MONASH University
Accident Research Centre

IMPROVED SIDE IMPACT PROTECTION:
A Review of Injury Patterns, Injury Tolerance and Dummy Measurement Capabilities

by

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Abstract:

Side impact crashes account for a substantial proportion of injuries and Harm to Australian passenger car occupants. Twenty five percent of serious casualties and 28% of fatalities to vehicle occupants in Victoria occurred from side impacts. This crash configuration accounted for one-third of vehicle occupant Harm (approximately A$1 billion annually) during the early nineties.

This project aimed to develop a method for optimising the safety systems of new passenger vehicles to minimise occupant Harm in side impact collisions.

A representative sample of crashes and injuries to occupants in Australian passenger cars involved in real-world side impact crashes was analysed in terms of injury incidence and societal harm.

The analysis of side impact crash data has been used to set the priorities for the development of a means of assessing injury in side impacts. The available human impact tolerance data for side impacts was reviewed, as a basis for the development of the necessary Injury Assessment Functions IAFs. Preliminary values for lateral injury criteria have been proposed, mainly based on cadaver test results.

The steps required to develop and validate the required IAFs are described.

Key Words:

injury, dummy, crash, side impact, human tolerance, injury criteria, HARM, safety

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PREFACE

The Improved Side Impact Protection (ISIP) project was a collaborative research project involving Monash University, the Department of Transport and Regional Services, the Australian Transport Safety Bureau, Holden, the Australian Automobile Association, Autoliv Australia, and a number of other local and international specialist partners and contributors. ISIP had three years of funding by the Australian Research Council's Strategic Partnerships with Industry, Research and Training (SPIRT) scheme, commencing in 1998. The Australian Research Council of the Department of Employment, Education, Training and Youth Affairs, offers financial support for collaborative research ventures between universities, government and industry partners for fundamental and innovative research that have the potential to make significant advancement in high priority community problem areas.

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EXECUTIVE SUMMARY

Side impact crashes account for a substantial proportion of injuries and Harm to Australian passenger car occupants. Twenty five percent of serious casualties and 28% of fatalities to vehicle occupants in Victoria occurred from side impacts, which accounted for one-third of vehicle occupant Harm (approximately A$1 billion annually) during the early nineties.

Current attempts at providing increased side impact protection have focussed on new car safety regulations. In Australia all new car models must meet either existing American or European standards (FMVSS 214 and ECE Regulation 95 respectively). Mandating these standards has been shown to be financially beneficial, but neither standard guarantees optimum benefits for Australian car occupants.

The objective of this project was to develop a method to allow vehicle designers to optimise the safety systems of new passenger vehicles and minimise occupant Harm in side impact collisions. The study was divided into four tasks:

1. The collection and analysis of a representative sample of crashes and injuries to occupants in Australian passenger cars involved in real-world side impact collisions;

2. The refinement of the Harm matrices at MUARC to obtain an indication of the societal cost of injuries of a given severity to particular body regions.

3. The development of a means of assessing injury in side impacts. This required the formulation of a series of dummy based Injury Assessment Functions for the major body regions to enable the prediction of the risk and severity of injury from the response of a surrogate /dummy occupant in side impact crashes.

4. The development of a computational model which incorporated the crash profiles, vehicle structural model, surrogate/vehicle interaction model, IAFs and Harm matrices. This model provided a basis for including the minimisation of Harm in design optimisation.

The work completed for Tasks 1 and 3 in the first year of the project has been summarised in this report.

REAL WORLD DATA ANALYSIS

Three main databases were used to determine the characteristics of side impacts. These included the Crashed Vehicle File of crashes involving hospitalization or death, the Federal Office of Road Safety’s Fatal file and the Transport Accident Commission of Victoria’s minor injury database.

The Crashed Vehicle File indicated that the modal side impact velocity was 25-30 km/h, and that the majority (53.8%) of side impacts are car-to-car impacts and a further 22.2% are car-to-pole impacts. In addition 70% of lateral impacts were near-side impacts and the remainder were far-side impacts.

The analysis found that head injuries constituted the majority of Harm in side impacts. The next most important sources of Harm were the thorax and then the lower extremities. The total head Harm however, was considerably larger in far-side as opposed to near-side lateral impacts despite the fact that near-side impacts constitute the majority of all side impacts. In

addition it was found that the mean Harm from car-to-pole impacts was considerably greater than that for car-to-car impacts.

The door was the predominant source of injuries in side impacts although when a front passenger was present, then impacts with other occupants become the primary source of injuries. In car-to-pole impacts injuries from impacts with external objects were also significant.

The results of the real-world data analyses indicated that priority needs to be given to the development of injury functions that indicate the risk of head and then thoracic injuries in side impacts. Anomalies in the data meant that spinal and brain injuries were under-reported and may consequently deserve a higher priority than the statistics on Harm suggest. The data also indicated that the reliable assessment of Harm from dummy responses requires that the dummies reliably replicate the head impacts of occupants in real-world impacts.

THE INJURY ASSESSMENT FUNCTIONS

The available human impact tolerance data for side impacts was reviewed, as a basis for the development of the necessary Injury Assessment Functions. The preliminary injury criteria developed were mainly cadaver test based and utilised measures suited to the response and measurement capabilities of the specific dummies to be used in the project (BioSID and SID IIs). In order of injury priority based on Harm, the following preliminary injury criteria were selected. All, except those for the neck, were based upon cadaver rather than dummy responses.

Head

For the head, the injury criteria were related to HIC based on the work by Mertz, Prasad & Nusholtz (1996) for frontal head impacts resulting in skull fracture, with allowance for the lower threshold of skull fracture in lateral head impacts shown by JARI.

Thorax

For the thorax, the injury criteria used were based on compression (as a percentage of full chest width) and the viscous criteria, V•C for cadavers, as proposed by Viano, Asbury, King & Begeman (1989).

Lower Extremities

For the lower extremities simple dynamic lateral three point bending strength of human long bones were used as a 50 percent risk of fracture for the lower extremities, based on work by Nyquist (1985, 1986) combined with a rotational load limit for the flexed knee, from Gibson Newman, Zellnor, & Wiley (1992). Other injuries to the lower extremities in side impacts were not well enough defined to suggest associated injury criteria.

Shoulder and Upper Extremities

For the shoulder and upper extremities no specific injury criteria were chosen as the current dummies are not able to make appropriate separate response measurements for these body regions. The shoulder region was treated as part of the thorax and no response measurements are yet available for the dummy upper extremities.

Pelvis

For the pelvis, the injury criteria used were based on the pelvic impact force to cadavers, as proposed by Bouquet et. al. (1998).

Abdomen

For the abdomen, the injury criteria used were based on compression (as a percentage of full chest width) and the viscous criteria, V•C for cadavers, as proposed by Viano et. al. (1989).

Neck

For the neck, there was little data available for an injury criteria for side impact. The suggested values were based on the single point injury assessment reference values for tension, compression, lateral shear and lateral bending in dummies, as proposed by Mertz (1984).

DUMMY CAPABILITIES

A brief review was conducted of the biofidelity of the responses of the two dummies used in the project. The dummies were the BioSID and the SID IIs, which represent a fiftieth percentile North American male and a fifth percentile North American female. The available side impact dummies were compared by the method proposed by the International Standards Organisation dummy working group, ISO (1997).

FUTURE WORK

The review of the available human impact tolerance data for side impacts combined with the analysis of the injury priorities revealed those areas where developments of IAFs are necessary. For all body regions the IAFs currently available were inadequate: either, due to lack of knowledge of the injury mechanism for the individual body regions; or, due to mismatches between the injury severity probabilities available (ie. the available IAFs) and the injury severity distributions from real accidents. The priority areas for these developments were found to be the head which forms about 50% of the Harm due to side impact and the thorax, which forms about 22%. In both cases the continuous risk functions need to be extended to cover more of the injury severity distribution found in real accidents.

Chapter 1
INTRODUCTION

1.1 BACKGROUND

Side impact crashes account for a substantial proportion of injuries and Harm to Australian passenger car occupants. Fildes, Lane, Lenard, & Vulcan (1994) reported that 25% of serious casualties and 28% of fatalities to vehicle occupants in Victoria occurred from side impacts, which accounted for one-third of vehicle occupant Harm (approximately A$1 billion annually) during the early nineties.

Current attempts at providing increased side impact protection have focussed on new car safety regulations. In Australia all new car models must meet either existing American or European standards (FMVSS 214 and ECE Regulation 95 respectively). Mandating these standards has been shown to be financially beneficial by Fildes, Digges, Carr, Dyte, & Vulcan (1995), but the authors suggested that it was unlikely that either of these standards could guarantee optimum benefits for car occupants, especially in Australia.

The concept of “Harm” was developed in the US and applied to the National Accident Sampling System (NASS) database by the National Highway Traffic Safety Administration (NHTSA). It was used as a means of determining countermeasure benefits for road safety programs by putting a community “value” on injury (Malliaris, Hitchcock & Hedland, 1982; Malliaris, Hitchcock, & Hansen, 1985; Malliaris and Digges, 1987). In its original form, it was used to make global assessments of benefits using known overall outcome data. By the 1990s though, this concept had been redeveloped to enable Harm to be derived using a more systematic summation of the range of body region and contact source costs in a class of crash, (Newman, Tylko, & Miller, 1992; Fildes et. al., 1994). This revised “building block” method has proven to be a very useful means of assessing the benefits of new safety measures. Available test or real-world crash data on performance improvements can be converted into likely injury savings for particular body regions and these can be summed to make an “objective” estimate of benefits for the proposed measure.

The objective of the ISIP project was to develop the method to allow vehicle designers to optimise the safety systems of new passenger vehicles to minimise occupant Harm in side impact collisions. The project is innovative in its scope and if successful will be an international first in this area.

1.2 THE PROJECT OVERVIEW

A number of specific research tasks were planned for the project and are outlined below. A single make and model of vehicle (a Holden Commodore) was the focus for the development of the initial optimisation model. However, it is expected that the process may be generalised to other makes and models of passenger cars.

Task 1 - Injury Distribution Patterns

The first task involves the collection and analysis of a representative sample of crashes and injuries to occupants in Australian passenger cars involved in real-world side impact collisions. A suitable database of mass accident statistics was assembled using the data from several Australian states. Detailed retrospective crash investigation data on more than 100 side impact crashes was collected using the current Monash University Accident Research Centre (MUARC) (NASS) procedure. This detail was necessary given the level of detailed information required for the optimisation model. Where possible, other overseas crash investigation data were used to supplement the local crash data. This extra data was used where there were insufficient local cases available. Care was taken to ensure that it was weighted to match the various crash configurations and types in Australia.

Task 2 - Harm Matrices

The next phase involved the development and further refinement of the Harm matrices at MUARC, taking account of more recent crash patterns. This task also involved updating the Bureau of Transport's injury costs to incorporate current price levels and overcome some of the earlier deficiencies. The historical injury costs were revised to include the latest actual treatment, rehabilitation, loss of income and long-term impairment charges, as well as adequate allowance for family, psychological damage and loss of quality of life. This work was undertaken in conjunction with the Bureau of Transport Economics and Roadwatch in WA.

Task 3 - Injury Assessment Functions

The assessment of injury during the design phase relied heavily on the development of a family of accurate Injury Assessment Functions (IAFs) for each body region in side impact collisions. The IAFs predict the relationship between the response of a surrogate occupant in a representative series of side impact crashes and the risk and severity of injury to the population of crash involved vehicle occupants. The project was based on use of the SID IIs and the BioSID side impact test dummies, being the most current occupant surrogates available.

Task 4 - Design Optimisation

The final phase of the research program involved the development of a computational model incorporating the core crash profile, vehicle structural model, surrogate /vehicle interaction model, IAFs and Harm matrices. This model provided a basis for including the minimisation of Harm in vehicle design optimisation.

1.3 OBJECTIVES OF THIS RESEARCH

The objectives of this research were twofold:

- to analyse real world crash data in Australia to show the type and severity of crashes and the extent and patterns of injury to occupants in side impacts; and
- to review available side impact injury tolerance data and to develop a family of preliminary injury assessment criteria for the development of dummy based IAFs for injury assessment during vehicle design. The work summarised in this report lays the basis for the successful completion of Task 3.

1.4 PROCESS AND AVAILABLE RESOURCES

1.4.1 Task 1 - Real-World Data Analysis

Chapter 2 of this report provides an extensive analysis of real-world crash data. Three sources of real-world data were sufficiently detailed for this analysis.

1. ***TAC Injury Compensation data*** from 1989 to 1997 for the whole of the state of Victoria. These data include all Victorian casualties who's injuries exceed the minimum entrance threshold of $500. They are particularly valuable in that the database held at MUARC include both police and TAC details, enabling an analysis of both crash and injury outcomes.

2. ***The Crashed Vehicle File*** for 1989 to 1992, comprising a detailed examination of over 500 representative crashes in this state using the National Accident Analysis Sample (NASS) procedure. Vehicles were assessed for type of impact, extent of deformation, crash severity and intrusion, while occupant details comprised personal characteristics, detailed list of all injuries by body part and severity and source of injury inside and outside the vehicle.

3. ***Harm database*** at MUARC which was constructed in the early 1990s from annual fatality, hospitalisation and medical treated data and has been used for assessing the patterns of Harm and potential benefits for a range of vehicle safety initiatives.

These databases are supplementary and permit a very detailed analysis of the patterns of both side impact crashes and the injuries that result to vehicle occupants in Australia. Databases 2 and 3 (above) were the most valuable because of the level of detail they contained and their direct relevance to vehicle safety improvement.

1.4.2 Task 3 - Injury Assessment Functions

Some IAFs are available for the analysis of frontal crashes. However, less emphasis has been put into this area for the development of side impact protection for vehicles. So the IAFs are not as well formulated for this impact direction. Considerable work needs to be done to address this shortage. The following approach was chosen, to ensure the inclusion of the most recent developments in the area, and to minimise the need for undertaking an extensive and time consuming research program in Australia:

1. a detailed review of recent developments at key biomechanical research centres around the world was undertaken;

2. a seminar was held in Detroit in conjunction with the 1998 Enhanced Safety of Vehicles (ESV) Conference, where a selection of the world specialists in injury tolerance discussed the project's aims and objectives;

3. this report combines a review of the available literature for side impact tolerance with the results of the discussions in points 1 and 2. It outlines the critical areas where tolerance information is needed and is matched by the capabilities of the available dummies. It summarises the information available regarding side impact injury tolerance.

4. finally, the report maps out the developments necessary in this area for the successful completion of the project.

Based on the report's recommendations, new research projects will be initiated where possible. A number of overseas biomechanical research groups have already agreed to co-operate with the ISIP team with these tasks. The continuing work will include several graduate student projects to develop IAFs in particular body regions. The monitoring of overseas developments in this area is critical and will be continued.

1.5 REPORT OVERVIEW

The present report has four major parts:

- real-world side impact data analysis - Chapter 2;
- review of available injury assessment functions - Chapter 3;
- dummy capabilities - Chapter 4; and
- General discussion - Chapter 5.

Chapter 2
REAL-WORLD DATA ANALYSIS

2.1 INTRODUCTION

Central to the optimisation procedure is the need for accurate crash statistics on the types and severities of side impact crashes likely to be experienced, the patterns of injuries to occupants in these crashes, and the causes of injury inside and outside the vehicle that need to be considered when designing for improved protection. This chapter sets out to provide the data from the various sources available. These data sources are described below.

2.2 DATABASES AVAILABLE

2.2.1 Crashed Vehicle File

The most suitable source of data available for use in this analysis was from the systematic inspection of vehicles involved in real world crashes where at least one occupant was either hospitalised or killed, the so-called “Crashed Vehicle File”. These inspections commenced in 1989, concluded in 1992 and comprised a total of 501 crashes involving 606 injured occupants. Of these cases, there were 198 side impacts and 234 injured occupants that were of interest for this analysis.

Information was collected on crash type, principal direction of force, crash profile, vehicle deformations, occupant details, injuries sustained and the sources of these injuries. Change of velocity during impact was assessed using the CRASH3 computation of Delta-V. All injuries were scored for severity using the Abbreviated Injury Scale (AIS85) procedure and vehicle damage was assessed using the US inspection system specified by the National Accident Sampling System (NASS).

It was possible to undertake a thorough analysis of injuries by various crash configurations and impacting objects using these data. However, they only represented a sample of crashes, albeit representative of side impacts in the state of Victoria during the early 1990s. While it would be possible to normalise these for Australia, it was not possible to do this at this time. Nevertheless, they did provide a valuable detailed analysis of real world crashes and injuries in side impacts, which would be particularly valuable for the International Harmonisation of Research Activity (IHRA) committee’s deliberations.

2.2.2 Harm Database

Another source of data was the Australian Harm database. This database was constructed from three data sources, namely the Federal Office of Road Safety’s Fatal File, the Transport Accident Commission of Victoria’s minor injury database, and the Crashed Vehicle File of real-world crash data. These 3 databases were merged into a single source of all severity injury and adjusted to represent the total annual number of crashes and crash configurations in Australia (see Monash University Accident Research Centre (1992) for a more complete description of this procedure). Table 2.1 shows the overall level of Harm for vehicle occupants each year by body region and injury severity level. Each Harm cell in the Table (in A$million) illustrates the societal cost of these injuries, hence demonstrating the total societal cost of crash injury in Australia. This database contains both injury details and contact sources and can be broken down by various vehicle and crash types, occupant seating positions, and impacting object and was thus potentially very useful for aspects of this analysis.

2.3 SIDE IMPACT HARM ANALYSIS

To begin with, it was important to demonstrate the size of the problem in terms of the annual societal Harm to Australian passenger car occupants. Harm reflects a combination of the frequency and costliness (or seriousness) of injuries to the individuals involved as well as to society in general. The Harm database described earlier provided the data for this analysis. While this database is now 7 to 8 years old, it is still the best source of information currently available to demonstrate the extent of side impact crash trauma. It is important to upgrade this database in the near future and this is a task to be undertaken by the study team at a later date when more recent frequency and cost information becomes available.

2.3.1 Harm by Body Region & Severity

The first series of analyses examined the annual extent of side impact Harm to passenger car occupants in Australia, broken down by body region and injury severity level in terms of the Abbreviated Injury Severity (AIS) level as specified by the Association for the Advancement of Automotive Medicine (AIS85). Table 2.1 shows the results of this analysis.

Table 2.1 Harm by body region and injury severity level in side impacts

Body Region	AIS 1	AIS 2	AIS 3	AIS 4	AIS 5	AIS 6	Total
	A$million	A$million	A$million	A$million	A$million	A4million	A4million
HEAD	5.4	38.2	73.9	85.2	214.6	20.8	438.0
FACE	19.6	10.6	2.2	1.4	0.0	0.0	33.8
NECK	4.2	3.0	3.3	0.1	4.3	0.9	15.8
HARD THX	8.1	10.6	54.9	51.8	12.9	1.3	139.5
HEART+LSK	0.0	4.2	7.0	7.4	15.1	33.4	67.2
ABD-LSK	6.9	2.3	2.4	4.0	0.2	0.9	16.7
PELVIS	1.0	10.5	16.3	0.9	0.1	0.0	28.8
SPINE	0.9	4.5	2.2	2.1	19.4	8.2	37.3
SHOULDER	1.7	14.8	1.4	0.0	0.0	0.0	17.9
UPPER LIMB	14.1	24.0	13.5	0.0	0.0	0.0	51.7
THIGH/KNEE	2.4	9.2	25.2	0.2	0.0	0.0	37.0
LEG/FOOT	11.9	16.6	14.5	0.0	0.0	0.0	43.1
TOTAL	76.2	148.6	216.7	153.0	266.6	65.5	926.6

Of special note, three-quarters of all Harm sustained in side impact crashes in Australia involved injury severities of AIS 3 or greater. Fatal Harm (AIS 6) accounted for only 7% of total side impact Harm, although it should be recognised that some fatalities occur at lower injury severity levels. AIS 5+ injuries accounted for approximately 36% of total side impact Harm.

2.3.2 Near-Side and Far-Side Harm

Tables 2.2 to 2.4 illustrate the breakdown of Harm for near-side and far-side impacts overall, as well as by minor (AIS 1-2) and major (AIS 3+) injuries.

Table 2.2 Harm by body region for near- and far-side crashes

Body Region	Near-Side		Far-Side		Total	
	A$million	**Percent**	**A$million**	**Percent**	**A$million**	**Percent**
HEAD	203.7	36.5%	234.4	63.6%	438.0	47.3%
FACE	19.5	3.5%	14.3	3.9%	33.8	3.6%
NECK	4.6	0.8%	11.2	3.0%	15.8	1.7%
HARD THX	114.9	20.6%	24.6	6.7%	139.5	15.1%
HEART+LSK	50.5	9.1%	16.6	4.5%	67.2	7.3%
ABD-LSK	10.4	1.9%	6.3	1.7%	16.7	1.8%
PELVIS	25.7	4.6%	3.1	0.8%	28.8	3.1%
SPINE	24.4	4.4%	12.9	3.5%	37.3	4.0%
SHOULDER	14.3	2.6%	3.6	1.0%	17.9	1.9%
UPPER LIMB	32.6	5.8%	19.1	5.2%	51.7	5.6%
THIGH/KNEE	28.6	5.1%	8.4	2.3%	37.0	4.0%
LEG/FOOT	29.2	5.2%	13.8	3.8%	43.1	4.6%
TOTAL	558.4	60%	368.2	40%	926.6	100.0%

Table 2.2 shows that almost half the Harm in side impact crashes involves head injury to the occupants and is considerably greater than other sources of Harm. The chest including organs was the next most substantial Harm source (22.4%) followed by lower limb (8.6%) and upper limb (5.6%) Harm.

Table 2.3 Minor Harm (AIS 1-2) by body region for near- and far-side crashes

Body Region	Near-Side		Far-Side		Total	
	A$million	**Percent**	**A$million**	**Percent**	**A$million**	**Percent**
HEAD	28.7	19.8%	14.9	18.7%	43.6	19.4%
FACE	17.6	12.1%	12.5	15.7%	30.1	13.4%
NECK	2.5	1.7%	4.7	5.9%	7.2	3.2%
HARD THX	12.0	8.3%	6.7	8.4%	18.7	8.3%
HEART+LSK	3.5	2.4%	0.8	1.0%	4.3	1.9%
ABD-LSK	5.4	3.7%	3.8	4.8%	9.2	4.1%
PELVIS	10.3	7.1%	1.2	1.5%	11.4	5.1%
SPINE	3.2	2.2%	2.3	2.8%	5.4	2.4%
SHOULDER	14.3	9.8%	2.2	2.7%	16.4	7.3%
UPPER LIMB	23.5	16.2%	14.6	18.3%	38.1	17.0%
THIGH/KNEE	7.4	5.1%	4.3	5.3%	11.6	5.2%
LEG/FOOT	16.7	11.5%	11.9	14.9%	28.6	12.7%
TOTAL	144.92	64%	79.85	36%	224.77	100.0%

Table 2.4 Major Harm (AIS 3+) by body region for near- and far-side crashes

Body Region	Near-Side		Far-Side		Total	
	A$million	Percent	A$million	Percent	A$million	Percent
HEAD	175.0	42.3%	219.4	76.1%	394.4	56.2%
FACE	1.9	0.5%	1.7	0.6%	3.6	0.5%
NECK	2.1	0.5%	6.5	2.3%	8.6	1.2%
HARD THX	102.9	24.9%	17.9	6.2%	120.8	17.2%
HEART+LSK	47.1	11.4%	15.9	5.5%	62.9	9.0%
ABD-LSK	5.0	1.2%	2.5	0.9%	7.5	1.1%
PELVIS	15.4	3.7%	1.9	0.7%	17.3	2.5%
SPINE	21.2	5.1%	10.6	3.7%	31.9	4.5%
SHOULDER	0.0	0.0%	1.4	0.5%	1.4	0.2%
UPPER LIMB	9.1	2.2%	4.5	1.5%	13.5	1.9%
THIGH/KNEE	21.3	5.1%	4.1	1.4%	25.4	3.6%
LEG/FOOT	12.5	3.0%	1.9	0.7%	14.5	2.1%
TOTAL	413.5	59%	288.4	41%	701.8	100.0%

From Tables 2.3 and 2.4, it is apparent that three-quarters of side impact Harm involved major injuries of AIS 3 and above in severity. The majority of Harm suffered in far-side crashes is to the head (76%) and the total Harm from head injury is greater than in near-side crashes ($A234.3 million versus $A203.7 million in major and minor harm). Again, the overwhelming importance of head Harm is apparent from Table 2.4 where this body region accounted for over 56% of major Harm from side impacts. The only other noteworthy source of major side impact Harm was to the chest (hard thorax plus organs) accounting for a further 26.2%. While major Harm to the lower limbs was only 5.7% of the total, it should be noted that the most severe injury to the lower limbs is only ever an AIS 3 in the AIS classification system.

Table 2.5 Harm by body region and injury severity level in near-side impacts

ALL OCCUPANTS IN NEAR SIDE IMPACTS							
Body Region	**AIS 1**	**AIS 2**	**AIS 3**	**AIS 4**	**AIS 5**	**AIS 6**	**TOTAL**
HEAD	3.2	25.5	37.3	48.3	74.8	14.5	203.6
FACE	11.2	6.3	0.5	1.4	0.0	0.0	19.4
NECK	2.2	0.3	1.1	0.1	0.0	0.9	4.6
HARD THX	4.4	7.6	43.4	46.8	11.4	1.3	114.9
HEART+LSK	0.0	3.5	6.0	5.9	11.8	23.3	50.5
ABD-LSK	4.2	1.2	1.8	2.3	0.1	0.9	10.5
PELVIS	0.8	9.5	14.5	0.8	0.1	0.0	25.7
SPINE	0.6	2.6	2.0	1.4	12.2	5.8	24.6
SHOULDER	1.2	13.1	0.0	0.0	0.0	0.0	14.3
UPPER LIMB	9.6	13.9	9.1	0.0	0.0	0.0	32.6
THIGH/KNEE	1.7	5.6	21.1	0.2	0.0	0.0	28.6
LEG/FOOT	6.9	9.8	12.5	0.0	0.0	0.0	29.2
TOTAL	46.0	98.9	149.3	107.2	110.4	46.7	558.5

Table 2.5 shows the distribution of Harm by body region and AIS level for occupants injured in near-side crashes. These findings provide further evidence of the severe nature of head, chest, internal organ and spinal injury to occupants involved in these collisions.

Table 2.6 Harm by body region and injury severity level in far-side impacts

ALL OCCUPANTS IN FAR SIDE IMPACTS							
Body Region	**AIS 1**	**AIS 2**	**AIS 3**	**AIS 4**	**AIS 5**	**AIS 6**	**TOTAL**
HEAD	2.2	12.7	36.5	36.9	139.7	6.3	234.3
FACE	8.3	4.2	1.7	0	0	0	14.2
NECK	2.0	2.7	2.2	0	4.3	0	11.2
HARD THX	3.7	3.0	11.4	5.0	1.5	0	24.6
HEART+LSK	0	0.8	1.0	1.5	3.3	10.1	16.7
ABD-LSK	2.7	1.1	0.6	1.7	0.1	0	6.2
PELVIS	0.1	1.0	1.8	0.1	0	0	3.0
SPINE	0.4	1.9	0.3	0.7	7.2	2.4	12.9
SHOULDER	0.5	1.7	1.4	0	0	0	3.6
UPPER LIMB	4.5	10.1	4.5	0	0	0	19.1
THIGH/KNEE	0.7	3.6	4.1	0	0	0	8.4
LEG/FOOT	5.0	6.9	1.9	0	0	0	13.8
TOTAL	30.1	49.7	67.4	45.9	156.1	18.8	368.0

A similar distribution of Harm by body region and by AIS level of injury severity for far-side crashes is also shown in Table 2.6. Again, while the patterns are somewhat different, there was a substantial amount of severe head, internal organ and to a lesser degree, spinal injuries resulting from these crashes. Interestingly, the amount of hard thorax Harm has diminished markedly and the amount of head Harm increased in far-side over near-side crashes, as a result of the greater distance from the impact object and the different body movement kinematics.

2.4 TYPE OF SIDE IMPACT CRASHES

The best source of data for a detailed analysis of the types of side impact crash configurations was the Crashed Vehicle File (CVF) held at the Monash University Accident Research Centre. This database contained details on 198 side impacts involving 234 injured occupants and comprised detailed information on the types of crashes, their severities, the impacting vehicle or object, and occupants involved.

2.4.1 Overall Findings

The types of side impacts, the vehicle types, occupant seating positions, and the occupant's age and sex for the 234 injured occupants is shown in Table 2.7 below.

Table 2.7 Population characteristics of the crashes and injured occupants in the Crashed Vehicle File (198 crashes, 234 injured occupants)

CHARACTERISTIC	VALUE
1. IMPACT VELOCITY	
Mean Delta-V	35.3km/h
Standard Deviation	15.6km/h
Range	8-113km/h
2. VEHICLE TYPES	
Mini	4%
Small	28%
Compact	44%
Intermediates	23%
Large	1%
Mean vehicle weight	1086kg
3. SEATING POSITION	
Driver	60%
Front-Left	27%
Rear	13%
Near-side occupants	70%
Far-side occupants	30%
4. PATIENT SEX	
Males	48%
Females	52%
5. PATIENT AGE	
< 17 years	5%
17 - 25 yrs	26%
26 - 55 yrs	44%
56 - 75 yrs	19%
> 75 years	6%

2.4.2 Striking Vehicle or Object

The next analysis undertaken was to compare the various vehicle types that impacted the occupant's passenger car, shown in Table 2.8. Interest was in four striking vehicle or object types, namely (i) trucks, greater than 3.5 tonne; (ii) 4WD=four-wheel-drives, passenger vans and light commercials; (iii) other passenger cars or their derivatives; and (iv) roadside poles or trees. This Table shows that car-to-vehicle crashes accounted for 73%, car-to-pole (or tree) for 22% and car-to-other for 5% of the sample of side impacts in the CVF sample.

