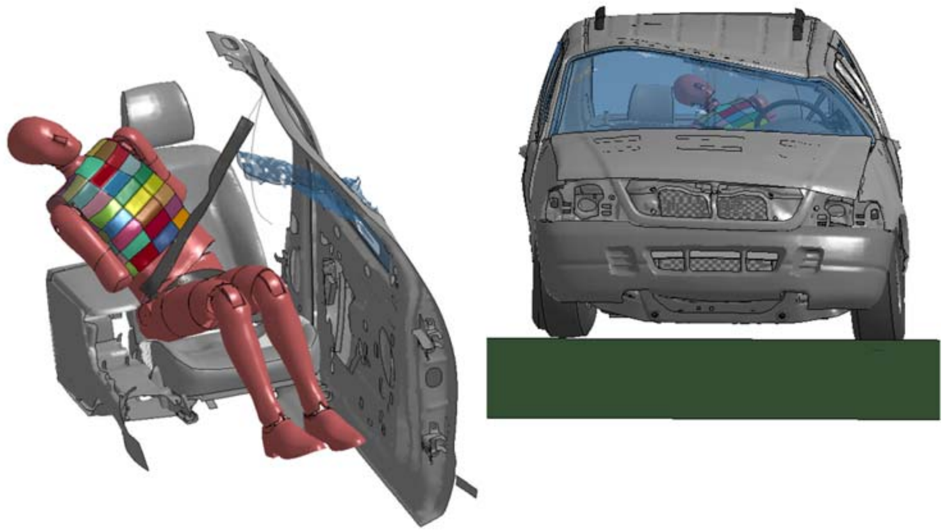


Figure 6.23 Position 5 - ATD restrained by lap belt at end of 4th quarter-turn (left) and corresponding vehicle position (right)

The maximum sash belt axial forces for the ATD in Positions 1, 2 and 5 were observed to be between 0.95 kN and 1.23 kN. These peak forces occurred as the vehicle rotated just beyond ninety degrees and the ATD's thorax was partially restrained from moving anteriorly by the sash belt (Figure 6.24). The maximum sash belt axial force for the ATD in Position 8 was observed to be 1.33 kN and occurred while the vehicle was inverted and the ATD's head was pushed inboard and rearwards by the roof rail (Figure 6.25). This resulted in the thorax pivoting forwards and pressing against the locked seatbelt sash thus resulting in the observed loads. This observed axial force is similar to the sash belt axial forces observed in previous studies.[16]

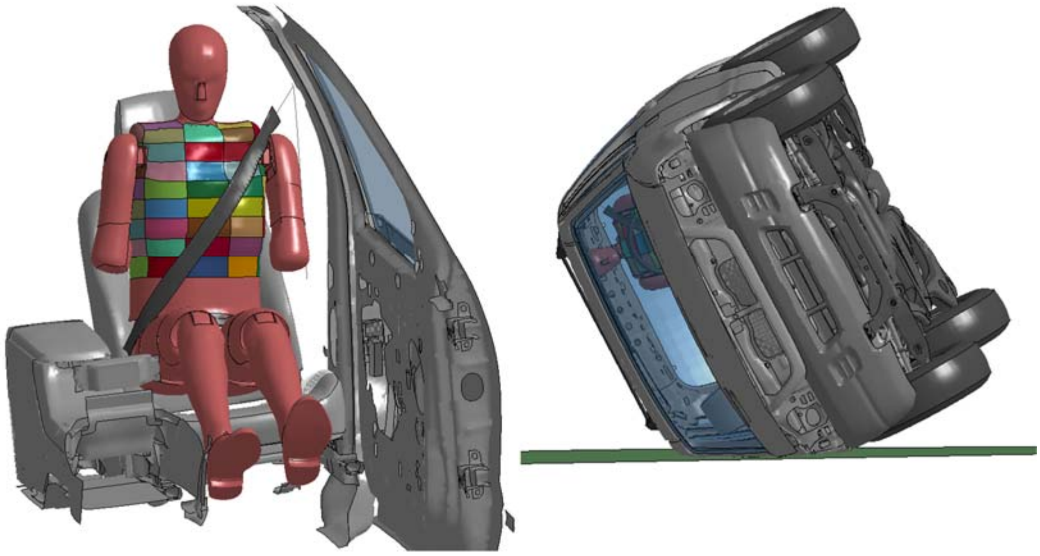


Figure 6.24 Position 2 - ATD when maximum sash belt load was observed (left) and corresponding vehicle position (right)

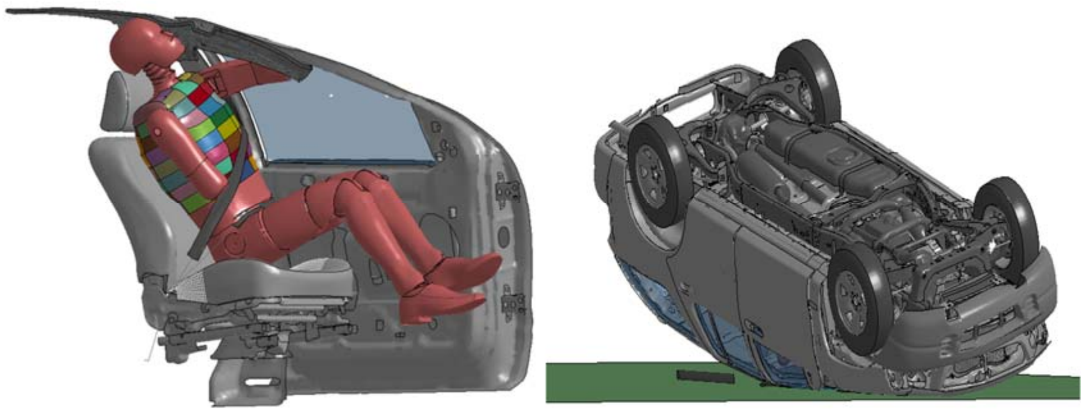


Figure 6.25 Position 8 - ATD pushed posteriorly (left) and corresponding vehicle position (right)

No existing literature is available to allow a comparison of the observed sash belt axial forces to real-world axial sash belt forces during an inversion to determine if thoracic injuries were likely to have occurred due to the observed forces. However, the observed sash belt axial loads form this study are significantly lower than the reported 3.3 kN force to the sternum and 8.8 kN force distributed to the shoulder and chest required to cause minor injury in frontal crashes.[132, 163]

The NASS-CDS case report has noted that the seatbelt was a “possible” cause of lateral thoracic injuries in this crash. This study has not been able to confirm that the seatbelt was the cause of these injuries potentially due to the current ATDs not being able to measure oblique loading.[14, 147] However, this study shows that right thoracic injuries may have occurred from impact with the centre console. It is not certain as to how the left thoracic injuries may have occurred as the simulations do not indicate that the left thorax had come into contact with the driver’s door interior nor was the seatbelt a potential cause of this injury. However, it is noted that bilateral thoracic injuries can occur from unilateral thoracic impacts.[164]

Previous studies have observed that the seatbelt sash can sometimes slide below the shoulder to the upper arm and thorax.[84, 116] This was not observed to have occurred in the four FE simulations.

The ATD was observed to rotate about its z-axis during the rollover and impact the centre console at an oblique angle. For example, Figure 6.26 shows the ATD right rear thorax impacting the centre console. Current side impact dummies do not adequately measure injurious accelerations, velocities or forces under oblique loading conditions.[14, 147] Oblique thoracic impact testing has been identified as important in side impact testing as the thorax of ATDs has been observed to rotate about their vertical axis during these crash tests.[162] Additionally, previous studies have also hypothesised that less chest compression is required to result in serious thoracic injury in oblique impacts compared to lateral impacts given the same impact velocity.[163] The results from this study indicate that developing an ATD capable of measuring injurious oblique thoracic impacts will be useful in rollover crash testing where lateral thoracic injury is to be studied.

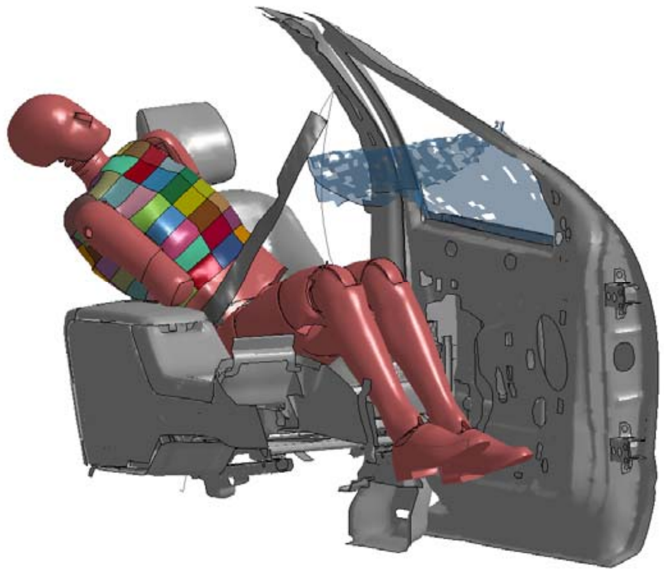


Figure 6.26 Position 2 - ATD at 2,300 ms with right thorax impacting against the centre console

The NASS-CDS case report noted that contusions were identified on the driver's left and central abdomen and that these injuries were attributed to the seatbelt (Table 6.4). These injuries suggest that submarining may have occurred. If so, the driver's kinematics would potentially be different to that of the ATD in the FE simulations as the lap belt was not observed to have risen up from the pelvis nor the ATD observed to have submarined in any of the four completed FE simulations. This potential kinematic difference between the actual crash and the simulation may have affected the outcomes of this study. Further, rollover occupant injury is highly sensitive to the occupant position and orientation at the instance where the occupant impacts the vehicle interior components.[78]

6.5.3 Limitations

The limitations of this study should be noted. Firstly, the reconstruction of the rollover relied on limited information from the NASS-CDS report such as the reported 10 m rollover distance and direction the vehicle was facing during the trip and final resting position as indicated on the scene diagram. Secondly, the NASS-CDS reported travel speed is estimated by crash investigators or law enforcement officials rather than obtained from rigorous computer reconstructions. This may have contributed to the difference in rollover distance between the real-world crash and the reconstruction. Thirdly, side impact ATDs were not designed to be used in rollover crash testing. For example the EuroSID-2re used in this reconstruction was instrumented for left thoracic impacts thus may not allow for accurate bilateral injury assessment. Further, side impact ATDs are currently not designed to measure oblique thoracic impacts which occurred in the FE simulations. Fourthly, potential gouging of the ground by the vehicle was not modelled in this study. Fifthly, only four of the nine simulations ran to completion.

6.6 Additional FE Vehicle and ATD Simulation for Door Impact

From the four completed simulations, it was observed that the ATD’s head had contacted the vehicle’s roof interior and/or vehicle’s roof rail interior during the 2nd quarter-turn. At this instance in the rollover simulation, the vehicle’s left roof rail contacted the ground and continued to roll onto the roof. It was hypothesised that the ATD’s head contact with the vehicle’s roof liner and/or roof rail interior may have prevented the ATD’s thorax from contacting the driver’s door interior. Further, it was also hypothesised that the ATD’s arm contact with the driver’s door glazing, which had shattered but not broken away from the door, may also prevent the thorax from further moving towards the door thus preventing it from potentially contacting the driver’s door interior. To explore these hypotheses further, an additional simulation was performed where the ATD’s head and driver’s door glazing were removed. This simulation was performed with the ATD in Position 2 (Table 6.7 and Figure 6.7). The results from the simulation indicated that with the head removed the ATD left shoulder contacted the B-pillar interior and prevented the thorax from contacting the driver’s door interior. As a result, it was excluded that the contact of the ATD head onto the roof liner or the ATD arm with the door glazing prevented the ATD’s thorax from impacting the driver’s door interior.

6.7 Conclusions

A real-world rollover crash where the driver of a Ford Explorer sustained AIS3+ bilateral thoracic injuries was reconstructed using a combination of PC-CRASH and LS-DYNA. PC-CRASH was used to replicate the vehicle’s pretrip trajectory up to the point of trip. The vehicle kinematics and position at the point of trip that were obtained from the PC-CRASH simulation were then assigned as the initial conditions to the FE vehicle model. This FE model was then used to simulate the rollover phase of the crash. A model of the EuroSID-2re ATD was then placed in the driver's seat of the FE vehicle model in four different postures. The data obtained from the ATD were assessed to determine if the reported AIS3+ bilateral thoracic injuries could be replicated.

The ATD spinal acceleration, rib deflection and thoracic lateral impact velocity were obtained from the FE simulations and compared to existing injury criteria at two key events in the rollover. The first key event in the rollover was where the ATD left thorax had the potential of contacting the driver's door interior during the 2nd to 3rd quarter-turn. The second key event was when the ATD right thorax impacted against the centre console at the end of the 4th quarter-turn.

Thoracic lateral impact velocity indicates that there is a 0.31 probability that an AIS3+ thoracic injury occurred during the 4th quarter-turn when the ATD impacted the centre console with a velocity of 4.95 m/s. Previous studies have indicated that a blunt lateral thoracic impact velocity between 3.62 m/s and 4.6 m/s resulted in PMHSs sustaining multiple rib fractures corresponding to an AIS2 to AIS4 injury severity. These injuries are similar to those sustained by the driver in the considered real-world rollover crash. Further, the ATD thorax impact with the centre console is observed to have coincided with a significant decrease in the vehicle's lateral velocity, thus, supports the hypothesis stated in Section 2.7. That is, a significant decrease in a rollover vehicle's lateral velocity may be associated with an occupant flailing into the vehicle interior components and, as a result, sustaining AIS3+ thoracic injuries.

The ATD was observed to have the potential of impacting the vehicle door interior at the end of the 2nd and the start of the 3rd quarter-turn; however, the considered injury criteria indicate that lateral thorax injury was not likely to have occurred at this instance in the rollover. This instance in the rollover was observed to coincide with a significant decrease in vehicle lateral velocity and vehicle damage to the top half of the left door. It is noted that this vehicle segment damage was found to be associated with an occupant sustaining serious thoracic injury in Chapter 5 thus, should be explored in future studies. Future studies may also be directed to performing further parametric studies to understand how occupant posture affects the outcome of thoracic injuries. Parametric studies should also focus on vehicle-to-ground contact during the 2nd to 3rd and 4th quarter-turn to determine whether vehicle kinematics may be related to injurious lateral thoracic injuries at these points in the rollover phase. This study has also highlighted that an ATD with biofidelic oblique lateral impact response may be required for rollover crash testing and future studies should also be directed to this area. Thus, future studies may also consider using a WorldSID ATD as previous studies have indicated that this ATD is characterised by a more biofidelic response to oblique loading.[161]

7 Application of Flail-Space to Rollover Crash Kinematics

7.1 Introduction

The results from the rollover reconstruction in Chapter 6 identified where in the rollover sequence thoracic injuries may potentially be occurring. As such, an additional real-world rollover crash was selected for reconstruction in PC-CRASH.[31] The main purpose of this further investigation was to determine if, indeed, flailing of the torso into the door during a rollover crash event is the source of the thorax injuries that have been noted by previous researchers, noting that the door is the most frequently cited source of AIS3+ thoracic injuries.[12] In this study, the flail-space model results from Chapter 3 was used to determine if the occupant in a rollover vehicle crash was subjected to flailing velocities that could result in an AIS3+ thoracic injury based purely on rollover vehicle kinematics obtained from a PC-CRASH reconstruction. By performing this analysis without having to carry out a resource intensive FE analysis, confidence that injuries are caused by such flailing can provide the necessary evidence for design countermeasures. That is, acceleration thresholds at which side airbags and seatbelt pre-tensioners should be triggered to better restrain occupants in a rollover crash, thus reducing potential AIS3+ thoracic injuries.

7.2 Method

This study was performed in three steps. Firstly, a real-world rollover crash was selected for reconstruction. Secondly, PC-CRASH was then used to reconstruct the crash. Thirdly, the vehicle kinematics from PC-CRASH were analysed using the impact velocity versus AIS3+ thoracic injury likelihood outcome from the flail-space validation study in Chapter 3. These three steps are described in detail in the following subsections.

7.2.1 Selection of Rollover Crash Case

The NASS-CDS rollover crash cases from 2001 to 2012, inclusive, from Chapter 4 were obtained (Refer to Figure 4.1). However, some additional filtering criteria were added (Figure 7.1):

- AIS3+ injury occurred only to the thorax (i.e., no other body regions sustained an AIS3+ injury),
- the door interior was cited as the source of the injury ,
- the confidence level that the door interior was the source of the injury was "certain",
- the rollover occurred on a straight, dry and level environment and
- the rollover occurred on a sealed road surface.

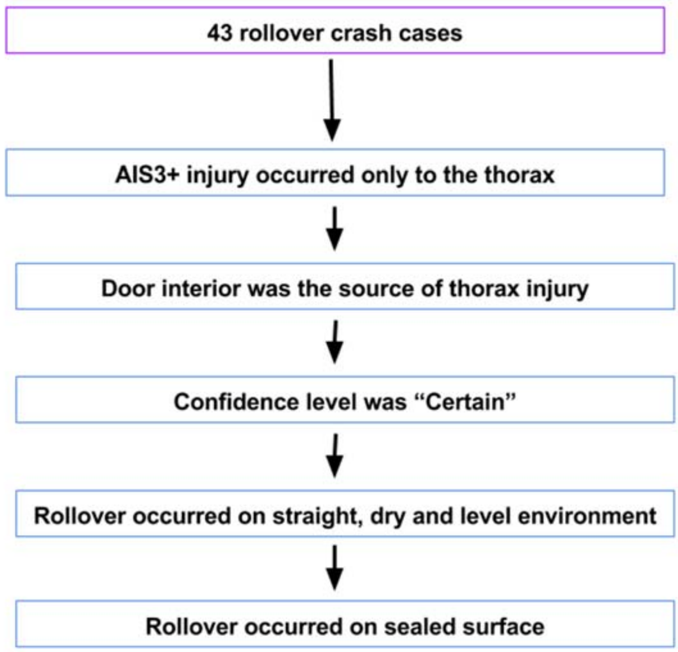


Figure 7.1 Filtering for rollover crash case

Filtering for AIS3+ injuries that occurred only to the thorax was performed to isolate the thorax from other frequently seriously injured body regions such as the head and neck. That is, the factors that may confound the aetiology of thoracic injuries were reduced.

In Chapter 4, the door interior was identified as the most frequently cited source of thoracic injuries and was, therefore, included in the filter. The confidence level of "certain" was also included in the filter in order to minimise the likelihood that the door interior was not actually the source of the thoracic injury.

Rollover crashes have been identified to occur most frequently on dry, straight and level environments [12] and was, therefore, included in the filter. Further, rollover crashes that occur on unsealed surfaces introduces additional variables that complicate crash simulations (e.g. coefficient of friction varies depending on the soil type), thus, were excluded in the filtering process.

It is noted that the filtering criteria shown in Figure 7.1 differs from the filtering criteria described in and used for the case selection in Chapters 4, 5 and 6. Further, the aforementioned filtering criteria shown in Figure 7.1 were not included in the filtering criteria in Chapter 6 since no rollover crashes would have satisfied these filtering criteria.

7.2.2 PC-CRASH Modelling

PC-CRASH was used to simulate the rollover crash. The reconstruction techniques outlined in Chapter 6 Section 6.3.4.1 were applied to this reconstruction; thus, will not be repeated here.

The vehicle's inertial properties can influence the vehicle trajectory and rollover kinematics. Therefore, accurate inertial properties for the Isuzu Rodeo were obtained from existing literature and applied to the vehicle model.[129]

7.2.3 Analysis of PC-CRASH Results

In order for an occupant to flail into vehicle interior components, there must be a significant change in a vehicle's lateral and roll velocity. Thus, the vehicle lateral and roll velocities at the vehicle CG from the reconstruction were plotted in PC-CRASH and each plot was then divided into segments that correlated with the vehicle quarter-turns. Significant changes in the vehicle's lateral and roll velocities that occurred during any of the vehicle quarter-turns were then identified. The change in vehicle lateral velocity, potentially resulting in the occupant flailing into the vehicle interior (Figure 7.2), was then calculated with the following equation:

$$delta\_V_{lateral} = v_2 - v_1 \qquad \text{Equation 7.1}$$

Where v_1 and v_2 are the initial and final lateral velocity, respectively, for the considered segment on the plot.

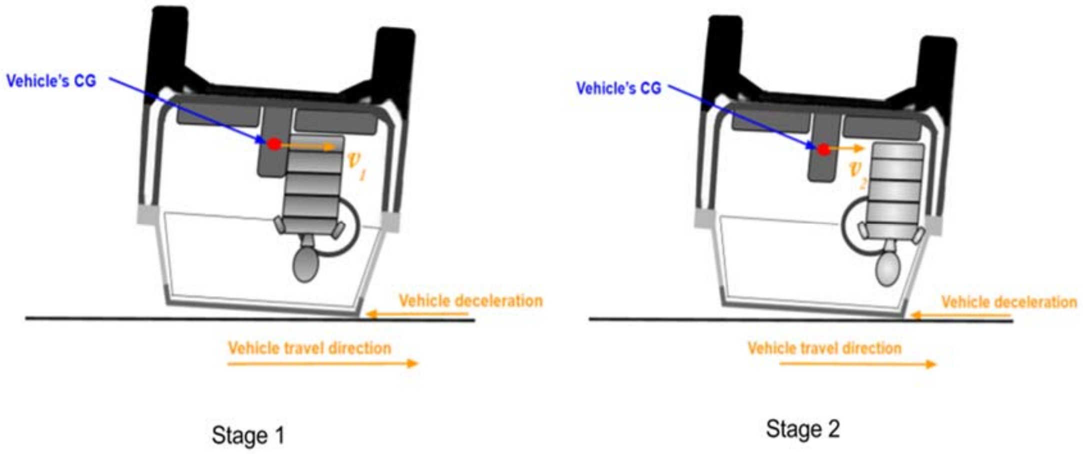


Figure 7.2 Change in vehicle lateral velocity resulting in occupant flailing into vehicle interior components,(view from the rear of vehicle)

The tangential velocity at which the occupant impacts the vehicle interior components due to a change in vehicle roll velocity (Figure 7.3) was calculated with the following equation:

$$delta\_V_{tangential} = (\omega_2 - \omega_1) \times r \qquad \text{Equation 7.2}$$

Where ω_1 and ω_2 are the initial and final vehicle roll velocity, respectively, for the considered segment on the plot and r is the radius arm, which is the distance from the vehicle CG to the level of occupant's thorax that impacts the vehicle interior (Figure 7.4), relative to a vehicle's frame of reference.

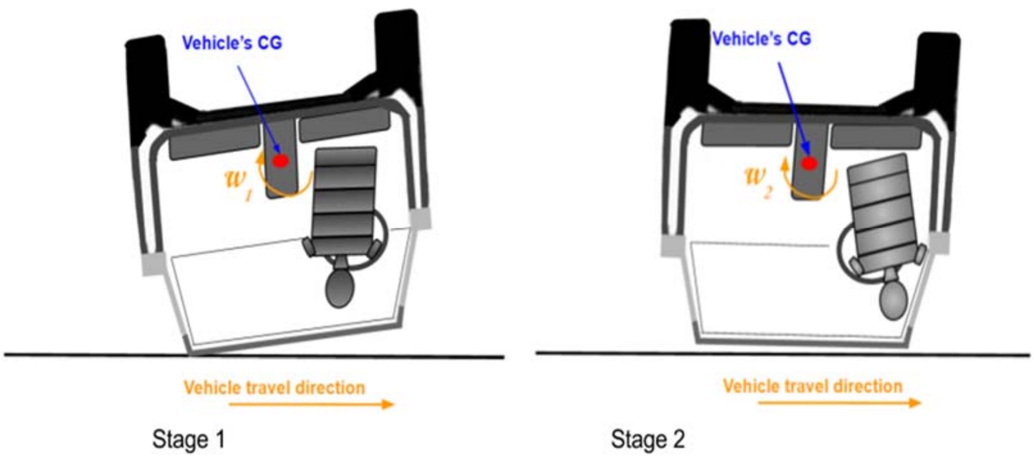


Figure 7.3 Change in vehicle roll velocity resulting in occupant flailing into vehicle interior components (viewed from the rear of vehicle)

It is noted that the tangential velocity at which the occupant impacts the vehicle door interior is dependent on the radius arm distance. Four radius arm distances were measured from the FE model in Chapter 6 and applied to this study, namely: 0.3, 0.4, 0.5 and 0.6 m (Figure 7.5). From Equation 7.2, it is also noted that an occupant seated in the driver's seat will flail towards the vehicle's door (i.e., outboard) if there is an increase in rotational velocity but will flail towards the vehicle CG (i.e., inboard) if there is a decrease in rotational velocity.

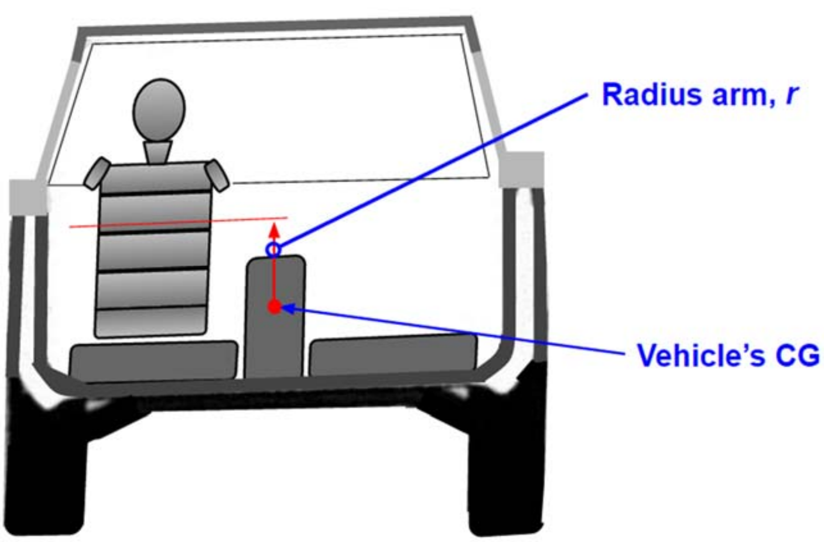


Figure 7.4 Radius arm for tangential velocity calculation

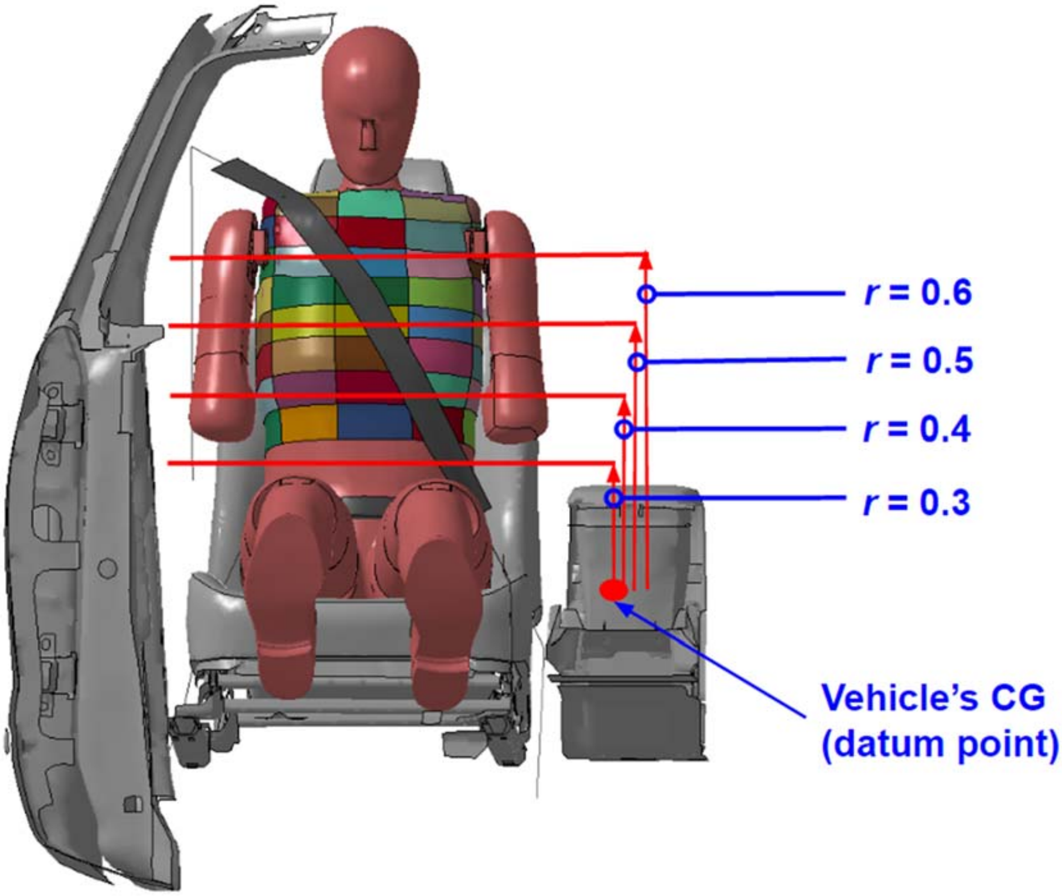


Figure 7.5 Considered radius arm distances from vehicle CG

The velocity with which the occupant impacts the vehicle interior components (i.e., flail velocity) (Figure 7.6) is then obtained by the summation of $delta\_V_{lateral}$ and $delta\_V_{tangential}$.

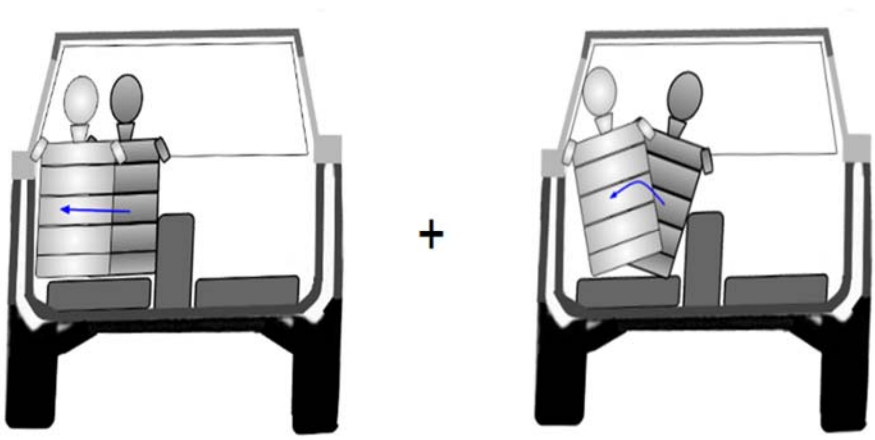


Figure 7.6 Occupant translating and pivoting

7.3 Results

7.3.1 Selection of Rollover Crash Case

Only two rollover crashes satisfied the filtering criteria shown in Figure 7.1, namely: NASS-CDS case number 2007-76-19 and NASS-CDS case number 2004-48-005

NASS-CDS case number 2007-76-19 was excluded for this study since this case file does not state the rollover distance and this information could not be determined from the scene diagram as it was not drawn to scale. Therefore, NASS-CDS case number 2004-48-005 was selected for this study.

7.3.2 Rollover Crash Case Description

The vehicle documented in the NASS-CDS case file 2004-48-005 (Figure 7.7 and Figure 7.8) was a 2001 Isuzu Rodeo travelling west at an estimated speed of 72 km/h. The road the vehicle was travelling on was a dry asphalt-sealed four-lane (two lanes in either direction) median-divided roadway. The vehicle tripped and rollover eight quarter-turns over a distance of 44 metres before coming to a stop (Figure 7.9).

Figure 7.7 View of vehicle from front left oblique angle

Figure 7.8 View of vehicle from front right oblique angle

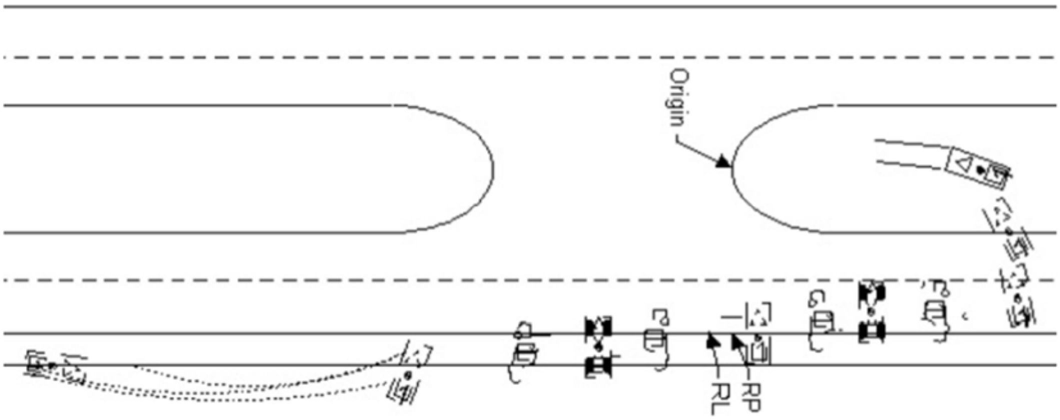


Figure 7.9 NASS-CDS scene diagram

The driver of the vehicle was a 26 year old female with a height and mass of 173 cm and 54 kg, respectively. The driver was the only occupant in the vehicle and sustained nine injuries including an AIS3 unilateral left lung contusion attributed to contact with the driver door interior (Table 7.1). It is noted from the NASS-CDS case report that the thoracic injury was not attributed to intrusion of the driver door into the occupant space.

Table 7.1 Summary of driver's injuries

Body Region	Injury	Aspect	AIS	Source	Confidence Level
Thorax	Lung contusion with or without hemo/pneumothorax	Left	3	Left door interior	Certain
Upper Extremity	Finger fracture	Left	1	Roof	Certain
Whole	Unconsciousness	N/A	1	Roof	Certain
Posterior	Cervical spine strain with no fracture or dislocation	N/A	1	Roof	Certain
Upper Extremity	Skin contusion	Left	1	Roof	Certain
Upper Extremity	Skin abrasion	Bilateral	1	Roof	Certain
Thorax	Skin contusion	Left	1	Left door interior	Certain
Lower Extremity	Skin abrasion	Bilateral	1	Knee bolster	Certain
Lower Extremity	Skin contusion	Bilateral	1	Knee bolster	Certain

7.3.3 PC-CRASH Modelling

The simulation in PC-CRASH resulted in the vehicle rolling over eight quarter-turns over a distance of 23.5 metres. The vehicle lateral and roll velocities are plotted in Figure 7.10 and Figure 7.11, respectively.

