Prevention of Head Injuries to Car Occupants:

An Investigation of Interior Padding Options

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Abstract

Head injuries to car occupants resulting from crashes on Australian roads are a major cause of death and permanent brain damage. This report evaluates the benefits that would be likely to accrue from the use of padding materials to reduce the severity of impacts to the head. A review of the international literature was conducted to examine the range of possible countermeasures, with particular reference to padding the upper interior of the passenger compartment. Three sets of data analyses were then carried out: first, a summary of objects typically struck by the head in a representative sample of crashes; secondly, an examination of actual brain injuries sustained in a sample of crashes, and an assessment of likely outcomes had the objects struck by the head been padded; and finally, a HARM analysis to estimate the cost of head injuries and the likely financial benefits from various countermeasures. Results indicate that there is considerable potential for reducing the severity and consequences of impacts to the head by padding the upper interior of the passenger compartment. The total annual benefit of this measure, in terms of reduced HARM, would be about $123 million, or $154 per car (with a 5% discount rate). However, an even greater level of protection would be provided by the use of protective headwear. The total benefits associated with headwear in the form of a soft shell bicycle helmet were estimated to be $380 million (assuming a fully airbag equipped fleet), or $476 per car ($626 for cars without airbags).

Keywords

SAFETY, ACCIDENT, INJURY, HEAD INJURY, OCCUPANT PROTECTION, VEHICLE DESIGN, PADDING, HARM, HELMET

Executive Summary

Head injuries to car occupants in crashes on Australian roads are a major cause of death and permanent brain damage. Preventing impacts to the head and reducing the severity of the head impacts that do occur has the potential to save many lives and to reduce lifelong suffering by brain damaged individuals and those who have to care for them. This report evaluates the benefits that are likely to accrue from the use of padding materials to reduce the severity of the impact to the head.

The report begins with reference to the recent literature on car occupant head injuries. The range of possible head injury countermeasures is then reviewed briefly, with particular reference to padding the upper interior of the passenger compartment. Such padding, or other means of ensuring that the upper interior provides a specified level of head impact protection, will be required on some new cars in the United States in 1998 and all new cars by 2002. If a similar measure were to be adopted in Australia, it would be more than 15 years before half of the cars on the road provided the specified level of head protection. The development of some form of protective headwear, by comparison, would offer the occupants of all cars a way to reduce their risk of sustaining brain damage if involved in a road crash.

An analysis of factors related to head, neck and face injuries to car occupants follows, conducted by the Monash University Accident Research Centre (MUARC). The frequency with which various objects in the car cause injury to these body regions is listed, together with whether or not there was intrusion into the passenger compartment affecting the struck object. The role of contact with objects outside the car is also noted, although ejected occupants who had not been wearing a seat belt are not included in the data set. Drivers frequently sustained head injury from contact inside the vehicle with the steering assembly, door panel, instrument panel, roof and side window. The steering assembly was not a significant factor in head injuries to left front passengers. Contacts with A- and B-pillars and header and side rails were not frequently involved in head injuries to front seat occupants. This was thought to have been due to relatively high seat belt wearing rates.

The next section of the report presents the results of a detailed analysis of factors related to the occurrence of brain injury in three samples of crash involved car occupants studied by the NHMRC Road Accident Research Unit. On a case by case basis, selected characteristics of the injury to the brain are related to characteristics of the impact to the head and the object struck to identify those cases in which the provision of some means of energy absorption might reasonably be expected either to prevent or significantly reduce the severity of the injury to the brain in a similar crash. The results of this investigation indicate that there is considerable potential for reducing the severity and the consequences of impacts to the head by padding the upper interior of the passenger compartment. However, an even greater level of protection would be provided by the use of protective headwear.

Protective headwear, similar to a soft shell pedal cycle helmet, is estimated to be much more effective than padding the car in preventing cases of fatal brain injury and in improving the outcome in cases of severe brain injury. With each of these forms of protection the benefit appears likely to be greatest for cases which would otherwise sustain a brain injury of moderate severity (improved outcome in 40 and 25 per cent of cases respectively).

Headwear in the form of an energy absorbing head band covering the forehead and sides of the head would also provide a substantial level of protection (about half the benefits of a bicycle helmet).

In Chapter 4 the results of a Harm analysis are presented which estimate the likely financial community benefits which would be expected to come from the introduction of a range of countermeasures aimed at reducing head, neck and/or facial injuries to passenger car occupants involved in road crashes. “Harm” is a metric which estimates the societal cost of a given injury, taking into account the frequency with which that injury occurs as well as treatment, rehabilitation, loss of earnings, pain and suffering costs of injury. Obviously a Harm analysis needs to be based on a representative sample of crashes, as has been attempted in this report, if it is to yield nationally representative estimates.

The total annual benefit in terms of reduced Harm are estimated to be about $123 million for padding of the upper interior of the passenger compartment. The estimated benefit for protective headwear (in the form of a helmet) is between $380 million (assuming a fully airbag equipped fleet) and $500 million (assuming no vehicles with airbags). Estimated harm benefits are also given for other protective measures such as air bags alone, both front and side-mounted bags, and improved seat belt systems and penetration resistant side window glazing. The benefits are presented in terms of the savings per vehicle for two discount rates, 5 and 7 per cent. At the former discount rate the estimated benefit in savings of head and face Harm are $154 per car for padding of the upper interior, and $476 and $626 for protective headwear for cars with and without airbags.

Contents

CHAPTER 1 - INTRODUCTION

CHAPTER 2 - HEAD INJURY ANALYSIS CRASHED VEHICLE FILE

CHAPTER 3 - IN DEPTH ANALYSIS OF BRAIN INJURY CASES

CHAPTER 4 - HEAD INJURY HARM ANALYSIS

CHAPTER 5 - GENERAL DISCUSSION AND RECOMMENDATIONS

APPENDICES

Chapter 1

Introduction

Head injuries to car occupants in crashes on Australian roads are a major cause of death and permanent brain damage. Preventing impacts to the head and reducing the severity of the head impacts that do occur has the potential to save many lives and to reduce lifelong suffering by brain damaged individuals and those who have to care for them. This report evaluates the benefits that are likely to accrue from the use of padding materials to reduce the severity of the impact to the head.

The report begins with reference to the recent literature on car occupant head injuries. The range of possible head injury countermeasures is then reviewed briefly, with particular reference to the use of padding materials inside the passenger compartment. More detailed reviews of the literature are presented in appendices.

We then turn to data analyses carried out by the authoring organisations. Three different sets of data that view the problem in different ways are presented. First, a summary of objects typically struck by the head in a reasonably representative sample of crashes in Australia is presented. Secondly, a sample of Australian crashes is examined in detail, concentrating on the actual brain injuries sustained and, in each case, the likely consequences had the object struck by the head been padded. Finally, a HARM analysis is conducted to estimate the cost of head injuries to car occupants and the probable financial benefits of various countermeasures.

The report concludes with recommendations on ways to reduce head injuries to car occupants in Australia.

1.1 RECENT LITERATURE

1.1.1 The Epidemiology of Car Occupant Head Injury

Given the generally accepted view that head injuries are the most common type of severe or fatal injury sustained by car occupants in road crashes, it is perhaps surprising that not more is known about the epidemiology of head injury among this class of road user.

A review of the literature on head and neck injuries in passenger cars was published by the Federal Office of Road Safety in 1987 (McLean et al, 1987). As noted in that review, the sources of information on head injury to car occupants tend to be derived either from hospital-based studies of the incidence of head injury from all causes, or from detailed studies of road crashes. Whereas the former rarely provide more detailed circumstantial data than a simple classification of type of road user, the latter are rarely based on a representative sample of crashes, rendering extrapolation to the general population of car occupants difficult or even impractical.

Kraus (1987) addressed several of the common methodological inadequacies of population-based studies of head injury from all causes. He concluded that there were then only 10 studies world wide that were of satisfactory quality and that comparison of the findings of these studies was rarely possible because of substantial differences in definitions of the types and severity of head injury. None of these studies gave estimates of head injury rates for car occupants.

A hospital-based source of data on road crash injuries in Australia became available in 1992 with the establishment of the Road Injury Information Program by the National Injury Surveillance Unit of the Australian Institute of Health and Welfare. Occupants of motor vehicles accounted for approximately 40 per cent of persons injured in a road traffic crash, with an annual hospital admission rate of around 90 per 100,000 population (a further 6 per 100,000 died before reaching hospital). Over half of the injured vehicle occupants were drivers and for those drivers admitted to hospital the head was usually the most severely injured body region (16 cases per 100,000 population) (O'Connor and Trembath, 1994). This finding was consistent with results obtained from the National Accident Sampling System in the United States (NHTSA, 1994b).

Further information on the comparatively sparse recent literature on the epidemiology of head injuries to car occupants is presented in Appendix A.

Research into the crash circumstances associated with head injuries to car occupants has been carried out in Australia by the NHMRC Road Accident Research Unit (RARU) and Monash University Accident Research Centre (MUARC). The results of these studies are presented in the following chapters of this report.

1.1.2 Head Injury Biomechanics

A review of head injury biomechanics also follows as an appendix to this report (Appendix B). It is not intended to be primarily a summary of material published since the previous literature review of head and neck injuries to car occupants (McLean et al, 1987). Rather, an attempt has been made to cover some topics which were not addressed in the first review and to deal with some others in greater detail.

Much of the literature has focused on determining the kinematic parameters that invoke any or all the mechanisms of brain injury. Although research in this area has taken place over a period of more than 30 years, there is still no broad agreement over the critical parameters which determine the outcome of a head impact. Fan (1993) reviewed several major series of animal experiments and clinical trials and concluded that it was possible to say that brain injury outcome is highly dependent on the resulting rotational acceleration, translational acceleration, the duration of impact, contact effects of the impact and the presence or absence of skull fracture.

1.1.3 Head Impact Tolerance Criteria

The Head Injury Criterion (HIC) is by far the most widely used measure of the risk of an impact to the head resulting in a life-threatening brain injury. This is due in no small part to its specification in United States Federal Motor Vehicle Safety Standards. The Head Injury Criterion has been controversial since its inception, with many authors questioning its relevance. The derivation of HIC is described in Appendix B to illustrate some of the reasons for these concerns, and why HIC continues to be used.

1.1.4 Padding Characteristics

Much of this report deals with the possible application of energy absorbing padding materials to the reduction of the severity of head injury resulting from an impact to the head. Some basic characteristics of these materials are discussed in Appendix C.

1.1.5 Characteristics and Treatment of Head Injuries

Developments in the understanding of the nature of primary brain injury since the publication of the literature review referred to above (McLean et al, 1987) are discussed briefly in Appendix D, together with comments on recent developments affecting the efficacy of emergency management and subsequent care in minimising the severity of the resulting morbidity and the likelihood of a fatal outcome.

1.2 METHODS OF REDUCING HEAD INJURY

Apart from preventing road crashes from happening in the first place (which is outside the scope of this report) there are a number of ways of reducing the frequency and severity of impacts to the head of an occupant of a vehicle in a crash.

Recent advances in seat belt systems have the potential to reduce the risk of head and face impacts to front seat occupants in a frontal collision. This is achieved primarily by reducing the slack in the belt system by means of webbing locks and/or pretensioning devices. Although the major benefit provided by a seat belt is the prevention of ejection from the car, current seat belt systems cannot be expected to prevent partial ejection of the head through an open or broken side window. Side window glazing which is capable of preventing total or partial ejection even when the glass is fractured is not yet in production but is technically achievable.

The air bag is now well established as an effective means of preventing serious head and face injury in frontal impacts. Recently developed side mounted air bags were, and are, intended primarily to protect the torso from injury but airbags specifically designed to protect the head in a side impact are now coming onto the market in some countries.

The mechanical properties of the object struck by the head obviously have a strong influence on the risk of brain injury for an impact of a given severity. Ideally, the object struck should make contact with the head over as large an area as possible and deform in such a way as to absorb a large part of the energy of the impact. When the object struck is part of the interior of the passenger compartment it may be possible to change the design to reduce the risk of brain injury. For example, the A-pillar of the car could be constructed with a strong central core covered by a deformable outer shell of sheet metal. Alternatively, some form of energy absorbing padding may be attached to those parts of the interior of the vehicle that are struck by the head.

1.2.1 United States Head Protection Requirements

In the United States, the National Highway Traffic Safety Administration estimated that about 4,000 fatalities and 9,300 serious injuries resulted each year from an occupant's head striking the upper interior structures of light passenger vehicles (NHTSA, 1991b). Since 1968 there had been a head impact test requirement dealing with the instrument panel, seat backs, glove box, sunvisors and armrests (Federal Motor Vehicle Safety Standard (FMVSS) 201). These components are required to pass a test where a 15 pound headform impacting at 15 mph (24 km/h) is not permitted to have a resulting deceleration greater than 80g continuously for more than 3 milliseconds (NHTSA, 1992).

An advanced notice of proposed rulemaking to amend FMVSS 201 to include the vehicle's upper interior areas was published on 19 August 1988. The impactor used to test the upper interior is a free-motion headform projected at the same speed of 15 mph. In August 1995 an amendment to FMVSS 201 was issued which requires the manufacturers of passenger cars and light trucks to comply with the head impact protection requirements for the upper interior of the passenger compartment on 10 per cent of all relevant vehicles produced on and after 1 September, 1998, increasing to 100 per cent in three stages during the following four years.

The proposed testing apparatus is described in detail and its effectiveness is evaluated in a number of NHTSA reports (NHTSA, 1991a, 1991b, 1992, 1995). The addition of 1 inch of rigid foam padding to the upper interior structures of passenger cars was found to decrease the HIC values obtained in headform impact tests by about 40 per cent, with some variation (NHTSA, 1991b). For a 15 mph headform impact test, estimates were made of the proportion of the total US passenger car fleet that would pass a HIC < 1000 test both with and without 1 inch of padding being added to the current upper interior structures (NHTSA, 1991b). The results are shown in Table 1.1.

Table 1.1
Percentages of the Total US Fleet Passing a HIC 1000 Test With and Without Padding

Structure	% of Fleet Passing HIC 1000 Test	
	Unpadded	1 inch padding
A-pillar	32	98
Front header	71	100
Side rail	44	99
B-pillar	29	93

Estimates of the effectiveness of compliance with FMVSS 201 were given in terms of fatality and injury reductions by NHTSA (1995). For passenger cars (the Standard also applies to light trucks) the estimated number of fatalities prevented per year ranged from 575 to 711, and the reduction in the number of AIS 2-5 injuries ranged from 251 to 465.

Concern has often been expressed that padding the upper interior of the passenger compartment might result in the head "pocketing" into the padding on impact with a possible increase in the risk of neck injury as the unrestrained upper torso moves relative to the restrained head. This matter is addressed at some length by NHTSA (1995) in their final economic assessment of FMVSS 201 (Upper interior head protection). Their conclusion was that "NHTSA retains the position that padding the A-pillar with one inch-thick foam would not adversely affect the risk of neck injury, while it does significantly reduce head injury".

1.2.2 Padding the Car or the Head?

The data presented in Table 1.1 show that padding the upper interior of the passenger compartment has great potential for substantially reducing the risk of life-threatening head injury. The main disadvantage of reliance on padding the interior surfaces of vehicles where a head might hit is that this can only realistically be done on new cars. This requires long lead times, as noted above, and it would be more than 15 years from the time that a decision was made to require padding before half of the cars on the road in Australia provided such protection against head injury.

A complementary approach is to protect the head itself by placing the padding directly on the head in the form of protective headwear. A bicycle style soft shell helmet could provide a large degree of protection for the head very cheaply. A simpler form of headwear, in the form of a headband covering mainly the forehead, where most impacts to the heads of car occupants occur (see Figure 3.6), could offer almost as much benefit without as much bulk and even less weight. Protective headwear also has the very considerable advantage that it could be available within a matter of months for use by those who wish to reduce their risk of sustaining brain damage if involved in a road crash.

Chapter 2

Head Injury Analysis Crashed Vehicle File

To help determine priorities for head injury intervention, an analysis was undertaken of occupants who sustained a head, neck and face injury in a representative sample of moderate to severe passenger car crashes in this country. These data were available in the *Crashed Vehicle File* held at the Monash University Accident Research Centre (MUARC).

2.1 THE CRASHED VEHICLE FILE

The Crashed Vehicle File comprised a randomly selected sample of passenger car crashes that occurred in and around Melbourne, Victoria between 1989 and 1992 where at least one occupant was either hospitalised or killed. Details of the crashed vehicle were obtained from examination of the vehicle (and other vehicles where appropriate) by a trained mechanical engineer as soon as possible after the crash but not at the crash scene.

2.1.1 The Vehicle and Occupant Population

The population of crashed vehicles comprised post-1981 passenger cars and their derivatives (station wagons, panel vans, etc) that were involved in a road crash in Victoria where at least one occupant was injured severely enough to require admission to (or treatment in) hospital. The breakdown of the sample revealed 3% of the patients required medical treatment only, 82% were admitted for at least one night, while 15% died either at the scene or later in hospital (details of cases where occupants died at-the-scene were kindly provided by the Coroner's office). Previous reports had demonstrated that the cases collected in this study using this strategy were roughly representative of all serious injury cases in Victoria (Monash University Accident Research Centre 1992).

2.1.2 Inspection Procedure

The inspection procedure used by the National Accident Sampling System (NASS) of the National Highway Traffic Safety Administration in Washington, DC. was used in these inspections, with slight modifications to suit the Australian environment. As soon as possible after the crash, the vehicle inspector was despatched to examine the vehicle, make the necessary measurements and to take photographs. Where a second vehicle was involved, it was also tracked down and examined briefly to assess impact velocity.

Injury details were obtained from interview and hospital and coronial records obtained during visits to the treating hospital or morgue. The percentage of hospital to killed occupants roughly approximated figures for the whole of Victoria. A trained nurse conducted the inspections, again using the NASS format with local amendments. All injuries were scored for severity of injury using the Abbreviated Injury Severity scoring system (AIS85) of the Association for the Advancement of Automotive Medicine (AAAM). Five major trauma hospitals and the Coronial Services in Melbourne agreed to provide access to patients with due consideration to their confidentiality. Refusal rates in the study were extremely low (7 out of every 100 patients expressed a desire not to participate in the study).

2.1.3 Calculation of Impact Velocity

Impact speed in this study was defined as the change in velocity from the moment of impact until the study vehicle separated from its impacting source (delta-V). This value was calculated in this research using the CRASH 3 program made available by the National Highway Traffic Safety Administration. It should be noted that the delta-V values computed are best estimates of impact velocity and are subject to some error from the assumptions and vehicle stiffness values used in making these calculations. In this study, American stiffness values had to be used in the calculations of delta-V for vehicles of the same sizes as the Australian vehicles as local figures were not readily available. These errors could be reduced to some degree if appropriate stiffness values for Australian vehicles were to be provided by the local manufacturers.

2.1.4 Selection Criteria

The inclusion/exclusion criteria used in the study for determining the suitability of a crash are described below. Using these inclusion/exclusion criteria, roughly, one in twenty-five road trauma attendances were suitable for inclusion in the study.

Vehicle Suitability: Any car or derivative with a Victorian registration number that commenced with either a "B, C or D" or a personalised plate (this effectively included all vehicles first registered during 1982 or later). Any vehicle subsequently found to be re-registered or unsuitable was excluded from the study by the project team at a later date. Four-wheel-drive vehicles of a standard car design (eg, Subaru models or Toyota Tercel) were included as suitable vehicles. However, the usual high clearance four-wheel drive vehicle configuration was not considered to be a passenger car derivative and they were excluded from this study.

Crash Suitability: Because of the difficulty in interpreting the effects of multiple collisions and which crash caused which injury, only single collisions were included. The impacted object could have been either another car, a truck, or a movable or immovable object, including roll-overs. Where there was clear evidence that an unbelted vehicle occupant had been fully ejected from a vehicle during the collision (such as being thrown from a vehicle during a rollover), they were excluded from the study. This was because of the impossibility of interpreting vehicle injury source information for these cases. However, where a belted occupant suffered damage as a result of either a full or partial ejection from the vehicle, an assessment of vehicle contribution to their injuries was attempted.

Patient Suitability: Patient suitability consisted of any vehicle occupant who was admitted to one of the participating hospitals from a suitable vehicle or collision. The patient had to be defined as a recent road accident victim (TAC, MCA or other hospital coding) rather than a re-admission from a previous crash. Patients could be conscious or unconscious and fatalities and patients that subsequently died in hospital were also included. As noted earlier, details of fatalities where the patient died at the scene were kindly provided directly by the Coroner's Office in Melbourne.

In most cases it was not possible to obtain details on all occupants involved in the collision. However, where the condition and circumstances of other injured occupants could be obtained, these details were also collected. This included both adults and children. While occupants are required by law to be belted in all vehicles, a number of them nevertheless do not wear seat belts in cars. Hence, it was felt legitimate to include patients in the crashed vehicle sample who were both belted and unbelted so as not to bias the study and overlook another set of problems for a subgroup of vehicle occupants most at risk.

2.2 VARIABLES & ANALYSES OF THESE DATA

A number of independent variables were of particular interest in the crashed vehicle study. These included patient characteristics, injuries sustained (including AIS severity), vehicle damage and extent of deformation, direction of principal force, severity of impact (delta-V), component and equipment failures, cabin distortion and intrusions, use of restraints, and an assessment of the source of all injuries. The use of the restraint was especially relevant in this study as the inspection method used has been shown to be the only objective and accurate means of making these assessments (Cromark, Schneider and Blaisdell 1990).

