

Passenger Car Roof Crush Strength Requirements

Prepared by:

Michael Henderson

Michael Henderson Research

Michael Paine

Vehicle Design & Research

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Michael Paine
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Authors

Michael Henderson, Michael Paine

Performing Organisation

Michael Henderson Research
49 Bakers Road
Church Point NSW 2105

Vehicle Design & Research
10 Lanai Place
Beacon Hill NSW Australia 2100

Sponsored by / Available from

Federal Office of Road Safety
GPO Box 594
CANBERRA ACT 2601

NSW Roads and Traffic Authority
PO Box K198
Haymarket NSW 2000

Abstract

Rollover crashes are usually very destructive events. Vehicle damage often includes deformation of the roof and its supporting structures. Head and neck injuries are common, and associated with roof deformation. An investigation has been carried out to predict the effectiveness of applying FMVSS 216 in Australia to reduce rollover associated trauma. The main conclusion being that the FMVSS 216 is an inadequate standard, and that there would be little or no incremental benefit in introducing an Australian Design Rule based on it.

Keywords

ROLLOVER, ROOF CRUSH,

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EXECUTIVE SUMMARY

Rollover crashes, especially in the country, are usually very destructive events. About 15% of passenger cars in fatal crashes in Australia have overturned. Between about 13% and 16% of all passenger-car occupants killed in Australia died primarily as a result of injuries received in a rollover. Vehicle damage often includes deformation of the roof and its supporting structures. Head and neck injury are common, and associated with roof deformation. Strengthening of the roof is often suggested as an appropriate countermeasure for such injuries.

The Department of Transport, through the Federal Office of Road Safety, requested a review of the costs, benefits and feasibility of introducing a new Australian Design Rule based on the relevant US rule, which is Federal Motor Vehicle Safety Standard 216. This would apply in Australia only to passenger cars, and not include convertible models.

Review of the local statistics indicates that if a roof crush standard (or any other measure) were *perfectly* effective in preventing death or injury in rollover, the maximum benefit for belted occupants would be in the order of 30 deaths and 140 serious injuries prevented a year.

The cost to Australian manufacturers of introducing a standard based on FMVSS 216 is estimated by the Federal Chamber of Automotive Industries to be, for those small minority of current models (some 2%) which are believed not to comply with FMVSS 216, \$125,000 (average) per body style for development and testing programs.

Of those current models that are believed currently to comply with FMVSS 216, \$375,000 (average) per body style for certification requirements is estimated. In respect to future models, estimated costs for design, development, testing and certification to FMVSS 216 are estimated to be in the order of \$85,000 per body style.

The relationship of roof crush and strength to injury is the fundamental issue in determining whether roof strength standards (including FMVSS 216) might be of value in Australia. It has long been taken for granted that roof crush is directly and causally related to occupant injury. It is envisaged that the roof is forced "down" upon the head and neck of the occupant as the car overturns, and that this mechanism is the direct cause of the injury.

However, although there is almost certainly an *association* between roof strength and head/neck injury in rollover, whether this association is *causal* remains a matter of debate. Recent, comprehensive statistical studies have confirmed a positive relationship between roof damage and occupant injury. What has *not* been shown, however, is any relationship between differences in roof strength as measured in the test used for FMVSS 216 on injury outcomes.

Rollover testing has also resulted in debatable conclusions on the relationship between roof deformation, roof strength and occupant injury. The dummies used for such testing are not well suited to rollovers, because of the lack of biofidelity of the dummy neck. Further, rollover test conclusions have been based on biomechanical criteria - in particular, axial neck loads - that in themselves are open to doubt on their real-world validity.

For the purpose of this project, slow motion analysis of the videos of real-world rollovers in rally competition was performed. This revealed that substantial changes in the angular velocity occur as parts of the vehicle contact the ground. This results in high tangential forces on the occupants. The head and arms of occupants, despite restraints, commonly extend well outside open or broken side windows.

The combination of vertical acceleration/deceleration, horizontal decelerations and rotational acceleration/deceleration generally results in complex occupant kinematics during a roll-over. Occupants are thrown from side to side and up and down in a chaotic manner. Partial ejection through open or broken side windows is a strong possibility, even for restrained occupants. Roof damage mostly results from a combination of vertical and horizontal loads on the roof and its supporting structures.

Some testing of Australian vehicles to FMVSS 216 has been performed in Australia, at Monash University. With the exception of a 1990 sedan all vehicles passed this test. The results from these tests confirm that the loading which in the end defines the crush is a bending one on the A pillar, rather than an axial load. This is in accordance with field observations. The windscreen, and its bonding to the body structure, therefore has great influence on the resistance to crush, because the screen is supporting the pillar.

In the view of the present consultants, the FMVSS test method used to assess strength is unrelated to the kind of strength that is required in rollovers - particularly, resistance to bending of the A pillars (and to some extent bending of the B pillars) after the windscreen has broken. The kind of strength that is required will be more able to withstand inverted impact in the presence of forward motion, as well as impact with the ground after end-over-end and

launching rollovers, where height from the ground has been gained and the vertical velocity on impact is substantial.

Thus, the main conclusion of this review is that the FMVSS 216 is an inadequate standard, and that there would be little or no incremental benefit in introducing an Australian Design Rule based on it.

It is recommended as follows:

- that through international forums the Federal Office of Road Safety should closely monitor, and where appropriate encourage, moves to update and improve the existing FMVSS 216;
- that in the short term the Federal Office of Road Safety review the feasibility of introducing an Australian Design Rule based on the newly amended FMVSS 201 for head impact protection;
- that investigations be mounted into the incidence of ejection of restrained occupants, which could in turn be related to inadvertent unlatching of the seat-belt buckle and instability or weakness of the seats and their mountings;
- that related vehicle design improvements identified in the work of Rechnitzer and Lane, at Monash University, should be the subject of further study.

Rollover is an important cause of injury in road accidents in Australia. It is considered that improvement in roof strength (perhaps in certain key impact directions), along with other countermeasures, would decrease the incidence of rollover-related injuries, not only from contact with the ground during inversion but also from contact with roadside obstacles.

However, it is not considered that the introduction of an ADR based on FMVSS 216 would have more than a minimal effect among such countermeasures, and thus its introduction cannot be justified in its present form.

1 BACKGROUND

Rollover crashes, especially in the country, are usually very destructive events. Vehicle damage often includes deformation of the roof and its supporting structures. Head and neck injuries are common, and associated with roof deformation. Strengthening of the roof is suggested as an appropriate countermeasure for such injuries.

There are currently no rules covering the strength of the roofs of passenger cars in Australia. Similarly, there are no roof crush strength regulations in Europe and consideration of such standards appears to be of a low priority. Only in the north of America is there a requirement for the strength of vehicle roofs, and that requirement is about 20 years old.

The Department of Transport, through the Federal Office of Road Safety, has requested a review of the costs, benefits and feasibility of introducing a new Australian Design Rule based on the US rule, which is Federal Motor Vehicle Safety Standard 216. This would apply in Australia only to passenger cars, and not include convertible models.

The present report documents the results of this review.

1.1 Standards and regulations in other administrations

In the United States, the relevant regulation is based on US Federal Motor Vehicle Safety Standard (FMVSS) 216, *Roof Crush Resistance, Passenger Cars*. This standard establishes strength requirements for the roofs of passenger cars and is intended to reduce deaths and injuries resulting from the crushing of the roof into the passenger compartment in roll-over accidents. A copy of the standard is attached as Appendix 1.

In Canada, the only other country with such a requirement, their CMVSS 216 is identical with the American FMVSS.

In April 1991, the National Highway Traffic Safety Administration (NHTSA) announced that FMVSS 216 was to be extended to light trucks, buses and multi-passenger vehicles not exceeding 6000 pounds, and that requirement came into force in September 1993. American statistics have long indicated that the fatality rate when light trucks (including four-wheel drives and utility vehicles) are involved in rollover accidents is twice that for passenger cars.

In December 1994, NHTSA requested comments concerning test procedures employed to establish compliance with the roof crush standard FMVSS 216. The motor vehicle industry had argued that current test procedures may not be "effective" for vehicles with sloping aerodynamic roofs or raised roofs. The NHTSA is currently initiating research in response to these comments in order to determine whether to amend the standard.

In Europe, there is an ECE Regulation (Number 29) which was first issued in 1974 and which applies to commercial vehicles intended for the carriage of goods. This includes requirements for the strength of the roof and the rear wall of driving cabs, but is intended primarily to resist intrusion by dislodged goods.

In both the United States and Europe there is consideration of the possibility of introducing requirements for rollover *propensity* based on a maximum tilt table angle. However, the present report is not concerned with rollover propensity.

1.2 Previous reviews of relevant Australian regulations

Previous reviews of the Australian Design Rule system and the feasibility of new occupant protection measures for Australian cars have not covered the question of rollover protection in any depth. A review of the Australian Design Rules in 1982 concluded that rollover protection was adequately covered by the use of lap/sash seat belts (Vehicle Regulatory Review Team, 1982). A review of the feasibility of proposed occupant protection measures conducted for the Federal Office of Road Safety by the Monash University Accident Research Centre concentrated on protection in frontal crashes (Monash University Accident Research Centre, 1992). Similarly, a review of vehicle safety improvements for cars in the European market concentrated on other kinds of crash, and did not discuss the matter of rollover protection or the strength of passenger car roofs (European Transport Safety Council, 1993).

2 THE CHARACTERISTICS OF ROLLOVER CRASHES

2.1 The incidence of rollover

Rollover crashes are very harmful events. In 1993, 11% of all fatal crashes in Australia involved an overturning vehicle, and 10% of crashes resulting in serious injury did so (Attewell and Traficante, 1995).

There are several other estimates of the incidence of rollover in the literature, but few are comparable one with the other because of differences in vehicle type and distribution in the sample, geography and demography, crash severity and crash definition. Broadly, the more the severe the crashes in the sample analysed, the more likely it is that the crash included a rollover.

A summary of the number of occupant deaths in rollovers involving only passenger cars, as documented in the three FORS Fatality Files, is shown in Table 1. It can be seen that with a fair degree of stability since 1988, about 15% of passenger cars in fatal crashes overturned. Between about 13% and 16% of all passenger-car occupants killed in Australia died primarily as a result of injuries received in a rollover.

Table 1 - Passenger car¹ occupant fatalities and rollovers, Australia, 1988, 1990 and 1992

Source: FORS Fatality File, years 1988, 1990 and 1992

	Total occupants killed	Occupants killed in rollover vehicles	Occupants killed in rollover vehicles, percent of all occupants killed
1988	1432	347	15.9%
1990	1155	252	15.6%
1992	1046	228	13.3%

	Total vehicles with fatalities	Vehicle rollovers in fatal crashes	Vehicle rollovers in fatal crashes, percent of total vehicles with fatalities
1988	2091	320	15.3%
1990	1651	236	14.3%
1992	1436	215	14.9%

¹ "Passenger car" includes sedans, hatchbacks and station wagons which are not convertibles.

The type of rollover, as recorded in the 1992 Fatality File, is shown in Table 2. (The table is again for passenger cars, being sedans, hatchbacks and station wagons that are not convertibles.) Out of the 228 total number of occupants killed in rollovers, 179 cases (78.5%) died either without a collision occurring before the roll (88 cases), or after a collision that in itself was not life-threatening (91 cases).