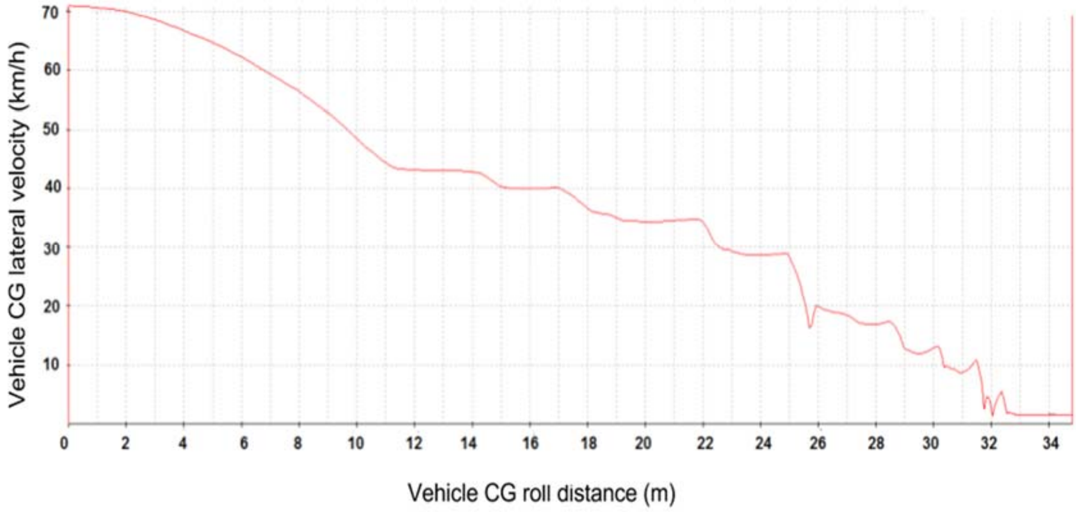


Figure 7.10 Vehicle velocity versus roll distance

Figure 7.11 Vehicle roll velocity versus roll distance

7.3.4 Analysis of PC-CRASH Results

A significant decrease in vehicle lateral velocity was observed to have occurred during the vehicle's 6th quarter-turn (Figure 7.12). The maximum and minimum vehicle lateral velocity during this quarter-turn was 26.27 km/h (7.30 m/s) and 16.26 km/h (4.52 m/s), respectively. This change in vehicle lateral velocity (i.e., $delta\_V_{lateral}$) is 10.01 km/h (2.78 m/s). Although the position of the occupant is not clear at this instance, for the purpose of this study, it was assumed that the driver was seated upright in the driver's seat. Given this condition, a change in vehicle lateral velocity during the 6th quarter-turn may have resulted in the driver flailing towards and impacting the driver's door interior (Figure 7.2).

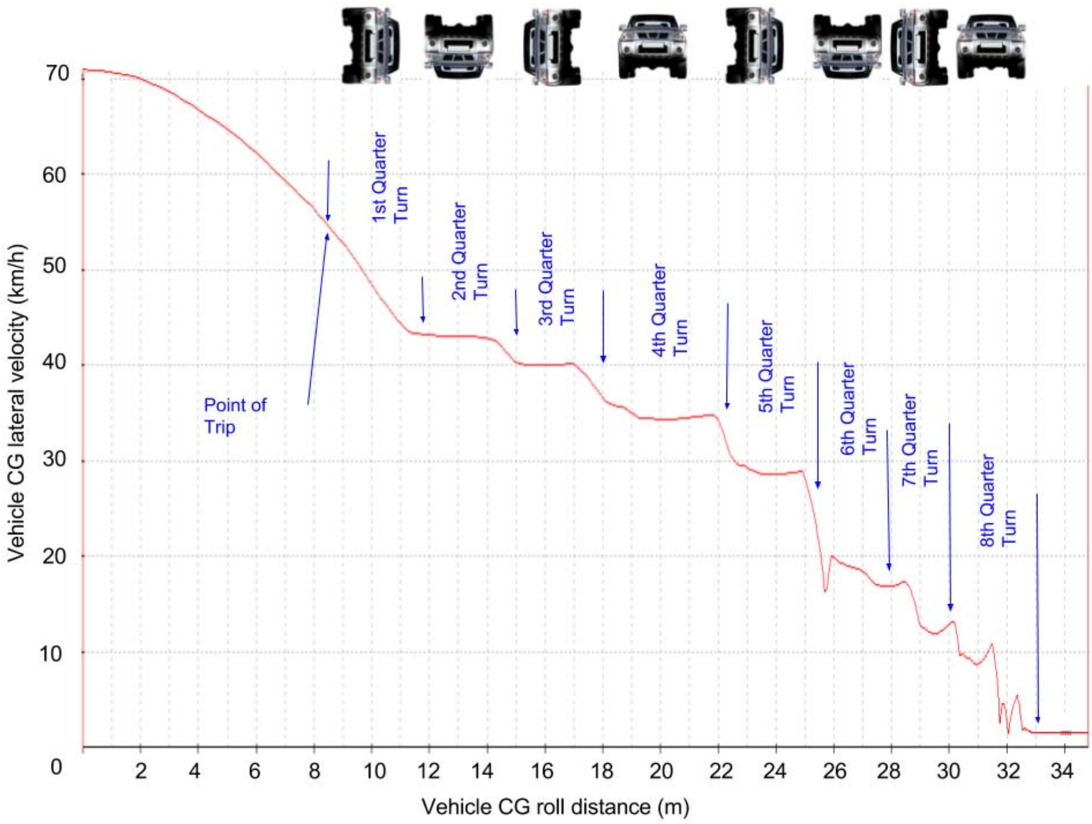


Figure 7.12 Vehicle velocity plot segmented into vehicle quarter-turns

A significant increase in vehicle roll velocity was observed during the vehicle's 6th quarter-turn (Figure 7.13). The minimum and maximum vehicle lateral roll velocity during this quarter-turn was 5.97 rad/s and 7.70 rad/s, respectively. This change in vehicle roll velocity during the 6th quarter-turn is 1.73 rad/s. Similar to the analysis for vehicle lateral velocity, it was assumed that the driver was seated upright in the driver's seat. Given this condition, the increase in vehicle roll velocity during the 6th quarter-turn may result in the driver flailing towards the driver's door interior (Figure 7.3). The results from the tangential velocity calculations (i.e., $delta\_V_{tangential}$), given the four radii distances outlined in Section 7.2.3, are presented in Table 7.2.

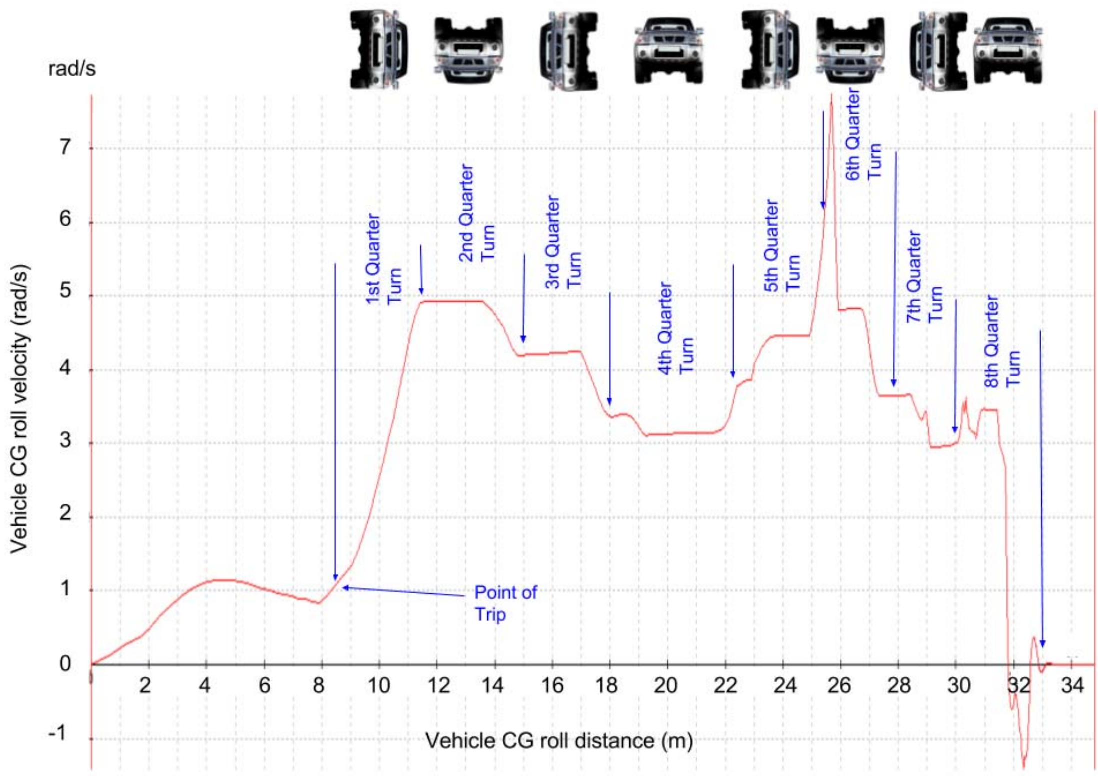


Figure 7.13 Vehicle roll velocity plot segmented into vehicle quarter-turns

Table 7.2 Tangential velocity

Radius Arm (m)	Tangential Velocity (m/s)
0.3	0.52
0.4	0.70
0.5	0.87
0.6	1.04

The tangential velocity and lateral velocity were then summed resulting in the flail velocity (Table 7.3). The corresponding likelihood of an AIS3+ thoracic injury was calculated using the results from the flail-space analysis from Chapter 3 (See Equation 3.6 and Figure 3.2).

Table 7.3 Flail velocity and AIS3+ thoracic injury likelihood

Radius arm (m)	**Tangential Velocity (m/s)**	**Vehicle Lateral Velocity (m/s)**	**Flail Velocity (m/s)**	**AIS3+ Thoracic Injury Likelihood**
0.3	0.52	2.78	3.30	0.14
0.4	0.70	2.78	3.47	0.16
0.5	0.87	2.78	3.65	0.17
0.6	1.04	2.78	3.82	0.19

The effect of gravity on the vehicle's vertical velocity was also investigated in the PC-CRASH simulation. It is noted that the vehicle was rolling on its roof during the 6th quarter-turn thus; the driver flailing into the vehicle's door interior due to gravity is not likely to have occurred as the driver was in an upside-down position. However, if gravity was considered on its own, a vehicle drop height of 2.08 m would be required in order for the vehicle to impact the ground with a velocity of 6.4 m/s (i.e., the impact velocity that is associated with a 50% likelihood of an occupant sustaining an AIS3+ thoracic injury as discussed in Chapter 3). Although PC-CRASH does not allow plotting of the height of the vehicle CG relative to the ground, a qualitative review of the simulation indicates that at no instance in the rollover sequence did the vehicle appeared to have reached a height greater than one metre above the ground level. Thus, gravity alone would not have caused the vehicle to impact the ground at a velocity of 6.4 m/s.

7.4 Discussion

The simulated vehicle roll distance of 23.5 metres was substantially less than the reported roll distance of 44 metres. A number of variables, such as vehicle-to-ground friction, vehicle velocity, steering input and braking, input were adjusted to increase the roll distance; however, it was not possible to increase the roll distance without a corresponding increase in vehicle quarter-turns.

The overlay of the NASS-CDS scene diagram with the results from the PC-CRASH simulation is presented in Figure 7.14. The simulation resulted in the vehicle rolling along the ground which, in turn, resulted in the shorter roll distance of 23.5 metres in comparison to the actual roll distance. The vehicle witness marks from the actual rollover crash (Figure 7.9) indicate that the vehicle had traversed a greater distance between each quarter roll than the vehicle in the simulation. This suggests that the actual rollover was not an over-the-ground rollover but, instead, an airborne rollover. A number of variables were adjusted to replicate an airborne rollover in PC-CRASH; however, it was not possible to simulate an airborne rollover. This appears to be a potential deficiency in PC-CRASH.

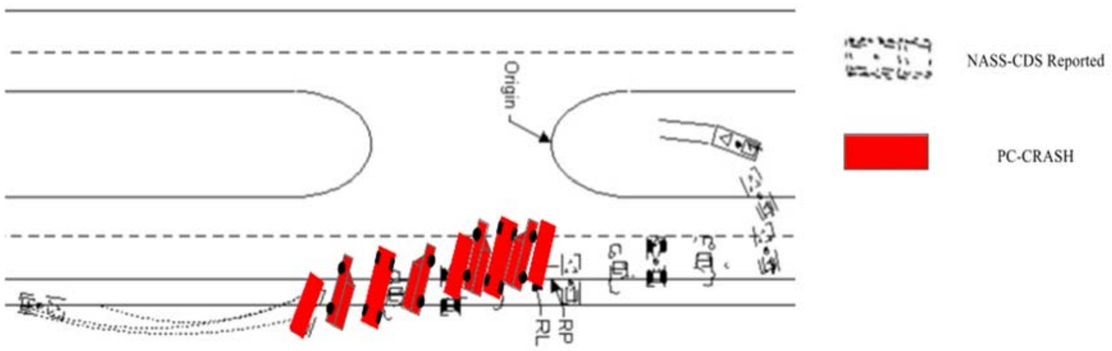


Figure 7.14 Overlay of NASS-CDS scene diagram and PC-CRASH simulation.

The results from the analysis of the PC-CRASH data indicate that the driver's AIS3+ thoracic injury would have occurred during the 6th quarter-turn. During this quarter-turn, the driver is likely to have sustained the AIS3+ thoracic injury by flailing into and impacting the driver's door interior.

Further, from Figure 7.7 it is noted that the vehicle sustained significant damage to the top of the driver's door during the rollover sequence. This damage is likely to have occurred while the vehicle was upside down (e.g. during the 6th quarter-turn) and resulted in significant change in the vehicle's kinematics, as shown in Figure 7.12 and Figure 7.13. This change in vehicle kinematics would have resulted in the driver flailing into and impacting the driver's door interior.

From Figure 7.8, it is noted that the bottom half of the driver's door did not sustain any damage from the rollover crash. This suggests that door intrusion into the occupant compartment did not cause the driver's thoracic injuries, as per NASS-CDS case report, but, rather, the driver flailing into and impacting the driver's door.

7.4.1 Limitations

A number of limitations were identified during the execution of this study. Firstly, the roll distance in the PC-CRASH simulation was significantly shorter than that of the real-world crash. Secondly, the NASS-CDS reported travel speed is estimated by crash investigators or law enforcement officials rather than obtained from rigorous computer reconstructions. This may have contributed to the difference in rollover distance between the real-world crash and the reconstruction. Thirdly, PC-CRASH could not simulate an airborne rollover to match the vehicle witness marks from the real-world crash. Fourthly, the driver's posture is not clear at the 6^{th} quarter-turn and the driver was assumed to be seated in an upright position in the driver's seat. Fifthly, it was assumed that the driver moved under their own inertia from stage 1, the start of the flail, to stage 2, the end of the flail (i.e., where the driver impacted the door interior). Sixthly, a FE model of an Isuzu Rodeo was not available, thus, an LS-DYNA reconstruction of this rollover crash could not be performed for detailed analysis.

7.5 Conclusion

A real-world rollover crash in which the driver sustained an AIS3+ thoracic injury attributed to an impact against the driver door interior was reconstructed in PC-CRASH. The plot of the simulated vehicle's lateral and roll velocity indicated that a significant change in both of these velocities occurred during the vehicle's 6^{th} quarter-turn. A tangential velocity was calculated from the vehicle roll velocity and summed with the vehicle's lateral velocity, thus, resulting in a flail velocity. The findings from Chapter 3 were then applied to the flail velocity. The result of this analysis indicates that the driver is likely to have sustained an AIS3+ thoracic injury during the vehicle's 6^{th} quarter-turn.

This study demonstrates how the results from the flail-space study from Chapter 3 can be applied to the motion of a rollover vehicle to evaluate the likelihood of AIS3+ thoracic injuries occurring through a reconstruction of rollover crash without having to carry out a resource intensive FE analysis.

Further, the observations from this study indicate that rollover crashes should be separated into over-the-ground and airborne rollovers in future investigations. The kinematics between these two rollover types may be vastly different to each other.

8 Summary, Conclusions and Recommendations

Serious thoracic injuries are one of the most frequently occurring injuries in tripped rollover passenger vehicle crashes.[12, 13, 93, 118, 125, 126] While studies have been performed to understand vehicle kinematics in rollover crashes [6, 8, 11, 37, 56, 65, 93, 116, 123] and epidemiology of rollover crashes [12, 27, 30, 33, 35, 43, 93, 97, 117, 153], few studies have been performed to understand the aetiology of thoracic injuries resulting from vehicle rollover crashes [70, 139]. As such, this thesis investigated and develops a better understanding of the aetiology of thoracic injuries resulting from single-vehicle rollover crashes where the occupant is restrained by a seatbelt and contained within the vehicle. This was achieved through the three aims of this thesis, which are reiterated below:

1) Develop a potential injury criterion for determining the likelihood of a serious thoracic injury occurring in a rollover crash based on thoracic lateral impact velocity.

2) Determine if the distribution of thoracic injuries and thoracic injury sources differs based on the occupant seated position and rollover direction.

3) Determine if significant rollover vehicle damage and, thus, a marked decrease in vehicle velocity at the moment when the vehicle impacts the ground, is associated with an occupant sustaining thoracic injuries.

The aims were achieved through a series of studies. In the first study, the lateral impact velocity from the flail-space model was validated against PMHS side-impact crash test data. This was performed in order to provide an injury assessment tool for further analysis of rollover crashes where serious thoracic injuries have occurred and addressed the first aim of this thesis. In the second study, the pathology of thoracic injuries was identified based on occupant seated position and vehicle rollover direction. This addressed the second aim of this thesis. In the third study, the association between vehicle damage and serious thoracic injuries were identified. In the fourth and fifth studies, the findings from the aforementioned studies were then applied to two computer simulation of real-world rollover crashes to study thoracic injury aetiology. The results from the computer simulations addressed the third aim and also indicate that sudden changes in vehicle kinematics can, indeed, result in a vehicle occupant in a rollover crash sustaining serious thoracic injuries. Thus, this key finding addressed the hypothesis of this thesis which is: *AIS3+ thoracic injuries are occurring when an occupant flails into and impacts vehicle interior components due to a sudden change in vehicle rollover kinematics.* The new findings from each of the aforementioned studies, summarised in greater detail below, will assist with future research in thoracic injury aetiology in rollover crashes.

In Chapter 3, data from 131 PMHS side-impact crash tests were consolidated into one data set. Multiple variable logistic regression analysis was performed on the consolidated data set to determine the variables associated with a PMHS sustaining AIS3+ and AIS4+ thoracic injuries. From this analysis, impact velocity, PMHS age and impact wall interface were all found to be significant variables for both the AIS3+ and AIS4+ models. These findings confirm results from previous studies that had reported PMHS age [76] and padding [67, 82] are significant variables associated with thoracic injury response.

Two single variable logistic regression models were then developed with thorax impact velocity and its association with AIS3+ and AIS4+ thoracic injury outcome. These two models were used to validate flail-space's lateral impact velocity criterion. The results from the single variable logistic regression models indicates that the current flail-space lateral occupant impact velocity of 9 m/s and 12 m/s result in a 85% and 67% likelihood of an occupant sustaining AIS3+ and AIS4+ thoracic injuries, respectively. This likelihood of an AIS3+ and AIS4+ is high and a lower impact velocity of 6.4 m/s is proposed, which corresponds to a 53% and 18% likelihood of sustaining an AIS3+ and AIS4+ thoracic injury, respectively.

The study documented in Chapter 3 is the first to validate the lateral component of the flail-space model against the risk of thoracic injuries. Future research should be directed into validating the acceleration based criterion for the flail-space model and also whole body response.

In Chapter 4, the distribution of thoracic injuries and their sources based on occupant seated position and vehicle rollover direction was explored. NASS-CDS data from 2001 to 2012, inclusive, were queried for rollover crashes where the vehicle was a passenger car or utility vehicle involved in a single-vehicle tripped rollover crash with at least one quarter rollover or more where the vehicle did not contact another object prior to, during or after rolling over; no airbags were deployed; the occupant was a front seat occupant of 16 years or older; the occupant was restrained and contained in the vehicle and the occupant sustained at least one AIS3+ thoracic injury. This query returned 43 cases.

An empirical analysis was then performed on the data to determine the distribution of thoracic injuries and thoracic injury sources based on occupant seated position and vehicle rollover direction. From this analysis, the left door interior and seatbelt were the two most frequently, and almost equally, coded injury sources for driver far-side rollovers. This was followed by the steering wheel, centre console and the seatback. For driver near-side rollovers, the left door interior was, by far, the most frequently coded source of injury followed by the seatback, seatbelt, steering wheel and centre console.

There were significantly less rollover crashes involving front seated passengers for both near- and far-side rollovers. As a result of this, no firm conclusions can be drawn based on the available data for these occupants.

These results indicate that occupant seated position and vehicle rollover direction need to be considered when performing rollover crash reconstruction for thoracic injury aetiology studies.

This study is a first in determining if thoracic injuries are different for near- and far-side rollover occupants. Future studies should be performed to determine if similar findings are observed for front seated passengers when significantly more data becomes available for these occupants.

In Chapter 5, a case-control study was performed to determine whether there was a correlation between vehicle damage and thoracic injury. NASS-CDS data from 2001 to 2012, inclusive, was queried with the same criteria described in Chapter 4. Cases consisted of rollover crashes where an occupant had sustained at least one AIS3+ thoracic injury while controls were rollover crashes where an occupant had not sustained any thoracic injuries. A total of 43 cases and 181 controls were used in this study.

Empirical analysis was first performed on the case and control data set. Utility vehicles were found to be involved in a greater proportion of cases than controls, a finding similar to that of previous studies.[26, 101, 123] Cases were also observed to have occurred on a dry surface more frequently than that of controls, a similar finding to that of Bambach *et al*.[12]

Multiple variable logistic regression was then performed to determine whether there was an association between vehicle damage and rollover variables and thoracic injuries. To accomplish this objective, the vehicle body was divided into 11 segments and damage to each segment was coded as either major damage or no to minor damage. The rollover variables included in the analysis consisted of number of vehicle quarter-turn rollovers, rollover location, vehicle category and surface condition.

The results from the analysis indicated that three variables and three vehicle segments are associated with an increase in odds of a rollover vehicle occupant sustaining serious thoracic injuries.

An increase in the number of vehicle quarter-turn rollovers is associated with increased odds in an occupant sustaining a thoracic injury and is similar to findings from previous studies.[12, 93, 153] This is likely due to higher velocity and/or crash energy and greater likelihood for occupant to impact vehicle interior.

Utility vehicles were found to be associated with increased odds in an occupant sustaining thoracic injuries, similar to findings from previous studies.[12] This is most likely due to the geometrically higher aspect ratios of utility vehicles compared to passenger cars resulting in a higher deceleration rate as the vehicle rolls.

Rollover crashes that occurred off the roadway were also found to be associated with higher odds of an occupant sustaining a thoracic injury. This is most likely due to the higher friction forces that occur when a vehicle furrows into the soft surface [3, 155] resulting in a higher deceleration compared to a rollover crash that occurs on a paved surface.

The three vehicle segments associated with an occupant sustaining a thoracic injury were the left door upper half, left half of the vehicle rearwards of the B-pillar and the right door upper half. These vehicle segments impacting the ground during the rollover sequence may be associated with a change in vehicle kinematics while the occupant travels in the vehicle at the pre-impact velocity. This difference in velocity between the vehicle and occupant is likely to result in the occupant impacting the vehicle interior components which, in turns, may result in a serious thoracic injury.

Future research on vehicle damage and its association with thoracic injuries should also be performed with the vehicle divided into smaller segments with a larger number of cases to confirm the findings of this study. Future studies could also include vehicle roof strength-to-weight ratio and its association with serious thoracic injuries.

In Chapter 6, a real-world NASS-CDS documented rollover crash in which the driver sustained serious thoracic injuries was simulated in LS-DYNA using a model of a EuroSID-2re ATD to model the driver. The simulation was performed to develop an understanding of thoracic injury aetiology and to determine where in the rollover sequence the injury occurred.

The likelihood of thoracic injury was evaluated with existing lateral thoracic injury criteria and the findings from the lateral flail-space model analysis from Chapter 3. From the computer simulation, the ATD was observed to have impacted the centre console at the end of the 4th quarter-turn. The analysis of this impact with the findings from Chapter 3 indicates that the driver’s serious thoracic injuries are likely to have occurred due to this impact, a similar finding to that of Tahan *et al.* [139] This instance in the rollover sequence was observed to also correspond to a significant decrease in vehicle lateral velocity thus, supports the hypothesis of this thesis. That is, serious thoracic injuries may be occurring an occupant flails into and impacts vehicle interior components due to a sudden change in vehicle kinematics.

The ATD was observed to have the potential of impacting the vehicle door interior at the end of the 2nd and the start of the 3rd quarter-turn. This coincided with a significant decrease in vehicle lateral velocity and vehicle damage to the top half of the left door. This vehicle segment damage was found to be associated with an occupant sustaining serious thoracic injury in Chapter 5.

These two observations indicate that future research should be directed to these two instances in the rollover sequence. Future research may also consider varying vehicle lateral velocity, roll rate, pitch and yaw at these instances in the rollover sequence as guided by other studies that have reported real world figures for these variables.

The result of the simulations also indicates that the likelihood of an occupant sustaining lateral thoracic injury is sensitive to the initial position of the ATD at the point of trip. Further, the torso was also observed to rotate about the ATD's z-axis during the rollover sequence and the torso's contact with the centre console was not a pure lateral contact but, rather, an oblique contact. These observations indicate that ATDs for rollover crash testing needs to be developed for oblique impacts. Further, future research should also be performed to determine if occupants pivot about the z-axis similar to that observed with the ATD.

This study was innovative in a number of areas. Firstly, it is the first time that a side-impact ATD has been used in a computer rollover simulation. It is also the first time that rotation about the ATD's z-axis during a rollover sequence has been observed and reported. Finally, it is also the first time that oblique thoracic impacts against vehicle interior during a rollover crash has been observed and report. This observation raises the question whether previously reported lateral thoracic injuries are occurring due to purely lateral impacts against vehicle interior component.

In Chapter 7, a study was performed to further the findings of Chapter 6. The study applied the findings from the flail-space validation study from Chapter 3 to overall vehicle kinematics to identify other instances in the rollover sequence where serious thoracic injuries may be occurring. Additionally, the findings in Chapter 4 indicate that the most frequently cited source of serious thoracic injuries is the vehicle door interior. As such, the study also sought to develop an understanding as to where serious thoracic injuries due to impact with the door interior may be occurring in the rollover sequence.

The study reconstructed a NASS-CDS real-world rollover crash in which an occupant sustained a serious thoracic injury, attributed to the vehicle door interior, in PC-CRASH. A significant change in the vehicle's lateral and roll velocities were observed during the 6^{th} quarter-turn. The summation of the vehicle lateral and roll velocity from the 6^{th} quarter-turn and evaluating this resultant flail velocity with the flail-space findings from Chapter 3 indicates that the driver's serious thoracic injury may have occurred during the 6^{th} quarter-turn. This injury is also likely to be the result of the driver impacting against the driver's door interior. This finding further supports the hypothesis of this thesis. That is, serious thoracic injuries may be occurring as an occupant flails into and impacts vehicle interior components due to a sudden change in vehicle kinematics.

The results from the PC-CRASH simulation also indicate that rollover crashes may need to be separated into over-the-ground and airborne rollovers crashes. The vehicle kinematics from these two categories of rollover crashes may differ substantially from each other and should be explored in future studies.

The findings of this thesis are significant for a number of reasons. Firstly, flail-space lateral impact velocity has been validated against PMHS testing. As a result of this, a model for serious lateral thoracic injuries as a function of lateral thoracic impact velocity has been developed. This model can be applied to future rollover crash testing for thoracic injury aetiology investigation. Secondly, it has been demonstrated that serious thoracic injury pathology and sources of these injuries differ depending on the occupant seated position and vehicle rollover direction. This needs to be considered when studying thoracic injury aetiology in rollover crashes. Thirdly, previous hypothesis that vehicle damage as a result of a rollover crash may be associated with an occupant sustaining serious thoracic injuries has been validated. Fourthly, two instances in the rollover sequence have been identified where there is potential for serious thoracic injuries to occur. That is, when the vehicle lands on its wheels and when the vehicle's roof contacts the ground while upside-down. Fifthly, thoracic impacts against vehicle interior components may occur at an oblique angle rather than purely laterally. Sixthly, sudden changes in vehicle kinematics can result in an occupant flailing and impacting against vehicle interior components and receiving serious thoracic injuries.

A number of general countermeasures should be applied to reduce the risk of serious thoracic injuries from occurring from rollover crashes while further research is performed to develop a more comprehensive understanding of these injuries. Firstly, the flailing of occupants within the vehicle interior during a rollover crashes should be minimised by the activation of seatbelt pre-tensioners. Secondly, occupant ejection and contact with vehicle interior components should be prevented through the deployment of side and curtain airbags which remain inflated for the duration of the rollover crash. Thirdly, the occupant survival space of a vehicle during a rollover crash needs to be preserved through the design of strong vehicle roofs. These countermeasures are, essentially, de Haven's crashworthiness principles.[32] Further, these countermeasures are already implemented for frontal and side impact crashes and need to be actuated for all new vehicles in the event of a rollover crash. This is a simple task as side and curtain airbags and seatbelt pre-tensioners already exists in modern New Car Assessment Program (NCAP) "Five-star" and the Insurance Institute for Highway Safety (IIHS) "Good" rated passenger vehicles. Similarly, roof strength is already tested by IIHS.

This thesis has advanced the knowledge of thoracic injury aetiology in rollover crashes; however, injuries to the thorax remain under-researched considering that the thorax is the second most frequently injured body regions in a rollover crash. In order to reduce the frequency of fatal and serious thoracic injuries in rollover crashes, more research needs to be directed to this area. This should also include assessing whether the above recommended countermeasures are effective in reducing serious thoracic injuries. It is from an more comprehensive understanding of thoracic injury aetiology that specific thoracic injury mitigating solutions can be developed, thus, reducing the number and extent of these type of injuries in rollover crashes. Through a reduction in fatal and serious thoracic injuries, alongside a reduction in head and neck injuries, rollover crashes may no longer be over-represented in the overall crash statistics in the future. Consequently, this reduction will also contribute to the overall reduction in road fatality rates.

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10 Appendix

Appendix A The Abbreviated Injury Scale

The Abbreviated Injury Scale (AIS) was developed in the 1970s as a system to code injuries through a series of numerical identifiers. The AIS has been updated in 1980, 1985, 1990, 1998 and 2005. [52] The code consists of a series of six digit numerical code, located to the left of a decimal point, which is used to identify the body region injured. A single digit numerical code, located to the right of a decimal point, assigns a severity rank from 0, indicating no injury, to 6, indicating maximum injury (Table A.1). [51]

The Maximum AIS (MAIS) injury is the injury with the highest severity rank in a patient which has sustained multiple injuries.

Table A.1 AIS injury severity rank (Source: AAAM)

AIS Injury Severity Rank	Description
0	No injury
1	Minor injury
2	Moderate injury
3	Serious injury
4	Severe injury
5	Critical injury
6	Maximum injury
9	Unknown

Appendix B NASS-CDS Description

The National Automotive Sampling System (NASS) Crashworthiness Data System (CDS) is a national crash data collection program operated by the United States' National Highway Traffic Safety Administration (NHTSA).

Each year, the NASS-CDS selects approximately 5,000 crashes to be included in the sample. In order for a crash considered for inclusion in the sample, it must satisfy the following criteria:

1) The crash must be reported to the police,

2) The crash result in property damage and/or personal injury, and

3) The crash must involve at least one towed vehicle which is a passenger car, light truck, utility or can.

Once a crash has been selected, trained crash investigators obtain data from the crash site, photograph the crash site, locate and photograph the vehicle(s) involved, measure the crash damage and identify vehicle interior components impacted by the vehicle occupants. The crash investigators also interview crash victims and review medical records to determine the nature and severity of the injuries.

The NASS-CDS is a probability sample of all police reported crashes in the United States and is stratified by geographical regions. Within each region a sample of police jurisdictions are selected and within each police jurisdiction a number of crash cases selected. Crash cases are selected based on crash type and severity. Each crash case is allocated a weighting factor, $n_{weighted}$, from which national estimates can be calculated. However, the national estimates may differ from the actual values because each crash is based on a probability sample rather than a census of all crashes. [95]

Appendix C   Flail-Space Study Test Cases Details

The following table lists all the studies used in the flail-space model study, the impact wall interface, test method, impact velocity, PMHS mass, PMHS age and thorax AIS.