The dependent variables comprised crash and injury involvement rates per 100 vehicles or patients in the population of crashes investigated in the follow-up study of crashed vehicles. Interactions between injury and vehicle source were especially important comparisons in this study. Presentation of the results was confined to reporting percentage differences in involvement and rank ordering of involvement rates for injuries per body region and vehicle components.

Table 2.1
Population Characteristics of the Crashed Vehicle File for those Sustaining a Head, Neck or Face Injury (n=476) with All Injured Occupants (n=606)

CHARACTERISTIC	HEAD INJURED	ALL INJURED
1. IMPACT VELOCITY		
Mean Delta-V	48.5km/h	45.7km/h
Standard Deviation	22.3km/h	21.5km/h
Range	8-144km/h	5-144km/h
2. CRASH TYPE		
Frontal	56%	56%
Side Impact	40%	41%
Rear End	0%	0%
Rollover	4%	3%
3. VEHICLE TYPES		
Mini	3%	4%
Small	25%	26%
Compact	42%	42%
Intermediate	29%	27%
Large	1%	1%
4. SEATING POSITION		
Driver	65%	63%
Front-Left	25%	26%
Rear	10%	11%
5. PATIENT SEX		
Male	52%	49%
Female	48%	51%
6. PATIENT AGE		
<17yrs	4%	5%
17-25yrs	34%	31%
26-55yrs	45%	43%
56-75yrs	14%	17%
>75yrs	3%	4%

NB: Head injured here refers to any occupant who sustained a head, neck or face injury in the crash

2.3 OVERALL RESULTS

The final data base comprised details on 501 vehicles involving 606 patients from crashes that occurred in Victoria between the 1st April 1989 and the 31st July 1992, comprising 69% metropolitan and 31% rural crashes. The crashed vehicle database contains information on 572 variables for each crash investigated.

Analysis of the crash configurations on the data base showed that frontal crashes accounted for 56% of all crashed vehicles inspected, side impact 41%, roll-overs 3%, and there were no rear-end collisions included in the sample. While the proportion of frontal collisions was slightly less than that reported among TAC claims for the same period (56% cf 65%, Fildes et al 1991), there were differences in the proportions of side impact (41% cf 14%), rear end (0% cf. 11%), and roll-overs (3% cf. 10%).

Given the focus of this particular report, the analysis will concentrate on the results of those sustaining a head, neck or face injury (readers interested in other aspects of these data are referred to earlier reports by Fildes et al, 1991, 1992, 1994).

2.4 HEAD INJURY CRASHES

Details were available on 353 crashes involving 476 head, neck or face injured occupants. The population characteristics of the head injured and total samples are shown in Table 2.1. Of particular note, there were very few population differences observed between those sustaining a head, neck or face injury with the total sample. This is probably a function of the high proportion of these injuries among the severely injured passenger car occupants (79% of injured occupants sustained a head, neck or face injury during their crash). Clearly, the frequency of these injuries warrants closer consideration of injury countermeasures.

2.4.1 Impact Velocity

The change of velocity on impact (delta-V) was measured using the CRASH3 program provided by NHTSA and the mean and standard deviation values are shown in Table 2.1. In addition, Figure 2.1 shows the speed histograms for the total sample and those involving a head, neck or face injured occupant (a subset of the total sample distribution). Of special importance, the correlation between the two distributions was greatest at the higher velocities illustrating that the likelihood of a head injury was greater in crashes at higher velocities. While it is somewhat reassuring to note that the bulk of head injuries are not occurring at low impact speeds, nevertheless, there are still considerable numbers of them occurring at speeds for which occupants should be protected from this life threatening trauma.

Figure 2.1
Change of velocity on impact (delta-V) for all crashes and those where someone sustained a head, neck or facial injury

Table 2.2
Type of Head, Neck or Face Injury Sustained (n=476 occupants)

TYPE OF INJURY	DRIVERS (n=305)	FLP (n=118)	REAR (n=49)
HEAD			
Contusion	51%	41%	41%
Fracture/dislocation	21	30	14
Laceration	22	20	12
Abrasion	2	3	6
Concussion	2	0	2
Crush	1	2	2
Sprain/strain	0	0	0
NECK			
Laceration	89%	67%	57%
Contusion	71	58	55
Fracture/dislocation	41	39	33
Abrasion	30	35	59
Concussion	0	0	0
Crush	0	0	0
Sprain/strain	0	0	0
FACE			
Fracture/dislocation	14%	19%	12%
Contusion	6	8	14
Sprain/strain	5	5	2
Abrasion	4	3	12
Laceration	2	0	2
Concussion	0	0	0
Crush	0.3	0	0

NB: Figures refer to the percentage of head, face and neck lesions for vehicle occupants who sustained at least 1 head, face or neck injury at any level of severity.

2.4.2 Types of Lesions

The various types of head, neck and facial lesions is shown in Table 2.2. Fractures (dislocations), contusions, lacerations and to a lessor degree, abrasions, were the predominant types of lesions among head, neck and facial injuries. The percentages varied slightly depending on seating position, no doubt influenced to some extent by contact source.

2.4.3 Injury Severity & Seating Position

Table 2.3 shows the severity of injury and probability of sustaining a severe injury by seating position for all occupants and those who experienced a head, neck or facial injury. There were a number of differences between these populations, most noticeably that the head injured group had an Injury Severity Score (ISS) between 10% and 19% higher than the all injured group. This was not too surprising as many of these injuries do tend to be very severe compared to other injury types and are also commonly associated with multiple injuries to other body regions. While the probability of a severe injury decreased with increasing severity, it is somewhat disconcerting that roughly 3 out of 10 hospitalised patients and 4 out of 10 head injured patients had an ISS score greater than 25 (i.e., were quite severely injured and with a moderate to high threat to life).

Table 2.3
Seat Position by Probability and Severity of Injury for Those Sustaining a Head, Neck or Face Injury and for all Injured Occupants in The CVF

SEATING POS'N	OCCUPANTS	AV. ISS*	PROBABILITY OF A SEVERE INJURY		
			AIS>2	ISS>15	ISS>25
All Occupants					
DRIVER	378	24.7	0.65	0.58	0.37
FLP	156	25.8	0.69	0.65	0.37
REAR	67	25.6	0.60	0.52	0.34
Head, Neck or Face Injured Occupants					
DRIVER	304	27.2	0.69	0.64	0.42
FLP	119	30.4	0.79	0.75	0.45
REAR	49	30.4	0.69	0.61	0.43

** Injury Severity Score (ISS) is a generally accepted measure of the overall severity of injury to an vehicle occupant (Baker et al 1980). It is calculated by adding the square of the 3 highest Abbreviated Injury Scores (AIS) recorded for 3 separate body regions injured.*

2.4.4 Head Injuries and Intrusion

Table 2.4 shows the number of head, neck or face injuries by contact source with and without intrusion of that member as well as intrusions where there were no contacts. The instrument panel and door (with its components) were the most commonly intruded and struck components inside the vehicle.

Table 2.4
All Injury Contacts for Head Injured Occupants, With and Without Intrusion

CONTACT SOURCE	*INTRUSION NO CONTACT*		*CONTACT NO INTRUSION*		*INTRUSION WITH CONTACT*	
	DRIVERS	*ALL*	*DRIVERS*	*ALL*	*DRIVERS*	*ALL*
Front Header Rail	*12*	*18*	*3*	*6*	*1*	*1*
Side Rail	*23*	*37*	*1*	*2*	*2*	*5*
Roof	*14*	*29*	*5*	*9*	*16*	*19*
A-pillar	*53*	*76*	-	-	*11*	*19*
B-pillar	*45*	*70*	*4*	*9*	*7*	*13*
Other pillar	-	*5*	*1*	*2*	-	*1*
Instrument Panel	*15*	*18*	*94*	*134*	*74*	*104*
Door (+components)	*25*	*36*	*23*	*33*	*66*	*121*
Floor + toepan	*63*	*89*	*36*	*50*	*55*	*71*

NB: Figures refer to the ***number*** *of intrusions with and without contact by vehicle occupants who sustained at least 1 head, face or neck injury at any level of severity.*

2.4.5 Head Injuries and Ejection

Table 2.5 shows the percentage of head, neck and face injuries sustained with and without the occupant being ejected from the vehicle. Of note, there was a higher likelihood of a head, face and neck injury (including severe injury) with the striking object for those not ejected than those ejected but considerably less likelihood of a contact with the ground. Most of these contacts would probably have been sustained in side impacts on the impacted side. The higher likelihood of injury from the windshield for those contained in the vehicle shows that the path for those ejected was either rarely through the front screen or that they sustained more severe injury from other external sources once ejected.

Table 2.5
Head, Neck or Face Injury Contacts for Head Injured Occupants, With and Without Ejection

CONTACT SOURCE	*CONTACTS WITH EJECTION*			*CONTACTS WITHOUT EJECTION*		
	HEAD	*FACE*	*NECK*	*HEAD*	*FACE*	*NECK*
Windshield	-	*4*	-	*27 (11)*	*53*	*5 (2)*
Back light	-	*4*	*4*	*1*	-	-
Striking object	*13 (13)*	*13 (4)*	*4*	*43 (35)*	*31 (3)*	*9 (3)*
Ground	*74 (35)*	*14*	*6*	*8 (5)*	*5*	*1*

NB: Figures for ALL injuries refer to the ***percentage*** *of head, face or neck injury contacts at any level of severity. Figures in parenthesis show the percentage of severe (AIS>2) injury contacts. There were 125 cases where an occupant contacted these regions without ejection and 23 cases with.*

2.5 INJURY BY SOURCE ANALYSIS

The final analysis undertaken here was to link head, face and neck injuries with their various sources of injury inside and outside the vehicle. The Crashed Vehicle File is particularly useful for undertaking these types of causal analyses.

2.5.1 Source of Injury

The source of injury by seating position findings for those sustaining a head, neck or face injury is shown in Table 2.6. The most frequent components inside the vehicle associated with severe (AIS>2) head injuries to front seat occupants include the steering assembly and the roof for drivers and the instrument panel for front-left passengers (FLP). A- and B-pillars were associated with around 5% of these severe injuries. Header rails, surprisingly, were only involved in 2% and 3% of severe head injuries, probably the result of high seatbelt wearing levels in this country. For rear seat passengers, the most common source of head injury inside the vehicle was the side rail and C-pillar. Interestingly, 1 in 5 of these injuries to front seat occupants were the result of contact with the striking object such as an impacting car or pole in a side collision.

Table 2.6
Points of Contact for Head, Neck or Face Injuries Sustained by Head Injured Occupants

CONTACT	DRIVERS (n=304)		FLP (n=119)		REAR (n=49)	
SOURCE	ALL	(AIS>2)	ALL	(AIS>2)	ALL	(AIS>2)
Windshield	29%	(1%)	45%	(4%)	4%	(2%)
Front Header Rail	5%	(2%)	11%	(3%)	4%	(2%)
Back light	1%	(0%)	0%	(0%)	4%	(0%)
Side Rail	2%	(1%)	3%	(1%)	10%	(8%)
Roof	33%	(17%)	8%	(1%)	8%	(2%)
A-pillar	18%	(5%)	22%	(5%)	0%	(0%)
B-pillar	6%	(4%)	13%	(4%)	2%	(0%)
Other pillar	1%	(0%)	0%	(0%)	10%	(6%)
Instrument Panel	31%	(7%)	113%	(27%)	27%	(2%)
Steering Assy	161%	(20%)	3%	(1%)	0%	(0%)
Side Window	18%	(2%)	30%	(3%)	33%	(2%)
Flying Glass	8%	(0%)	4%	(0%)	2%	(0%)
Door (+components)	17%	(5%)	9%	(1%)	8%	(0%)
Seats + Head Rest.	1%	(0%)	0%	(0%)	20%	(0%)
Other Occupants	7%	(4%)	8%	(4%)	14%	(0%)
Floor + toepan	0%	(0%)	0%	(0%)	6%	(0%)
Seat belt Assy	6%	(1%)	6%	(0%)	12%	(0%)
Striking Object	51%	(22%)	43%	(22%)	37%	(14%)
Ground	19%	(5%)	25%	(8%)	76%	(8%)
Non-Contacts	16%	(6%)	24%	(12%)	16%	(4%)

NB: Figures for ALL injuries refer to the percentage of vehicle occupants who sustained at least 1 head, face or neck injury at any level of severity. Figures in parenthesis show the percentages of serious head, neck or face injury (AIS>2). Averages are the mean number of injuries per occupant.

2.5.2 Injury-Source Analysis by Seating Position

The type of head, neck and facial injuries and the source of injury inside and outside the vehicle for those hospitalised or killed by seating position is shown in Tables 2.7 to 2.9. The main findings from these analyses are noted below.

DRIVERS: The most frequent causes of head and face injury for drivers for both all and severe injuries were from the steering assembly, the striking object, door panels, the roof, and the instrument panel. While neck injuries were less frequent generally, the two most common sources were from the steering wheel and from non-contacts (eg; whiplash). The roof was the most common source of severe neck injury to drivers, albeit in only 2% of cases.

FRONT-LEFT PASSENGERS: Front left passengers sustained frequent head and facial injuries from contacting the instrument panel, front windscreen and header, the striking object, doors and side windows. Common neck injuries occurred from instrument panel and non-contacts, although 3% of severe neck injury cases for these people were the result of contacts with the instrument panel and the striking object.

REAR PASSENGERS: Rear seat passengers had relatively fewer head, neck and facial injuries compared to the front seat occupants. Frequent head and face injury resulted from contact with the side windows (and surrounds), the striking object, seat and head restraint of the seat in front of them, and the ground (there was a higher likelihood that rear seat passengers were unbelted at the time of their collision). A sizeable proportion (10%) of these rear seat passengers, though, suffered a non-contact neck injury of which 4% were severe.

Table 2.7
Drivers Who Sustained a Head, Neck or Face Injury in all Impact Types
(N=304)

Contact source		Head	Face	Neck-Spine	*TOTAL*
Front screen & header	All	5	11	1	***17***
	AIS>2	*(1)*		*(0.3)*	***(1)***
Steering assembly	All	21	36	5	***62***
	AIS>2	*(6)*	*(1)*	*(1)*	***(8)***
Instrument panel	All	6	9	1	***16***
	AIS>2	*(3)*			***(3)***
A-pillar	All	4	3	0.3	***7***
	AIS>2	*(1)*			***(1)***
B-pillar	All	2	1		***3***
	AIS>2	*(2)*			***(2)***
C-pillar	All	1		1	***2***
	AIS>2				***(0)***
Roof side rail	All	1	0.3	0.3	***2***
	AIS>2			*(0.3)*	***(0)***
Roof	All	6	4	3	***13***
	AIS>2	*(3)*		*(2)*	***(5)***
Door panel	All	8	1	1	***10***
	AIS>2	*(1)*			***(1)***
Side windows	All	6	6		***12***
	AIS>2	*(1)*			***(1)***
Floor & toe pan	All				***0***
	AIS>2				***(0)***
Seat & head restraint	All	1			***1***
	AIS>2	*(1)*			***(1)***
Seat belt	All	0.3		4	***4***
	AIS>2				***(0)***
Other occupants	All	2	1		***3***
	AIS>2	*(1)*	*(0.3)*		***(1)***
Striking object	All	10	7	2	***19***
	AIS>2	*(7)*	*(1)*		***(8)***
Ground	All	4	3	1	***8***
	AIS>2	*(1)*			***(1)***
Flying glass	All	0.3	6		***6***
	AIS>2				***(0)***
Non-contact	All	6	0.3	5	***11***
	AIS>2	*(2)*		*(1)*	***(3)***
Other/unknown	All	6	7	1	***14***
	AIS>2	*(1)*		*(0.3)*	***(1)***
TOTALS	***All***	***90***	***96***	***26***	***211***
	AIS>2	***(31)***	***(2)***	***(5)***	***(38)***

Top row figures are the injury/source contact rates per 100 injured occupants for all injury severities. Those in parenthesis equivalent contact rates for severe (AIS>2) injuries. Multiple injuries are included where separate injury sources were invo

Table 2.8
Front-Left Passengers Who Sustained a Head, Neck or Face Injury in all Impact Types (N=119)

Contact source		**Head**	**Face**	**Neck-Spine**	***TOTAL***
Front screen & header	All	8	18	1	***27***
	AIS>2	*(3)*		*(1)*	***(4)***
Steering assembly	All	1	1		***2***
	AIS>2	*(1)*			***(1)***
Instrument panel	All	13	18	6	***37***
	AIS>2	*(8)*		*(3)*	***(11)***
A-pillar	All	4	4	2	***10***
	AIS>2	*(1)*		*(1)*	***(2)***
B-pillar	All	5	3		***8***
	AIS>2	*(2)*			***(2)***
C-pillar	All				***0***
	AIS>2				***(0)***
Roof side rail	All	1	2		***3***
	AIS>2	*(1)*			***(1)***
Roof	All	3	2	1	***6***
	AIS>2	*(1)*			***(1)***
Door panel	All	7	1	2	***10***
	AIS>2	*(1)*			***(1)***
Side windows	All	8	13	1	***22***
	AIS>2	*(2)*			***(2)***
Floor & toe pan	All				***0***
	AIS>2				***(0)***
Seat & head restraint	All				***0***
	AIS>2				***(0)***
Seat belt	All		1	4	***5***
	AIS>2				***(0)***
Other occupants	All	3	3		***6***
	AIS>2	*(3)*			***(3)***
Striking object	All	9	8	4	***21***
	AIS>2	*(7)*		*(3)*	***(10)***
Ground	All	6	3	1	***10***
	AIS>2	*(3)*			***(3)***
Flying glass	All	1	3		***4***
	AIS>2				***(0)***
Non-contact	All	10	1	9	***20***
	AIS>2	*(4)*		*(4)*	***(8)***
Other/unknown	All	7	7		***14***
	AIS>2	*(3)*			***(3)***
TOTALS	***All***	***86***	***88***	***31***	***205***
	AIS>2	***(40)***	***(0)***	***(12)***	***(52)***

Top row figures are the injury/source contact rates per 100 injured occupants for all injury severities. Those in parenthesis a equivalent contact rates for severe (AIS>2) injuries. Multiple injuries are included where separate injury sources were involv

Table 2.9
Rear Passengers Who Sustained a Head, Neck or Face Injury in all Impact Types (N=49)

Contact source		**Head**	**Face**	**Neck-Spine**	***TOTAL***
Front screen & header	All	4	2	2	***8***
	AIS>2	*(4)*			***(4)***
Instrument panel	All	4	4		***8***
	AIS>2				***(0)***
A-pillar	All				***0***
	AIS>2				***(0)***
B-pillar	All		2		***2***
	AIS>2				***(0)***
C-pillar	All	2	4		***6***
	AIS>2	*(2)*			***(2)***
Roof side rail	All	4		2	***6***
	AIS>2	*(2)*		*(2)*	***(4)***
Roof	All	4	2		***6***
	AIS>2	*(2)*			***(2)***
Door panel	All		4		***4***
	AIS>2				***(0)***
Side windows	All	6	12		***18***
	AIS>2	*(2)*			***(2)***
Floor & toe pan	All		4		***4***
	AIS>2				***(0)***
Rear screen & header	All		2	2	***4***
	AIS>2				***(0)***
Seat & head restraint	All		10	2	***12***
	AIS>2				***(0)***
Seat belt	All			8	***8***
	AIS>2				***(0)***
Other occupants	All	4	2		***6***
	AIS>2				***(0)***
Striking object	All	10	8		***18***
	AIS>2	*(4)*			***(4)***
Ground	All	8	10	6	***24***
	AIS>2				***(0)***
Flying glass	All		2		***2***
	AIS>2				***(0)***
Non-contact	All	6		10	***16***
	AIS>2			*(4)*	***(4)***
Other/unknown	All	16	10	2	***28***
	AIS>2	*(2)*			***(2)***
TOTALS	***All***	***68***	***78***	***34***	***180***
	AIS>2	***(18)***	***(0)***	***(6)***	***(24)***

Top row figures are the injury/source contact rates per 100 injured occupants for all injury severities. Those in parenthesis are the equivalent contact rates for severe (AIS>2) injuries. Multiple injuries are included where separate injury sources were involved.

2.5.3 Injury-Source Analysis by Type of Crash

The final set of results shows an injury-source analysis for these occupants, broken down by type of collision and are shown in Tables 2.10 to 2.12.

FRONTAL CRASHES: The most common source of head and face injury in frontal crashes was from contact with the steering assembly, instrument panel and windscreen and header. Neck injuries often occurred from contact with the steering assembly, seatbelt and non-contacts. The most frequent source of severe neck injury was again, non-contact injuries.

SIDE IMPACTS: As expected, the most common sources of head and face injury in side impacts was from the door and side windows, the striking object, from non-contacts and from the B-pillar. The most severe of these resulted from impact with the striking object. 8% of facial injuries were from flying glass, although of relatively minor severity. Neck injuries in side impacts were roughly evenly spread across non-contacts, the striking object and the door.

ROLLOVERS: Occupants in rollovers commonly sustained head and face injury from the roof, the ground, the side windows and roof side rails. Once more, there was a relatively high level of facial injury from flying glass as well as from the front windscreen and header rail. An alarming 20% of these occupants suffered a severe neck injury in these crashes while 13% sustained a neck injury (low severity) from the seatbelt during the crash.