Overturning is a particularly prominent feature of *rural* fatal crashes. In 16% of rural fatal crashes, the impact primarily associated with the death is overturning. This is an incidence more than three times the 5% of urban fatal crashes in which the primary impact is associated with a rollover (Henderson, 1995). The more remote the location, the more likely it is that overturning is a component of the crash.

Table 2 - Passenger car rollovers and occupant fatalities by type of rollover, Australia, 1992 (Source: FORS Fatality File, 1992)

Type of rollover	Occupant fatalities	Rollover vehicles, occupant fatalities	Rollover vehicles, no occupant fatalities
Without prior collision	88	82	2
After non-lethal major frontal collision	19	19	4
After non-lethal major drivers side collision	9	9	1
After non-lethal major passengers side collision	11	7	0
After non-lethal major rear collision	6	6	0
After non-lethal minor frontal side collision	30	28	1
After non-lethal minor drivers side collision	8	4	1
After non-lethal minor passengers side collision	2	2	0
After non-lethal unspecified collision	6	6	1
Sub-total (after non-lethal prior	91	81	8
After lethal major frontal collision	20	17	0
After lethal major drivers side collision	14	12	0
After lethal major passengers side collision	12	11	0
After lethal minor frontal collision	2	1	0
After lethal unspecified collision	1	1	0
Sub-total (after lethal prior collision)	49	42	0
Total	228	205	10

In comparison with passenger cars, there is a much higher proportion of four-wheel drives and vans in which the primary cause of the occupant death is overturning. On rural roads, overturning is associated with 15% of fatal crashes involving passenger cars. The incidence is more than twice as high for vans and four-wheel-drive vehicles, at 32% and 34% respectively. This relatively high risk of overturning in a crash is well recognised among crash analysts in this country and others.¹ However, the focus for this report is on passenger cars, which are numerically far more highly represented in all crashes, including fatal rollovers.

2.2 Data from the FORS Fatality File

The 1992 FORS Fatality File was reviewed in more detail for the purpose of the present study, including examination of the individual files for cases involving rollover. As shown in Tables 1 and 2, there were 228 occupants killed in all passenger cars (not including convertibles) that rolled over. Table 2 shows that of these, 179 were reported to have died in rollovers without prior lethal collision. Examination of the case files revealed some miscoding, in that some of these 179 were not rollovers, and some in fact did involve a probably fatal prior collision. After extracting these cases, a sample of 172 cases formed the base data set.

Table 3 shows the number and percentages of the occupants who were wearing seat belts, by location in the vehicle and sex (not including missing data). The very low proportion of males wearing seat belts (46%) is noteworthy. Other data have shown that individuals who crash are generally less likely to have been wearing seat belts.² A known benefit of wearing seat belts is the prevention of ejection. Table 4 shows, not surprisingly, that the vast

¹ There are other factors that may affect the relatively high incidence of rollover-related fatalities in these vehicles. There is a higher percentage of them involved in crashes on semi-remote and remote roads than passenger cars, and fatal crashes on such roads are relatively likely to cause death by overturning because there are relatively few roadside obstacles or other vehicles to hit. Further, the seat-belt wearing rate among the fatally-injured occupants of these vehicles is lower (at around 30%) than among fatally-injured occupants of passenger cars (around 60%), and they may thus be more likely to be killed in rollover crashes.

² A low belt-wearing percentage in fatal crashes is also an indication of seat-belt effectiveness. The more effective the belt, the less likely it is that an occupant will be killed when restrained. The logical extension of this is that if a restraint system was 95% effective in a certain kind of crash, then nearly all killed in such crashes must have been unrestrained: a belt-wearing rate of 5%.

majority of those who were ejected were not wearing seat belts, and vice versa. Tables 5 and 6 show the high incidence of severe head and chest injury in this sample, among both those who were ejected and those who were not. Out of the 172 cases, more than half were recorded to have sustained head injuries of MAIS 4 or more, and more than one-third chest injuries of MAIS of 4 or more.

Table 3 - Seat belt wearing, by position in car and sex (missing and unknown data excluded) (Source: FORS Fatality File, 1992)

Position	MALES				FEMALES			
	Worn	Not worn	Total	% worn	Worn	Not worn	Total	% worn
Driver	27	31	58	47%	12	6	24	50%
Front left	9	8	17	53%	9	2	11	82%
Rear right	2	3	5	40%	2	2	4	50%
Rear centre	0	0	0		1	1	2	50%
Rear left	1	3	4	25%	2	1	3	67%
Totals	39	45	84	46%	26	12	45	58%

Table 4 - Ejection versus seat-belt wearing (missing and unknown data excluded) (Source: FORS Fatality File, 1992)

	Worn	Not worn	Total	% worn
Fully ejected	5	38	43	12%
Partly ejected	3	7	10	30%
Not ejected	57	14	71	80%

Table 5 - Ejection versus head injury severity (*maximum AIS*) (missing and unknown data excluded) (Source: FORS Fatality File, 1992)

	MAIS 0-3	MAIS 4-6	Total	% MAIS 4+
Fully ejected	13	34	47	72%
Partly ejected	1	8	9	89%
Not ejected	26	51	77	66%
Total	40	93	133	70%

Table 6 - Ejection versus chest injury severity (*maximum AIS*) (missing and unknown data excluded) (Source: FORS Fatality File, 1992)

	MAIS 0-3	MAIS 4-6	Total	% MAIS 4+
Fully ejected	15	21	36	58%
Partly ejected	4	4	8	50%
Not ejected	27	33	60	55%
Total	46	58	104	56%

Any standard for roof strength will be intended to have its beneficial effect primarily on belted occupants. Accordingly, from the base data set of 172 cases, a subsample was selected where seat belts were definitely worn, detailed information on the crash was available, and the rollover was the direct cause of death. This selection process left 61 cases for more detailed analysis. Detailed examination of the case files revealed that nine crashes, involving ten fatalities, had been miscoded (for example, death not due to rollover, not a rollover, or seat belt not worn). This left 51 cases for further examination. A short note on each of these cases will be found in Appendix 2.

Table 7 shows maximum AIS for the head by seating position, for these 51 belted cases. The driver and the front left passenger would be those who might benefit from a roof crush standard based on FMVSS 216. In these two positions, there were 18 drivers and 12 passengers, 30 in all, who sustained head injuries of AIS 4 or more, among whom there were nine who sustained AIS 6 (unsurvivable) head injury.

Table 7 - Maximum head AIS by seating position (belted only) (Source: FORS Fatality File, 1992)

	Maximum AIS (head)							Total
	0	1	2	3	4	5	6	
Driver	4	1	1	6	7	5	6	30
Front left	1	0	0	2	5	4	3	15
Rear right	1	0	0	0	1	1	0	3
Rear left	0	0	0	1	1	1	0	3
Totals	6	1	1	9	14	11	9	51

There were few spinal injuries in this sample of belted occupants. Only one driver was reported to have sustained a neck injury of maximum AIS 6 (a "pure" rollover in a 1976 Ford Falcon), although examination of the case files suggested that some other neck injuries had not been coded.

Thus, very approximately, of all occupants killed in rollovers where the cause of death was directly related to the overturning, about 30 (17% of 172) sustained severe head injury (MAIS 4+) and one an unsurvivable severe neck injury despite wearing seat belts. The serious injury database shows that there were 1661 occupants hospitalised after rollovers in Australia in 1993 (Attewell and Traficante, 1995). Only 235 (23% of 1661) of hospitalised car occupants were reported to have been wearing seat belts. About 60% of deaths in rollovers are a direct result of the rollover itself, and if the same applies to injury, then about 141 (60% of 235) belted occupants were injured because of the overturning. It is assumed that roof strength standards would be of little or no benefit to unbelted occupants.

Thus, if a roof crush standard (or any other measure) were *perfectly* effective in preventing death or injury in rollover, the maximum benefit for belted occupants would be in the order of 30 deaths and 140 serious injuries prevented a year.

The average cost of fatal crashes in 1993 was \$752,400, and a hospitalised injury \$113,100. Thus, the total annual cost of the above "preventable" rollover crashes is in the order of \$39 million (BTCE, 1993).

Unfortunately, while the FORS Fatality File records the location of damage to a vehicle, it includes very little information on the extent of vehicle damage. The point of primary impact (that is, the location of the impact that probably caused the death, as opposed to the impact that caused the most damage) is identified in most files. However, the *degree* of damage, whether at the point of primary impact or otherwise, is not identified.

The crash files for the 51 cases that complied with the following criteria were examined in detail: seat belt worn, fatality information available, rollover the direct cause of death, and vehicle model known. These examinations identified some interesting case histories, but the lack of damage data for all but a handful made more valid analysis of the contribution of roof crush impossible. In particular, in the files that are held permanently, little information is available for NSW fatalities, which are a substantial proportion of the whole (24 out of the 51, or 47%).

Detailed examination of the case files did confirm that in many cases the overturning vehicle also collided with a roadside obstacle, as will be seen from the short summaries in Appendix 2. The distortion of the roof that was associated with fatal injuries was not always due to the overturning as such, but also a result of impact of the roof against a solid object such as a tree. Most of the fatal head injuries were associated with head-to-roof contact, and with contact with the road and other external surfaces. "Lozenging", or "side-away" of the roof structures, in particular, appeared to allow partial ejection of the head although a seat belt was worn. In one or two cases where photographs were available in the file, survival (of occupants other than the deceased) was on the face of it surprising, given extreme damage and distortion of the roof structures in the vicinity of the survivor.

As noted in Table 4, there were a few cases where the deceased occupant was ejected apparently despite wearing a seat belt. To the extent possible these circumstances were confirmed. Apparently the occupant either slipped out of the belt, or the seat back deformed enough to allow the occupant to be dislodged from behind the belt, or the structure was sufficiently destroyed to disrupt the belt mountings. It was not possible to discern whether in any of these cases the belt buckle had become unfastened.

Following the above analysis of the 1992 Fatality File, an idea was gained of the size of the problem, and an idea of the savings to be gained if deaths and injuries to belted occupants in rollovers were to be totally prevented. Unfortunately, the level of detail in the Fatality File does not allow assessment of whether strengthening of the roof would have prevented the death in each

case, let alone whether the imposition of a standard such as FMVSS 216 would have done so.

Accordingly, the world literature was reviewed in order to ascertain whether other analysts had been able to come to relevant conclusions.

3 LITERATURE REVIEW

3.1 The mechanism of injury in rollover

The mechanisms of injury in rollover crashes are not well understood. The complex nature of the rollover event means that it is difficult to reproduce consistently. Because the reconstruction of rollover crashes is consequently also a complex matter, it has been difficult clearly to associate injuries with occupant kinematics and vehicle deformation. This has led to great debate about the extent to which roof deformation is the cause of injury.

A serious problem is controlling for the severity of the rollover crash. For non-rollover crashes the delta V is now widely accepted as a measure of crash severity. The delta V may be defined as the change in velocity of the centre of gravity of a vehicle from the time of first contact to the time of separation. This period is rarely more than 100 milliseconds or so. Although many rollover crashes are associated with impact either before or after the rollover, the rollover event itself may take several seconds and its severity cannot be assessed in terms of delta V. Without consistent test procedures it is difficult to assess either the risk of injury presented by a given design feature or the potential effectiveness of occupant protection countermeasures.