Reference	Test Number	Impact Wall Interface	Test Method	Impact Velocity (m/sec)	PMHS Mass (kg)	PMHS Age (years)	Thorax AIS
Cavanaugh *et al*. (1993)	4	Rigid Wall	Sled	9.00	57.6	69	4
Cavanaugh *et al*. (1993)	5	Rigid Wall	Sled	6.70	44	67	4
Cavanaugh *et al*. (1993)	6	Rigid Wall	Sled	9.00	61.2	60	4
Cavanaugh *et al*. (1993)	7	Rigid Wall	Sled	6.70	74.8	66	4
Cavanaugh *et al*. (1993)	8	Rigid Wall	Sled	6.70	73.9	64	5
Cavanaugh *et al*. (1993)	9	ARSAN Pad	Sled	9.00	54.9	61	5
Cavanaugh *et al*. (1993)	10	Paper Honeycomb - 6"	Sled	9.00	62.1	60	2
Cavanaugh *et al*. (1993)	11	Paper Honeycomb - 4"	Sled	9.00	55.3	54	2
Cavanaugh *et al*. (1993)	12	Paper Honeycomb - 4"	Sled	9.00	54.4	68	5
Cavanaugh *et al*. (1993)	13	Paper Honeycomb - 4"	Sled	9.00	66.7	62	4
Kallieris & Mattern (1986)	8011	Rigid Wall	Sled	6.67	89	27	0
Kallieris & Mattern (1986)	8013	Rigid Wall	Sled	6.94	95	33	3
Kallieris & Mattern (1986)	8014	Rigid Wall	Sled	6.39	84	60	3
Kallieris & Mattern (1986)	8017	Rigid Wall	Sled	6.67	70	38	3
Kallieris & Mattern (1986)	8018	APR pad	Sled	8.61	61	21	3
Kallieris & Mattern (1986)	8020	APR pad	Sled	8.33	67	26	1
Kallieris & Mattern (1986)	8021	HNCB pad	Sled	8.89	63	29	0
Kallieris & Mattern (1986)	8023	HNCB pad	Sled	9.17	82	41	3
Kallieris & Mattern (1986)	8024	Rigid Wall	Sled	9.17	65	24	0
Kallieris & Mattern (1986)	8102	Rigid Wall	Sled	9.17	65	57	4
Kallieris & Mattern (1986)	8104	Rigid Wall	Sled	8.89	80	56	4
Kallieris & Mattern (1986)	8106	Rigid Wall	Sled	8.89	82	37	3
Kallieris & Mattern (1986)	8111	HNCB pad	Sled	8.89	59	43	0
Kallieris & Mattern (1986)	8112	HNCB pad	Sled	8.89	46	33	3
Kallieris & Mattern (1986)	8115	HNCB pad	Sled	6.39	73	44	0
Kallieris & Mattern (1986)	8116	Rigid Wall	Sled	11.11	77	22	4
Kallieris & Mattern (1986)	8121	HNCB pad	Sled	8.89	57	48	0

Kallieris & Mattern (1986)	8122	Rigid Wall	Sled	11.11	76	23	4
Kallieris & Mattern (1986)	8125	Rigid Wall	Sled	8.89	65	38	4
Kallieris & Mattern (1986)	8127	Rigid Wall	Sled	11.11	77	30	3
Kallieris & Mattern (1986)	8202	Rigid Wall	Sled	8.89	68	47	4
Kallieris & Mattern (1986)	8208	APR pad	Sled	8.61	99	61	0
Kallieris & Mattern (1986)	8209	Rigid Wall	Sled	11.11	51	27	5
Kallieris & Mattern (1986)	8212	Rigid Wall	Sled	11.11	75	17	5
Kallieris & Mattern (1986)	8214	Rigid Wall	Sled	8.89	61	22	4
Kallieris & Mattern (1986)	8215	Rigid Wall	Sled	6.39	69	18	1
Kallieris & Mattern (1986)	8216	Rigid Wall	Sled	8.61	50	21	3
Kallieris & Mattern (1986)	8218	Rigid Wall	Sled	6.39	85	28	3
Kallieris & Mattern (1986)	8219	Rigid Wall	Sled	6.39	67	47	3
Kallieris & Mattern (1986)	8220	Rigid Wall	Sled	8.61	73	41	4
Kallieris & Mattern (1986)	8221	APR pad	Sled	8.89	99	48	4
Kallieris & Mattern (1986)	8222	APR pad	Sled	8.89	77	50	4
Kallieris & Mattern (1986)	8308	Volvo Door	Sled	4.44	78	45	0
Kallieris & Mattern (1986)	8310	6" Ensolite Padded	Sled	7.50	56	30	0
Kallieris & Mattern (1986)	8311	12" Ensolite Padded	Sled	8.61	61	26	0
Kallieris & Mattern (1986)	8312	6" Ensolite Padded	Sled	8.89	77	34	0
Kallieris & Mattern (1986)	8316	Volvo Door	Sled	9.72	68	52	4
Kallieris & Mattern (1986)	8320	12" Ensolite Padded	Sled	8.61	52	17	0
Kallieris & Mattern (1986)	8321	Volvo Door	Sled	10.00	58	38	4
Kallieris & Mattern (1986)	8330	Volvo Door	Sled	5.28	86	42	0
Kallieris & Mattern (1986)	8331	Volvo Door	Sled	7.50	62	43	3
Kallieris & Mattern (1986)	8405	2" Ensolite Padded	Sled	8.89	64	79	4
Kuppa *et al* (2000)	3320	Padded Wall	Sled	8.89	74	82	4
Kuppa *et al* (2000)	3321	Padded Wall	Sled	8.89	42	75	4
Kuppa *et al* (2000)	3322	Rigid Wall	Sled	8.89	72	73	4
Kuppa *et al* (2000)	3323	Padded Wall	Sled	8.89	81	59	4
Kuppa *et al* (2000)	3324	Rigid Wall	Sled	8.89	75	77	4
Kuppa *et al* (2000)	3325	Rigid Wall	Sled	8.89	61	63	4
Kuppa *et al*. (2004)	SC101	Rigid Wall	Sled	6.67	89	73	4
Kuppa *et al*. (2004)	SC102	Rigid Wall	Sled	6.67	72	27	0
Kuppa *et al*. (2004)	SC103	Rigid Wall	Sled	6.67	76	55	3
Kuppa *et al*. (2004)	SC105	Rigid Wall	Sled	6.67	71	70	0
Kuppa *et al*. (2004)	SC106	Padded Wall	Sled	6.67	64	56	2
Kuppa *et al*. (2004)	SC107	Padded Wall	Sled	8.89	93	50	2
Kuppa *et al*. (2004)	SC108	Rigid Wall	Sled	8.89	83	44	2
Kuppa *et al*. (2004)	SC109	Rigid Wall	Sled	8.89	62	49	4

Kuppa *et al*. (2004)	SC114	Padded Wall	Sled	8.89	100	63	4
Kuppa *et al*. (2004)	SC115	Padded Wall	Sled	6.67	66	72	4
Kuppa *et al*. (2004)	SC116	Padded Wall	Sled	8.89	76	67	3
Kuppa *et al*. (2004)	SC119	Padded Wall	Sled	6.67	42	75	3
Kuppa *et al*. (2004)	SC120	Rigid Wall	Sled	6.67	74	67	0
Kuppa *et al*. (2004)	SC121	Rigid Wall	Sled	6.67	67	86	3
Kuppa *et al*. (2004)	SC122	Padded Wall	Sled	6.67	53	79	1
Kuppa *et al*. (2004)	SC123	Padded Wall	Sled	6.67	63	62	3
Kuppa *et al*. (2004)	SC124	Rigid Wall	Sled	6.67	63	45	0
Kuppa *et al*. (2004)	SC131	Rigid Wall	Sled	6.67	75	48	4
Kuppa *et al*. (2004)	SC132	Padded Wall	Sled	8.89	73	65	4
Kuppa *et al*. (2004)	SC133	Padded Wall	Sled	8.89	74	73	4
Kuppa *et al*. (2004)	SC134	Padded Wall	Sled	8.89	62	58	3
Kuppa *et al*. (2004)	SC135	Rigid Wall	Sled	6.67	62	56	4
Kuppa *et al*. (2004)	SC136	Padded Wall	Sled	6.67	61	54	2
Kuppa *et al*. (2004)	SC137	Padded Wall	Sled	6.67	50	73	2
Kuppa *et al*. (2004)	SC138	Padded Wall	Sled	6.67	48	58	3
Marcus *et al*. (1983)	H-82008	Padded Wall	Sled	8.75	99	61	4
Marcus *et al*. (1983)	H-82009	Rigid Wall	Sled	11.31	51	27	5
Marcus *et al*. (1983)	H-82012	Rigid Wall	Sled	11.31	75	17	5
Marcus *et al*. (1983)	H-82014	Rigid Wall	Sled	9.08	61	22	4
Marcus *et al*. (1983)	H-82015	Rigid Wall	Sled	6.53	69	18	1
Marcus *et al*. (1983)	H-82016	Rigid Wall	Sled	8.75	50	21	2
Marcus *et al*. (1983)	H-82018	Rigid Wall	Sled	6.53	85	28	3
Marcus *et al*. (1983)	H-82019	Rigid Wall	Sled	6.53	67	47	3
Marcus *et al*. (1983)	H-82020	Rigid Wall	Sled	8.75	73	41	4
Marcus *et al*. (1983)	H-82021	Padded Wall	Sled	9.08	99	48	4
Marcus *et al*. (1983)	H-82022	Padded Wall	Sled	9.08	77	50	4
Melvin *et al*. (1976)	003	Rigid Wall	Sled	6.94	102.1	60	2
Melvin *et al*. (1976)	009	Rigid Wall	Sled	11.94	44.1	75	6
Melvin *et al*. (1976)	010	Rigid Wall	Sled	9.17	87.8	84	4
Melvin *et al*. (1976)	011	Rigid Wall	Sled	9.17	74.9	69	4
Melvin *et al*. (1976)	029	Padded Wall	Sled	6.34	62.5	67	3
Melvin *et al*. (1976)	039	Padded Wall	Sled	9.17	73.9	72	4
Melvin *et al*. (1976)	042	Padded Wall	Sled	11.94	64.5	58	4
Pintar *et al*. (1997)	OSU 577	Rigid Wall	Sled	8.89	52	74	4
Pintar *et al*. (1997)	OSU 578	Rigid Wall	Sled	8.89	51	73	4
Pintar *et al*. (1997)	OSU 579	Rigid Wall	Sled	8.89	98	68	4
Pintar *et al*. (1997)	OSU 580	10 cm Padded Wall	Sled	8.89	56	75	3

Pintar *et al*. (1997)	OSU 581	10 cm Padded Wall	Sled	8.89	45	80	4
Robbins *et al* (1979)	76T034	Simulated Research	Sled	8.94	59	62	4
Robbins *et al* (1979)	76T062	Rigid Wall	Pendulum	4.25	50.1	69	5
Robbins *et al* (1979)	76T065	Rigid	Pendulum	4.25	94.7	63	1
Robbins *et al* (1979)	76T071	Rigid	Pendulum	4.25	80.7	60	1
Robbins *et al* (1979)	76T074	Rigid	Pendulum	4.25	54	60	2
Robbins *et al* (1979)	76T077	Rigid	Pendulum	6.08	73.7	79	3
Robbins *et al* (1979)	76T080	Rigid	Pendulum	6.08	40.8	64	4
Robbins *et al* (1979)	76T095	Flat Padded Wall	Sled	8.94	92.8	77	4
Robbins *et al* (1979)	76T098	Flat Padded Wall	Sled	8.94	59	71	4
Viano *et al*. (1989)	2	Rigid	Pendulum	9.40	107	49	4
Viano *et al*. (1989)	3	Rigid	Pendulum	8.70	44	76	4
Viano *et al*. (1989)	4	Rigid	Pendulum	5.99	69.85	63	3
Viano *et al*. (1989)	5	Rigid	Pendulum	6.48	56.25	38	2
Viano *et al*. (1989)	7	Rigid	Pendulum	6.73	56.25	66	3
Viano *et al*. (1989)	9	Rigid	Pendulum	6.71	61.69	64	3
Viano *et al*. (1989)	11	Rigid	Pendulum	6.71	76.2	40	3
Viano *et al*. (1989)	14	Rigid	Pendulum	8.30	70.76	49	3
Viano *et al*. (1989)	17	Rigid	Pendulum	5.50	70.3	29	0
Viano *et al*. (1989)	18	Rigid	Pendulum	9.70	70.3	29	4
Viano *et al*. (1989)	29	Rigid	Pendulum	5.20	83.91	52	0
Viano *et al*. (1989)	33	Rigid	Pendulum	9.70	53.07	52	4
Viano *et al*. (1989)	36	Rigid	Pendulum	4.00	67.59	37	0
Viano *et al*. (1989)	37	Rigid	Pendulum	10.20	67.59	37	5
Viano *et al*. (1989)	40	Rigid	Pendulum	3.62	75.76	64	2
Viano *et al*. (1989)	41	Rigid	Pendulum	3.80	75.76	64	0

Appendix D Flail-Space Study Test Cases Thoracic Injury List

The following table lists all the test cases used in the flail-space model study and the thoracic injury sustained by each PMHS. Where the "Other Thoracic Injuries" section has been left blank, no other injuries were specified for that study.

Reference	Test Number	Left Rib Fractures	Right Rib Fractures	Total Number of Rib Fractures	Number of Left Ribs Fractured	Number of Right Ribs Fractured	Total Number of Fractured Ribs	Other Thoracic Injuries	Notes
Cavanaugh *et al*. (1993)	4	19		22					
Cavanaugh *et al*. (1993)	5	12		20					
Cavanaugh *et al*. (1993)	6	11		13					
Cavanaugh *et al*. (1993)	7	13		16					
Cavanaugh *et al*. (1993)	8	15		24					
Cavanaugh *et al*. (1993)	9	23		34				AIS 5 aorta injury.	
Cavanaugh *et al*. (1993)	10	3		5					
Cavanaugh *et al*. (1993)	11	2		3					
Cavanaugh *et al*. (1993)	12	15		25				AIS 5 aorta injury.	
Cavanaugh *et al*. (1993)	13	11		18					
Kallieris & Mattern (1986)	8011	1	0						
Kallieris & Mattern (1986)	8013	7	0						
Kallieris & Mattern (1986)	8014	4	0						
Kallieris & Mattern (1986)	8017	7	0						
Kallieris & Mattern (1986)	8018	0	0						
Kallieris & Mattern (1986)	8020	3	0						
Kallieris & Mattern (1986)	8021	0	0						
Kallieris & Mattern (1986)	8023	0	0						
Kallieris & Mattern (1986)	8024	0	0						
Kallieris & Mattern (1986)	8102	23	5						
Kallieris & Mattern (1986)	8104	25	11						
Kallieris & Mattern (1986)	8106	16	0						
Kallieris & Mattern (1986)	8111	0	0						
Kallieris & Mattern (1986)	8112	5	0						

Kallieris & Mattern (1986)	8115	0	0						
Kallieris & Mattern (1986)	8116	15	0						
Kallieris & Mattern (1986)	8121	0	0						
Kallieris & Mattern (1986)	8122	21	1						
Kallieris & Mattern (1986)	8125	15	0						
Kallieris & Mattern (1986)	8127	9	0						
Kallieris & Mattern (1986)	8202	20	0						
Kallieris & Mattern (1986)	8208	15	3						
Kallieris & Mattern (1986)	8209	20	1						
Kallieris & Mattern (1986)	8212	17	0						
Kallieris & Mattern (1986)	8214	18	0						
Kallieris & Mattern (1986)	8215	2	0						
Kallieris & Mattern (1986)	8216	11	0						
Kallieris & Mattern (1986)	8218	9	0						
Kallieris & Mattern (1986)	8219	7	0						
Kallieris & Mattern (1986)	8220	17	3						
Kallieris & Mattern (1986)	8221	21	4						
Kallieris & Mattern (1986)	8222	20	5						
Kallieris & Mattern (1986)	8308	0	0						
Kallieris & Mattern (1986)	8310	0	0						
Kallieris & Mattern (1986)	8311	0	0						
Kallieris & Mattern (1986)	8312	0	0						
Kallieris & Mattern (1986)	8316	9	4						
Kallieris & Mattern (1986)	8320	0	0						
Kallieris & Mattern (1986)	8321	20	4						
Kallieris & Mattern (1986)	8330	0	0						
Kallieris & Mattern (1986)	8331	13	0						
Kallieris & Mattern (1986)	8405	19	0						
Kuppa *et al* (2000)	3320			33					
Kuppa *et al* (2000)	3321			25					
Kuppa *et al* (2000)	3322			12					
Kuppa *et al* (2000)	3323			21					
Kuppa *et al* (2000)	3324			34					
Kuppa *et al* (2000)	3325			16					
Kuppa *et al*. (2004)	SC101			15					
Kuppa *et al*. (2004)	SC102			0					
Kuppa *et al*. (2004)	SC103			11					
Kuppa *et al*. (2004)	SC105			0					
Kuppa *et al*. (2004)	SC106			2					

Kuppa *et al*. (2004)	SC107			3					
Kuppa *et al*. (2004)	SC108			3					
Kuppa *et al*. (2004)	SC109			5					
Kuppa *et al*. (2004)	SC114			17					
Kuppa *et al*. (2004)	SC115			10					
Kuppa *et al*. (2004)	SC116			11					
Kuppa *et al*. (2004)	SC119			11					
Kuppa *et al*. (2004)	SC120			0					
Kuppa *et al*. (2004)	SC121			9					
Kuppa *et al*. (2004)	SC122			1					
Kuppa *et al*. (2004)	SC123			7					
Kuppa *et al*. (2004)	SC124			0					
Kuppa *et al*. (2004)	SC131			15					
Kuppa *et al*. (2004)	SC132			12					
Kuppa *et al*. (2004)	SC133			20					
Kuppa *et al*. (2004)	SC134			6					
Kuppa *et al*. (2004)	SC135			11					
Kuppa *et al*. (2004)	SC136			3					
Kuppa *et al*. (2004)	SC137			3					
Kuppa *et al*. (2004)	SC138			6					
Marcus *et al*. (1983)	H-82008						10		
Marcus *et al*. (1983)	H-82009						13		
Marcus *et al*. (1983)	H-82012						9		
Marcus *et al*. (1983)	H-82014						12		
Marcus *et al*. (1983)	H-82015						2		
Marcus *et al*. (1983)	H-82016						8		
Marcus *et al*. (1983)	H-82018						9		
Marcus *et al*. (1983)	H-82019						7		
Marcus *et al*. (1983)	H-82020						11		
Marcus *et al*. (1983)	H-82021						13		
Marcus *et al*. (1983)	H-82022						15		
Melvin *et al*. (1976)	003			1					
Melvin *et al*. (1976)	009	26	15	41					
Melvin *et al*. (1976)	010			0					
Melvin *et al*. (1976)	011				7	5			
Melvin *et al*. (1976)	029			4					
Melvin *et al*. (1976)	039			11				Slight surface haemorrhage on heart.	

Melvin *et al*. (1976)	042			12					
Pintar *et al*. (1997)	OSU 577								No thoracic injuries
Pintar *et al*. (1997)	OSU 578								No thoracic injuries
Pintar *et al*. (1997)	OSU 579								No thoracic injuries
Pintar *et al*. (1997)	OSU 580								No thoracic injuries
Pintar *et al*. (1997)	OSU 581								No thoracic injuries
Robbins *et al* (1979)	76T034			38					
Robbins *et al* (1979)	76T062	7		7				Heart muscle laceration.	
Robbins *et al* (1979)	76T065	0		0				Superficial haemorrhage at aortic arch.	
Robbins *et al* (1979)	76T071	0		0				Superficial haemorrhage on pericardium and diaphragm.	
Robbins *et al* (1979)	76T074	2		2					
Robbins *et al* (1979)	76T077	3		3				Superficial contusion on chest wall, left lung, left diaphragm and pericardium.	
Robbins *et al* (1979)	76T080	14	2	16				Superficial haemorrhage on aorta membrane.	
Robbins *et al* (1979)	76T095				7	3	10	Superficial left ventricle contusion, left lung laceration.	
Robbins *et al* (1979)	76T098				4	9	13	Pericardium haemorrhage near aorta, pneumothorax and right lung laceration.	
Viano *et al*. (1989)	2			14					

Viano *et al*. (1989)	3			19					
Viano *et al*. (1989)	4			7					
Viano *et al*. (1989)	5			3					
Viano *et al*. (1989)	7			6					
Viano *et al*. (1989)	9			5					
Viano *et al*. (1989)	11			5					
Viano *et al*. (1989)	14			6					
Viano *et al*. (1989)	17			0					
Viano *et al*. (1989)	18			10					
Viano *et al*. (1989)	29			0					
Viano *et al*. (1989)	33			12					
Viano *et al*. (1989)	36			0					
Viano *et al*. (1989)	37			15					
Viano *et al*. (1989)	40			2					
Viano *et al*. (1989)	41			0					

Appendix E Flail-Space Study Additional Multiple Variable Regression Analysis Results

The following tables are from the results of the multiple variable regression analysis where only sled tests were included in the model.

Table E.1 AIS3+ thoracic injury multiple variable logistic regression model with sled test only

Parameter	MLE Ratio Estimate	Standard Error	Odds Ratio Point Estimate	95% CI	p-value
PMHS Mass	-0.0020	0.0177	0.998	0.964, 1.033	0.9088
Impact Wall	0.6986	0.2817	2.180	1.340, 12.202	0.0131
Impact Velocity	0.7791	0.2143	2.180	1.432, 3.317	0.0003
PMHS Age	0.0532	0.0158	1.055	1.023, 1.088	0.0007

Table E.2 AIS4+ thoracic injury multiple variable logistic regression model with sled test only

Parameter	MLE Ratio Estimate	Standard Error	Odds Ratio Point Estimate	95% CI	p-value
PMHS Mass	0.0016	0.0175	1.002	0.968, 1.036	0.9285
Impact Wall	0.8862	0.3131	5.885	1.725, 20.078	0.0046
Impact Velocity	1.4862	0.3022	4.420	2.445, 7.991	<0.0001
PMHS Age	0.0844	0.0205	1.088	1.045, 1.133	<0.0001

Appendix F List of Rollover Crash Cases

The following table lists the rollover crash cases referred to in Chapter 4 and Chapter 5 (first three columns) and segment damage coding (column 4 to column 14) referred to in Chapter 5. It is noted that no rollover crashes matched the aforementioned filtering criteria as documented in Chapter 4 for 2012 and this is reflected in the list of cases listed below.

Year	PSU	CASEID	Left 1	Left 2	Left 3	Left 4	Right 1	Right 2	Right 3	Right 4	Top 1	Top 2	Top 3
2001	78	89A	0	1	0	1	0	1	0	0	0	1	0
2002	12	90J	0	0	0	0	1	1	0	0	1	1	0
2002	12	90J	0	0	0	0	1	1	0	0	1	1	0
2002	48	180J	0	0	0	1	0	1	0	1	0	1	0
2002	78	45C	1	1	1	1	0	1	0	1	0	1	0
2002	78	105J	1	1	0	0	1	1	0	1	1	1	0
2002	78	115J	0	1	0	1	0	0	0	1	0	1	0
2003	48	202K	0	1	0	1	1	1	0	0	0	0	0
2003	78	55J	1	1	0	1	1	1	1	0	0	1	0
2003	78	84J	0	0	0	1	1	1	0	1	1	1	0
2004	11	134J	0	1	0	0	0	1	0	0	0	1	0
2004	48	5J	0	1	0	1	1	0	0	0	0	1	0
2004	78	57K	0	0	0	0	1	1	0	0	1	1	0
2004	78	71B	1	1	0	1	0	0	0	0	1	1	0
2005	11	34F	1	0	0	0	0	0	0	0	1	0	0
2005	13	138K	0	0	0	0	0	1	0	0	0	1	0
2005	48	129K	0	0	0	0	1	1	0	1	1	1	0
2005	48	248K	1	1	0	0	0	0	0	0	0	1	0

2005	74	86A	0	1	0	1	1	1	0	0	0	1	0
2005	78	23K	0	0	0	1	0	1	0	0	0	1	0
2006	41	176K	0	1	0	1	0	0	0	0	0	1	0
2006	47	64C	1	1	0	1	1	1	0	1	1	1	1
2006	78	92K	0	0	0	0	1	1	1	1	1	1	0
2007	48	114J	0	1	0	1	0	0	0	0	0	1	0
2007	48	165K	0	0	0	1	1	1	0	0	1	1	1
2007	50	89K	1	1	0	0	0	0	0	0	0	1	0
2007	76	19K	1	1	1	1	1	0	0	0	0	1	0
2008	12	160E	0	0	0	1	1	1	0	1	0	1	0
2008	48	195K	0	1	0	0	1	1	0	0	0	1	0
2008	49	125B	0	0	0	0	1	1	0	1	0	1	0
2008	76	60K	0	0	0	0	0	1	0	0	0	0	0
2008	78	78C	0	1	0	0	1	1	1	0	1	1	0
2008	78	157K	0	1	0	1	1	0	0	0	0	1	0
2009	45	249K	0	1	0	0	0	0	0	0	0	1	0
2009	76	119K	1	1	0	0	1	1	1	1	1	1	0
2009	78	88K	1	0	0	1	1	1	0	0	1	1	0
2009	78	117K	0	0	0	1	0	1	0	1	0	1	0
2010	41	196B	0	1	0	1	0	1	0	0	0	1	0
2010	78	45K	0	1	0	1	0	0	0	1	0	1	0
2010	78	154J	0	0	0	0	0	1	0	0	0	1	0
2011	73	61K	0	1	0	1	1	1	0	1	1	1	1
2011	78	29K	1	1	0	0	0	0	0	0	0	1	0
2011	78	38K	0	0	0	0	1	1	0	1	0	1	0

Appendix G List of Rollover Crash Controls

The following table lists the rollover crash controls referred to in Chapter 4 and Chapter 5 (first three columns) and segment damage coding (column 4 to column 14) referred to in Chapter 5. It is noted that no rollover crashes from 2012 matched the filtering criteria documented in Chapter 4 and Chapter 5 for cases; thus, no rollover crashes were selected from the 2012 data set for controls.

YEAR	PSU	CASEID	Left 1	Left 2	Left 3	Left 4	Right 1	Right 2	Right 3	Right 4	Top 1	Top 2	Top 3
2001	11	92E	0	0	0	0	0	1	0	1	0	1	0
2001	11	106E	0	0	0	0	0	1	0	0	0	1	0
2001	11	48E	0	0	0	1	0	0	0	0	1	1	0
2001	11	61C	0	0	0	0	0	1	0	0	0	1	0
2001	11	203E	0	0	0	0	0	1	0	0	0	1	0
2002	4	67G	0	0	0	0	1	0	0	0	0	1	0
2002	8	230E	0	0	0	1	0	0	0	0	0	1	0
2002	11	69E	0	1	0	0	0	1	0	0	1	1	0
2002	11	165H	0	0	0	0	0	1	0	0	0	1	0
2002	13	55E	1	0	0	0	0	0	0	0	1	1	0
2002	13	142F	0	0	0	0	0	1	0	0	0	0	0
2002	13	115J	1	1	1	1	0	0	0	1	0	1	0
2002	45	132K	1	1	0	1	0	0	0	1	0	1	0
2002	13	23B	0	0	0	0	0	0	0	0	0	1	0
2002	11	161E	0	0	0	1	1	0	0	0	0	0	0
2002	13	12D	1	0	0	0	0	0	0	1	0	1	0
2002	13	93F	0	0	0	0	1	0	0	1	0	1	0

2002	11	223J	1	0	0	0	0	1	0	1	0	1	0
2002	48	144J	0	1	0	0	0	1	0	1	0	1	0
2003	13	1E	0	0	0	0	0	0	0	0	0	1	1
2003	9	185C	0	0	0	0	0	1	0	0	0	1	0
2003	13	22D	0	1	0	0	0	0	0	0	0	1	0
2003	41	102A	0	1	0	1	0	0	0	0	0	1	0
2003	11	26K	1	1	0	0	1	0	0	0	0	1	0
2003	11	103G	0	0	0	0	0	1	0	0	0	1	0
2003	9	151G	0	0	0	0	0	0	0	0	0	0	0
2003	11	70E	0	0	0	0	0	0	0	0	0	0	0
2003	13	152G	0	0	0	0	0	0	0	0	0	1	0
2003	11	7E	0	0	0	1	0	0	0	0	0	1	0
2003	13	160F	0	0	0	0	0	1	0	0	0	1	0
2003	78	62F	0	1	0	1	0	0	0	0	0	1	0
2004	4	5H	0	0	1	0	0	0	0	0	0	0	0
2004	9	68J	0	1	0	1	0	0	0	0	1	1	0
2004	11	132J	0	0	0	0	1	1	0	1	1	1	1
2004	9	233K	0	1	0	0	0	0	0	0	0	1	0
2004	11	139E	1	1	0	1	0	1	0	0	0	1	0
2004	13	24H	0	0	0	0	0	0	0	0	1	1	0
2004	11	88F	0	0	0	0	0	1	0	0	0	1	0
2004	11	180H	0	0	0	0	0	0	0	0	0	1	0
2004	12	178F	0	0	0	0	1	0	0	0	1	1	0
2004	11	11E	0	0	0	0	0	1	0	0	0	1	0
2004	13	37H	0	0	1	0	0	0	1	0	0	1	0

2004	11	29E	1	0	0	0	0	0	0	1	0	0	0
2004	11	244C	0	1	0	0	0	0	0	0	0	1	0
2004	13	55K	1	1	0	0	0	0	0	0	0	1	0
2004	13	202E	0	0	0	0	0	0	0	0	0	0	0
2004	41	17C	0	0	0	1	1	1	0	1	0	1	0
2005	9	35K	0	0	0	0	1	0	0	0	0	0	0
2005	12	133E	1	0	0	0	0	0	0	0	0	1	0
2005	13	1H	0	0	0	0	1	0	0	0	0	0	0
2005	13	101D	0	1	0	1	0	0	1	0	0	1	0
2005	43	101E	0	1	0	0	0	0	0	0	0	1	0
2005	48	24C	0	0	0	0	0	0	0	0	0	0	0
2005	12	19E	0	1	0	0	0	0	0	0	0	1	0
2005	13	13H	0	0	0	0	0	0	0	0	0	1	0
2005	41	106K	0	0	0	0	0	1	0	1	0	1	0
2005	45	55C	0	0	0	1	1	0	0	0	1	1	0
2005	74	146F	0	1	0	0	0	0	0	0	0	1	0
2005	78	4J	0	0	0	0	0	1	0	0	0	1	0
2005	11	155J	1	1	0	0	0	0	0	1	0	1	0
2005	43	174F	1	1	0	0	0	1	0	0	0	1	0
2005	47	80C	1	1	0	0	0	0	0	0	1	1	0
2005	12	6G	0	0	0	0	0	0	0	0	0	0	0
2005	12	219D	0	0	0	1	1	0	0	0	0	1	0
2005	13	126D	1	1	0	0	1	0	1	0	1	0	0
2005	43	102F	1	1	0	1	0	1	0	0	0	1	0
2005	74	148B	1	0	0	0	1	1	1	0	1	1	0

2005	12	162E	0	0	0	0	0	1	0	0	0	1	0
2005	13	136F	0	1	0	0	0	0	0	0	0	1	0
2005	74	188C	0	1	0	1	1	1	0	1	1	1	0
2005	78	49J	0	1	0	1	0	0	0	0	0	1	0
2005	11	93D	0	0	0	0	0	0	0	0	0	1	0
2005	12	222D	1	0	0	0	0	0	0	1	0	1	0
2006	8	215F	0	0	0	0	0	0	0	0	0	1	0
2006	11	68E	0	0	0	0	0	0	0	0	0	0	0
2006	13	52D	0	1	0	0	0	0	0	1	0	1	0
2006	13	103F	0	1	0	1	0	0	0	0	0	1	0
2006	13	162D	1	0	0	1	0	0	0	1	0	1	0
2006	45	91K	1	1	0	0	0	0	0	0	0	1	0
2006	48	107K	0	0	0	0	0	1	0	1	0	1	0
2006	13	43D	0	0	0	0	0	0	0	0	0	0	0
2006	13	157C	1	1	0	0	0	1	0	0	1	1	0
2006	43	97F	0	0	0	0	0	0	0	0	0	0	0
2006	11	194K	1	0	0	0	0	1	0	0	0	1	0
2006	13	54G	0	0	0	1	0	0	0	0	0	0	0
2006	13	214D	1	1	1	0	0	1	1	0	0	1	0
2006	45	103B	0	1	0	0	1	0	0	0	0	1	0
2006	11	64F	0	0	0	0	0	0	0	1	0	0	0
2006	13	66F	0	0	0	0	0	1	0	1	0	1	0
2006	43	170E	1	0	1	1	0	0	0	0	1	1	0
2006	48	114K	0	0	0	0	1	1	0	1	0	1	0
2006	50	59K	0	0	0	0	0	0	0	1	0	1	0

2007	2	24F	0	0	0	0	0	0	0	0	0	1	0
2007	9	148E	0	0	0	0	0	0	0	0	0	1	0
2007	11	178F	0	0	0	0	0	0	0	1	0	1	0
2007	13	1F	0	0	0	0	0	0	0	0	0	0	0
2007	13	103F	0	0	0	0	0	0	0	1	0	1	0
2007	13	159H	0	0	0	0	0	0	0	0	0	1	0
2007	11	80D	0	0	0	0	0	1	0	1	0	1	0
2007	45	6D	1	1	0	1	0	1	0	1	0	1	1
2007	47	156D	1	0	1	1	0	0	0	1	0	1	0
2007	11	113E	0	0	0	0	1	1	0	0	1	1	0
2007	13	37F	0	0	0	0	0	0	0	0	0	1	0
2007	13	111D	0	0	0	0	0	0	0	0	0	1	0
2007	13	201F	0	1	0	0	0	0	0	0	0	1	0
2007	43	144K	0	1	0	0	0	0	0	0	0	1	0
2007	11	198H	0	0	0	0	0	1	0	0	0	0	0
2007	13	76E	0	0	0	0	0	1	0	1	0	1	0
2007	13	202G	0	0	0	0	0	1	0	0	0	1	0
2007	43	62F	0	1	0	0	0	0	0	0	0	1	0
2007	43	203K	1	0	1	1	0	0	0	0	1	1	0
2007	47	13K	0	0	1	0	0	0	0	0	0	1	0
2007	11	81E	1	0	0	1	0	0	0	1	0	1	0
2007	11	193B	0	1	0	0	0	0	0	1	0	1	0
2007	47	91B	0	1	0	1	0	0	0	1	0	1	0
2007	48	235K	0	1	0	1	0	0	0	0	0	1	0
2008	11	87E	1	1	0	0	0	0	0	0	0	1	0