Table 2.8 Side impact crashes

Crash type	No.	%
Truck into car	22	9.4%
4WD into car	22	9.4%
Car into car	126	53.8%
Car into pole	52	22.2%
Car into other	12	5.1%
TOTALS	**234**	**100%**

NB: Other includes motorcycles, trams, fixed objects, and pedestrians

2.4.3 Mass of Striking & Struck Vehicle

The mass of the striking and struck vehicle is shown in Tables 2.9 to 2.11 for car-to-car and car-to-pole collisions. Most noticeable was that the mass of the striking vehicle was generally larger than the struck vehicle, 78% of the struck vehicles were less than 1300 kg while 48% of the striking vehicles were more than 1300 kg. This imbalance was slightly less for far-side crashes and greater for near-side crashes.

Table 2.9 Mass of the struck car by type of crash in vehicle-to-car side impacts.

Mass of struck car	Near-side		Far-side		Total	
	No.	%	No.	%	No.	%
<900kg	26	16%	10	6%	36	23%
901-1150kg	41	26%	10	6%	51	32%
1151-1300kg	27	17%	9	6%	36	23%
1301+kg	12	8%	7	4%	19	12%
4WD	10	6%	6	4%	16	10%
TOTAL	116	73%	42	27%	158	100%

Table 2.10 Mass of the striking vehicle by type of crash in vehicle-to-car side impact.

Vehicle Mass (striking vehicle)	Near-side		Far-side		Total	
	No.	%	No.	%	No.	%
<900kg	6	7%	1	1%	7	8%
901-1150kg	16	19%	5	6%	21	24%
1151-1300kg	11	13%	6	7%	17	20%
1301+kg	23	27%	10	12%	33	38%
4WD	4	5%	4	5%	8	9%
TOTAL	60	70%	26	30%	86	100%

Table 2.11 Mass of the struck car by type of crash in pole-to-car side impact

Vehicle Mass	Near-side		Far-side		Total	
	No.	%	No.	%	No.	%
<900kg	4	8%	0	0%	4	8%
901-1150kg	6	12%	5	10%	11	21%
1151-1300kg	9	17%	9	17%	18	35%
1301+kg	14	27%	5	10%	19	37%
TOTAL	33	63%	19	37%	52	100%

About two-thirds of the vehicles involved in side impacts with a pole were less than 1300kg which is less than the similar figure for vehicle-to-car impacts. This should be treated with some caution, given the relatively small numbers involved.

2.4.4 Seating in Near-Side and Far-Side Impacts

Seating position by near-side and far-side crashes is shown in Table 2.12. Note that the near-side crash in Australia for a driver is a right hand side crash and for a left front passenger, a left hand side crash. These results show that near-side crashes accounted for 73% of all side impacts where someone was hospitalised or killed. Of these, 39% were drivers, 24% front passengers, and 10% rear seat passengers. Far-side crashes accounted for the remaining 27% of side impacts comprising 15% of drivers alone and 12% with a driver and a front seat passenger.

Table 2.12 Seating position by injured occupants in side impact crashes

Seating Position	CVF	
	No.	%
Near-side Crashes		
Driver	89	39%
Front passengers	55	24%
Left-rear	15	7%
Right-rear	6	3%
Far-side Crashes		
Driver alone	35	15%
Driver + front passenger	24	10%
Rear alone	-	0%
Rear with other pass.	4	2%

2.4.5 Side Impact Crash Configurations

The area of the side of the car impacted and the direction of the impacting vehicle or pole among the side impact crashes inspected is shown in Tables 2.13 and 2.14 below.

Table 2.13 Direction and area impacted in a side collision with another vehicle

Area of the car impacted in side collision	Perpendicular		Oblique		Total	
	No.	%	No.	%	No.	%
Pure compartment only	30	18%	10	6%	40	24%
Compartment with overlap	54	32%	61	36%	115	68%
No compartment contact	9	5%	6	4%	15	9%
TOTALS	**93**	**55%**	**77**	**45%**	**170**	**100%**

Table 2.14 Direction and area impacted in a side collision with a pole

Area of the car impacted in side collision	Perpendicular		Oblique		Total	
	No.	**%**	**No.**	**%**	**No.**	**%**
Pure compartment only	18	35%	14	27%	32	58%
Compartment with overlap	1	2%	11	21%	12	30%
No compartment contact	1	2%	7	13%	8	12%
TOTALS	**20**	**38%**	**32**	**62%**	**52**	**100%**

These findings reveal the types of side impact configurations and the likelihood of compartment and non-compartment involvement for the sample of severely injured occupants in the CVF. Not surprisingly, as the sample was for severely injured passenger car occupants, most crashes (91% of car-to-vehicle and 88% of car-to-pole crashes) involved the passenger compartment.

2.4.6 Side Impact Crash Severities

Severity of the crash was assessed by calculating delta-V using CRASH3 and these findings for various types of impacts are shown in Figures 2.1 and 2.2.

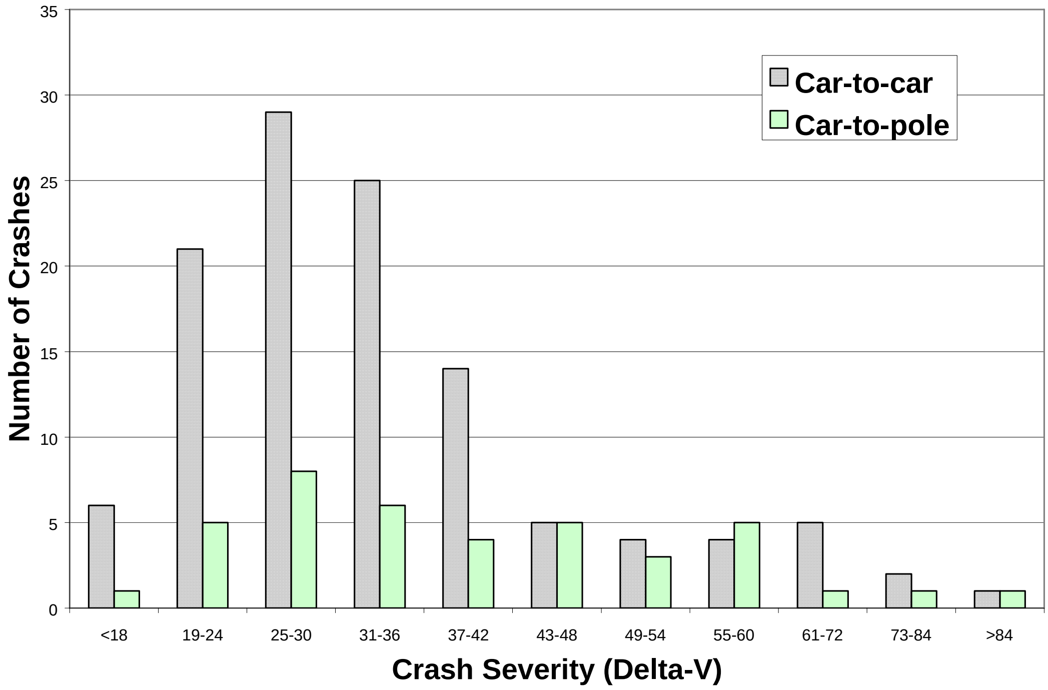


Figure 2.1 Crash severities for cars impacted by another car or a pole in a side collision

Figure 2.1 shows that the modal crash speed for vehicle-to-car and pole-to-vehicle side impacts where someone was injured sufficiently enough to be either hospitalised or killed was between 25 and 30 km/h. 70% of vehicle-to-car crashes occurred at delta-Vs less than 36 km/h while the equivalent figure for pole-to-car crashes was closer to 48 km/h.

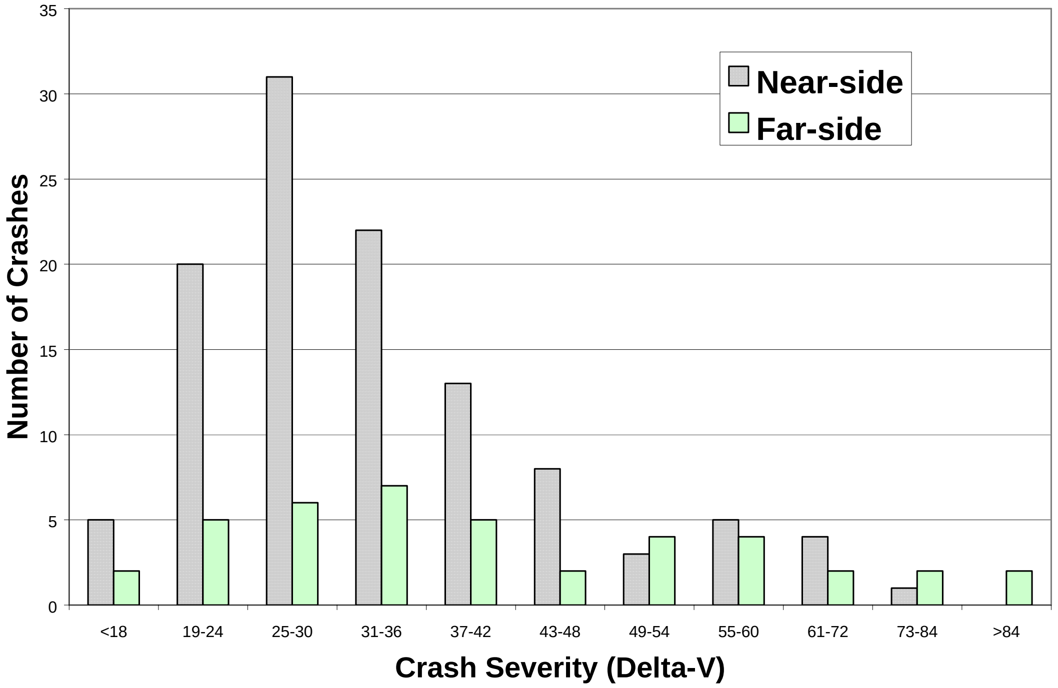


Figure 2.2 Crash severities for near-side and far-side crashes from CVF

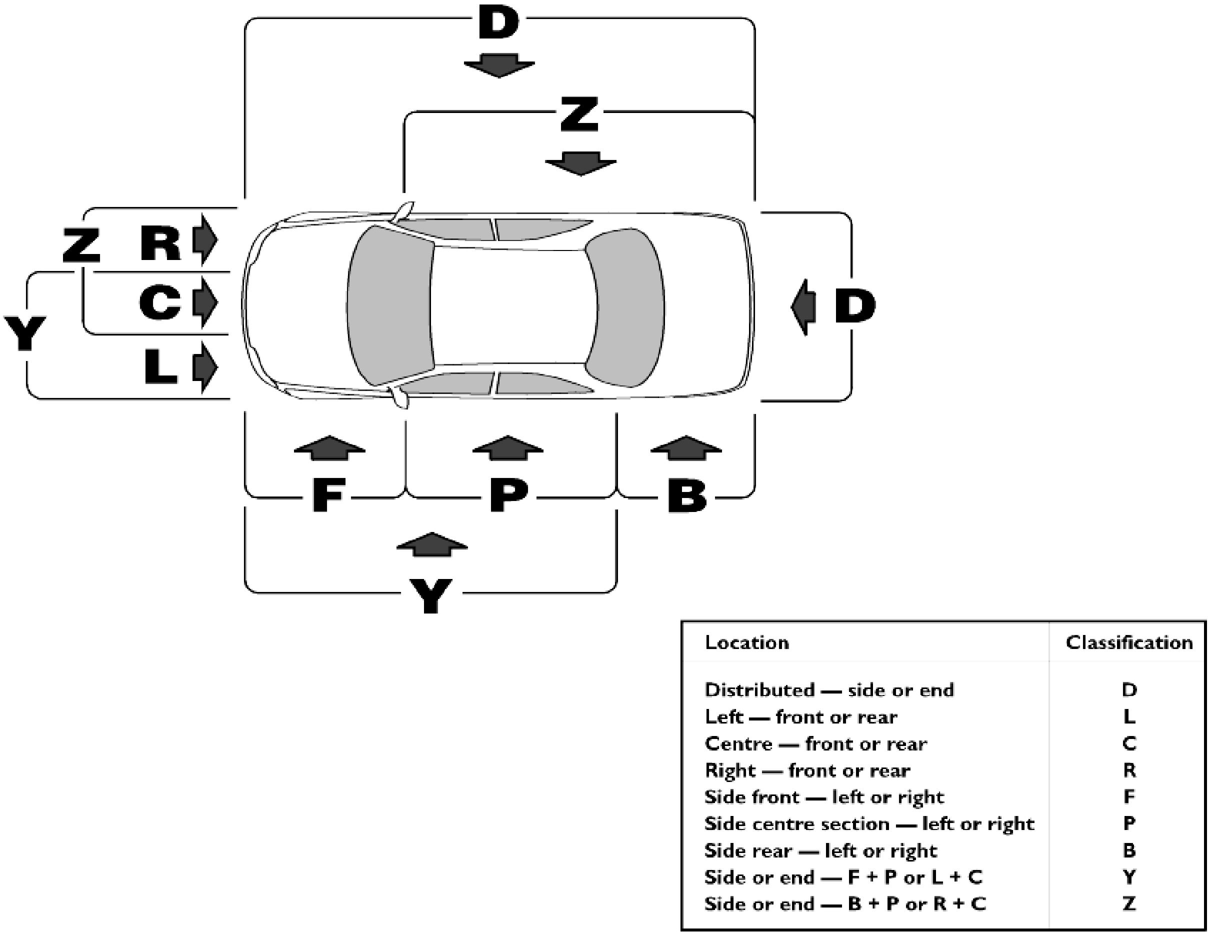
Figure 2.2 shows that the modal crash speed for near-side impacts where someone was injured sufficiently enough to be either hospitalised or killed was between 25 and 30 km/h. In far-side crashes, the modal value was higher at 31 to 36 km/h. In other words, it takes a more severe crash to be severely injured in a far-side than a near-side crash.

Table 2.15 Side impact crash severity by region of the car struck

	All Crash	NEAR	FAR	F/B	P	Z	Y	D
0-18 km/h	4.5%	4.5%	4.9%	16.7%	2.0%	9.1%	1.8%	0.0%
19-24 km/h	16.7%	17.9%	12.2%	41.7%	25.5%	9.1%	8.8%	0.0%
25-30 km/h	23.7%	27.7%	14.6%	0.0%	27.5%	27.3%	22.8%	33.3%
31-36 km/h	19.9%	19.6%	17.1%	25.0%	19.6%	33.3%	12.3%	0.0%
37-42 km/h	11.5%	11.6%	12.2%	8.3%	3.9%	9.1%	19.3%	33.3%
43-48 km/h	6.4%	7.1%	4.9%	0.0%	9.8%	3.0%	5.3%	33.3%
49-54 km/h	4.5%	2.7%	9.8%	8.3%	3.9%	0.0%	7.0%	0.0%
55-60 km/h	5.8%	4.5%	9.8%	0.0%	2.0%	9.1%	8.8%	0.0%
61-72 km/h	3.8%	3.6%	4.9%	0.0%	3.9%	0.0%	7.0%	0.0%
73-84 km/h	1.9%	0.9%	4.9%	0.0%	2.0%	0.0%	3.5%	0.0%
>84 km/h	1.3%	0.0%	4.9%	0.0%	0.0%	0.0%	3.5%	0.0%

Note: the location codes are defined in Figure 2.3 below.

The region of the vehicle struck is shown in Table 2.15 and these regions are defined in Figure 2.3.



Location	Classification
Distributed — side or end	D
Left — front or rear	L
Centre — front or rear	C
Right — front or rear	R
Side front — left or right	F
Side centre section — left or right	P
Side rear — left or right	B
Side or end — F + P or L + C	Y
Side or end — B + P or R + C	Z

Figure 2.3 Explanation of the location codes in Table 2.15, from SAE 1980

2.5 INJURIES IN SIDE IMPACTS

This section of the analysis is aimed at identifying the patterns of injuries sustained by 157 severely injured occupants from a sample of side impact passenger car crashes. It is important to note that this analysis focuses on drivers and front left passengers only. Cases where there was a front centre occupant, an otherwise unspecified ‘front occupant’ and \ or rear occupants were excluded from the analysis.

As noted earlier, occupants (cases) had to be injured severely enough to be either hospitalised or killed to be included in the sample.

Injury details were obtained from hospital or coronial records and were scored using the National Accident Sampling System (NASS) and the Abbreviated Injury Scale (AIS) (AAAM, 1990). In addition, a source was identified for each injury (where possible) from a close inspection of the vehicle and evidence of contact or suspected contact.

In analysing the data, it was also possible to calculate the Injury Severity Score (ISS). The ISS represents a measure of multiple injury severity and equals the sum of the squares of the AIS scores for the 3 most severely injured body regions (AAAM, 1990). These results are presented in the next series of Tables.

2.5.1 Mean Injury Severity & Harm

Table 2.16 shows the mean ISS, the mean HARM, and observed probability of injury for vehicle-to-car and pole-to-car crashes. For the cases in the sample, the mean ISS ranged from 22 - 39, with the mean ISS being higher in pole-to-car crashes than in vehicle-to-car collisions. In vehicle-to-car crashes, where both the driver and front left passenger were present and cases where the only the driver was present, there was no discernible difference between near and far-side crashes in the mean ISS. In vehicle-to-pole crashes, the mean ISS was higher for both near and far-side crashes when both the driver and front left passenger were present in the vehicle compared to driver only crashes. Mean HARM values for each crash configuration are also shown and are seen to follow the same pattern as that of ISS. However, given the relatively few cases, particularly in far side vehicle-to-pole crashes, caution must be exercised in interpreting these results.

Table 2.16 Mean Injury Severity Score (ISS), probability of injury and Harm sustained by front seat occupants in all side impacts and in near-side and far-side crashes.

Side Impact & Occupant	Number of cases	Mean ISS[#]	Mean Harm ($ 000s)	Observed Probability of injury		
				AIS 2+	AIS 3+	ISS 15+
Vehicle-to-car: all impacts	110	22.5	203	0.96	0.75	0.54
Pole-to-car: all impacts	47	28.5	384	0.96	0.87	0.66
Vehicle-to-car: drivers / FLP [both present] in near-side impacts	35	24.8	223	.97	.88	.57
Pole-to-car: drivers / FLP [both present] in near-side impacts	10	39.7	709	1.00	1.00	1.00
Vehicle-to-car: drivers only in near-side impacts	43	20.8	164	.97	.70	.56
Pole-to-car: drivers only in near-side impacts	19	25.9	281	1.00	.89	.52
Vehicle-to-Car: drivers / FLP [both present] in far-side impacts	9	23.5	247	.78	.55	.44
Car-to-Pole: drivers / FLP [both present] in far-side impacts	8	27.9	262	.87	.75	.62
Vehicle-to-car: drivers only in far-side impacts	23	21.4	227	1.00	.74	.52
Pole-to-car: drivers only in far-side impacts	10	22.7	354	.90	.80	.60

[#] ISS score is the sum of the 3 MAIS body region scores squared.

2.5.2 Type of Injury – Near-Side Crashes

Table 2.17 shows the distribution of body region injuries for minor (AIS 1-2) and major (AIS 3+) injuries in vehicle-to-car and pole-to-car near-side impact crashes where both a driver and front left passenger were present in the vehicle. A near-side crash for a driver in Australia is one that occurred on the RH side of the vehicle. For front passengers, it is the left side of the vehicle. The figures presented relate to the percentage of occupants sustaining the injury for each body region. For example, in Table 2.17, 31% of occupants in vehicle-to-car crashes sustained an AIS 3+ injury to the head.

For crashes involving another vehicle, a substantial proportion of major injuries (AIS 3+) occurred in the hard thorax region (40% of occupants), the head (31%), pelvis (23%), and the internal organs (20%). In pole-to-car crashes, the pattern showed major injury to the head (50%), organs (50%), pelvis (30%), spine (30%), neck (30%) and the hard thorax (20%). There were also a relatively high number of major injuries to the upper limbs and thigh / knee in pole-to-car collisions. In examining pole-to-car crashes, it is important to note the small (N=10) cases of occupants involved and to exercise caution in drawing conclusions from these cases.

Table 2.17 Percent body regions injured by drivers and front passengers in near-side impacts [where both driver & a FLP present] (by % occupants)

Body Region Injured	Vehicle-to-car (n=35 occupants)		Pole-to-car (n=10 occupants)		All Near-Side Impacts (n=45 occupants)	
	AIS 1-2	AIS 3+	AIS 1-2	AIS 3+	AIS 1-2	AIS 3+
Head	57%	31%	50%	50%	55%	36%
Face	40%	Nil	90%	10%	51%	2%
Neck	8%	8%	10%	30%	9%	13%
Hard Thorax	40%	40%	60%	20%	44%	36%
Organs*	14%	20%	30%	50%	18%	27%
Abdomen#	40%	6%	40%	20%	40%	9%
Pelvis	48%	23%	40%	30%	47%	24%
Spine	6%	Nil	20%	30%	9%	7%
Shoulder	37%	Nil	30%	Nil	35%	Nil
Upper limbs	31%	3%	60%	20%	38%	7%
Thigh/knee	23%	11%	50%	20%	29%	13%
Leg/foot	31%	8%	60%	10%	38%	9%

** Organs include the heart, liver, spleen and kidneys*
 # Abdomen is minus the liver, spleen and kidneys but includes all other organs in that region

The injury analysis in Table 2.17 included injuries sustained by both drivers and front passengers in near-side crashes that potentially involved some interactive injury contacts (ie., where occupants sustained some injuries from each other). A clearer picture of the injuries from the side impact itself is found by analysing driver only near-side crashes (Figure 2.18).

In vehicle-to-car crashes where only the driver was present, the highest proportion of AIS 3+ injuries were to the hard thorax followed by the head, pelvis and organs. In pole-to-car crashes, occupants sustained a high proportion of AIS 3+ injuries to the head, organs, hard thorax and lower extremity. The injury patterns for the other body regions, though, are basically the same in terms of rank ordering, although some rates have reduced for both vehicle-to-car and pole-to-car crashes. The most noteworthy difference between Table 2.17 and Table 2.18 is in the proportion of occupants with major head injuries in pole-to-car crashes. There were markedly fewer major head injuries with drivers only present (26% of occupants) compared to drivers with front passengers (50%) in pole-to-car crashes. This result highlights the interactive effects of multiple occupants on injury outcomes.

Table 2.18 Percent body regions injured by drivers only (no front passengers) in near-side impacts (by % occupants)

Body Region Injured	Vehicle-to-car (n=43 occupants)		Pole-to-car (n=19 occupants)		All Side Impacts (n=62 occupants)	
	AIS 1-2	AIS 3+	AIS 1-2	AIS 3+	AIS 1-2	AIS 3+
Head	58%	21%	58%	26%	58%	23%
Face	37%	2%	47%	Nil	40%	2%
Neck	9%	2%	10%	10%	10%	5%
Hard Thorax	35%	37%	42%	16%	37%	31%
Organs	11%	11%	10%	16%	11%	13%
Abdomen	30%	2%	26%	5%	29%	3%
Pelvis	44%	11%	31%	10%	40%	11%
Spine	14%	Nil	16%	Nil	14%	Nil
Shoulder	30%	Nil	42%	Nil	34%	Nil
Upper limbs	49%	7%	52%	5%	50%	6%
Thigh/knee	32%	7%	42%	16%	35%	10%
Leg/foot	28%	7%	37%	16%	30%	10%

2.5.3 Type of Injury – Far-Side Crashes

Table 2.19 shows the proportion of drivers and front left passengers sustaining AIS 1-2 and AIS 3+ injuries by body region. For vehicle-to-car crashes, the most frequent major body region injuries were to the head (33% of occupants), the hard thorax (17%), and the organs (13%). In far-side pole-to-car crashes, similar major body region injuries were observed for drivers and front passenger to the hard thorax and head (25% of occupants each). These comparisons need to be treated with considerable caution because of the low number of cases involved.

Table 2.19 Injuries sustained by drivers and front passengers in far side impacts (both present) (by % occupants)

Body Region Injured	Vehicle-to-car (n=9 occupants)		Pole-to-car (n=8 occupants)		All Far-Side Impacts (n=17 occupants)	
	AIS 1-2	AIS 3+	AIS 1-2	AIS 3+	AIS 1-2	AIS 3+
Head	22%	33%	37%	25%	29%	29%
Face	44%	Nil	37%	Nil	41%	Nil
Neck	Nil	9%	25%	12%	12%	12%
Hard Thorax	55%	17%	50%	25%	53%	35%
Organs (H,L,S,K)	11%	13%	Nil	12%	6%	18%
Abdomen - LSK	55%	9%	37%	12%	47%	12%
Pelvis	22%	9%	37%	Nil	29%	6%
Spine	Nil	Nil	12%	Nil	6%	Nil
Shoulder	22%	Nil	25%	Nil	24%	Nil
Upper limbs	55%	9%	62%	12%	59%	12%
Thigh/knee	44%	9%	50%	12%	47%	6%
Leg/foot	44%	Nil	12%	Nil	29%	Nil

Table 2.20 shows the proportion of drivers, where only drivers were present in the vehicle, sustaining AIS 1-2 and AIS 3+ injuries by body region. For vehicle-to-car far-side crashes (with no front-left passenger), the major body region injuries occurred to the head (48%), hard thorax (17%), and organs (13%). For pole-to-car impacts, 50% of occupants sustained an AIS 3+ injury to the head and 20% of occupants sustained an AIS 3+ injury to the thigh / knee. These comparisons need to be treated with caution given of the low number of cases involved, particularly in the case of pole-to-car impacts.

Table 2.20 Injuries sustained by drivers in far side impacts (drivers present only) (by % occupants)

Body Region Injured	Vehicle-to-car (n=23 occupants)		Pole-to-car (n=10 occupants)		All Far-Side Impacts (n=33 occupants)	
	AIS 1-2	AIS 3+	AIS 1-2	AIS 3+	AIS 1-2	AIS 3+
Head	61%	48%	60%	50%	61%	48%
Face	35%	Nil	70%	Nil	45%	Nil
Neck	17%	9%	40%	Nil	24%	6%
Hard Thorax	74%	17%	40%	10%	64%	15%
Organs (H,L,S,K)	9%	13%	Nil	Nil	6%	9%
Abdomen - LSK	35%	9%	50%	Nil	39%	6%
Pelvis	22%	9%	40%	10%	27%	9%
Spine	9%	Nil	Nil	Nil	6%	Nil
Shoulder	22%	Nil	50%	10%	30%	3%
Upper limbs	52%	9%	50%	Nil	52%	6%
Thigh/knee	26%	9%	50%	20%	33%	12%
Leg/foot	26%	Nil	30%	10%	27%	3%

2.5.4 Source of Injury – Near-Side Crashes

As noted earlier, attempts were made to determine the source of each injury from detailed inspections of the vehicles and the findings are shown in the following Tables. The figures presented relate to the percentage of occupants sustaining the injury for each contact source. For example, in Table 2.21, 3% of occupants in vehicle-to-car crashes sustained an AIS 1-2 injury to due to contact with the windscreen and header.

Table 2.21 shows the contact source for injuries for near-side crashes where both a driver and front left passenger were present. The most frequent source of major injuries (AIS 3+) for drivers and front passengers in near-side impacts in vehicle-to-car crashes was the door (74% of occupants) and other occupants (17%). In pole-to-car crashes, it was the door (60%), A-pillar and Instrument panel (20% each) and other-exterior contact sources (example, the ground or pole, 30% of occupants). It is noteworthy that there were considerably more exterior contacts in side impacts with pole-to-car impacts than with vehicle-to-car impacts.

Table 2.21 Source of body regions injured by drivers and front passengers in near-side impacts (by % occupants)

Source of Injury	Vehicle-to-car (n=35 occupants)		Pole-to-car (n=10 occupants)		All Near-Side Impacts (n=45 occupants)	
	AIS 1-2	AIS 3+	AIS 1-2	AIS 3+	AIS 1-2	AIS 3+
Windscreen & header	3%	Nil	10%	10%	4%	2%
Steering assembly	Nil	3%	Nil	Nil	Nil	2%
Instrument panel	20%	6%	60%	20%	29%	9%
Console	3%	3%	10%	Nil	4%	2%
Side window	17%	3%	30%	Nil	20%	2%
A-pillar	6%	3%	20%	20%	9%	7%
B-pillar	20%	6%	Nil	Nil	16%	4%
C-pillar	3%	Nil	Nil	Nil	2%	Nil
Roof side rail	Nil	Nil	10%	Nil	2%	Nil
Roof surface	Nil	Nil	10%	Nil	2%	Nil
Door	77%	74%	80%	60%	78%	71%
Floor & toe pan	9%	6%	10%	10%	9%	7%
Rear screen	Nil	Nil	Nil	Nil	Nil	Nil
Seats & headrest	3%	Nil	Nil	Nil	2%	Nil
Seatbelt	31%	6%	20%	Nil	29%	4%
Other occupant	11%	17%	Nil	Nil	9%	13%
Exterior object	Nil	Nil	10%	10%	2%	2%
Other & Unknown	26%	14%	20%	10%	24%	13%
Deceleration / non-contact	Nil	Nil	Nil	Nil	Nil	Nil
Exterior other vehicle	9%	3%	Nil	Nil	7%	2
Other - exterior	3%	3%	40%	30%	11%	9%

Table 2.22 shows the contact source for injuries for drivers in near-side crashes where only a driver was present. The most frequent source of major injuries (AIS 3+) for drivers was the door (63% of occupants). In pole-to-car crashes, 63% of occupants sustained an AIS 3+ injury due to a door contact and 16% of occupants sustained an AIS 3+ injury due to contact with ‘other – exterior’ aspect, such as the ground or pole.