There are several full scale vehicle rollover test procedures that have been used at various times, and some will be reviewed briefly in this report. However, the relationship between them and real world crashes is not clearly understood.

Rollover crashes are such complex events that it is often difficult to establish exactly what part of the interior of the car was responsible for injury to a restrained occupant in rollover. Both Hight et al (1972) and Mackay and Tampen (1970) found the roof to be the most frequent source of rollover injuries, and both of these teams found that the heads and faces of occupants were the parts most frequently injured.

Terhune (1991), using the North Carolina Accident Database and National Accident Sampling System (NASS) data showed that the effect of rollovers on injuries was closely related to the higher crash speed of rollover crashes, that rollover increases the serious injury risk by 10-50%, and that rollover substantially increases injury risk even for drivers who are not ejected. He also found that ejection accounted in his sample for about half all drivers who were

seriously injured in rollovers. Terhune used intrusion variables which were added to the 1985 and 1986 NASS data base.

In order to examine the effect of roof crush his analysis examined only drivers using restraints, and compared head and neck injury with chest and abdominal injuries. To demonstrate that roof crush is causing head or neck injuries it is not enough to show a correlation between roof intrusion and head injury rates, because both the intrusion and the injuries could be resulting from the overall severity of the crash. If the roof intrusion is causing the injuries there should be a sharp increase in head injuries when the roof crush exceeds a certain point. In addition, if the head/neck injuries increase with roof intrusion but other injuries do not, that would suggest a causal connection between the intrusion and the head/neck injuries. Terhune's results showed that the rates for head injury did systematically increase with intrusion magnitude. However, the conclusions were unfortunately ambiguous because of the low numbers of belted drivers in the sample.

3.2 The importance of ejection

From the very first analyses, studies have confirmed the importance of ejection as a consequence of rollover crashes (Partyka, 1979). Both rollover and ejection were found to be each independently associated with a higher rate of fatality than in non-rollover crashes and non-ejection cases. Partyka concluded that ejection and rollover increase the odds of the risk of death by 34 times and two times respectively.

Malliaris and Digges (1987) analysed the incidence of ejections reported on the Fatal Accident Reporting System (FARS) file for crashes between 1975 and 1985. They found that the risk of death for those ejected from passenger vehicles was six times higher than for those not ejected in similar crashes, irrespective of the seating position.

3.3 Speed and rollover dynamics

Using both NASS and FARS data, Malliaris and DeBlois (1991) confirmed the importance of pre-crash travel speed in rollover crashes in the files for both non-fatal and for fatal crashes. For fatal crashes, the mean pre-crash travel speed for rollover-involved cars was 63.4 miles per hour, as opposed to 45.3 miles per hour for cars in all other fatal crashes. In addition, the characteristics of crashes showed that those involving a lateral slide were far more commonly associated with rollover than other kinds of crash. Travel speed in conjunction with the potential for lateral slide appears to influence profoundly not only the incidence but also the severity of rollovers. Computer simulation of some of the

key characteristics of the rollover event has shown that vehicle damage, in particular roof crush, is relatively insensitive to roll rate but is influenced to a great extent by vertical velocity (Digges and Klisch, 1991).

Segal (cited in Digges et al, 1991) studied a sample of 267 severe rollover crashes in the National Crash Severity Study (NCSS) file of crashes from 1977 to 1979. For about half these cases the pre-crash speed was estimated to be greater than 50 miles per hour. In most cases the car had skidded sideways before rolling, and most had both a lateral and forward component of velocity. The overturning motion was primarily a roll in 80% of the cases, with about 15% of vehicles having primarily a pitch motion and the remaining 5% a combined pitch and roll. Most of the vehicles rolled four quarter turns or less, and Segal noted that the severity of injury appeared to be related to the number of quarter turns experienced by the vehicle. The degree of roof crush was relatively independent of the number of roll turns.

3.4 The relationship of roof crush to crash severity

Still the subject of intense debate is whether injuries in rollover result mainly from the overturning or from the forces inherent in the higher crash speeds associated with rollover. In other words, is the fact that people are injured in rollovers simply a reflection of the relatively high severity of rollover crashes? Questions remain as to the importance of reducing roof crush, occupant ejection or rollover itself. As early as the 1950s and 1960s (Garrett, 1968) it was recognised that rollover crashes were associated with high rates of serious injury and that prominent in the data were roof crush, door openings and occupant ejection.

Mackay and Tampen (1970) commented that the correlation they had shown at that time between roof crush and injury level did not necessarily mean that the roof collapse caused the injuries, because both could be consequences of high collision forces. Hight et al (1972) agreed with these findings, and concluded that injury severity in rollover depends primarily on the independent factors of occupant ejection and vehicle impacts additional to the rollover.

3.5 The relationship of roof crush and strength to injury

3.5.1 The first challenge to assumptions: the issue of "cause"

The relationship of roof crush and strength to injury is, of course, the fundamental issue in determining whether roof strength standards (including FMVSS 216) might be of value in Australia. As noted above, in all discussions

about rollover crashes and occupant injury throughout the 1960s and 1970s it appeared to be taken for granted that roof crush was directly and causally related to occupant injury. Simply put, the roof was forced "down" upon the head and neck of the occupant as the car overturned, and this mechanism was the direct cause of the injury.

Huelke et al (1977) found that small cars experienced much less roof crush in rollover crashes than large cars. These authors, in a finding that has been confirmed by later research (Partyka et al, 1987; Council and Reinfurt, 1987), established that larger cars in rollovers tend to have higher injury rates than small cars in rollovers. This led to the conclusion that roof crush in the larger cars may be positively associated with injury in rollover, and confirmed assumptions that roof crush may be the cause of occupant injury.

However, in 1983 Huelke and Compton (1983) forced a re-examination of these assumptions. The sample of NCSS data analysed by these authors included 836 rollover crashes of all types, including 498 passenger cars with roof damage due to ground contact. They found that of those cars that had rolled, the smaller vehicles were over-represented when compared to their proportion in the NCSS tow-away accident population. The exceptions were a few sub-compact American cars and sports cars. The more serious injuries and fatalities were found to be 17 times more frequent among occupants who were ejected.

Although roof damage was common, only 15% of the more serious rollover injuries were attributed to occupant contact against the roof. Roof damage in the NCSS file is indicated by zones denoting the extent of crush; zones 1 to 5 extend from the roof surface to the level of the bottom of the side window and windscreen. These authors found that the rate of AIS 3 to 6 injuries increased as the roof deformation extended beyond zone 3, equivalent to about one-third of the distance down the side window. Not surprisingly, in cars with little roof deformation almost all the injuries were AIS 1 or 2, with the severity increasing in association with the degree of roof deformation. In rollover the head was the most often injured region of the body, but most of the head injuries were AIS 1 or 2. The more severe head injuries were in 75% of cases associated with ejection. In rollover crashes the chest, extremities and head were seriously injured more often than the back, neck or abdomen.

Among those not ejected, serious injuries of the chest and extremities predominated. There were few AIS 3 - 6 neck injuries at low and high levels of roof deformation. The majority occurred in cars with roof deformation in zones 3 and 4 (about the middle of the side window). Head and neck injuries were much more common among those occupants who were ejected.

Huelke and Compton stated categorically that roof deformation is not *causally* related to injury severity. They however go beyond causal relationships by stating as follows: "*If roof deformation were related to the more severe cervical injuries one would expect more injuries in zones 5 - 7, but this is not the case*". It is certainly true that in their sample there were a lower absolute number of head and neck injuries in crashes resulting in deformation of this severity, but there were also fewer crashes of this kind. Table 8 shows that using these authors' data, in 0.52% of crashes resulting in crush to zones 1 and 2 there were AIS 3+ injuries to the head and/or neck. However, there was a 1.45% incidence of AIS 3+ head/neck injuries with crush in zones 3 - 5, and 5.55% in zones 6 and over. The numbers are small in these very severe crashes, but they do show a relationship between crush and head/neck injury, even if it is not a causal one.

Table 8 - Head/neck 3+ injuries as percentage of rollover crashes by crush zone - non-ejected occupants in rollover

(Source: Huelke and Compton, 1983)

Crush zone	Number	Head/neck injury, AIS 3+	
		Number	Per cent
1 and 2	193	1	0.52%
3 to 5	1520	22	1.45%
6 and over	54	3	5.55%

The authors also state that roof deformation is not related to head/neck injury among ejected occupants. This is a reasonable proposition, but they do not give figures for roof crush incidence among vehicles from which passengers were ejected and therefore the risk cannot be calculated. The authors also correctly state that their data support earlier findings that roof deformation may be related to the severity of the crash.

In another paper the same authors (Huelke et al, 1985) took the examination of ejection further and showed that more than half of the more serious injuries (AIS 3 and more) occurred within the car before the ejection. They also established that in rollover crashes ejection was mainly through the side windows.

Strother et al (1984) suggested that the early literature on occupant crash protection had not recognised the distinction between the first and second collisions and thus placed unwarranted emphasis on any deformation that reduced occupant survival space. Intrusion was wrongly thought to be the *cause* of injuries. Following that line of thought led to the early experimental safety vehicle program, which incorporated a "strong box" concept and resulted in the development of what Strother et al refer to as impractical tank-like prototype vehicles that were generally too small on the inside to be suitable for the market.

Intrusion, they suggest, is the consequence of the first impact with the vehicle against some other object. Injury, on the other hand, is generally the consequence of the second impact between the occupant and a part of the occupied vehicle. Because the severity of both the first and the second impacts is related to the overall accident severity, some correlation between the effect of each stage (intrusion and injury) would be expected. Correlation, however, does not establish a cause and effect relationship. The stated purpose of FMVSS 216 was "to reduce deaths and injuries due to the crushing of the roof into the passenger compartment in rollover accidents". These authors argue, however, that making roof structures stiffer would *reduce* safety by adding weight above the centre of gravity (thus increasing the propensity for rollover) and reducing visibility for the driver. In addition, a stiffer roof would absorb less energy when struck, which in turn would increase the probability of additional rolls and ground impacts with the associated risk of more occupant contacts and ejection.

The logic of this argument is worked through by reference to a theoretical situation in which an occupant is positioned normally in, and falls in unison with, the occupant compartment of an inverted vehicle striking the ground vertically. The vehicle and the occupant are travelling at the same velocity at the instant the roof strikes the ground. After roof touches down, the occupant traverses the remaining interior space before contacting the roof, which may or may not deform. The occupant will then contact the roof with at most a slightly higher velocity than at the instant the roof struck the ground. The body of the vehicle follows at a speed decelerated by the crush of the roof. If there is no crush, the vehicle stops at the same time as the roof. In either case the vehicle does nothing to change the velocity of the unrestrained occupant into the roof, and therefore cannot affect the resulting injuries. *Short of actually squeezing the occupant between the two surfaces of the occupant compartment* (our emphasis), as the authors say, the intrusion of the roof has no effect on the injury potential for the occupant. For restrained occupants outside the roof

crush zone these authors suggest that crush is desirable, because it will reduce the loading of the seat belts on the body.