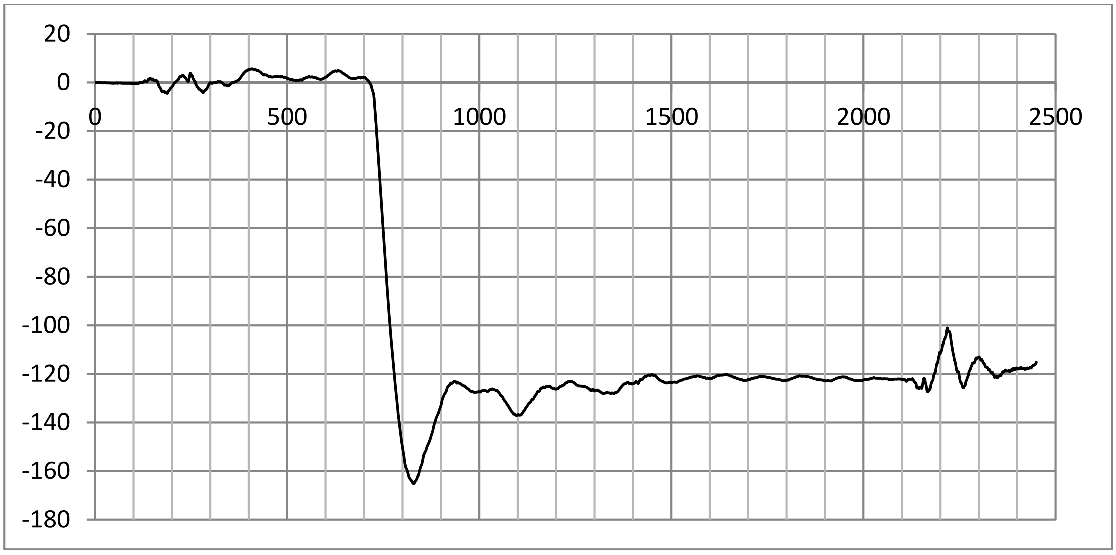
2008	11	244F	0	0	0	0	1	0	0	0	0	0	0
2008	13	54C	0	1	0	0	0	0	0	0	0	1	0
2008	13	264F	0	0	0	0	0	0	0	0	0	0	0
2008	12	29G	0	0	0	0	0	0	0	0	0	0	0
2008	13	59F	0	0	0	0	1	1	0	0	0	1	0
2008	13	163F	1	1	0	0	0	0	0	0	0	1	0
2008	48	198C	0	0	0	0	1	0	0	0	1	0	0
2008	11	43E	0	0	0	0	0	0	0	0	1	0	0
2008	11	180F	1	1	0	0	0	0	0	0	0	1	0
2008	12	250E	1	1	0	0	1	0	0	0	0	1	0
2008	13	275F	1	0	0	0	1	0	0	0	0	1	0
2008	11	135F	1	0	0	0	0	1	0	0	0	1	0
2008	12	127B	0	0	0	0	0	0	0	1	0	1	0
2008	13	56F	0	0	0	0	0	0	0	0	0	1	0
2008	13	219F	0	0	0	1	0	0	0	0	0	1	0
2008	73	205K	0	1	0	0	0	0	0	0	0	1	0
2008	76	77K	1	1	0	0	0	0	0	1	0	1	0
2008	78	63K	1	1	0	0	1	0	0	0	1	1	0
2009	2	135F	1	0	0	0	1	0	0	1	1	1	0
2009	11	146E	0	0	0	0	0	0	0	0	0	1	1
2009	13	279E	0	1	0	0	0	0	0	0	0	1	0
2009	43	180F	0	1	0	0	0	1	0	1	0	1	0
2009	11	182E	0	1	0	1	0	0	0	0	0	1	0
2009	41	250E	0	0	0	0	1	1	0	0	0	0	0
2009	78	91J	1	1	0	1	0	0	0	0	0	0	0

2009	11	170E	0	0	0	1	0	0	0	0	0	1	0
2009	13	209E	0	1	0	1	1	1	0	0	1	1	0
2009	43	66F	1	0	0	0	0	0	0	0	0	0	0
2009	13	280F	0	0	0	0	0	0	0	0	0	0	0
2009	48	38C	0	0	0	0	0	0	0	0	0	0	0
2009	76	34F	0	0	0	0	0	0	0	0	0	0	0
2009	78	8K	0	1	0	0	1	1	0	0	0	1	0
2009	5	31F	0	0	0	1	0	0	0	0	0	1	0
2009	13	286H	0	0	0	0	0	0	0	0	0	0	0
2010	8	13G	0	1	0	1	0	0	0	0	0	1	0
2010	11	148H	0	1	0	0	1	1	0	0	0	1	0
2010	13	244F	0	0	0	0	0	0	0	0	0	0	0
2010	49	162D	0	0	0	0	0	1	0	0	1	0	0
2010	78	41F	1	0	0	1	0	0	0	0	0	1	0
2010	11	152G	0	0	0	0	0	0	0	0	0	0	0
2010	13	243H	0	0	0	1	0	0	0	0	0	0	0
2010	74	11D	0	0	0	0	0	0	0	0	1	0	0
2010	11	167F	0	0	1	0	1	0	0	0	0	1	0
2010	43	41F	0	1	0	0	0	0	0	0	0	0	0
2010	76	124E	1	1	0	1	1	1	0	0	1	1	0
2010	8	78H	0	1	0	0	1	1	0	0	0	1	0
2010	45	232E	0	0	0	0	0	1	0	1	0	1	0
2010	78	52K	1	0	0	0	1	1	0	0	0	1	0
2010	11	21F	1	1	0	0	0	0	0	0	0	1	0
2011	11	3F	0	1	0	0	1	0	0	0	0	1	0

2011	76	136J	0	1	0	1	1	0	0	1	0	1	1
2011	79	18F	0	0	0	0	0	0	0	0	0	0	0
2011	11	153H	1	1	0	0	0	1	0	0	0	1	0
2011	13	127F	1	1	0	0	0	0	0	0	0	0	0
2011	76	94K	1	0	0	0	0	1	1	0	0	0	0
2011	12	26F	0	0	0	0	0	1	0	0	0	1	0
2011	43	9F	0	0	0	0	0	0	0	1	0	1	1
2011	76	100E	1	0	0	1	1	0	0	0	1	1	0
2011	13	8F	0	1	0	0	0	0	0	0	0	1	0
2011	74	109E	1	0	0	0	1	1	0	0	0	1	0
2011	78	13K	0	1	1	0	1	1	1	1	0	1	0
2011	13	147H	0	0	0	0	0	0	0	1	0	1	0
2011	76	153F	0	0	0	1	1	0	0	0	1	1	0
2011	78	13K	0	1	0	0	1	1	1	0	0	1	0

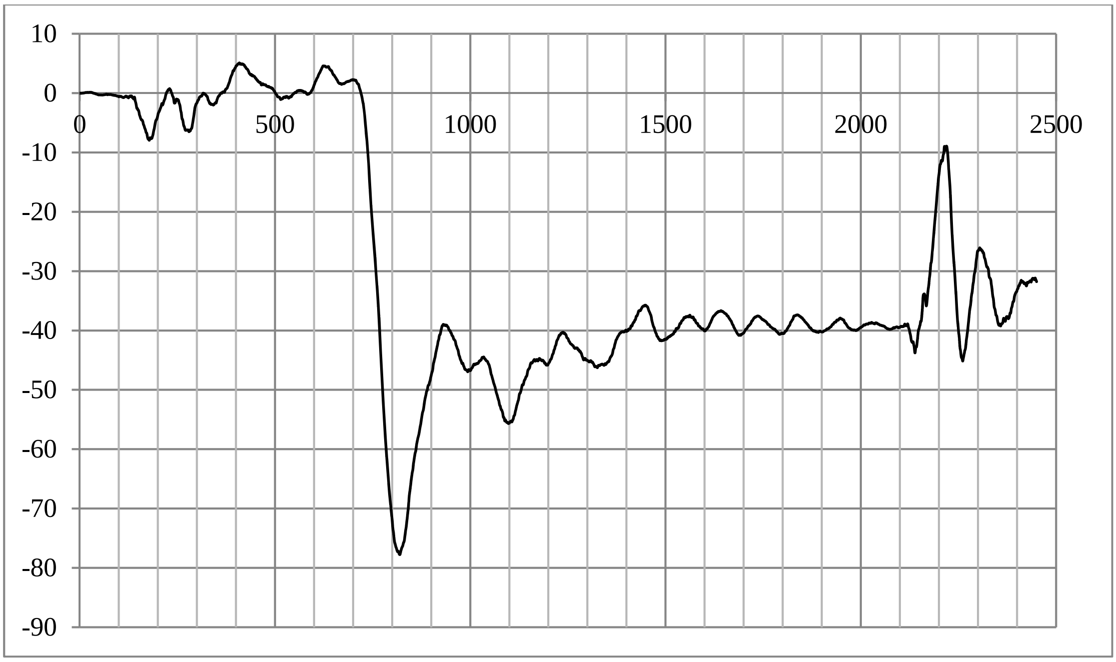
Appendix H A-Pillar Deformation Time History Plot

The time history plot below is of the FE vehicle left A-pillar deformation.



Appendix I B-Pillar Deformation Time History Plot

The time history plot below is of the FE vehicle left B-pillar deformation.



Appendix J Rib Deflection Time History Plots

The time history plots below are of the upper, middle and lower rib deflection for the ATD in Position 1, 2, 5 and 8.

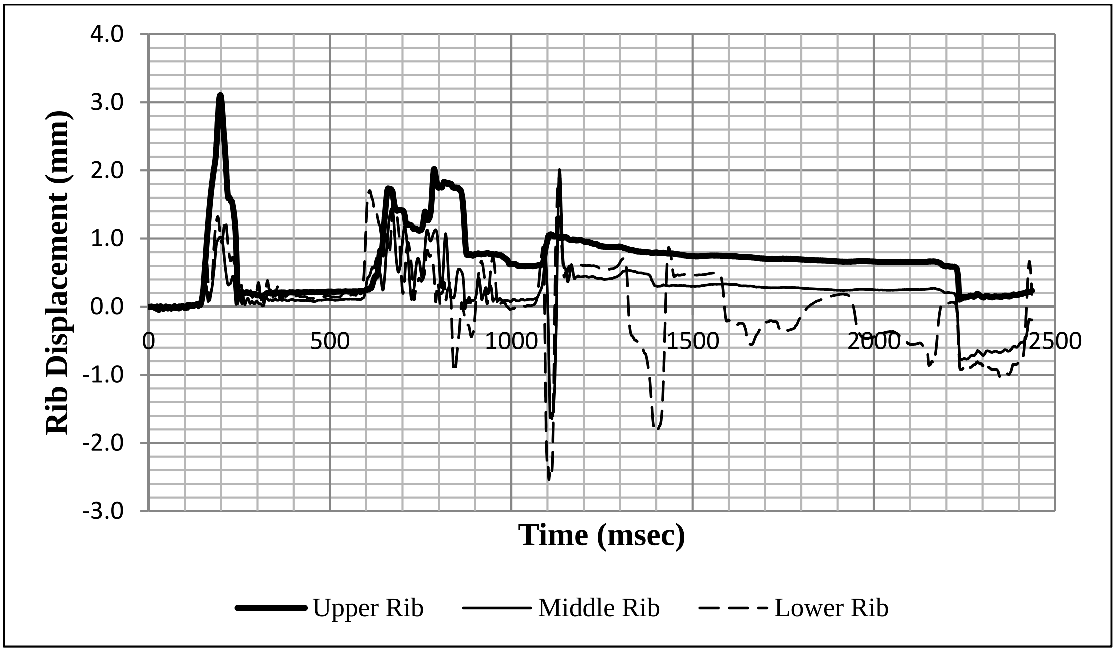


Figure J.1 ATD Position 1 rib displacement

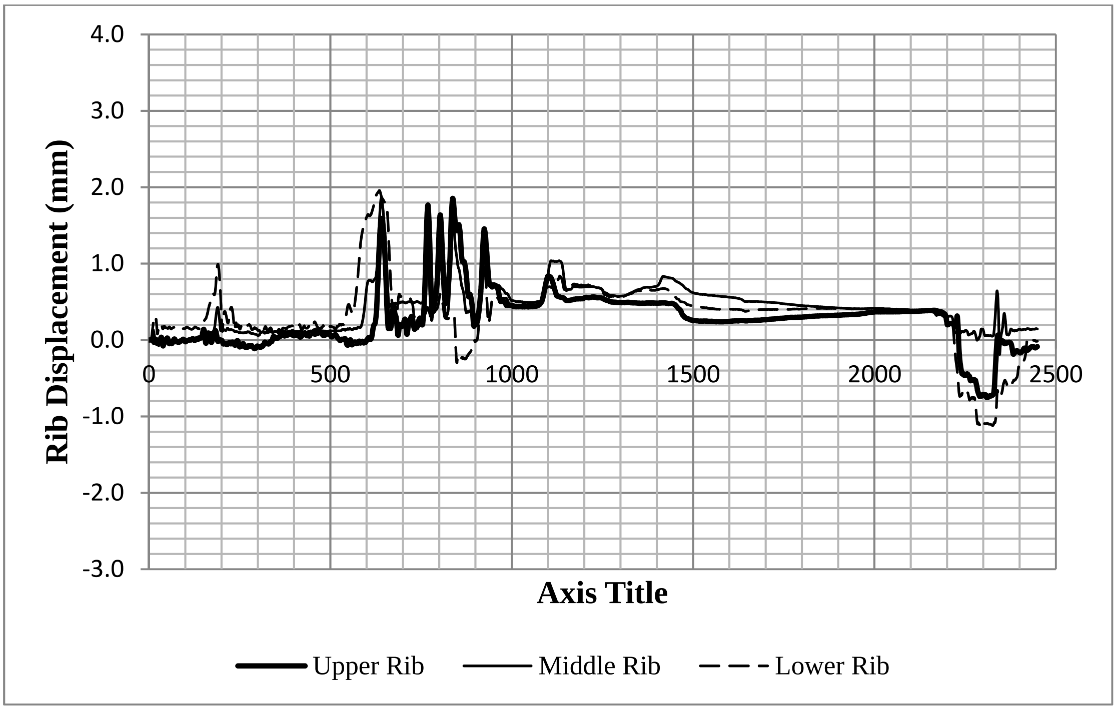


Figure J.2 ATD Position 2 rib displacement

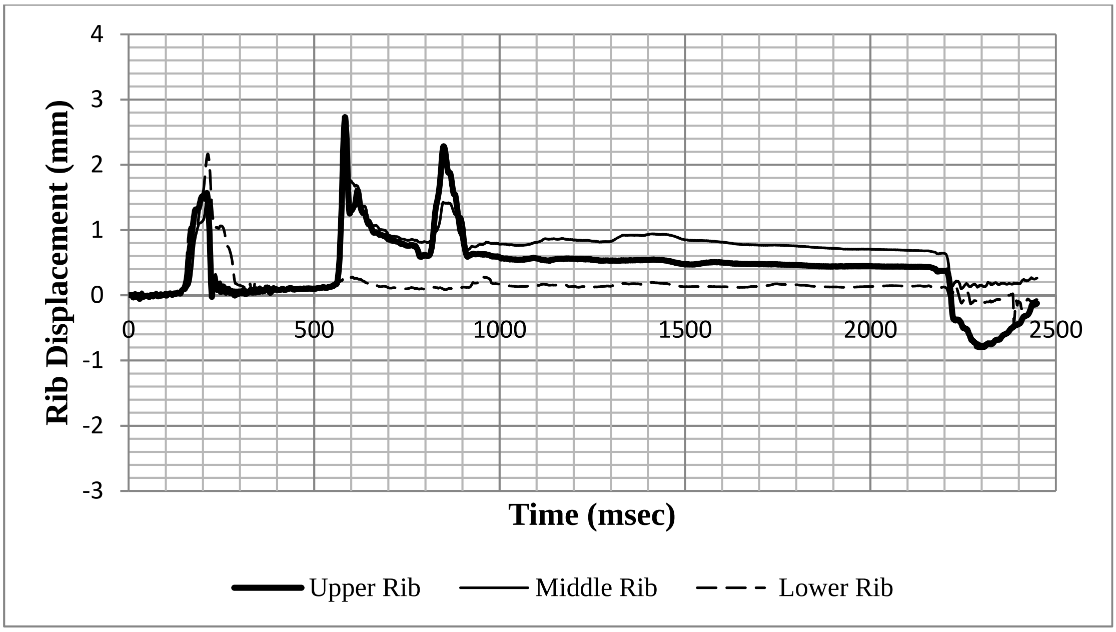


Figure J.3 ATD Position 5 rib discplacement

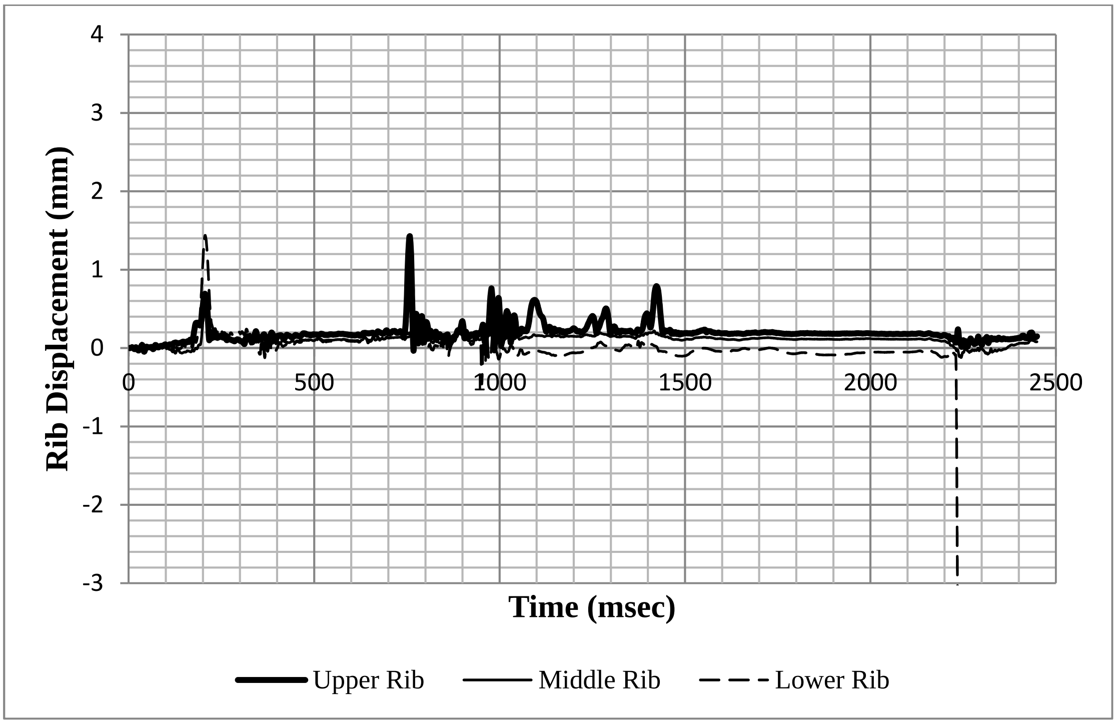


Figure J.4 ATD Position 8 rib discplacement

Appendix K Upper Spine Acceleration Time History Plots

The time history plots below are of the upper spine acceleration for the ATD in Position 1, 2, 5 and 8.

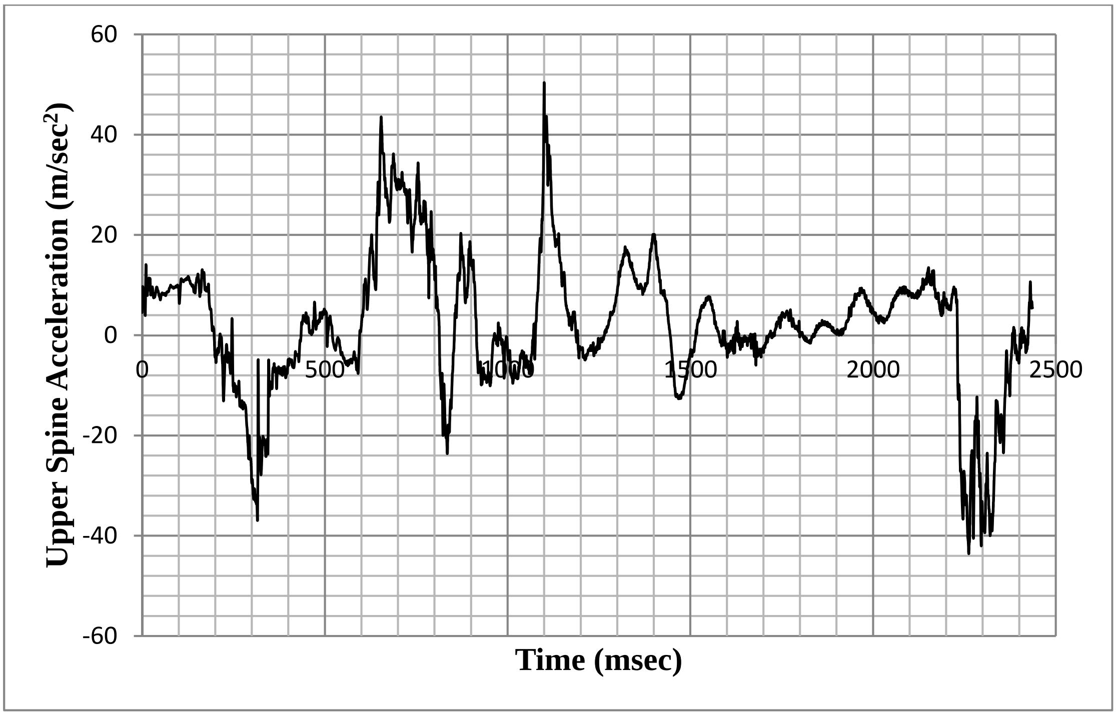


Figure K.1 ATD Position 1 upper spine acceleration

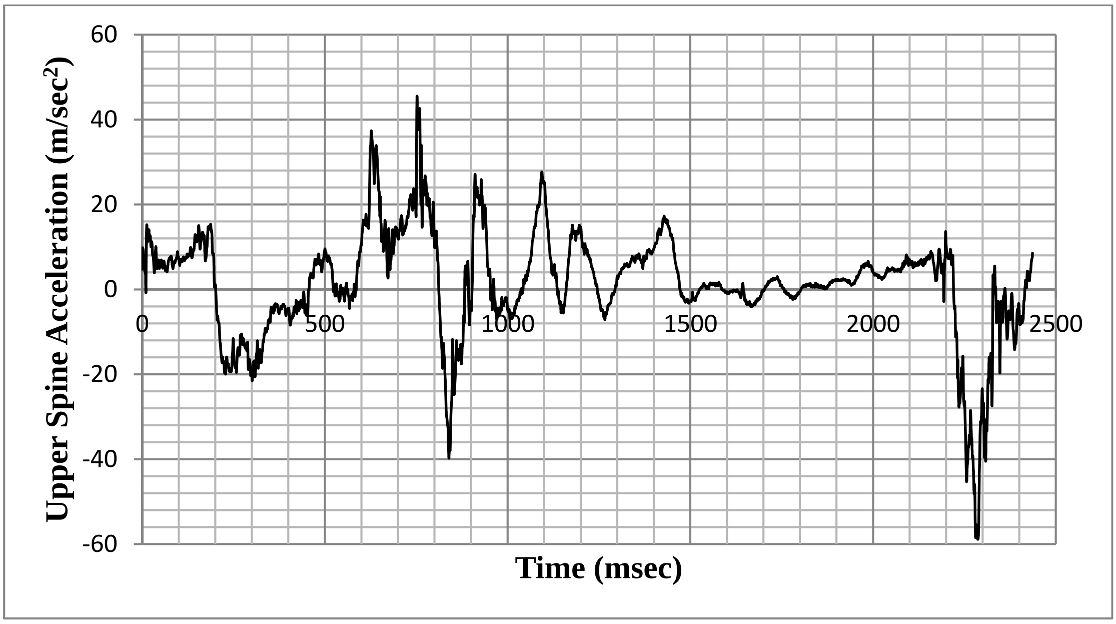


Figure K.2 ATD Position 2 upper spine acceleration

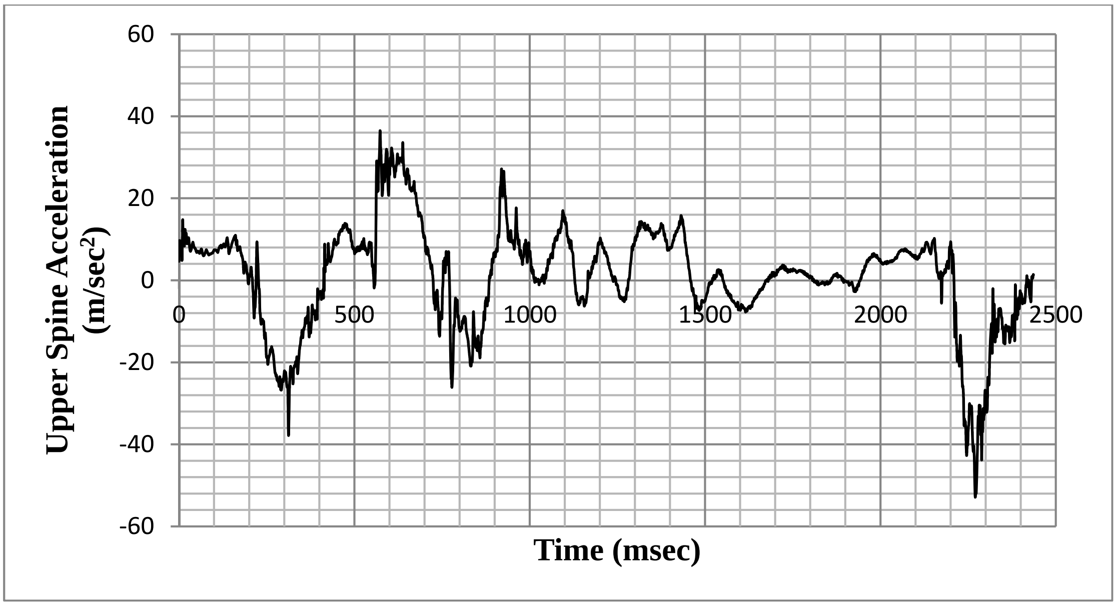


Figure K.3 ATD Position 5 upper spine acceleration

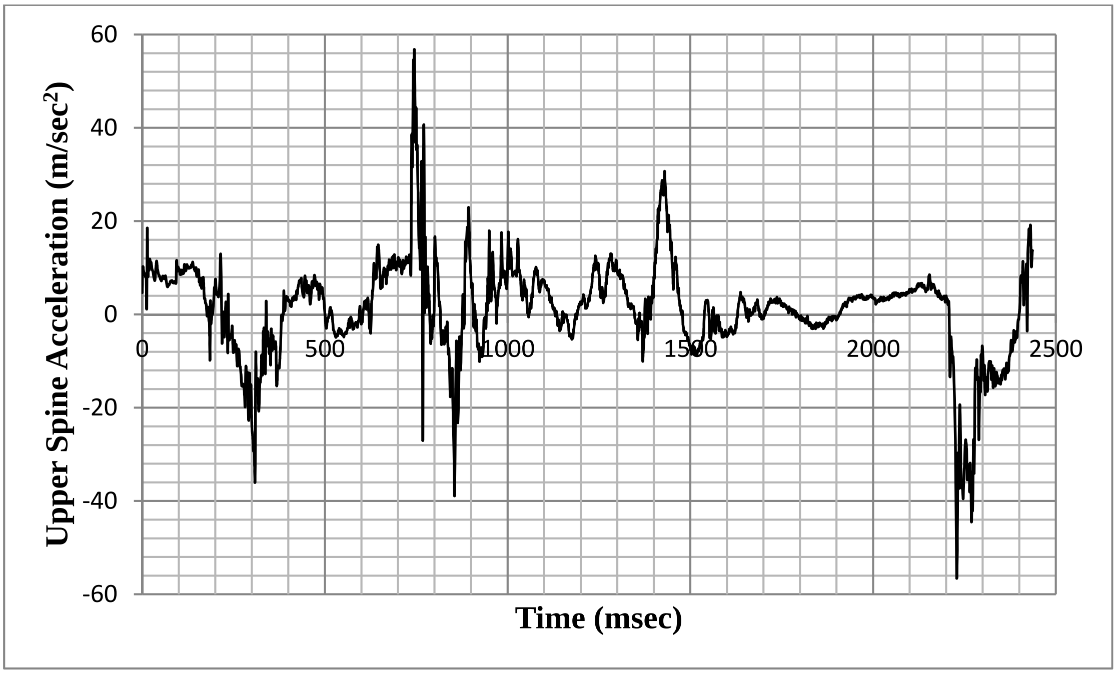


Figure K.4 ATD Position 8 upper spine acceleration

Appendix L Lower Spine Acceleration Time History Plots

The time history plots below are of the lower spine acceleration for the ATD in Position 1, 2, 5 and 8.

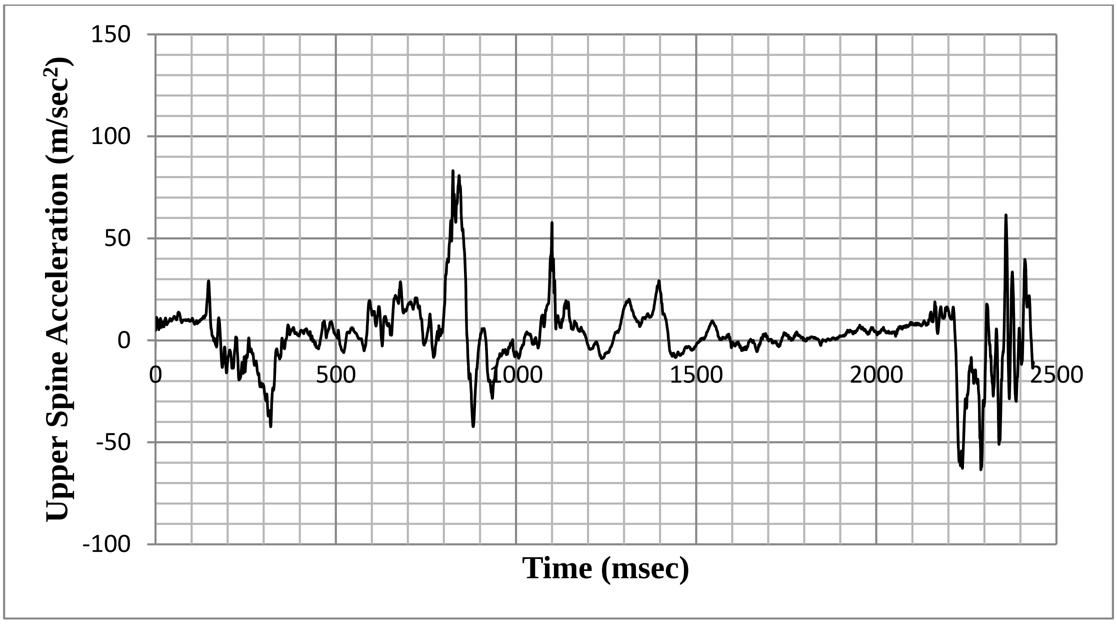


Figure L.1 ATD Position 1 lower spine acceleration

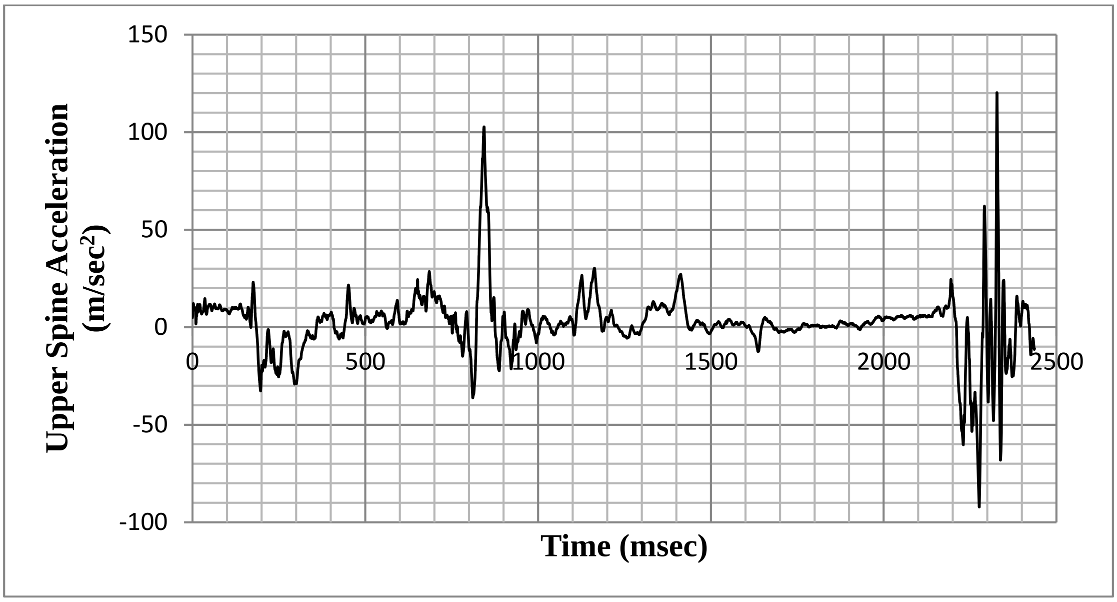


Figure L.2 ATD Position 2 lower spine acceleration

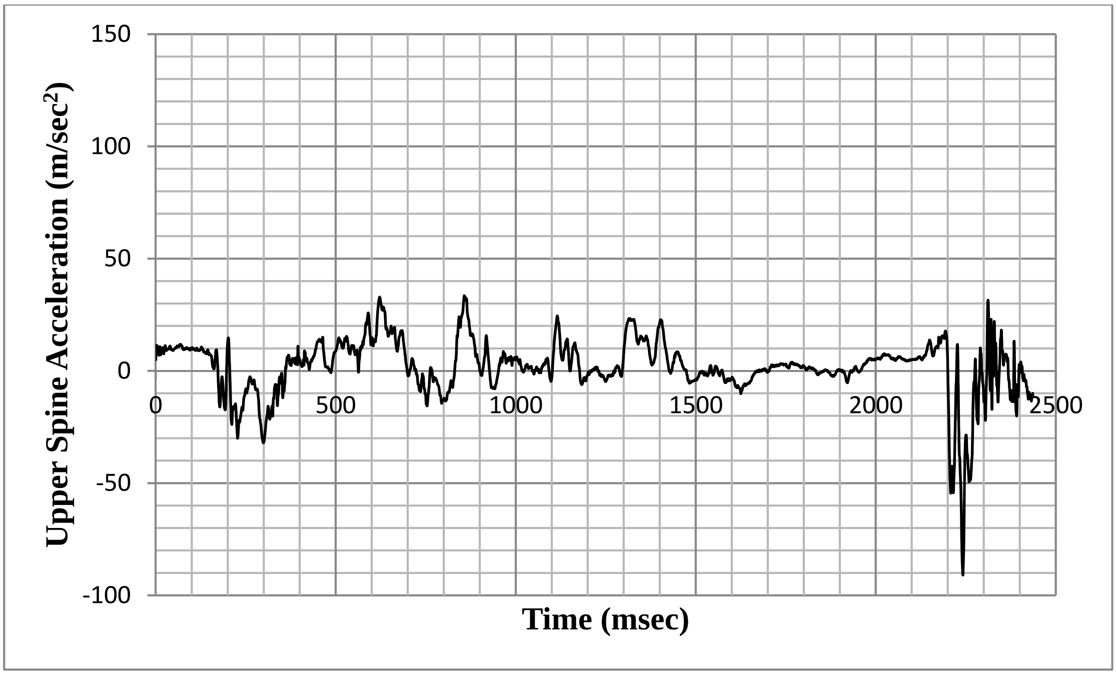


Figure L.3 ATD Position 5 lower spine acceleration

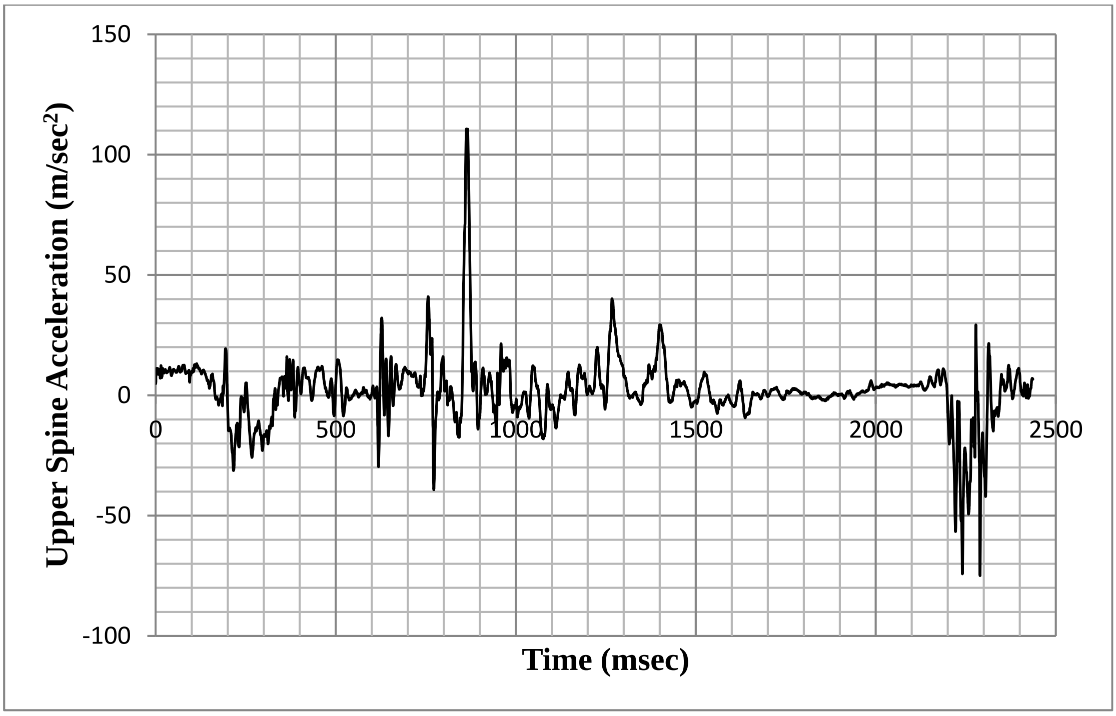


Figure L.4 ATD Position 8 lower spine acceleration

Appendix M Lower Spine Y-Axis Velocity Time History Plots

The time history plots below are of the lower spine y-axis velocity for the ATD in Position 1, 2, 5 and 8 which were used in the calculation of ASA-10.