Table 2.22 Source of body regions injured by drivers in near-side impacts (driver present only) (by % occupants)

Source of Injury	Vehicle-to-car (n=43 occupants)		Pole-to-car (n=19 occupants)		All Near-Side Impacts (n=62 occupants)	
	AIS 1-2	AIS 3+	AIS 1-2	AIS 3+	AIS 1-2	AIS 3+
Windscreen & header	Nil	Nil	5%	Nil	2%	Nil
Steering assembly	Nil	2%	Nil	5%	Nil	3%
Instrument panel	21%	Nil	32%	10%	24%	3%
Console	5%	Nil	Nil	Nil	3%	Nil
Side window	14%	Nil	11%	Nil	13%	Nil
A-pillar	12%	2%	Nil	Nil	8%	2%
B-pillar	5%	4%	5%	Nil	5%	3%
C-pillar	Nil	Nil	Nil	Nil	Nil	Nil
Roof side rail	Nil	Nil	5%	Nil	2%	Nil
Roof surface	Nil	Nil	5%	5%	2%	2%
Door	79%	63%	68%	63%	76%	63%
Floor & toe pan	12%	Nil	21%	5%	15%	2%
Rear screen	Nil	Nil	Nil	Nil	Nil	Nil
Seats & headrest	2%	Nil	5%	5%	3%	Nil
Seatbelt	19%	Nil	37%	Nil	24%	2%
Other occupant	Nil	Nil	Nil	Nil	Nil	Nil
Exterior object	2%	2%	Nil	Nil	2%	2%
Other & Unknown	47%	4%	47%	5%	47%	5%
Deceleration / non-contact	Nil	Nil	Nil	Nil	Nil	Nil
Exterior other vehicle	14%	9%	Nil	Nil	10%	6%
Other - exterior	5%	Nil	26%	16%	11%	5%

2.5.5 Source of Injury - Far-Side Crashes

Table 2.23 shows that the greatest sources of major injury to the driver and front passengers when both were present in a far-side crash were each other (56% of occupants sustained an AIS 3+ injury) followed by the door panel (33%). Similarly, the most frequent source of major injury to drivers and front passengers together in far-side crashes with a pole was other occupants (12%). Once again, caution is required in interpreting these figures due to the small numbers available for analysis.

Table 2.23 Injuries sustained by drivers and front passengers in far side impacts (both present) (by % occupants)

Source of Injury	Vehicle-to-car (n=9 occupants)		Pole-to-car (n=8 occupants)		All Far-Side Impacts (n=17 occupants)	
	AIS 1-2	AIS 3+	AIS 1-2	AIS 3+	AIS 1-2	AIS 3+
Windscreen & header	Nil	Nil	Nil	Nil	Nil	Nil
Steering assembly	Nil	Nil	Nil	12%	Nil	6%
Instrument panel	44%	Nil	37%	12%	41%	6%
Console	Nil	Nil	Nil	Nil	Nil	Nil
Side window	Nil	Nil	Nil	Nil	Nil	Nil
A-pillar	Nil	Nil	12%	Nil	6%	Nil
B-pillar	11%	Nil	Nil	Nil	6%	Nil
C-pillar	Nil	Nil	Nil	Nil	Nil	Nil
Roof side rail	Nil	Nil	Nil	Nil	Nil	Nil
Roof surface	Nil	Nil	Nil	12%	Nil	6%
Door	22%	33%	Nil	Nil	12%	18%
Floor & toe pan	11%	Nil	Nil	Nil	6%	Nil
Rear screen	Nil	Nil	Nil	Nil	Nil	Nil
Seats & headrest	Nil	Nil	12%	Nil	6%	Nil
Seatbelt	56%	Nil	37%	12%	47%	6%
Other occupant	78%	56%	25%	12%	53%	35%
Exterior object	Nil	Nil	25%	12%	12%	6%
Other & Unknown	33%	11%	12%	Nil	24%	6%
Deceleration / non-contact	Nil	Nil	Nil	Nil	Nil	Nil
Exterior other vehicle	Nil	Nil	Nil	Nil	Nil	Nil
Other - exterior	Nil	Nil	25%	12%	12%	6%

Table 2.24 shows the equivalent source of injury to drivers when there was no front passenger present in both vehicle-to-car and pole-to-car impacts. These numbers are small and the findings need to be treated cautiously. Nevertheless, in vehicle-to-car side impacts, major injury (AIS 3+) was most commonly attributed to contact with the door (30% of occupants sustaining an AIS 3+ injury) and seatbelt (22% of occupants sustaining an AIS 3+ injury) while for car-to-pole crashes, the major injury sources were the roof and the door. As with the analysis presented in the preceding Tables, there were only a limited number of cases for analysis here so these findings should be treated as indicative only.

Table 2.24 Injuries sustained by drivers in far side impacts (no front passengers present) (by % occupants)

Source of Injury	Vehicle-to-car (n=23 occupants)		Pole-to-car (n=10 occupants)		All Far-Side Impacts (n=33 occupants)	
	AIS 1-2	AIS 3+	AIS 1-2	AIS 3+	AIS 1-2	AIS 3+
Windscreen & header	4%	4%	Nil	Nil	3%	3%
Steering assembly	Nil	9%	Nil	10%	Nil	9%
Instrument panel	30%	13%	60%	10%	39%	12%
Console	13%	Nil	Nil	Nil	9%	Nil
Side window	30%	9%	20%	Nil	27%	6%
A-pillar	4%	4%	10%	Nil	6%	3%
B-pillar	Nil	4%	10%	Nil	3%	3%
C-pillar	Nil	Nil	10%	Nil	3%	Nil
Roof side rail	4%	4%	Nil	Nil	3%	3%
Roof surface	4%	4%	40%	40%	15%	15%
Door	43%	30%	30%	30%	39%	30%
Floor & toe pan	4%	Nil	Nil	Nil	3%	Nil
Rear screen	Nil	Nil	10%	Nil	3%	Nil
Seats & headrest	Nil	Nil	Nil	Nil	Nil	Nil
Seatbelt	61%	22%	60%	10%	61%	18%
Other occupant	Nil	Nil	Nil	Nil	Nil	Nil
Exterior object	Nil	Nil	Nil	Nil	Nil	Nil
Other & Unknown	26%	4%	40%	10%	30%	6%
Deceleration / non-contact	Nil	Nil	Nil	Nil	Nil	Nil
Exterior other vehicle	4%	9%	Nil	Nil	3%	6%
Other - exterior	4%	4%	30%	10%	12%	3%

2.5.6 Injury Lesions

The types of lesions involved in side impact injuries to hospitalised or killed occupants in side impact crashes are shown below in Table 2.25.

Table 2.25 Injury lesions for injured occupants in all side impact crashes

CODES	Abrasions & Lacerations A,L	Sprain & Strain S,T	Contusion Bruising C	LOC H,K	Rupture & Perforation R,P,V	Fracture & Dislocation D,F,Z	Crush N	Detachment Separation G	Amputation Severence M,E	Burns B	Other Lesion U,O
Head	51		68	103	6	34	3				10
Face	82		46		1	18		2			2
Chest	30	1	65		10	111		1	7	1	6
Abdomen	16		53		10					1	32
Pelvis	16		35			73		2			4
Heart	8		11		5						3
Organs	38		66		19			1			30
Shoulder	21		25			37					
Upper arm	18		26			13					
Thigh	22		40			21				1	
Knee	31	1	12		1	3	1	1			3
Lower Leg	31		34			19	1				15
Ankle/foot	15		17		1	6	1				
Neck/Spine	10	7	8			17			2		1
TOTAL	389	9	506	103	53	352	6	7	9	3	106

2.6 SUMMARY AND INJURY ASSESSMENT PRIORITIES

2.6.1 Summary of Types of Side Impact Crashes

In summary, there are a number of features of side impacts from the Crashed Vehicle File (CVF) of crashes involving hospitalisation or death. The first is that the greatest proportion (60%) of Harm results from near-side impacts. In addition, the modal impact velocity was 25-30 km/h and the majority of impacts result from car-to-car collisions with the most frequent source of injury being the occupant's door. When both the driver and front passenger were present however, the most frequent source of injury was another occupant. Another feature of side impacts is that the struck vehicle in car-to-car crashes tends to be lighter than the striking car.

In addition, the CVF indicates that the majority (53.8%) of side impacts are car-to-car impacts with car-to-pole crashes accounting for a further 22.2% of side impacts. The mean Harm caused by car-to-pole collisions however, is almost double that of car-to-car impacts in lateral collisions. In line with this, calculated delta-Vs indicate that the proportion of impacts above the modal impact speed was higher in car-to-pole impacts than car-to-car impacts.

In car-to-pole impacts the direction of impact is most likely to be oblique whereas most car-to-car side impacts are perpendicular. In driver only car-to-pole impacts the head and internal organs and hard thorax were most likely to suffer major injury whereas in near-side car-to-car impacts the thorax and head were most likely to be injured. It is not surprising then, that even though the door is the predominant source of major injury in both types of impacts, near side car-to-pole impacts injuries are more likely to be the result of impacts with the external objects or the instrument panel. All of the above suggests that serious head injuries are more likely in car-to-pole impacts.

In far-side impacts greater impact speeds appear to be required to obtain equivalent Harm. In addition, a far greater proportion of the Harm from severe injuries is due to head injuries and less from injuries to the thorax.

2.6.2 Summary of Injury Data and Implications for Injury Assessment Priorities

A consistent outcome of the real-world crash data is that injuries to the head constitute the majority of Harm in side impacts. This is true in both near side and far side impacts for both drivers and front seat occupants. Head injuries however, cause a far greater proportion of the Harm in far-side, as opposed to near-side, impacts. In addition, the total head Harm in far side impacts is greater despite there being fewer far-side impacts that result in injury.

A break down of the extent of annual side impact Harm by body region and injury severity is provided in Table 2.1, and this forms a useful basis for the ordering of priorities. Table 2.26 orders the body regions in terms of total harm due to side impact crashes. After the head, with 50.9% of Harm, the most important regions are the thorax (22.3%) when internal injuries to the heart, spleen, liver and kidney are included, and the lower extremities (8.6%). The next highest priority regions are the spine as a whole and the shoulder and upper extremities combined, but little detail is available in the current analysis regarding the specific injuries to these regions.

Table 2.26 The injury priority of the regions of the body as a result of side impacts

Priority	Body Region	Harm
1	Head	50.9%
2	Thorax (inc. hslk)	22.3%
3	Lower Extremities	8.6%
4	Upper Extremities	5.6%
5	Spine	4.1%
6	Face	3.6%
7	Pelvis	3.1%
8	Shoulder	1.9%
9	Abdomen	1.8%
10	Neck	1.7%
		100%

At a more detailed level the greatest level of Harm by body region and injury severity level are listed in order below (see Table 2.27). If injuries to the heart, liver, spleen and kidney are divided from those to the hard thorax the key contributors to Harm become AIS 2,3,4,5 & 6 head injuries; AIS 3 & 4 hard thorax injuries, AIS 3 lower limb injuries, AIS 6 heart, liver, spleen and kidney injuries, and AIS 2 upper limb injuries.

Table 2.27 The greatest sources of Harm by body region and injury severity in side impacts

	Body Region	AIS	Harm ($Amill)
1	Head (exc. face)	5	214.6
2	Head (exc. face)	4	85.2
3	Head (exc. face)	3	73.9
4	Thorax (inc. H,L,S,K)	3	61.9
5	Thorax (inc. H,L,S,K)	4	59.2
6	Lower limbs	3	39.7
7	Upper limbs (inc. shoulder)	2	38.8
8	Head (exc. face)	2	38.2
9	Thorax (inc. H,L,S,K)	6	34.7
10	Thorax (inc. H,L,S,K)	5	28.0
11	Lower limbs	2	25.8
12	Head (exc. face)	6	20.8

[* H,L,S,K is the heart, liver, spleen and kidney]

Interpretations of the body region priorities require some discussion. These regions differ from those used in the AIS scheme, for both the 1985 and 1990 versions. Also there is significant under reporting for some areas, such as the neck, at both the minor and major ends of the severity distribution.

The ISIP Experts meeting in Detroit at the time of the 1998 Conference on the Enhanced Safety of Vehicles, underlined the fact that there were not enough available tolerance data to adequately map all body region injury in side impacts to Harm. However, David Viano suggested that there was the possibility of being able to address the critical areas of injury, MUARC (1998). He went on to suggest that the injury severities to address for each body region, were those that were significantly above the baseline in terms of Harm by body region and injury severity. This approach to the problem of allocating priorities would also give a guide as to the best allocation of resources, when the available tolerance data was being expanded. Based on Table 2.1, the critical injury severity regions to be addressed are presented in Table 2.28. The shaded regions in this figure indicate the injury severity priority areas for each body region and the three levels of shading indicate the priority, darker is higher. Where there are only low levels of injury, which was generally taken to be a Harm of less than $2.5 million, then the area is left blank. It is important to understand that these priorities are for the individual body regions.

Table 2.28 The three highest priority areas for the individual body regions, darker shading is higher priority

Body Region	AIS 1	AIS 2	AIS 3	AIS 4	AIS 5	AIS 6
Head			░	▓	█	
Thorax (inc. hlsk			█	▓	░	
Lower Extremities		▓	█			
Upper Extremities	░	█	░			
Spine	▓	░			█	▓
Face	█	▓				
Pelvis		▓	█			
Shoulder		█				
Abdomen	█			▓		
Neck	▓		░		█	

Priority in the whole project therefore must be given to head injury of AIS 3+, followed by thoracic injury of AIS 3+. The grouping of the data used in this analysis has caused some distortion with the grading of priorities. For instance the thorax has been grouped with the liver, spleen and kidneys for the hard thorax definition used in the Thoracic Trauma Index (TTI). From the viewpoint of the development of injury assessment data, it would be better to have these internal organ injuries grouped with the abdominal injuries to match the cadaver test data and the AIS classification. If spine and neck injury are grouped then spinal injury as a whole becomes a much higher priority. Shoulder and upper extremity injury should also possibly be connected in the AIS classification and testing. The priority areas outlined in this table give a guide to the injuries by body region that must be addressed to allow unbiased assessment of injury from the dummy responses.

2.6.3 Implications for Dummy Response Requirements

The importance of head injuries in the Harm arising from side impacts means that it is particularly important that any dummy used to assess likely injuries in side impacts is capable of reliably replicating the kinematics and impacts of the head in real-world crashes. This is particularly true for the types of collisions that result in the severe head injuries that generate the most Harm. The BioSID has poor biofidelity in this regard because of the stiffness of the shoulder in lateral impacts, but it is the best available until the World SID becomes available. The stiffer shoulder tends to result in fewer head impacts than would normally occur for human occupants in side impacts.

Chapter 3
INJURY ASSESSMENT

3.1 INTRODUCTION

A review of human impact tolerance data for side impacts is presented here. This review is the first step to developing the necessary Injury Assessment Functions (IAFs), for use in the modelling component of the ISIP project. An accepted set of injury assessment reference functions is integral to the success of the project. The IAFs are required to define the real-world side impact injury risk for particular types of injury from the responses obtained from the core human surrogate/ vehicle interaction model. The object of this work is to be able to define the injury risk for those types of injuries that occur most frequently, and are associated with the greatest Harm. Injury types that fall into this category are identified from the crash analysis in Chapter 2 - Real-World Data Analysis.

Injury occurs when a biological system has been deformed beyond its recoverable limit, resulting in physical and physiological disruption. Different types of injuries result from different injury mechanisms. An injury mechanism describes the type of loading, or the biomechanical response, which results in anatomical and functional damage. There are three principal types of loading, that either acting alone or in combination, form the basis of most impact injury mechanisms. These are compression, acceleration and impulse loading (or shock).

An injury threshold, for a particular type of injury describes the level of loading for a particular mechanism, where injury will occur. Increasing the level of loading usually increases the severity of the injury, however in some circumstances increased loading actually changes the type (and therefore the mechanism) of injury. Injury threshold levels for specific injury types usually occur at different levels for different individuals. This is due to factors such as age, gender and general physical condition.

The type and severity of an injury must be described by a standardised injury scale. In the ISIP project a widely accepted anatomically based scale, the Abbreviated Injury Scale (AIS) is used, AAAM (1990). It describes an injury in terms of its anatomical location, type of injury and relative severity in terms of threat to life. This is used in conjunction with the concept of societal Harm, which is described in greater detail in chapter 2 of this report. Harm assigns an economic value to different types and severities of injury and does this by body region.

Recently, intervention programs in the area of traffic safety have been moving to assign priority to those injuries causing long-term disability, Norin, Krafft, Korner, Nygren, & Tingvall (1997). One of the reasons for this change is that minor injuries, such as AIS 1 neck injury, may lead to significant long term disability. As yet no disability scale has been widely accepted, though several are undergoing intensive development, AAAM (1994).

Several methods are used for studying injury mechanisms and injury threshold levels. These generally involve the use of a human surrogate, such as a cadaver, dummy, animal, or a human volunteer. Although there are a number of problems associated with the use of each type of human surrogate, for experimental work to identify injury mechanisms and threshold levels in this area, there is no alternative. For this reason it is necessary to have some understanding of the limitations implied with the use of each approach.

For the assessment of injury potential, for example, in vehicle and safety equipment developmental and compliance testing, repeatability and reliability are required. This has led to the development of families of mechanical human surrogates for this purpose. These devices are usually known as anthropomorphic test dummies. Such mechanical surrogates are not capable of exactly replicating human responses. The capability of a dummy to behave in a human like manner under impact conditions is called its **biofidelity**.

The relationship between the injury mechanism, type and quantification of loading and the resulting injury severity is an **injury criterion**. The injury criterion, sometimes also called the **injury tolerance level**, can be defined as a measurable physical parameter that correlates well with the injury severity of a particular body region. Examples of frequently used criteria are linear accelerations experienced by a particular body part, global forces or moments acting on the body or deflection of particular structures. In many cases, a function derived from single or multiple measured physical parameters shows better correlation with real world injury severity than the absolute measured value. Examples of such derived functions are discussed later and include the Head Injury Criterion (HIC), which is based on time and acceleration and the NHTSA neck injury criterion (Nij), which uses axial force and bending moment.

This relationship between injury risk, or the probability of receiving a particular injury at the various levels of severity and the responses of the human surrogate, either mechanical or mathematical, has been called an **injury assessment reference value** (IARV). The best known set of IARVs were developed at GM for use with the Hybrid III dummy, Mertz (1984). Initially these IARVs were based on injury risk for a single point injury criterion. More recently it has become necessary to have more than a single point available for injury risk assessment. These curves giving variation of the risk of a given injury are known as **injury assessment functions** (IAFs).

3.2 SOURCES OF DATA

For the ISIP project, the real world injury risk for each body region was required for assessing the resultant Harm. This injury risk was obtained from the responses of the core human surrogate/vehicle interaction model, and so, a set of IAFs needed to be developed. Before reviewing the available sources for such injury risk data, it maybe helpful to comment on the methods used for determining human injury response, and hence injury criteria:

1. A **human volunteer** is instrumented and subjected to a controlled series of impacts at increasing levels. The threshold of the impacts is set to avoid injuring the volunteer. This type of testing has the advantage that a human is the basis for the testing. This method has certain drawbacks:

    - it is only able to indicate the threshold of minor injury;
    - the attachment of the instrumentation may lead to less reliable data;
    - the type of individual volunteer, for example military personnel, may not be representative of the general population; and,
    - the effects of muscle tension, learned behaviour and involuntary reactions may dominate the results.

2. A **cadaver** is instrumented and subjected to impact forces. Autopsy shows the injuries incurred, which are then correlated with the measurements taken. This type of testing has the advantage that at least the framework of the surrogate has some resemblance to a human. Problems do exist with this technique as well, notably that:

    - available subjects are generally older and more debilitated than the average population;
    - subjects are in short supply;
    - the response of the cadaver depends on the pretest treatment (frozen, embalmed, fresh, etc.);
    - the effects of pressurisation of body systems such as the airways, vascular system and the central nervous system are missing without special techniques;
    - the effects of active musculature are absent unless special techniques, such as embalming, are used to simulate muscle tension; and,
    - many signs of injury on a living subject (eg muscle strain, pain, loss of consciousness) are not available.

3. An **animal** is instrumented and subjected to impact forces. An autopsy or a clinical examination shows the injuries incurred, which are then correlated with the measurements taken and scaled to give estimates of human response to impact. In the past primates and pigs have been used to study automotive injury and it has been very useful in defining injury mechanisms. Using anaesthetised animals can also provide information on how injury and vital signs are related. The biggest drawback of this approach is in transforming the differences in the animal anatomy, responses and injuries into human injury criteria.

4. A **dummy** may also be used to develop injury criteria through accident reconstruction. If the accident conditions are fully investigated, and the victim's injuries are fully documented, the accidents can be reconstructed, that is staged, with a dummy as surrogate for the victim. This technique is more useful for developing injury assessment functions, than human injury criteria. The measurements of the dummy responses to the crash can be paired with the injuries (and lack there of) recorded for the victim. In this way it is possible to develop dummy based IAFs. Issues to be considered in relation to this method include:

    - the assessment of the adequacy of the reproduction of an impact condition is subjective;
    - dummies in the past were only available in limited sizes, which meant the victim was often not closely matched;
    - the measured dummy response is dependent on the instrumentation;
    - dummies lack perfect biofidelity, and can only approximate human response;
    - the lack of biofidelity of the dummy becomes more marked where serious injury occurs, for example when fractures occur;
    - an IAF is not directly applicable to humans; and,
    - an IAF may only apply to the specific dummy type used in the reconstruction.

5. A **crash victim simulation** uses computer models of the dummy, and more recently of the human, to reproduce a well-documented accident. One advantage of computer

models over dummies is the ability to match the physical characteristics of the accident victim more closely. However, there are problems, in that:

- such models are handicapped by the minimal amount of human biomechanical data available;
- reliability is limited by the biofidelity of the computer simulation;
- thorough model validation is necessary; and,
- the higher the level of similitude obtained the greater the computing power required.

The computer modelling techniques are becoming more sophisticated as increased computing power and better human response data become available.

The priorities for the IAFs needed in this chapter were established in chapter 2. This chapter describes briefly the relevant injuries for each body region in side impact, the injury mechanisms and injury criteria available from the literature and suggests preliminary injury criteria.

3.3 SIGN CONVENTION USED IN THIS REPORT

The sign convention that will be used for the coordinate axes in this report (shown in Figure 3.2.1), is commonly used for biomechanics, White and Panjabi (1990). This convention is different to that suggested by the SAE for use with dummies, SAE (1988).

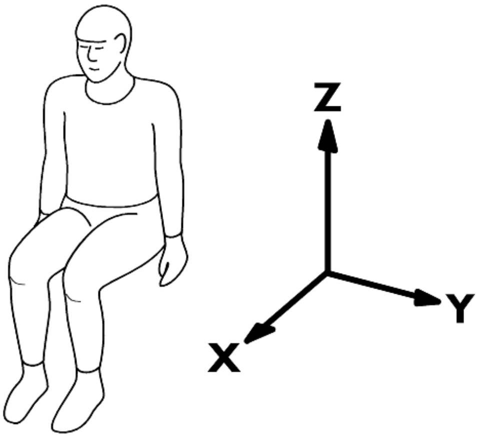


Figure 3.3.1 Sign convention used in the report

3.4 INJURY ASSESSMENT BY BODY REGION

3.4.1 Introduction

In the following review each body region is dealt with in the following format:

- a brief description of injury types and a summary of the injuries that occur to the specific body region derived from Chapter 2: Real World Data Analysis and the literature where necessary;

- a review of the available literature regarding injury tolerance for the body region with discussion of the sources and test methodology used to obtain the data. This includes both static and dynamic cadaver tests, as well as volunteer, animal and reconstruction data; and,
- a discussion of the available injury tolerance data for side impact, with the proposal of preliminary injury tolerance curves where possible. The emphasis has been placed on applicable continuous risk curves which have general acceptance.

The assumption is made that the reader has an adequate level understanding of basic anatomy to understand the structure of each of the body regions addressed.

It is necessary to be careful about the rating of priorities as presented in Table 2.28. As the outcome of this work is to develop an optimisation process for the design of side impact protection, it is necessary that the injury assessment be comprehensive. It must be able to address the full range of possible side impact injury to ensure that balanced design solutions are produced. An example from early experience with the FMVSS 214 in the US is illustrative in this regard. This standard was the first dynamic side impact test standard. To meet the new crash test requirements some vehicle designers resorted to loading the abdominal area of the SID dummy, Dalmotas, Newman, & Gibson, (1996). The SID dummy mandated for the test, has no measurement capability in this area and so it was possible to comply with the regulation but in a manner most likely to be injurious to the occupant.

At this point in time the only accepted injury assessment functions available for use in side impacts with the BioSID dummy, are some individual reference values proposed by Mertz (1992) and Viano et. al. (1995). The reason for the choice of the dummy types for this project and these injury assessment reference values are discussed in Chapter 4: Dummy Capabilities.

The injury tolerances suggested here for each of the body regions are for the initial use of the optimisation modelling and as a starting point for the development of the injury assessment functions for use with the dummy responses over the next two years of the project. These are presented in a summary form as an Attachment.

3.4.2 Head

Head Injuries

Head injury, or more specifically, brain injury, is the most threatening of injuries, both to life, and to quality of life. Head injury is the most critical area of impact trauma resulting from car crashes. Brain injury is under-identified in Australian car crash data. Hospitals frequently classify head injury as less serious than fractured pelvis, based on time in hospital, without consideration of the on-going consequences, the costs to individual and community. There is a growing awareness of the incidence of non-fatal brain injuries and their impact on the individual, the family unit and the community. Brain injury has been appropriately called the silent epidemic by Bucanen (1989), and there has been a dramatic increase in brain injury in the last decade, not as a result of increased accidents, but because of increased survival.

The use of ambulances with life support systems, helicopter ambulances and the use of cat scans to identify haemorrhaging and location of blood clots have contributed to this increased survival. The long-term consequences and the personal cost of a brain injury are very evident to the victim and to those close by. The community cost is progressively being recognised. It is becoming evident that brain injury is a major social issue, both in Australia and world-wide. As improvements are made in cardio-pulmonary resuscitation and in life support treatment in Mobile Intensive Care Ambulances and in hospital Intensive Care Units, many people now survive what would previously have been a fatal head injury. In Australia, over 8,000 people each year suffer non-fatal head injuries as a result of motor vehicle crashes (AIHW, 1994). This is focusing future concern on developing strategies for reduction of head injury frequency and severity. An improved understanding of the biomechanics of brain injury is critical to the development of improved occupant protection.

In their analysis in Chapter 2 of injury and Harm resulting from side impact crashes in Australia, Working Group 1 identified that head injuries were the most frequent injuries, caused the most Harm (51%) to the Australian community and were the most debilitating and life threatening injuries that occurred. The analysis also identified that head injuries of AIS 3 and greater severity caused the most Harm, and hence warranted priority in occupant protection considerations. The most frequent injury was loss of consciousness, which has a minimum severity of AIS 2, followed by contusion/bruising, then abrasion/laceration and fracture/dislocations were the fourth most frequent injury to the head. The most common cause of the abrasions/lacerations to the head was head contact with the vehicle side window, but the fracture/dislocations were most commonly caused by contact with exterior sources or the vehicle side structure. This clearly emphasises that occupant protection against head injury was the most important task for design to improve occupant protection.

Head injuries can be separated into three anatomical categories.

Injuries to the scalp: (AIS 1+) These injuries consist of laceration and contusion resulting from direct mechanical action.

Injuries to the skull: (AIS 2+) Skull fracture will occur if the bones of the skull are deformed beyond their elastic limit.

Injuries to the brain: (AIS 1+ to 4+) The brain will be injured if any part of it is distorted, stretched, compressed or torn from the skull interior. Brain injuries are usually classified into two categories, diffuse or focal. Diffuse injuries include brain swelling, concussion, shearing injury and diffuse axonal injury (DAI). Focal injuries include epidural or subdural hematoma, intracerebral hematoma and contusion, (Ono, Kikuchi, Nakamura, Koyabashi, & Nakamura, 1980). Distortion of the brain tissue may result from skull deformation, ie. direct crushing, or from some form of inertial loading to the brain as a result of a rapid change in head velocity due to an impact. The rapid change in motion of the head may be either rotational or translational and is usually measured in terms of head acceleration.

Note that loss of consciousness is an indicator of brain injury. Headache is considered to indicate minor injury, AIS 1, loss of consciousness for less than 1 hour rates AIS 2, loss of consciousness between 1 and 6 hours rates AIS 3, and AIS 4 is assigned to unconsciousness between 6 and 24 hours. Any loss of consciousness indicates some level of brain injury, with increasing time indicating increasing risk of irrecoverable injury.

McLean et. al. (1997) investigated the need for interior padding in vehicles to reduce the severity of impact to the head in motor vehicle crashes. The researchers analysed the position of such impacts on the head, but did not break the crash types down by direction of impact. The data indicates that over 60% of the more severe and fatal head injuries occurred as a result of lateral impacts to the head. The impact sites are shown plotted for non fatal crashes in Figures 3.4.2.1 and for fatal crashes in Figure 3.4.2.2.