Strother et al also throw doubt on the utility of padding of the roof surfaces, and suggest that proper use of a lap/shoulder seat belt will almost always prevent neck injury of AIS 3+ in a rollover crash. They do concede there remains a possibility that a restrained occupant in rollover would be at greater risk of injury due to roof crush, but suggest that this would not apply until roof crush exceeds about 18 inches. (This would presumably lead to the "squeezing" effect referred to above, and which appears to be a feature of some real-world crashes.) However, when this paper was written (1984) there were very few statistical data in the United States relating to severe injuries in belted occupants in rollover crashes.

Support for contentions such as the above, and for the related arguments by Mackay et al (1991) and Huelke and Compton (1983), was strengthened by a paper by Plastiras et al (1985). (This paper was a precursor to that of Moffatt and Padmanaban, 1995, reviewed further below.) These authors examined the relationship of performance in the roof crush test (FMVSS 216) and the likelihood of injury following rollover for a selection of different car models. Their hypothesis was that if FMVSS 216 was effective, then cars that performed relatively "better" in the roof crush test would also perform relatively "better" in protecting passengers in rollover crashes on the road. Injury rates obtained from accident and injury data from the State of Washington (using police reported data) revealed that there was no apparent relationship between roof crush performance, as measured by the roof crush test specified in FMVSS 216, and occupant protection as measured by injury rates reported in the Washington state accident data base. (There was no comparison, of course, between vehicles complying with FMVSS 216 and vehicles which were not in compliance.)

In England, Mackay et al (1991) analysed the rollover crash characteristics and injury consequences for occupants in 158 urban rollovers involving 282 occupants. These authors found that the typical urban rollover was not a dramatic crash, but was associated with a generally low level of injury severity for both restrained and unrestrained occupants. Those who were ejected were far more likely to be fatally injured than those who were not. These authors again stated that roof crush was not found to be responsible for causing injury, and that there appeared to be little to support the view that roof crush is directly related to occupant injury severity in rollover crashes. They reiterated the view earlier expressed by Huelke and others that roof crush was merely an indication of accident severity and that injury severity increases with accident severity.

Mackay et al (1991) tabulated intrusion (in centimetres) against maximum AIS (MAIS). Their results are summarised in Table 9, which is based on Table 13 in their paper. It may be seen that among occupants with an MAIS of 1 or 2, 64% were injured with intrusion of 1 to 15 cm and 36% with intrusion of more than 15 cm. For occupants with an MAIS of 3 to 6, 40% were injured with 1 – 15 cm and 60% with intrusion of more than 15 cm.

Table 9 - Maximum AIS by roof intrusion

(Source: Mackay et al, 1991)

Roof intrusion	MAIS 1-2		MAIS 3-6		Total
	Number	Per cent	Number	Per cent	
1 - 15 cm	45	64	6	40	51
> 15 cm	25	36	9	60	34
All	70	100	15	100	85

The numbers for severe injuries are rather small in this sample, but they are strongly indicative of a relationship between the more severe injuries and the more severe intrusion. Although this relationship does not quite reach statistical significance if techniques are employed to allow for the small numbers, it does strongly suggest that severe deformation is related to severe injury. The authors feel confident in stating that "from the available data it would appear that roof intrusion and injury severity are not causally related". This may be true. However, they also state in the paper that "roof crush in this study did not relate to injury severity". Their data do not support such a firm conclusion on the matter, and a causal connection is neither proved nor disproved.

That a relationship existed, whether causal or not, was shown by McGuigan and Bondy (1984), cited in Terhune (1991). They studied severe injuries in a NCSS sample. They also examined roof intrusion and noted a step increase in severe injuries beyond 16 inches of roof crush. Looking specifically for a relationship between roof crush and injury, Cohen et al (1989), using National Accident Sampling System (NASS) data from 1981 to 1986, found that the

primary area of damage and the extent of roof crush were good indicators of injury for restrained and unrestrained occupants who were not ejected.

A similar study was performed by Friedman and Friedman (1991), who concluded from their analyses that vehicle upper structure should be the next high priority goal in reducing severe casualties. Using data from the 1982 and 1983 NASS files they selected out data for rollover crashes involving passenger vehicles. They analysed the proximity of roof crush to occupant location, and showed an increased risk of critical injury and death of approximately four times in rollover impacts for occupants in the proximity of significant roof crush (restrained and unrestrained occupants combined.) They reviewed 15 cases of critical injury or death in real world rollover crashes, and showed that occupants under a significantly crushing roof were likely to suffer critical neck or brain injury. On the other hand, those not in the proximity of the crushing roof suffered no critical injuries. They concluded that all the critical injuries would have been eliminated by the inclusion of a stronger roof structure plus two inches of interior force-limiting metal padding.

The US National Highway Traffic Safety Administration, which might be regarded as having a vested interest in that FMVSS 216 is "their" standard, has expressed rather equivocal views in its various reports. In the original Notice of Proposed Rulemaking issued in January 1971, NHTSA noted that there had been a few comments that "suggested that there is no causal relationship between roof deformation and occupant injuries in rollover accidents. However, available data has shown that for non-ejected front seat occupants in rollover accidents, serious injuries are more frequent when the roof collapses".

In recent years Kahane (1989) has stated that the roof has to be strong enough to resist crush in rollovers, restating an earlier NHTSA position that the relationship between roof crush and injury is self evident and supported by statistics. Rains and Kianthra (1995) compared 35 rollovers with mostly minor head injuries with 120 rollovers without head injuries and concluded that roof crush causes injury, but did not address the issue that roof crush and crash severity are also related and that the causal association between injury and roof crush is not well established by this or other analyses.

3.5.2 *The relationship of FMVSS 216 strength to injury*

A substantial contribution to the debate on the relationship between roof strength and occupant injury in rollover was recently reported by Moffatt and Padmanaban (1995). They used police-reported crash data from four American states, analysing accident data for vehicles of known roof strength. They looked for relationships between severe injury, severe roof damage, and roof strength in rollover crashes. They also evaluated the relationship between vehicle shape (the ratio of the vehicle's height to the track width) and rollover injury and roof damage. The study was sponsored by General Motors, and only GM cars were included because their roof strength in terms of the FMVSS 216 test was known to the authors. Model years 1980 through 1991 were included.

In the FMVSS 216 test, a 30 inch by 72 inch platen is slowly pushed by a gear-driven or hydraulic ram in to the roof at the A pillar (see Appendix 1). The platen is angled sideways at 25 degrees from the horizontal, and angled fore-and-aft at 5 degrees. Compliance is demonstrated if the peak reaction force on the roof is 5000 pounds or 1.5 times the weight of the vehicle within 5 inches of roof crush.

A typical trace of ram travel against applied load shows a flattening curve that reaches a peak, then falls sharply as the roof structure collapses. Peaks in recent vehicles ranged from 5,384 pounds (11,845 kg) for a Chevrolet S-10 pickup to 9,909 pounds (21,800 kg) for a Pontiac Fiero sports car. Heavier vehicles have higher crash energies, so the authors evaluated roof strength by comparing the ratios of peak roof strength to vehicle weight.

The accident data were from a 17-state database maintained by the authors' organisation, Failure Analysis Associates. The states of Florida, Texas, Michigan and North Carolina report the key variables : VIN coding, vehicle descriptions, collision damage scale and roof damage scale. Occupant variables included injury severity, restraint use, alcohol use and driver characteristics. For vehicles of known roof strength these data included 60,758 single-vehicle rollovers, with 96,154 occupants. The accuracy of the state data was assessed by comparison of a subsample of crashes that were also in the NASS database.

The rollover safety performance of each vehicle of known roof strength was measured by calculating the percentage of its occupants who suffered severe (fatal or incapacitating) injuries, given that a single-vehicle rollover had occurred. Plots of roof strength/vehicle weight ratios against injury rates showed considerable scatter and no discernible trend. This implies that there

was no apparent relationship between roof strength/vehicle weight ratio and severe occupant injury in rollovers. Matched pair analysis was conducted for vehicles of a similar type that had had their roof strengthened over time; again, no significant differences were found. The lack of relationship in these analyses held, whether or not seat belts were being worn.

To control for driver and vehicle characteristics, a logistic model was constructed that took account of the following factors: roof strength/vehicle weight ratio, vehicle aspect ratio, roof damage, driver age/gender/belt use/alcohol use, rural/urban, body style (two-door/four-door), and vehicle weight. Given that a single-vehicle rollover had occurred, the factors influencing injury were in order of importance as follows:

1. **Belt use.** Unbelted occupants were about four times more likely to be severely injured than belted occupants.
2. **Roof damage.** Occupants in vehicles with severe roof damage were about three times more likely to be severely injured.
3. **Alcohol use.** Drunk drivers were about two times more likely to be severely injured than sober drivers.
4. **Driver gender.** Female drivers were about 1.5 times more likely to be severely injured than male drivers.
5. **Driver age.** Older drivers (more than 25 years) were about 1.5 times more likely to be severely injured than younger drivers.
6. **Vehicle body style.** Drivers of two-door cars were about 1.25 times more likely to be severely injured than drivers of four-door cars.
7. **Aspect ratio.** High-roof vehicles had fewer severe injuries.
8. **Land use.** Rollovers in rural areas had severe injury rates about 1.13 times higher than urban areas.
9. **Vehicle weight.** Heavier vehicles had higher severe injury rates in rollovers.

Most of the above factors are consistent with "common sense" or earlier less comprehensive studies, including the positive relationship between roof damage and occupant injury. What the model did *not* show, however, was any

relationship between differences in *roof strength* on injury outcomes, either for high-roof vehicles or low-roof vehicles. Roof damage was associated with severe injuries and more severe crashes, but roof strength did not appear to be influencing roof damage.

Injury risks were then compared for vehicles of different roof strengths in crashes of common severity. As previously noted, delta V is inappropriate as a measure for rollovers, and state crash data did not have information on pre-crash speeds or the number of rolls. However, the states employed in the analysis did use the Traffic Accident Damage (TAD) scale, which quantifies general crash damage. Again, no correlation was found between roof strength and occupant injury in crashes of given severity. The NASS data were similarly analysed, and gave the same results.

Police-reported belt use was also examined as a separate issue. Occupant ejection was confirmed as the most important source of fatal injury in rollovers, and the severity of injury was mitigated by restraint usage. Also, non-ejected belted occupants had fewer severe injuries than non-ejected unbelted occupants.

Although not directly related to the present project, it is worth noting the results for convertibles. Comparisons were made between convertible and non-convertible models of the same GM models. The severe injury rates in rollovers were found to be about twice as high for convertibles as non-convertibles, for both belted and unbelted occupants. It does appear, therefore, that the complete absence of a roof is strongly related to injury in rollover.

It is difficult to question the results of this very large study. The single most important point is that the roof strength that was shown *not* to be related to occupant injury is the roof strength *as measured by the FMVSS 216 method*. In other words, it may be the test method that is at fault, not the concept that strengthening roofs can prevent injury. At present, this is speculation. The merits and derivation of the test method are described later in this report.

3.5.3 Rollover testing for the relationship of roof crush to injury potential

As a step towards determining the relationship of roof crush to injury potential, a series of rollover tests were performed under industry (General Motors) auspices during the 1980s (Orlowski et al, 1985; Bahling et al, 1990). In two series of tests a total of 16 rollover crash tests were conducted, eight in the first series and eight in the second. All the test vehicles were 1983 Chevrolet Malibu sedans and the crash test series are therefore known respectively as

"Malibu 1" and "Malibu 2". The series of tests were undertaken to examine the assumption widely held in the 1970s that the stronger the roof, the less likely it would be that an occupant would be injured in the area of deformation. The tests were also undertaken in the light of field and statistical studies such as those of Huelke (1983) which appeared to challenge this assumption.