Table 2.10
Occupants Who Sustained a Head, Neck or Face Injury in a Frontal Impact
(N=260)

Contact source		**Head**	**Face**	**Neck-Spine**	***TOTAL***
Front screen & header	All	8	20	2	***29***
	AIS>2	*(3)*	*(0)*	*(0)*	***(3)***
Steering assembly	All	25	41	6	***71***
	AIS>2	*(7)*	*(1)*	*(1)*	***(9)***
Instrument panel	All	12	16	3	***32***
	AIS>2	*(6)*	*(0)*	*(1)*	***(7)***
A-pillar	All	5	5	0	***10***
	AIS>2	*(1)*	*(0)*	*(0)*	***(1)***
B-pillar	All	0	0	0	***0***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
C-pillar	All	0	0	0	***0***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Roof side rail	All	0	0	0	***0***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Roof	All	2	1	0	***3***
	AIS>2	*(1)*	*(0)*	*(0)*	***(1)***
Door panel	All	0	0	0	***0***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Side windows	All	0	2	0	***2***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Floor & toe pan	All	0	1	0	***1***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Seat & head restraint	All	0	2	0	***2***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Seat belt	All	0	0	6	***6***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Other occupants	All	1	0	0	***2***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Striking object	All	2	2	0	***5***
	AIS>2	*(1)*	*(0)*	*(0)*	***(1)***
Ground	All	2	2	0	***4***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Flying glass	All	0	3	0	***3***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Non-contact	All	5	0	8	***14***
	AIS>2	*(0)*	*(0)*	*(2)*	***(2)***
Other/unknown	All	5	6	0	***12***
	AIS>2	*(1)*	*(0)*	*(0)*	***(2)***
TOTALS	***All***	***68***	***101***	***27***	***197***
	AIS>2	***(20)***	***(1)***	***(5)***	***(27)***

Top row figures are the injury/source contact rates per 100 injured occupants for all injury severities. Those in parenthesis are the equivalent contact rates for severe (AIS>2) injuries. Multiple injuries are included where separate injury sources were involved.

Table 2.11
Occupants Who Sustained a Head, Neck or Face Injury in a Side Impact
(N=182)

Contact source		Head	Face	Neck-Spine	*TOTAL*
Front screen & header	All	2	2	1	***4***
	AIS>2	*(1)*	*(0)*	*(1)*	***(1)***
Steering assembly	All	0	1	1	***2***
	AIS>2	*(0)*	*(0)*	*(1)*	***(1)***
Instrument panel	All	2	4	1	***7***
	AIS>2	*(1)*	*(0)*	*(0)*	***(1)***
A-pillar	All	3	1	1	***4***
	AIS>2	*(1)*	*(0)*	*(1)*	***(1)***
B-pillar	All	7	3	0	***10***
	AIS>2	*(4)*	*(0)*	*(0)*	***(4)***
C-pillar	All	1	1	1	***2***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Roof side rail	All	1	1	1	***3***
	AIS>2	*(1)*	*(0)*	*(1)*	***(2)***
Roof	All	4	4	1	***9***
	AIS>2	*(3)*	*(0)*	*(1)*	***(3)***
Door panel	All	17	3	3	***23***
	AIS>2	*(2)*	*(0)*	*(0)*	***(2)***
Side windows	All	13	16	1	***30***
	AIS>2	*(2)*	*(0)*	*(0)*	***(2)***
Floor & toe pan	All	0	0	0	***0***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Seat & head restraint	All	1	0	0	***1***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Seat belt	All	1	1	2	***3***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Other occupants	All	4	3	0	***7***
	AIS>2	*(3)*	*(1)*	*(0)*	***(3)***
Striking object	All	19	13	4	***35***
	AIS>2	*(13)*	*(1)*	*(2)*	***(15)***
Ground	All	4	4	2	***9***
	AIS>2	*(1)*	*(0)*	*(0)*	***(1)***
Flying glass	All	1	8	0	***9***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Non-contact	All	10	0	5	***15***
	AIS>2	*(5)*	*(0)*	*(2)*	***(7)***
Other/unknown	All	12	12	2	***26***
	AIS>2	*(2)*	*(0)*	*(0)*	***(2)***
TOTALS	***All***	***101***	***75***	***23***	***198***
	AIS>2	***(37)***	***(1)***	***(7)***	***(45)***

Top row figures are the injury/source contact rates per 100 injured occupants for all injury severities. Those in parenthesis are the equivalent contact rates for severe (AIS>2) injuries. Multiple injuries are included where separate injury sources were involved.

Table 2.12
Occupants Who Sustained a Head, Neck or Face Injury in a Rollover Crash (N=15)

Contact source		**Head**	**Face**	**Neck-Spine**	***TOTAL***
Front screen & header	All	7	13	0	***20***
	AIS>2	*(7)*	*(0)*	*(0)*	***(7)***
Steering assembly	All	0	0	0	***0***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Instrument panel	All	0	0	0	***0***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
A-pillar	All	0	0	0	***0***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
B-pillar	All	0	0	0	***0***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
C-pillar	All	7	7	0	***13***
	AIS>2	*(7)*	*(0)*	*(0)*	***(7)***
Roof side rail	All	13	7	0	***20***
	AIS>2	*(7)*	*(0)*	*(0)*	***(7)***
Roof	All	47	20	40	***107***
	AIS>2	*(0)*	*(0)*	*(20)*	***(20)***
Door panel	All	0	7	0	***7***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Side windows	All	27	20	0	***47***
	AIS>2	*(7)*	*(0)*	*(0)*	***(7)***
Floor & toe pan	All	0	0	0	***0***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Seat & head restraint	All	0	0	0	***0***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Seat belt	All	0	0	13	***13***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Other occupants	All	0	0	0	***0***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Striking object	All	7	7	0	***13***
	AIS>2	*(7)*	*(0)*	*(0)*	***(7)***
Ground	All	40	27	0	***67***
	AIS>2	*(13)*	*(0)*	*(0)*	***(13)***
Flying glass	All	0	13	0	***13***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Non-contact	All	0	0	0	***0***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
Other/unknown	All	7	0	0	***7***
	AIS>2	*(0)*	*(0)*	*(0)*	***(0)***
TOTALS	***All***	***153***	***120***	***53***	***327***
	AIS>2	***(47)***	***(0)***	***(20)***	***(67)***

Top row figures are the injury/source contact rates per 100 injured occupants for all injury severities. Those in parenthesis are the equivalent contact rates for severe (AIS>2) injuries. Multiple injuries are included where separate injury sources were involved.

2.6 SUMMARY OF HEAD INJURY RESULTS

The main findings from the head, neck and face injury analysis can be summarised as follows.

1. Head, neck and face injuries are relatively frequent among those hospitalised or killed in passenger car crashes in this country (80% of these people sustained such an injury).

2. While the likelihood of a head, neck or face injury is higher at higher crash speeds, there is still a considerable number of them occurring at speeds for which occupants should be protected.

3. Fractures, contusions, lacerations and abrasions were the most common form of head injury lesions. While some of these are relatively minor injuries, others are more severe and can be life threatening.

4. Drivers frequently sustained head injury from contact inside the vehicle with the steering assembly, door panel, instrument panel, roof, and side window. Front left passenger head injuries were associated with instrument panel, windscreen, side window, and door panel contacts.

5. Contacts with A- and B-pillars and header and side rails were not frequently involved in head injuries to front seat occupants, probably because of the high seat belt wearing rates in this country.

6. Rear seat passengers sustained a lower proportion of head injuries overall than front seat passengers, involving mainly side windows and non-contacts.

7. There were a sizeable number of head, neck and face injuries to occupants of all seating positions from contacts with the impacting object and the ground. This was especially so in side impacts and rollovers.

8. The instrument panel and the door were frequently struck in crashes where intrusion occurred. The probability of a contact with these components was much higher with than without intrusion.

9. There were many more head, neck and facial injuries (including severe ones) when the occupant was ejected during the crash. For those not ejected, there were more contacts with the windshield and the striking object, albeit less frequently.

10. While front seat airbags are likely to lead to a marked decrease in these injuries especially among front seat occupants, there is still considerable scope for further reducing these life threatening injuries using other (additional) vehicle safety countermeasures.

Chapter 3

In Depth Analysis of Brain Injury Cases

This section presents a detailed analysis of factors related to the occurrence of brain injury in three samples of crash involved car occupants studied by the NHMRC Road Accident Research Unit since 1983. On a case by case basis, selected characteristics of the injury to the brain are related to characteristics of the impact to the head and the object struck to identify those cases in which the provision of some means of energy absorption might reasonably be expected to prevent, or significantly reduce the severity of the injury to the brain in a similar crash.

When the object struck by the head is not known, as is often the case when an occupant is wholly or partially ejected from the car, the nature and severity of the injury to the head, and particularly the brain, is used as the basis for the assessment of the likely benefits in terms of improved outcome from the provision of padding materials. The possible effects of other head injury countermeasures such as airbags, for example, have not been considered.

3.1 METHOD OF INVESTIGATION

3.1.1 Case Selection

Two samples were investigated in the course of an on-going study of brain injury mechanisms in road crashes. The first of these comprises car occupants who were fatally injured and who sustained a brain injury, although it was not necessarily the cause of death.

The second sample from the study of brain injury mechanisms consists of injured car occupants who were admitted to neurosurgical care at the Royal Adelaide Hospital or the Adelaide Children's Hospital.

A third sample of cases was drawn from car occupants who were injured in rural road crashes to which an ambulance was called. Each of the crashes was investigated at the scene by a member of the NHMRC Road Accident Research Unit before the vehicles had been moved. The cases selected from this sample all had evidence of some degree of brain injury, although it was often of minor severity.

It should be noted that this investigation is based solely on cases in which a car occupant sustained a discernible brain injury. Therefore it is not possible to estimate the risk of a crash-involved car occupant sustaining a brain injury from the data presented.

3.1.2 Rating Brain Injury Severity

The severity of the brain injury in each case was assigned to one of three categories: minor, moderate or severe, according to the following criteria:

For non-fatal cases:

Minor:	Evidence of concussion or a period of unconsciousness,
Moderate:	Prolonged unconsciousness, usually resulting in some degree of permanent neurological impairment, and
Severe:	Brain injury of a severity likely to be unsurvivable. (There were no such cases in the non-fatal sample.)

For the fatal cases:
Not all of the fatally injured occupants had a fatal brain injury. Brain injury severity was therefore assessed according to the cause or causes of death as determined at autopsy by the forensic

pathologist and the nature and extent of the brain lesions identified by neuropathological examination.

24

3.1.3 Impact Location on the Head

All of the cases selected had an identifiable point of impact on the head. In cases in which there was more than one impact to the head the location was taken to be the point of the more significant impact.

The location of the impact on the head in the fatal cases was determined by a RARU investigator at the autopsy.

3.1.4 Object Struck by the Head

A detailed inspection was made of the vehicle or vehicles involved and the crash scene in an attempt to determine the object associated with the sole, or main, impact to the head. This inspection was performed with knowledge of the nature of the scalp lesion resulting from the impact. In the absence of evidence of a head impact with an identifiable object, the object struck is listed as unknown.

3.1.5 Effect of Padding on Outcome

In each case an assessment was made of whether reducing the severity of the head impact would have changed the outcome of the crash in terms of the level of eventual recovery or otherwise from the injuries sustained. It was assumed that the circumstances of the crash were unchanged apart from the provision of padding material either on the part of the car that was struck by the head or in the form of protective headwear.

The effectiveness of both padding and protective headwear in fatal crashes is limited by at least two factors. In some fatal crashes the force of the impact was so great that no amount of padding of any kind would have prevented fatal head injuries. In many of the other fatal cases, the occupants died from, or would have died from, a fatal injury or injuries to another body region/s even if the head could have been perfectly protected. In fact, 44 (59.5 per cent) of the 74 fatal cases had a fatal injury to another body region.

In non fatal cases the presence of injuries to other body regions was also taken into account in estimating the likely effect that head protection could have had on the eventual outcome.

3.2 RESULTS

In total, 117 cases met the above selection criteria. Seventy four (63%) of the 117 cases were fatal.

3.2.1 Characteristics of the Cases by Outcome

The characteristics of the cases are summarised in Table 3.1 in terms of age, sex, seated position, belt use and ejection, together with whether the outcome was fatal or non-fatal.

There were no meaningful differences between the fatal and non-fatal cases by either age or sex. There was a higher percentage of fatal cases who were more than 75 years of age, as would be expected because case fatality rates are higher for the elderly, but the numbers of cases were very small in this age group.

More than 80 per cent of the injured occupants listed in Table 3.1 were seated in the front seat and most of them were drivers. There were more occupants who were wearing a seat belt at the time of their crash than those who were not, in both the fatal and non-fatal groups. However, the belt wearing rate was very much lower than was seen in surveys of belt use in the general population of car occupants. For example, a survey based on the capital city and selected rural areas of South Australia in 1988 yielded an estimated belt wearing rate of 85 per cent (Rungie and Trembath, 1988).

There was a higher percentage of fatal than non-fatal cases for which belt wearing could not be reliably established. This was partly due to the severity of the damage to the vehicles in some of the fatal cases but it is likely that in most of the cases for which belt wearing is listed as "unknown" the belt was not worn.

The frequency of ejection from the car was greater among the fatally injured cases, which is consistent with the well established increased risk of sustaining a severe or fatal injury if ejected.

The higher proportion of fatal than non-fatal cases involved in crashes in 60 km/h speed limit zones was primarily a consequence of most of the latter group being drawn from the study of rural crashes on roads having a speed limit of 80 km/h or greater.

Table 3.1
Characteristics of the Cases by Outcome

Variable	**Outcome**		(Column %)
	Fatal	**Non-Fatal**	**Total**
Age (years)			
0-15	9.5%	9.3%	9.4%
16-30	54.1	48.8	52.1
31-45	14.9	20.9	17.1
46-60	8.1	14.0	10.3
61-75	5.4	4.7	5.1
76+	8.1	2.3	6.0
Sex			
Male	68.9	72.1	70.1
Female	31.1	27.9	29.9
Seated position			
Driver	54.1	60.5	56.4
Front centre	1.4	-	0.9
Front left	33.8	20.9	29.1
Rear right	2.7	9.3	5.1
Rear centre	-	4.7	1.7
Rear left	8.1	4.7	6.8
Seatbelt worn			
Yes	40.5	48.8	43.6
Probably yes	5.4	2.3	4.3
Probably no	8.1	7.0	7.7
No	23.0	39.5	29.9
No belt available	1.4	-	-
Unknown	21.6	2.3	14.5
Ejection			
No	87.8	95.3	90.6
Partial	2.7	-	1.7
Complete	9.5	4.7	7.7
Speed limit (km/h)			
60	32.4	20.9	28.2
80	16.2	11.6	14.5
100	9.5	7.0	8.5
110	41.9	60.5	48.7
Total: Row %	63.2	36.8	100.0
No.of cases	74	43	117

The year of manufacture of the case vehicles ranged from 1966 to 1990 with both the mean and the median year being 1977. The age of cars in use in Australia has not changed greatly over the past decade. It has clear implications for the rate at which improvements in the crashworthiness of new cars can be expected to benefit the whole population of car occupants.

3.2.2 Head Impact and Injury by Outcome

The locations of the impact points on the head are grouped into five categories shown in Table 3.2, with the boundaries between the zones being at 45 degrees to the fore and aft axis of the head as viewed from above, and the fifth category being for impacts on the vertex.

More than 85 per cent of the impacts were to the front or sides of the head in both the fatal and non-fatal cases (Table 3.2). There was a higher percentage of impacts to the sides of the head among the fatal cases. This difference is statistically significant (Chi square $_{1\ d.f.}$ = 4.11, $p< 0.05$) but no allowance has been made for possible differences in the severity of the impacts to the head in the two outcome groups.

Table 3.2
Head Impact and Injury by Outcome

Variable	**Outcome**		(Column %)
	Fatal	**Non-Fatal**	**Total**
Impact on head			
Front	41.9%	65.1%	50.4%
Left	17.6	14.0	16.2
Right	25.7	9.3	19.7
Rear	12.2	4.7	9.4
Top	2.7	7.0	4.3
Skull fracture			
Yes	59.5	34.9	50.4
No	40.5	65.1	49.6
Brain injury			
Minor	21.6	74.4	41.0
Moderate	12.2	25.6	17.1
Severe	66.2	-	41.9
Total: Row %	63.2	36.8	100.0
No. of cases	74	43	117

Skull fracture was proportionally almost twice as common in the fatal group, mainly because 70 per cent of the non-fatal cases were taken from the rural crash study files. The case selection criteria for that study included only a requirement that an ambulance be called to the scene of the crash. Although those criteria are modified here by the selection of cases who had evidence of injury to the brain, many of those cases of brain injury were of minor severity.

The definition of brain injury severity naturally resulted in a high percentage (66.2%) of the fatal cases being rated as severe. Brain injury was in fact the sole cause of death in most (61.2%) of these severe cases. In the cases in which death was not thought to have been due to injury to the brain, most (68%) had a fatal injury to only one body region, with the remainder having multiple fatal injuries to body regions other than the head.

The ratio of minor to moderate brain injury severity among the non-fatal cases was higher than for the fatal cases. Once again, this was largely a consequence of the case selection criteria for the rural road crash study, as noted above.

3.2.3 Brain Injury Severity

The severity of the brain injury sustained by each occupant was assigned one of three levels, as noted above. The distribution of the variables listed in Table 3.1 is shown in Table 3.3 by brain injury severity. As noted above, the number of cases in the various categories is often small, and no attempt has been made to control for the severity of the impact to the head.

There was little evidence of a relationship between brain injury severity and seated position. Although seat belt wearing appears to be negatively associated with brain injury severity in Table 3.3, in most cases in which seat belt wearing is listed as "unknown" it is likely that the belt was not worn, as noted earlier. If that possibility is allowed for, there is no apparent association between belt wearing and brain injury severity.

Table 3.3
Characteristics of the Cases by Brain Injury Severity

Variable	**Brain Injury Severity** (column percentages)		
	Minor	**Moderate**	**Severe**
Sex			
Male	64.6%	66.7%	76.0%
Female	35.4	33.3	24.0
Age (years)			
0-15	6.3	9.5	12.0
16-30	45.8	57.1	54.0
31-45	22.9	14.3	16.0
46-60	12.5	9.5	8.0
61-75	8.3	-	4.0
76+	4.2	9.5	6.0
Seated position			
Driver	62.5	47.6	54.0
Front left	22.9	33.3	34.0
Front centre	-	-	2.0
Rear right	4.2	9.5	4.0
Rear left	8.3	4.8	6.0
Rear centre	2.1	4.8	-
Seatbelt worn			
Yes	45.8	33.3	46.0
Probably yes	4.2	9.5	4.0
Probably no	6.3	14.3	6.0
No	37.5	28.6	20.0
No belt available	2.9	-	-
Unknown	4.2	14.3	24.0
Ejection			
No	91.7	90.5	88.0
Partial	4.2	-	-
Complete	4.2	9.5	12.0
Speed limit (km/h)			
60	12.5	55.0	32.7
80	12.5	20.0	14.3
100	8.3	10.0	8.2
110	66.7	15.0	44.9
Total: Row %	40.3	17.6	42.0
No. of cases	48	20	49

The apparently negative association between the speed limit at the crash site and brain injury severity is primarily a consequence of the fact that the sample of “out of town” rural crashes to which an ambulance was called contained many cases of comparatively minor injuries, as noted previously.

The presence of an impact on the front of the head, compared to elsewhere on the head, was negatively associated with the severity of brain injury (Table 3.4). This probably reflects differences in the three samples of cases on which this study is based as much as any possibly greater tolerance of the brain to an impact to the front rather than to the side of the head. The number of cases of occipital, or rear, impact was too small to discern any meaningful relationship with brain injury severity.

Table 3.4
Head Impact and Skull Fracture by Brain Injury Severity

Variable	**Brain Injury Severity** (Column percentages)		
	Minor	**Moderate**	**Severe**
Skull fracture			
Yes	27.1	38.1	78.0
No	72.9	61.9	22.0
Impact on head			
Front	66.7	47.6	34.0
Left	8.3	28.6	18.0
Right	12.5	14.3	32.0
Rear	6.3	4.8	14.0
Top	6.3	4.8	2.0
Total: Row %	40.3	17.6	42.0
No. of cases	48	20	49

3.2.4 Location of Impacts on the Head

Figures 3.1 and 3.2 show the location of impacts on the head for the non-fatal and fatal cases, respectively. Note that the fatal injury was not necessarily to the head.

There was a higher proportion of the impacts to the face compared to the cranium in the non-fatal cases. The impacts also tended to be distributed on the front and sides of the head.

Figures 3.3 to 3.5 show the location of the sole or major impact to the head by the severity of the resulting brain injury. It can be seen once again that the impacts are concentrated on the front of the head, and particularly on the forehead, as was indicated by the data in Tables 3.2 and 3.4. The proportion of impacts on the face compared to the cranium decreases markedly with increasing brain injury severity.