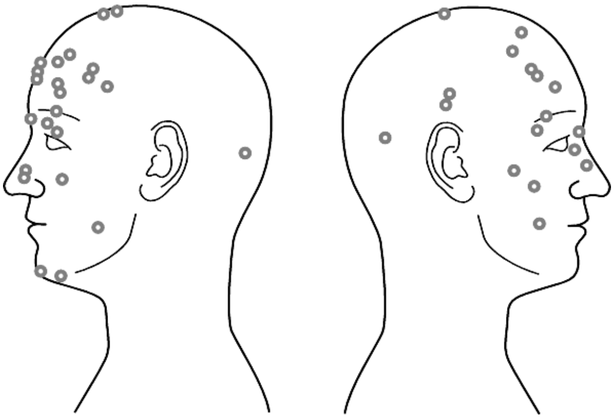


Figure 3.4.2.1 Location of car occupant head impacts in cases of non-fatal injury, McLean et. al. 1997.

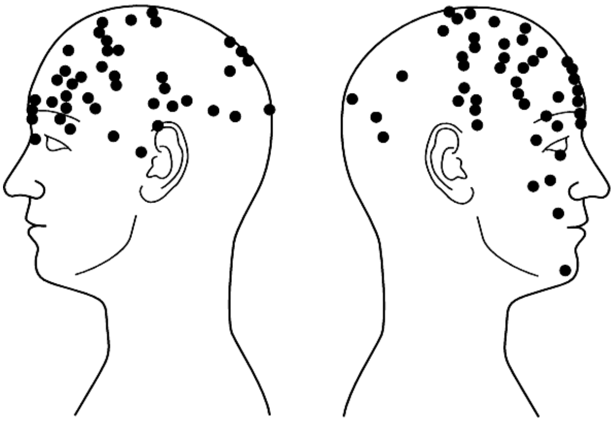


Figure 3.4.2.2 Location of car occupant head impacts in cases of fatal injury, McLean et. al. 1997

Head Injury Assessment Review

Holbourn (1943) suggested that rotational motion could be a more obvious correlate with brain injury than simple translational motion. It was not until 1970 however, that Hirsch and Ommaya were able to show in animal experiments that rotational acceleration was necessary to produce diffuse type brain injury, Ommaya (1988). These researchers suggested that 50% of all brain injury was due to rotational effects.

In the meantime, the first attempt to measure the tolerance of the head to blunt impact was carried out by researchers at Wayne State University in Detroit, notably Gurdjian and Lissner, from the 1940s through to the 1960s. They subjected cadaver heads to a blow to the forehead and related the linear acceleration of the head to whether or not the impact produced fractures in the frontal bone. Eight skulls were hit and the results of six of the eight cases were plotted on a graph having the linear (straight line) acceleration of the head on the vertical axis and time (measured in milliseconds) on the horizontal axis. One of the eight points was omitted in error and another was misplotted. The plotted points approximately lay on a curve which, is shown in Figure 3.4.2.3. Additional data points from other studies in which the duration of the impact was longer were added later, and the slope of the extended curve approached the horizontal at 80g after about 10 milliseconds.

The curve, defined by the data points from the original cadaver studies and supplemented by the additional data, became known as the Wayne State Tolerance Curve (WSTC). It was thought to provide an indication of the tolerance of the brain to impact, in terms of the time history of the acceleration imparted to the head. This was a considerable extrapolation from the original tests, in which the outcome measure had been simply the presence or absence of skull fracture. The validity of the Wayne State Tolerance Curve (WSTC) depended primarily on the assumption that if the skull of a living human was fractured then that injury would probably be accompanied by concussion.

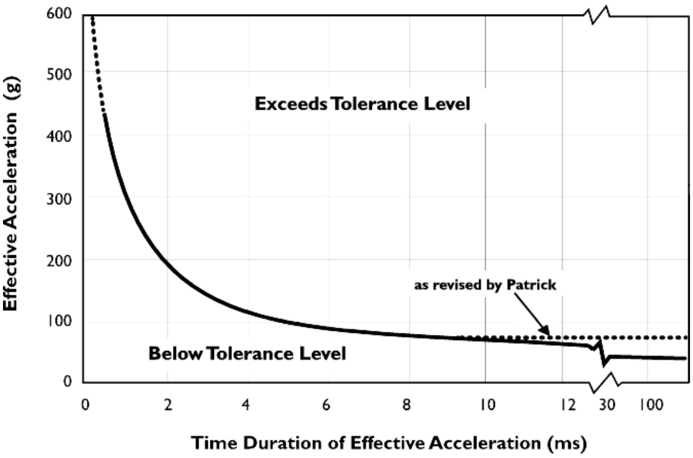


Figure 3.4.2.3 WSU Tolerance Curve (WSTC) for impacts to the forehead, SAE (1986)

In 1966, at the STAPP Conference, Charles Gadd of General Motors proposed a head injury severity index based on the Wayne State Tolerance Curve. Gadd reasoned that some measure of the area under the acceleration/time curve for a given impact could form the basis for such an index. However it was apparent that a low level of acceleration lasting for a long time was not injurious whereas a higher level of acceleration acting for a shorter time was much more likely to be so, even though the area under the acceleration/time curve could be the same. Gadd, therefore, decided to weight the area measure in favour of the acceleration component. He did this by raising the acceleration value to the 2.5 power. He chose this number (2.5) because it happened to be the absolute slope of the Wayne State curve, when plotted on logarithmic axes. This approximation may have fit the meagre experimental data available, but only gave a poor fit to the actual tolerance curve, and has been the cause of much of the later criticism of HIC.

The mathematical expression for the Gadd Severity index is as follows:

$$\int a^{2.5} dt$$

where ‘a’ (g) is the effective acceleration of the head , and t (milliseconds) is the time from the start of the impact.

The Gadd Severity Index, or as it was initially called, the Severity Index, was thought by some still not to deal adequately with long duration, low acceleration impacts. At the 1971 STAPP Conference, John Versace of Ford Motor Company proposed a modification of the Gadd Severity Index, which he called the Head Injury Criterion (HIC). The change was proposed to focus the severity index on that part of the impact that was likely to be relevant to the risk of injury to the brain. It was done by integrating the resultant acceleration/time curve over whatever time interval yields the maximum value of HIC. As this will vary from one impact to another, the expression for Versace’s modified index simply refers to times t_1 and t_2. The expression for HIC is:

$$HIC = \left(t_2 - t_1\right)\int_{t_1}^{t_2} \frac{a^{2.5}}{\left(t_2 - t_1\right)} dt$$

where t_1 and t_2 are selected to yield the maximum value.

Since then, the need to restrict the time interval (t_2- t_1) has been suggested, to avoid the possibility of obtaining high HIC values from long duration, low acceleration cases, which may occur with the use of an airbag, for example. Federal Motor Vehicle Safety Standard, FMVSS, 208 uses a 36ms clip. A more recent review of HIC by Mertz, Prasad, & Irwin (1996), supported a change to a 15 ms clip on the basis that the critical injury causing events all occur in this early part of the impact, Prasad and Mertz (1985). This may only be adapting the criteria to match the available experimental data, which only has short duration impacts. Mertz et. al. (1996) reanalysed available cadaver head impact data for frontal impacts and derived separate HIC based risk curves for skull fracture, Figure 3.4.2.4, and AIS 4+ brain injury, Figure 3.4.2.5. The skull fracture curve is based on cadaver tests which included multiple impacts to the skull before fracture was observed. The AIS 4+ brain injury curve is incomplete in that it only includes those injuries able to be found following a cadaver test. These injuries do include focal injuries, such as blood vessel tears and major contusions, but diffuse injuries are unable to be identified. The risk curve, Mertz et. al. (1996), obtained for skull fracture is very similar to that for AIS 4+ brain injury.

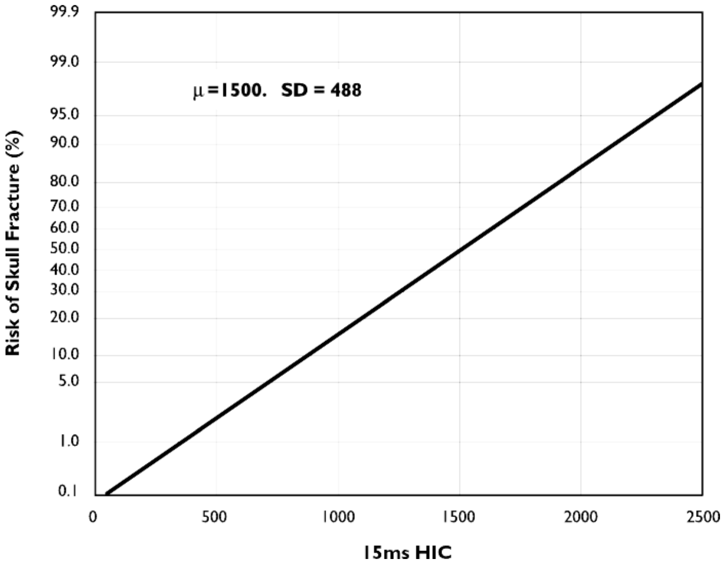


Figure 3.4.2.4 Risk of skull fracture for frontal impacts as a function of 15ms HIC, Mertz et. al. (1996)

Viano and King (1997) also suggest a HIC based probability of injury function for frontal impacts, but do not include enough details to evaluate it fully.

The brain injury risk function for frontal impacts proposed by Mertz et. al. (1996), suggests an 18% probability of AIS 4+ injury at a HIC of 1000. In the lead up to the recent changes in FMVSS 201, the National Highway Traffic Safety Administration (NHTSA) expanded the brain injury risk curve to include the probability of different injury levels by extrapolating from the probability of injury curves developed for the Thoracic Trauma Index (TTI), described later in this chapter (Kanianthra, Fan, & Rains, 1996). A combination of the injury risk probability and HIC distribution in real world crashes was used to determine how injuries are shifted from higher to lower severity as HIC is reduced. These expanded HIC probability of injury curves are shown in Figure 3.4.2.6.

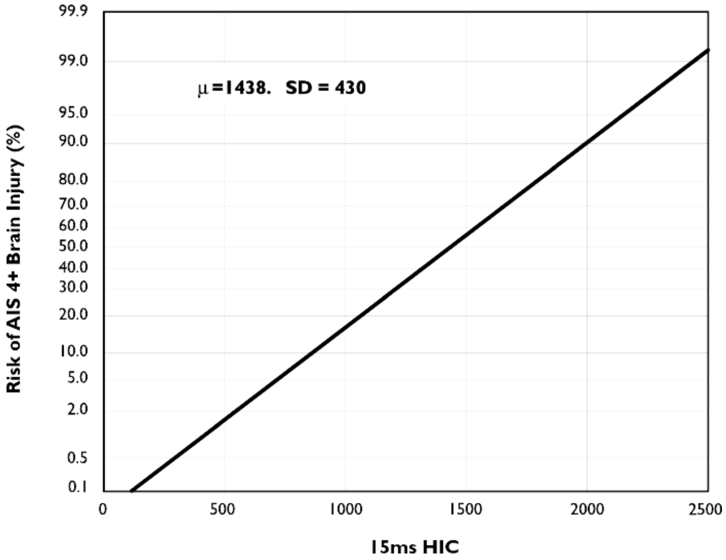


Figure 3.4.2.5 Risk of AIS 4+ brain injury for frontal impacts as a function of 15ms HIC, Mertz et. al. (1996)

The injury risk curves generated in this manner have several conceptual problems. The regularity of the shape of the curves is based more on the analysis method than the actual data. As well, the regular spacing of the severity curves is arbitrarily chosen as the detail data does not exist. It is well known that the AIS values are not linear. A more experimentally based set of probability of injury curves is given in the section on the thorax, see Figure 3.4.5.3. This figure is derived from chest injury probability for cadaver tests (n=94). It illustrates the lack of regular spacing and the variation in curve shape for each severity level to be expected in such curves.

The deficiencies in the derivation of HIC have been discussed by a number of researchers, particularly Newman (1980) in considerable detail. These problems include the limited data, the inclusion of poor data, poor documentation of some of the experiments, techniques to do with extrapolation and scaling and the meaning of effective acceleration. Researchers have also shown that HIC relates well to the probability of cadaver skull fracture in frontal impacts, Hertz (1993), which is perhaps not surprising given the derivation of the original points on the Wayne State curve. However, HIC bears, at best, a crude relationship to one of the factors, now thought to be important in brain injury causation, by its inability to predict brain injury as a result of rotational acceleration.

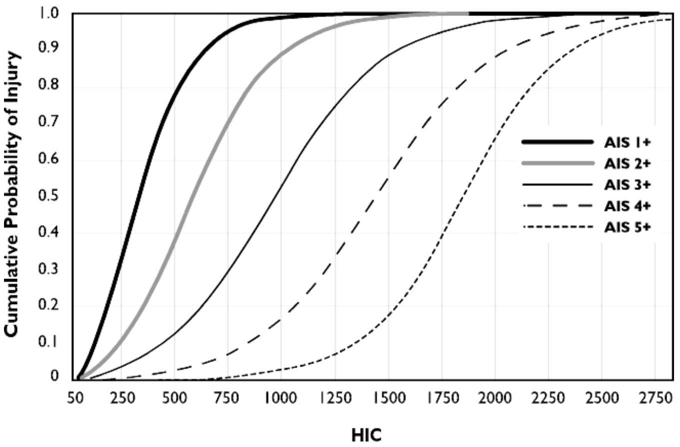


Figure 3.4.2.6 Expanded HIC probability curves for frontal impacts, after Kanianthra et. al. (1996), from Ryan, Hendrie, & Mullan (1998)

The JARI Human Head Tolerance Curves, JHTC, were developed to overcome some of the deficiencies with the Wayne State curve. They generally supported the shape and values suggested in the WSTC. The JARI tolerance curves, see Figure 3.4.2.7, included different limits according to the location of the impact on the head, and were based on a combination of animal and human skull tests and dimensional modelling, Ono et. al. (1980). The WSTC and JHTC are compared in Figure 3.4.2.8. The frontal impact JHTC data show that the threshold for human skull fracture is slightly higher than that for cerebral concussion. The lateral head impact direction of the work at JARI was discussed in more detail by Kikuchi, Ono, Nakamura (1982) and is shown in Figure 3.4.2.9. They found that the tolerance for skull fracture as a result of lateral impacts was lower than for sagittal and occipital impacts, but that the threshold for concussion was higher. It has been suggested that an HIC of 800 be used as a threshold in side impacts to the head. This appears to be only correct for impacts of 6-8 ms in duration. Recently, the use of a detailed finite element model of the human head has supported the dimensional correlations between the experimental values and those in the curves in Figure 3.4.2.7, (Ruan & Prasad, 1994).

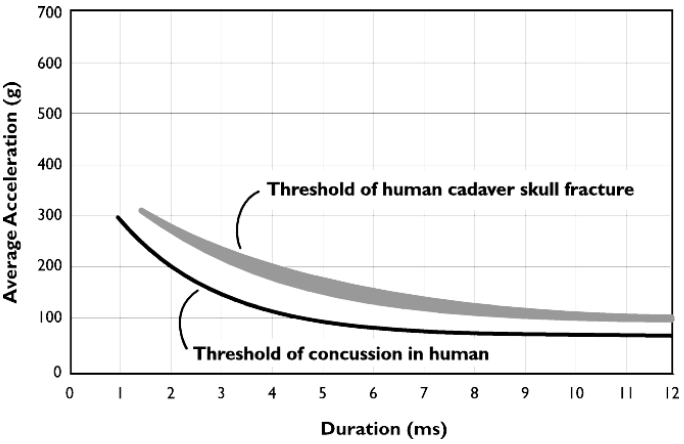


Figure 3.4.2.7 The JARI Human Head Impact Tolerance Curves (JHTC) for frontal impacts, from Ono et. al. (1980)

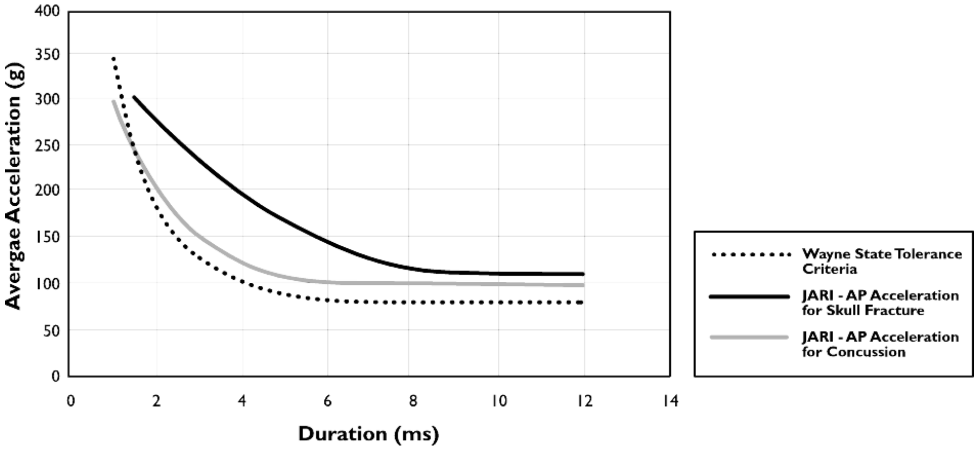


Figure 3.4.2.8 A comparison of the JHTC
and the WSTC for anterior posterior (AP) impacts to the head

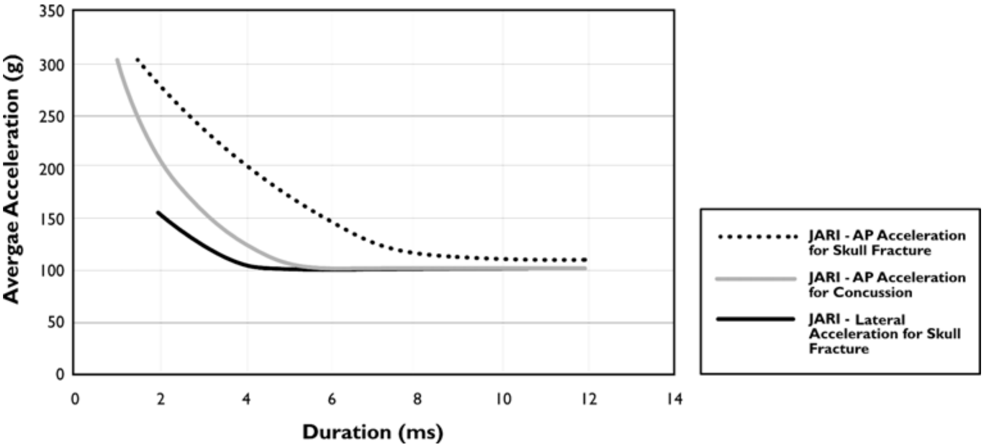


Figure 3.4.2.9 A comparison of the JHTC for lateral
and anterior posterior (AP) impacts to the head

An experimental study by McIntosh et. al. (1996), based on both padded and unpadded lateral impacts on 14 intact cadaver head and necks, found that an HIC of 1000 related to a 70% likelihood of MAIS 3 injury for lateral impact.

Stalnaker (1985) derived a lumped parameter model of brain injury in lateral impacts, based on animal experiments. He proposed the Mean Strain Criteria (MSC), using this mathematical estimate of the impact-induced strain in the brain. The model was tuned to produce the same driving point impedance as cadaver heads loaded laterally. The model has since been further developed into the Translational Head Injury Model (THIM), Rojanavanich and Stalnaker (1989), see Figure 3.4.2.10.

This simple model provides an understanding of the injury mechanisms connected with head impacts. Each component of the system of masses and springs and damping are an analogue of the physical system of the brain and head. In figure 3.4.2.10, **m** is the mass of the impacted portion of the skull, **m_2** the remaining head mass, **K** the skull stiffness and **C_2** the damping provided by the cerebrospinal fluid. A corresponding Translational Energy Criterion (TEC) was developed which indicated that the energy dissipated in the lumped parameter model by the damper connecting the two masses best predicts injury, and the power stored in the spring best predicts skull fracture. The TEC has been also formulated for use with the Hybrid III head form from accident reconstructions carried out by the National Highway safety Administration, NHTSA.

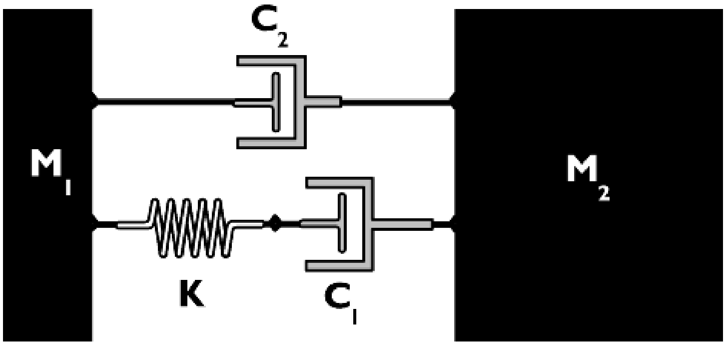
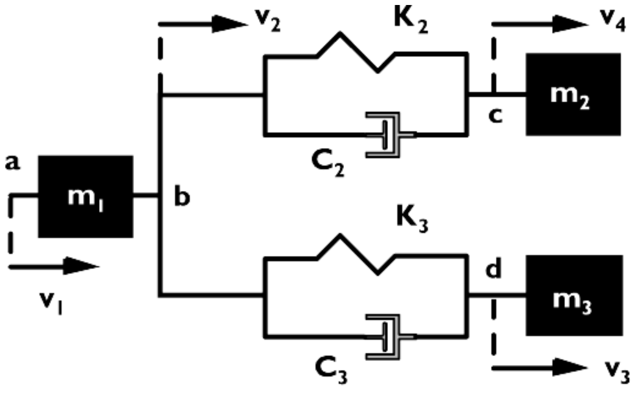


Figure 3.4.2.10 The Translational Head Injury Model, THIM, lumped parameter model for brain injury, from Rojanavanich and Stalnaker (1989), where M1, M2, K, C1 and C2 are the THIM model parameters

Willinger, Ryan, McLean & Kopp (1992) continued the development of the lumped parameter approach, and used the results of further impedance testing on volunteers and cadaver heads to propose changes to the model. The model is shown in Figure 3.4.2.11. The model has had limited verification for the prediction of acute subdural hematoma (ASDH), from the fatal brain injury and accident data collected by the Road Accident Research Unit, Adelaide.



head	m_1 kg	m_2 kg	m_3 kg	K_2 N/m	K_3 N/m	C_2 N/ms	C_3 N/ms
vivo	0.4	1.6	2.2	0.7E6	10E6	200	1500
vitro	0.8	1.7	3.6	0.7E6	25E6	600	70

Figure 3.4.2.11 The lumped parameter model proposed by Willinger et. al. (1992) and the suggested values for the parameters volunteers (in vivo) and cadaver (in vitro) head impedance. The notation “E6” denotes times 10^6

Melvin (1992), in a review of brain injury biomechanics, points out that all these approaches to the assessment of head injury have included elements of translational and rotational motion. These elements have been mixed during the experimental impacts, on which the assessments are based. Such a mixture of loading is typical of head impacts in real crashes and given the complexity of the structure of the brain, makes the analysis of specific injury mechanisms extremely difficult. He suggests that there is some way to go before this will be resolved.

Ommaya (1988) summarised the many experimental animal studies with which he had been involved, and extrapolated from the experimental data, proposing limits for allowable rotational acceleration for the human head. These limits are given in Table 3.4.2.1. He went further and suggested that a combined criteria was necessary for the prediction of head injury, and that such a criteria must link both rotational and translation effects. He suggested that the MSC, proposed by Stalnaker (1985) should be used in conjunction with the rotational acceleration limits.

Table 3.4.2.1 The allowable limits for rotational acceleration and velocity measured about the centre of gravity of the head, Ommaya (1988)

Rotational Velocity Change rad/s	Rotational Acceleration rad/s^2	AIS
>30	<1700	2
	<3000	3
	<3900	4
	<4500	5
<30	<4500	0 or 1
	<4500	5

Margulies and Thibault (1992) proposed human tolerance criterion for diffuse axonal injury specifically for lateral rotational loads to the head. This criterion was based on a combination of animal studies, physical models and analytical models. The animal data was scaled to human brain geometry and several different brain masses were used to derive threshold curves for the onset of moderate to severe diffuse axonal injury (DAI), see Figure 3.4.2.12. Turning these thresholds into a set of injury risk curves is more problematic, the authors suggest that there is a continuum of axonal injury, and that further work is required to define this better. The only validation of the results has been a comparison with a study of blows to the head performed with volunteer boxers who were wearing an instrumented helmet. Twelve sub concussive blows to the head, which produced lateral flexion only were investigated and found to fit below the injury threshold. The model was also used in a theoretical evaluation of the importance of head contact in side impacts in producing diffuse brain injuries, Meaney, Thibault, & Gennarelli (1994). The authors found that head contact was necessary to produce diffuse brain injuries in such impacts.

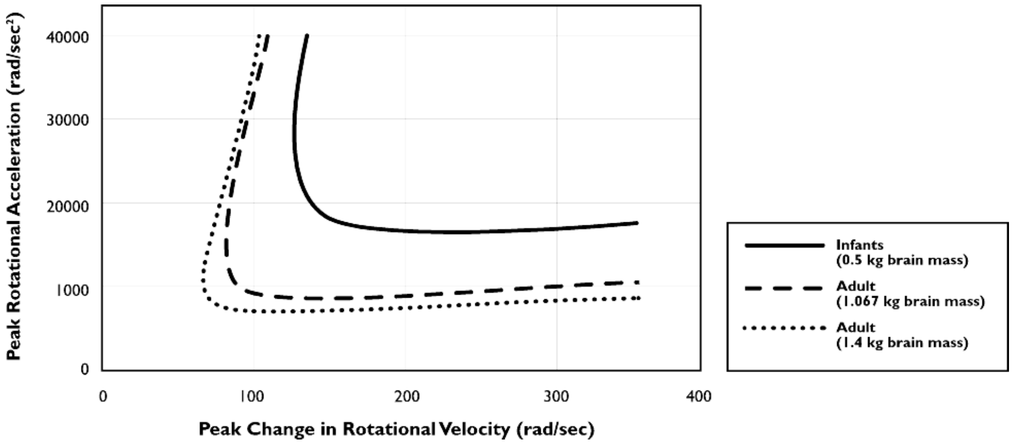


Figure 3.4.2.12 Moderate to severe diffuse axonal injury (DAI), thresholds for a range of human brain masses, for infant (500g brain mass, heavy solid line) and adult (1067g, solid line and 1400g, dashed line), Margulies and Thibault (1992)

Newman (1986) proposed a combined criterion, which he refers to by the acronym GAMBIT (Generalised Acceleration Model for Brain Injury), which follows a classical engineering approach used for modelling strain. This takes into account the combined effect of both translational and rotational kinematics, and is of the form:

$$G(t) = \left\{ \left[\frac{a(t)}{a_c} \right]^m + \left[\frac{\alpha(t)}{\alpha_c} \right]^n \right\}^{1/S}$$

where a(t) and α(t) are the instantaneous translational and rotational acceleration respectively. The parameters a_c and α_c are limiting critical values, and n, m and s are empirical constants selected to fit the data. If m = n = s = 1 a simple linear fit arises between the translational and rotational components, while m = n = s =2 gives an elliptical fit.

On the basis that a 250g translational limit is used for most helmet design and a 10,000 rad/s^2 rotational limit fits well with the work of Margulies and Thibault (1992), Newman proposed that a reasonable criteria should be:

$$G = 4\mathrm{a}_{\mathrm{m}}\mathrm{x}10^{-3} + \alpha_{\mathrm{m}}\mathrm{x}10^{-5} < 1$$

where a_m and α_m are the respective maxima. This version of GAMBIT has been criticised for the lack of a time dependency for the two accelerations, but there is no existing time based criteria for rotational acceleration.

Lee, Melvin & Veno (1987) successfully used GAMBIT to describe the regions of injury in a simple two dimensional finite element model of acute subdural hematoma in monkeys. Kramer and Appel (1990) used the GAMBIT model with the crashed vehicle database collected by the Medical School of Hannover, Germany. The crashes, involving restrained drivers in frontal impacts, were analysed by means of an anatomically based mathematical model to obtain injury risk functions. By using an optimisation method, a head injury risk curve was generated for reversible and irreversible brain injury, which was taken to lie between AIS 2 and 3, see Figure 3.4.2.13. The GAMBIT parameters, which gave this result were limiting translational acceleration of 250g and rotational acceleration of 25,000 rad/s^2.

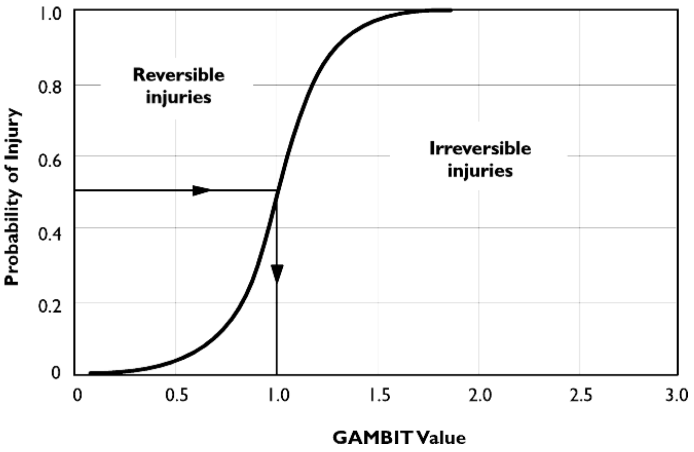


Figure 3.4.2.13 The risk of head injury as a function of Gambit for frontal accidents, Kramer and Appel (1990)

Melvin (1992), in his review of brain injury biomechanics, suggests that a multi-level modelling approach, involving detailed finite element models as well as simpler physical and mathematical models, is required to sort out the problems in this area and find better means of injury assessment than are now currently available.

Injury Criteria for the Head

Despite the acknowledged inadequacies of HIC as an injury criteria, particularly with respect to rotational head injury, it is the most widely used and best validated measure of brain risk injury from a blunt impact to the head. This is partly because it is specified in vehicle safety legislation in the United States and in a proposed European test procedure, but also because no alternative, except maximum acceleration as used for helmets, has become available.