In each of the Malibu tests the vehicle was launched into a lateral roll, with the right (passenger) side leading, from a fixture referred to as a "dolly". On the dolly the car was inclined at an angle of 23 degrees and moved along a track at the assigned test speed of 30 miles per hour. It was brought to an abrupt stop, following which the vehicle was launched into a rollover. Eight of the test vehicles had the standard production roof, and the other eight incorporated a roll cage fabricated from steel tubing. This strengthening resulted in little or no deformation in the rollover crash tests. Hybrid III 50th percentile male dummies were placed in the left and right front seats and were instrumented with triaxial head accelerometers and the Hybrid III neck transducer. This measures axial compression and tension, anterior/posterior shear and bending moment, and lateral shear and bending moment.

The dummies used three-point seat belts with a cinching latch plate. The lap belts were adjusted on the dummies to include enough slack to allow both the heads of the dummy and human volunteers to just touch the roof when the vehicle was suspended stationary in the inverted position.

The kinematics of the dummies when the vehicle was airborne were dictated by centrifugal acceleration, which at peak roll velocities reached 3 or 4 g. Responding to this acceleration, unbelted dummies moved upwards and outwards to the extent the vehicle interior structure permitted. Belted dummies moved in a similar fashion, but were further restricted by the lap belts. The researchers concluded that if a roof-to-ground impact occurred with the dummy at the point of impact, the velocity change experienced by the vehicle determined the velocity change experienced by the dummy. High dummy head-to-vehicle velocities were only observed to occur in unbelted dummies. In all the tests the buttocks of the dummies lifted off the seat cushion at the beginning of the test and seldom touched the cushion again. The dummy was never compressed between the seat cushion and the roof.

Although the details of each test differed, a common "injury" measurement was axial compression of the neck. Accordingly, axial neck compression was selected as a comparison measurement. It was determined that the two most significant factors related to axial neck compression were the orientation of the body at impact and the proximity of the dummy to the point of impact. The

more the head, neck and torso were aligned at impact, and the closer the head was to the point of impact, the higher the axial neck loads.

No significant difference was found in the axial neck loadings measured in the roll cage vehicles when compared with the production roof vehicles for dummies at the first point of impact. Further, the peak neck loads occurred before any significant roof deformation occurred, and when the roof did deform it did not result in increased neck loads. Even with 11 inches of roof deformation there was no evidence of the dummy being compressed between the seat and the roof. Axial neck loads resulted from the dummy torso continuing to move towards the neck when the head stops against the roof.

The standard production vehicles impacted the ground more times during the typical three or four complete rolls than the vehicles with roll cages fitted. The authors note that analysis of the potential effect of roof strengthening should include allowance for this factor and also for the orientation of the dummy and its location relative to the impact point.

The benefit of seat belts determined by these authors was the elimination of ejection. Seat belts did not reduce axial neck loads for dummies at the point of impact. Peak neck loads were shown to occur before peak lap belt loads. Although the lap belts did not reduce neck loads they maintained the dummy in an upright position. This enhanced the potential for neck loading, given a vehicle to ground impact.

In association with test series Malibu 2, five additional tests were also conducted in which vehicles were dropped on their roof from a height of 12 inches. Again, in all these tests the neck loading was seen to result from the neck being loaded by the dummy's torso when the head impacted the ground and stopped. The dummy was never compressed between the roof and seat cushion. For neither belted nor unbelted dummies did the roll cage add reduce axial neck loadings. Seat belts did not result in a reduction of neck loads for dummies at the point of impact, but may have provided some benefit for a dummy remote to the point of initial impact.

The position reached by these authors is that a deforming roof does not "come down" on an occupant, but rather that the roof support structure deforms. The occupant is not "under" the roof, but rather the occupant is over the roof when the roof impacts the ground. The occupant is not injured by the roof crush but rather by the impact with the ground and the subsequent loading of the neck by the torso. Roof crush simply reflects the magnitude and location of the impact of the roof with the ground. The harder the hit the greater the deformation and the greater the potential for injury. Increasing the roof strength will reduce

deformation but it will not reduce neck loading when the occupant is at the point of impact. In summary, therefore, the position of these authors as a result of the Malibu tests is that increasing roof strength will not reduce neck injury.

Friedman and Friedman (1991) disagree. They argue that as shown by other tests, severe neck injury is most likely when the head impact contact velocity is two to three metres per second or more, and the cervical spine is aligned and generally perpendicular to the contact surface. Brain-damaging head contact requires much higher velocities and forces not frequently occurring in rollovers. The lateral forces that generate the roll in the first place tend to move the occupants sideways, and centrifugal forces thrust them into contact with interior surfaces when the roll rate is high. The point of this commonsense analysis is that straightforward axial loading of the neck is likely to be an extremely rare event in real crashes. Far more likely is that the neck will be flexed as the car rolls, sometimes in association with contact with the car's interior.

The dolly rollovers in the Malibu series were thus very unrepresentative of real world crashes. Dummies are designed with necks that are much stiffer than in humans, so that they will sit erect with the neck aligned. The head will remain in this position when it is loaded. The effect of this is that the neck receives an axial loading when the top of the head is impacted. The way that the cars were launched from the dolly meant that the initial direction of movement of the dummy occupants was contrary to the direction of the vehicle rotation, whereas in the real world - because rollover is generally initiated by a tripping action - the first motion of the occupants will be in the other direction. This type of crash test (lateral launching from a dolly) is unlikely to load the roof significantly, and in fact the roofs of two of the eight standard vehicles did not collapse at all.

None of the roll caged vehicles were deformed. Friedman and Friedman suggest that a quite modest improvement in roof crush resistance would therefore prevent most intrusion in most rollovers. In fact, out of all 32 Malibu 1 and 2 dummy injury measurements, the only dummy neck flexion "injury" occurred in the worst case roof collapse with deformation within a few centimetres of the bottom of the side window and windscreen. In that case the driver dummy did sustain flexion loading of over the 189 Nm suggested as a tentative criterion by Mertz and Patrick (1971).

Friedman and Friedman (1991) summarise the number of occasions during the multiple rolls that dummies exceeded tolerance levels for lateral neck loads. For the eight restrained rollover tests, the driver experienced 10 lateral flexion injuries in the production cars and only one in the roll-caged cars.

In regard to axial loads, Figure 9 in Bahling et al (1995) summarises the Malibu data as a whole. It shows that there is substantial scatter in the data up to around 6000 N, with little difference between the standard and rollcaged vehicles, whether a seat belt was worn or not. However, the loadings over 7000 N all occurred in far-side occupants (passengers) in cars with standard roofs. These readings lifted the average axial neck loadings for occupants of cars with standard roofs to well over the average for rollcaged vehicles.

The danger to the neck is a function not only of the loading but also the time over which it is applied. Rechnitzer and Lane (1994) have used base Malibu data to obtain the time for which the neck loads were above 75% of peak for 10 msec, and shown that the mean 10 msec load for rollcaged cars was 2680 N, and for production cars 3990 N. This would indicate that for rollcaged cars the neck loadings were reduced below a tentative boundary for the risk of an AIS 5 neck injury. Bahling et al (1995) discount the importance of such "statistical" calculations, pointing to the difference in vehicle dynamics for the two groups of cars, with and without rollcages.

Any beneficial effects that seat belts might have had in the Malibu tests were minimised by the fact that the tests were undertaken with seat belts locked in a position that allowed 100 millimetres of vertical excursion. It is therefore not surprising that those restraints were shown to be not very effective in the production vehicles with standard roofs. On the other hand it can be seen that they had a substantially beneficial effect for the driver dummies in the rollcaged vehicles: in only two instances with roll cages did the neck axial load exceed 4000 N, as opposed to 11 cases in the cars with the standard roofs.

Further examination of the Malibu data also shows that the passenger in the production vehicles generally fared better in the tests than the driver. This is to be expected, because the test method results in the driver side of the roof being the first to touch the ground. The roof over the passenger may not touch the ground at all. The first substantial impact is on the driver's side once the car has turned 180 degrees.

Syson (1995) has also been critical of the Malibu research and the conclusions of the authors. He has recently pointed out that the underlying assumption that an occupant is a relatively rigid homogeneous mass is untrue for an average human being, yet it is the assumption which underlies the position that roof crush is unrelated to injury. Syson therefore examined whether the differences between the injuries to live subjects and test dummies might be resolved by an analysis of their different force deflection properties, and he used a simple mathematical model to examine the interaction between the head/neck/torso complex and the roof interior. The model was validated using data from the

published Malibu studies. Because the model predicted the published results with a high degree of accuracy, it was used to identify those parameters that appeared to have the most significant effects on neck loads.

Syson's results showed that using a figure for neck stiffness in the model equivalent to that for the Hybrid III dummy led to a good agreement between his calculations and the results of the testing in the Malibu series. There was approximately constant neck force in the initial roof contact, independent of roof strength. Also, the neck force exceeded projected human tolerance levels in both the model and the tests, taken to be an axial neck load of 6500 N. However, reducing the neck stiffness to a value more closely representing that of cadaver test data, about one-tenth of the dummy neck stiffness, altered the picture significantly.

The risk of neck injury depends on both the magnitude and the duration of forces (as for most parts of the body). The neck force on initial roof contact was similar in *magnitude*, whatever the roof stiffness. However, for the rigid roof case the neck force *duration* at a high force level was too short to indicate injury potential. On the other hand, in the production vehicle the *duration* of neck force was sufficient to indicate an AIS 5 or higher injury level. Further, the increase in force level agreed with the magnitude and duration of the roof deformation curve.

What this means in the real world is that at first impact the human neck may receive a short sharp shock axially, which is not injurious. As the roof collapses, the neck is forced to bend under the combined loads of the inverted torso and the distortion of the roof and lateral supports. It is this flexion/compression that results in cervical spine injury, but it is this mechanism that is not examined in the Malibu series or taken proper account of in some analysts' discussions about the *causal* connection between roof crush and injury.

Restraint system loading was found to be modest in most of the simulated drops. Even using a relatively stiff belt had little effect on neck loads when the stiffness of the Hybrid III neck was simulated. However, again, using a neck stiffness for the model that more closely compared with cadaver data, it was apparent that an effective belt did reduce both the magnitude and duration of neck forces, particularly in simulations with increased roof stiffness. Because of these low belt forces, and because of the slack introduced into the system, it is not surprising that belt effects in the Malibu testing were found to be insignificant.

Syson simulated the effect of advanced belt systems by building in a model for pre-tensioners. Using figures for cadaver neck stiffness, neck forces in rollover were lower with a soft belt plus pre-load than with a stiffer belt with all the other parameters held constant. He suggested that this indicated that a rollover sensor would be a valuable addition to existing belt systems with pre-tensioning devices.

Other parameters were not found to be very influential. Head clearance had only a minor effect, but the greater the head clearance the longer the delay before neck forces reached significant levels. Seat stiffness was not found to be a factor. Padding had no significant effect on neck loads, and the model indicated that padding was unlikely to reduce neck forces usefully unless it is more than 5 cm thick.