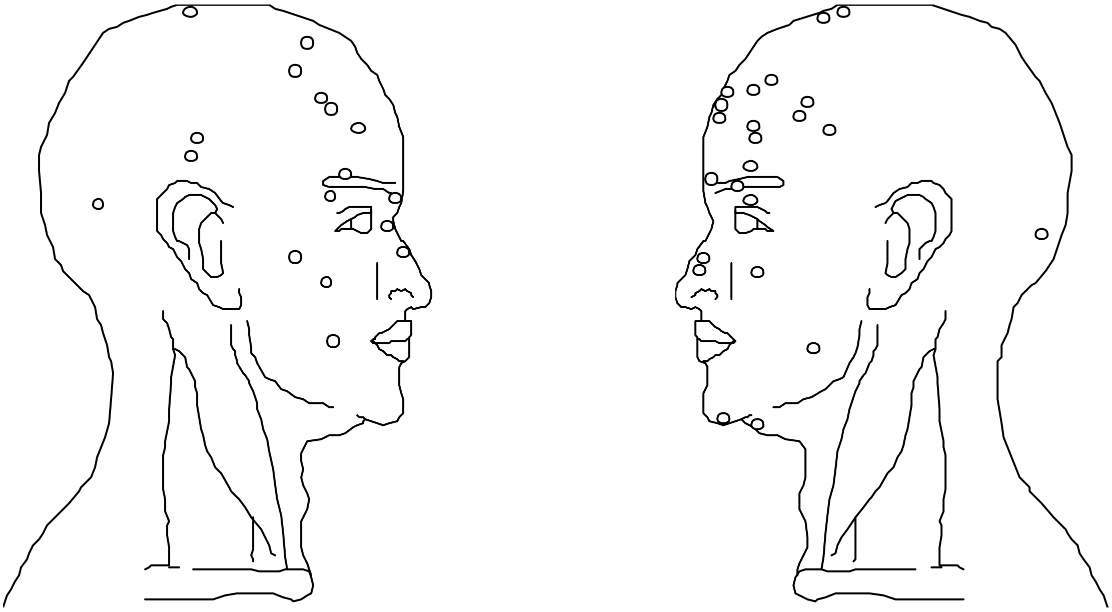


Figure 3.1
Location of car occupant head impacts in cases of non-fatal injury.

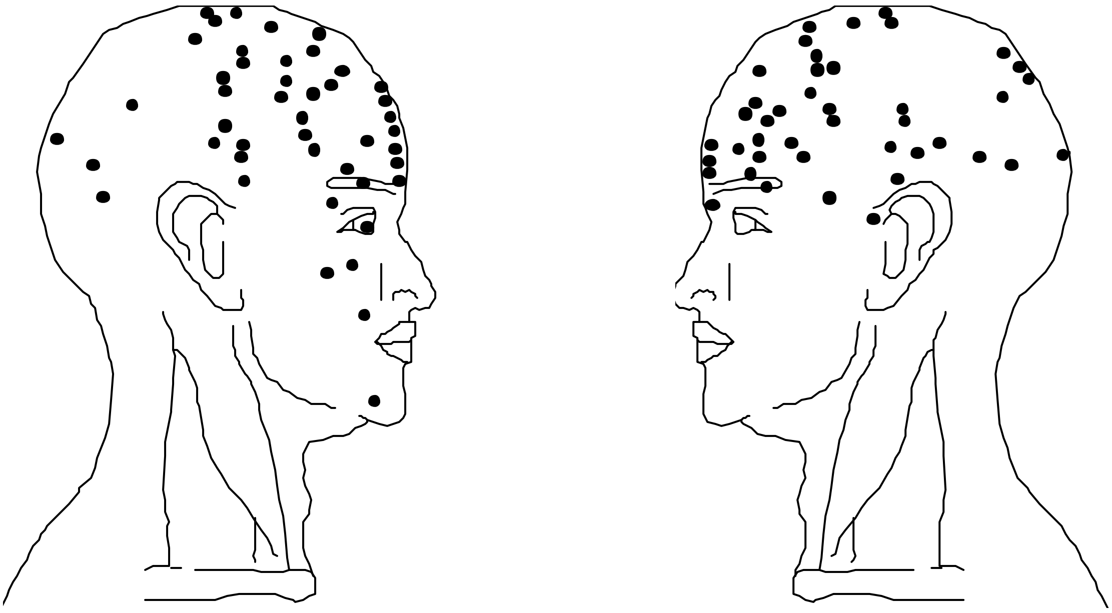


Figure 3.2
Location of car occupant head impacts in cases of fatal injury.

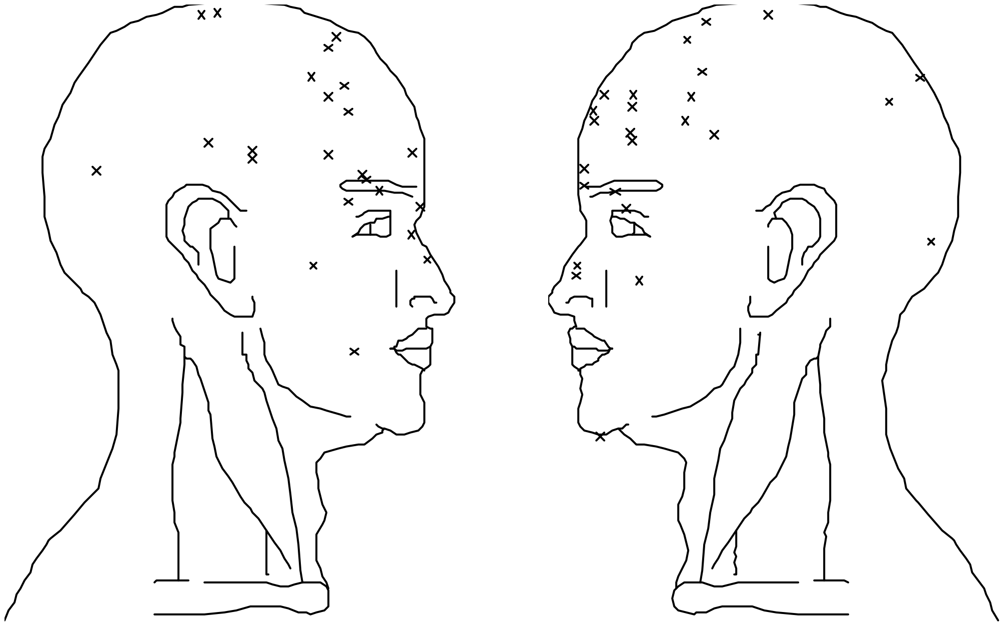


Figure 3.3
Location of car occupant head impacts in cases of minor brain injury.

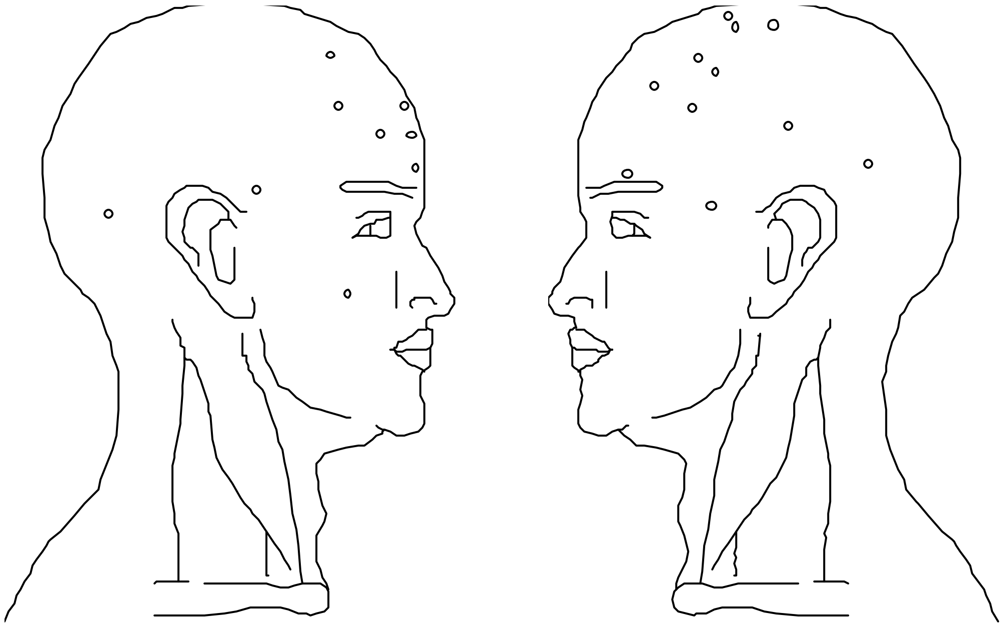


Figure 3.4
Location of car occupant head impacts in cases of moderate brain injury

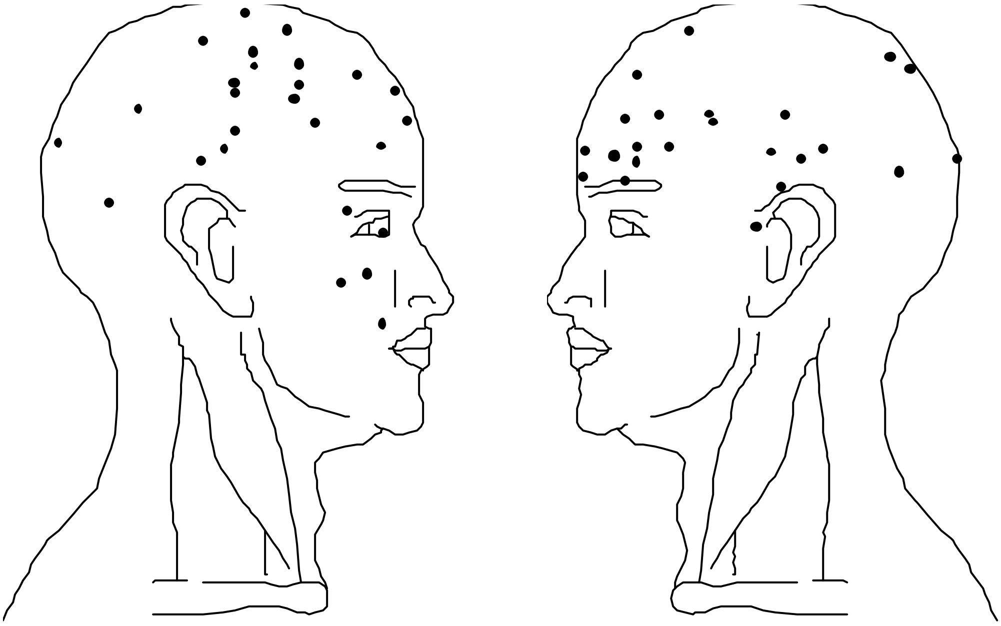


Figure 3.5
Location of car occupant head impacts in cases of severe brain injury.

3.2.5 Objects Struck by the Head

The identifiable objects struck by the head included parts of the interior of the car, other objects outside the car, the ground and another occupant. In just over 30 per cent of the cases, although there was evidence of an impact to the head, we were not able confidently to identify the object struck. The objects struck are related to the severity of the resulting brain injury in Table 3.5.

Table 3.5
Objects Struck by the Head by Brain Injury Severity

Object Struck	**Brain Injury Severity** (Number of Cases)		
	Minor	**Moderate**	**Severe**
Windscreen	6	2	1
Steering assembly	7	1	2
Instrument panel	3	1	3
A-pillar*	1	1	3
B-pillar*	1	3	4
C-pillar*	-	2	-
Roof side rail*	-	2	2
Roof*	7	1	6
Side window	2	1	-
Door frame	-	3	4
Striking object	1	-	10
Other occupant	-	-	1
Other/unknown	20	3	13
Number of cases	48	20	49

*Note: Objects which are included in the definition of the "upper interior" of the passenger compartment are marked with an asterisk.

The relatively high frequency of head impacts with the roof of the car is due partly to marked deformation of the passenger compartment in side impact collisions, with and without rollover. In some cases the part of the roof struck by the head had been forced in and downwards by a lateral impact with a pole or tree, and so the roof panel was interposed between the occupant's head and the intruding object.

This draws attention to the possible benefit to be gained from padding the interior surface of the roof panel, even though the panel itself may deform readily when struck by the head of an occupant. There will, of course, always be some cases in which a practicable thickness of padding will not be able to absorb enough of the energy of what is effectively a head impact with a pole to modify the outcome to any meaningful extent.

The objects marked with an asterisk in Table 3.5 are those which are included in the definition of the "upper interior" of the passenger compartment in the amendments to the relevant United States Federal Motor Vehicle Safety Standard (FMVSS 201) which requires a specified level of energy absorption in the event of a head impact. These objects accounted for 40 per cent of the identified head impact locations in this study. When the "unknown object struck" cases are taken into account, this percentage could be reduced to about 30 per cent.

As noted previously, all of the cases selected for this study had some degree of injury to the brain, so the data presented here should not be taken as an indication of the risk of the head striking the upper interior.

3.3 REDUCING HEAD IMPACT SEVERITY: EFFECT ON RECOVERY FROM INJURY

An attempt was made to quantify the extent to which the maximum practicable reduction of the severity of the head impact would have changed the outcome for a range of fatal and non-fatal cases investigated by RARU. The results by fatal and non-fatal are shown in Table 3.6 and the results for the three severities of brain injury are shown in Table 3.7.

Table 3.6
Effect of Reducing the Head Impact Severity on Recovery from Injury
(by Fatal / Non-Fatal)

Beneficial Effect	**Observed Outcome** (Column percentages)		
	Fatal	**Non-Fatal**	**Total**
Yes	4.1%	25.6%	12.0%
Probably	13.5	27.9	18.8
Possibly	14.9	16.3	15.4
Unlikely	16.2	23.3	18.8
No	51.4	7.0	35.0
Number of cases	74	43	117

Collapsing the "beneficial effect" categories into "probably" and "unlikely" by splitting at the mid point of "possibly" indicates that reducing the severity of the head impact may have been likely to have had a beneficial effect on recovery from injury in about 25 per cent of the cases in which the observed outcome was a fatality. This means that the predicted effect is a 25 per cent reduction in fatalities. Of course, the residual disabilities among the additional survivors may still have been severe.

This may appear to be an unexpectedly small reduction but it should be remembered that there were fatal injuries to other body regions in some cases. It was also often difficult to allocate a realistic probability of survival to a case involving a clearly fatal brain injury and a very severe injury to another body region. If the severity of the brain injury were to have been substantially reduced by reducing the head impact severity, it was by no means clear that the injury to the other body region would not have been a threat to life.

35

It is therefore not surprising that the probable effect of reducing the severity of the head impact appeared likely to be greater for the non-fatal cases. Given the maximum realistically possible reduction in head impact severity, 62 per cent of the cases may have experienced a beneficial effect on outcome in terms of recovery from injury

Table 3.7
Effect of Reducing the Head Impact Severity on Outcome
(by Brain Injury Severity)

Beneficial Effect	**Observed Brain Injury Severity** (Column percentages)		
	Minor	**Moderate**	**Severe**
Yes	12.5%	25.0%	6.1%
Probably	16.7	20.0	20.4
Possibly	14.6	10.0	18.4
Unlikely	25.0	5.0	18.4
No	31.3	40.0	36.7
Number of cases	48	20	49

Assessing the likely effect of reducing the head impact severity for each of the three categories of observed brain injury severity indicated that the outcome might have been improved in 37 per cent of the cases of minor brain injuries, 50 per cent of moderate brain injuries and 36 per cent of severe brain injuries. Once again, it is important to remember that most of these occupants had injuries to other body regions as well as to the head. In some cases the other injuries were the main determinant of the eventual outcome.

3.4 PADDING THE UPPER INTERIOR

3.4.1 Estimated Effect on Outcome

An assessment was made of whether the addition of padding to the part of the vehicle struck (in cases in which that part could be padded) would have been likely to have changed the outcome of the crash. The results by fatal and non-fatal head injury are shown in Table 3.8 and the results for the three severities of brain injury are shown in Table 3.9.

Table 3.8
Effect of Padding the Upper Interior of the Car on Outcome
(by Fatal / Non-Fatal)

Beneficial Effect	**Observed Outcome** (Column percentages)		
	Fatal	**Non-fatal**	**Total**
Yes	-	9.1	3.0
Probably	-	54.5	18.2
Possibly	9.1	36.4	18.2
Unlikely	40.9	-	27.3
No	50.0	-	33.3
Number of cases	22	11	33

There was a head impact with an identifiable object in 81 cases (69.2%) out of the 117 in the study. Of these, 69 were with the structure of the occupant's car and 33 of the 69 involved a part of the car that is relevant to the proposed amendment to FMVSS 201, viz: the roof, the roof side rails, and the pillars of the car.

The low number of cases with known head impact locations on parts of the car that can be padded makes interpretation of the Tables difficult. However, they indicate that padding would be likely to have a much greater effect on non-fatal cases than fatal cases. The effect is also likely to be greatest for moderate brain injury followed by minor brain injury and appears likely to have very little benefit for severe brain injury.

Table 3.9
Effect of Padding the Upper Interior of the Car on Outcome
(by Brain Injury Severity)

Beneficial Effect	**Observed Brain Injury Severity** (Column percentages)		
	Minor	**Moderate**	**Severe**
Yes	11.1	-	-
Probably	11.1	55.6	-
Possibly	33.3	11.1	13.3
Unlikely	11.1	11.1	46.7
No	33.3	22.2	40.0
Number of cases	9	9	15

Following the procedure outlined above, it is predicted that padding would be likely to change the outcome in 34 per cent of cases of minor brain injuries, 61 per cent of moderate brain injuries and 7 per cent of severe brain injuries. These estimates apply to case vehicles in which upper interior padding could have been placed at the primary head impact site.

To obtain an overall effectiveness measure, regardless of the object struck by the head, the above percentages are multiplied by the proportion of cases that involve an impact with an area that would be padded under compliance with FMVSS 201. Based on the 81 cases for which the object struck by the head was identified, this proportion is 33/81. The result is that the outcome of a crash would be expected to be improved meaningfully by padding of the upper interior in 16 per cent of minor brain injury cases, 25 per cent of moderate brain injury cases and 3 per cent of severe brain injury cases.

The corresponding calculation for fatal versus non-fatal outcome yields a predicted overall effectiveness of upper interior padding in effecting a meaningful improvement in outcome of 33 per cent for non-fatal cases and 2 per cent for fatal cases.

The estimates in this paper of the likely effectiveness of padding the upper interior of the vehicle involve two notable assumptions. The first assumption is that in about 40 per cent of the cases in which the object struck by the head was not identified it was actually part of the upper interior of the car.

The second, and more important, assumption is that the sample of cases considered here is representative of the whole population of cases of brain injured car occupants in Australia. It is likely that such bias that exists is towards the more severe cases of brain injury. Because padding of the upper interior of the car is estimated to be more likely to be beneficial in cases in which the brain injury is less severe, it is probable that the above estimates of the likely overall effectiveness of padding the upper interior of the car in reducing the severity of brain injury and improving the outcome are conservative.

3.4.2 Comparison with NHTSA Effectiveness Estimates

The apparently greater benefit for non-fatal cases is not consistent with predictions of the probable effect of the amendment to FMVSS 201. The Final Economic Assessment for Upper Interior Head Protection contains estimates which indicate a much greater effect on fatalities (approximately a 40 per cent reduction) than on AIS 2-5 injuries (approximately a 2.5 per cent reduction) (NHTSA, 1995). The difference between the NHTSA assessment and the one presented here may be due partly to differences in the characteristics of the samples of injured occupants on which the assessments were based.

The NHTSA sample comprised occupants with a head injury that was more severe than any injury to another body region and was caused by contact with the upper interior of the car. The samples examined here comprised fatally injured car occupants and others who had sustained a head injury, without reference in the selection process to other injuries. The number of cases on which the assessment of the effect of padding the upper interior is based is also very small.

It is more likely, however, that the difference arose from the very different methods of estimating the effect on outcome. The NHTSA estimates are based on a derived association between the severity of a head injury and the probable value of the Head Injury Criterion (HIC). Insofar as padding the upper interior changes the HIC level for a given impact, the corresponding change in injury severity, and fatal/non fatal injury, can be calculated.

In the study reported in this section, the likelihood that padding would modify the outcome is based on a case by case consideration of the characteristics of the injury to the brain and the skull, in the context of the characteristics of the object struck by the head and the presence and severity of injuries to any other body regions.

The assessment procedure adopted by NHTSA (1995) took into account what was referred to as the “trickle down effect”, referring to the displacement of fatal or very severe head injuries to less severe categories, thereby reducing the overall effectiveness of padding the upper interior at those lower injury severity levels. Furthermore, it was assumed, based on physical testing, that some cars would have some degree of energy absorption in the existing trim on the upper interior, possibly sufficient to substantially reduce the incidence of minor head injuries or even to comply with the new requirements contained in the amendment to FMVSS 201. In the latter case, enactment of the amendment would not change the pattern or incidence of head injury in those cars.

In the present study the predicted reduction in fatal head injuries is so small that any trickle down effect from the prevention of fatal brain injury would also be small. That is not so for the predicted effect of padding on brain injuries of minor severity because the reduction of 25 per cent in cases of moderately severe brain injury would inevitably shift some of those cases to the minor brain injury severity category. The percentage reductions listed in the preceding section refer to changes in given injury severity or outcome categories and, as such, do not make any allowance for this effect.

3.5 PROTECTIVE HEADWEAR

The term “protective headwear” is used in this report to emphasise that a meaningful level of protection against brain injury can be provided by the use of a simple head band by car occupants. A lightweight soft shell pedal cycle helmet would provide an even greater level of protection.

3.5.1 Protective Head Band

Soft shell pedal cycle helmets are commonplace but the concept of a protective headband in the present context is new. Figure 3.6 shows the type of head band that is envisaged. A strip of energy absorbing plastic foam covers the forehead and extends around to the sides of the head in front of the ears. A plastic foam (Confor foam) is commercially available which is very soft to the touch but which is almost rigid at high rates of loading, and therefore can absorb some of the energy of an impact to the head. The band is held in place by an elastic or adjustable strap.

The head band shown in Figure 3.6, which we refer to as the RARU head band, would play a protective role in 44 per cent of the head impacts recorded in this study. The percentage of impact locations covered is almost the same regardless of the severity of the resulting brain injury in the absence of padding.