Several groups of researchers have proposed risk criteria for frontal impacts based on HIC, and these are presented in Figure 3.4.2.14. HIC has a major shortcoming for application to side impacts, in that it is based on translational acceleration during frontal impacts, but there is no demonstrably superior criterion in terms of relevance to the severity of head injury in humans. Rotational acceleration is equally important for the prediction of head injury, but as yet no such criteria has been validated.

Investigating the HIC based probability of skull fracture curves proposed by the various researchers discussed earlier, shows that there remains major disagreements in both the shape and the relative magnitude of the injury risk, see Figure 3.4.2.14. Hertz (1993) suggests that a HIC of 1000 will have a 47% chance of a skull fracture for frontal impacts, while Mertz et. al. (1996) suggests that the risk is 18%. The values suggested by Hertz are more closely in agreement with the values put forward by Viano and King (1997).

The work of Kikuchi et. al. (1982) indicates that the frontal and lateral impacts to the head have different tolerances, with the lateral impact tolerance for skull fracture being about 80% lower than for frontal) and this difference must be included in any risk function for side impact head injury. The simplest method of doing this is to offset the HIC value from the frontal tolerance by 200. So, based on the Hertz figures, a HIC of 800 will have a skull fracture risk of 47% in a lateral impact to the head. This figure is in closer agreement with the tolerance curve of McIntosh et. al. (1996), which is based on lateral impacts to cadaver heads and this can be seen in Figure 3.4.2.15.

In figure 3.4.2.16 lateral injury risk functions for skull fracture are plotted. The proposed preliminary risk function is the unbroken curve on the right. This was obtained by offsetting the Mertz (as distinct from the Hertz et. al., 1996) skull fracture curve by a HIC value of 200. Mertz curve is used as it does not suggest unreasonably high risks of fracture for low HIC values.

The skull fracture risk curve is based on 15 ms HIC and this will be used for the injury risk function.

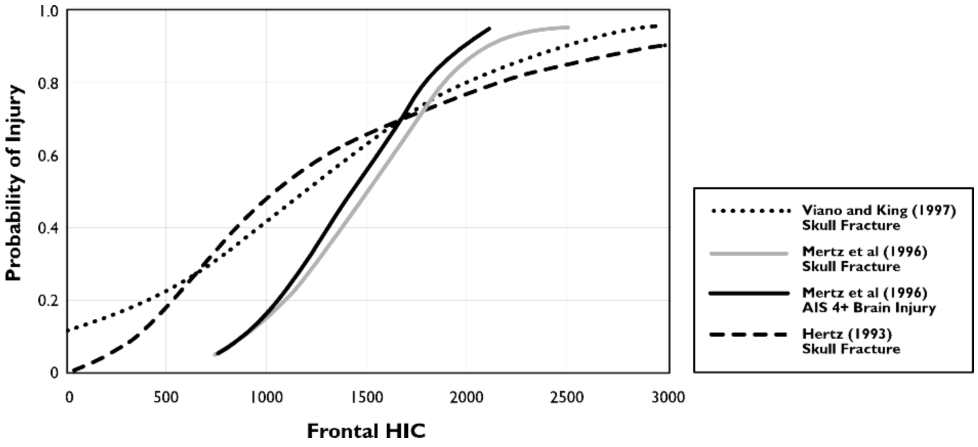


Figure 3.4.2.14 Comparison of the available HIC based injury risk functions for frontal impact to the head

Head Injury Summary

Protection against brain injury is clearly the first priority of any side impact protection strategy. The Head Injury Criterion is the most widely used index to assess head injury risk, both in motor vehicle safety development and in impact injury research. This is due to the specification of HIC within the American Federal Motor Vehicle Safety Standards, the European ECE regulations and the Australian Design Rules, as a measure of occupant protection. Its acceptance is reinforced by the lack of a generally accepted alternative. Consequently, HIC is now the dominant measure of head injury risk throughout the automotive industry.

The simple mechanical models of the brain developed by early researchers provided additional insights beyond what was gained by assuming the head was a rigid body at risk of injury from linear acceleration. However, consideration of the complexity of the skull-brain system has shown that this is inadequate, and research by workers such as Ryan & McLean indicates the complexity of the injuries suffered. The brain consists of various regions with different material properties and potentially different modes and risks of injury. Rotation represents potentially the greatest risk of injury not only due to the bony protuberances inside the skull, and because of the fragile bridging veins, but as a result of induced strains in these various regions of the brain. HIC has shortcomings for application to side impact crashes, as it is based on a mix of translational and rotational acceleration during frontal impacts. The head rotation expected as a result of a side impact crash may differ significantly.

Despite the acknowledged inadequacies of HIC as a criterion for brain injury risk, it represents the most appropriate measure for brain injury risk in lateral impacts currently available, and consequently will be used in the ISIP project, due to the lack of any suitable alternative measure.

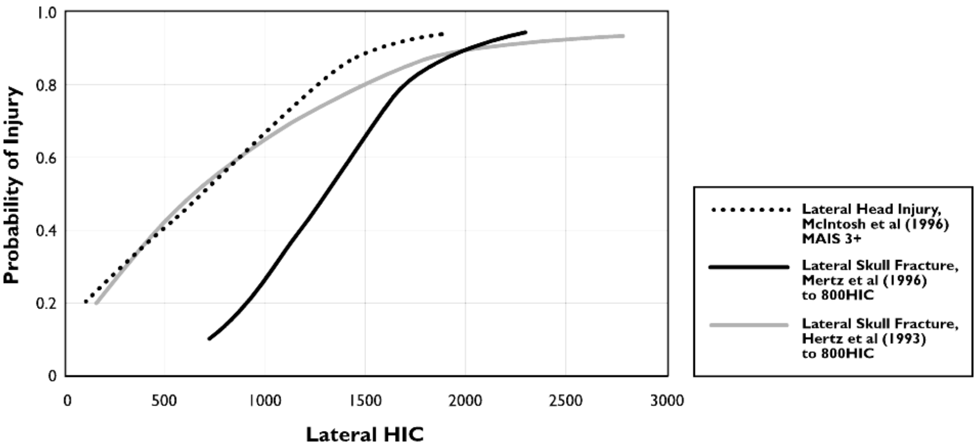


Figure 3.4.2.15 Proposed lateral head injury risk function compared with the AIS 3 curve for lateral impacts obtained by McIntosh et. al. (1996)

3.4.3 Neck

Neck injury is under-identified in field data. It is frequently not identified in hospital databases because the symptoms of minor neck injury are often not evident to the victim until several days after the crash. Consequently many neck injuries are treated outside the hospital system, and hence outside the crash injury data collection system. Nevertheless, minor neck injury can have significant, long term and debilitating effects and is potentially the second most costly injury to the Australian community, after head injury. In addition, more serious neck injury may not be identified during post mortem examination, if the primary cause of death is identified as more apparent injury to the head or thorax, (Taylor and Twomey, 1993).

Much of the injury caused by side impact crashes is low and mid severity, non-life threatening injury, but injury which can have long-term consequences. Neck injuries account for almost 50% of all car crash injuries with long term consequences (von Koch, Nygren, & Tingvall, 1994). In the United States, 66% of claims for automobile crash injury include neck injury (Insurance Institute, 1995).

Relatively little is known about soft tissue neck injury. Fundamental questions remain to be answered regarding the patho-physiology, diagnosis, treatment, clinical cause and prevention of this injury. So-called whiplash injuries are classified as an AIS 1, or minor injury, as they propose little threat to life. According to Swedish research, whiplash leads to long term problems in about 10% of cases compared to 1% for all other injuries classified as AIS 1. Women also sustain neck injury more frequently than men, particularly in side impact crashes. One study indicated a 65% higher frequency of injury (Krafft, 1998).

Catastrophic injury of the spine involves the spinal cord. It occurs when disruption of the alignment of the vertebrae causes cord injury. Severing of the cord is not needed to cause irreversible damage. Burst fractures of the vertebrae can be caused by excessive compressive loading, causing fragments to move apart and into the spinal canal, injuring the spinal cord. This may not be shown on subsequent x-rays as the bone fragments can return to the original position after the loading is removed.

The spine is split into four anatomical areas; the cervical (neck), thoracic, lumbar and sacral regions. For the purposes of this review, this section on the spine will only address the neck. The thoracic region will be dealt with as part of the thorax and the sacral region will be dealt with as part of the pelvis. This leaves the lumbar region as yet unaccounted for. There is little definition in the real world injury analysis from chapter 2 with regard to the level and severity of the injuries to the spine.

Neck Injuries

Injuries to the neck make up less than 2% of the total Harm in chapter 2 and can be separated into three separate categories:

Soft tissue injury: (AIS 1) these injuries consist of laceration and contusion of the soft tissues of the neck due to direct mechanical action and muscle and ligament strains due to loading by the head (whiplash type injury);

Fractures to the bony structure: (AIS 2/3) the vertebral bodies will fracture when the applied load is too great;

Spinal cord injuries: (AIS 3+) when the spinal cord is involved then the relative severity of the injury rapidly increases.

The incidence of neck injury from the analysis of side impact crashes in chapter 2 indicates that the severities of greatest priority are AIS 1, AIS 3 and AIS 5, which relate to soft tissue injuries, fractures and catastrophic neck injuries respectively. The source of neck injury is not coded, but the common injuries are abrasions/lacerations and fracture/dislocations. Both minor and fatal neck injuries tend to be significantly under reported.

Neck Injury Assessment Review

Significant work has been done to characterise the biomechanical response of the neck. However, this has included little about the tolerance of the neck to impact loads. The most commonly quoted neck injury criteria for "significant injury" were developed by Mertz (1984), as the Injury Assessment Reference Values or IARVs. These have been used at GM with the Hybrid III to assist in the evaluation of airbag restraint systems in frontal impacts. The values are all given some time dependency, but only the maximums are given here in Table 3.4.3.1.

Table 3.4.3.1 The maximum values and load conditions for the neck injury assessment reference values for the Hybrid III dummy in frontal impacts, Mertz (1984)

Neck Loading	Load Axis	IARV
Flexion Moment	+ My	190 Nm
Extension Moment	- My	57 Nm
Anterior/Posterior Shear Force	± Fz	3.1 kN
Axial Tension Force	+ Fz	3.3 kN
Axial Compression Force	- Fz	4.0 kN

These values represent the magnitude of the forces and moments, as measured at the head/neck junction on a Hybrid III dummy. They are set to what is considered an acceptable risk level by the vehicle industry of 5 - 10% risk of serious injury (AIS 3+). It is instructive to trace their derivation.

The neck movement requirements for frontal impacts used in the IRAVs were based on multiple sled tests on restrained and seated cadavers (n=6) and a volunteer, at subinjury threshold levels, Mertz and Patrick (1971) and earlier work by Mertz and Patrick (1967) on whiplash injury. These studies characterised the responses of the neck to inertia loading of the head in flexion and extension. The cadavers were subjected to frontal accelerations of up to 14 g, with no dislocations of the neck vertebrae detectable by x-rays. The volunteer was exposed to accelerations of up to 9.6 g. The neck loads were calculated by treating the head as applying an inertial mass loading to the neck. Figure 3.4.3.1 shows the free body diagram of the head for inertia loading of the neck, as used by Mertz and Patrick (1971). The allowable head angle with respect to the torso was plotted against the flexion and extension bending moments at the head neck junction, ie. at the occipital condyles and were presented as response corridors.

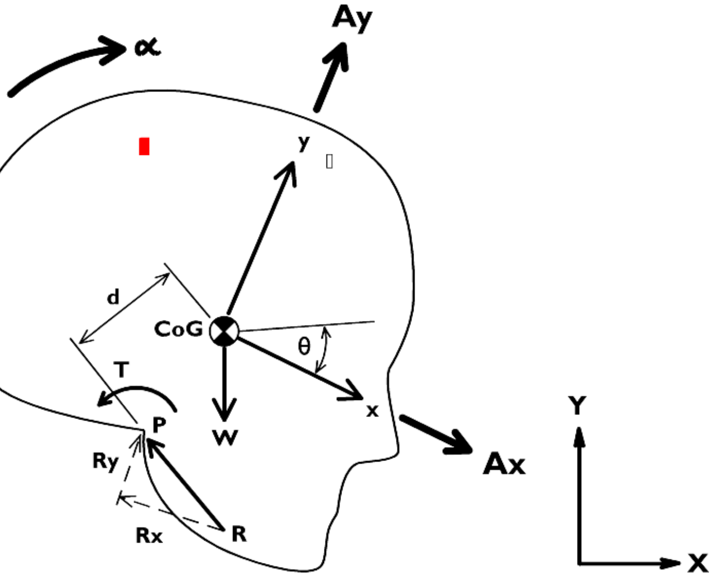


Figure 3.4.3.1   Free body diagram of the head undergoing inertia loading

Patrick and Chou (1976) extended the sled tests of Mertz and Patrick (1971) to 54 lateral tests involving four volunteers with sled decelerations of 0.8-11.7g using the same test set up. Eighteen lateral bending tests were conducted using decelerations of 1.6 to 6.7g. Similar corridors of allowable head angle and neck bending response were derived, see Figure 3.4.3.2. Near the voluntary lateral flexion limit (at about 40 degrees) the effects of the neck ligaments begin to influence the neck bending response causing the rapid rise in the neck moment required for further flexion.

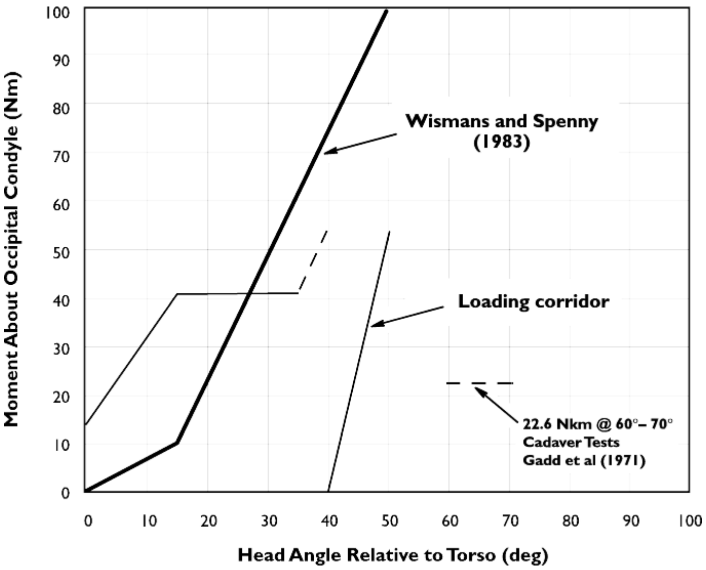


Figure 3.4.3.2 The lateral neck bending moment corridors for side impacts, after Patrick and Chou (1976) with some volunteer, Wismans and Spenny (1983) and cadaver test results, Gadd et. al. (1971)

Nyquist, Begman, King, & Mertz (1980) examined injury severity to three-point belt restrained occupants of Volvo cars which had sustained a frontal collision. The authors classified the crashes according to barrier equivalent velocity, BEV. A group of twenty two occupants were judged to have undergone a crash with a mean BEV of 48.3 km/h. Of these, three occupants were said to have sustained an AIS 1 neck injury. Three sled tests were run at this velocity change with an acceleration pulse approximating that of a Volvo into a rigid barrier. The sled buck used was a 1970 Volvo sedan and the Hybrid III ATD was set up as a right front seat passenger. The three axes neck loads (as well as other dummy parameters) were measured and averaged for the three tests. The mean value of the maximums of the forces provided the basis for the axial tension and fore and aft shear loading IARVs for the neck. These curves were presented as time dependent load curves. No discussion was given by the researchers as to the effects of the combined loading in these tests or in the IARVs.

The IARV for axial compression of the neck is based on a Hybrid III reconstruction of a football training tackling block accident (Mertz, Hodgson, Thomas, & Nyquist, 1978). The results obtained from this study are used as the tolerance curve for the adult population, but it is based on one case of injury to a high school football player. The time dependent aspect of the IARV was dealt with by using the response curve of axial force versus time from a single test to give multiple time durations.

The volunteer tests by other researchers, such as in the static tests by McGill, Jones, Bennet, & Bishop (1994), support the shape of these response curves of Mertz and Patrick (1971) in frontal and Patrick and Chou (1976) for side impact neck injuries. Analysis of the dynamic volunteer tests by the Navy Biodynamics Laboratory, NBDL, by Wismans and Spenny (1983) and Wismans, Van Oorschot & Woltring (1986), have confirmed the magnitude of the non-injury areas of the corridors. These tests were carried out at NBDL, as a part of a series of frontal, oblique and lateral tests with the lateral testing done at 5g severity. For the nine lateral tests the volunteers were calculated to undergo lateral bending moments at the upper neck of up to 40Nm and at the lower neck of up to 150Nm without injury. The calculations were made by modelling the neck as a two pivot mechanism and the head as a rigid body.

Such calculations of neck loads are difficult to carry out precisely and require the accurate measurement of the head trajectory by either film analysis, a three dimensional angular rate sensor array or the use of a minimum of a 9 accelerometer array (Baughn, Kaleps, & Shipley, 1996). These techniques are very difficult to apply to lateral impact conditions as the head response is multi-axial unlike in frontal impact conditions, and when head contact occurs the measurement methods are susceptible to increasing errors.

The results of isolated specimen testing of the neck, such as by Shea, Wittenberg, Edwards, White, & Hayes (1992), and White and Panjabi (1990), have also confirmed the characteristic behaviour of the neck for motion involving rotation, flexion, extension, lateral flexion and torsion. The neck has an initial region of motion with little except active muscle resistance followed by a sharply increasing resistance as the voluntary motion limits are exceeded. The increasing resistance is due to the ligaments running out of available motion. This behaviour of the neck is also a factor in the suggestion by McElhaney & Myers (1992) that neck injury is more likely to occur when the motion of the head is restricted. The flexibility of the neck under many loading situations will allow it to escape injury, but if the neck becomes constrained at both ends, then the allowable flexibility will be rapidly exceeded. This constraint may be the result of impact forces as a result of head contact.

The dynamic response time of the neck muscles, measured by recording the muscle activity, by electromyogram, of volunteers during sled tests is of the order of 100 ms for appreciable muscle forces to be developed, Szabo & Welch (1996) and Schneider et. al. (1975). This is too slow to have a major effect on the neck response, as the lumped parameter modelling work of de Jager, Sauren, Thunnissen, & Wismans (1996) indicated.

Kramer and Appel (1990) used a different method to obtain injury assessment functions from crash data. They developed computer simulations of various parts of the human body, including a complex anatomically based neck model, including individual vertebra. They correlated the output of this model with 17 frontal vehicle accidents with neck injury that were investigated in detail. This small database reflects that neck injuries tend to be either minor or devastating. The injury risk based on reversible neck injury or AIS 2/3 is presented in Figure 3.4.3.3. Kramer had insufficient numbers to segregate the full range of neck injury severities. The family of neck bending moment IAFs, that he developed is shown in Figure 3.4.3.4, Kramer (1987). The analysis was unable to distinguish between flexion and extension. The classical 190Nm limit before flexion injury of Mertz and Patrick (1967) is right down in the tail with only a 2% chance of a minor neck injury.

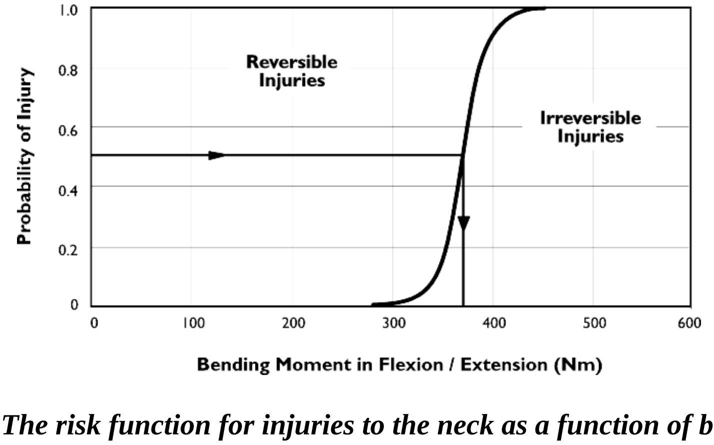


Figure 3.4.3.3 The risk function for injuries to the neck as a function of bending moment, Kramer and Appel (1990)

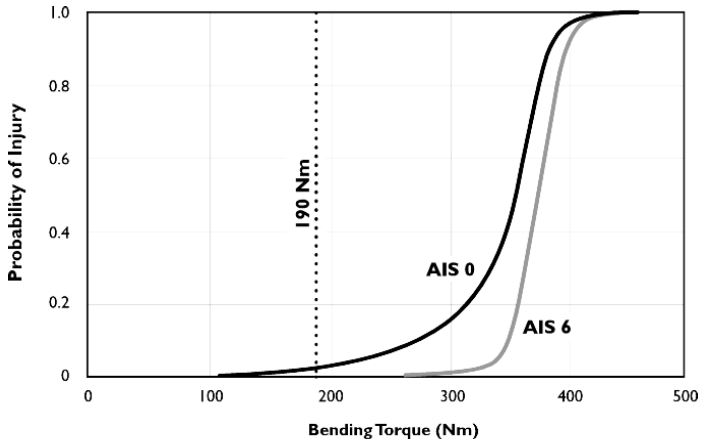


Figure 3.4.3.4 The neck bending moment injury assessment functions for frontal impacts developed by Kramer (1987)

Kallieris, Mattern, Miltner, Smidt, & Stein (1991) studied neck injuries to cadavers in 37 simulated automobile accidents (23 frontal, 14 lateral collisions). The subjects were targeted to provide translational and rotational kinematics of the head from film analysis. The authors found the best correlation to neck AIS to be with head linear acceleration along the path (r = 0.58). Minor injuries to the neck (AIS 1) were observed in frontal collisions at a head acceleration along the path of 18.5 to 20.9 g. This criterion reflects a similar approach as used by Mertz when he calculated neck loads from the head inertial load, and is not of relevance when head impact occurs.

Neck response and injury was also investigated in four lateral full scale (ie. car to car) cadaver tests by Kallieris, Rizetti, Mattern, Thunnissen, & Philippens (1996). Only shear forces at the occipital condyles were evaluated using projected head mass and the clivus acceleration. The lateral shear forces ranged from 1900N to 4500N. The authors reported that for the two most severe tests (3035 N and 4500N) the near side of the occipital condyle was fractured, this being the point of highest loading in shear.

Bendjellal, Tarriere, Gillet, Mack, & Guillon (1987) investigated head and neck responses under high g-level lateral deceleration. A rigid seat was attached to a sled and it was decelerated from a velocity of 6m/s. A lap belt and pelvic strap restrained the cadaver. Shoulder straps and nylon belt around the chest secured the subject’s torso. Four tests were carried out with decelerations of between 6.6 and 9.2g and seven tests were performed at 12.2-14.7g. The authors describe the effect of the sled acceleration on the subject. The subject’s shoulder deflected and the head described a movement of pure translation in the impact plane. This was followed by a 3D movement of the head, in which it rotated and the neck flexed laterally.

The peak amplitudes for the cadaver subjects were greater than for the volunteers due to the absence of muscle tone. The angular displacements were similar, except that flexion was not seen in the volunteer tests. Head rotation in torsion was much greater in the volunteer tests (by 50%). Similar patterns were observed in high severity test except that greater displacements occurred. The initial head position influenced the resultant movement pattern. No injuries occurred except in one high speed test which resulted in cervical fractures. For two similar tests carried out more recently, without injury, the dynamic neck moments were calculated to be 55 Nm and 38 Nm.

The effects of combined loads were included in a neck injury indicator developed by Prasad and Daniel (1984). In an experimental study based on comparing neck injuries to piglets with the loading measured in a three year old child dummy neck, they observed that the correlation of neck injury severity to measured dynamic load was best, if combined loading was considered. For a combination of axial load in tension and extension bending, the line between severe and no injury, shown in Figure 3.4.3.5, is of the form:

$$aM + bF = C$$

where M is the bending moment and F the axial force in the surrogate neck.

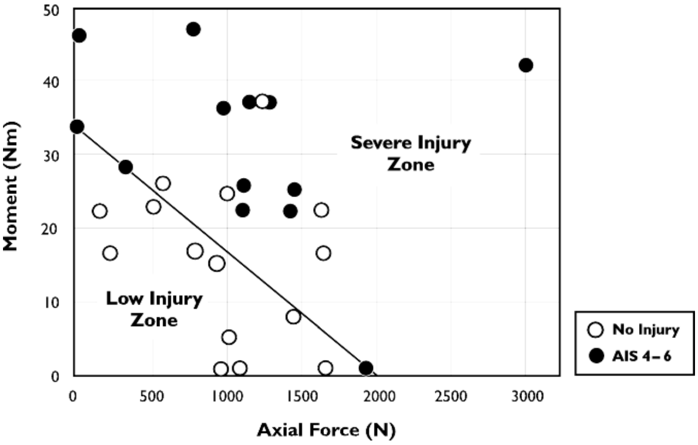


Figure 3.4.3.5 The association between child dummy neck moment and axial force and piglet neck injury severity in matched tests, Prasad and Daniel (1984)

Mertz, Prasad, & Irwin (1997) combined the data from Prasad and Daniels (1984) with some similar experimental data obtained by Mertz & Weber (1982). An injury risk curve for the 3 year old dummy neck loaded in tension, bending (extension) and their combined effect was derived using the methods suggested by Mertz and Weber (1982). These risk curves were assumed to be representative of three year old children, whose necks are loaded in bending (extension) and axial tension and these loads combined. By scaling on the basis of the dimensional similitude, the critical dimension was found to be the neck circumference. Muscle strength based risk curves were subsequently derived for these load conditions for the family of Hybrid III dummies.

Also based on the work by Prasad and Daniel (1984) and a reassessment of the other available neck injury data, Kleinberger, Sun, Eppinger, Kuppa, & Saul (1998) proposed the Nij Criteria for the neck in frontal impacts. This takes the sum of the normalised axial loads and moments of the neck on a continuous basis through the loading sequence:

$$N_{ij} = F_z/F_{int} + M_y/M_{int}$$

where F_z is the axial load, F_{int} is the critical intercept value of the load and M_y is the flexion extension bending moment.

The values chosen for the critical intercepts, F_{int} and M_{int}, are dummy specific and must be scaled for the various dummies using the approach suggested by Mertz. A Madymo neck model was used to determine a scaling factor for the human and the 50th percentile Hybrid III dummy neck loads. The critical intercept values for the Nij neck injury calculation for the two dummy necks in frontal impacts, as used in the ISIP project are given in Table 3.4.3.2.

Table 3.4.3.2 The proposed critical intercept values for the Nij neck injury calculation for frontal loading, Kleinberger et. al. (1998)

Dummy	Tension N	Compression N	Flexion Nm	Extension Nm
SID IIs Small Female	3200	3200	210	60
BioSID Mid male	3600	3600	410	125

The dummy neck loads (from the Hybrid III) obtained from NCAP testing were compared with NASS accident data incidence of neck injury in the field accident data. Kleinberger et. al. (1998) suggest that an Nij=1.4 corresponds to a 30% risk of AIS 3+ neck injury, Figure 3.4.3.6. The authors then extend the approach to obtain an AIS 5+ neck injury risk curve for humans in frontal impacts, Figure 3.4.3.7.

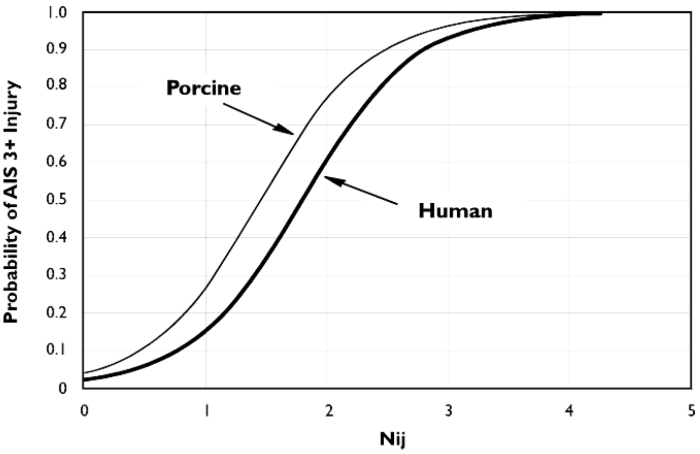


Figure 3.4.3.6 The porcine injury tolerance curve based on the test data obtained by Prasad and Daniel (1984) with the offset suggested by Kleinberger et. al. (1998) to match the distribution of neck injury in frontal accidents in the NASS data

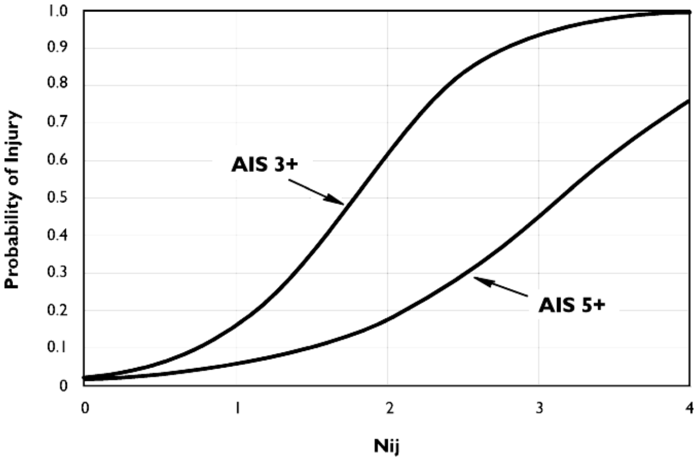


Figure 3.4.3.7 The neck injury risk assessment curves for frontal impacts as proposed by Kleinberger et. al. (1998)

For the other area of priority for neck injury around AIS 1 or whiplash, Boström et. al. (1996) proposed a neck injury criteria, NIC, based on a modelling study of a hypothesis of Aldman and the experimental work of Svensson (1993) with anaesthetised pigs. The authors suggest that volume changes resulting from sagittal plane neck bending, ie. flexion/extension are the cause of some whiplash injury, ie. AIS 1 neck injury. For this type of injury, a neck criterion based on the relative acceleration of the torso and head was derived:

$$\mathrm{NIC} = a_{rel} \times 0.2 + v^2_{rel}$$

where:

a_{rel} is the relative acceleration between the head and the upper torso,
0.2 is a neck length scale factor, and
v_{rel} relative velocity between the head and the upper torso.