When the effect of neck stiffness was examined with all other parameters being held constant, the maximum neck force exceeded suggested upper human tolerance levels when Hybrid III neck stiffness levels were used. However, when using a neck stiffness similar to that of cadavers the peak neck forces were below the lower tolerance levels. Whenever roof deformation resulted in compression of the simulated occupant between the roof and the seat, neck forces exceeded tolerance levels because of the extended load duration. This explanation is consistent with findings of flexion/compression neck injury in rollover crashes in the field and the failure to find a reduction in neck loading with a rigid roof in tests with the Hybrid 3 dummies. This shows that there is a problem associated with using a test device that is designed to predict injuries in frontal collisions in other impact configurations. It is arguable that all the conclusions of the Malibu testing are an artefact of the lack of biofidelity of the Hybrid III neck.

Examination, again, of the published axial neck loads in the Malibu tests for restrained occupants shows that if a lower level neck injury criterion of 4000 N is used, the number of possible predicted injuries is reduced from 40 to 20, 14 of which were in production roof vehicles. Using the upper criterion of 6500 N reduces the number of potentially injurious impacts to six, with only one predicted injury in a roll cage equipped vehicle.

The use of an arbitrary neck load as an injury criterion based on an unsuitable human surrogate results in the prediction of an unreasonably large number of potentially injurious impacts, because the majority of the lower level impacts occurred in reinforced roof vehicles. Further, in both the unbelted and belted Malibu tests, conclusions were based on biomechanical criteria that in themselves were open to doubt. McElhaney and Myers (1993), for example, state that while testing axial neck loads to failure is a measurable and useful

biomechanical parameter, "*this parameter alone is a poor predictor of the risk for neck injury*".

All in all, the Malibu tests are very far from being proof that reinforcing roof structures does not increase occupant protection.³

3.6 Rollovers and spinal injury

Spinal injury is predominantly a feature of motorised transport. In particular, although numerically of lower incidence than head and chest injuries, a type of injury that is positively associated with both a high degree of harm and with rollover crashes is injury to the cervical spine. Around 1,500 road injury hospital admissions and attendances are for spinal injury each year in Australia (O'Connor and Trembath, 1995). Some two-thirds of the spinal injuries are AIS 3 or greater. The mean length of stay in hospital for these injuries is over two weeks, and over 17 days for males. About 1,000 of these spinal injuries occurred in drivers or passengers of motor vehicles (excluding Queensland).

Naturally, few of these spinal injuries occurred in rollover crashes, but injury to the spine does appear to be more of a risk in rollovers than other kinds of crash. Wigglesworth (1991) analysed accident reports for 67 patients admitted to three spinal cord injury units in Australia in 1987. Among vehicle occupants, out of a total of 44 cases 38 occurred as a consequence of rollovers. Whether or not the occupants were wearing seat belts was not known. However, it was known that seat belts were used by 23 of the 38 who were injured.

Thurman et al (1995) described the incidence of motor vehicle related spinal cord injuries in Utah, using hospital registry data for 1989 to 1991 and police accident reports. Forty-nine per cent of all the spinal cord injuries involved motor vehicles. Among occupants of motor vehicles, 70% were involved in a rollover with 39% being ejected. Only 25% reported using seat belts. These authors concluded that spinal cord injuries were much more likely to be associated with rollover compared with other types of occupant injuries.

3

Without impugning the motives of any of the researchers concerned, it is relevant to point out that both litigation and the prospect of unwanted rule-making are factors in the debate on whether increasing roof crush resistance will decrease injury. For example, researchers such as Mackay, Moffatt, Huelke, Orlovski, Strother and Plastiras all either work for the US motor vehicle industry or for consultancies primarily supported by the industry. On the other hand, researchers who generally support the position that roof crush is causally related to injury, including Syson and Friedman, work for consultancies which often provide advice in support of plaintiffs in litigation against manufacturers.

Rollover emerged as a much stronger risk factor for spinal cord injury than for head injuries or for deaths in general. Data on roof crush were not available. The reported use of seat belts was substantially higher among cases involving rollover without ejection, which suggested that seat belts were effective in preventing spinal cord injury associated with ejection. However, seat belts appeared to be less effective in preventing spinal cord injuries associated with rollover in the absence of ejection.

A major epidemiological study in the United States estimated that 40% of spinal cord injuries occurred in motor vehicle accidents (Kalspeck et al, 1980).

A later study of the epidemiology and biomechanics of motor vehicle related spinal trauma was recently reported by Yoganandan et al (1989). Motor vehicle accident-related data on spinal injuries were obtained from clinical data gathered from patients in Wisconsin hospitals, fatalities in Milwaukee county and the computerised NASS files. The purpose of the clinical study was to determine the most commonly injured anatomical levels in the cervical spine, to classify them on the basis of impairment and to determine the mechanism of injury. The NASS data gave figures for the wider population and enabled tabulation by crash type.

The results of this study showed that while cervical column injuries are complex and may occur at any level they concentrate statistically in two primary zones. These are at the craniocervical junction for fatally injured victims, and in the lower cervical spine for survivors. The majority of paralysing injuries in survivors, resulting in both complete and incomplete quadriplegia, were produced by flexion/compression loading with disruption of the posterior elements and compression fractures of the vertebral bodies. Comparison with injuries to other parts of the spine showed that injuries of AIS 3+ level were primarily related to bony structures. In contrast, neck trauma of this severity was in 20% of cases related to cord injury with 65% related to the bone. For the cervical spine, seat belts appeared to significantly reduce the incidence of AIS 3+ injuries while increasing injuries of AIS 1.

At the AIS 2 and AIS 3+ injury levels, rollovers were clearly associated with the highest risk, both for the cervical and thoracolumbar spine.

The authors concluded that head impact with the vehicle interior was a significant causal agent in cervical spine injury, especially at the higher injury severity levels. Axial shear, bending and torsional loads transmitted to the cervical spine by the skull appear to be the primary agents in this regard. The beneficial overall role of seat belts in the reduction of serious cervical spine

injuries was regarded as most probably due to prevention of contact between the head and the vehicle.

An important implication for anthropomorphic test dummy neck development following from the above findings is that dynamic biofidelity of the dummy neck (in particular an accurate representation of load transmission to the neck via head contact) is required for injury assessment using dummy neck force and moment measurements.

Rechnitzer and Lane (1994) discuss at length the findings of Toscano, reported in a 1986 thesis at Monash University. He studied the origins of cases of spinal cord injury admitted to the only dedicated spinal injury unit in Victoria, and in the case of vehicle accidents visited the scenes and studied the vehicles. Fourteen of the 41 car crash cases were rollovers. He found that in rollover crashes, 80% of the spinal cord injuries resulted in quadriplegia, as opposed to 43% in non-rollover crashes. He attributed six cases to roof crush, noting especially that the neck injuries were sustained by the occupants sitting "under" the crush and not elsewhere in the vehicle where the roof was not crushed. He also noted that cars of more recent vintage (1982 and later) appeared more likely to sustain roof crush than older models.

4 AUSTRALIAN RESEARCH ON ROLLOVER AND ROOF CRUSH

A recent Australian study of rollover crashes was aimed at investigation of the relationship between vehicle design and the nature and severity of occupant injuries. Rechnitzer and Lane (1994), of the Monash University Accident Research Centre, reviewed the literature on rollover crashes and, as the present consultants have done, re-analysed results from published rollover crash tests. They also studied in depth a selection of real-world rollover crashes.

They concluded from their literature review and review of experimental rollover results that among restrained occupants injuries occur (in descending order) to the head, upper limbs, chest, lower limbs and neck. For injuries of AIS 3 and more the head and chest predominate.

At the start of most rollovers the vehicle has a significant lateral velocity. The occupants become displaced from their seats and move towards, and may impact the roof. They may impose high loads on the glazing and the doors. Experimental rollover studies (such as the Malibu series) were open to some criticism, but in the opinion of Rechnitzer and Lane they showed that dummy neck loads were significantly lower in cars with strengthened roofs than in cars with standard roofs. These experimental studies used standard dummies developed for frontal impacts which may be inappropriate for rollover studies. The weight of evidence, in their opinion, appeared to be in agreement with a relationship between roof crush and occupant injury. There is a convincing relationship between rollover and spinal cord injury and strong evidence of a connection between local roof crush and spinal cord injury. Rechnitzer and Lane point to the effectiveness of roll cages in preventing injury in rollover crashes in road and track racing.

Rechnitzer and Lane made a valuable contribution to the original rollover literature by investigating in detail a sample of 43 crashes involving rollover. The sample was intended to be representative of the range of crash types involving partial or full rollover of the vehicle, with injury severity ranging from none to fatal. The methodology of the study was broadly similar to other in-depth crash studies undertaken by the Monash University Accident Research Centre.

This new in-depth crash study confirmed once again that ejection is a significant factor in fatal crashes. Of the 13 fatalities in the sample, ejection occurred in about half the cases, with the seat belt not having been worn. Partial ejection of the head can occur even among occupants wearing seat

belts. This in turn can arise following breakage of the glass in the side window and vertical and lateral deformation of the roof.

Current seat belt designs are only partially effective in rollover crashes because they provide little effective restraint against head excursion outside the vehicle. Further, these authors suggest that in some vehicles the seat belt buckle design may be deficient for rollover conditions, and may unlatch during the rollover. In two fatal cases the occupant was found ejected, the belt buckle was found undone, but the seat belt showed signs of loading.

A lack of roof integrity on certain vehicle models, particularly four-wheel drive vehicles, was shown to contribute significantly to the risk of severe injury. Nearly all roof structures and framing are unpadded and contribute to occupant head injuries including scalp lacerations, skull fractures and brain injury.

Rechnitzer and Lane concluded that severe spinal injuries could arise from three factors related to vehicle design. The first is "mechanistic", simply being the loss of vertical occupant space through roof intrusion, both vertical and lateral. This, thereby, imposes bending and compression loading of the spine. The second factor is impact loading via head contact with the ledge formed by the underside of the roof and the frame of the door. This can result in inertial body loads acting on the cervical spine. Third, they note the lack of effective padding on potential head contact surfaces and consequently the lack of an intervening energy-absorbing structure to reduce impact and acceleration loads acting on the spine or head.

They conclude that high degrees of roof intrusion do not necessarily reflect the severity of the rollover but they do relate to the capacity of the vehicle's roof to resist rollover loads, particularly in the region of the A pillar. Only when combined with general levels of structural deformation is roof intrusion a more accurate reflection of impact severity. Severe injuries to occupants who are not ejected, particularly to the head, spine and thorax, only appeared to occur to occupants seated to the side of the vehicle where significant roof contact occurred with the ground or road surface, or where there was significant roof crush. Therefore, these severe injuries cannot be ascribed to crash severity alone.

Finally, these authors note that because of the complexity of the rollover event, to some extent the actual injuries received by occupants are partially dependent on the precise position of the occupant in relation to the vehicle at any given instant of the crash; in a word, on luck.