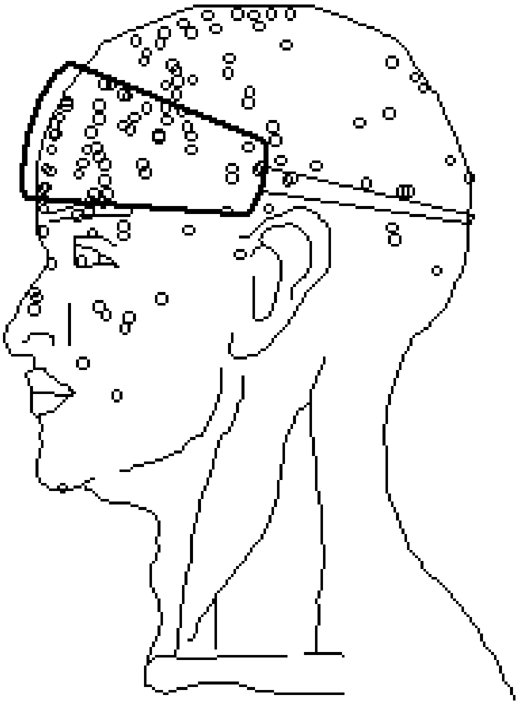


Figure 3.6
Location of impacts to the head in relation to the area covered by the RARU head band.

3.5.2 Effect of Protective Headwear on Outcome

For each of the cases an assessment was made about whether the wearing of protective headwear, in the form of a soft shell pedal cycle helmet, would have changed the outcome of the crash. The likely benefits to be expected from the use of the RARU head band rather than a pedal cycle helmet would be just over half of those reported in this section of the report. This is based on the proportion of the impact locations covered by a cycle helmet that would also be covered by the head band.

The assessment was based on all of the 117 cases, not only on those for which the object struck by the head was known. This meant that the estimate of the likelihood of any beneficial effect was derived largely from the characteristics of the injuries to the head, as well as the brain, supplemented by information on the object struck when that was available. The results by fatal and non-fatal outcome are shown in Table 3.10 and by brain injury severity in Table 3.11.

Table 3.10
Effect of Protective Headwear on Outcome: by Fatality

Beneficial Effect	**Observed Outcome** (Column percentages)		
	Fatal	**Non-Fatal**	**Total**
Yes	1.4%	16.3%	6.8%
Probably	10.8	25.6	16.2
Possibly	10.8	16.3	12.8
Unlikely	21.6	27.9	23.9
No	55.4	14.0	40.2
Total Number	74	43	117

As with the estimates of the effect of padding the car, the use of protective headwear appears likely to be more effective in improving the outcome in the non fatal cases in the sample (in 50 per cent of those cases) than in the cases which were fatally injured (18 per cent).

Table 3.11
Effect of Protective Headwear on Outcome: by Brain Injury Severity

Beneficial Effect	Observed Brain Injury Severity (Column percentages)		
	Minor	**Moderate**	**Severe**
Yes	10.4%	10.0%	2.0%
Probably	14.6	20.0	16.3
Possibly	6.3	20.0	16.3
Unlikely	33.3	5.0	22.4
No	35.4	45.0	42.9
Total Number	48	20	49

The data in Table 3.11 indicate that protective headwear of a type similar to a lightweight helmet intended for use by pedal cyclists would be likely to improve the outcome for car occupants in 28 per cent of cases of minor brain injuries, 40 per cent of cases of moderate brain injuries and 26 per cent of severe brain injuries. The percentage of cases with an improved outcome resulting from use of the RARU head band, shown in Figure 3.6, would be expected to be just over half of those for the use of a cycle helmet.

3.6 SUMMARY

Protective headwear approaches the ideal type of head protection for car occupants much more closely than padding of the upper interior of the passenger compartment, although the benefits of padding are still significant especially in less serious crashes. The percentages shown in Table 3.12 are estimates based on small samples but, with that qualification, they do indicate that protective headwear is likely to be considerably more effective than padding the car in improving the outcome in cases of brain injury, including preventing the injury altogether in some cases.

Table 3.12
Percentage of Cases in Which the Specified Type of Head Protection Would be Expected to Improve the Outcome

Type of Head Protection	Outcome		Brain Injury Severity		
	Non fatal	**Fatal**	**Minor**	**Moderate**	**Severe**
Ideal head protection	62%	25%	37%	50%	36%
Protective headwear[1]	50	18	28	40	26
Padding upper interior	33	2	16	25	3

Note: [1] In the form of a lightweight helmet intended for use by pedal cyclists. The RARU head band would be approximately half as effective.

3.7 CONCLUSIONS

The results of this investigation indicate that there is considerable potential for reducing the severity and the consequences of brain injuries by padding the upper interior of the passenger compartment. However, an even greater level of protection is provided by the use of protective headwear. With each of these forms of head protection the benefit appears likely to be greatest for cases which would otherwise sustain a brain injury of moderate severity.

Chapter 4

Head Injury Harm Analysis

A Harm analysis was undertaken to provide details on what the likely benefits would be from the introduction of a range of countermeasures aimed at reducing head, neck and/or facial injuries to passenger car occupants involved in road crashes.

4.1 THE CONCEPT OF HARM

The concept of "Harm" was first developed in the US and applied to the National Accident Sampling System (NASS) database during the 1980s by the National Highway Traffic Safety Administration (NHTSA) as a means of determining countermeasure benefits for road safety programs (Malliaris, Hitchcock and Hedlund 1982; Malliaris, Hitchcock and Hansen 1985; Malliaris and Digges 1987). Harm is a metric for quantifying injury costs from road trauma, involving both a frequency and a unit cost component. In its most general form, Harm can be used as a measure of the total cost of road trauma. [In Steadman and Bryan's (1988) publication, for instance, total cost of road trauma (Harm) was listed as $5 Billion which comprised allowances for treatment and rehabilitation costs, lost earnings, legal costs, and pain and suffering]. However, Harm can also be broken down into small units by type of road user, body region injured and severity of the injury sustained. This form of Harm is particularly useful for determining the benefits of individual countermeasures as it allows the summation of individual body region saving estimates. This "building block" approach is able to utilise all data sources available on likely injury reductions and has the advantage of providing a more systematic and rigorous estimate of injury savings than the more global approach.

This alternative use of Harm was first applied to quantify the benefits of safety countermeasures by the Monash University Accident Research Centre for the Federal Office of Road Safety under the direction and guidance of Kennerly Digges of Kennerly Digges and Associates, Charlottesville, Virginia in the US and has been previously reported in FORS reports CR 100 (Monash University Accident Research Centre 1992) and CR 154 (Fildes, Digges, Dyte, Carr & Vulcan 1995).

4.1.1 The Harm Method

The component Harm method requires an extensive national database on crash outcomes, similar to that developed in the Crashed Vehicle File (see previous chapter). However, as the CVF only involved hospitalised or killed occupants and was confined to crashes in and around Melbourne, it was necessary to supplement these data with non-hospitalised case information and to expand these data to represent the whole of Australia. This process was fully explained in FORS report CR 100 (Monash University Accident Research Centre 1992) and will not be repeated here.

Once this database was completed, it was then possible to specify existing Harm distributions by body region injured, AIS level, contact source and restraint condition. Harm matrices were subsequently produced for each of these comparisons and the necessary relevance figures for each body region and restraint condition saving was then used to adjust these distributions to arrive at the overall benefits for each countermeasure. An example of the component Harm method is given in Appendix E.

4.1.2 Computing Harm Reductions

Relevance figures refer to the amount of Harm per body region AIS level that is likely to be saved by the introduction of a particular countermeasure and are the critical determinants of the benefit calculations. In Table B of the example shown in Appendix E, for instance, it is assumed that the airbag is *relevant* (that is, will reduce face injuries to restrained front seat occupants from contacts with the steering wheel) for 80% of AIS 1, 90% of AIS 2, and 95% of AIS 3 and above injuries. When applied to the existing Harm distribution, the reduction in Harm is shown in the "Basis" column of Table B (an 87% overall reduction in Harm).

In making these adjustments, however, it was not generally assumed that all these injuries would be prevented but rather ameliorated. Thus, an injury severity "*shift*" was assumed. In this instance, an AIS 2 shift was assumed for all these injuries such that the 95% of AIS 6 facial injuries saved would became AIS 4s, AIS 5s would become AIS 3s, AIS 4s would become AIS 2s, and so on. The AIS 2s and below were totally removed by this process. In shifting this Harm to a lower AIS level, it was necessary to add back some Harm (albeit at a lessor injury cost) and this is what is shown in the "Residual" column. The 87% Harm reduction therefore is subsequently modified to a final 86% reduction in this example.

In determining relevance and injury severity shift figures, data from test and crash findings published in the road safety literature were incorporated wherever possible to reduce the amount of guess-work required in making these calculations. Where no published figures were available, the study team were forced to use the consensus view of a panel of experts in estimating the likely injury mitigations. The amount of published data is normally a function of the attention a particular measure has received by the research community as well as its newness. While some of the head injury measure effects have been well documented (eg: head padding), there was not much published data on others such as protective headwear and so heavy reliance needed to be made on expert panel assessments for computing the likely benefits of these.

4.2 COUNTERMEASURES AND ASSUMPTIONS

Countermeasures likely to reduce the severity of head, neck and face impacts were discussed in a previous chapter of this report and include:

- upper padding to the pillars, front and rear header and side rails;
- roof padding;
- side airbags (torso and head injury mitigation units);
- protective head wear;
- improved side window glazing;
- better seat belt systems (beyond ADR 69 technology); and
- frontal airbags (drivers and passengers);
- head space within the cabin (both forwards and sidewards).

It was not possible at this time to compute benefits for the last measure reliably and there was no knowledge of any international effort or interest in specifying head space in vehicle design (Australia would be a sole voice in calling for such a requirement). Hence, no attempt was made to calculate the savings for this countermeasure.

While head and face benefits from a frontal airbag were really beyond the scope of this study, they had been assessed previously in CR 100 and so these additional injury benefits were included again here for completeness. For each of the computed measures, it was expected that the benefits will accrue principally from reduced head, face and neck injuries (other benefits such as reduced upper limb injuries have been overlooked here).

In determining relevance figures for many of the countermeasures, substantial reliance was made on the work undertaken by the National Highway Traffic Safety Administration in Washington DC in preparing their regulatory impact analysis for upper interior head protection (NHTSA 1992) as well as the work of the National Crash Analysis Centre of George Washington University, in Virginia

(Digges 1994). Other publications by Monk and Sullivan (1986) and Hollowell and Fry (1991) were also invaluable in arriving at relevance figures.

4.2.1 Pillar and Rail Padding

NHTSA carried out an extensive regulatory analysis of the likely effects of pillar and roof header and side rail padding in preparation for regulating this treatment (FMVSS 201, December 1992). The Europeans are also contemplating a similar regulation as part of its side impact protection package. The US regulation calls for a free-motion test using a Hybrid III head form at 15mph (24km/h) and at an angle between 0 and 50 degrees relative to the horizontal plane of the vehicle. The standard calls for all upper surfaces to be tested with a Head Injury Criterion or HIC of 1000. While the US benefit figures were not directly applicable here because of substantial differences in belt wearing behaviour between the US and Australia, nevertheless the rationale developed in NHTSA (1992) was indeed suitable. The resultant benefits and the relative effectiveness figures are shown in Table 4.1 below.

Table 4.1
Effectiveness benefits for pillar and rail padding (NHTSA 1992)

HIC Criteria	Fatalities	Effectiveness	AIS 2+	Effectiveness
HIC 1000	1266	29%	754	23%

From these figures, it seems that the effectiveness of padding to reduce AIS 2 and 3 injuries is much less than for AIS 6 fatal injuries. The relevance figures adopted in the Harm analysis for head injuries for padding for both restrained and unrestrained occupants is shown in Table 4.2. These figures are based on relevant impact areas. Occupant Harm from deaths associated with other than head injuries were removed from the benefit opportunities. While NHTSA's regulatory analysis would claim an effectiveness of 23% for AIS 1 - 5 injuries, RARU data in Chapter 3 suggests the figure should be much higher (75%) and recent motorcycle helmet figures by Johnson, Walker and Utter (1995) suggest 67%. Based on the figures in Table 4.1, head injury relevance for the 1000/1000 padding for AIS 6 (fatalities) was taken as 29% effective. Non-fatal AIS 1 to 5 relevance was assumed to be 10 percentage points higher at 39%, given the superior RARU data findings over those published by NHTSA. The equivalent figures for the 1000/800 padding level were 36% and 46% respectively. A shift in injury severity of AIS 3 was assumed for potentially fatal injuries (AIS 4-6) and an AIS 2 shift for probable non-fatal injuries (AIS 1-3).

Table 4.2
Effectiveness figures used for pillar and rail padding

AIS Level	HIC 1000/1000	HIC 1000/800
1	39%	46%
2	39%	46%
3	39%	46%
4	39%	46%
5	39%	46%
6	29%	36%

Facial injuries from padding the steering wheel were previously specified in CR 100 as shown in Table 4.3 below. As the type and level of padding upper structures was assumed to be similar to that likely to be used to reduce facial injuries from contacts with the steering wheel, these figures were judged suitable for use again here. An AIS 3 injury shift was assumed for facial injuries after rail and column padding.

Table 4.3
Relevance figures used for face
injuries for pillar and rail padding

AIS Level	Relevance
1	80%
2	90%
3	95%
4	nil
5	nil
6	nil

4.2.2 Roof Padding

It was assumed that the effects of roof padding would be similar to the other upper structure padding for head injury reduction. That is, that the levels and types of padding necessary to meet FMVSS 201 (notionally up to 1 inch of firm foam padding) would also be suitable for padding the roof surface. Thus, the relevance figures in Table 4.2 were taken as suitable here for both head and face injuries using the global Harm reduction method. No spine or neck benefits were assumed here.

4.2.3 Side Airbags

There are currently two types of side impact airbags available or under development by Autoliv in Europe that were known to the study team. The first was the *"torso bag"* which is fitted in the door panel and similar to that currently provided by Volvo in their 850 model cars. The second Autoliv unit, the *"head bag"*, attaches to the side rail and aims to provide head protection and is currently under development we understand for use in BMW cars. The torso bag principally aims to provide chest injury protection but does offer some head and face benefits from mitigated head/door contacts as well as from changes in trajectory patterns in side impact crashes. These benefits were assessed in the previous side impact regulation benefit study and have been included here again for completeness.

Table 4.4
Relevance figures used for head and face injuries
from head-high side airbags (figures adapted from CR 100)

AIS Level	Head Relevance	Face Relevance
1	60%	50%
2	60%	60%
3	60%	60%
4	60%	60%
5	60%	60%
6	60%	60%

The head bag had not been previously assessed and there were no data available on its effectiveness. However, it seemed reasonable to assume that it would be about as effective in side crashes as a driver's Eurobag (smaller sized facebag) would be at reducing these injuries in frontal crashes. In addition, it should also have a significant benefit in preventing head ejections and rollovers. The relevance figures adopted for head and face contacts in side impacts are shown in Table 4.4 with an AIS 2 shift. Savings in head and face injuries during ejection were calculated on the basis of reductions in exterior contacts from the head going out of the window for crashes above 20km/h for which an AIS 3 shift was assumed at all levels of injury.

4.2.4 Protective Headwear

Protective headwear for passenger car occupants has been discussed as a means by which occupants can protect themselves, irrespective of the level of countermeasure provided by the car manufacturer. The benefits of protective headwear, however, are clearly dependent on what other countermeasures are available, such as whether the upper interior of the passenger compartment is padded and whether the car is fitted with an airbag or not. For the purpose of computing these benefits, however, it was assumed that no other head injury countermeasure was available beyond airbags. Separate benefits were then calculated both with and without airbag protection.

Protective headwear was assumed to provide the same level of protection as roof and rail padding was previously, only for all head injuries (no benefits were assumed at all for facial injuries as the envisaged forms of protective headwear are not likely to provide these benefits, apart from some protection of the forehead). Moreover, no benefits were allowed for unrestrained occupants either as it was assumed that these forgetful or deviant types would be unlikely to wear protective headwear.

A few words of caution need to be added about the effectiveness of this countermeasure. There is no evidence of likely usage rates for protective headwear and the benefits are obviously very much dependent upon the level of usage (both in terms of the likely number of wearers and consistency of use) within the population. Secondly, incorrect use of protective headwear is also likely to moderate these benefits.

In computing these benefits, no attempt was made to adjust the figures to take account of the qualifications outlined in the preceding paragraph. Thus, the annual savings presented must be viewed as maximum benefits and are clearly likely to be an over-estimate. It was necessary though to make these population estimates in order to determine the unit benefit of protective headwear (the saving per vehicle over the life of the car) which is far more relevant for this measure. Even so, these unit benefits still assume that all occupants use protective headwear every time they use the vehicle during its lifetime.

4.2.5 Improved Belt Systems

Seatbelt pre-tensioning was assumed to provide some additional head and facial injury benefits by reducing the frequency of roof, header rail and A-pillar contacts (but not those from contact with the side rails). It was assumed that the benefit would be similar to that provided by 1000/800 padding but at a higher level of injury reduction (an AIS 3 injury shift) as many of these contacts would be totally prevented. In this instance, it was felt that some neck injury reductions could be justified by fewer head contacts with these components thus similar relevance and injury shift figures for head injuries were included here for the neck.

4.2.6 Better Side Glazing

Benefits from reductions in laceration, fewer cuts from flying glass and less ejection injury through the side windows would be gained by providing more secure side window glazing materials. Side glazing constructions incorporating plastic laminates such as "Securiflex" are available in some cars overseas, although interestingly for airconditioning benefits mainly. It is felt that this product would also have injury reduction benefits too.

Ejection benefits require windows to be closed to be effective. Some evidence from the US suggests that this is the case in around 50% of crashes (occupants are ejected through closed windows in around half the number of these cases). While the number of ejectees is considerably less in Australia with higher seat belt wearing rates, nevertheless the proportion of those ejected through closed windows is not expected to be grossly different. Thus, a 25% relevance figure seemed appropriate for this Harm. A large injury severity shift of AIS 3 would be expected for these injuries as ejectees often suffer fatal head injuries.

4.3 CALCULATING INDIVIDUAL VEHICLE SAVINGS

The annual Harm saved by each of the countermeasures specified assumes that all vehicles on the road instantaneously meet this standard. In fact, of course, it can take many years for this situation to arise as the average age of vehicles in Australia is 10.6 years (Australian Bureau of Statistics, 1997) and there are many vehicles aged 25 years or more still operating in this country. In establishing benefit-cost relationships, it is necessary to convert annual Harm saved (a community benefit) into a saving spread across the life of an individual vehicle to compare this with the cost of having to meet this new requirement. This is achieved by estimating the average risk of a vehicle being involved in a crash for each year of its life and multiplying that risk by the annual Harm saved per crash for that time period. The average Harm savings can then be summed across the life of the vehicle. There are alternative methods for making these estimates, each with their particular strengths and weaknesses.

4.3.1 Immediate Past History

In these calculations, it was assumed that the immediate past history of crashworthiness, new car sales and crash patterns would continue and therefore be the best predictor of future crash risk, vehicle population size and salvage rates. This eliminates the need for tenuous subjective predictions and has credibility in that the past is often the best predictor of the future in dealing with human behaviour. It does assume of course that the crashworthiness history of the vehicle fleet will not alter dramatically.

The method assumes that the risk of a new car being involved in a casualty crash during, say the 3rd year of its life, is the same as the risk of a car which was first registered 3 years ago having a crash this year. To calculate this yearly risk, the frequency of crashes for 3 year old cars is divided by the total number of cars sold 3 years ago. The risk of a crash across the lifetime of a car then is the sum of each years crash experience over the number of new cars sold. The process of focussing on each crash year and the number of vehicle sales each year takes account of vehicles that exit from the vehicle fleet through wreckage, wear and tear, etc. as well as the lower distances travelled by older cars and the different characteristics of those who driver older cars. The history of new registrations and crash and repair rates and previous average vehicle life figures were computed for all Australian states between 1965 and 1990 and published in Table 7.1, page 74 in Monash University Accident Research Centre (1992). These figures were again used in these calculations.

The next step is to assume that the percent of total Harm saved for all cars of a certain age group is equal to the percent of total relevant casualty crashes involving that age group. The formula used helps explain this:

$$\frac{H_3}{H} = \frac{F_3}{F} \qquad \text{or} \qquad H_3 = \frac{F_3}{F} \times H$$

where H_3 = Harm reduction for all cars in their third year

H = total annual Harm reduction for all cars

F_3 = number of cars involved in casualty crashes in third year

F = total number of cars involved in casualty crashes in one year

The average Harm reduction for any one car in its third year is calculated by dividing H_3 by the number of new cars registered three years ago. The total benefit for a single car is then obtained by adding up the Harm reductions for each year of its life and discounting these benefits back to the first year.

4.3.2 Discounting Procedure and Rate

When predicting the likely benefits of a new countermeasure, it is normal to discount future benefits back to the present so that they can be compared with present day costs of the measure. The discounting procedure used in these calculations first takes the annual Harm saved and attributes this (discounted) to for one car over its expected lifetime. The selection of an appropriate discount rate is really a matter of opinion (there is no magic number). Traditionally, the Commonwealth Government has used 7% as an appropriate rate, while other state governments, however, have used a range of different values (the Victorian Government, for instance, has used 4% in similar cost effectiveness studies). A smaller discount rate gives greater weight to future benefits and is thus less conservative.