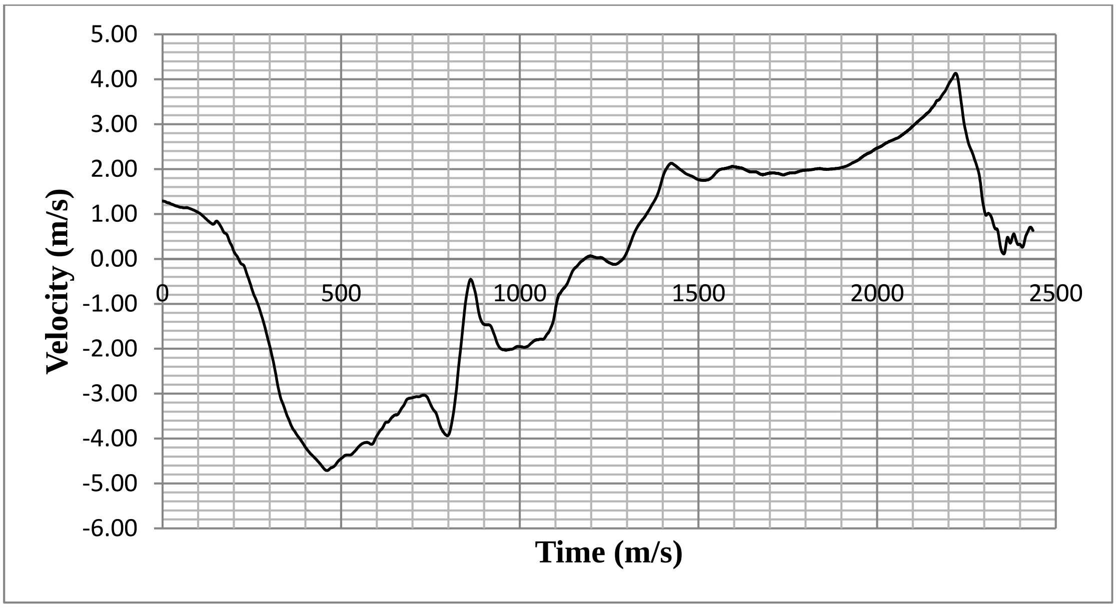


Figure M.1 ATD Position 1 lower spine y-axis velocity

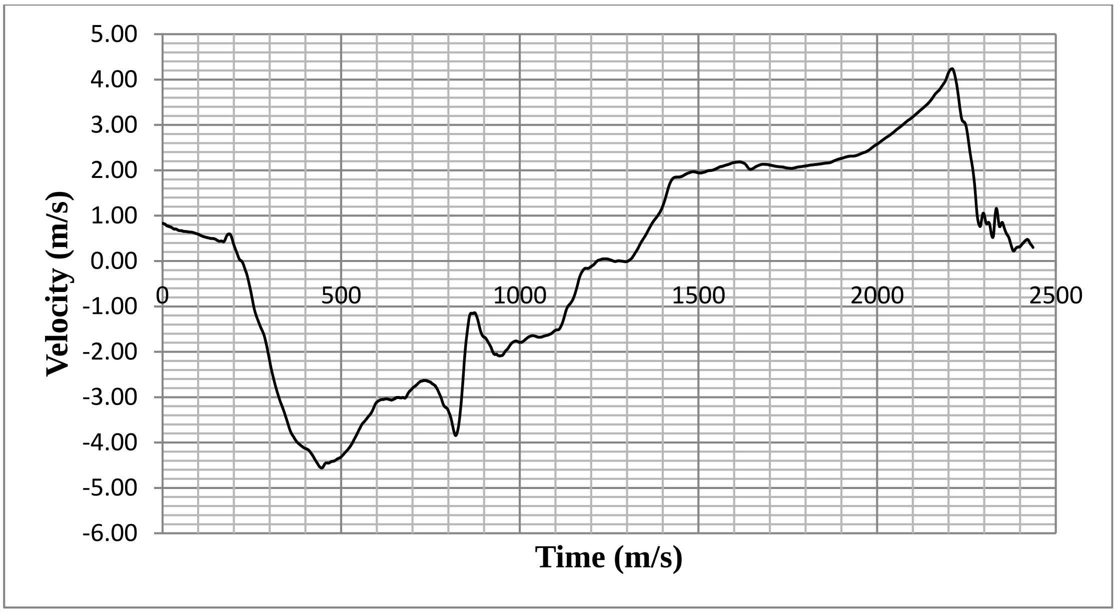


Figure M.2 ATD Position 2 lower y-axis velocity

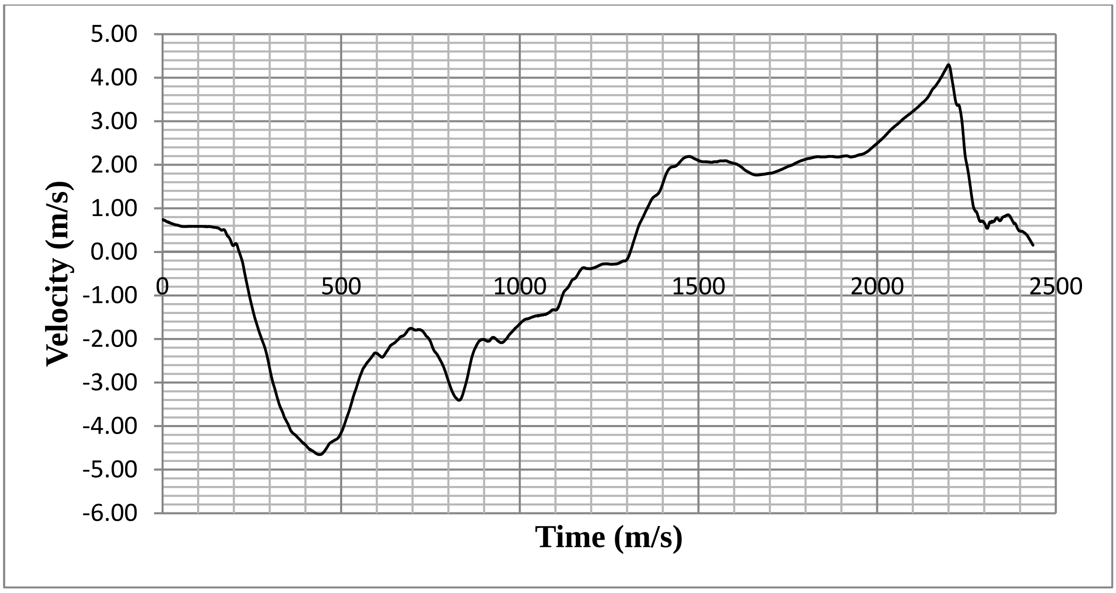


Figure M.3 ATD Position 5 lower y-axis velocity

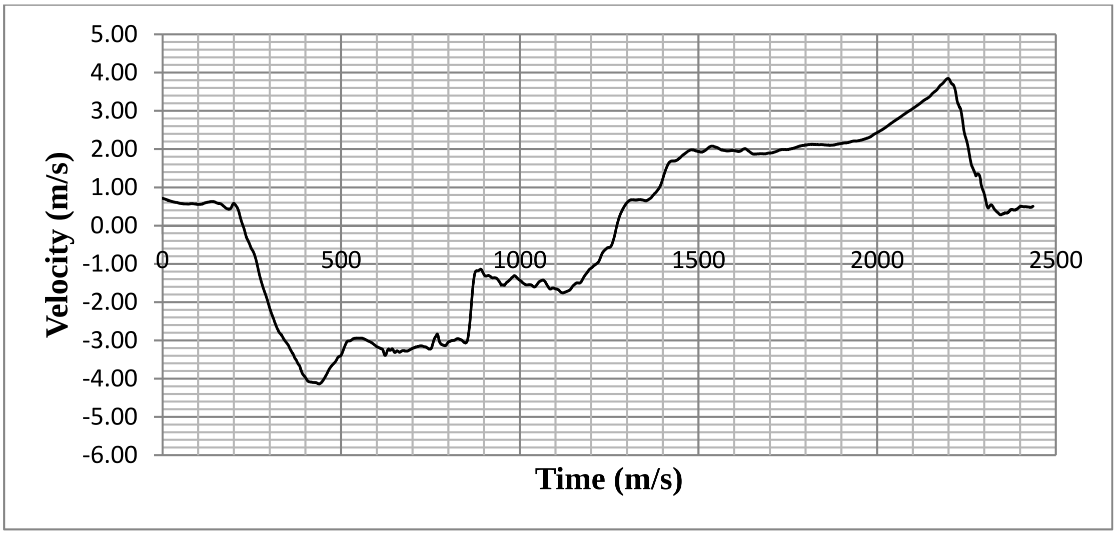


Figure M.4 ATD Position 8 lower y-axis velocity

Appendix N Viscous Criteria Time History Plots

The time history plots below are of the …… for the ATD in Position 1, 2, 5 and 8.

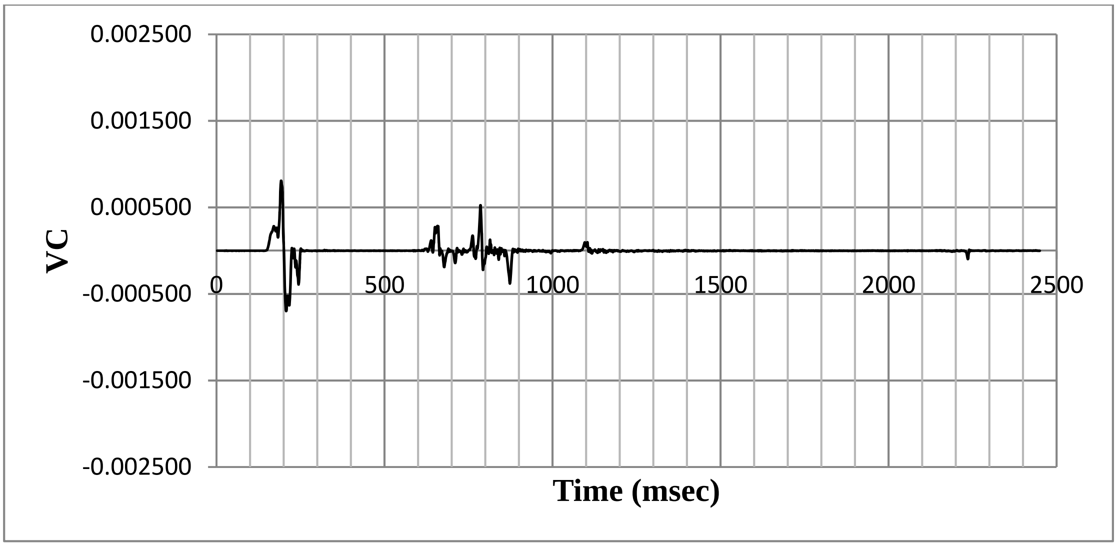


Figure N.1 ATD Position 1 upper rib VC

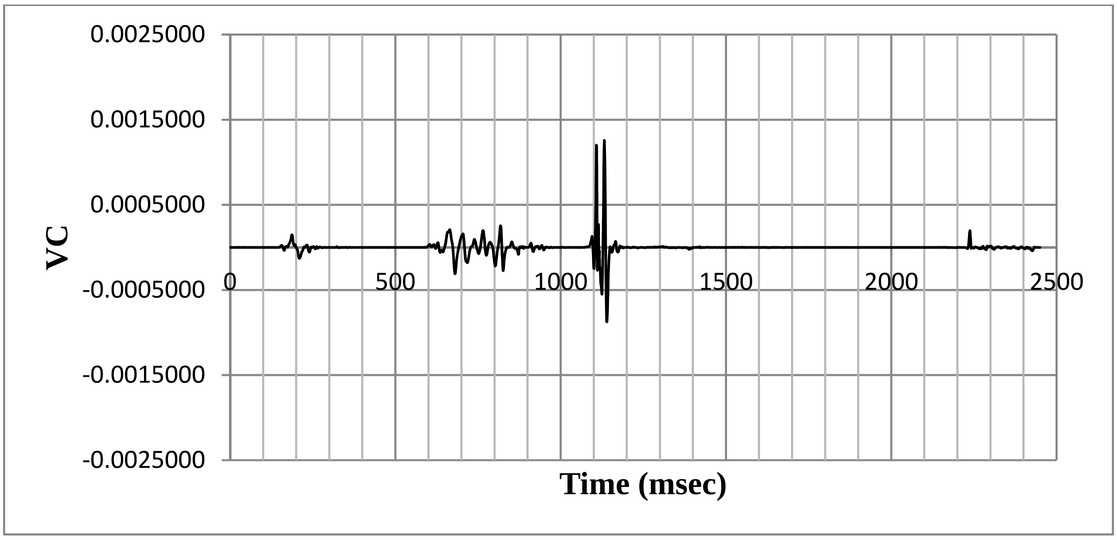


Figure N.2 ATD Position 1 middle rib VC

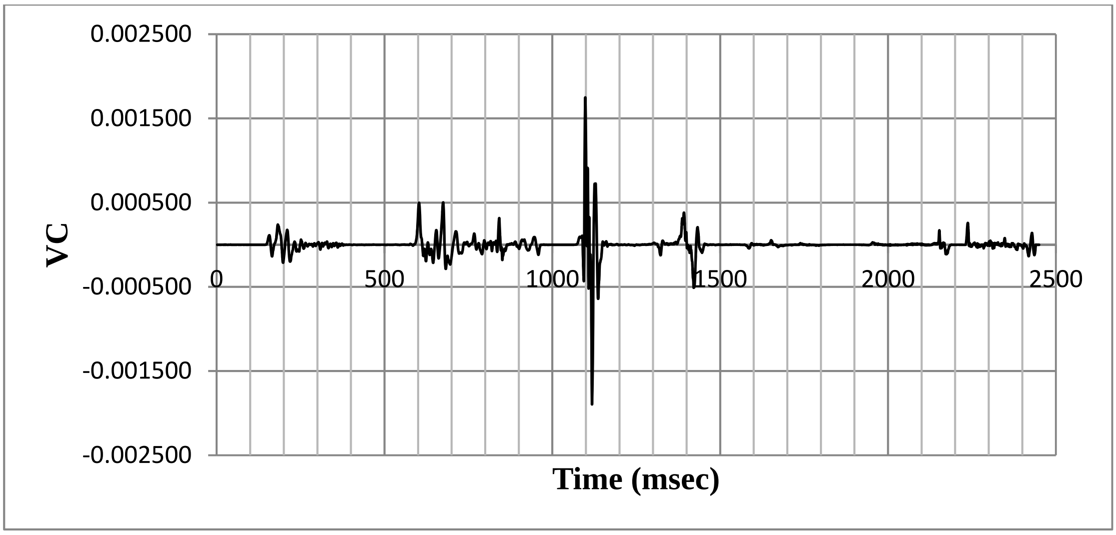


Figure N.3 ATD Position 1 lower rib VC

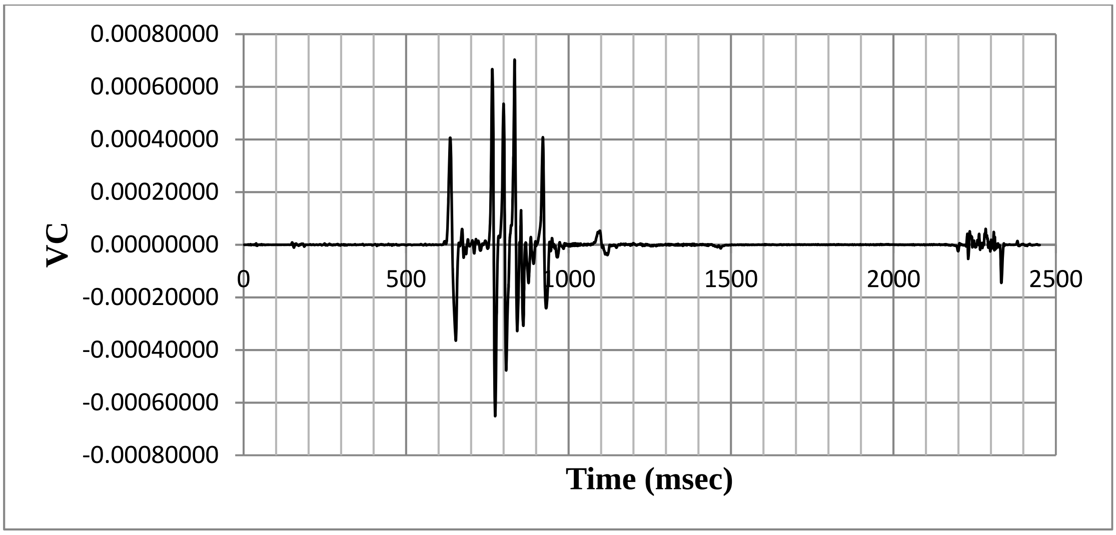


Figure N.4 ATD Position 2 upper rib VC

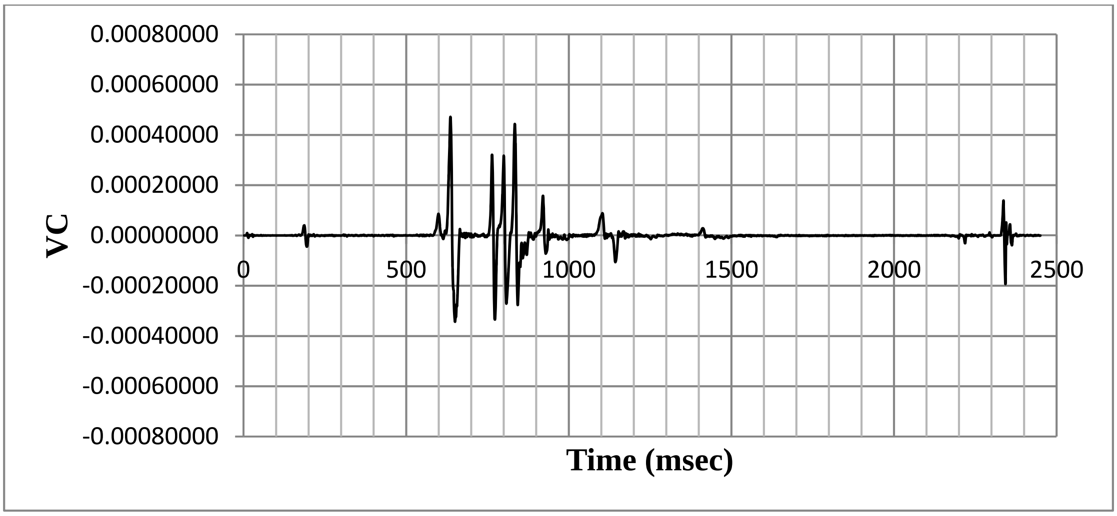


Figure N.5 ATD Position 2 middle rib VC

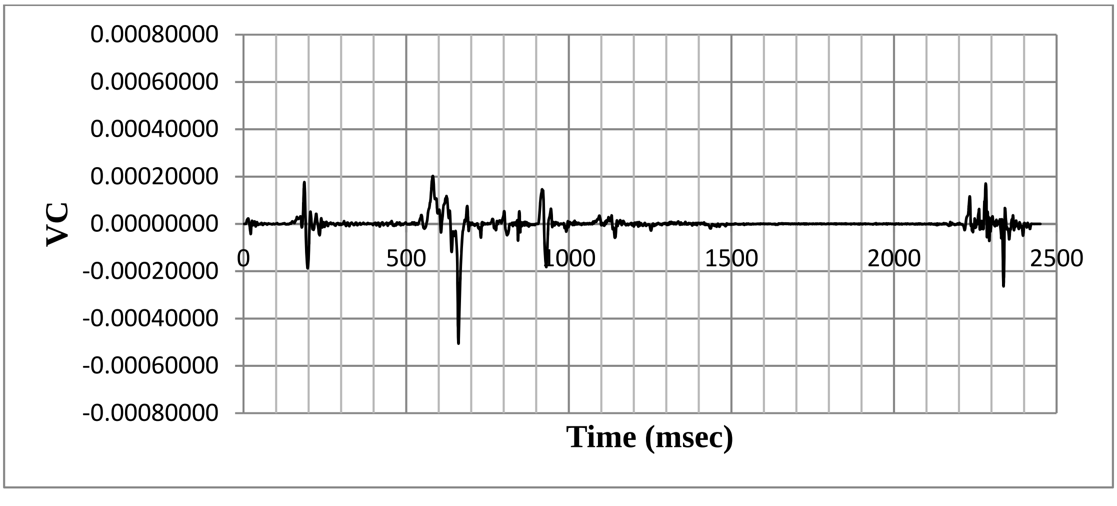


Figure N.6 ATD Position 2 lower rib VC

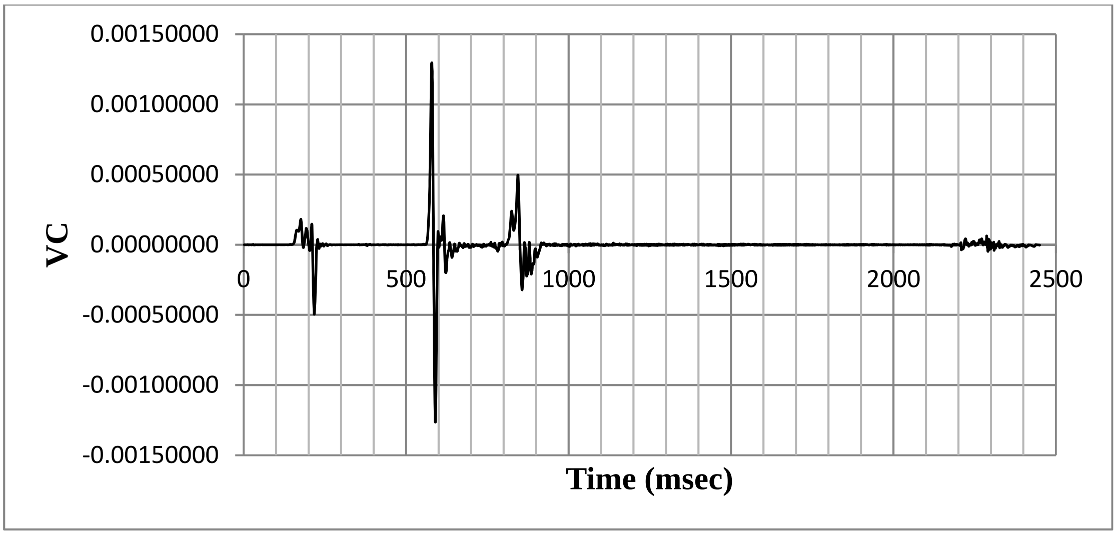


Figure N.7 ATD Position 5 upper rib VC

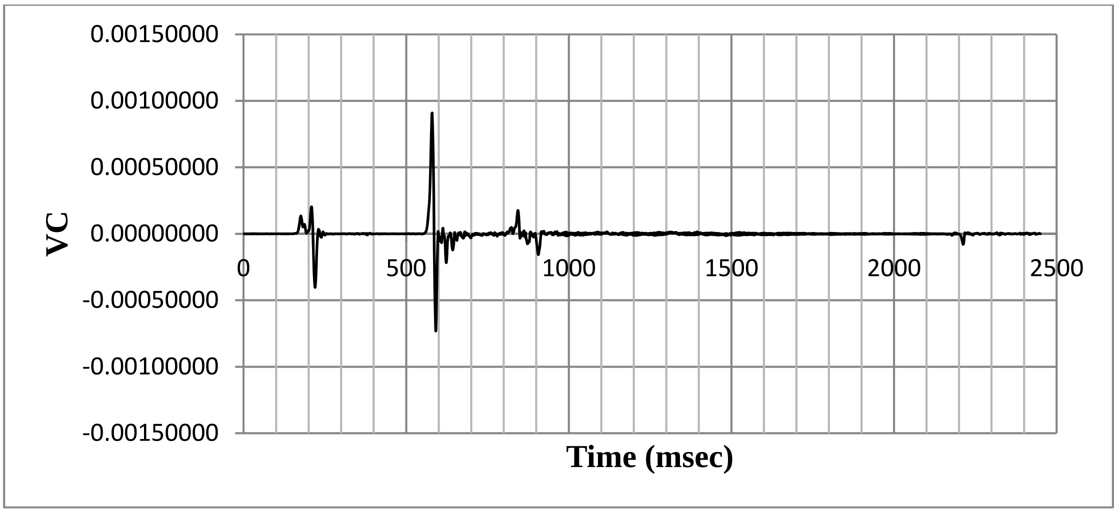


Figure N.8 ATD Position 5 middle rib VC

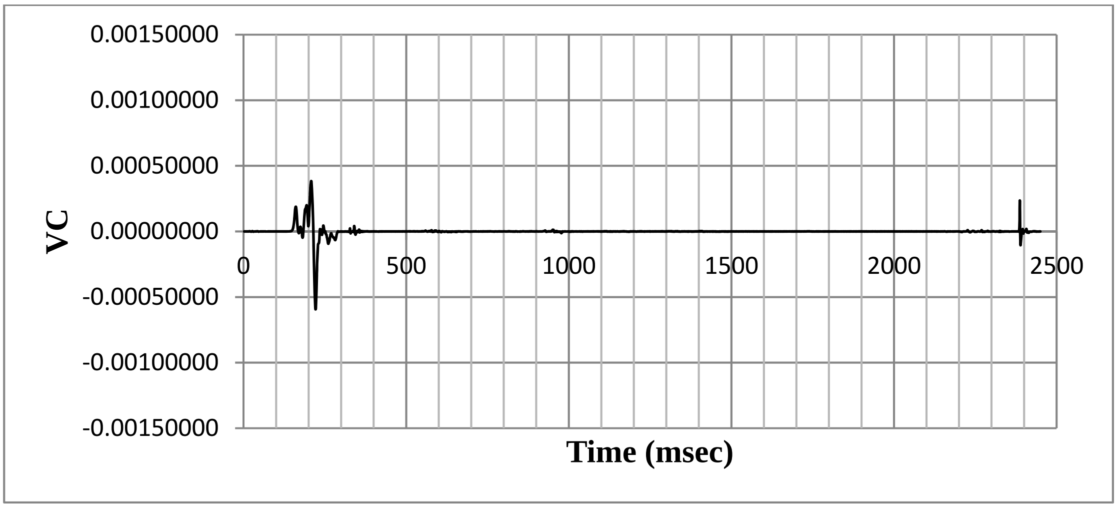


Figure N.9 ATD Position 5 lower rib VC

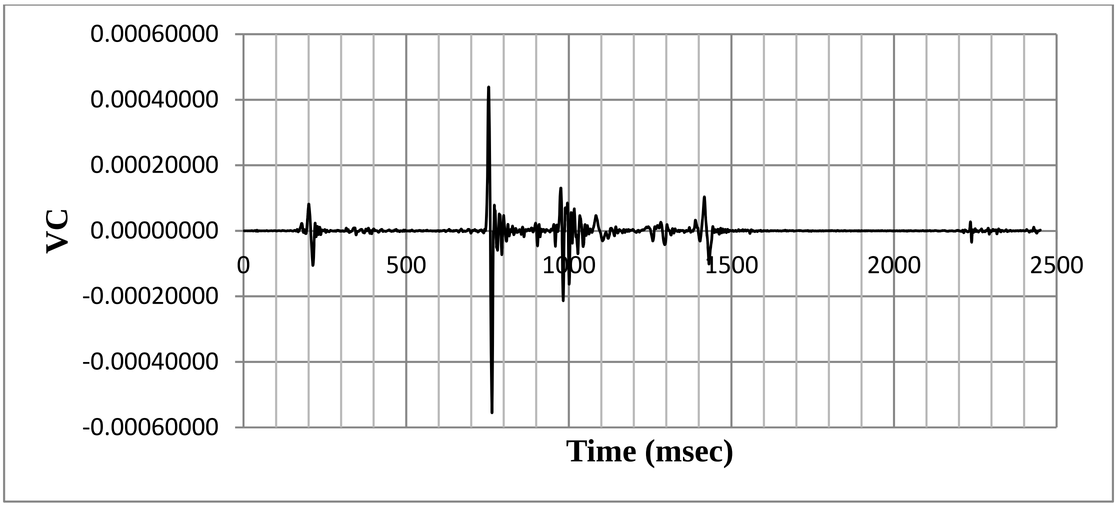


Figure N.10 ATD Position 8 upper rib VC

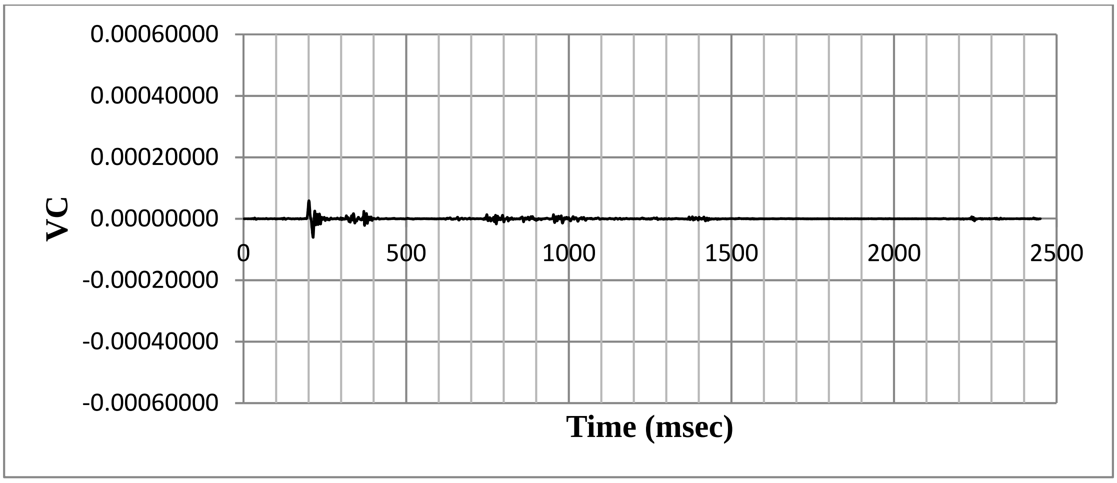


Figure N.11 ATD Position 8 middle rib VC

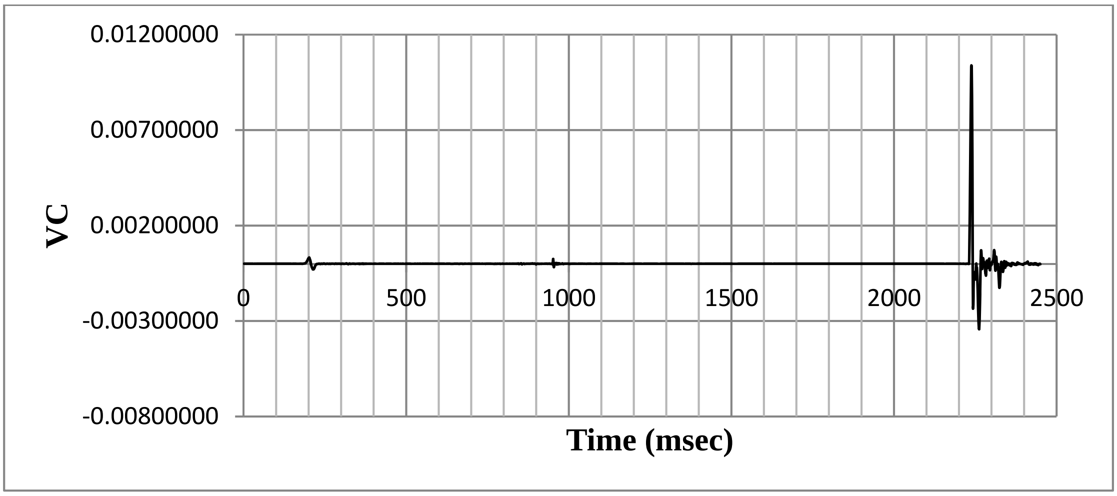


Figure N.12 ATD Position 8 lower rib VC

Appendix O Lateral Impact Velocity Time History Plots

The time history plots below are of the thorax lateral impact velocity for the ATD in Position 1, 2, 5 and 8.