The authors suggest that the criteria is also appropriate for humans and that an appropriate value is that $\mathrm{NIC} < 15\ \mathrm{m^2/s^2}$, but it has yet to be validated. The injuries due to the injury mechanism, that form the basis for this criteria, are only a portion of the AIS 1 injuries that are the result of rear impacts. How the criteria apply to side impacts is also unknown.

Injury Criteria for the Neck

There are no existing injury assessment functions for the neck in side impacts. The critical loading consists of the combined effects of F_y (lateral shear), F_z (tension/compression), M_x (lateral flexion) and M_z (torsion). The mechanisms of injury and the phasing of these loads during side impacts differ from frontal impacts and further work is required to do more than propose a set of neck injury reference values for significant injury (5-10% risk of serious injury or AIS 3+). These values, based on the frontal IARVs, are given in Table 3.4.3.3 for use with the specified dummies. They have been derived from a variety of sources, principally Mertz (1984). The allowable axial force and lateral shear is assumed to be similar to that for frontal impacts and lateral bending is assumed to lie between the flexion and extension allowable values.

Table 3.4.3.3 The proposed critical lateral neck injury reference values IARVs for a 15% risk of AIS 3+ injury

Dummy	Axial (Comp) $-F_z$(N)	Axial (Tension) $+F_z$(N)	Lateral Shear F_y(N)	Lateral Bending M_x(Nm)
SID IIs Small Female	3600	3200	2750	60
BioSID Mid Male	4000	3600	3100	125

3.4.4 Shoulder and Upper Extremity Injuries

Injuries

Injuries to the shoulder and upper extremities combined to form 7.5% of the total Harm in side impact crashes, and can be separated into two separate categories:

Soft tissue injury: (AIS 1) these injuries consist of laceration and contusion of the soft tissues of the shoulder and upper extremities due to direct mechanical action and muscle and ligament strains due to loading by the arm.

Fracture/dislocations: (AIS 2/3) the long bones and joints will fracture or be dislocated when the applied load is too great.

On the basis of Harm in Chapter 2 the greatest priority for the shoulder is AIS 2 injury due to dislocation of the joint capsule and fracture/dislocation of the clavicle as a result of contact with the door or another occupant. For the upper extremities it is AIS 1 to 3 consisting of contusions and bruising followed by fracture/dislocations, which are mainly due to the vehicle door.

Injury Criteria Review

The upper extremity is kept out of the way in most cadaver tests. Usually the arm is elevated and higher than the primary point of impact. Work is going on to develop an injury sensing arm to test airbags in frontal collisions. There are very different patterns of movements of the arm during tests with cadavers and dummies even under the same conditions. The resultant injury patterns in cadaver testing, though are typical of those found in field accident data with injuries up to AIS 2, Kallieris et. al. (1997). Difficulties were found in predicting whether the fractures will occur in the upper or lower arm due to variation in the movement pattern of the dummy arm. The forearm was found to have an increased risk of injury in this testing with the presence of an airbag, as the arm impact is at a higher velocity and often the arm comes into contact with the steering wheel.

Cavanaugh, Jaggers, Malhotra, & King (1989) conducted sled tests on 8 cadavers using a modified Heidelberg test set up, at velocities of 6.7m/s and 9.0m/s. The researchers reported the shoulder impact results separately, in later testing by this group the shoulder injuries are not reported. The average shoulder force at the side wall was 3.40 kN for the 6.7m/s tests and 5.47 kN for the 9.0 m/s tests. During these impacts there was no separation of the sterno-clavicular joint or fractures to the clavicle. However, acromio-clavicular separation usually occurred. In two cases the thoracic spine translated towards the scapula on the impacted side and there was a large (36-119g) acceleration of the sternum anteriorly. In the four higher velocity tests (9m/s), the maximum shoulder injury severity was AIS 2 for quite high force levels.

Data is available for the bending strength of the long bones, radius, ulna and humerus to fracture. Yamada (1970) gives bending strengths for wet long bones in both the anteroposterior and lateromedial directions, Table 3.4.4.1. There are significant differences in these strengths with age and gender (women had only 5/6 of the strength of the males).

Table 3.4.4.1 Bending load to fracture in kilograms for wet human long bones in three point bending, Yamada (1970)

Bone	Age (yrs)					
	20-39	40-49	50-59	60-69	70-89	Average
Humerus	151±12	142±10	131±10	125±9	115±8	136
Radius	60±7	54±4	53±8	49±4	44±3	53
Ulna	72±5	64±8	62±6	60±4	56±4	64

Kallieris et. al. (1997) found that the humerus has a maximum bending moment to fracture of between 115-155Nm for quasi-static testing at a slow loading rate. Kirkish, Begeman, Paravasthu (1996) suggested a strength in bending of 230Nm when the test data was normalised and scaled for dynamic impacts.

The lower arm bones have a lower maximum bending moment of approximately 120Nm when scaled for dynamic loading, Saul, Backaitis, Beeke, & Ore (1996). Bass et. al. (1997) found the humerus position and the degree of pronation/supination also altered the likelihood of forearm fractures due to the change in alignment between the ulna and radius.

Injury Criteria for the Shoulder and Upper Extremities

No separate injury criteria are proposed, as there is no current method available for measuring the dummy response for injuries to those body regions.

3.4.5 Thorax

Thoracic Injuries

Injuries to the thorax make up 22% of the total of Harm in side impact crashes, and can be best described in terms of the AIS severity levels:

AIS 1: Soft tissue injury consisting of laceration and contusion, one rib fracture;

AIS 2: Major skin laceration and partial tear of the bronchus, 2-3 rib fractures;

AIS 3: Minor heart and lung contusion, >3 rib fractures on one side, < 3 on other;

AIS 4: Severe heart and lung contusion, torn aorta, flail chest; and,

AIS 5: Major aortic laceration, heart perforation, bilateral flail chest.

The incidence of thoracic injury from the analysis of side impact crashes in chapter 2 indicates that the severity of greatest priority is AIS 3 and greater. The most common causes of abrasions/lacerations, bruising/contusions and fracture/dislocations are the vehicle door and the restraint system.

Some confusion occurs with the grouping of organs, often the liver, spleen and kidneys are included as part of the thorax. This varies from that used for the AIS scale, where these organs are grouped in the abdomen.

Thoracic Injury Criteria Review

The first chest injury criterion was suggested by Kroell, Schneider, & Nahum (1974), who proposed that thoracic compression (C) correlated well with thoracic injury, based on frontal impact cadaveric tests. These tests made use of a pendulum with a flat face. A later correlation developed by Kroell and his co-workers was:

$$\text{AIS} = 19.56\, C_{max} - 3.78$$

This suggests there is a continuous relationship between C_{max} and AIS, which is not possible given the derivation of AIS. Newman et. al. (1992), fitted curves with the 50%

probability of injury point centred on the Kroell steps, to provide a distribution of injury, and IAF. This set of curves is shown in Figure 3.4.5.1.

Tarriere et. al. (1979) dropped 17 cadavers laterally 0.5 m to 2.0 m onto various surfaces instrumented with load plates. Film analysis was used to measure the chest deflections and criteria were proposed for the half chest 35% compression gave 8 rib fractures, and for the full chest, 30% compression gave 9 rib fractures.

The US FMVSS 214 for side impact is based on an acceleration criteria for the thorax and pelvis. The criterion is the Thoracic Trauma Index, TTI, which is the average of the lateral chest wall and spinal acceleration with an age factor. Anatomically the TTI was based around the concept of the hard thorax.

$$\mathrm{TTI} = 1.4 \times \mathrm{AGE} + 0.5\,(\mathrm{RIBy} + \mathrm{SPINEy})\,(\mathrm{MASS} / \mathrm{MASSstd})$$

The limiting value of TTI specified in FMVSS 214, is 90g for 2-door passenger vehicles and 85g for 4-door vehicles. The test dummy associated with this standard is the Side Impact Dummy (SID). The thorax injuries were found to be highly directional. The testing of cadavers was mainly with impacts from the left hand side. The presence of the liver on the right tending to mask other injuries.

The TTI criterion was proposed by Eppinger, Marcus, & Morgan (1984) and was extensively validated, with 84 tests (using the Heidelberg sled set up), Morgan, Marcus, & Eppinger (1986). More recent supplementary testing has included 17 tests (using the Heidelberg sled set up) by Cavanaugh, Zhu, Huang, & King (1993), 42 by Kallieris, Boggasch, & Mattern (1994) and 26 (using a modified Heidelberg sled set up) by Pintar et. al. (1997).

In the Heidelberg test set up the cadaver is accelerated up to the test velocity with the sled and the sled stopped, causing the cadaver to slide into an instrumented wall, see Figure 3.4.5.2. The rationale for the use of this sled set up was to reproduce the impact of the vehicle door with the nearside occupant. In reality the occupant is not hit by a flat panel during a crash. This sled set up forces a specific sharing of the impact load by the various body components – shoulder, thorax, abdomen and pelvis.

For the specific requirements of this project it is not known how well this test protocol represents the loads on an occupant for the more intrusive crash situations such as occur with pole and stiff vehicle impacts. Lau and Viano (1988) point out the differences the test method (eg. wall or pendulum) has on acceleration based criteria such as TTI, where the effect of the whole body acceleration in the sled test is significant.

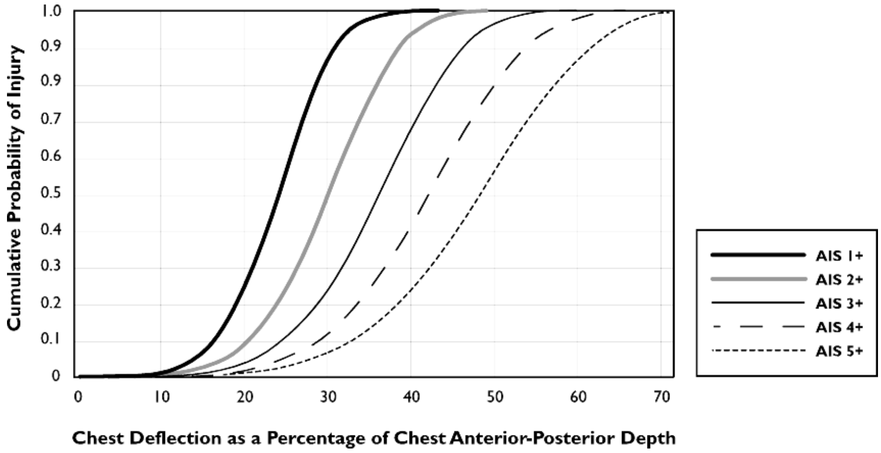


Figure 3.4.5.1 Probability of chest injury in frontal impacts as a function of chest deflection following Newman et. al. (1992), from Ryan et. al. (1998)

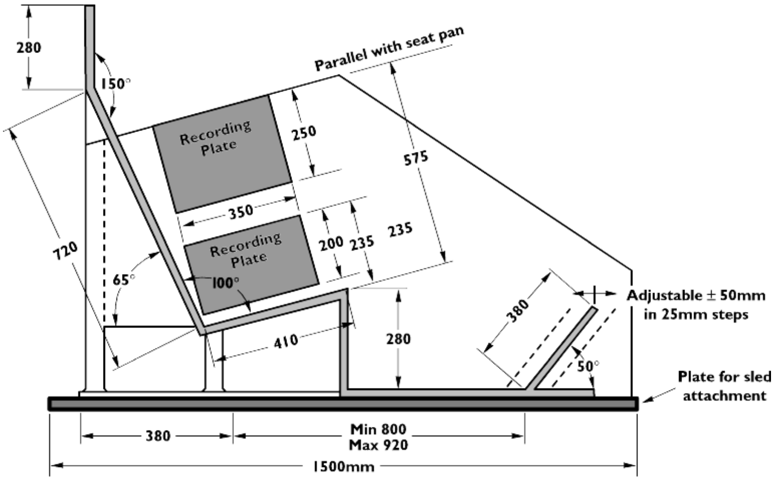


Figure 3.4.5.2 Heidelberg force measuring sled, Morgan et. al. (1986)

Morgan et. al. (1986) generated curves of the probability of AIS 3, 4 and 5 chest injury based the TTI test data, see Figure 3.4.5.3.

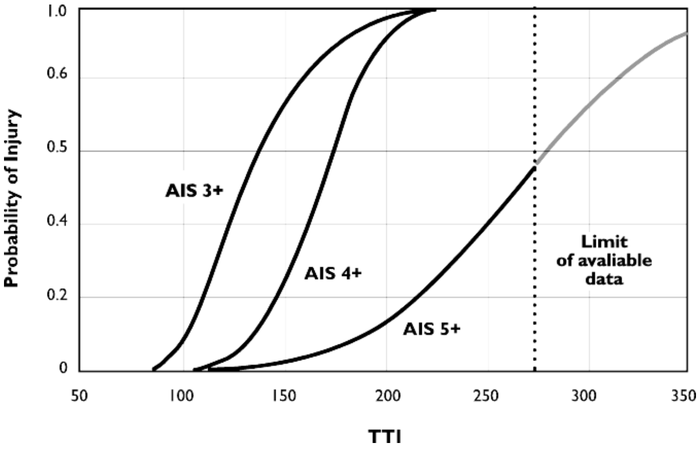


Figure 3.4.5.3 The probability of AIS 3, 4 and 5 chest injury based on 84 cadaver tests, Morgan et. al. (1986)

Lau and Viano (1986) performed experiments on rabbits and swine and determined that a Viscous Criterion, V•C, was a good indicator of thoracic injury for speeds of impact experienced by automotive occupants in frontal impacts. This criterion is computed by taking the instantaneous product of chest wall velocity (V) and percent compression (C) of the chest depth. V•C can be applied equally to adults and children because viscous criterion levels experienced are not dimensionally dependent. The dependence of the injury type on the velocity of deformation, is shown in Figure 3.4.5.4. For the case shown in the diagram crushing injury is the critical injury up to a velocity between 2m/s and 4m/s, and then viscous injury predominates at higher velocities.

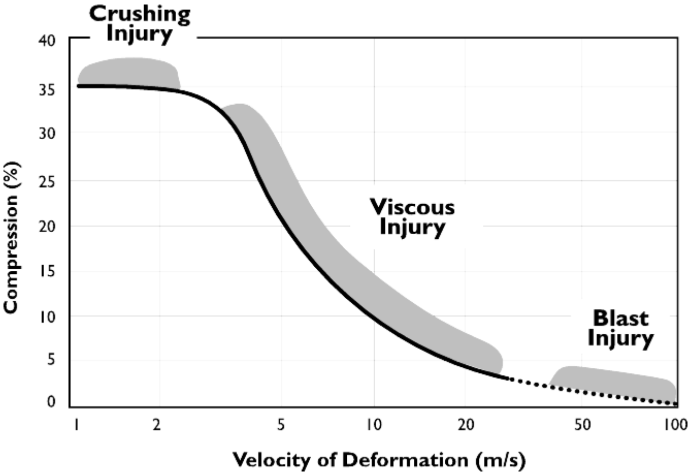


Figure 3.4.5.4 The dependence of the type of soft tissue injury on the velocity of deformation, from Viano and Lau (1985)

Viano and his co-workers also observed statistical differences in the biomechanical responses and injuries between the living and post-mortem animals. The live animals were observed to have 26% less rib fractures for the same level of chest impact.

The criteria has also been applied to side impact, Viano, Lau, Asbury, King, &Begeman (1989) proposed limiting values of 40 percent compression and 1.0 m/s for C and V•C, respectively, for a 50 percent probability of an AIS 4 or greater injury. The researchers carried out 16 lateral impacts on cadaver thoraxes. The tests were at three velocities between 4.5 and 9.4 m/s with a flat pendulum of 23.4 kg. V•C, was found to be the best predictor of serious thoracic injury and next was compression. The compression responses were derived from film data. The value of C in this case was computed based on the entire lateral width of the chest.

The thoracic injuries in the testing by Viano et. al. (1989), included lacerations to lung diaphragm, kidney or spleen in three of the six high velocity tests. In these high velocity tests five of the six cadavers had flail chest with an average of 14 rib fractures. Injury risk functions were proposed for both V•C and percent compression, see Figure 3.4.5.5.

The use of the pendulum in this test series makes the results more representative of blunt trauma in side impacts. It does not present the problems with load sharing and point loading given by the instrumented wall.

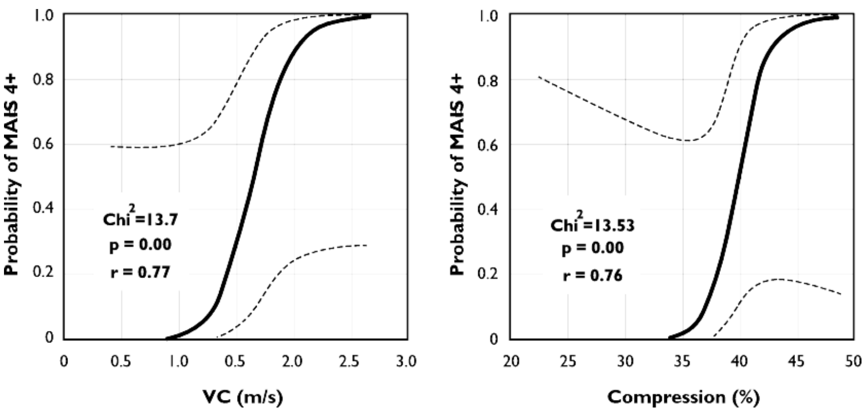


Figure 3.4.5.5 Logist functions for the probability of serious injury of the thorax, Viano et. al. (1989).

Ridella and Viano (1990) discussed the need to find the velocity of the transition between viscous and crushing injury mechanisms for a specific test situation. The authors suggested a transition velocity of 4.5 m/s for cadaver thoracic impacts.

Several groups have carried out more recent test series to evaluate thoracic tolerance. These have all used modified forms of the Heidelberg instrumented sled.

Cavanaugh, Walilko, Malhotra, Zhu, & King (1990a) conducted 12 side impact sled tests with cadavers sitting on a Heidelberg type seat impacting three surface conditions:

- flat rigid side wall;
- side wall with a 6 inch pelvic offset; and,
- flat padded side wall.

The cadavers were instrumented with accelerometers and pressure transducers, the wall was instrumented with nine load cells in strips, see Figure 3.4.5.2. The result obtained by these researchers were:

- 25% probability of AIS 4+ injury for C = 32%
- 25% probability of AIS 4+, TTI = 143
- 25% probability of AIS 4+, V•C = 0.85m/s, and
- 50% probability of AIS 4+, V•C = 0.97m/s
- 50% probability of AIS 4+ injury for C = 37.3%.

More recent data obtained by Cavanaugh, Walilko, Chung, & King (1995) indicate that these values should be 33 percent and 1.0 m/s with C referenced to the half chest width. The reason why these values are close to each other despite the use of a different reference value for C is the fact that the non-impacted side of the chest also undergoes a large deformation. Statistical analyses of the test data showed that C and V•C have a higher Chi squared value, a higher correlation coefficient (r_2) and a lower p-value than TTI.

Pintar et. al. (1997) performed 26 cadaver tests also using a modified Heidelberg type sled. Thorax, abdomen, and pelvic load plates were used against a rigid and padded wall and a pelvic offset condition. The chest deflections and accelerations of T12, and ribs 4 and 8 were recorded and two test speeds of 6.7 m/s and 8.9 m/s were used.

These researchers found:

- 25% probability of AIS 4+ injury, for C = 22%;
- 25% probability of AIS 4+, TTI = 151;
- 25% probability of AIS 4+, V•C = 0.54m/s; and,
- 50% probability of AIS 4+ injury for C = 30%;
- 50% probability of AIS 4+, TTI = 169;
- 50% probability of AIS 4+, V•C = 1.26m/s.

Kallieris et. al. (1994) tested 63 restrained cadavers in side impacts in two test conditions, 42 in a vehicle buck and 21 in the original Heidelberg test set up. The specimens were instrumented with a full 12 accelerometer thoracic array. The researchers found the following injury risk probabilities:

- 50% probability of AIS 4+, TTI = 155
- 50% probability of AIS 4+, V•C= 0.83m/s

Pintar et. al. (1997) found that TTI gave the best fit to their data, followed by V•C max and then compression. Kallieris et. al. (1994) also found a similar ordering of the correlations, with TTI the best. This was attributed to the inclusion of the age factor. Although TTI has the longest history as a means of assessing thoracic injury, and has the best test correlation and consistency, it is not easy to use the criteria with the BioSID dummy as it has no central spine.

The risk functions based on TTI derived from these test programs are shown in Figure 3.4.5.6.

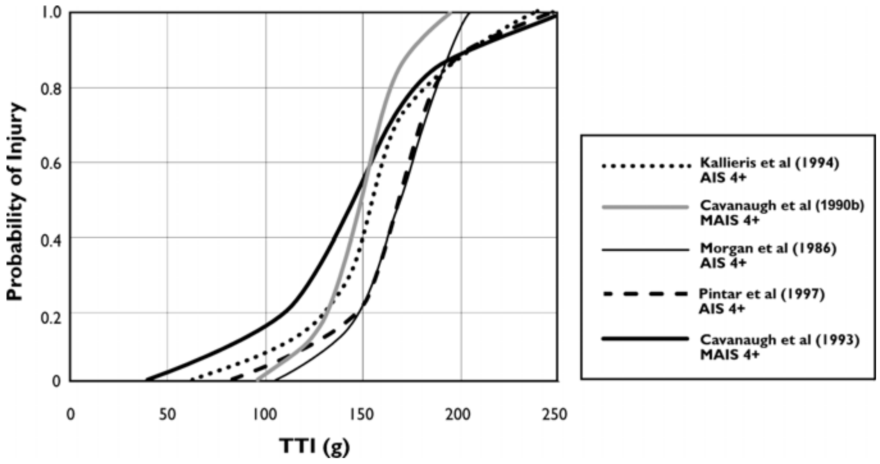


Figure 3.4.5.6 Comparison of the available risk of thoracic injury to MAIS 4+ for TTI

Injury Criteria for the Thorax

Given the constraints regarding the dummies (including the absence of a central spine in the BioSID), it is suggested that compression, percent of full thorax width, and the viscous criterion, V•C, be used as the injury criteria for the thorax with a transition velocity of 4.5 m/s. A comparison of the risk functions obtained by the various researchers for these criteria are shown in Figure 3.4.5.7 for compression and Figure 3.4.5.8 for the viscous criterion. The injury risk curves obtained for the 14, 23.4 kg pendulum impacts for MAIS 4+ thoracic injury by Viano et. al. (1989), would appear to be most appropriate, as they are able to be used for concentrated load situations and are suitable for the available dummy instrumentation.

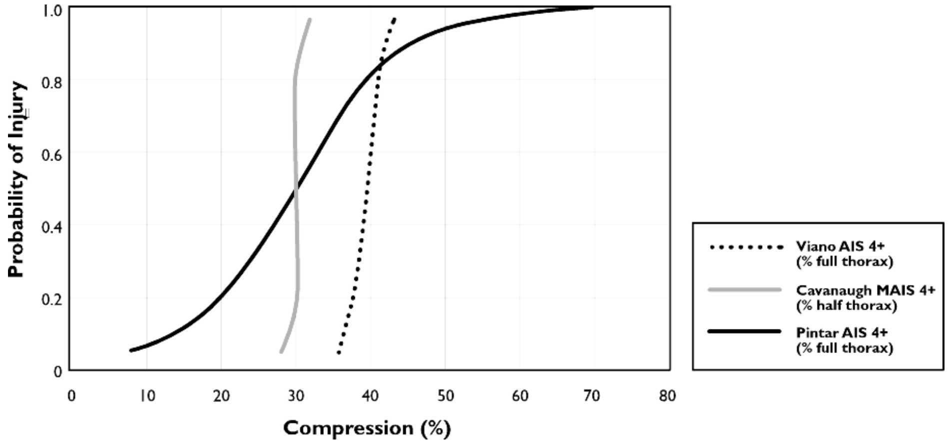


Figure 3.4.5.7 Comparison of the available risk of thoracic injury to MAIS 4+ for compression

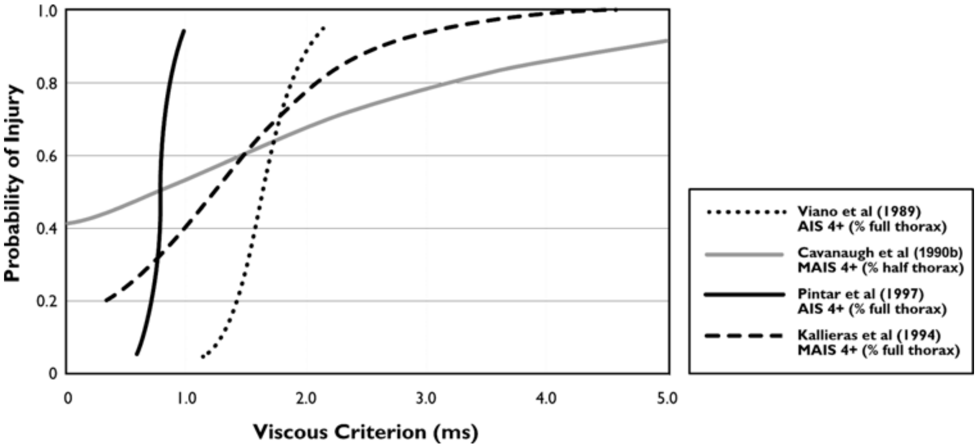


Figure 3.4.5.8 Comparison of the available risk of thoracic injury to MAIS 4+ for V•C

3.4.6 Abdomen

Abdominal Injuries

Injuries to the abdomen excluding the liver, spine and kidneys only account for 1.8% of the total Harm in side impact crashes.

Soft tissue injury:(AIS 1) due to direct mechanical action. Some specific organs such as the liver, kidneys and spleen are usually grouped with the thorax and so more severe injuries are less common.

The incidence of abdominal injury from the analysis of side impact crashes in Chapter 2 indicates that the severity of greatest priority is AIS 1 followed by AIS 4 and greater. The most common injury is contusion and bruising, due to the door and the belt.

Additional Injury Criteria Review

Little abdominal injury tolerance or test data is available for lateral impacts and this is summarised by Rouhanna (1992). Most of the previous investigations into particular injury mechanisms have focussed upon frontal impacts, especially seat belt and steering wheel loadings to the lower abdomen.

The work by Rouhana, Jedrzejczak, & McCleary (1989) proposed AIS 3+ and AIS 4+ boundaries for frontal impacts to the abdomen by a belt impactor. This work was extrapolated by Newman et. al. (1992) to give an injury probability for abdominal injury based on penetration, see Figure 3.4.6.1.

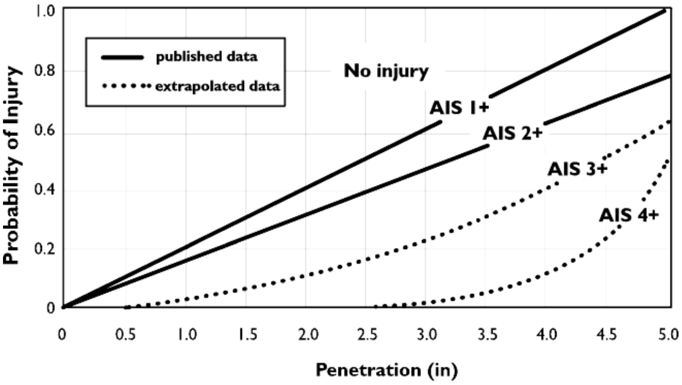


Figure 3.4.6.1 Probability distribution of abdominal injury as a function of penetration of a seat belt, after Newman et. al. (1992)

Walfisch et. al. (1980) performed lateral drop tests on 4 cadavers from a height of 1 or 2 m onto simulated armrests. The authors defined abdominal injury limits in terms of the three threshold values, below which there was no injury and above which there was injury:

- Force 4500N;
- pressure 260 kPa; and,
- penetration 28% of the half abdomen.

Stalnaker and Ulman (1985) found V•C to be a good predictor of abdominal injury in lower primates. They found that V•C versus AIS injury severity was invariant with species type even though the mass ratio of the species included was 25.75 to 1.

Viano et. al. (1989) carried out 14 lateral impacts on cadaver abdomens. The tests were at three velocities between 4.5 and 9.4 m/s with a flat pendulum of 23.4 kg. The viscous response or V•C was found to be the best predictor of serious abdominal injury and next was compression. The compression responses were derived from film data. The authors found that a 25% probability of serious injury (MAIS 4+) occurred at 2m/s V•C or a compression of the full abdomen of 44%, as shown in Figure 3.4.6.2. The correlations for moderate injury were poor for all the criteria checked.

Ridella and Viano (1990) discuss this poor correlation at lower severities and emphasise that it is necessary to find the velocity of the transition between viscous and crushing injury mechanisms for a specific test situation. The viscous criterion works best for the more severe injuries. The authors suggest a transition velocity of 2.1 m/s for abdominal impacts based on test data obtained from swine.