The Department of Finance (1991) recommend that where possible, sensitivity analysis be undertaken involving a range of different discount rates. Current practice is to compare the benefits at 5% and 7% to gauge the likely usefulness of any new countermeasure. It is acknowledged that the choice of the discount rate has a marked effect on the calculation. Not only does it influence the BCR, but also the cost of death or serious injury (Steadman & Bryan 1988 used a 7% discount rate in determining the cost of injury for each injury severity level and noted that a 4% rate would increase the cost of injury overall by 17%). For these calculations, injury costs have been taken at the BTCE 7% discount rate but the Harm benefits have been calculated for both 5% and 7% discount rates.

4.3.3 Life Period of Vehicle Fleet

Another contentious issue is what constitutes the life period of the vehicle fleet. It was argued earlier that the average life of a vehicle in Australia is around 11 years but that there are still a number of roadworthy vehicles 25 years old or more. A recent study by Newstead et al (1997) which examined the role of vehicle age and crashworthiness showed that the risk of severe injury has not changed all that markedly over the last several years. Previous studies have used a 25 year fleet life period (Monash University Accident Research Centre 1992: Fildes et al 1995) and this period has subsequently been shown not to unduly influence the results compared with a 15 year period (Fildes et al 1996). Accordingly, a 25 year life was again used for determining the benefits of head injury countermeasures here.

4.4 SUMMARY OF HARM BENEFITS

Tables 4.5 to 4.7 show the summary of annual Harm saved per body region and restraint condition and the Unit Harm saved for all countermeasures considered, assuming both a 5% and 7% discount rate. These figures were derived from the individual body region and contact source calculations undertaken for each countermeasure which are shown in the series of Tables presented in Appendix E (the figures in Table 4.7 were derived from previous calculations for frontal airbags reported in CR 100 (Monash University Accident Research Centre 1992) and are included here for completeness. The benefits to be derived for each head injury countermeasure are discussed below.

TABLE 4.5
Summary of Head and Face Harm Benefits for Several Vehicle Measures

BODY REGION	RAIL/PILLA PADDING		ROOF PADDING		SEATBELT SYSTEMS	BETTER GLAZING
	1000/800	1000/1000	1000/800	1000/1000		
TOTAL HEAD BENEFITS	71.4	60.5	48.3	41.0	56.5	51.7
TOTAL FACE BENEFITS	2.85	2.0	0.6	0.3	4.2	2.7
TOTAL ANNUAL HARM (A$million)	**74.3**	**62.5**	**48.9**	**41.3**	**60.6**	**54.4**
UNIT HARM PER VEHICLE (A$ per car @ 7% discount)	**81**	**68**	**53**	**45**	**66**	**59**
UNIT HARM PER VEHICLE (A$ per car @ 5% discount)	**93**	**78**	**61**	**52**	**76**	**68**

TABLE 4.6
Summary of Head and Face Harm Benefits for Side Bags and Protective Headwear

BODY REGION	TORSO SIDEBAG	HEAD SIDEBAG	PROTECTIVE HEADWEAR			
			NO BAGS		WITH BAGS	
			DRIVER	ALL	DRIVER	ALL
HEAD - Restrained	28.9	81.3	354.9	499.8	240.8	379.5
HEAD - Unrestrained		10.6	-	-	-	-
FACE - Restrained	0.8	17.1	0.0	0.0	0.0	0.0
FACE - Unrestrained		0.6	-	-	-	-
TOTAL ANNUAL HARM (A$ million)	**29.8**	**109.6**	**354.9**	**499.8**	**240.8**	**379.5**
UNIT HARM PER VEHICLE (A$ per car @ 7% discount)	**32**	**119**	**386**	**543**	**262**	**413**
UNIT HARM PER VEHICLE (A$ per car @ 5% discount)	**37**	**137**	**445**	**626**	**302**	**476**

TABLE 4.7
Summary of Head and Face Harm Benefits from Frontal Airbags
(from Monash University Accident Research Centre, 1992)

BODY REGION	DRIVER AIRBAG	PASSENGER AIRBAG	MAXIMUM FACEBAG	MINIMUM FACEBAG
HEAD - Restrained	192.7	23.8	146.3	102.6
HEAD - Unrestrained	56.5	20.6	47.5	28.3
FACE - Restrained	70.5	1.5	52.8	42.6
FACE - Unrestrained	19.9	2.5	14.9	7.8
TOTAL ANNUAL HARM (A$ million)	**339.6**	**48.4**	**261.5**	**181.3**
UNIT HARM PER VEHICLE (A$ per car @ 7% discount)	**369**	**53**	**284**	**197**
UNIT HARM PER VEHICLE (A$ per car @ 5% discount)	**426**	**61**	**328**	**227**

NB: Figures published in the original report were much larger than those listed here as other body region savings were included.

4.4.1 Rail & Column Padding

Head and facial Harm benefits from padding the header rails, side rails and pillars are listed in Table 4.5. Two levels of padding were considered to meet either 1000 or 800 HIC for side rail criteria. The annual Harm saved in head and face injury mitigation, assuming all vehicles in the fleet comply, would be somewhere between $63 million and $74 million dependent upon level of padding and discount rate. Unit Harm benefits (the savings per car) vary from $68 to $93. These Harm reductions are considerably less than equivalent figures published in the US notice of proposed rulemaking for FMVSS 201. These differences can be explained by the higher level of unrestrained occupants in the US compared to Australia (40-50% c.f. 6%) as rail and pillar contacts are far more likely among unrestrained occupants (see previous chapter). Nevertheless, benefits of this order are not insignificant and approach break-even costs of $60 to $83 per car, reported in CR 100 (Monash University Accident Research Centre, 1992).

4.4.2 Roof Padding

The same levels of rail and column padding were also considered for the roof as shown in Table 4.5. Annual Harm benefits of between $41 million and $49 million would accrue if the whole vehicle fleet was fitted with roof padding of this order with unit Harm benefits somewhere between $45 and $61 per car, depending on the level of padding and discount rate.

4.4.3 Improved Seatbelt Systems

It was argued that pre-tensioning seatbelts would likely lead to reduction in head, neck and face injuries from fewer contacts with the roof, header rail and A-pillar (but not the side rails). The main advantage of these devices would be in restricting occupant movement from the seat thereby mitigating a number of these injuries. Calculations shown in Table 4.5 show that the total fleet benefit would be $61 million each year with a unit Harm saving of between $66 and $76 per car, given either a 7% or a 5% discount rate.

4.4.4 Better Side Glazing

Products such as "Securiflex" comprising a sandwich of glass and plastic films are used on some European cars to reduce airconditioning loads. This construction is also likely to have road safety benefits by reducing head and face injuries from external contacts among ejected occupants and fewer lacerations from flying glass in the event of a collision. Table 4.5 shows that these units have an expected annual benefit to the total fleet of $54 million with a unit Harm benefit between $59 and $68 per car. These measures, in particular, would seem to be highly cost-beneficial.

4.4.5 Side Airbags

Two types of airbags of benefit in side impact crashes were considered in this analysis, namely torso and head side airbags. These units are either available in current models or are understood to be under development and testing. It was assumed that both would offer some advantage in reduced head and face injuries, although the results in Table 4.6 show the head bag to be considerably superior. This is not surprising as it offers direct protection for the head and face, compared to only auxiliary benefit from the torso bag through a more pronounced (less injurious) trajectory path for the occupant away from the striking object. Fleet savings for the head bag in the front compartment only in terms of reduced head and face injuries alone would be $110 million annually with a unit Harm benefit of somewhere between $119 and $137 per car. The equivalent head and face Harm benefits for the torso side airbag would be only one-quarter of this, although it should be stressed that these units fitted to the door of the car would also offer significant chest benefits, not seemingly available with the proposed head unit.

4.4.6 Protective Headwear

A head injury countermeasure that is receiving more serious attention lately is protective headwear for car occupants. These units are advantaged in that the occupant can improve his or her own protection independently of what car manufacturers offer in their vehicles by choosing to wear these units (assuming that suitable units are available) and that they are likely to offer protection from any head contact in the event of an accident. The benefits, though, will be severely discounted if occupants fail to wear these units consistently (non-compliance) or if only a proportion of occupants choose to wear them.

It was argued that annual fleet Harm benefits are not relevant for these units given the dependence on compliance. However, assuming that all occupants in a car were to use protective headwear regularly and that all cars in the vehicle fleet were not fitted with driver airbags, they would reduce head and face Harm by $500 million each year with unit Harm benefits between $543 and $626 per car, as shown in Table 4.6. Drivers' injury savings alone constitute more than 70% of these expected benefits. The equivalent figures for protective headwear as a supplement to airbags is still a sizeable $380 million annually or a unit benefit of $413 to $476 per car. This would be a worthy countermeasure indeed if problems in non-compliance and use could be overcome. No disbenefit was allowed for the slight possibility of any increase in injuries resulting from added mass or reduced head space.

4.4.7 Frontal Airbags

This study was primarily concerned with new countermeasures and especially the benefits of reduced head, face and neck injuries from padding inside the vehicle. While frontal airbags were really outside the scope of this study, their benefits were included to allow comparison with the other measures listed. These units are becoming more familiar among new cars sold in this country and their benefits have been previously reported in an earlier FORS report, CR 100 (Monash University Accident Research Centre, 1992). For completeness, the resultant head and face injury benefits only of these devices have been shown again in Table 4.7. The ultimate benefits for frontal airbags will depend to a large degree on their design (fullsize airbag or facebag), whether driver only or available for both drivers and passengers as well as the discount rate used to take account of future savings. Harm benefits of reduced head and face injuries to drivers alone were calculated to be between $181 and $340 million annually with unit Harm benefits ranging from $197 to $426 per car across its expected life. The equivalent benefit for front passengers would be $48 million annually or up to $61 unit Harm savings. It should be stressed that an additional 40% benefit would also accrue from reductions in chest and abdominal injuries from these units (see report CR 100).

Chapter 5

General Discussion and Recommendations

This study set out to assess the current state of knowledge in relation to occupant head injury in Australian passenger car crashes to understand the extent and nature of the problem better and to identify opportunities to reduce the number and severity of head injuries to passenger car occupants. The study comprised several research tasks, namely (i), a review of the road safety literature emphasising head injuries to passenger car occupants, (ii) analyses of the Crashed Vehicle File at MUARC and the brain injury database at RARU to determine extent and severity of injury, (iii) characteristics and the mechanisms of brain injury, (iv) a review of suitable countermeasures to reduce these injuries, and (v) a Harm analysis to estimate the likely benefits of these countermeasures to Australian passenger car occupants. A number of important and interesting findings are evident from this research.

5.1 EXTENT OF HEAD INJURY IN PASSENGER CAR CRASHES

Despite a number of initiatives aimed at preventing life threatening injuries to the head, they are still relatively frequent outcomes among those hospitalised or killed from road crashes in this country and account for a sizeable amount of Harm to modern passenger car occupants.

Analysis of the in-depth and CVF real world crash data shows that for those injured seriously enough to be hospitalised or killed, a head, neck or facial injury was sustained in more than three-quarters of all cases. A fatal head injury was sustained by 66% of fatal cases where in approximately two-thirds of these, the head injury was the sole cause of death.

Among those sustaining a head injury leading to at least hospitalisation, the most common type of head injuries were contusions and lacerations. However, between 21% and 30% of front seat passengers did experience a fracture of the skull. Not surprisingly, this was considerably higher among the fatally injured (60%). Hospitalised occupants sustained a severe head injury (AIS>2) in up to three-quarters of all head-injured cases.

5.2 CAUSES OF HEAD INJURY

The most common sources of head, neck and face injury inside the vehicle were from contacts with the steering assembly, door and instrument panel, the roof and side rails as well as from the side window. Many of these contacts resulted in severe injury (AIS 2 and greater) and in the extreme, were the primary cause of death of the occupant. The roof was a surprisingly common source of severe injury to these occupants, even though only a small percent of the cases involved rollover collisions. The roof was the second largest cause of severe brain injury after the striking object among both fatal and non-fatal head injured occupants in the RARU database.

There was also a sizeable number of head, neck and face injuries from contacts with exterior objects such as the ground, and the impacting object. This was especially so in side impact and rollover crashes. This could not be attributed to ejection entirely as the ejection rates in Australia are low compared to other countries with lower seat belt wearing rates, notably the USA. Partial ejections in side impacts and rollovers, though, are still relatively common in crashes in this country as seat belts are unable to offer this level of protection.

Contacts with the A-pillar were not as frequently associated with head injuries to Australian passenger car occupants as is evident overseas. This is probably a function of the high seat belt wearing rates in this country and the protective effects of these units. There was also not a strong association between intrusion and contact source, except for the roof and the instrument panel. This was especially noteworthy in side impacts and rollovers. In short, many of the head injuries were from contacts not necessarily involving intrusion and conversely, there were many instances of intrusion where no head, neck or face injury subsequently occurred.

5.3 MECHANISMS OF INJURY

A detailed analysis of the mechanisms of head injury was outside the scope of this study and is an area where further research is still required.

5.4 HEAD INJURY COUNTERMEASURES

While the main emphasis of this study was on head padding, a number of other possible countermeasures to head, neck and facial injury are also discussed briefly in this section. To place the likely effects of these countermeasures in the context of what is theoretically possible, we first refer back to the RARU estimate of the likely effect of ideal practicable head protection.

5.4.1 Effect on Fatalities of Reducing the Severity of the Head Impact

An attempt was made to quantify the extent to which the maximum practicable reduction of the severity of the head impact would have changed the outcome for a range of fatal and non-fatal cases investigated by RARU. Not surprisingly, the probable benefit of reducing the severity of the head injury was assessed to be greatest (up to 62%) among the non-fatal cases. A reduction of 25% of fatalities was predicted, although it was pointed out that the residual disabilities were still likely to be severe among these additional survivors.

5.4.2 Rail and Pillar Padding

Padding of the upper interior of the passenger compartment was the countermeasure of primary interest in this study. In the United States, Federal Motor Vehicle Safety Standard FMVSS 201 (Occupant Protection in Interior Impact), which related to occupant contacts with interior areas such as the instrument panel, seat back, sunvisor and armrests, was amended on August 18, 1995 to include a performance specification for head protection in occupant impacts with the header and side rails and also the “A” and “B” pillars.

FMVSS 201 specifies Head Injury Criterion (HIC) levels for a 15 pound spherical free motion headform impacting 15 specified points on the above-listed areas at 15 mph. The Head Injury Criterion (HIC) is not to exceed a value of 1000. (A slight adjustment is made to transform the measured HIC value to that which would be recorded were a conventional Hybrid III dummy head used rather than the spherical headform.) This performance requirement is likely to be met in most vehicles by padding the relevant areas.

The National Highway Traffic Safety Administration has estimated that the amendment to FMVSS 201 will prevent about 1,000 fatalities and a smaller number of severe head injuries per year in the United States (NHTSA, 1995).

5.4.3 Roof Padding

The amendments to US Federal Motor Vehicle Safety Standard (FMVSS) 201 do not cover the roof as it is claimed that this area does not require padding (the metal itself can act to provide padding benefits under some circumstances). The results of this study showed that head strikes with the roof were common sources of head injury of both minor and severe outcomes. In the latter outcome, the roof panel was often interposed between the head and an intruding object such as a utility pole. However, many of these strikes occurred without rollover and intrusion. As the roof contains structural components as well as sheet metal panels, there would seem to be merit in padding the roof in addition to the other components.

59

5.4.4 Improved Seat Belt Systems

Seat belts are clearly one of the more successful injury countermeasures that have been introduced in passenger cars over the last 20 years or so. Even so, some current designs of these units are still causing a degree of injury to the chest and neck by their inability to fit the occupant optimally and the inherent slackness in many of these systems. The need for improved seat belt systems was highlighted in Fildes et al (1991) and seat belt retractors, webbing clamps and better belt alignment were called for. While the primary benefit would be in reduced chest and neck injuries, there would also be some head and face benefits from fewer strikes with interior components.

5.4.5 Side Glazing Materials which Restrain the Head

A number of severe head strikes with external objects was observed in both the CVF and the RARU databases, especially in side impact collisions. While these studies were not always able to identify partial head ejections, it was clear that many of these contacts resulted from the head being thrown through the side window and onto the impacting object (evidence from the US suggests that this is the case in around 50% of the crashes). As the side windows almost always shatter in a side collision in which the point of impact is near the affected occupant, there is nothing to prevent these partial ejections of the head in these crashes. Side glazing constructions incorporating plastic laminates such as "Securiflex" are likely to provide better head restraint in side impact collisions and therefore be of benefit in reduced head and facial injuries.

5.4.6 Head Side Airbag

Autoliv have developed a side impact airbag that offers head and face impact protection from strikes with the side rail as well as the neighbouring roof and door frame. The bag is a "sausage" arrangement that is located on the side rail on both sides of the front compartment. It is understood that these units are currently being fitted to BMW production cars. It appears that they are the only unit currently available that offers head impact protection in side crashes. While these units may be incompatible with side rail padding at this time, they are nevertheless likely to offer superior protection, albeit above their firing threshold.

5.4.7 Protective Headwear

One of the most effective ways for occupants to gain improved head injury protection would be to use protective headwear while travelling in passenger cars. Not only would these units offer similar benefits to padding for contacts with the header, side rails and pillars, they would also offer considerable protection from other componentary inside and outside the vehicle in the event of a crash. The types of protective headwear envisaged here range from a simple headband to something similar to a soft shell pedal cyclist’s helmet, possibly adapted to suit passenger car occupant needs. The ultimate benefits to society will be dictated by the wearing rates among occupants. It is unlikely that there will be any meaningful disbenefits from the added mass to the head (estimated to be an increase of less than 5%) and an increase in size and hence opportunity for head strikes, particularly when compared to the very large benefits likely to accrue from the use of protective headwear.

5.4.8 Torso Side Airbag

Several European manufactured vehicles are currently offering side impact airbags that aim to protect the torso in a side impact collision. Their designs are varied but at least offer reduced hard thorax injuries and some head and facial benefits from enhancing the trajectory of the occupant away from the impacting object.

5.5 LIKELY HARM BENEFITS

To estimate the benefits likely to accrue if the head, neck and facial injury countermeasures identified were present in Australian passenger cars, a Harm Reduction analysis was undertaken, using the method developed in previous studies by MUARC. Current Harm patterns were identified and assumptions were made about the likely injury mitigations that would apply, given the lack of real world injury reduction findings currently available. Unit Harm benefits were estimated using both a 5% and a 7% discount rate and assuming current sales and salvage patterns and a vehicle life period of 25 years.

While this analysis was not intended to be a full cost-benefit analysis, it was to provide an indication of the likely societal benefits and the break-even costs of these units. The annual Harm saved and unit Harm benefits for these measures are shown in Table 5.1.

Table 5.1
Summary of Head and Face Injury Countermeasures

COUNTERMEASURE	ANNUAL HEAD HARM SAVED ($million)	% TOTAL HARM	UNIT HARM ($ per car)	
			7% Discount	5% Discount
Rail & pillar padding 1000/800	$74.3	2.4%	$81	$93
Rail & pillar padding 1000/1000	$62.5	2.0%	$68	$78
Roof padding 1000/800	$48.9	1.6%	$53	$61
Roof padding 1000/1000	$41.3	1.3%	$45	$52
Improved seat belts	$60.6	1.9%	$66	$76
Better side glazing	$54.4	1.7%	$59	$68
Head side airbag	$109.6	3.5%	$119	$137
Torso side airbag	$29.8	1.0%	$32	$37
Headwear without front airbags	$499.8	15.9%	$543	$626
Headwear with front airbags	$379.5	12.0%	$413	$476

NB: Headwear benefits based on 100% wearing rates by all passenger car occupants. Percent reduction in Harm based on total passenger car occupant Harm figure of $3142 million (MUARC 1992).

Padding to ensure a head form HIC test figure of less than 1000 for both front and side rails and pillars would lead to a head and face benefit of $68 to $78 per passenger car. The benefit would be approximately 20% higher if the side requirement was for a HIC<800 as is under consideration currently by NHTSA. Similar roof padding would gain an additional minimum $45 to $52 benefit per car based on these calculations.

Head side airbags in every passenger car would lead to a sizeable reduction in head and face injuries with a resultant unit Harm benefit of between $119 and $137 per car. Torso airbag benefits are more modest in terms of head and face injury savings but this is not surprising as these units are really intended to provide maximum benefits for the thorax.

Side glazing unit Harm benefits of between $59 and $68 per car would appear to be cost effective. Improved seat belt designs would likely provide benefits ranging from $66 to $76 in reduced head and neck injuries alone and are difficult to ignore.

62

By far the largest benefits in reduced head and facial injuries, though, would be gained if all occupants were to wear protective headwear. For a 100% wearing rate, the unit benefits would be between $413 and $476 per car, even with a driver's side frontal airbag fitted. Assuming that the cost of these units would be, at most, similar to that of soft shell bicycle helmets (approximately $40 each) and an average occupancy rate in passenger cars of 2.0 occupants, it is clear that these units would be very cost effective indeed.

5.6 RECOMMENDATIONS

As a result of this research, a number of recommendations seem apparent and these are discussed further below.

5.6.1 Rail and Pillar Padding

The evidence presented shows that there is a case for padding the inside of the vehicle in areas commonly contacted by the head in road crashes. This includes the head and side rails as well as the A- and B-pillars for front seat occupants and the side rails and possibly the rear header and C-pillar for rear seat occupants. This is expected to alleviate the number and severity of many of these injurious contacts in both frontal and side crashes and save the community between $64 and $73 million annually when all cars in the fleet would be expected to meet this requirement. The break-even unit cost for this added protection would be between $68 and $93 per car. The level of protection and suitable materials may need further consideration but it seems that the technology is currently available to provide this benefit. Regulation, similar to the amendment to US Federal Motor Vehicle Safety Standard (FMVSS) 201, and that currently under contemplation in Europe, may be necessary to ensure that this protection is available to the occupants of all new passenger cars in Australia in the future.