5 THE KINETICS OF ROLLOVER

5.1 Rollover tests

Since the early days of crash testing, rollovers have commonly been part of the test procedure. Unfortunately, with the exception of the Malibu series described above, rollover tests have rarely been studied in relation to the potential for occupant injury. Given the low seat belt wearing rate in the United States until recently, and the known association between ejection and occupant injury in rollover, it is not surprising that most rollover tests in that country have been evaluated in terms of their potential for ejection. The original FMVSS 208 contained a rollover test requirement for vehicles that conformed to the (then) option of providing complete passive protection, but that was not a popular option. A dolly rollover test methodology has more recently been proposed (by manufacturers including Mercedes Benz) for FMVSS 208, but even that has only an occupant containment criteria, and in any event the proposal is not proceeding swiftly. Nevertheless, as has been known for many years, there is still a significant injury potential (not necessarily related to roof crush) for occupants who stay in the vehicle, whether they wear seat belts or not.

Rollover tests are usually conducted either by tripping or ramping a remotely controlled vehicle, by tipping a vehicle down a slope, or by launching a vehicle from a tilted moving platform. All of these test methods have been criticised at various times for their lack of realism. However, they have nevertheless provided a substantial body of information.

5.2 Rollovers in the real world

In order to obtain a better view of the dynamics of real-world rollovers for the purpose of this project, a detailed analysis was conducted of two videos of crashes involving rally vehicles in Scandinavia (Crash Kings, 1994; Rally Hits, undated). These crashes are not necessarily representative of the rollover crashes which occur with normal vehicles on Australian roads and the film footage is likely to be biased towards the more spectacular crashes. However, the analysis can give an indication of the types of rollover crashes which occur and the dynamics of these crashes - particularly the number and speed of turns. The general characteristics of the roads are not untypical of what would be found in rural Australia, including two-lane roads with tarmac surfaces and (predominantly in the videos) gravel roads. Many of the rollovers followed trips in roadside ditches and down small embankments, again typical of Australian

roadsides. A high proportion involved contact with roadside obstacles, mostly trees, before, during or after the rollover event.

The pre-crash speeds could not be determined with any accuracy. Although the travelling speeds were likely to be higher than typical on equivalent roads in Australia, they were probably not untypical of the speeds that precede similar crashes, wherever in the world they occur.

All the occupants were wearing crash helmets and all the vehicles were fitted with roll cages (providing support at least in the region of the B pillar, and usually at the A pillar as well), as far as could be ascertained. The introductions to the videos indicate that no serious injuries occurred in any of the recorded crashes, which again indicates that the crashes were not at extreme speeds or of extreme severity.

There were a total of 129 incidents where a vehicle at least rolled on to the roof. Of these,

- 40% were "pure" side rolls, at 90 degrees to the longitudinal axis of the vehicle;
- 42% were corkscrew actions, where the vehicle had substantial forwards motion as well as the rolling action. These tended to involve complex crash dynamics;
- 18% were end over end, where the main motion was a pitching action (mostly forwards but some rearwards after the vehicle had spun around 180 degrees);

From further analysis of the video with the most rollovers (Crash Kings, 1994):

- 36% were less than one full roll (most of these were a half roll onto the roof);
- 40% were at least one full roll but less than two full rolls;
- 13% were at least two full rolls but less than three full rolls;
- 11% were at least three full rolls;
- 8 out of the 10 end-over-end crashes involved a half roll onto the roof. These crashes tended to be much slower than the other types but the final impact with the ground tended to be very severe.

The average time per roll for corkscrew and side-on crashes was very similar. A typical single full roll took 2.3 seconds. A typical double roll took 1.5 seconds per roll and a typical multiple roll (three or more) took 1.1 seconds per roll. The average for crashes involving one or more rolls was 1.7 seconds.

Slow motion analysis of the videos revealed that substantial changes in the angular velocity occur as parts of the vehicle contact the ground. This results in high tangential forces on the occupants. In some video frames the head and arms of occupants (most of whom were wearing at least four-point rally-style harnesses) can be clearly seen extended well outside open/broken side windows. This appears to be a whipping action which, fortunately, tends to pull the occupant back inside the vehicle just before the adjacent cantrail (roof header rail) makes contact with the ground.

5.3 Simplified crash dynamics in a sideways rollover

Based on observations of the videos, the following notes present some estimates of the speeds and accelerations involved in a sideways rollover (somewhere near 90 degrees to the direction of vehicle travel).

5.3.1 Vertical motion of vehicle centre of gravity

The method is to plot the approximate height of the centre of gravity (C of G) of the vehicle during various stages of the rollover. The vertical velocity of the centre of gravity can then be approximated. Its profile will be roughly saw-toothed in shape as the C of G of the vehicle first rises then free-falls under gravity. At the end of each fall the vehicle will rebound as it strikes the ground. (See Figure 1.)

The decelerations and rebound speed will be governed by the deformation characteristics of the vehicle and the ground surface, but in most cases it is evident that the rebound speed approaches that of the impact speed.

Key features of this analysis are as follows:

- As the vehicle rolls over a "corner", the C of G reaches its highest point and, if the speed of the roll is sufficient, the acceleration of the C of G might go positive (note the effect of the earth's gravity has been included). This means that the vehicle loses contact with the ground. In some of the rally crashes this effect was so strong that the roof did not contact the ground at all during the first half roll.

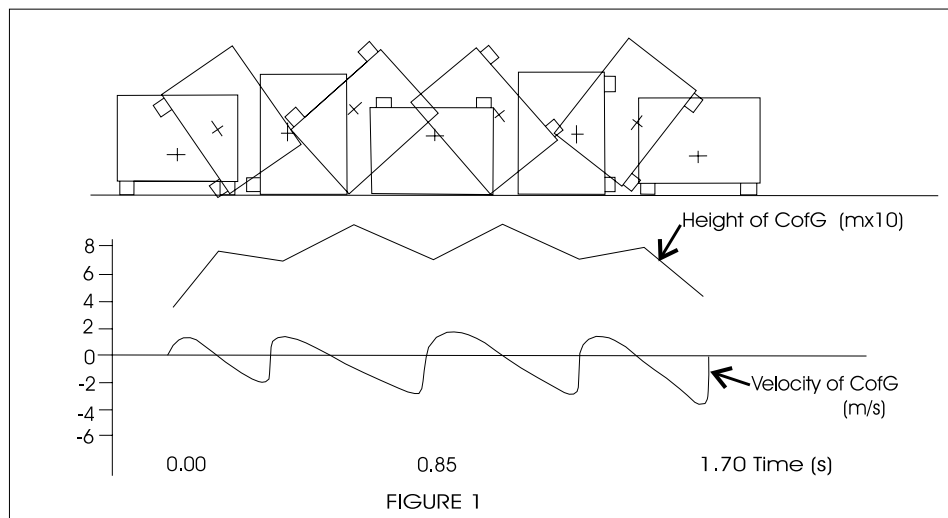


Figure 1: Vertical Motion of Vehicle Centre of Gravity

- The largest change in vertical velocity, and therefore largest vertical acceleration, occurs when the underside of the vehicle is in contact with the ground, at the start of the roll and at the end of a full roll. This is a manifestation of the location of the C of G of the vehicle, which is closer to the underside of the vehicle than the roof. In typical passenger cars the vertical distance from the C of G to the roof is similar to the transverse distance from the C of G to the side of the vehicle, and therefore there is relatively little vertical motion of the C of G as the vehicle rolls from its side to the roof to the other side. Low aspect ratio vehicles such as sports cars have a smaller distance between the C of G and the roof, and therefore the vertical loads occurring when the roof is in contact with the ground can be expected to be higher. This might partly explain the finding by Moffatt and Padmanaban (1995) that high roof vehicles have generally less roof damage than low roof sports cars.
- The typical vertical speed of the vehicle C of G at the instance of impact with the ground is estimated to be about 2 m/s for this scenario.

5.3.2 Horizontal motion of vehicle centre of gravity

During the initial trip event, and during each subsequent contact with the ground, the vehicle will be subjected to horizontal decelerations. Robinette et al (1993) found that the typical horizontal deceleration (apparently averaged over the entire event) was 0.43 g. The actual horizontal velocity profile will be step-like, with the steep portions corresponding to "corner" contacts with the ground. Assuming that the transverse velocity is zero at the completion of a full

roll, then the change in horizontal velocity during each ground contact would be about 2 m/s, for an initial velocity of 11 m/s (about 40 km/h).

Note that during the initial tripping event it is likely that there will be substantial horizontal deceleration, which will tend to throw the occupants in the direction of the roll. This appears to be the mechanism of ejection for the unrestrained dummy in the paper by Habberstad et al (1986): the dummy was ejected before the vehicle reached the first quarter of the roll.

5.3.3 Rotational motion

A complete revolution in 1.7 seconds indicates an average angular velocity of 3.8 radians per second. The distance from the C of G to the corner of the roof is about 1.3 m for a typical passenger car, therefore the tangential velocity of the corner of the roof will be 5 m/s. The average radial acceleration ("centrifugal force") experienced by an object at this point will be $1.3 \times 3.8^2 = 19$ m/s/s, or about 2 g.

After the tripping event which initiated the roll, the vehicle will be moving sideways with a typical horizontal velocity of 11 m/s (assuming the trip speed was just sufficient to cause the roll; see Gillespie, 1992, p 326), therefore the first two contacts of the roof with the ground will probably involve relative speeds of about 6 m/s (11 minus 5) and the impact will tend to *increase the speed of rotation of the vehicle*. In effect, the occupants will experience angular accelerations in a direction opposite to the direction of the roll during these first two roof contacts (and opposite to the direction in which they were thrown at the start of the roll).

As the horizontal speed of the vehicle drops (due to the braking effect of the ground impacts), the tangential speed of the corner of the roof may eventually exceed the horizontal speed of the vehicle, and the impact will tend to *decrease the speed of rotation of the vehicle*. In effect, the occupants will then experience an angular acceleration in the same direction as the roll. The observation of rally crashes where an occupant's head and arms are extended outside the side window are probably due to this angular *deceleration*, the peak of which would usually occur as the vehicle tips over on its wheels near the end of the first roll or at the start of the second roll. At each of these points C of G of the vehicle is passing through its highest point, therefore the occupants tend to become "weightless". An unrestrained occupant has a high risk of being ejected at this point, if the side window is open or broken.

Rotational speed will have a similar step-like profile to horizontal velocity. To obtain a rough estimate of the change in rotational speed during each ground

contact, assume that the maximum rotational speed is reached after half a revolution (at the third ground contact). For a maximum rotational speed of 6 rad/s (based on a average of 3.8 rad/s for a full roll) the change during each contact will therefore be about 2 rad/s. This is equivalent to a linear velocity change of about 2 m/s in the region of an occupant's head, in a direction tangential to the C of G of the vehicle.

5.3.4 Combined effect

The combination of vertical acceleration/deceleration, horizontal decelerations and rotational acceleration/deceleration generally results in complex occupant kinematics during a roll-over. Occupants are thrown from side to side and up and down in a chaotic manner. Partial ejection through open or broken side windows is a strong possibility, even for restrained occupants.

Subject to the limitations of the approximations used, it was found that the changes in velocity during each contact with the ground were similar for each of the three motions: vertical, horizontal and rotational (tangential). For a trip speed of 11 m/s (about 40 km/h, a typical minimum for a passenger car), these three changes in velocity are estimated to be about 2 m/s. The effects of the rotational motion tend to either reinforce or cancel the other two motions, depending on the phase of each. Therefore, peak velocity changes of about 4 m/s could occur. Head strikes with an unyielding surface at this velocity are likely to produce severe head injuries (Friedman and Friedman, 1991).