Rouhanna (1992) in his review of abdominal injury makes several points with regard to the complexities of developing abdominal injury criteria based on his experience with animal tests:

- Fluid filled organs exhibit different mechanical characteristics at different loading rates;
- Pressure generated is important to the abdominal injury mechanisms;
- The position of the impact is important; and,
- A relaxed abdominal wall will increase injury severity.

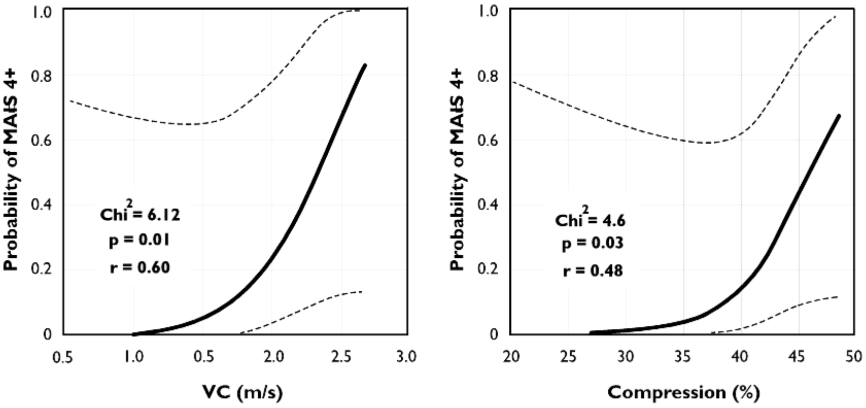


Figure 3.4.6.2 Probability of MAIS 4+ injuries for the viscous response and compression of the abdomen, Viano et. al. (1989)

Cavanaugh, Walilko, Jaekoo, & King (1996) showed that V•C was a good predictor of injury to the abdomen when used with the rib 4-5 response of the BioSID dummy.

Injury Criteria for the Abdomen

It is suggested that compression, as a percentage of the full abdomen, and the viscous criterion, V•C, be used as the injury criteria for the abdomen with a transition velocity of 2.1m/s. The proposed injury risk curves are Viano et. al.'s (1989) MAIS 4+ curves which are based on 14, 23.4 kg pendulum impacts to cadavers at three different speeds.

3.4.7 Pelvis

Pelvic Injuries

Injuries to the pelvis make up 3.1% of the total Harm in side impacts. These injuries can be separated into two separate categories:

Soft tissue injury: (AIS 1) these injuries consist of laceration and contusion of the soft tissues due to direct mechanical action.

Fractures to the bony structure: (AIS 2/3) the pelvic ring will fracture or dislocate when the applied load is too great, and the more severe include displaced fractures with vascular disruption.

The incidence of pelvic injury from the analysis of side impact crashes in Chapter 2 indicates that the severities of greatest priority are AIS 2 and 3. The most common cause of abrasions and lacerations was the vehicle door or the belt system, while fractures/dislocations were most frequently due to the vehicle door.

Injury Criteria Review

A field accident analysis of 219 occupants, by Guillemot et. al. (1998), showed that the most common injury to the pelvis was fracture of the pubic rami. In those case where fractures resulted, 69% of the occupants were seated on the near side location. The other types of fractures of the pelvis (acetabulum, sacro-iliac joint, diaphysis, and proximal femur) were almost totally reliant on the occupant being on the near side of the vehicle as well. The accident data was compared to dynamic tests on 12 isolated pelves, using a drop tower and a 30 Joule impact energy. The authors found that the field fracture data and the experimentally reproduced fractures correlated well.

Closed fractures of the pelvis are rated AIS 2 to 5. Pubic rami fractures are typically the first that occur, as it is the weak link in the pelvis. The force of impact is translated through the greater trochanter to the region of the acetabulum resulting in fractures of the acetabular ring. In the human body the loading due to side impacts from a flat surface is shared 68% through the trochanter and 32% via the iliac wing, Bouquet et. al. (1998).

Acceleration has been a commonly used injury criterion in safety testing, FMVSS 214 specifies a maximum of 130g for the pelvis. Haffner (1985), based on the sled and body buck tests used to formulate FMVSS 214, showed that the lateral acceleration to produce fracture was higher when the iliac crest and the greater trochanter were engaged. The implication being that there is a difference between sled tests and pendulum testing for pelvic injuries.

Deformation has been found to be a best predictor of injury, Guillemot et. al. (1998) and Viano et. al. (1989). Viano et. al. (1989) used a 23.4 kg pendulum impactor in 14 lateral tests on the pelves of cadavers at three impact velocities, 4.5, 6.7 and 9.4m/s. Deflection was obtained by analysis of the high speed film of the impact. Pubic rami fractures were found to correlated with compression of the pelvis, not impact force or acceleration; For the pelvis a criterion of 25% likelihood of serious injury was 27% compression of the full width.

Deformation is difficult to measure accurately in cadaver testing, as a result the response data for the design of the dummies is based around force time corridors, ISO (1997). Force measurements have been found to be reasonable predictors of the likelihood of fracture resulting from a side impact in the pelvic region.

Cesari, Ramet, & Bouquet (1982) used a pendulum to impact 60 seated cadaver specimens on the greater trochanter. The impactor mass was 17.3 kg with a hemi-spherically shaped impactor face of radius 600mm, both a rigid and padded impactor faces were used. AIS 2 and 3 injuries corresponded to a 5.6kN force in women and a 8.6kN force in men. With the padded impactor a higher velocity was required to produce the same injuries, but the force values were of the same order of magnitude.

Bouquet et. al. (1998) impacted 11 cadavers with a flat faced pendulum weighing 12 to 16 kg, with accelerometers attached. Movements and deformations were obtained by the analysis of high speed film. A 50% likelihood of AIS 2 injuries equated to a 7.6 kN force limit. For 50% likelihood of AIS 3 injury, an 11.4 kN force limit was found, see Figure 3.4.7.1. The AIS scores were found to correlate well with the deflection measurements and the V•C criteria, as well as the impact energy.

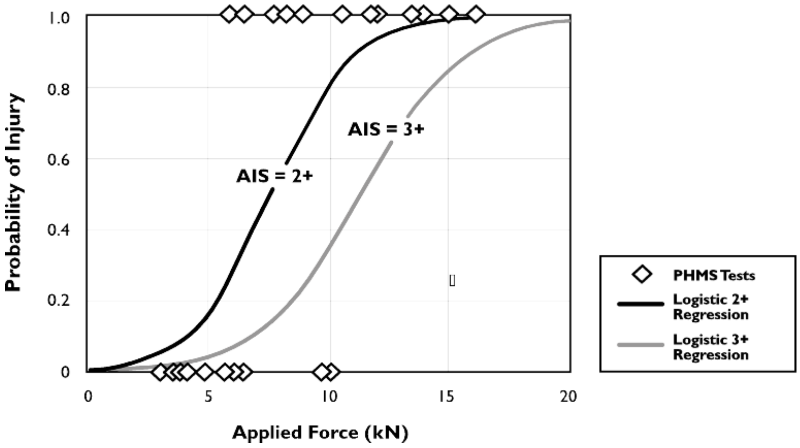


Figure 3.4.7.1 Human pelvic force criterion based on 11 cadaver tests, from Bouquet et. al. (1998)

Cavanaugh et. al. (1990a) carried out side sled tests on 12 cadavers using a modified Heidelberg set up. Pelvic force was found to be a good predictor of injury, see Figure 3.4.7.2, with a 25% probability of fracture of the pelvis at a peak force of 8 kN. A Vmax x Cmax of 2.7 m/s was the best predictor of 25% probability of pelvic fracture and a half width compression of 32.6% also gave good correlation.

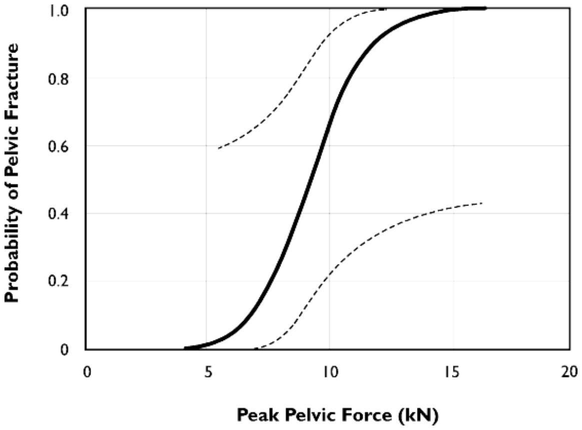


Figure 3.4.7.2 Logistic curve of the probability of pelvic fracture and peak force, Cavanaugh et. al. (1990a)

Injury Criteria for the Pelvis

The measurement of peak force suits the dummy instrumentation capabilities. The results obtained by Cavanaugh et. al. (1990a) are compared with those of Bouquet et. al. (1998) in Figure 3.4.7.3. The injury criteria should be based on impactor tests to 11 cadavers by Bouquet et. al. (1998) for which AIS 2 and 3 curves are available.

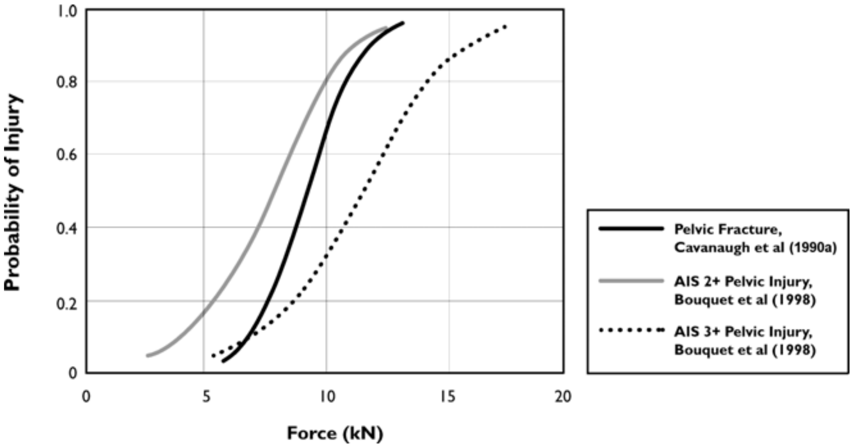


Figure 3.4.7.3 The pelvic fracture force obtained by Cavanaugh et. al. (1990a) compared with the AIS 2 and 3 human pelvic force criterion, Bouquet et. al. (1998)

3.4.8 Lower Extremities

Injuries

Injuries to the lower extremities make up 8.6% of the total Harm in side impacts. These injuries can be separated into three separate categories:

Soft tissue injury: (AIS 1) these injuries consist of laceration and contusion of the soft tissues of the lower extremity due to direct mechanical action.

Fractures to the long bones: (AIS 2/3) the long bones will fracture when an applied transverse load or bending moment is too great.

Fracture/dislocation of the knee joint and ankle: (AIS 3+) these injuries occur when the foot is trapped by intrusion.

The incidence of lower extremity injury from the analysis of side impact crashes in chapter 2 indicates that the severities of greatest priority are AIS 2 and 3. The most common injuries to the leg and foot were abrasion/lacerations and contusion/bruising with a lesser number of fracture dislocations. The main cause of the abrasions and lacerations to the leg was the vehicle instrument panel, while contusions/bruising were frequently from the vehicle instrument panel and door.

Otte (1996) found that in side impacts the most serious lower limb injuries to vehicle occupants are isolated fractures to the femur and tibia. There is need for knee, foot and ankle injury assessment in lateral impacts but at present no data is available.

Injury Criteria Review

Kress et. al. (1993) subjected embalmed and fresh bone human femurs to frontal (n=6) and lateral (n=7) impacts by a mini-sled at 7m/s. The legs were simply supported. The authors found that the average breaking force for lateral impacts was 3053N. The fresh bones were stronger than the embalmed.

Gibson, Newman, Zellner, & Wiley (1992) derived static bending test criteria for human long bones from Yamada (1970). These were 283Nm for the femur and 253N for the tibia. These authors also report on two tests to failure of the knee in varo-valgus rotation. The average peak knee loads were 125Nm.

Nyquist (1985) impacted the tibia through the normal soft tissues in antero-posterior and lateral-medial directions with a 25 mm diameter cylindrical impactor of 32 kg mass. The specimens were placed in simple supports with force transducers attached near the proximal and distal ends while the load was applied at midspan. No signs of increased strength with increased loading rate were apparent, but the fractures were of a bending type with initiation occurring at the side experiencing tensile stress. The bending moment at fracture for both directions of loading was 308 Nm on average (317 Nm for males and 278 Nm for females).

In other tests lateral loading gave femur bending moments of 310 Nm for males and 180 Nm for females, Nyquist (1986). The author also found that the dynamic fracture tolerance of the femur was higher than for static loading.

The female femur has 5/6ths of the bending strength of the male and bending load to fracture does not differ significantly between AP and LM loading, Yamada (1970).

Injury Criteria for the Lower Extremities

Following are general averages for the loads tolerated by the femur, tibia, and knee joint for lateral impacts, Nyquist (1985) and (1986), Yamada (1970) and Kress et. al. (1993). It is suggested that the lower limb injuries can be assumed to be mainly due to bending in the long bones, tibia and femur. The injury assessment functions are single point values, which are 50% probability of AIS 2 or greater.

Table 3.4.8.1 Extrapolated lateral dynamic bending movement for fracture/dislocation of the human upper and lower leg and knee

Region of Leg	Lateral Bending Movement for Fracture	
	Male	*Female*
Upper leg	354 Nm	295 Nm
Lower leg	317 Nm	278 Nm
Knee	125 Nm	104 Nm

3.5 INJURY TOLERANCE CURVES

3.5.1 Head Injury Tolerance

The lateral head injury assessment is based on combining the probability of injury curves for 15ms HIC for skull fracture and some AIS 4+ brain injury as a result of frontal impact, obtained by Mertz et. al. (1996). These curves are almost the same, the lower one is for some AIS 4+ brain injuries, and is used here as the basis for the lateral injury risk curve. To allow for the lower tolerances of the head in lateral impacts, the curve has been offset from a HIC of 1000 to 800 as suggested by the work on head injury carried out at JARI, Kikuchi et. al. (1982).

The calculation for HIC is limited to 15ms is based on the work of Hodgson and Thomas (1972), which showed that skull fracture and brain injury is unlikely if the duration of the effective part of the impact is greater than 15ms. This is supported by the later analysis by Mertz et. al. (1996).

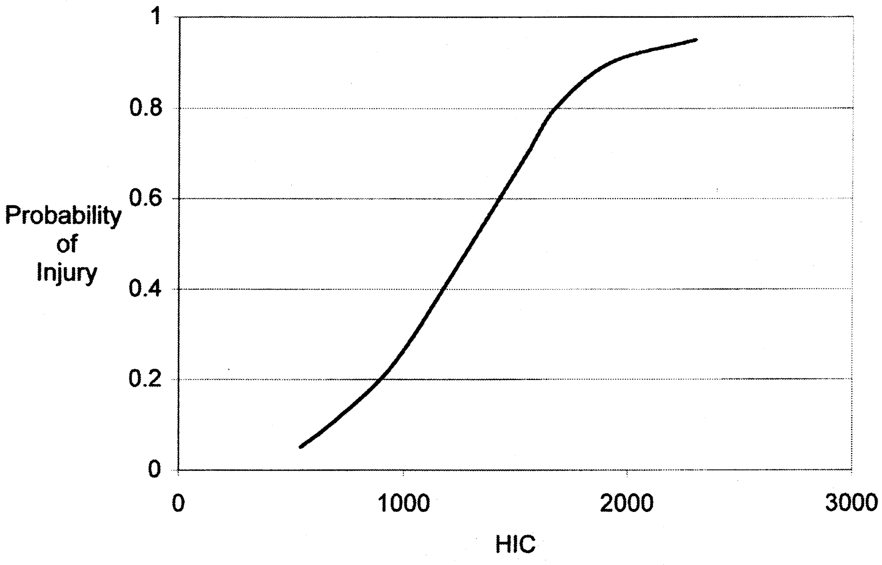


Figure 3.5.1 ***Plot of probability of lateral skull fracture and some AIS 4+ brain injury for lateral impacts and 15ms HIC, after Mertz et. al. (1996)***

Equation for HIC:

$$\mathrm{HIC} = (t_2 - t_1)\int_{t_1}^{t_2} a^{2.5} / (t_2 - t_1) dt$$

where

- t_1 and t_2 are selected to yield the maximum value
- (t_1 - t_2) is limited to a maximum of 15ms.

Table 3.5.1 Tabulated values for the probability of skull fracture and some AIS 4+ brain injury for lateral impacts and 15ms HIC duration, as shown in Figure 3.5.1

Probability of Injury	15 ms HIC
0.05	545
0.1	675
0.2	900
0.3	1050
0.4	1175
0.5	1300
0.6	1425
0.7	1550
0.8	1675
0.9	1925
0.95	2300
1.0	-

3.5.2 Neck Injury Tolerance

The neck injury assessment function for significant injury is based on discrete limiting values at which such injury is likely to occur, for loading of the neck axially (F_Z) in lateral shear (F_y) and in lateral bending (M_X). It is based on the work of Mertz and Patrick (1971) and Mertz (1984). There will be a 10 to 15% risk of AIS 3+ injury if the loading on the neck exceeds the values in Table 3.5.2.

Table 3.5.2 The proposed critical lateral neck loading values for 15% risk of AIS 3+ injury

Dummy	Axial Fx (N)	Lateral Shear Fy (N)	Lat. Bending Mx (Nm)
SID IIs Small Female	3200	2750	60
BioSID Mid Male	3600	3100	125

3.5.3 Thoracic Injury Tolerance

The lateral thoracic injury assessment functions are based on the probability of injury curves (AIS 4+) for percentage compression (%) and viscous strain V•C (m/s) for the full thorax, obtained by Viano et. al. (1989).

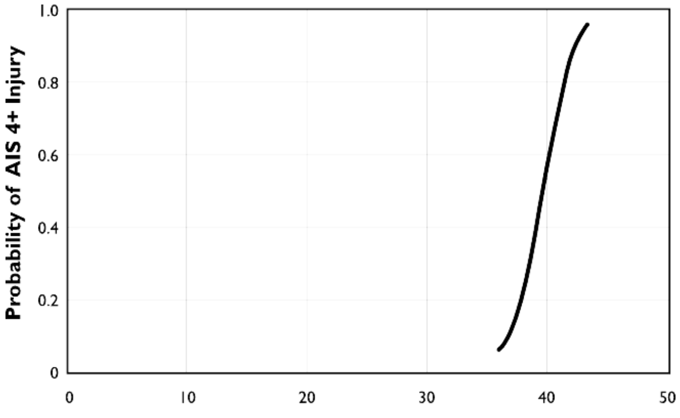


Figure 3.5.2 Plot of probability of AIS 4+ thoracic injury against compression after Viano et. al. (1989)

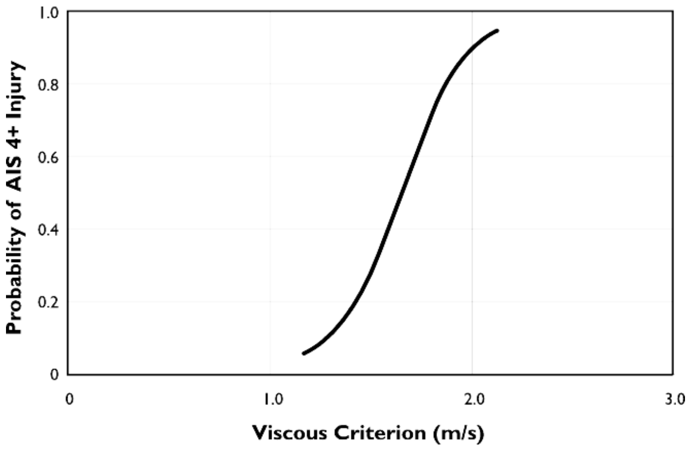


Figure 3.5.3 Plot of probability of AIS 4+ thoracic injury against viscous strain after Viano et. al. (1989)

Table 3.5.3 Tabulated values for the probability of AIS 4+ thoracic injury for compression (%) and viscous strain, V•C, as shown in the plots in Figures 3.5.2 and 3.5.3

Probability of AIS 4+ Injury	Compression %	V•C m/s
0.05	35.79	1.16
0.1	36.74	1.29
0.2	37.76	1.42
0.3	38.45	1.51
0.4	39.52	1.58
0.5	39.52	1.65
0.6	40.03	1.71
0.7	40.59	1.79
0.8	41.27	1.88
0.9	42.30	2.01
0.95	43.25	2.13
1	-	-

Predictive Equations:

For the Viscous response – $P(V{\bullet}C) = [1 + \exp(10.02 - 6.08\ V{\bullet}C)]^{-1}$
For the Compression response – $P(C) = [1 + \exp(31.22 - 0.79\ C)]^{-1}$

3.5.4 Abdominal Injury Tolerance

The lateral abdominal injury assessment is based on the probability of AIS 4+ injury curves for percentage compression (%) and viscous strain V•C (m/s) for the full abdominal width, obtained by Viano et. al. (1989).

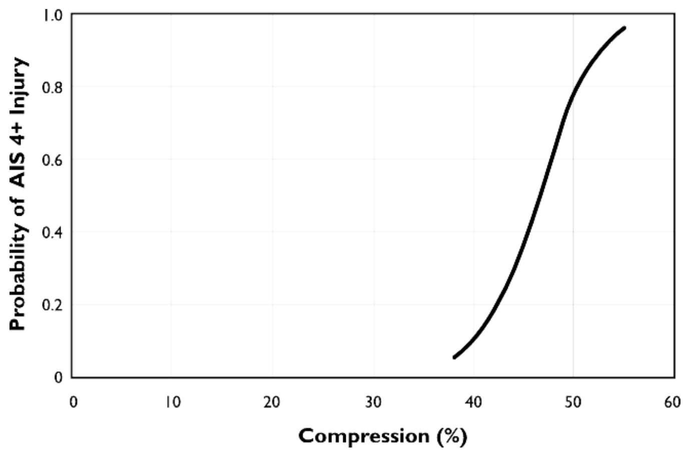


Figure 3.5.4 Plot of the probability of AIS 4+ abdominal injury against compression (%), after Viano et. al. (1989)

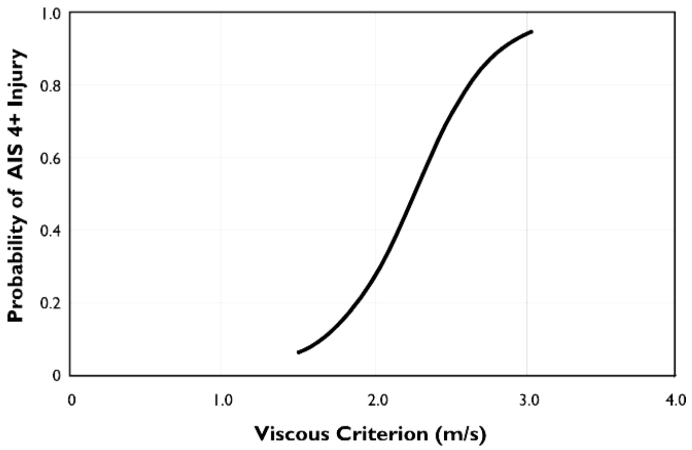


Figure 3.5.5 Plot of probability of AIS 4+ abdominal injury against viscous strain, V•C (m/s), after Viano et (1989)

Table 3.5.4 Tabulated values for the probability of AIS 4+ abdominal injury for viscous strain, V•C, and compression (%) as shown in the plots in Figures 3.5.4 and 3.5.5

Probability of AIS 4+ Injury	Compression %	V•C m/s
0.05	38.13	1.49
0.1	40.26	1.69
0.2	42.58	1.90
0.3	44.12	2.05
0.4	45.38	2.16
0.5	46.54	2.27
0.6	47.70	2.37
0.7	48.96	2.49
0.8	50.50	2.63
0.9	52.82	2.84
0.95	54.95	3.04
1	-	-

Predictive Equations:

For the Viscous response – $P(V\cdot C) = [1 + \exp(8.64 - 3.81\ V\cdot C)]-1$
For the Compression response – $P(C) = [1 + \exp(16.29 - 0.35\ C)]-1$

3.5.5 Lateral Pelvic Injury Tolerance

The pelvic injury assessment functions are based on the probability of injury curves for impact force (kN) obtained by Bouquet et. al. (1998).

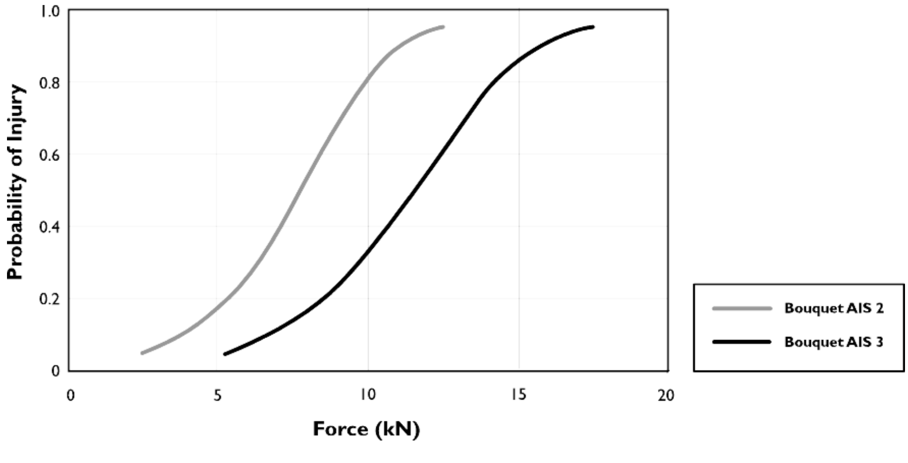


Figure 3.5.6 The probability of AIS 2+ and 3+ pelvic injury for impact force after Bouquet et. al. (1998)

Table 3.5.5 Tabulated values for the probability of AIS 2+ and 3+ pelvic injury for impact force, as shown in Figure 3.5.6

Probability of Injury	Force kN	
	For AIS 2+ Injury	For AIS 3+ Injury
0.05	2.50	5.27
0.1	3.89	6.67
0.2	5.28	8.57
0.3	6.35	9.73
0.4	7.10	10.70
0.5	7.77	11.60
0.6	8.47	12.50
0.7	9.10	13.30
0.8	10.00	14.25
0.9	11.10	15.83
0.95	12.50	17.50
1	-	-

3.5.6 Lower Extremities Injuries

The lateral impact injury assessment for the lower extremities is based on single value 50% likelihood of fracture (AIS 2+) for the long bones of the upper (femur) and lower leg (tibia and fibula) and knee, as given in Table 3.5.6. These values are based on lateral 3 point bending cadaver test data obtained by Yamada (1970), Gibson et. al. (1992), Kress at al (1993) and Nyquist (1985) for the lower leg.

Table 3.5.6 Lateral bending moment for fracture of the upper and lower leg in 3 point bending and the knee, AIS 2+ injury

Region of Leg	Dynamic Lateral Bending Moment for Fracture (Nm)	
	Male	Female
Upper leg	354	295
Lower leg	317	278
Knee	125	104

Chapter 4
DUMMY CAPABILITIES

4.1 INTRODUCTION

The objective of this section of the report is too present an overview of the capabilities of the dummies chosen for use in the project. The two dummies are the BioSID, which is designed to be representative of a 50th percentile North American male, and the SID IIs, which represents a 5th percentile female and also a youth of approximately 12 years of age.

4.2 DUMMY BIOFIDELITY

The BioSID dummy uses the head and neck components from the 50th percentile Hybrid III dummy. Benson, Perl, & Smith (1991) found that the standard Hybrid III head and skin (1887 +/- 100 N/mm) satisfactorily represented the force/stiffness characteristics for the temporal and parietal areas of cadaver heads (mean stiffness 1800 +/- 881 N/mm). The comparison used drop tests from two heights, 0.15 m and 0.38 m to confirm this.

The BioSID lacks shoulders and upper extremities usable for measurements. The upper rib is designed to represent the shoulder and the upper extremity is a simple pad designed for repeatability in a test environment. Ideally the arm would be instrumented in order to obtain bending moments so that the fracture threshold for the humerus, radius and ulna could be used to predict injury. Such changes would require a major dummy redesign.

Viano et. al. (1995) compared the cadaver test data from Viano et. al. (1989) to similar lateral pendulum tests with the EuroSID I and BioSID dummies. For these tests the authors conclude that the BioSID has better biofidelity than the EuroSID I with regard to the three body regions, thorax, abdomen and pelvis. The responses of the BioSID were found to be better with regard to peak contact force particularly for the high speed tests. . The results of these tests for the BioSID are presented with the cadaver test corridors in Figures 4.2.1, 4.2.2 and 4.2.3. Although it is the best dummy currently available the BioSID is generally stiffer, i.e. it produces higher impact forces than the cadavers, particularly at the higher impact velocities.

Cavanaugh et. al. (1995) compared the BioSID to cadavers on the modified Heidelberg test set up and came to similar conclusions, overall the BioSID thorax was stiffer than the cadavers. The same authors in the following year, Cavanaugh et. al. (1996), showed that V•C was a good predictor of injury to the abdomen when used with the rib 4-5 response of the BioSID dummy.

These tests do not conform to the International Standards Organisation (ISO) tests used to rate the biofidelity of side impact dummies presented in ISO (1997). This report presents an approach for a comprehensive check on the biofidelity of such dummies and is summarised here.