5.6.2 Roof Padding

There was a sizeable number of head injuries from contact with the roof, not all of which resulted from intrusion of this surface nor associated with rollover collisions. The analyses conducted here showed that similar padding to that considered for the rails and pillars on the inside of the roof panel would result in reduced head and face injuries in most crashes, even with roof intrusions in many instances. The Harm analysis suggested that the benefits would be up to $50 million annually with full compliance for a break-even cost of between $45 to $61 per car. There is no current international regulation that requires roof padding but conceivably this could be part of a roof and rail requirement.

5.6.3 Protective Headwear

The most promising occupant head injury countermeasure is headwear designed to provide head and face injury protection. Designs along the lines of a soft shell bicycle helmet, or simply a headband containing energy absorbing padding across the forehead and around to the ears, (Figure 3.6) would provide benefits well in excess of other measures listed here and be made available within months rather than having to wait for appropriately modified new vehicles to come onto the market.

At between $413 and $476 unit Harm benefit and assuming 2.0 persons per car on average, protective headwear is likely to be very cost effective. Of course, the impressive financial benefits shown in this study of up to $380 million annually, even in cars fitted with frontal airbags, would be entirely dependent upon population compliance with this measure.

In the short term, it is recommended that the use of protective headwear be promoted by means of demonstration programs to show the benefits likely to accrue to both individuals and the community at large. This assumes that a range of suitable protective headwear is available, which should be the obvious first step in any campaign to promote its use in passenger cars.

The use of protective headwear by car occupants in Australia could potentially reduce the number of fatalities and cases of brain damage to at least the same extent as the use of helmets by pedal cyclists and motorcyclists. This is partly due to the the higher level of exposure among vehicle occupants.

5.6.4 Side Window Glazing

There has been very little discussion of the need for improved side window glazing to reduce shattering and ensure a degree of restraint for occupants' heads, especially in side impact crashes. Materials are available that would provide this level of extra protection and their fitment might also provide added air conditioning benefits. Harm reductions of around $55 million annually would accrue eventually and the break-even cost would be $59 to $68 per car. Fitment to front passengers' windows should be highest priority as this would yield greatest benefit. There are no current standards or proposals available it seems for mandating these improvements, although this would be one option available for Australia for ensuring this level of protection. Given the apparent air conditioning benefits, too, it might be possible for industry to agree to fitment of these improved side windows materials without regulation.

5.6.5 Improved Seatbelt Designs

The benefits of improved seatbelt designs to reduce spool-out and provide greater levels of restraint in crashes have been apparent for a number of years and there are now a number of current technologies available. ADR 69 and consumer advisory information seems to be having some effect on fitment rates, judging by the number of current models which offer webbing clamps and/or pre-tensioners as standard equipment. Moreover, there is now a higher incidence of fitting seat belt attachments to the seat, rather that the floor, which should lead to improved belt angles around the pelvis and abdomen, thereby reducing the incidence of severe abdominal injuries. With these improvements, fewer, and less severe head and neck injuries would also be expected, providing a benefit of more than $60 million annually in reduced head and neck injury trauma. Given recent history of improved seat belt designs, there does not seem to be a need for further regulation at this stage, although these injuries need to be monitored to ensure that future designs are optimal for reducing these injuries.

5.6.6 Side Airbags

Head and torso side airbags are beginning to appear in a select number of new passenger cars. Either of these units would be expected to mitigate head and face injuries, although the former would have the greatest benefits ($110 million c.f., $30 million annually). At $119 to $137 unit Harm saving per passenger car, it is unlikely that the head and side airbag would be fully cost effective. In addition, the interaction between the airbag and any side rail padding requirement could be somewhat problematic. These units should be encouraged, nevertheless, as they will benefit those individuals involved in a side impact who have chosen to pay the added cost for their car to be equipped with them, even though the case for specific regulation to mandate fitment would seem difficult to sustain at this time.

5.6.7 Additional Research

The need for continuing research into head injury causation and mitigation among crash-involved car occupants has been evident throughout this study. In particular, the marked differences in the estimates of the effectiveness of padding of the upper interior of the passenger compartment on fatal and non fatal head injury cases in the study conducted by RARU and that conducted by NHTSA warrant further investigation.

The actual effects of padding the upper interior of the passenger compartment in the manner mandated for cars in the United States cannot be evaluated in Australia until a sufficient number of new cars which comply with those requirements come onto the market. The evaluation of the effectiveness of protective headwear may be able to be carried out in conjunction with a demonstration program, with the effectiveness findings being used in an assessment of the likely level of acceptance of such a measure.

Appendix A

The Epidemiology of Car Occupant Head Injury

As noted in the previous review by McLean et al (1987), the sources of information on head injury to car occupants tend to be derived either from hospital-based studies of the incidence of head injury from all causes, or from detailed studies of road crashes. Whereas the former rarely provide more detailed circumstantial data than a simple classification of type of road user, the latter are rarely based on a representative sample of crashes, rendering extrapolation to the general population of car occupants difficult or even impractical.

Kraus (1987) addressed several of the common methodological inadequacies of population-based studies of head injury from all causes. He concluded that there were then only 10 studies world wide that were of satisfactory quality and that comparison of the findings of these studies was rarely possible because of substantial differences in definitions of the types and severity of head injury.

Fife (1987) made use of data from the United States National Health Interview Survey rather than data from hospital separations. He reported that most persons who sustained a head injury in a road crash received medical attention but only 16 per cent were admitted to hospital (26 per cent of those who were injured in a motor vehicle crash). Furthermore, the rate of hospitalisation varied with age and income.

None of the studies referred to thus far gave estimates of head injury rates specific for car occupants.

The National Accident Sampling System maintained by the United States National Highway Traffic Safety Administration is the best example of a nationally representative road crash injury data base. In the years 1988 to 1990, approximately 55 per cent of car occupants involved in crashes in which a vehicle had to be towed from the scene were not injured. A further 36 per cent sustained minor injuries, 6 per cent moderate injuries and about 2 per cent sustained injuries that were rated as being serious or worse. (NHTSA, 1994b) When only the more severe injuries were considered, the head was the most commonly injured body region.

A hospital-based source of data on road crash injuries in Australia has become available with the establishment in 1992 of the Road Injury Information Program by the National Injury Surveillance Unit of the Australian Institute of Health and Welfare. Occupants of motor vehicles accounted for approximately 40 per cent of cases injured in a road traffic crash, with an annual hospital admission rate of around 90 per 100,000 population (a further 6 per 100,000 died before reaching hospital). Over half of the vehicle occupants were drivers.

For drivers admitted to hospital, the head was the most common severely injured body region (16 cases per 100,000 population) as was the case in the United States. (O'Connor and Trembath, 1994)

When attempting to estimate the incidence of head injury in New South Wales, Lyle et al approached the task in a curious way. Noting that a study conducted by Kraus (1984) in San Diego County was methodologically sound, they applied the incidence rates from that County to New South Wales, relying on the not inconsiderable assumption that the incidence of brain injuries would probably be similar in the two regions.

Research into the crash circumstances associated with head injuries to car occupants has been carried out in Australia by the NHMRC Road Accident Research Unit and Monash University Accident Research Centre. The results of these studies are presented in the body of this report.

Appendix B

Head Injury Biomechanics

SKULL FRACTURE

It is sometimes assumed that a countermeasure which reduces the risk of skull fracture will also reduce the risk of injury to the brain. While it is clear that distributing the force of an impact over as wide an area of the skull as possible will reduce the risk of the skull being fractured, it is important to note that brain injury may occur with or without skull fracture, and skull fracture may occur without brain injury.

Skull fractures may be grouped into three main categories: penetration fractures at the impact site, comminuted depressed fractures at the impact site, and linear fractures remote from the impact site.

Melvin and Evans (1971) suggest that depressed fractures tend to occur when the surface area of the striking object is less than about one square inch. Comminuted depressed fractures are a typical response of the skull in the transition from highly focal impacts to blunt impacts. (Melvin and Evans, 1971) Local bending of the impact site initiates tensile stresses in the inner table of the bone, and this is the initial site of fracture. Remote linear fractures are frequently associated with blunt head impact (Hodgson et al., 1970; Gurdjian et al., 1949) and commonly include fractures to the base of the skull, often extending into the cranium.

The direct fracture strength of the skull is dependent on the skull geometry in the struck region, together with the area of the impactor; the larger the area of the impactor, the higher the fracture strength. (Allsop et al, 1991) It has also been noted by various authors that the base of the skull is highly susceptible to remote fracturing. In particular, fractures to the sphenoid bone in the base of the skull are common among those presenting with head injury, probably due to the anatomical configuration of that bone. (Unger et al., 1990)

BRAIN INJURY MECHANISMS

Viano et al. (1989) classify brain injury mechanisms as either contact or inertial. As the name suggests, contact mechanisms of injury occur due to the contact that takes place between the head and the struck (or striking) object. Contact forces cause local skull deformation that can result in brain contusion or blood vessel disruption underlying the site of the impact. Inertial mechanisms arise from the rigid body accelerations of the skull during impact. The mechanical properties of the tissues that comprise the head differ substantially from each other and the brain and skull are not fully coupled; so when the skull is subjected to high levels of acceleration, relative motion between the skull and the brain is thought to occur, as well as deformation in the brain tissue itself. Relative motion between the skull and the brain can cause tears in veins that bridge the brain and the skull and can force the brain tissue against bony protuberances inside the cranium (Viano et al., 1989). Brain deformation can cause intracerebral stresses and strains which have been postulated as being a cause of diffuse axonal injury (Margulies and Thibault, 1989).

Much of the literature has focused on determining the kinematic parameters that invoke any or all the mechanisms of brain injury. Although research in this area has taken place over a period of more than 30 years, there is still no broad agreement over the critical parameters which determine the outcome of a head impact. Fan (1993) reviewed several major series of animal experiments and clinical trials and concluded that it was possible to say that brain injury outcome is highly dependent on the resulting rotational acceleration, translational acceleration, the duration of impact, contact effects of the impact and the presence or absence of skull fracture.

HEAD IMPACT TOLERANCE CRITERIA

The Head Injury Criterion (HIC) is by far the most widely used measure of the risk of an impact to the head resulting in a life-threatening brain injury. This is due in no small part to its specification in United States Federal Motor Vehicle Safety Standards. The Head Injury Criterion has been controversial since its inception, with many authors questioning its relevance, and significant effort has been put into trying to find suitable alternatives. The derivation of HIC is described below to illustrate some of the reasons for these concerns, and why HIC continues to be used.

Lissner (1960) published a curve which was generated when he plotted the acceleration of impact against the pulse duration for a series of fracture causing impacts with cadaver heads. Additional data was added to this original set by various authors, and the resulting curve became known as the Wayne State Tolerance Curve (WSTC) (Figure B.1).

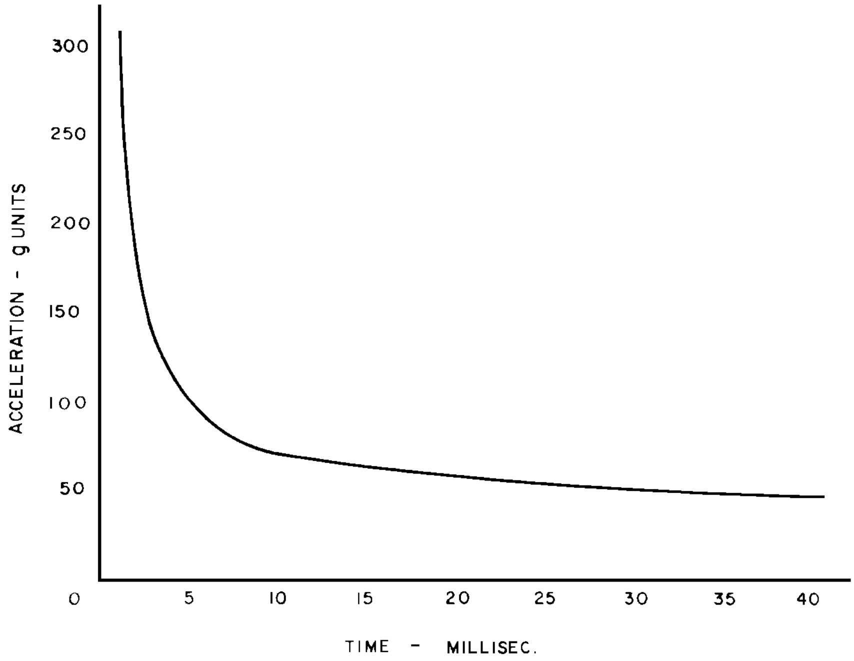


Figure B.1
The Wayne State University Cerebral Concussion Curve.

The WSTC was meant to represent a relationship between acceleration, pulse duration, and intracranial pressure. It purports to describe, given an ‘average’ acceleration and impulse duration, the limit beyond which cerebral concussion would occur. The curve has been the subject of much criticism, both in its construction and application.

In 1966, Gadd introduced the Gadd Severity Index (SI) which put the WSTC into the form of the following equation.

$$SI = \int_0^{t_1} a^{2.5} dt$$

where
a = the head acceleration impulse function
t_1= the impulse duration

According to Gadd, if the SI exceeds a value of one thousand, the impact acceleration should be considered to be ‘dangerous to life’.

In 1971, Versace modified Gadd’s equation to address the averaging of the acceleration that was part of the original WSTC and to counter some of the problems of the SI in handling long impulse durations (Versace, 1971). What he proposed would become the Head Injury Criterion (HIC) which is of the following form

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

where t_2 and t_1 are chosen to maximise the function. Again, if the value of HIC exceeded 1,000, it was considered to be life threatening.

As mentioned earlier, HIC is the most widely used index to assess head injury risk. This is due in no small part to its use in American Federal Motor Vehicle Safety Standards (McLean, 1993). However HIC has been the subject of criticism; mainly in that it is single valued, when the tissues of the head vary widely in their mechanical and failure behaviour; it does not take into account rotational components of the impulse; the data that were used for its construction are dubious (the presence of skull fracture was used as an indicator of cerebral concussion).

In defence of the WSTC as an index of head injury, Hodgson and Thomas (1970) mention that the study of high speed film of head impacts shows that little rotation is experienced in typical head impacts and that the rationale of the curve is that if effective head accelerations are designed to be well below the curve, then the mechanisms which produce cerebral concussion will be diminished along with other injury producing mechanisms. They note however that the curve has been subject to misuse (Hodgson and Thomas, 1970 and 1971). They suggest that the WSTC should only be applied in cases of frontal impact against a flat rigid surface, when the acceleration impulse is of a roughly triangular shape (Hodgson and Thomas, 1971).

One of the most extensive criticisms of the WSTC and HIC comes from Newman (1980). In his critique he highlights shortcomings in the data used to construct the WSTC. Newman then proceeds to argue that by expressing injury risk as a function of acceleration and time, one has to assume that all other parameters associated with an impact are irrelevant or are somehow taken into account by the linear acceleration term. He goes on to say that head kinematics are only an output of the system; like injury they are a response to impact, and no evidence exists (to 1980) that could conclusively correlate injury with any kinematic parameter; therefore it is pointless to attempt to correlate injury with head kinematics. Newman also asserts that because anthropomorphic test devices only approximate the response of human beings, and because there is such a variation within the human population, the results of crash tests do not say anything meaningful about occupant head protection. Newman summarised several pieces of research that have attempted to examine the relationship between HIC and the Abbreviated Injury Score (AIS), and concluded that no correlation exists.

However many of Newman's criticisms have been attacked, both on his interpretation of the construction of the WSTC (Gadd, 1981) and on technical and theoretical grounds (Lockett, 1985). Lockett (1985) argues from first principles that the form of HIC is fundamentally correct. He concludes that different forms of a function similar in construction to HIC would seem, to a first order approximation, to be appropriate and that what is needed are the details of those functions for different kinds of impulsive loading, for different tissues.

There is also independent experimental support that HIC does provide some index to the risk of head injury. Stalnaker, found that the HIC function had some correlation to the Abbreviated Injury Scale ratings of head injuries of monkeys subjected to lateral impacts (Stalnaker, Low and Lin, 1987).

Work at the Japan Automobile Research Institute (JARI) also confirmed the existence of some concussion threshold curve (Ono *et al.*, 1980). In contrast to Newman who rejected the idea that a 'tolerance' curve existed, and instead there would be a continuum of injury, the work at JARI produced a concussion tolerance curve in the strictest sense. Known as the JARI Human Head Tolerance Curve (JHTC), the curve was produced from a series of monkey experiments, with the data scaled to apply to a human head. It was noted that in some experiments, the diagnosis of the extent of injury was concussion only, and later autopsy revealed some contusion. It was against this background that the curve was constructed. A series of cadaver experiments also allowed the construction of a threshold of cadaver skull fracture. The rationale behind these curves was that concussion is considered as a threshold for the transitory and reversible effects of head impact and that skull fracture is an indication of a danger threshold for more serious head injury. These curves are reproduced in Figure B.2. It was noted by the authors that there was a good agreement between the JHTC and the WSTC.

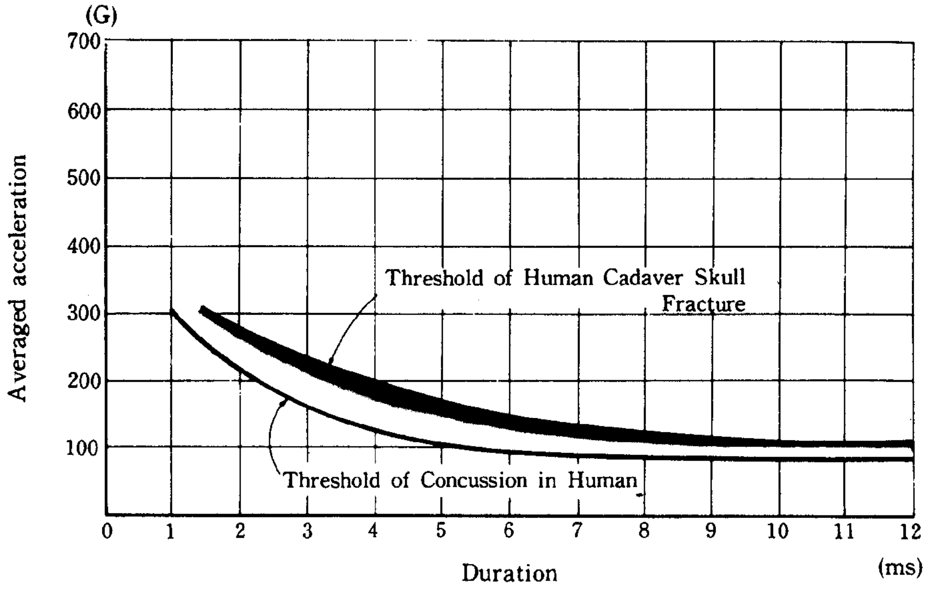


Figure B.2
JARI Human Head Tolerance Curve (JHTC)

Prasad and Mertz (1985) amassed the results of three separate series of cadaver experiments in an analysis to aid the US delegation to the ISO working group examining injury indices in automotive testing. One recommendation was that the HIC duration (t_2-t_1) should be limited to 15 ms. This recommendation was based on the experience of other workers who noted that quite high HIC values could be sustained for long pulse durations without injury. Further the US delegation recommended that if no head contact took place in an automotive test, HIC would be an inappropriate measure and neck load limits should be used instead.

Prasad and Mertz used a statistical method called the Mertz/Weber method to analyse the results of the series of cadaver experiments. This method assumes *apriori* that a correlation exists between HIC and the incidence of head injury, and that the likelihood of injury is normally distributed about some HIC value. A cumulative distribution curve of head injury as a function of HIC can then be constructed.

Hertz (1993) was able to improve on this distribution curve for skull fracture by choosing a lognormal statistical model. Using her model, the probability of skull fracture at an HIC value of 1000 is 47%. This distribution model was also used to test the hypothesis that HIC and the incidence of skull fracture are independent. This hypothesis was rejected at a significance level of $p = 0.0005$, indicating a statistically significant association between HIC and the incidence of skull fracture.

The non-applicability of HIC in non-impact situations has some support. After the analysis of impact accelerations experienced by American football players, human volunteer impacts with air-bags and impact tests with windscreens, Hodgson and Thomas (1972) hypothesised that a linear acceleration/time concussion tolerance curve may not exist and that only impacts of very short duration (e.g. with hard surfaces) may be of critical importance. They suggested that if the impact does not contain a critical HIC interval of less than 15 ms, the impact should be considered safe. There is observational evidence that, in fact, head injury without head contact is so rare that it is never seen in the clinical setting (Tarrierre, 1981 and McLean, 1994).

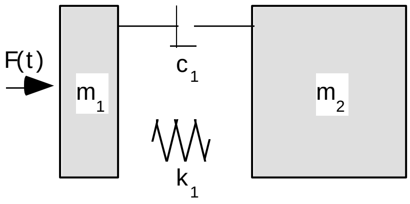
OTHER HEAD INJURY CRITERIA

Although there is some disagreement on the value of HIC as an index of head injury risk, there is a general consensus throughout the literature (e.g. Goldsmith, 1989) that if tolerance criteria are to be improved, they need to be developed to be specific to the different tissues of the head. Many researchers who support the above view often emphasise that acceleration does not cause the failure of tissues. Rather it is an excess of stress, strain (or some related parameter) in the tissue which causes the damage.