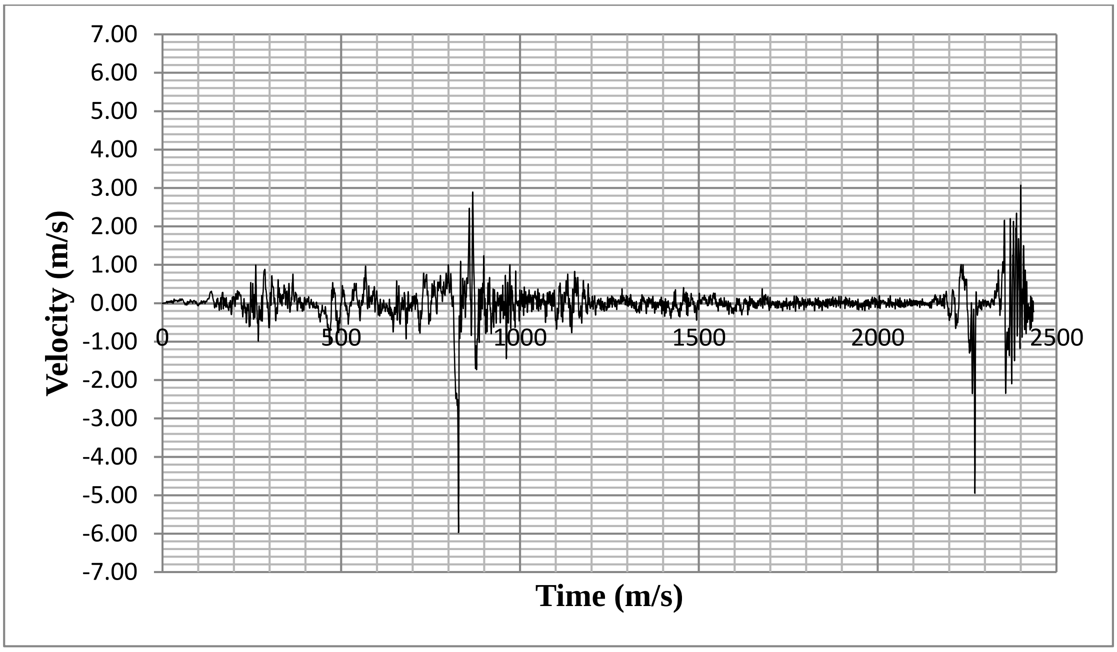


Figure O.1 ATD Position 1 Y-axis velocity for node 380839

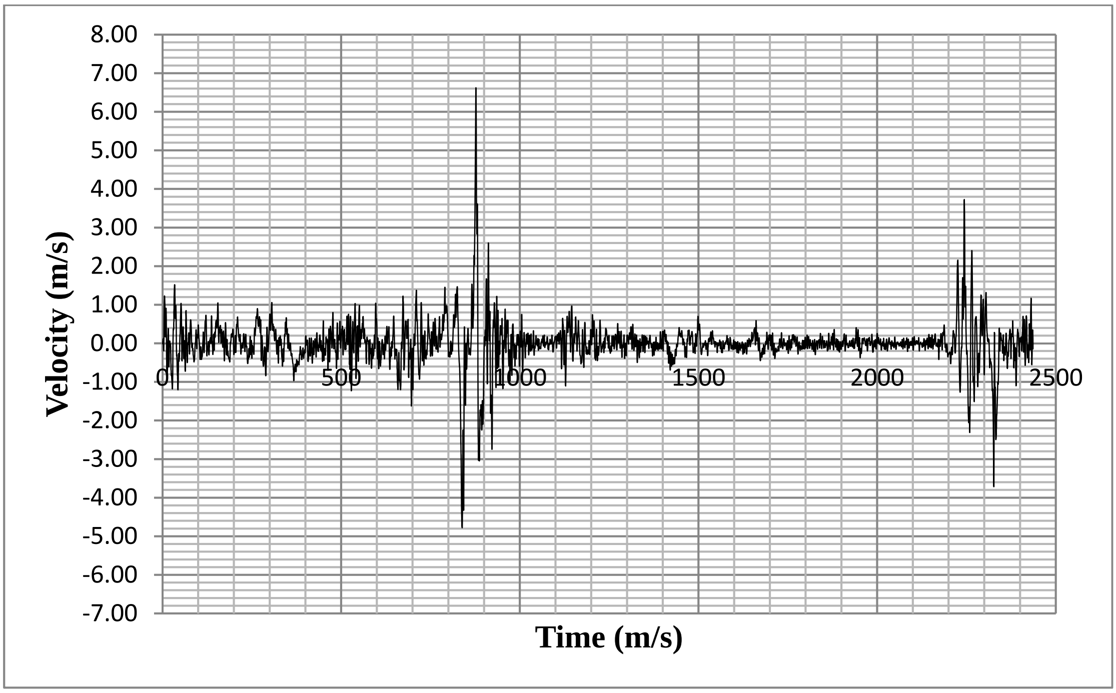


Figure O.2 ATD Position 2 Y-axis velocity for node 380823

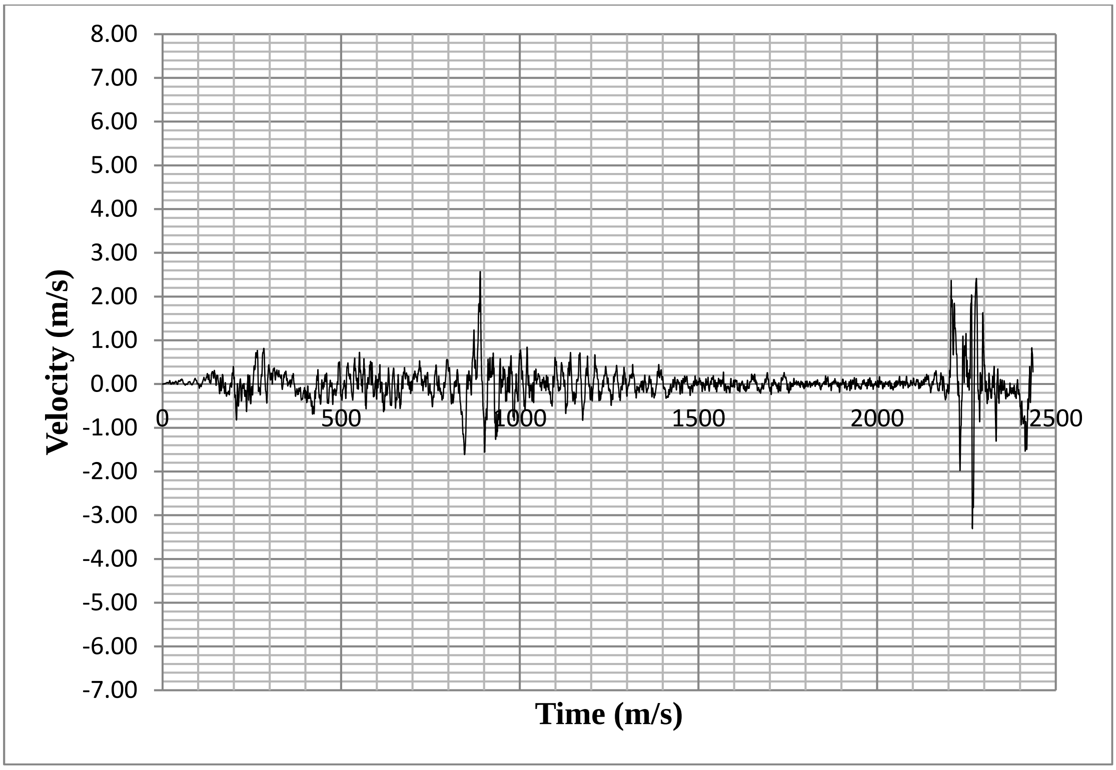


Figure O.3 ATD Position 5 Y-axis velocity for node 380870

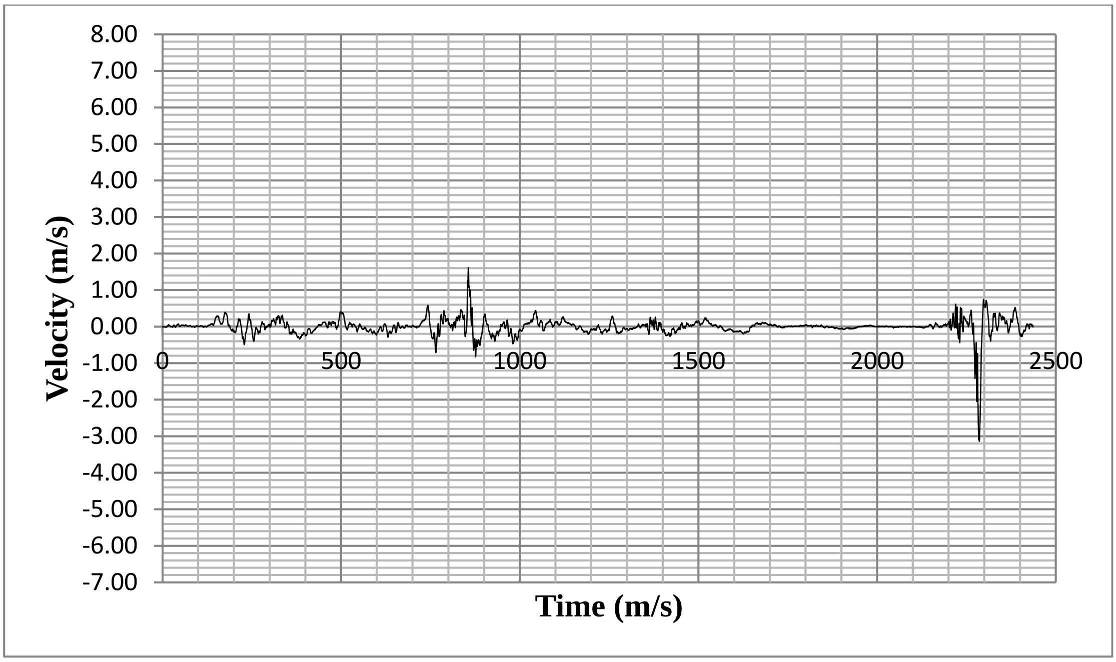


Figure O.4 ATD Position 8 Y-axis velocity for node 381218

Appendix P Thorax Force Time History Plots

The time history plots below are of the thorax force as presented in Tables 6.15 and Table 6.16 for the ATD in Position 1, 2, 5 and 8.

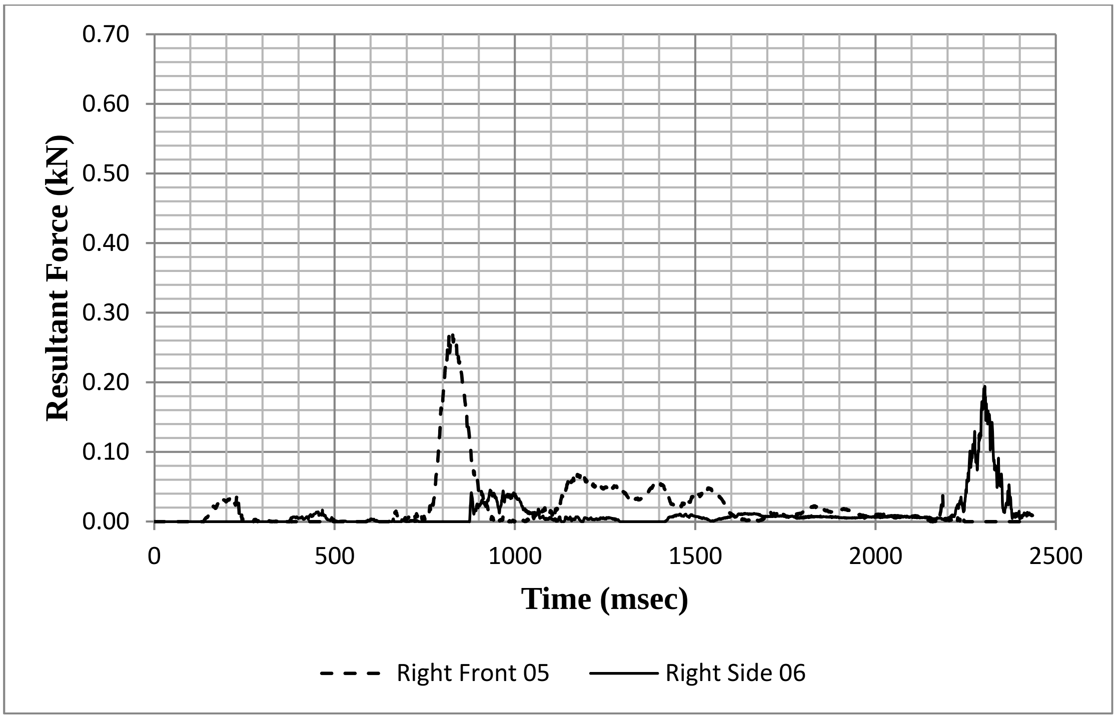


Figure P.1 ATD Position 1 thorax resultant force

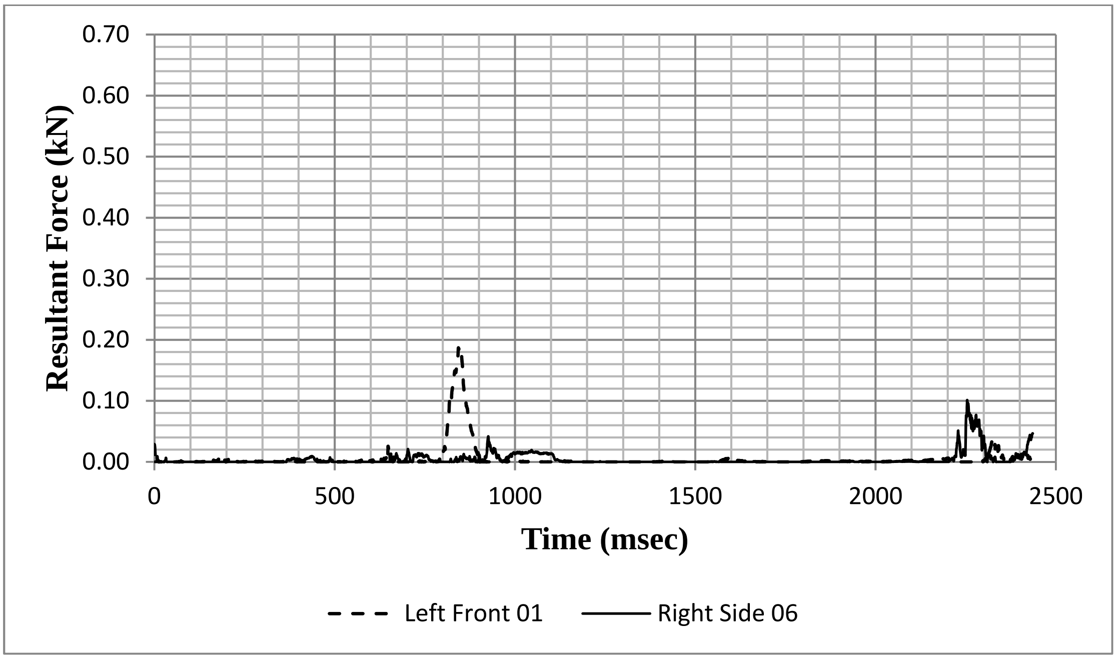


Figure P.2 ATD Position 2 thorax resultant force

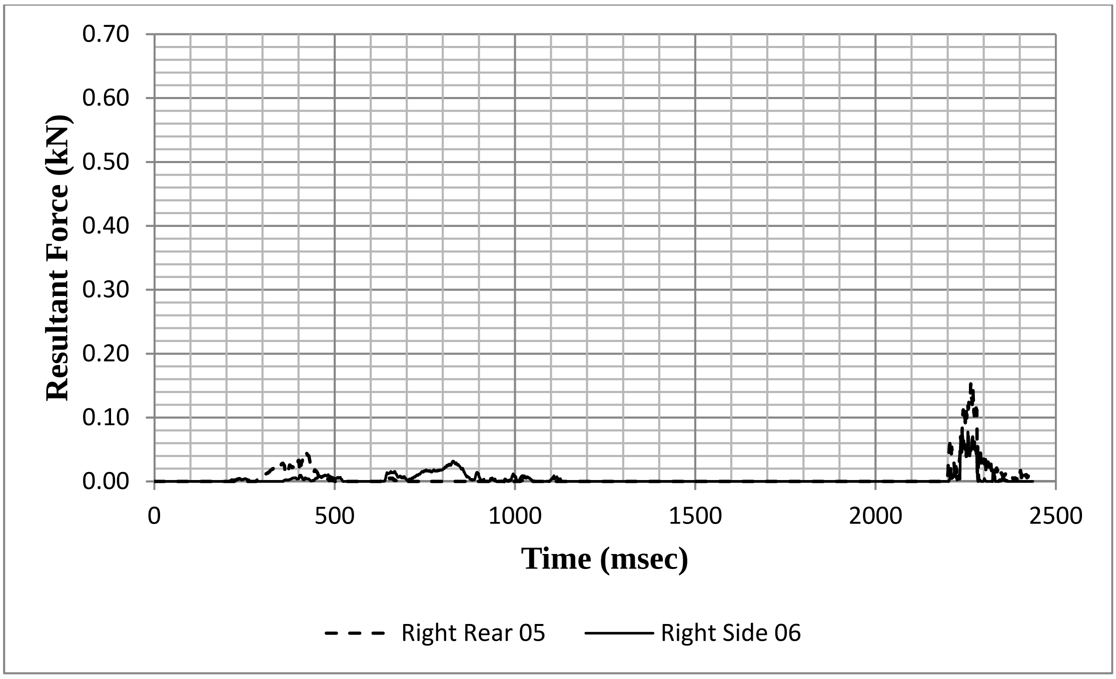


Figure P.3 ATD Position 5 thorax resultant force

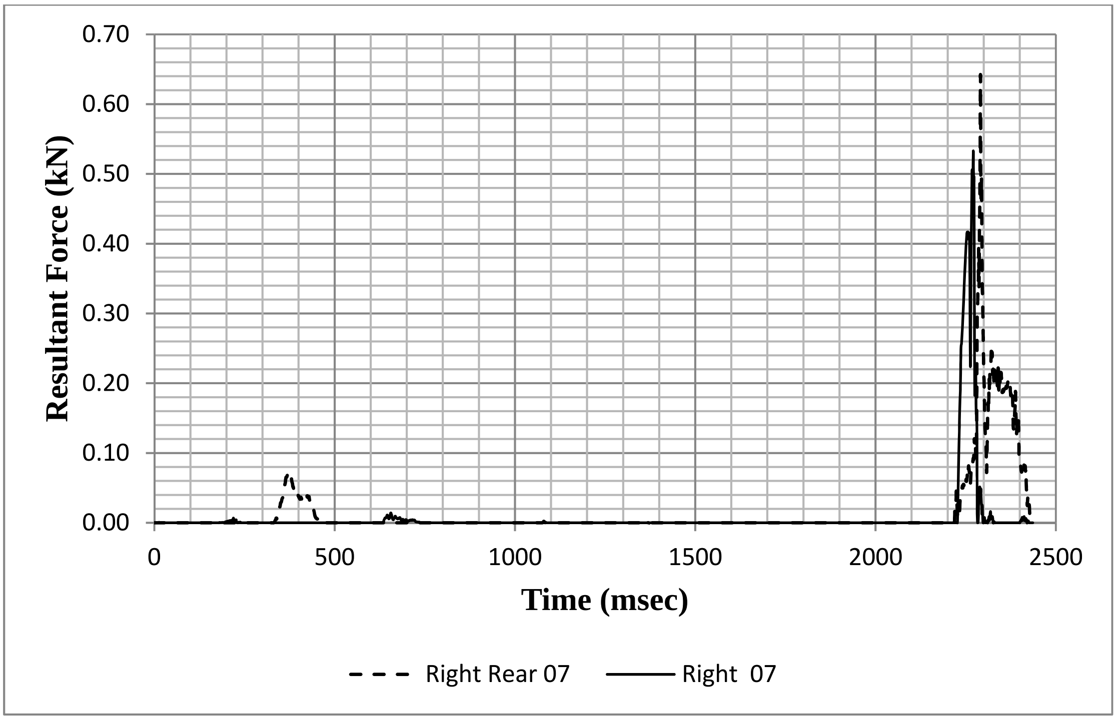


Figure P.4 ATD Position 8 thorax resultant force

Appendix Q Deformed Thorax Segments Force Time History Plots

The time history plots below are of the thorax force for the ATD in Position 1.

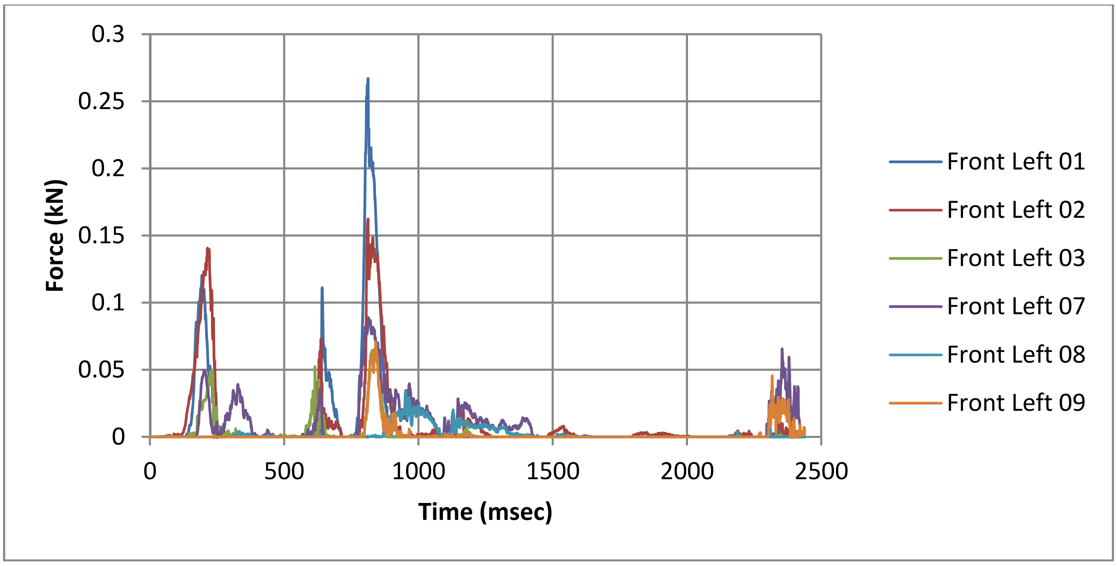


Figure Q.1 ATD Position 1 front left thorax force

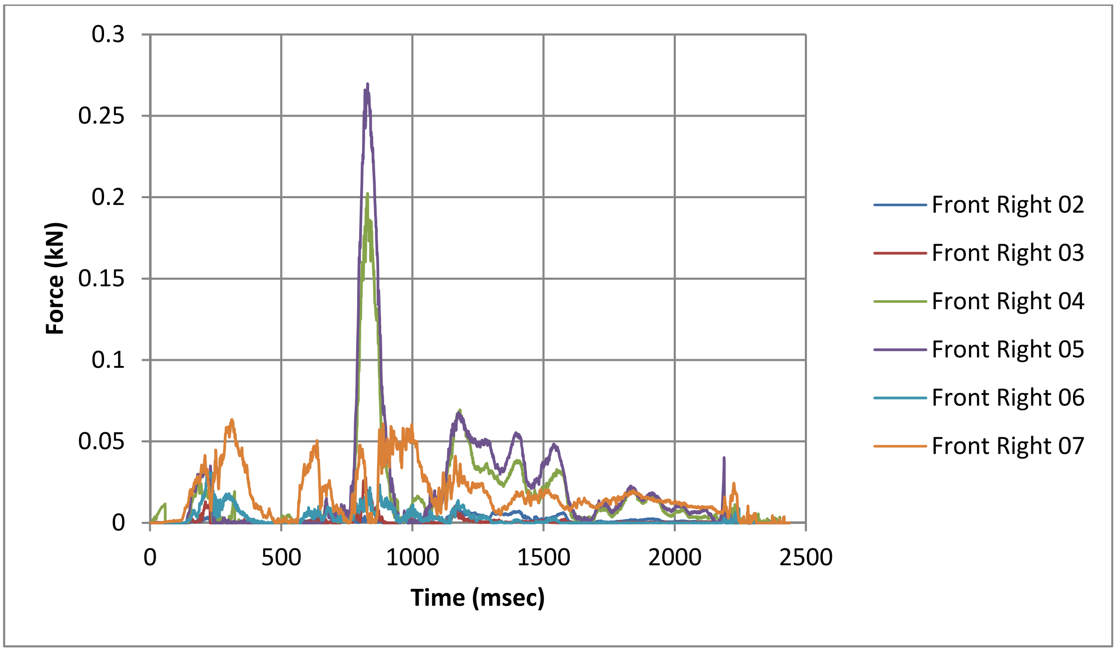


Figure Q.2 ATD Position 1 front right thorax resultant force

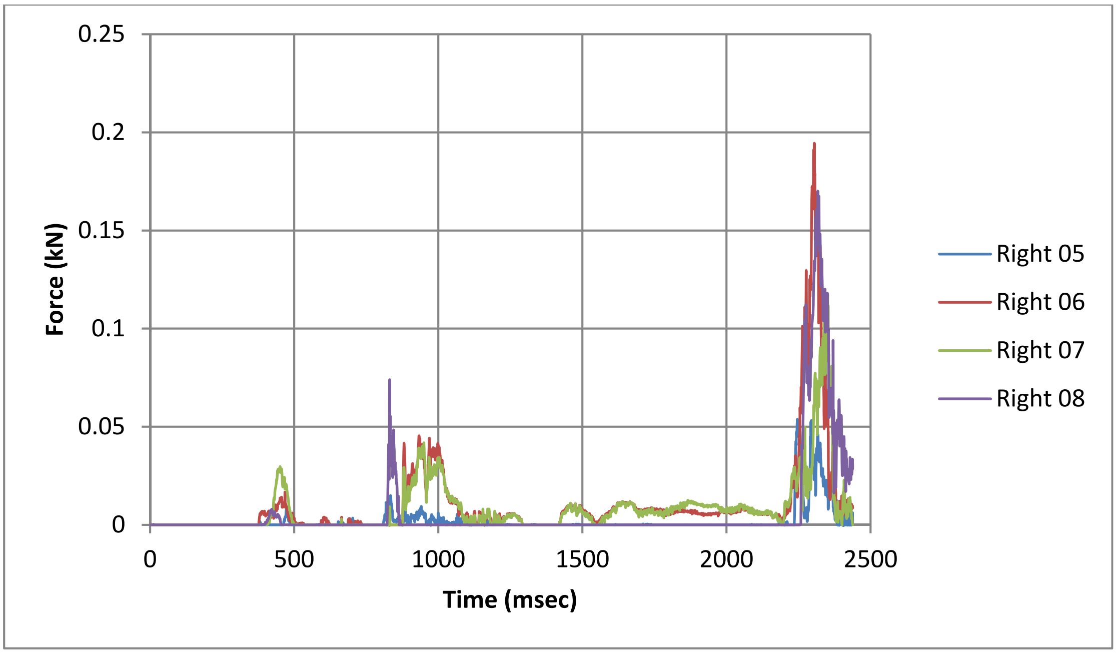


Figure Q.3 ATD Position 1 right thorax resultant force

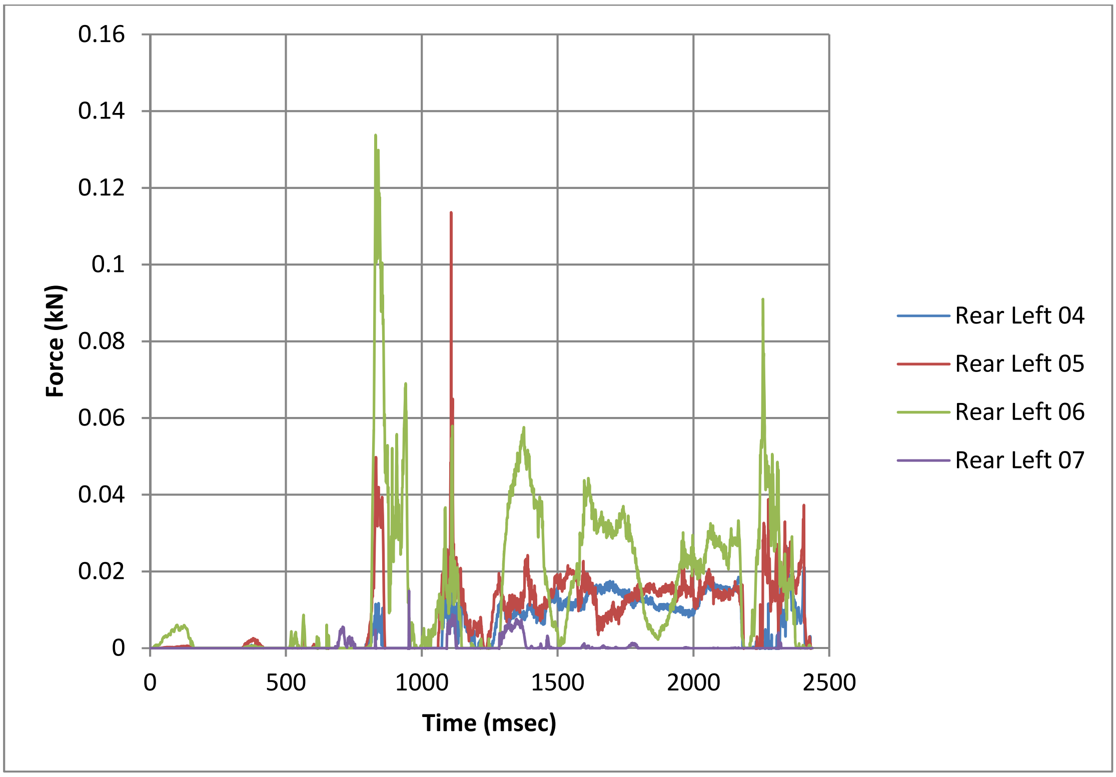


Figure Q.4 ATD Position 1rear left thorax resultant force

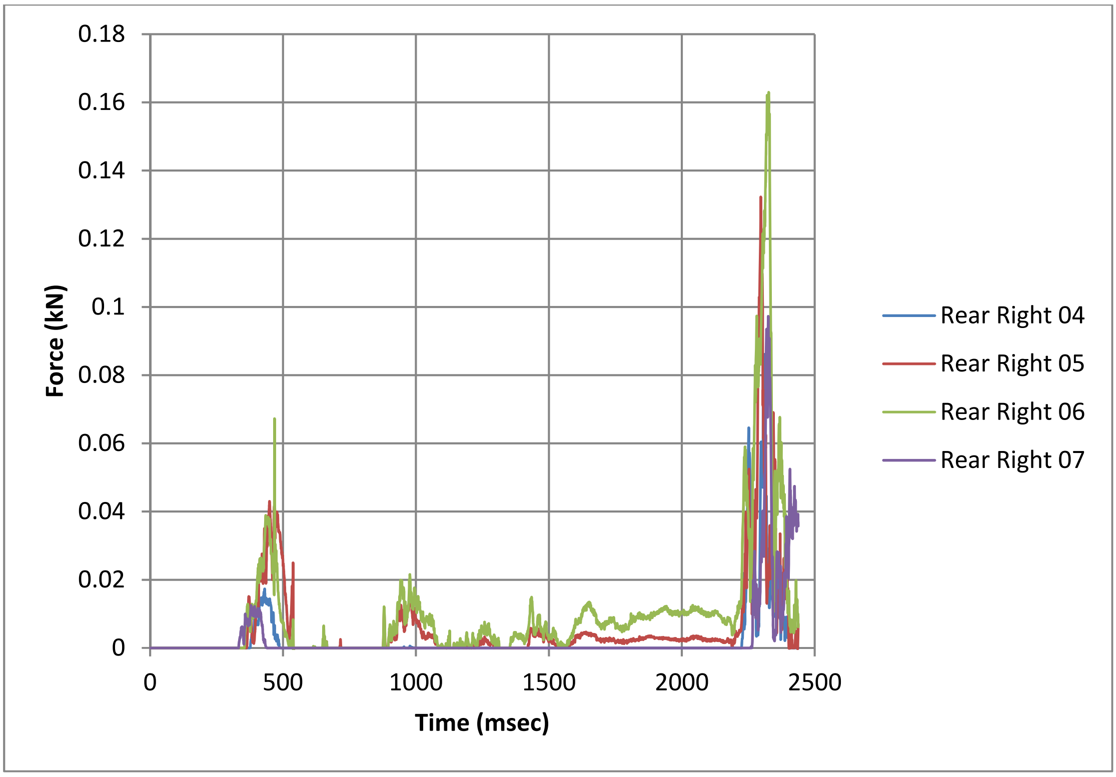


Figure Q.5 ATD Position 1rear right thorax resultant force

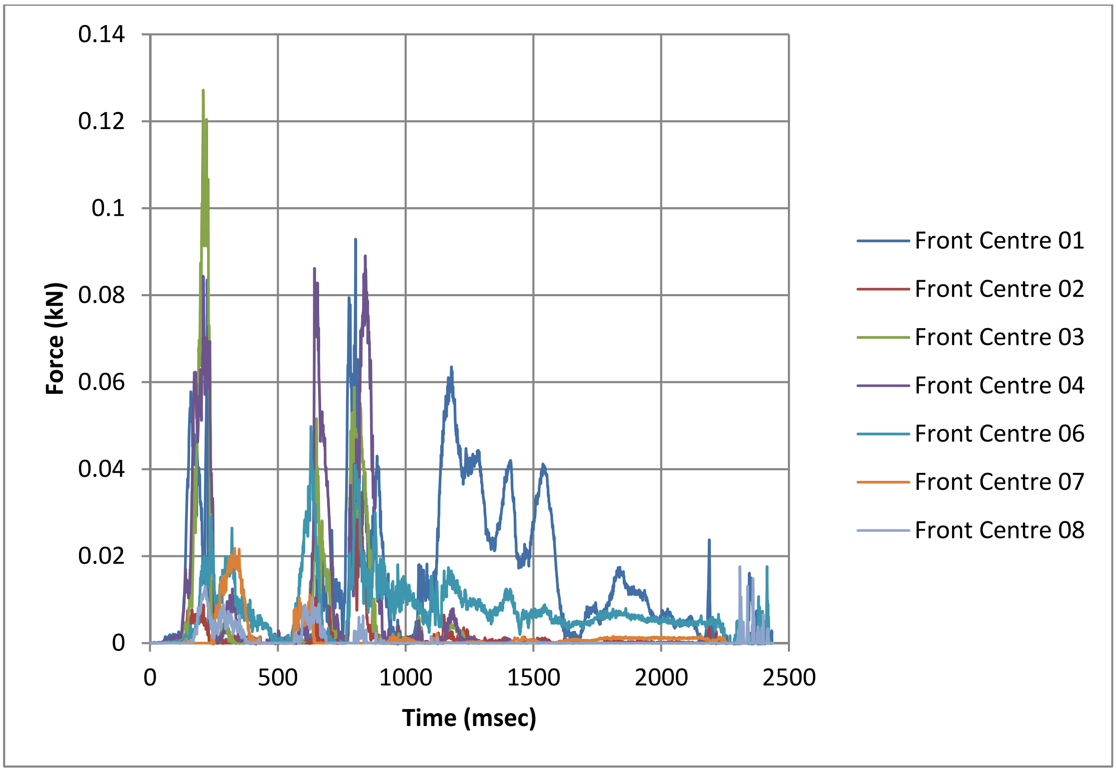


Figure Q.6 ATD Position 1front centre thorax resultant force

The time history plots below are of the thorax force for the ATD in Position 2.