Equation 1 is used to determine the overall biofidelity of the dummy.

$$B = \frac{\sum_{i=1,2..6} U_i B_i}{\sum_{i=1,2..6} \mathrm{U_i}} \qquad (1)$$

where, B - overall biofidelity rating which has a value between 0 (poorest) and 10 (best)
$\mathrm{B_i}$ - biofidelity rating for each of the body regions
$\mathrm{U_i}$ - weighting factor for each body region
i - subscript to represent each body region (i = 1 Head, i= 2 Neck , i= 3 Shoulder, i= 4 Thorax, i= 5 Abdomen and i= 6 Pelvis)

The equation used to calculate the biofidelity of a body region B, is shown in Equation 2.

$$B_i = \frac{\sum_{j=1,2..m} V_{i.j}\, T_{i,j}}{\sum_{j=1,2..m} V_{i.j}\, T_{i,j}} \qquad (2)$$

where, $V_{i.j}$ - weighting factor for each test condition for a given body region
$T_{i.j}$ - test biofidelity for each test condition for a given body region

The equation used to calculate the test biofidelity is shown in Equation 3.

$$T_{I,j} = \frac{\sum_{k=1,2..m} W_{i.j,k}\, R_{i,j,k}}{\sum_{k=1,2,\ldots,n} W_{i.j,k}} \qquad (3)$$

where, $W_{i.j,k}$ - weighting factor for each response measurement for which a requirement is given
R_{ijk} - the rating of how well a given response meets its requirement

Values for the response rating, R_{ijk}, are as follows:
$R_{\mathrm{ijk}} = 10.0$ if the response meets its requirements.
$R_{\mathrm{ijk}} = 5.0$ if the response is outside of its requirement, but lies within one corridor width of requirement.
$R_{\mathrm{ijk}} = 0$ if the response is outside of requirement by more than one corridor width of the requirement.

The ISO classifications are shown in Table 4.2.1, were used to assess the biofidelity of each of the dummies.

Table 4.2.1 ISO Biofidelity Classifications

Excellent	> 8.6 to10.0
Good	> 6.5 to 8.6
Fair	> 4.4 to 6.5
Marginal	> 2.6 to 4.4
Unacceptable	0 to 2.6

This biofidelity rating method was used to determine a biofidelity rating for the SID IIs Beta+-Prototype by the Occupant Safety Partnership Research Partnership (OSPRP) of the United States Council for Automotive Research (USCAR). The OSPRP also tested the other available side impact dummies - SID, EuroSID-1, BioSID and SID IIs to rate their relative capabilities, Scherer et. al. (1998). The tests used in this rating are shown in Table 4.2.2 and the ratings of the test dummies are shown in Table 4.2.3.

Table 4.2.2 The tests suggested in ISO (1997) for rating the biofidelity of test dummies in side impacts

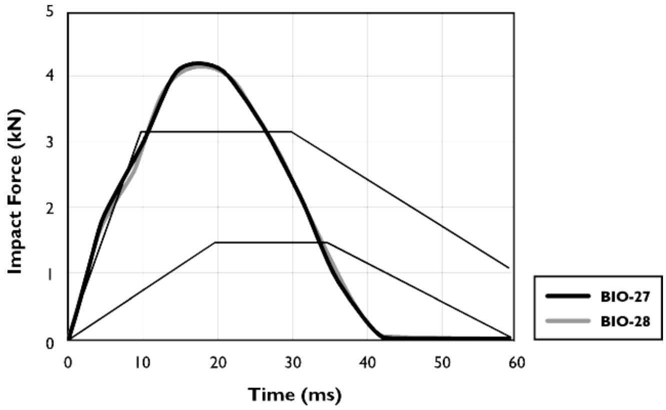
Requirement	Test Description
Head Test 1	200 mm Rigid Drop
Head Test 2	1200 mm Rigid Drop
Neck Test 1	7.2 g Sled Impact
Neck Test 2	6.7 g Sled Impact
Neck Test 3	12.2 g Sled Impact
Shoulder Test 1	4.5 m/s Pendulum
Shoulder Test 2	7.2 g Sled Impact
Shoulder Test 3	12.2 g Sled Impact
Shoulder Test 4	8.9 m/s Padded WSU Sled
Thorax Test 1	4.3 m/s Pendulum
Thorax Test 2	6.7 m/s Pendulum
Thorax Test 3	1.0 m Rigid Drop
Thorax Test 4	2.0 m Padded Drop
Thorax Test 5	6.8 m/s Rigid Heidelberg Sled
Thorax Test 6	8.9 m/s Padded WSU Sled
Abdomen Test 1	1.0 m Rigid Drop
Abdomen Test 2	2.0 m Rigid Drop
Abdomen Test 3	6.8 m/s Rigid WSU Sled
Abdomen Test 4	8.9 m/s Rigid WSU Sled
Abdomen Test 5	8.9 m/s Padded WSU Sled
Pelvis Test 1	6.0 m/s Pendulum
Pelvis Test 2	10.0 m/s Pendulum
Pelvis Test 3	0.5 m Rigid Drop
Pelvis Test 4	1.0 m Rigid Drop
Pelvis Test 5	2.0 m Padded Drop
Pelvis Test 6	3.0 m Padded Drop
Pelvis Test 7	6.8 m/s Rigid Heidelberg Sled
Pelvis Test 8	8.9 m/s Rigid Heidelberg Sled
Pelvis Test 9	8.9 m/s Padded Heidelberg Sled
Pelvis Test 10	6.8 m/s Rigid WSU Sled
Pelvis Test 11	8.9 m/s Rigid WSU Sled
Pelvis Test 12	8.9 m/s 15 psi Padded WSU Sled
Pelvis Test 13	8.9 m/s 23 psi Padded WSU Sled

Table 4.2.3 Comparison of SID, EuroSID-1, BioSID and SID IIs biofidelity ratings

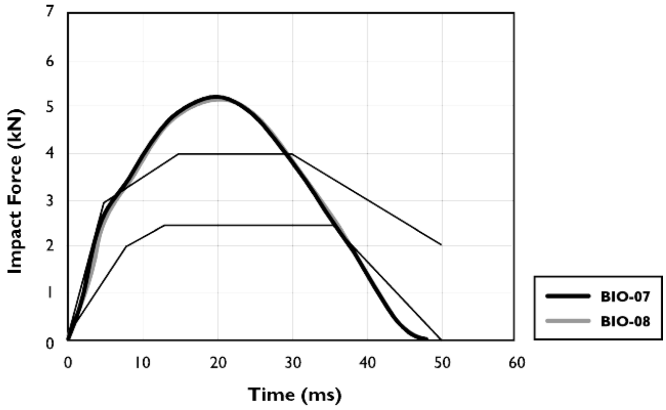
Dummy Requirement	**SID**	**EuroSID-1**	**BioSID**	**SID IIs**
Head Test 1	0	5.0	10.0	7.5
Head Test 2	0	*	0	*
Head Rating	**0**	**5.0**	**6.7**	**7.5**
Neck Test 1	2.9	7.8	7	6.6
Neck Test 2	*	*	*	3.3
Neck Test 3	1.7	*	5.2	4.4
Neck Rating	**2.5**	**7.8**	**7.0**	**4.9**
Shoulder Test 1	0	5.0	5.7	5.0
Shoulder Test 2	0	10.0	7.5	10.0
Shoulder Test 3	*	*	10.0	5.0
Shoulder Test 4	*	*	*	5.0
Shoulder Rating	**0**	**7.3**	**7.3**	**6.2**
Thorax Test 1	2.2	5.6	7.3	10.0
Thorax Test 2	0	5.0	10.0	10.0
Thorax Test 3	2.5	5.0	10.0	9.2
Thorax Test 4	5.0	5.0	5.3	*
Thorax Test 5	5.0	6.3	4.8	3.9
Thorax Test 6	5.3	*	5.3	5.0
Thorax Rating	**3.1**	**5.4**	**6.8**	**7.8**
Abdomen Test 1	4.7	0	6.3	9.3
Abdomen Test 2	4.0	2.0	4.7	*
Abdomen Test 3	*	*	*	5.0
Abdomen Test 4	*	*	*	*
Abdomen Test 5	*	*	*	10.0
Abdomen Rating	**4.4**	**0.9**	**5.6**	**8.8**
Pelvis Test 1	0	0	10.0	10.0
Pelvis Test 2	0	0	10.0	*
Pelvis Test 3	5.0	5.0	5.0	5.0
Pelvis Test 4	5.0	10.0	0	6.7
Pelvis Test 5	10.0	0	5.0	*
Pelvis Test 6	*	*	*	*
Pelvis Test 7	0	0	2.2	5.9
Pelvis Test 8	2.3	0	5.0	*
Pelvis Test 9	5.0	2.4	0	*
Pelvis Test 10	*	*	*	2.2
Pelvis Test 11	*	*	*	*
Pelvis Test 12	*	*	*	*
Pelvis Test 13	*	*	*	2.9
Pelvis Rating	**2.5**	**1.5**	**5.0**	**5.9**
Dummy Rating	**2.3**	**4.4**	**6.2**	**7.0**

* Test not conducted.

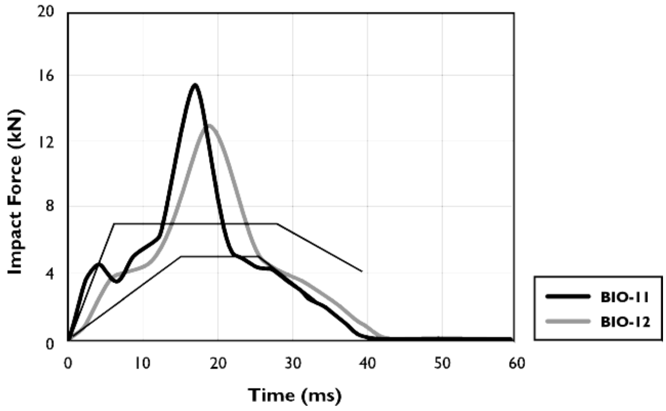
This table gives the relative biofidelity rankings of the various dummies with the overall rating for the BioSID as fair and for the SID IIs good. It is difficult to know how to interpret some of the ratings given. For example, the BioSID and EuroSID have similar tests and heads (both are from the Hybrid III frontal dummy), and yet the biofidelity ratings for the heads of these two dummies differ markedly.



4.4 m/s

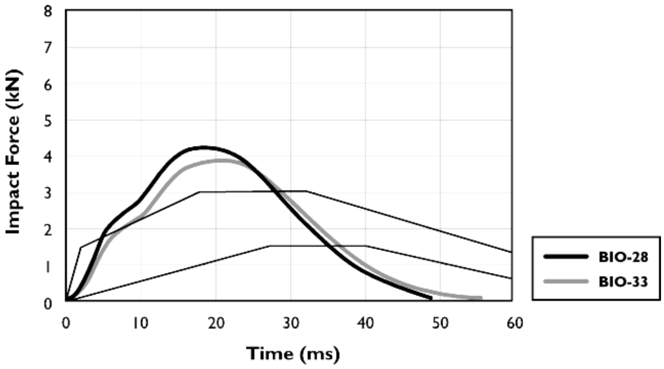


6.5 m/s

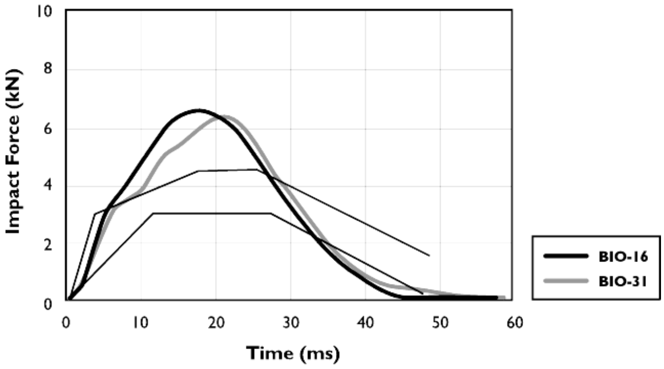


9.3 m/s

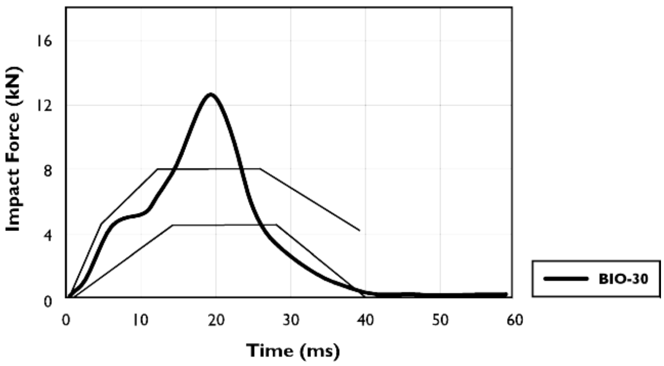
Figure 4.2.1 BioSID thoracic force time responses for lateral pendulum impacts at different velocities, compared with the corridors for the lateral cadaver tests, from Viano et. al. (1995)



4.8 m/s



5.8 m/s



9.4 m/s

Figure 4.2.2 BioSID abdominal force time responses for lateral pendulum impacts at different velocities, compared with the corridors for the lateral cadaver tests, from Viano et. al. (1995)

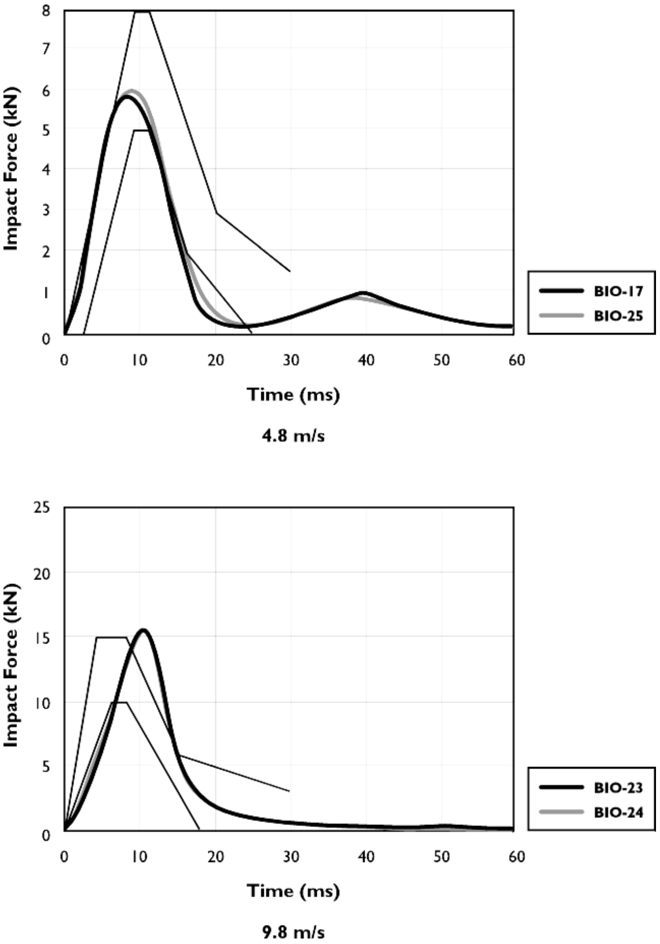


Figure 4.2.3 BioSID pelvic force time responses for lateral pendulum impacts at different velocities, compared with the corridors for the lateral cadaver tests, from Viano et. al. (1995)

The SID IIs is still being developed, and so biofidelity data is only just becoming available.

4.3 AVAILABLE SIDE IMPACT INJURY ASSESSMENT VALUES

The dummies chosen for the ISIP project are the BioSID and the SID IIs. These are the two most recent side impact dummies and have the best available combination of biofidelity (i.e. human like impact response) and measurement capability. Table 4.3.1 lists the instrumentation typically fitted to these dummies. This instrumentation in itself forms a significant constraint on the possible injury assessment capabilities of these dummies.

The only available side impact injury assessment values currently available are single point criteria, which have been suggested for use as injury assessment reference values for use with the BioSID dummy by various users. They are based on use with the current BioSID dummy instrumentation capability, and are presented in Table 4.3.1.

Table 4.3.1 Available injury assessment values for use with the BioSID dummy

Body Region	Dummy Instrumentation Capability	GM IARVs (1)	Tolerance Levels (2)	TC Target Levels (3)
Head Cof G	Acceln x,y,z	HIC < 1000		80g
Neck Upper	Force x,y,z Moment x, y, z			
Spine T1 T4 T12	Acceln x,y,z Acceln x,y,z Acceln x,y,z			
Shoulder - Rib	Force y Acceln y Dispt y			
Thorax Ribs 1, 2 & 3	Acceln y Dispt y	Lateral Rib/Spine Def. – 42 mm TTI – 90/85g (for sedan coupe) VC – 1m/s	VC = 1.37 m/s D = 64	D = 35 mm
Abdomen Ribs 1 & 2	Acceln y Dispt y	Lateral Compression - 39mm Force – 4.5 kN	V•C = 1.85 m/s D = 74.0 mm	D = 20 mm
Lumbar Base	Force x, y, z Moment x			
Pelvis C of G Pubis Iliac Sacrum	Acceln x,y,z Force y Force y Force y	Acceln y – 130 g Pubic Force – 10 kN Iliac Force – 10 kN	Fpubic = 3.6 kN 100g	Fpubic = 3.6 kN 135g
Lower Extremities Femur – Upper – Lower Knee Tibia – Upper – Lower	Force x, y, z Force x, y, z Force x, y, z Force x, y, z			

Notes:

(1) From Mertz (1992), for an 11-15% probability of serious injury (AIS 3+).

(2) From Viano (1995), for a 25% probability of AIS 4+ injury.

(3) From Dalmotas et. al. (1996), from the target levels for Transport Canada FMVSS 214 tests.

Chapter 5
FUTURE DEVELOPMENT

5.1 INTRODUCTION

The objective for Task 3 in this project was to develop a set of Injury Assessment Functions (IAFs) for use as means of assessing in side impact collisions. These IAFs must be able to predict the relationship between the response of a surrogate occupant in a representative series of side impact crashes and the risk and severity of injury to the population of crash involved vehicle occupants. The literature review reported on here is the culmination of several strands of the project.

- The side impact crash data at Monash has been analysed to obtain a better understanding of the injury incidence and causation in side impacts. This is summarised in Chapter 2 of this report.
- The priorities, in terms of Harm for the various body regions, have been determined.
- The literature on injury assessment in side impacts has been reviewed. This review is presented in Chapter 3.
- Preliminary injury criteria have been suggested for side impact to humans based on the priorities in terms of Harm above and are summarised in Chapter 3, Section 5.

The function of this section is to give an overall summary of why the preliminary injury criteria were chosen, and then discuss how these criteria maybe developed to give the injury assessment functions required by Task 4 for its modelling.

5.2 THE AVAILABLE INJURY CRITERIA

This report has summarised the available injury criteria for use in side impact crashes by body region, see Chapter 3. The aim, during this review, was to find human injury risk functions for loading to all the body regions in these types of impact. The review was only partially successful in doing this, as many of the body regions are lacking in definitive injury assessment data. So the next steps for Task 3 of this project are to take the injury assessment data currently available for each of the body regions in side impact crashes and develop it to fulfil the minimum requirements of the modelling in Task 4.

In terms of priority, the highest must be given to the head, as the region where more than 50.9% of the total Harm occurs, see Table 5.1. This is then followed by the thorax (22.3%), the lower extremities (8.6%), the upper extremities and shoulder (8.5%), the neck and spine (5.8%), the pelvis (3.1%) and the abdomen (1.8%).

At the Expert Group Meeting in Detroit in June, 1998, David Viano suggested that the best way to approach the lack of available injury assessment data was to look critically at each body region. This critical assessment needed to find those areas, which were critical in terms of contribution to the total Harm for the specific region, MUARC (1998). These areas would tend to stand out above the others in their contribution to overall Harm. Such critical regions would be where most research effort had been spent and were likely to be amenable to injury reduction. Interpreting the harm priorities from Table 2.26 gives the critical injury areas to be addressed for each body area. Table 5.1 gives the critical injury severity areas for each body region (with the highest priority, i.e. the greatest harm, in bold). The table also gives the lateral injury criteria for each body region, were available.

Table 5.1 The injury areas by body regions to be addressed with injury risk data, the highest priority injury for each body region is in bold

Priority	Body Region	Critical Injury Areas By AIS Severities	Available Injury Criteria
1	Head	3, 4, **5**	2, 4 +
2	Thorax (inc hlsk)	**3**, 4, 5	4 +
3	Lower Extremities	1, 2, **3**	2 + (single value)
4	Upper Extremities	1, **2**, 3	none
5	Spine	2, 5, **6**	none
6	Face	**1**, 2	none
7	Pelvis	2, **3**	2, 3
8	Shoulder	**2**	none
9	Abdomen	**1**, 4	4 +
10	Neck	1, 3, **5**	2 + (single value)

The missing areas in the available injury criterion column, are body regions with no injury assessment data available. These regions lack any current injury sensing capability for the dummies, the BioSID and the SID IIs. It is not part of the brief for this project to begin redesigning or adding measurement capabilities to these dummies.

The pelvis is the only area that is adequately addressed, and does not require further definition. For the other body regions the available injury risk curves need to be extended to address more injury severities and develop continuous risk functions for the neck and lower extremities.

As there were no fully developed injury assessment functions available for side impact, these preliminary injury criteria were chosen as far as possible with the following requirements in mind:

- injury criteria were required for all body regions, where injury was possible;
- the injury criteria needed to be based on test data, preferably with volunteers or cadavers as the test surrogates;
- the criteria needed to have a significant level of acceptance;
- the criteria needed to have, if possible, continuous injury risk distributions based on biomechanical data; and
- the criteria needed to be compatible with the available instrumentation in the dummies, BioSID and SID IIs.

The concern in Task 3 then becomes how to develop the available injury criteria into a set of injury assessment functions, which is comprehensive, balanced and able to fulfil the needs of

Task 4. This development needs to cover several areas. The first is to generate the extra injury severity risk distributions for each body region, which are needed, as demonstrated in Table 5.1. The design task requires the ability to discriminate between the different levels of injury, to know whether a design change has reduced the injury risk by one AIS level or two. Using the approach suggested by Viano reduces the task to manageable proportions, by focussing the development only on the critical injury areas. Significant work is still required however. The second area in Task 3 will be to verify the accuracy of the injury severity predictions, both with respect to the test data and the population at risk. The population at risk being vehicle occupants involved in the full spectrum of side impact crashes. The age and gender mix of this population is important and will have a significant effect on the assessment function development. The final area for Task 3 will be to participate in the validation of the model overall

5.3 GENERATION OF THE EXTRA INJURY SEVERITY RISK DISTRIBUTIONS

In general terms, the method for the generation of the extra injury severity risk distributions must take the following form. Existing test data will be revisited with the specific aim of filling in the extra injury severity curves required. The data may have been used in the original formulation, from which more injury severity information can be derived, or there may be other sets of data available, which may be combined. At the same time questions regarding discrepancies in injury recording and interpretation between the crash data and the test data will need to be addressed. The generation of the distribution curves will remain as far as possible based on biomechanical data to ensure that the shape of the curve at each severity has relevance to the injury mechanism.

This development of the expanded injury risk functions is best discussed in terms of body region. The following summarises briefly the concerns existing for each body region and outlines possible sources of data for generating the extra injury severity probability distributions.

Head

For the head the following need to be addressed:

- the effects of rotational acceleration need to be averaged into HIC in an undefined and non-linear way;
- HIC works best as a measure of the probability of skull fracture, how the risk of brain injury fits with this needs investigation;
- the lack of biofidelity of the dummy shoulder region causes problems with the head kinematics by reducing the likelihood and force of dummy head contact in side impacts. This will need to be investigated to ensure reliable prediction of head injury;
- the complex kinematics of the head on the neck, with rotations around all axes, also needs to be considered in this regard;
- HIC is based on cadaveric frontal impact tests, the risk of injury curve needs to be modified for lateral impacts; and,
- the available AIS 4+ risk distribution needs to be modified and extended to other severities (AIS 3 and 5).

Given the available resources, the most productive approach for the head is to verify the scaling of frontal HIC to side impacts to the head. Several alternative sets of test data appear to offer opportunities in this regard.

- The DOT HIC IAF curves, Kanianthra et. al. (1996)
- The lateral head impact work of McIntosh et. al. (1996)
- The work carried out at JARI, Ono et. al. (1980) and Kikuchi et. al. (1982)

Thorax

The thorax needs the following to be addressed:

- the confusion regarding hard thorax or other anatomical grouping of the internal organs needs to addressed in the accident data and the cadaver testing;
- the available AIS 4+ injury risk distribution needs to be extended to other severities (AIS 3 and 5);
- the transition velocity between compression and the viscous criteria requires verification for lateral impacts; and
- the matching of the “at risk” population needs to be considered.

For the thorax, sufficient test data exists at WSU (including the Viano data), Heidelberg and Wisconsin Medical College to base the extended severity curves on a re-analysis of the existing test data. Re-analysing the existing test data will also allow further confirmation of the shoulder, abdomen and pelvic injury tolerance, as well as for the thorax.

Lower Extremities

The lower extremities need the following to be addressed:

- the available single value IARVs need to be developed into continuous risk curves, at severity levels of AIS 1, 2 and 3;
- the inclusion of ankle and knee joint injury depends on injury incidence and test data becoming available; and
- the matching of the “at risk” population needs to be considered.

Sufficient test data exists for it to be re-analysed for the long bone fractures to be defined in terms of continuous curves. If the injury types and incidence to the knee and foot and ankle in side impacts were better defined, it may be possible to apply some of the research which has been recently carried out into frontal injury tolerance of the foot and ankle. It is planned that this area will be extended as the subject for a Ph.D.

Upper Extremities and Shoulder

At present no injury criteria have been suggested for the upper extremities and shoulder. The difficulties inherent in getting the side impact dummies to have injury sensing for the upper extremities is beyond the scope of this project. The shoulder is presently just lumped in with the rest of the thorax. The test data does exist to look more closely at the injury severity risk for the shoulder, but this is at a low priority for this project.

Spine

Little data exists to propose injury severity distributions or even injury criteria for the spine. Enough test data exists however, to be re-analysed for the purpose of deriving some injury tolerance criteria in side impacts. Specifically, the cadaveric side impact tests with the pelvic offset conditions at WSU could be used to review thoracic and lumbar spine injury in side impact. More details of the incidence and injury types in side impact crashes would be required, but this is a low priority for this project.

Face

No side impact injury criteria for the face have been proposed or exist. Some test data exists for frontal impacts, which may be suitable for use in side impacts. Better definition of the incidence and injury type in side impacts is required, if this is going to be investigated further.

Pelvis

The pelvis injury assessment appears adequate at present, especially if it is possible to do some matching to the at risk vehicle occupant population.

Abdomen

The abdomen needs the following to be addressed:

- the confusion regarding hard thorax vs anatomical grouping of the internal organs needs to addressed in the accident data and testing;
- the available AIS 4+ risk distribution needs to be modified and extended to other severities (AIS 1); and
- the matching of the “at risk” population needs to be considered.

Overall, abdominal injury is a low priority for this project. The current dummies are not readily able to sense AIS 1 injury in this region of the body.

Neck

Any improvement to the neck injury assessment capability would be useful, in particular:

- the available single value IARVs need to be developed into continuous risk curves, at severity levels of AIS 1, 3 and 5;
- any such risk curves need to be based on some form of combined loading;
- the matching of the “at risk” population needs to be considered; and
- whiplash associated injury, AIS 1 neck injury, needs to be addressed, but there is a lack of available injury criteria and data, especially for side impacts.

Overall, neck injury is a low priority for this project. The current dummies are not readily able to sense AIS 1 injury in this region of the body.

5.4 VERIFICATION OF PREDICTED INJURY DISTRIBUTIONS

Following the development of the expanded sets of injury severity risk functions for each body region, it becomes necessary to verify that the system as a whole is predicting realistic injury distributions during the modelling process.

It is possible to do this verification at several different levels, each with different constraints and requirements. It will be noted that in the discussion that follows the model referred to is the combination of the dummy model and the injury prediction. Ultimately, once the injury predictive capability of this section of the model has been verified, it would be used as part of a complete model of the impacted vehicle.

The first and most generic level is to use the mass vehicle crash injury data, such as kept by the Motor Accidents Authority of NSW (MAA), in conjunction with the dummy responses gathered in the course of a New Car Assessment Program (NCAP) Test to verify the injury predictions. The use of this technique, for a slightly different purpose, is illustrated in the work by Ryan et. al. (1998).

Another method is to tap into an intensive accident investigation program. This must include some means of classifying accident severity such as impact velocity, delta V or BEV, in all the accident cases used to be effective. The sources of such data are limited even on a worldwide basis and come down to the following:

1. Australia
    - The Monash University Accident Research Centre accident investigation team
    - Possibly the RTA of NSW Crashed Vehicle Project
    - Road Accident Research Unit data
2. Canada
    - Transport Canada Crashed Vehicle Study
3. Germany
    - The Hanover Medical School Accident Investigation Team
4. UK
    - ICE and TRL
5. USA
    - NASS data

Each of these countries also carries out a form of NCAP testing, and most are about to start side impact testing as part of the program. By matching the dummy response data from the NCAP side impact tests to matched vehicles in a similar crash scenario, injury distributions could be produced to verify the model predictions.

The most rigorous method to do this verification is to gather a series of real world side impact crash scenarios, preferably with more than one crash between identical cars in each. The scenario would require reconstruction of the impact with dummies in the specific vehicles. Such a process is underway between MUARC and Holden, with the former doing the accident investigation and the latter the crash testing. Transport Canada has a limited series of such accident reconstructions, but each is usually based on only one specific crash.

5.5 FUTURE DEVELOPMENT NEEDS

In summary, then the steps that are required to complete the requirements for Task 3 of this project and develop the injury criteria for cadavers into injury assessment functions are as follows:

- better definition of the detailed injury causation in crashes for some body regions is required;
- extension of the continuous injury risk functions to more injury severities and body regions;
- inclusion of the non-linear correlation between the dummies and the human population, particularly at higher impact severities;
- verification of the IAFs by correlation of the dummy responses in staged impacts with real world injuries found in similar crashes; and
- finally the overall model must be verified in the same manner.

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