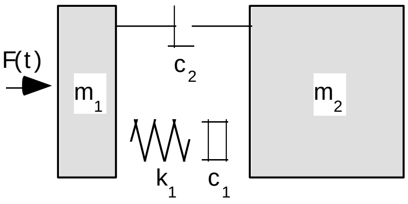
Another approach to the problem has been to examine the dynamic response of the head and from this, generate response models which try to predict the injury outcome of an impact.
One such series of models are known as the Translational Head Injury Models (THIMs) (Stalnaker, 1987). These were developed after measuring the dynamic response of sub-human primates and cadavers. Measurements of the dynamic response, in this case through the measurement of mechanical impedance, allow the investigator to develop a mathematical model that describes the behaviour of the system to any applied load.

Stalnaker developed such a model from impedance data that suggested that the response of the head was that of two masses linked by a spring and a damper (Figure B.3a) (Stalnaker, 1971a). This model became the basis of the Mean Strain Criterion (Stalnaker, 1971b) which correlates the amount of injury as being related to the deformation, or strain in the spring of the model. In 1985 this model was modified to more closely reflect impedance data recorded from scaled monkey and cadaver experiments. The result was a Translational Head Injury Model (THIM) which had a damper in series with the spring (Figure B.3b) (Stalnaker, 1985). The interpretation of the model was re-evaluated, and as a result the criteria for head injury differed from the earlier model.

Although the model is a mathematical one, and is not necessarily designed to represent physical reality, each element of the model represents some dynamic aspect of the head impact response. The smaller mass, m_1, was interpreted as the mass of the tissue that is locally deformed by the contact effects of an impact. The larger mass, m_2, is then the mass of the rest of the skull and brain which would have to be put into motion by energy transferred from m_1. The spring, k_1, was interpreted as the stiffness of the skull, while the damper in series with the spring, c_1, represented the dissipation of energy through the local deformation of the skull. It was found that the value for the other damper, c_2, did not vary with respect to the direction of the applied load, and was therefore interpreted as the dissipation of energy due to deformation of the brain tissue itself. For any given impact force, it would be the total energy dissipated in this damper (c_2) that would be available to injure the brain; not the deflection in the spring as defined in the Mean Strain Criterion. If the damper, c_1 cannot dissipate energy more rapidly than the rate at which strain energy is being accumulated in the spring, then the strain in the spring may exceed some critical value, analogous to the initiation of skull fracture. This scenario is described as an ‘overdriven impact’. Conversely, in an ‘under-driven impact’, the damping characteristic of the skull is able to dissipate energy as it accumulates in the spring. In this model, it is the peak rate of energy, or peak power, being absorbed by the spring that indicates a likelihood of skull fracture. These two conceptual criteria for brain injury and skull fracture were named the Translational Energy Criteria (TEC) (Stalnaker, 1987).



(a)



(b)

Figure B.3(a)
The earlier Translational Head Injury Model that modelled the mechanical response of the head as a 2 mass, 2 degree of freedom system. The model was the basis for the Mean Strain Criterion, which bases the risk of head injury on the deflection in the spring.

Figure B.3(b)
The most recent Translational Head Injury Model. This is the basis for the Translational Energy Criteria which uses the total energy dissipated by c_2 as a correlate for brain injury, and the rate of energy accumulating in k_1 as a correlate for the incidence of skull fracture.

A correlation between the TEC and observed injury was attempted. The original primate experiments that were the basis of the MSC were reanalysed and the force/time histories of these experiments were applied to the model. The grade of injury (as measured by the Abbreviated Injury Scale), and the incidence of skull fracture related well with the TEC predicted by the model. It was also found that, in the experiments, the HIC function correlated with the grade of injury. The TEC gave more information however, as it treated brain injury and skull fracture separately.

Willinger et al. (1991) have also taken a dynamic response approach to explain the incidence of peripheral brain injuries and more diffuse injuries such as diffuse axonal injury. Impedance data from volunteers suggested that the brain becomes isolated or decoupled from the skull at a frequency of about 100 Hz (Willinger et al., 1994). Impacts which contain high energy above this frequency (typically ‘hard’ impacts) therefore tend to induce relative motion between the skull and brain, causing peripheral injuries such as subdural haematoma and cortical contusions. According to this hypothesis, the brain is not so well isolated from the impact energy in impacts with ‘softer’ objects, which contain less energy at higher frequencies. In a gross sense, the brain and skull will move together under these impact conditions. The morphology of injuries caused by these impacts is expected to be qualitatively different, characterised by more diffuse brain injury. Willinger re-analysed monkey experiments performed to observe the relative effects of rotation and translation, and found that these qualitative differences were present in the experiments in a manner consistent with the hypothesis (Willinger et al., 1994).

Gennarelli and Thibault (1982a) found that to be able to continue to produce subdural haematomas when they increased the duration of the deceleration phase they also had to increase the level of the deceleration itself. This contrasted with their finding that axonal injury and concussion could be produced at lower deceleration levels when the duration of the deceleration phase was increased, a result which was consistent with the acceleration/time relationship shown in the Wayne State Tolerance curve (Figure A.2). Their explanation for this difference was that the bridging veins are sensitive to the rate at which the acceleration is applied. However, there is now evidence that the bridging veins are not strain rate sensitive. (Lee and Haut, 1989)

Lee et al. (1987), working with a two-dimensional finite element model of the brain of the rhesus monkey, concluded that the subdural haematomas may actually have been produced during the acceleration phase of the bi-phasic test device developed by Thibault and Gennarelli. This is because any increase in the duration of the deceleration phase had to be accompanied by a corresponding decrease in the duration of the acceleration phase, and hence an increase in the level of the acceleration was necessary to maintain a given level of deceleration.

The criteria discussed previously use linear acceleration as their bases. As a result of the evidence which shows the importance of rotational motion in injury causation, attempts have also been made to define some safe limit on rotation of the head due to impact. Ommaya and Hirsch (1971) summarised previous monkey studies to develop such a limit. Their hypothesis at that time was that rotational effects and contact effects equally contribute to the injury causing potential of a head impact. After scaling up to the human brain mass it was predicted that the limit for non-injurious rotational acceleration is in the order of 1,600 rad/s^2. The results of several other investigations were reported in Pincemaille et al. (1989), and the proposed limits of those investigations ranged between 1,700 and 4,500 rad/s^2 for rotational acceleration and 32 to 70 rad/s for the corresponding rotational velocity. In their study, Pincemaille et al. instrumented the heads of volunteer boxers and found that contrary to previous studies, the boxers could withstand angular accelerations well in excess of the published literature. They propose that the limit is in the region of 16,000 rad/s^2 with an associated rotational velocity of 25 rad/s, or 13,600 rad/s^2 when the associated rotational velocity is 48 rad/s. (Pincemaille et al., 1989)

There has been a growing recognition recently that even mild concussion can be associated with irreversible brain damage. Axonal injury may be found in humans who suffer only brief periods of unconsciousness. (Blumbergs et al., 1994)

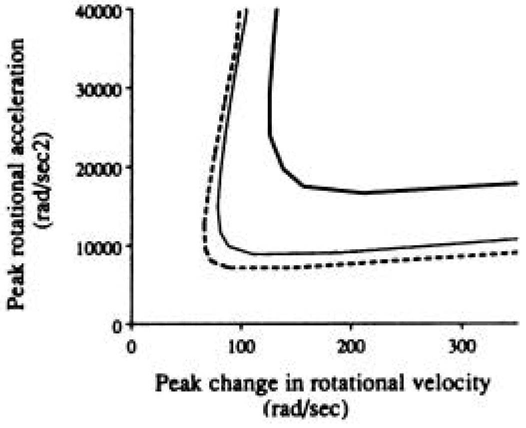


Figure B.4
Proposed DAI thresholds for a range of human head masses. DAI tolerances for infant (500g brain mass, heavy solid line) and adult (1067g, solid line; 1400 g dashed line).

Diffuse axonal injury (DAI) is recognised as an outcome of severe head trauma and has been observed experimentally (Gennarelli et al., 1982b). Margulies and Thibault (1992) have proposed a criterion for DAI. The criterion was developed from animal studies, physical model simulations and analytical models and is based on maximum permissible strain levels generated in the brain due to impulsive rotational acceleration of the head. As such, the criterion for critical strain varies depending on the brain mass. The criteria for three brain masses are illustrated in Figure B.4.

As has been illustrated, there have been many attempts to define criteria for critical impact to the head. These criteria have used different kinematic parameters as their basis, and many purport to relate well to observed injury. However, a complete and consistent picture has yet to emerge.

Appendix C

Padding Characteristics

An ideal energy absorbing material will be loaded to the maximum design load that the part of the human body that is being protected can withstand, almost instantaneously and remain at that level for the entire deformation phase of the loading. The unloading phase of the ideal material returns no energy to the system; i.e. the energy of the loading is entirely dissipated.

For example, the material with a load/deflection curve similar to curve 2-3 in Figure C.1 can only absorb approximately half of the energy of a material with a load/deflection curve similar to curve 1-3 which has an almost ideal loading phase. It is also desirable to dissipate as much of the impact energy as possible. The unloading curve 3 shows little energy rebound because most of the energy has been dissipated in the material.

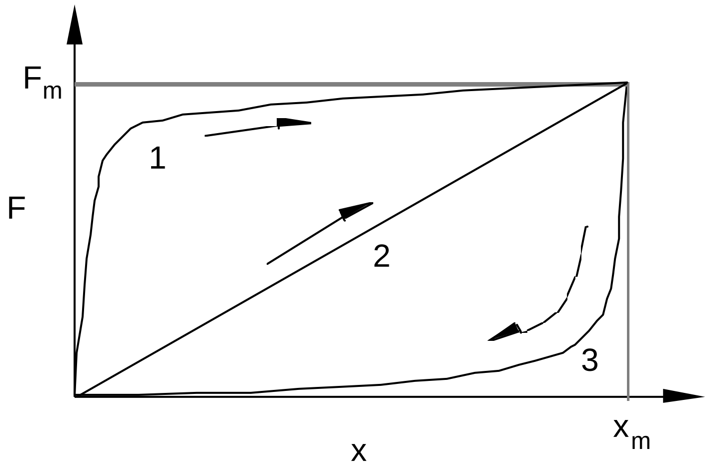


Figure C.1
Schematic Load Deflection Curves

F_m and x_m represent the maximum permissible force and the maximum deformation of the padding, respectively. (Adapted from Lockett, 1981 and Kanianthra, 1984)

The exact shape of the load/deformation curve for a specific part of the interior of a vehicle will depend not only on the material properties of the padding, but also on the shape of the padding, the behaviour of the related structural component and the shape of the part of the body which contacts the padding system.

Lockett *et al.* (1981) carried out a series of tests to characterise the properties of certain crash padding materials, and their behaviour under impact with objects of varying geometry. The tests were performed on a range of rigid and semi-rigid foams. The differences in behaviour of these two classes of materials are illustrated in Figure C.2. Previous research was cited that found that the stress strain relationship for foam was a function of strain and strain rate and could be written in the form:

$$s = g(e)\dot{e}$$

where

s = stress

$g(e)$ = a function of strain

$\dot{e}$ = strain rate

r = index

For semi-rigid materials, the equation $g(e\ )$ has the form

$$K(1-e\ )^{-n},$$

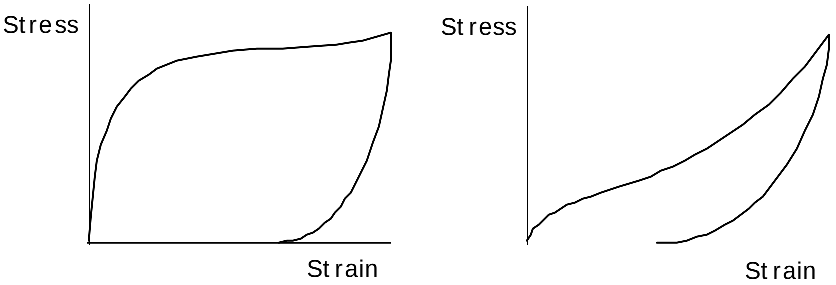
where K and n are constants. For rigid materials the form of $g(e\ )$ is

$$g(e) = K(1+me),$$

where K and m are real numbers. Further, for rigid foams over the range $0 = e = 0.6$, the term 'me' in the above equation is negligible so the function $g(e\ )$ can be adequately modelled as

$$g(e) = K = \text{constant}$$

It was also noted by Lockett *et al.* that the numerical values for *g*, *K* and *r* exhibited temperature dependence as could the form of the function, $g(e\ )$. Tables C.1 and C.2 summarise these properties for a range of materials. The rigid foams exhibited markedly less temperature dependence than the semi-rigid foams.



(a) (b)

Figure C.2
Schematic load/deflection curves of rigid foams (a) and semi-rigid foams (b) (Lockett *et al.*, 1981)

Table C.1
Data for rigid foams (at 20° C) (Lockett *et al.*, 1981)

	Material type	Density (kgm^{-3})	*K*	*r*	Temperature variation
1	Urethane	31.5	312	0.02	none
2	Urethane	75.5	730	0.06	-20%
3	Isocyanurate	50	385	0.06	-20%
4	Isocyanurate	53.5	374	0.05	-20%
5	Phenolic	43.5	67	0.08	none
6	Phenolic	50.5	327	0.03	none

Units for *K* are such that $Ke\acute{Y}$ is in kNm^{-2}
The temperature variation is the change in stress by heating the foam from -30° C to + 90° C.

From their results, Lockett *et al.* concluded that rigid and semi-rigid foams each have their advantages and disadvantages. Semi-rigid foams have a higher rate dependence (*r* value) than do rigid foams. This has the advantage that if the impact energy is less than the maximum the foam pad can withstand, the semi-rigid foam will express that energy as a large deformation and a lower force than a rigid foam would, which would tend to still reach the maximum design load but deform less. However, this advantage is offset by the fact semi-rigid foams also tend to be affected by temperature. The rigid foams depend on the breakdown of their structure for their energy absorbing effect, whereas the semi-rigid foams recover more after impact. The semi-rigid foams had more usable deformation depth than the rigid foams for the same thickness of padding. They concluded that a rigid foam with high rate dependence would be have desirable characteristics.

Table C.2
Data for semi-rigid foams (at 20° C)
(Lockett *et al.*, 1981)

	Material type	Density (kgm^{-3})	*r*	Temperature variation
7	Urethane	95	0.11	-70%
8	Urethane	85-89	0.16	-90%
9	Urethane	48,66	0.18	?
10	Urethane	120	0.09	?
11	Urethane	90	0.15	?
12	PVC nitrile	161	0.18	?
13	Ethylene	154	0.09	-90%
14	Ethylene	37	0.04	?
15	Scotfoam	52	0.30	?

The temperature variation is the change in stress by heating the foam from -30° C to + 90° C

The loading behaviour for a spherical indentor is different from loading by a flat object, due to the uneven loading caused by geometrical effects. Cited work in Lockett et al. (1981) showed that for rigid foams the load on a spherical indentor may be calculated as

$$L = 2pKd^2 e\acute{Y}\left[\frac{1}{n-1}\left(\frac{R}{d} - e + 1\right)\left\{(1-e)^{-n+1} - 1\right\} - \frac{1}{n-2}\left\{(1-e)^{-n+2} - 1\right\}\right],$$

where :

$R =$ the radus of the indentor ,

$u =$ the depth of penetration , and

$d =$ the thickness of the foam .

For semi-rigid foams this reduces to

$$L = pKd^2 e\left(\frac{2R}{d} - e\right)e\acute{Y}.$$

Both these equations are found to be more accurate if they are modified by a parameter which takes into account deformation of the foam outside the contact diameter;

$$\left(\frac{2R/d - e}{2R/d - e + 1}\right)^2$$

These governing equations were found to be valid under conditions of impact as long as the strain in the foam did not exceed per cent in which case the equations lose accuracy due to the effects of the foam ‘bottoming out’.

In addition, it was found that the geometry of the foam pad had an influence on the impact behaviour. Lockett *et al.* published formulae which allow the calculation of the maximum penetration u^* and acceleration g^* for padding that has a width which is less than twice the diameter of the impactor:

for $l < 2R < w$

$$u^* = \frac{MV^2}{4pK\left[R - \sqrt{R^2 - w^2/4}\right]^2}$$

$$g^* = \frac{2pK}{M}\left\{\frac{MV^2\sqrt{R^2 - w^2/4}}{4pK\left[R - \sqrt{R^2 - w^2/4}\right]^2}\right\} + \left[R - \sqrt{R^2 - w^2/4}\right]^2$$

where:
M = mass of the impactor
V = impact velocity
w = width of foam pad
l = length of foam pad
other symbols have their usual meanings .

It was found that geometrical effects could neutralise any differences between rigid and semi-rigid foams.

Since the publication of the paper by Lockett et al other padding materials have come onto the market. A rate sensitive foam ("Confor foam") presents little or no resistance to static loading but behaves like a rigid foam at high rates of application of a load, as in an impact. Gel materials, such as a polystyrene/glycol suspension, are also available which exhibit little shear resistance at low loading rates but high resistance under impact conditions. A gel filled pad has been developed to minimise the risk of falls in the elderly resulting in hip fracture. (Robinovitch et al., 1994)

Appendix D

Characteristics and Treatment of Head Injuries

Review of the Literature

SKULL AND BRAIN

Since the publication of our Report Head and Neck Injuries in Passenger Cars: A Review of the Literature (CR 59), understanding of primary brain injury has been advanced by a number of experimental studies. Adams (1962) has again presented an excellent general review of present knowledge. Povlishock et al (1989) have advanced evidence to suggest that injured nerve fibres (axons) may be intact in the first few hours after injury, but later undergo swelling, fragmentation and death. This has raised the hopeful possibility that long term disability may be minimised by some early therapeutic intervention (see below).

The pathology of minor head injuries has been explored by Blumbergs et al (1994) using immunochemical stains which show axonal changes within an hour or more after injury. These authors have found damaged axons in five elderly patients dying after minor head injury (concussion) from other causes. This important finding needs to be refined in younger accident victims, but gives strong support to earlier evidence (summarised in CR 59 p.2.6) suggesting that the symptoms persisting after a minor head injury may have a basis in structural brain damage. This has important medicolegal implications.

TREATMENT OF HEAD INJURIES

In the last decade, much attention has been given to improving the emergency management of road accident victims. There has been debate on the relative merits of immediate transport to hospital, compared with the provision at the roadside of procedures classed as advanced life support, such as endotracheal intubation and intravenous infusion; in a study carried out in South Carolina, Reins et al. (1988) concluded that paramedics with these skills gave improved pre-hospital treatment when compared with ambulance crews able to give only basic life support, though at the cost of longer periods of delay at the accident site.

However, this debate is still unresolved.

Given that in some cases such advanced support may be life-saving, should it be provided by trained paramedics, as in many North American trauma systems, or by medical retrieval teams, as in Germany? A comparative study by Schmidt et al (1992) appeared to favour the German system but considerations of logistics and cost suggest that medical retrieval teams have to be used in a selective way, and many feel that the two systems are complementary. In Australia, the states have to some considerable extent adopted different policies on the basis of perceived geographic and economic differences, and it should be possible over time to make useful comparisons, provided that efficient prospective trauma auditing is available.

In 1989, to improve the quality of emergency management, whether at the roadside or in hospital, the National Road Trauma Committee of the Royal Australasian College of Surgeons (1989) issued its first course manual on the early management of severe trauma (EMST) in association with a series of short courses giving practical hands-on instruction on the assessment and emergency treatment of major injuries, including head injuries. These courses are modelled on the Advanced Trauma Life Support courses introduced by the American College of Surgeons in 1978, and have been especially popular among surgeons, anaesthetists, emergency physicians and rural general practitioners.

82

In the definitive management of the severe head injuries so often resulting from road crashes, no major changes have been evident since our last review. There is continued emphasis on the need to maintain as far as possible a normal physiological state, and especially to maintain normal cerebral oxygenation; in practice, this means multidisciplinary intensive care and elaborate monitoring systems with special attention to continuous estimations of the cerebral perfusion pressure (arterial blood pressure — intracranial pressure), and to the blood oxygen and carbon dioxide levels. Measurement of these gas levels in the jugular vein near the skull base more accurately reflects the cerebral state.

Recent reports on the management of severe closed head injury have considered the merits of barbiturate therapy (Eisenberg et al 1988), hyperbaric oxygen therapy (Rockswold et al 1992), and hyperventilation (Cruz 1995); inspired by hopes that some of the effects of neurotrauma may be reversible, several supposedly neuroprotective drugs have been trialed or are in the process of trial (e.g. The European Study Group on Nimodipine in Severe Head Injury 1994). So far, none of these studies has led to a major change in accepted management plans, though barbiturate therapy is often used in selected cases of intractable raised intracranial pressure.

Intracranial haemorrhages, especially subdural haemorrhages, are an important case of death and disability in car occupant victims, and it is agreed that early operation is desirable — so much so that Sugrue et al (1995) have listed delay in performing a neurosurgical procedure as a negative performance indicator if in excess of *one hour* after admission. It remains to be shown that very early intervention will greatly affect the mortality from acute subdural haematoma which has hitherto carried a mortality usually in excess of 60%. Howard et al (1989) reported bad outcomes in only 33% of young (18-40) cases, but the results reported by Wilberger et al (1991) were less encouraging.

Head injury rehabilitation continues to cause much concern, but no dramatic advances in management have been reported in the last decade.

Appendix E

EXAMPLE OF THE HARM REDUCTION METHOD

This section only available in printed form.

84

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