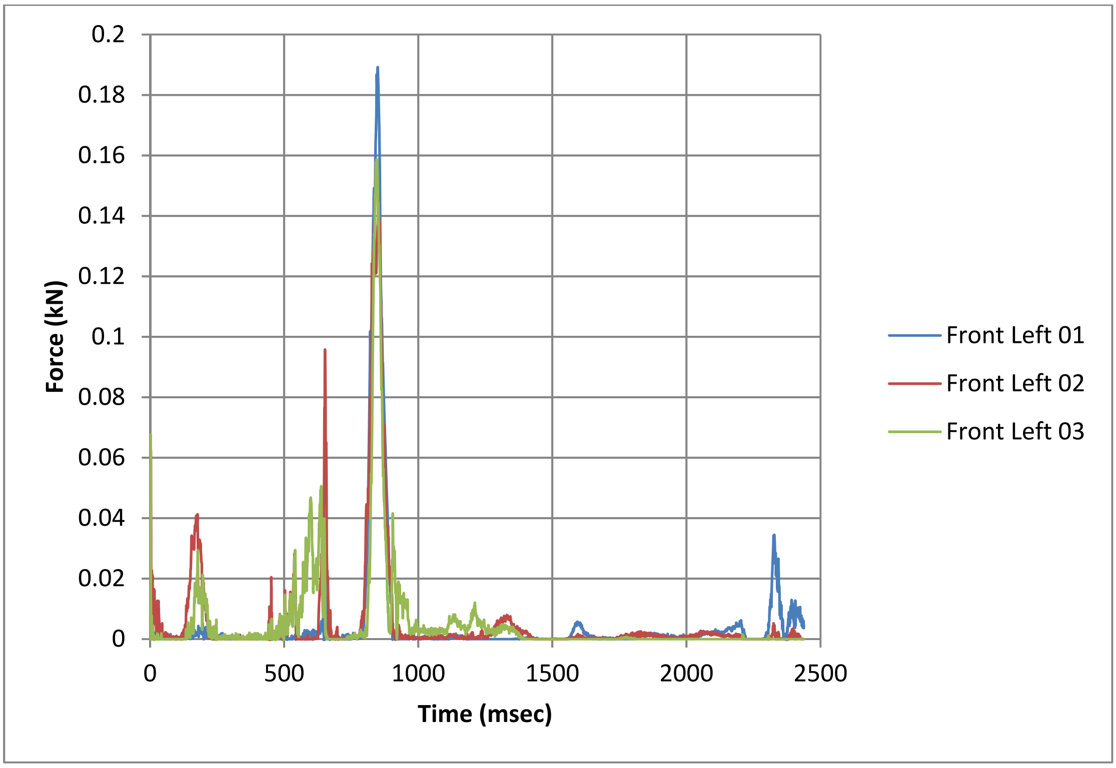


Figure Q.7 ATD Position 2 front left thorax force

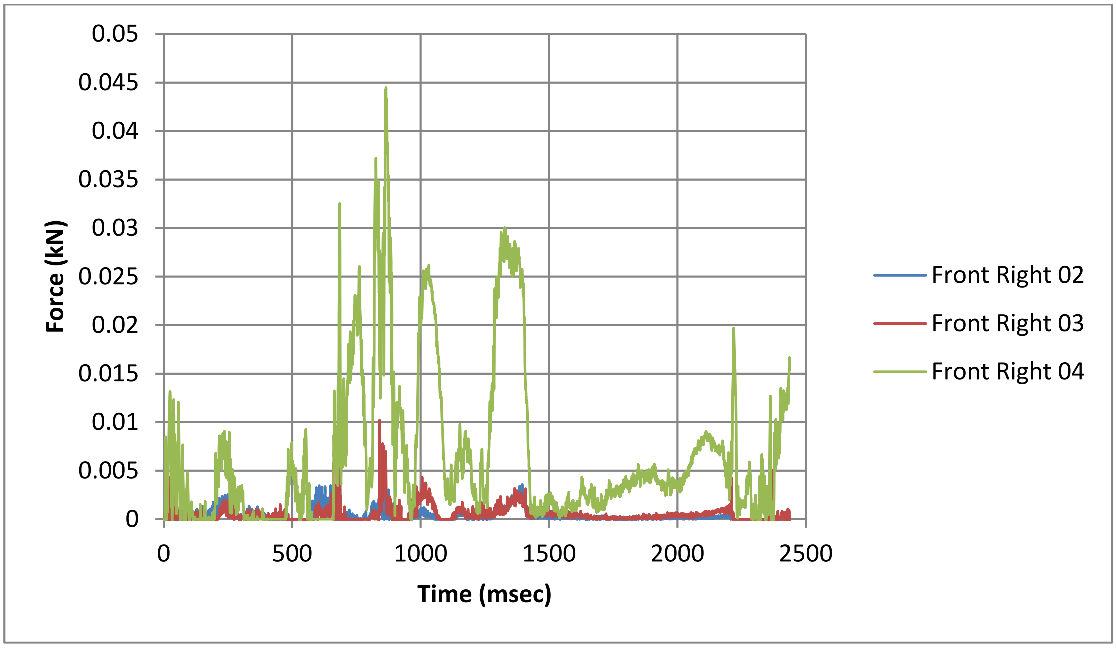


Figure Q.8 ATD Position 2 front right thorax resultant force

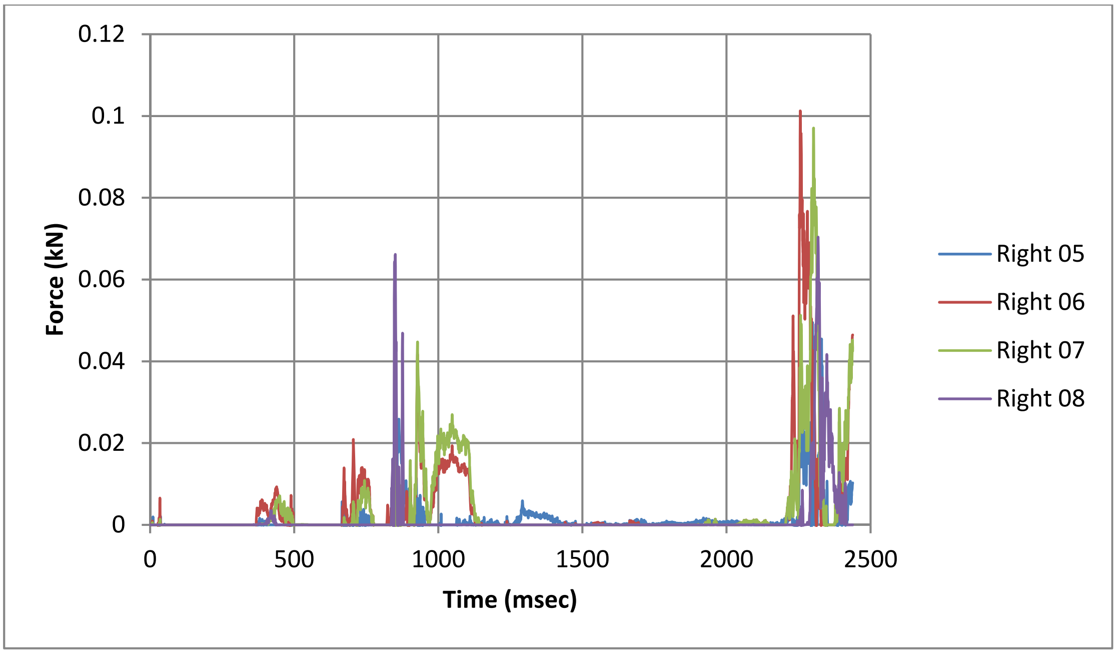


Figure Q.9 ATD Position 2 right thorax resultant force

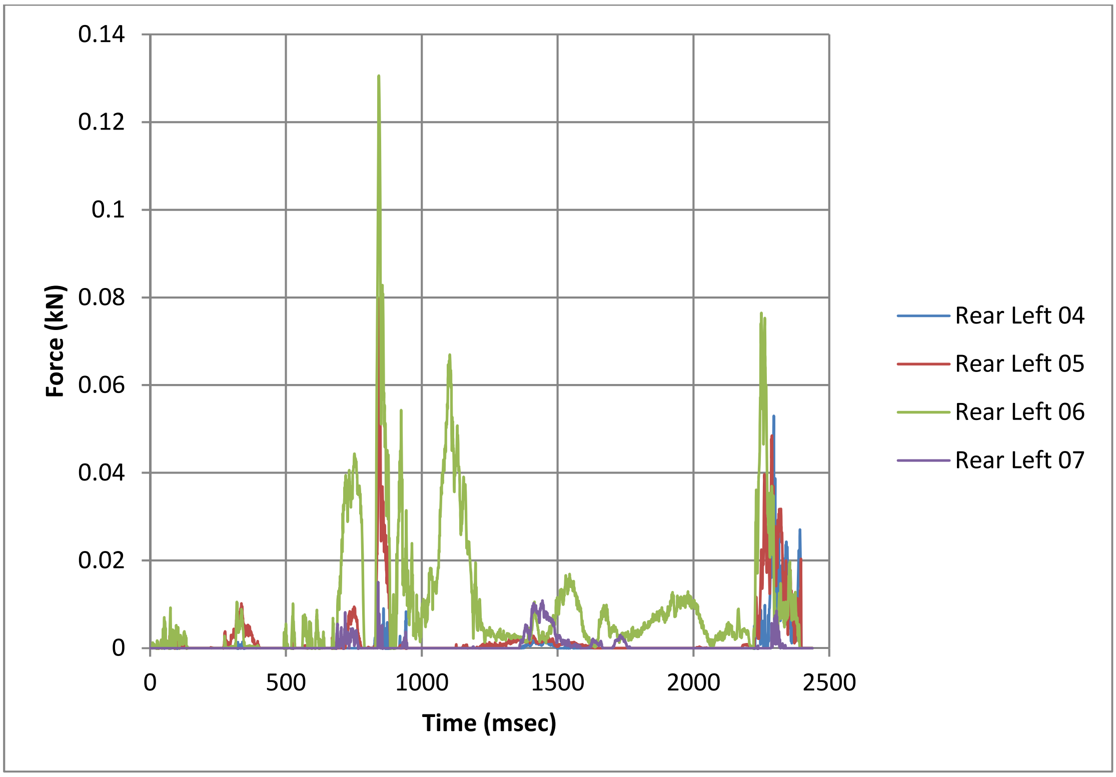


Figure Q.10 ATD Position 2 rear left thorax resultant force

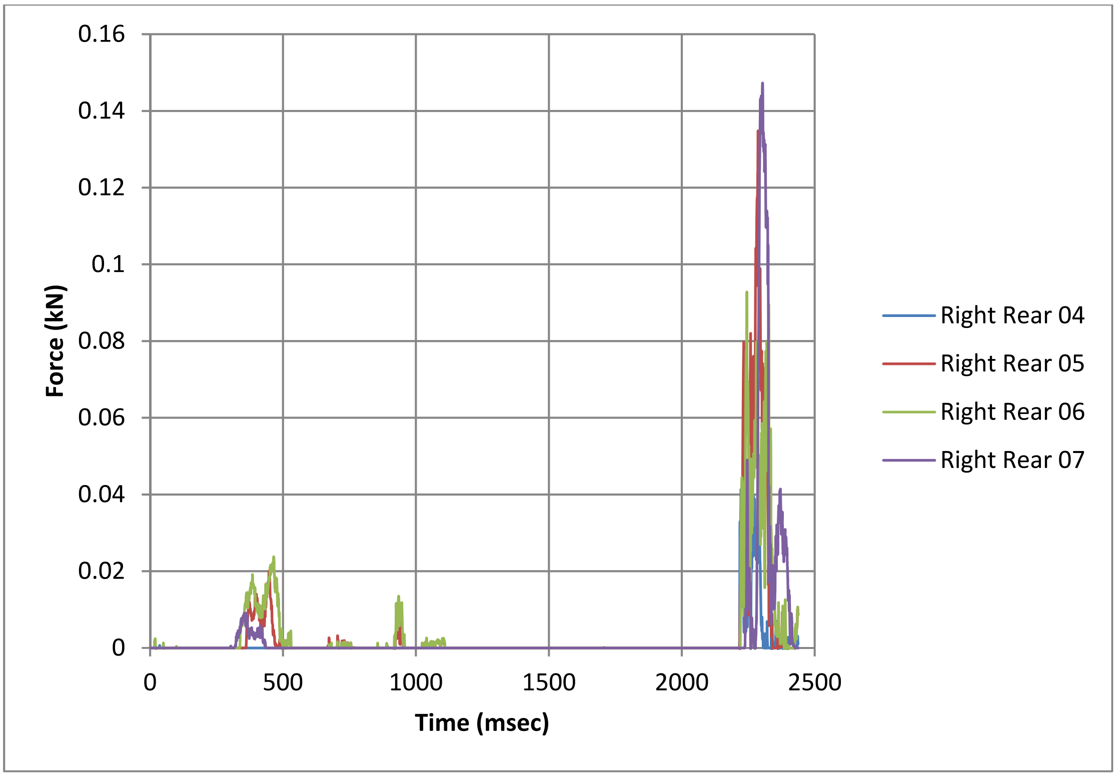


Figure Q.11 ATD Position 2 rear right thorax resultant force

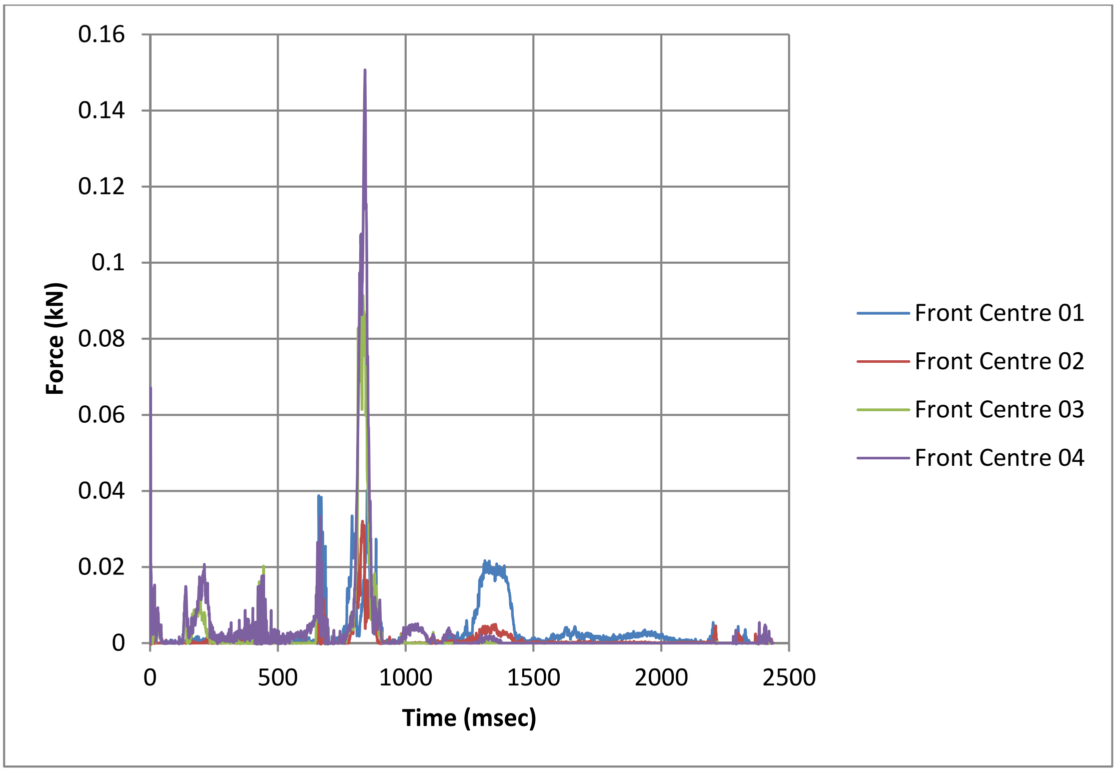


Figure Q.12 ATD Position 2 front centre thorax resultant force

The time history plots below are of the thorax force for the ATD in Position 5.

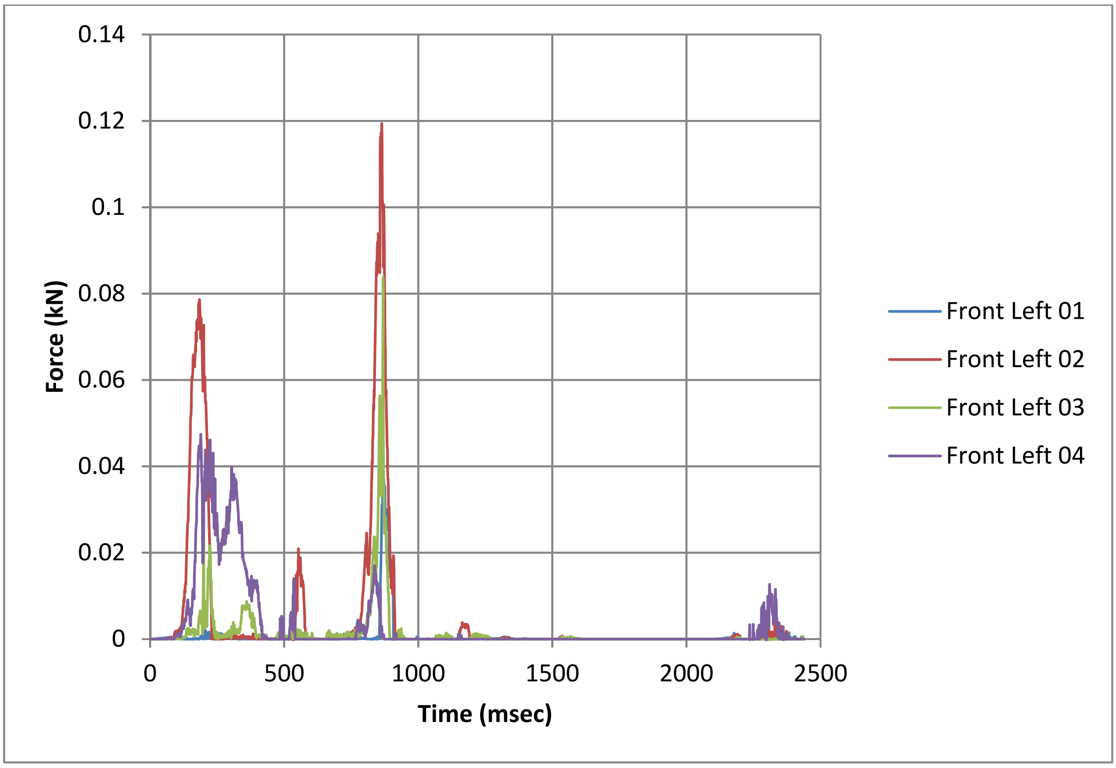


Figure Q.13 ATD Position 5 front left thorax force

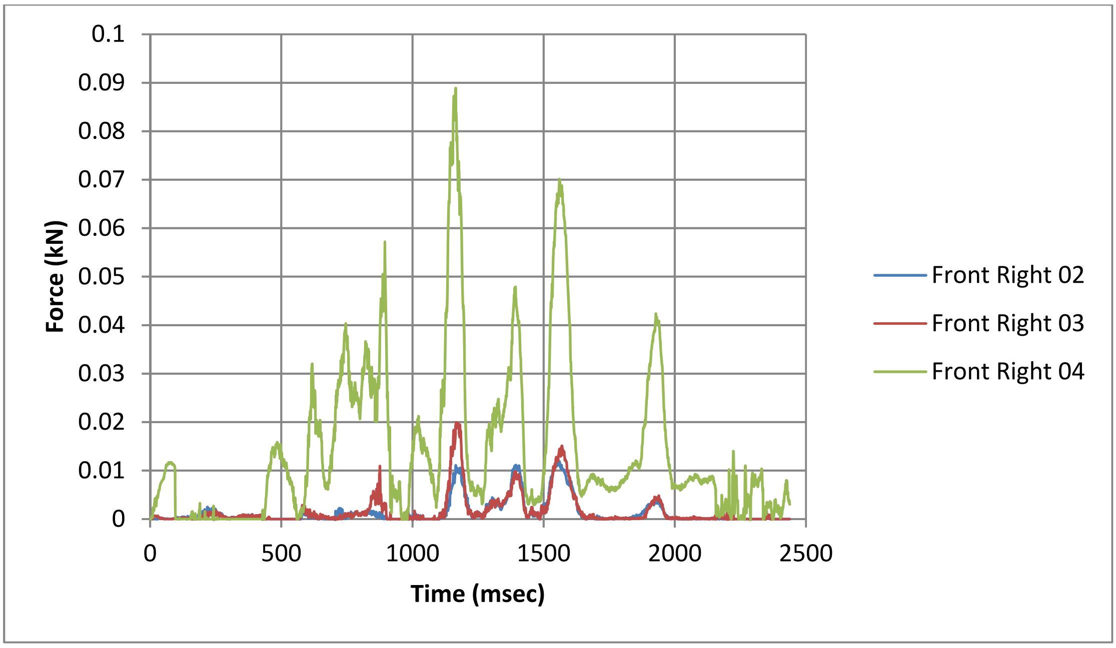


Figure Q.14 ATD Position 5 front right thorax resultant force

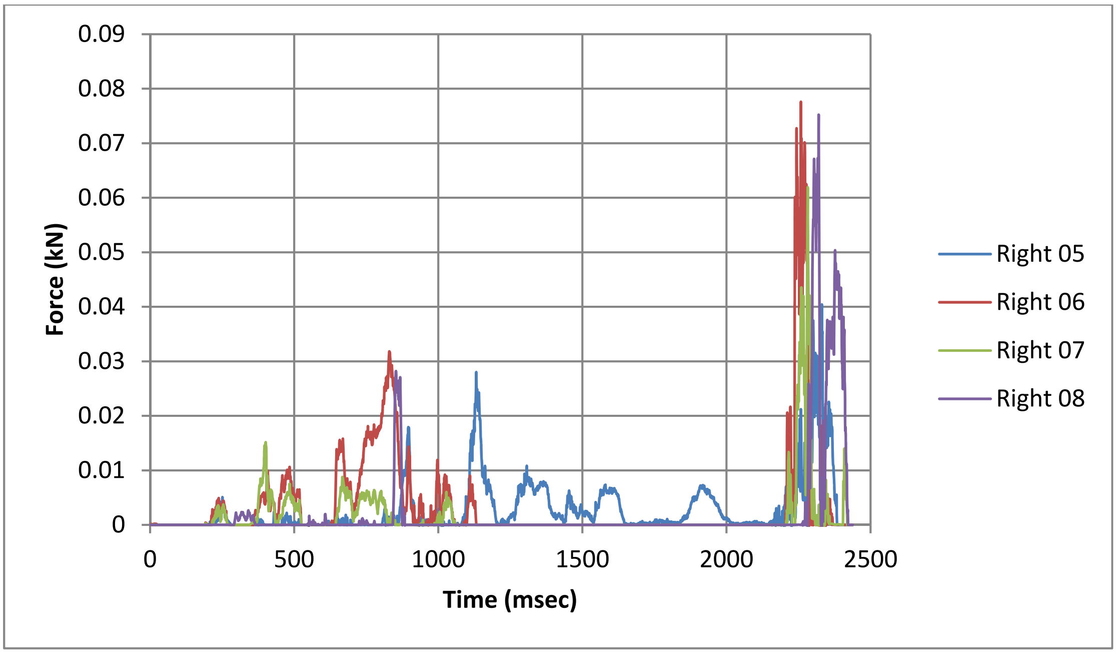


Figure Q.15 ATD Position 5 right thorax resultant force

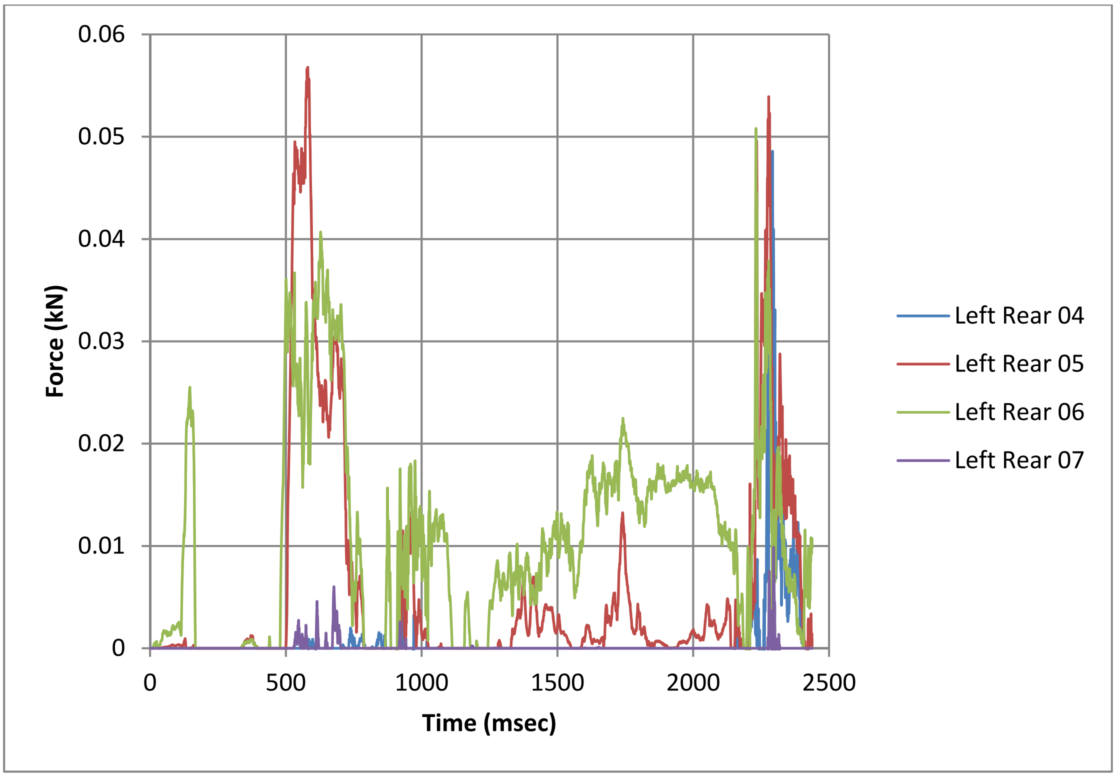


Figure Q.16 ATD Position 5 rear left thorax resultant force

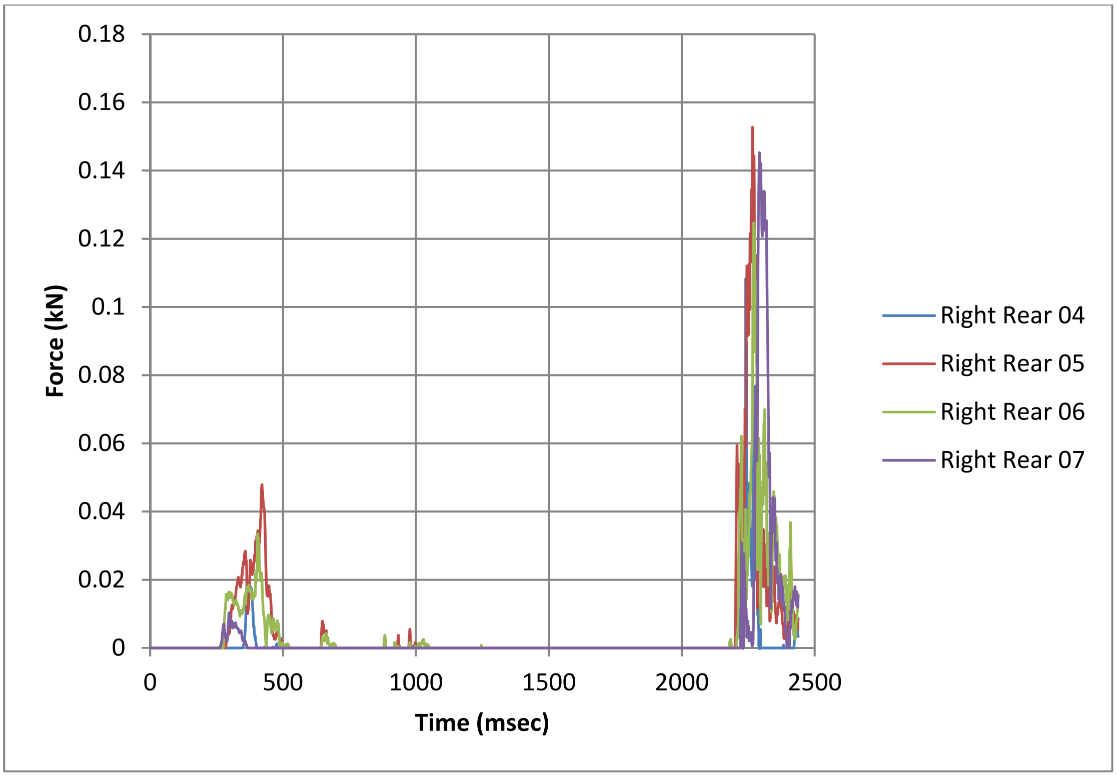


Figure Q.17 ATD Position 5 rear right thorax resultant force

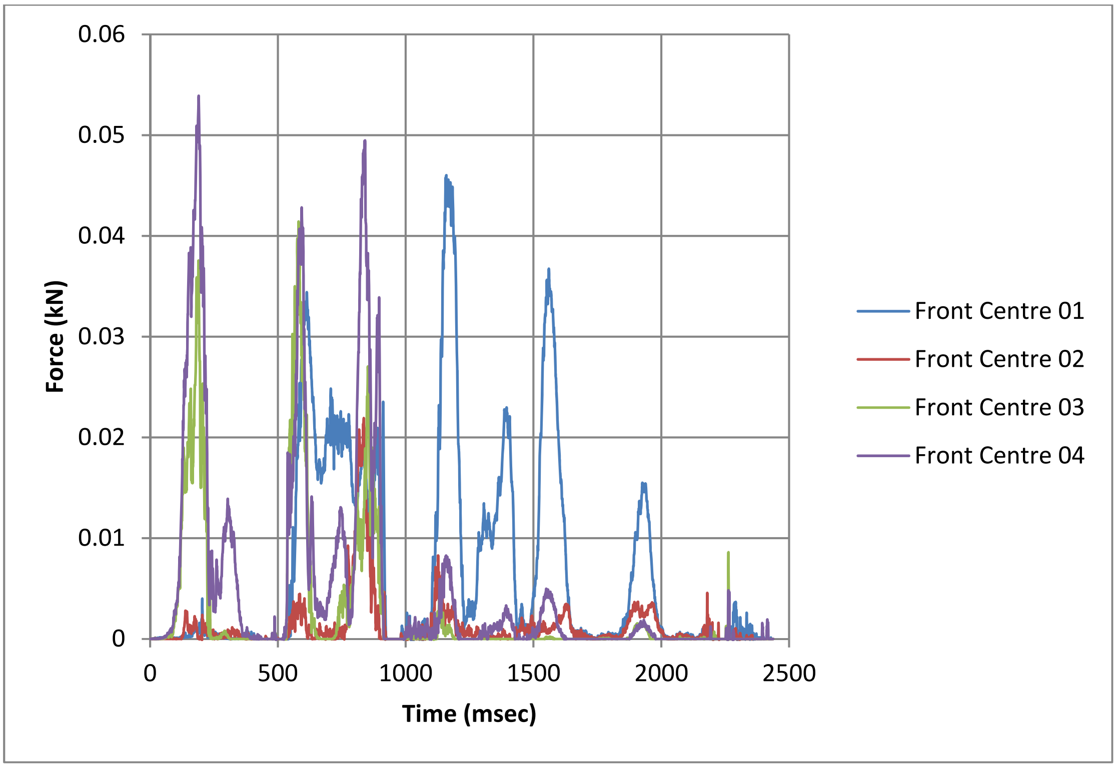


Figure Q.18 ATD Position 5 front centre thorax resultant force

The time history plots below are of the thorax force for the ATD in Position 8.

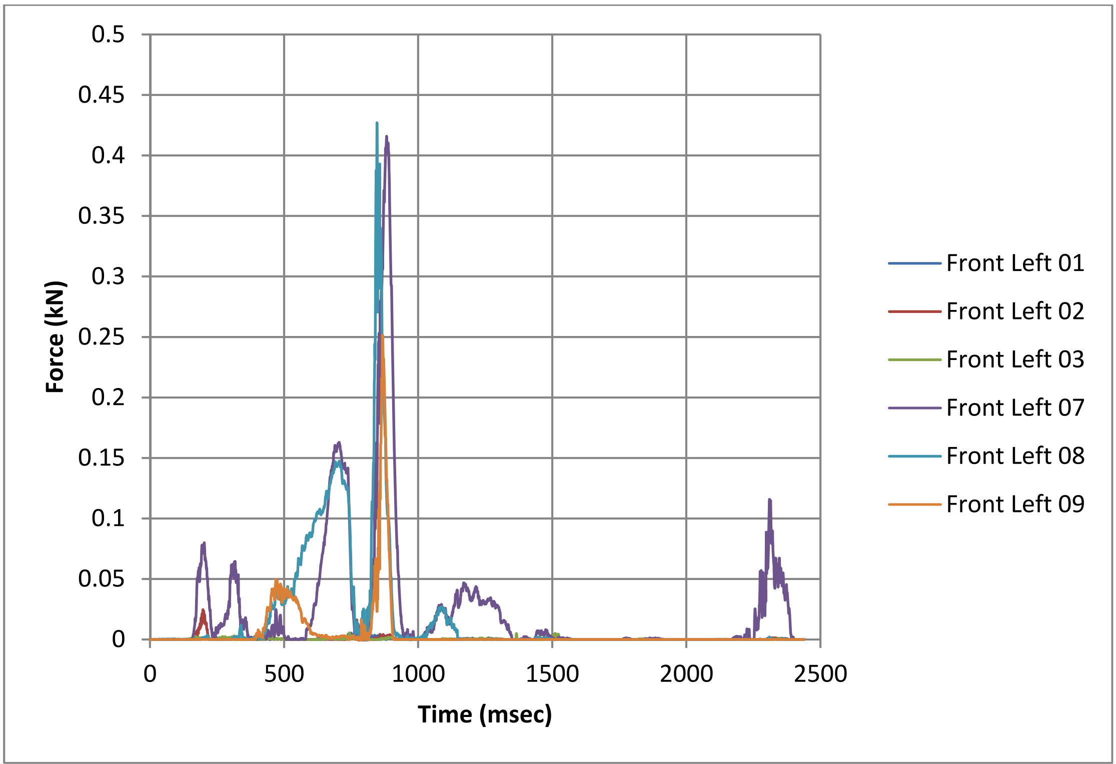


Figure Q.19 ATD Position 8 front left thorax force

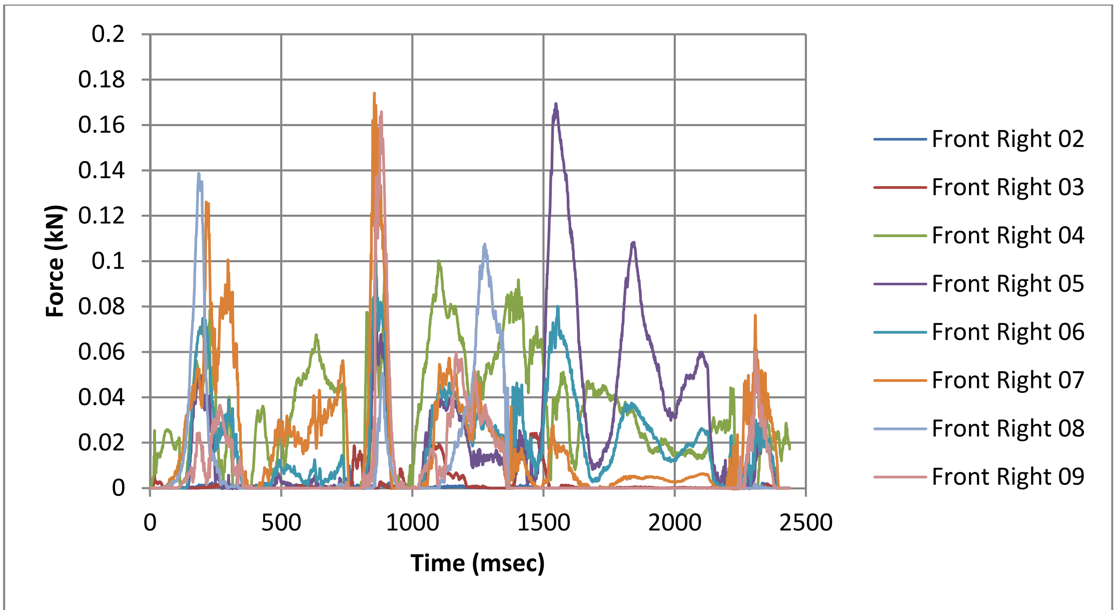


Figure Q.20 ATD Position 8 front right thorax resultant force

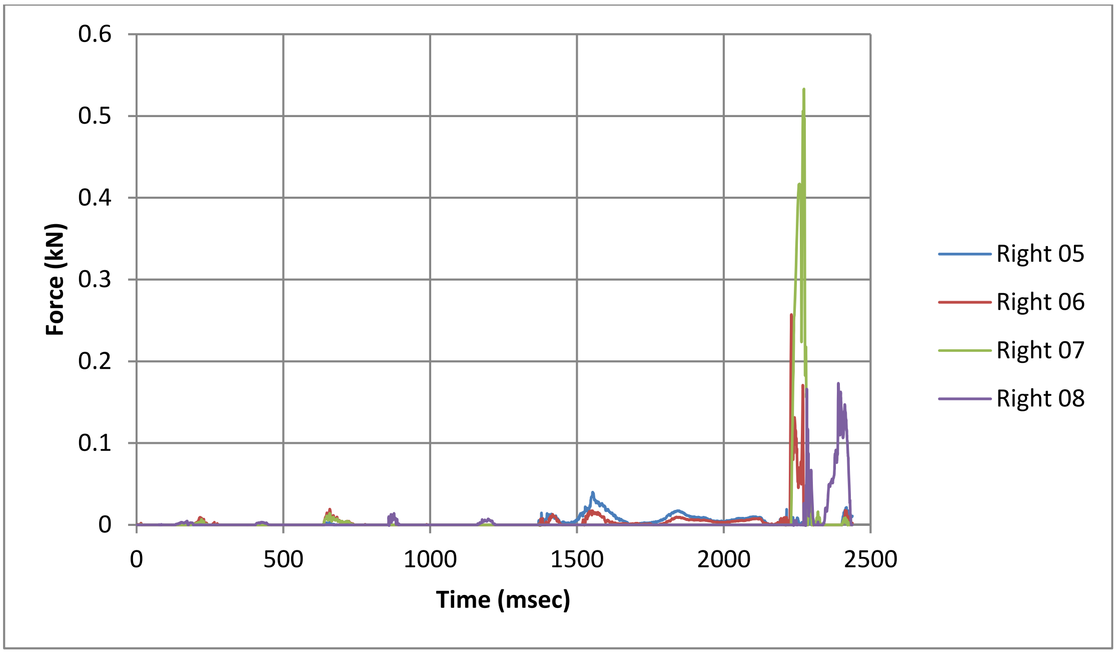


Figure Q.21 ATD Position 8 right thorax resultant force

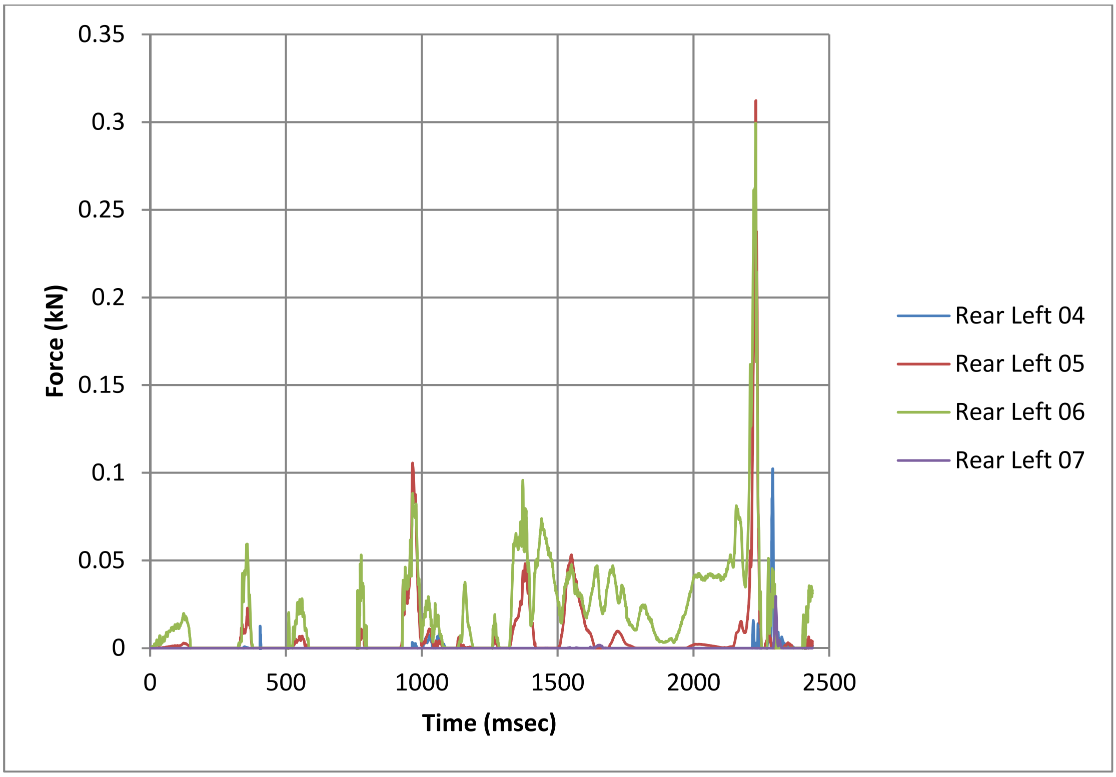


Figure Q.22 ATD Position 8 rear left thorax resultant force

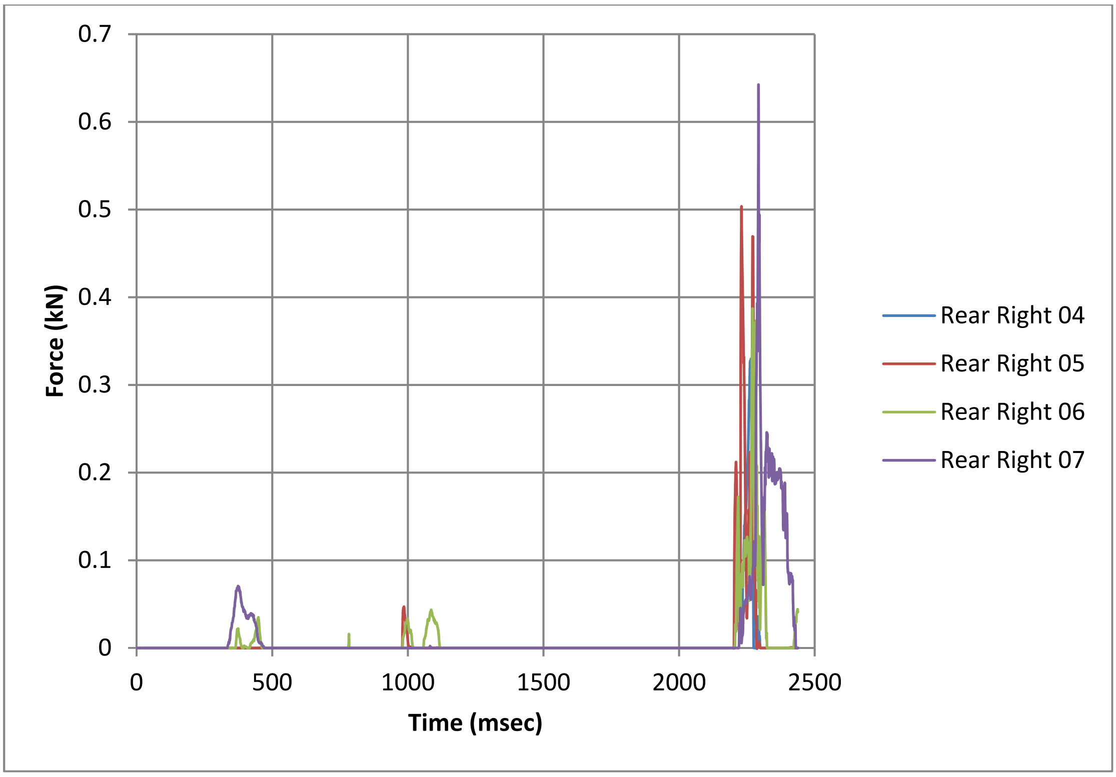


Figure Q.23 ATD Position 8 rear right thorax resultant force

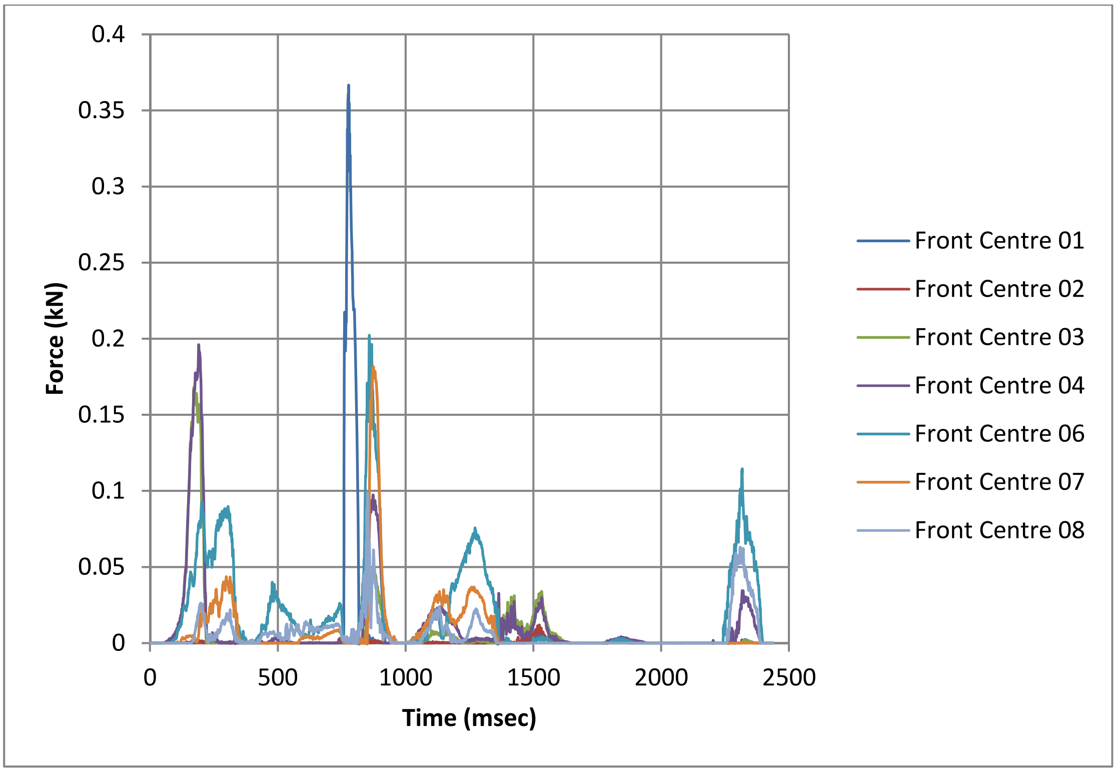


Figure Q.24 ATD Position 8 front centre thorax resultant force

Appendix R Seatbelt Axial Force Time History Plots

The time history plots below are of the thorax force for the ATD in Position 1, 2, 5 and 8.

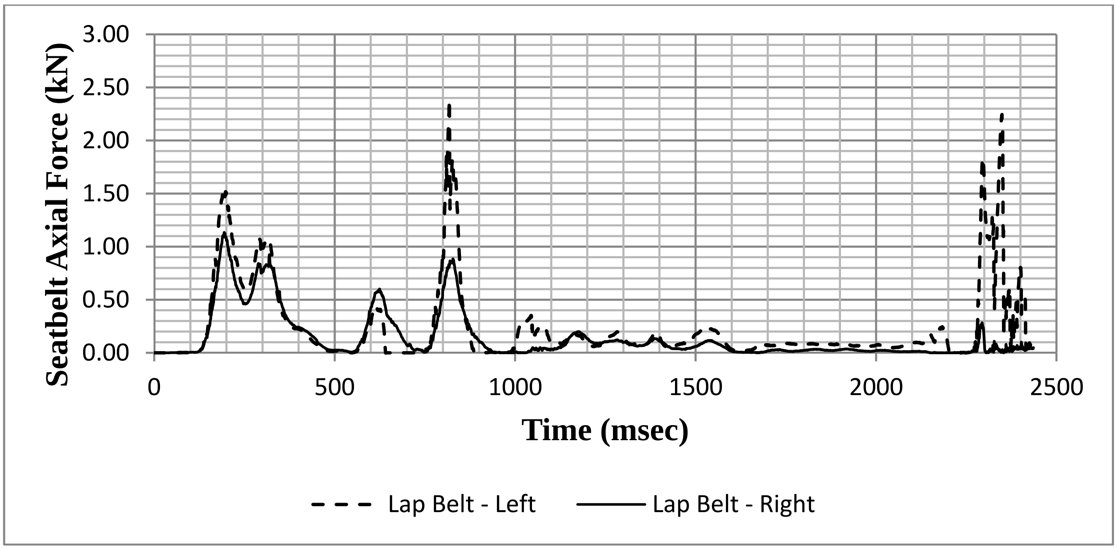


Figure R.1 ATD Position 1 lap belt axial force

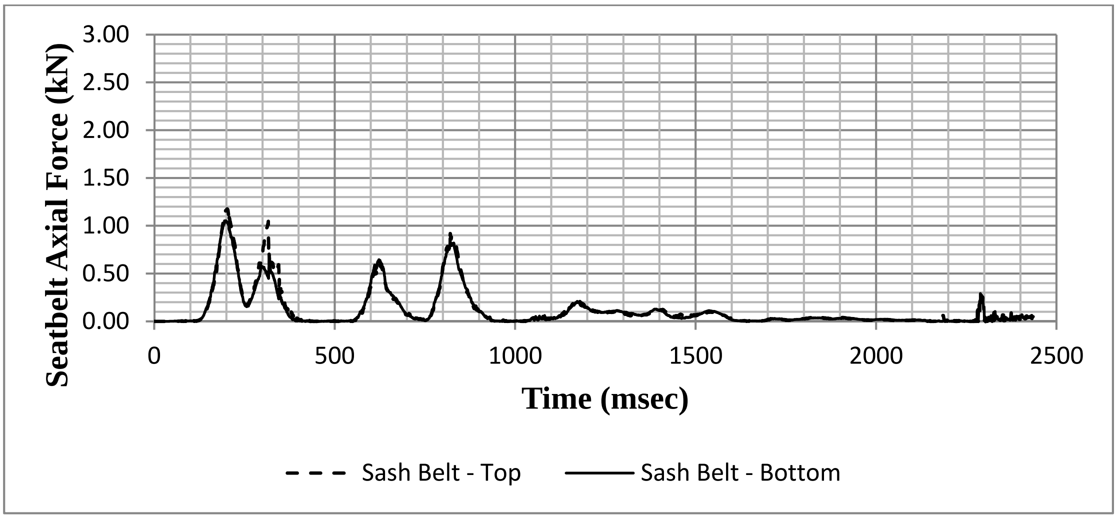


Figure R.2 ATD Position 1 sash belt axial force

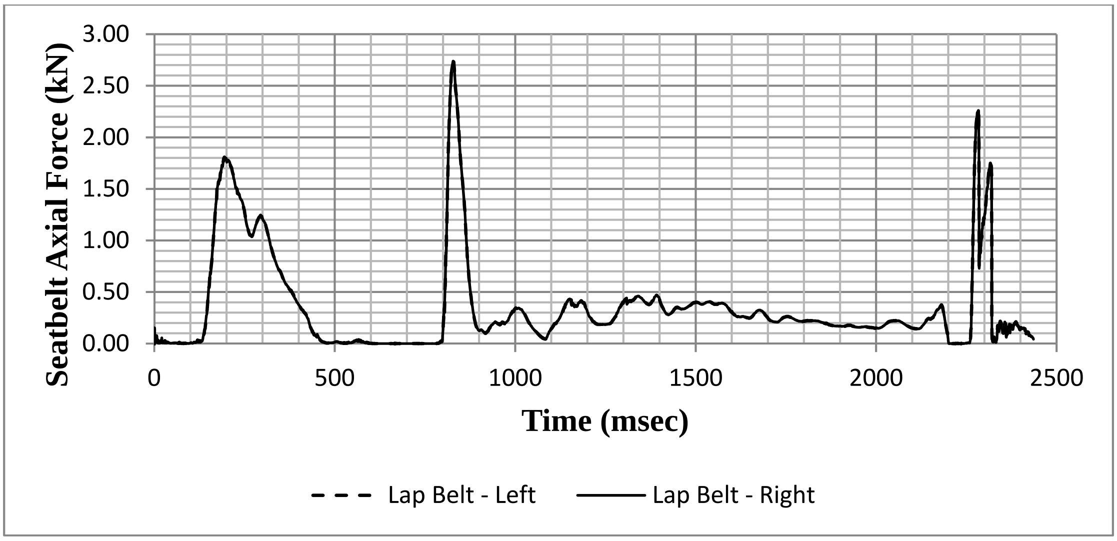


Figure R.3 ATD Position 2 lap belt axial force

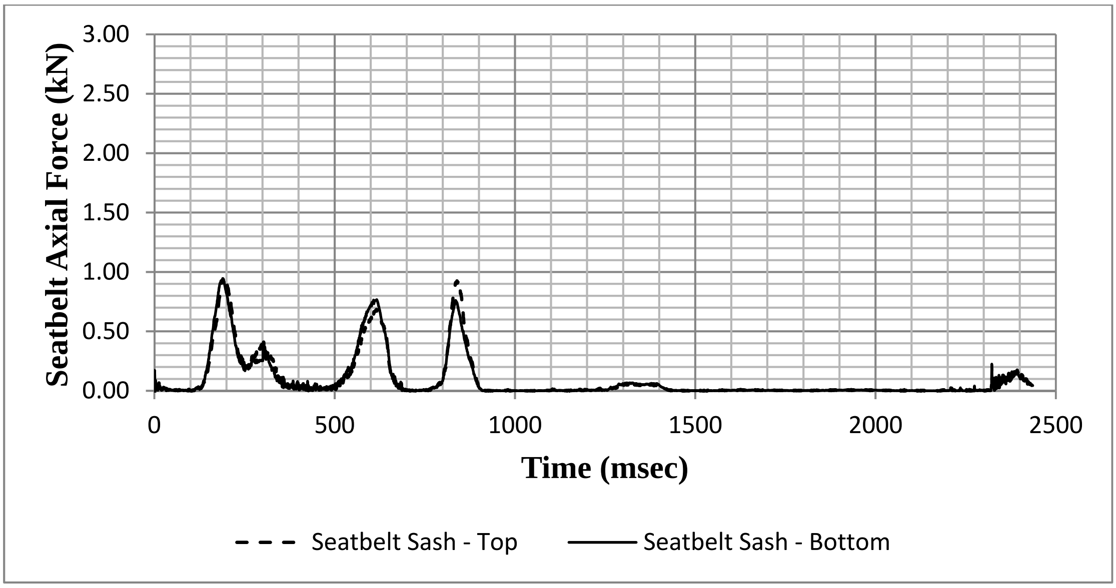


Figure R.4 ATD Position 2 sash belt axial force

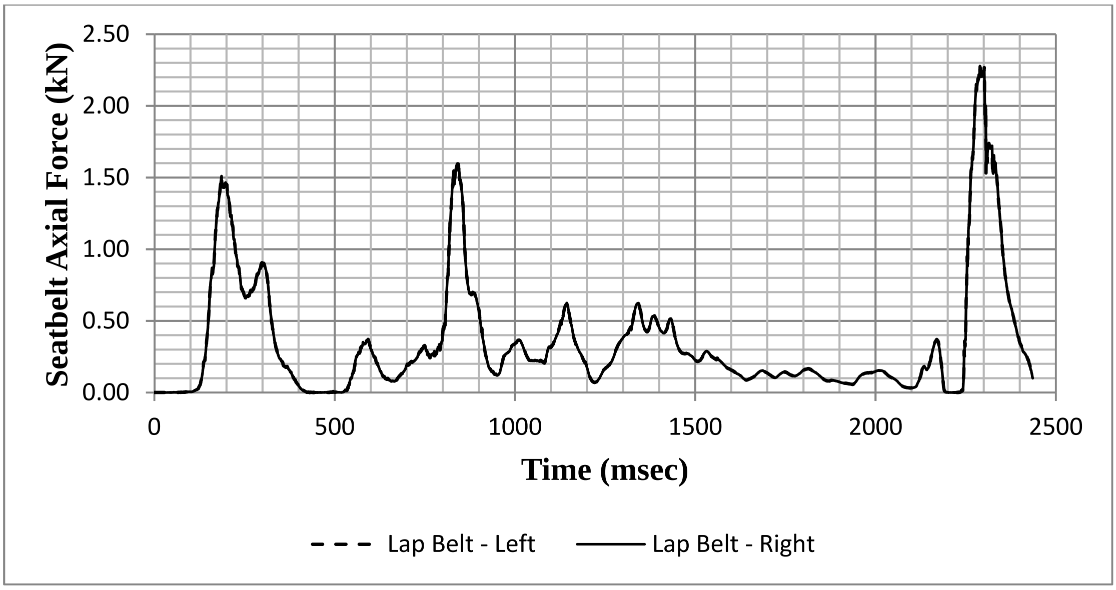


Figure R.5 ATD Position 5 lap belt axial force

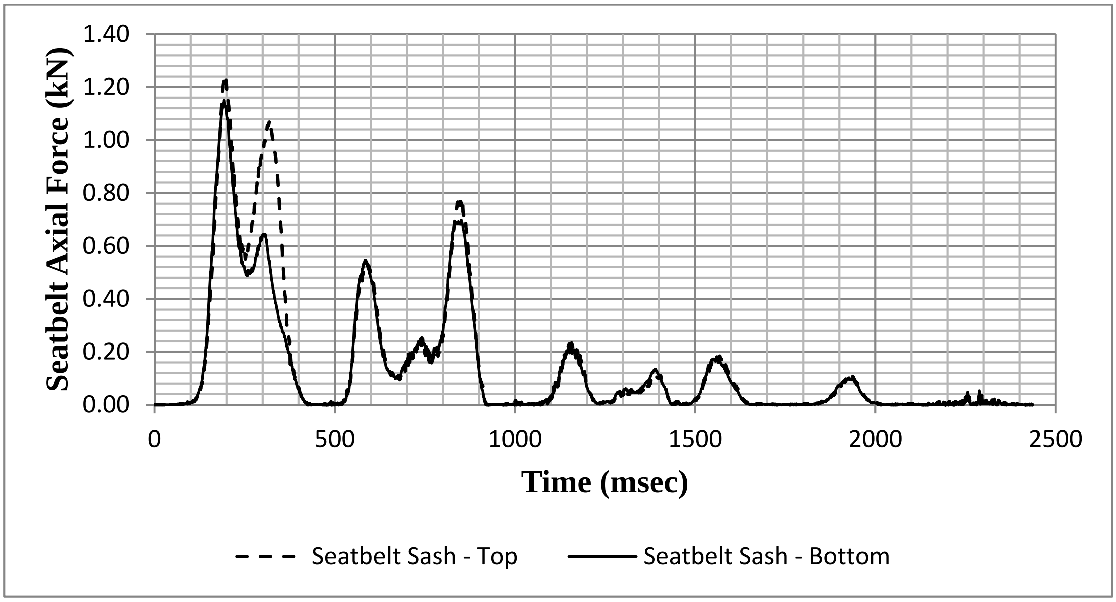


Figure R.6 ATD Position 5 sash belt axial force

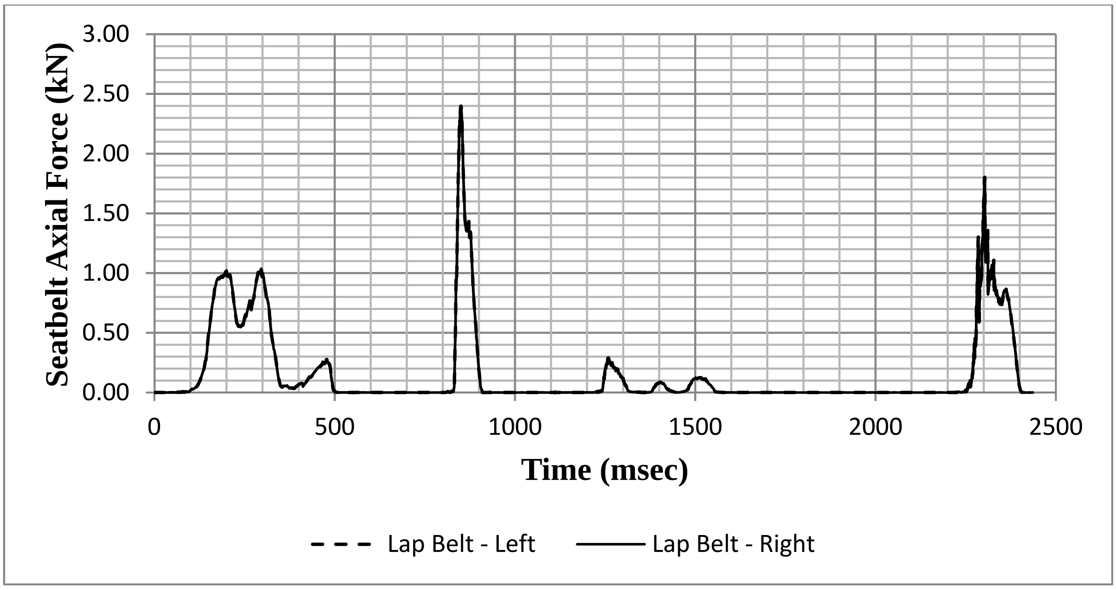


Figure R.7 ATD Position 8 lap belt axial force

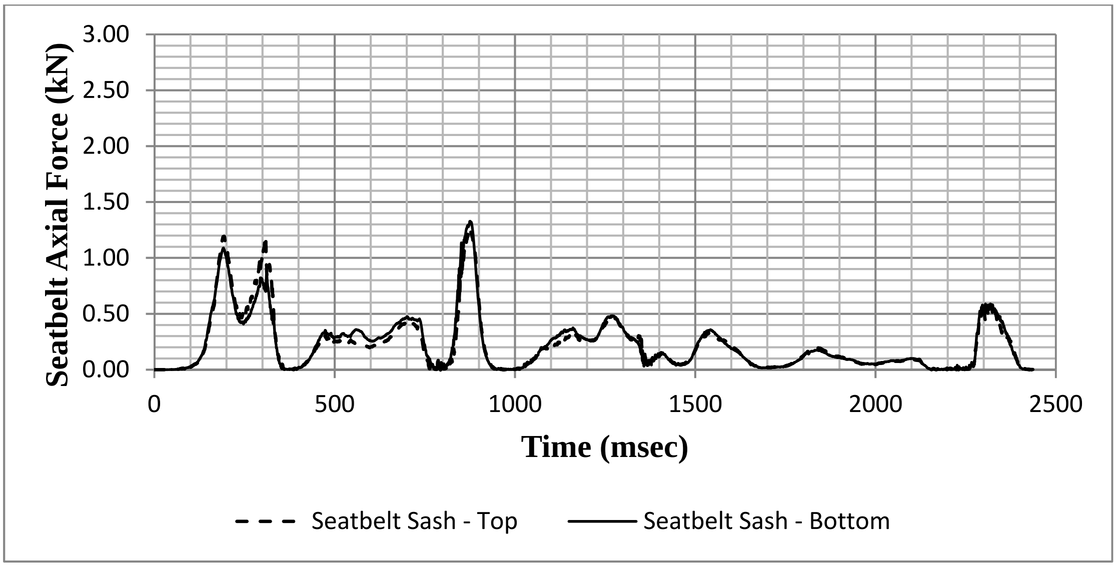


Figure R.8 ATD Position 8 sash belt axial force