5.4 The role of roof crush

This analysis raises several issues about roof crush and injuries.

- For simple side-on rollovers, the vertical impacts with the ground are likely to be of sufficiently low speed not to pose a direct problem with typical car roofs.
- End-over-end rollovers and launching rollovers, where the car centre of gravity gains significant height above the ground, involve much larger vertical impacts. Roof strength is more critical.
- Roof lozening (side-sway) is clearly a cause for concern. It is promoted by the kind of horizontal loading imposed when there is considerable forward movement of the car as it rolls. This tends to bend the roof supports. Among possible effects is shattering of the side window, so that the occupant is exposed to a greater risk of direct contact with the

ground or partial ejection. Restrained occupants who are partially ejected may be subjected to a whipping action that forces the inboard side of their head into contact with the outside upper edge of the side window frame.

Most of the energy absorption appears to take place when the wheels and underside of the vehicle contact the ground. Therefore a stiff roof structure is unlikely to prolong the roll.

6 ROOF CRUSH TESTS

6.1 A history of the development of FMVSS 216

The development of FMVSS was very much tied up with work that the Fisher Body Division of General Motors started in the mid-sixties.⁴ Fisher Body proposed in 1965 that equipment be constructed to measure the force/deflection characteristics of GM body structures, including the roof. While rollover and collision testing was being conducted by the research team at the GM Proving Ground, these test rollovers were seen as complicated, expensive and often irreproducible. Quantitative data were very hard to obtain, and were not often measured. Fisher Body suggested that the development of a static test could influence likely future legislation and provide data for use in any future product safety litigation.

Early testing used different ways of applying loads, but settled on a single hydraulic cylinder and a flat platen. Different sizes of platen were then tried, ranging from 12 inches by 12 inches to 72 inches by 30 inches.

In October 1967 the Department of Transportation published an Advance Notice of Proposed Rulemaking. It incorporated no requirements or test procedures, and stated:

"The administrator is considering issuance of an FMVSS to limit the amount of intrusion or penetration on exterior impact, including the front, rear, side and roof."

General Motors proposed the concept of a roof crush device based on the work by Fisher Body to both the Society of Automotive Engineers and to the Automobile Manufacturers Association. By July 1968 Fisher Body were using the 72 x 30 inch platen, but when the SAE test procedure was approved and issued as J-374 it incorporated the older 72 x 12 inch platen.

In January 1971 the US Federal Government issued a Notice of Proposed Rulemaking "*Roof Intrusion Protection, Passenger Cars*". It was noted in that proposal that "the strength of a vehicle roof affects the integrity of the

⁴ During the course of this project, most helpful discussions were held in the United States with Richard M Studer, now a vehicle safety consultant but until recently an engineer at General Motors and involved with the original development of standards for roof crush.

passenger compartment and the safety of occupants". The Preamble to FMVSS 216 stated (as it still does) that the roof crush standard "will provide protection in rollover accidents by improving the integrity of the door, side window and windshield retention areas."

The test requirement was the attainment of a force equal to 1.5 times the unloaded vehicle weight or 5,000 pounds, whichever is less, within 5 inches of test device travel. The platen configuration was to be a 12 x 12 inch plate with a rubber face, oriented at 10 degrees in pitch (fore-and-aft) and 25 degrees in roll (sideways). In December 1971, following comments by GM and other manufacturers that the proposed 10 degrees was too severe a requirement, the pitch orientation was reduced to 5 degrees. The platen size was increased to 72 x 30 inches.

FMVSS 216 was finally issued in January 1972, with the above requirements. The effective date was negotiated to be August 1973.

In passing, it might be recalled that a US federal law in 1964 enabled the General Services Administration to require unique safety provisions in vehicles purchased for the Federal Government. One proposed standard was for roll car structures for automotive vehicles, but it applied only to light utilities and specified the SAE ramp rollover test procedure. The proposals were revoked in 1967, presumably because of the development of the FMVSS.

6.2 Australian testing to FMVSS 216

Murray (1991) at Monash University in a series of tests during 1991 subjected a selection of vehicles available on the Australian market to the roof crush test as defined in the FMVSS 216 test procedure.

With the exception of a 1990 sedan all vehicles passed this test. Table 10 summarises the main outputs from six tests in this series. With the exception of the failure, the test results were of the same order of magnitude as the GM cars listed in Moffatt and Padmanaban (1995). The results from these tests confirm that the loading which in the end defines the crush is a bending one on the A pillar, rather than an axial load. This is in accordance with field observations. Murray (1994) points out that the windscreen, and its bonding to the body structure, therefore has great influence on the resistance to crush, because the

Table 10 - Results of Monash University roof crush testing (source: Murray, 1991)

	Maximum load		Displacement		Vehicle mass	Load/mass ratio	FMVSS criteria
	kN	pound	mm	inches	kg		
1990 Holden VN Commodore	23.70	5332	122.0	4.8	1300	1.82	Pass
1990 Ford E Falcon	14.30	3217	88.9	3.5	1386	1.05	Fail*
1991 Ford E Falcon	26.44	5949	81.0	3.2	1386	1.90	Pass
1991 Toyota Camry	33.20	7470	109.0	4.3	1170	2.84	Pass
1991 Nissan Pulsar hatchback	23.55	5299	114.4	4.5	1000	2.35	Pass
1991 Mitsubishi Magna	35.50	7987	87.0	3.4	1316	2.70	Pass

* The failure was apparently due to faulty windscreen bonding.

screen is supporting the pillar. He further points out that the failure he observed in his test series was because an incorrect windscreen bonding agent had been used. Without correct bonding, few cars could pass the US rule.

Murray points out that the test imposes loads approximately in the plane of the sheet of windscreen glass. The glass is quite strong when the loads are applied to it in this direction. However, in a field crash, there is normally forwards or rearwards movement which imposes prior bending loads, which in turn cause the glass to fail and leave roof strength entirely to the steel framing.

Murray has argued that there is a "probable" causal relationship between roof crush and head, neck and spinal injuries (Murray, 1994). In his opinion the FMVSS 216 test is valid only for slow sideways rollovers, not the more typical kind where a vehicle drops on its roof. Although satisfying FMVSS 216, a car need only drop about 38 mm (1.5 inches) before the roof is crushed enough to touch the typical occupant's head.

Murray suggests that a more satisfactory rule would be based on a drop test of 0.5 metre. The performance should be measured in terms of HIC and a maximum crush of 40 mm. However, if a present-day car was dropped from 0.5 metre it would result in a notional 650 mm or so of crush, so substantial redesign would be required.

A much less severe drop test is defined by SAE test standard J 996, *Inverted drop test*. There is also the severe ramp test J 857 (1980), *Rollover test without collision*, but the main problem with this, apart from its expense, is that it is difficult to obtain consistently reproducible results. It does, however, have the virtue of realism, in the sense that when the vehicle hits the ground inverted, it has considerable forwards velocity and imposes heavy bending loads on the A pillar.

7 THE COSTS OF AN AUSTRALIAN DESIGN RULE FOR ROOF STRENGTH

A requirement of the present project was to estimate the costs to the community of implementing an Australian Design Rule based on FMVSS 216. In 1993 the Federal Chamber of Automotive Industries (FCAI) had advised the Federal Office of Road safety that 98% of then-marketed passenger cars were believed to comply with FMVSS, although many had not actually been tested for compliance. For current models that did not comply, a cost of up to \$150,000 per body style was estimated for testing and compliance. For those believed to comply, a cost of between \$6,500 and \$50,000 per body style was estimated for certification.

More up to date information was required for the present project, so we arranged for the FCAI to conduct a new survey of the local industry.

Little appears to have changed, according to a letter received from the FCAI summarising the results of their survey. It is still estimated that 98% of currently marketed passenger cars are believed to comply with FMVSS 216, noting however that:

- while compliance testing for FMVSS 216 for a significant number of currently marketed models has not been undertaken, there is generally a high level of confidence that such vehicles would comply;
- the compliance of future models is unknown, but the expectation is that such models would comply;
- any future ADR adopting FMVSS 216 would exempt convertibles from the ADR requirements.

Of those current models which are believed not to comply with FMVSS 216, \$125,000 (average) per body style is estimated for development and testing programs.

Of those current models that are believed to comply with FMVSS 216, \$37,5000 (average) per body style for certification requirements is estimated.

In respect to future models, estimated costs for design, development, testing and certification to FMVSS 216 are in the order of \$85,000 per body style.

The FCAI expressed to these consultants the view that the introduction of an ADR for passenger roof crush strength is not justified, given the high expectation of the current level of compliance with FMVSS 216. An ADR would impose unnecessary testing and compliance costs on vehicle manufacturers, and additional workload on FORS staff for no perceived benefit.

8 DISCUSSION AND CONCLUSIONS

8.1 The primary issues

The fundamental questions are, what would be the benefits in introducing an ADR based on FMVSS 216 in terms of the reduction of injury, and what would be the costs of doing so?

The position of the FCAI is that because virtually all passenger cars either do now comply with FMVSS 216 requirements or will do so in the future, there would be no incremental benefit in introducing an ADR, whatever the cost. However, that it is possible for contemporary vehicles to fail is shown by the testing of Murray (1991), even if the failure he detected can be regarded as aberrant. Accordingly, an argument might be that an ADR is required to establish beyond doubt that all modern cars do in fact comply with this basic standard. The ADR would thereby have a policing role, rather than one which - as in the early days, or for the new ADR for frontal crash protection - is designed to stimulate advances in vehicle safety.

If the FCAI is correct in estimating that only 2% of passenger cars do not comply with FMVSS 216, then the ADR would be directly aimed at those 2% and would have this policing role for the rest. Unfortunately, it is not possible to ascertain which particular vehicles comprise that 2%. Nevertheless, it is possible to discuss what benefits might flow from converting that 2% from non-compliance to compliance, and this is of course the central issue.

Our review leads us to conclude that the evidence that an ADR based on FMVSS 216 would reduce injury and other forms of harm in rollover crashes is weak in the extreme. Apart from rather equivocal results from work by the NHTSA, all the statistical work on the effectiveness of FMVSS 216 has shown negative results. The most recent, biggest and best study, that of Moffatt and Padmanaban (1995), essentially settled the issue within the constraints of their research: they showed that roof strength *as measured by the FMVSS test method* in the GM vehicles studied is not significantly related either to the likelihood of severe injury or to severe roof damage in rollovers.

To many, these are counter-intuitive findings. However, they do *not* mean that strengthening roofs (and other countermeasures) cannot reduce injury to occupants in rollovers. In other words, perhaps those looking to reduce these injuries should be looking elsewhere, rather than at picking up this particular standard.

The tone of writing in much of the recent literature shows that this has become a very contentious (even adversarial) issue. One of the bones of contention has long been the issue of *cause*: does roof deformation have a *causal* relationship to occupant injury? Nearly all researchers, even those who adamantly hold that there is no *causal* relationship, concede that severe deformation of the roof over an occupant's seating position is *associated with* severe injury to that occupant, even while there is quibbling about the statistical strength of that association. This has been shown in in-depth field research, mass statistical studies, and test crashes involving dummies.

Many of the earliest researchers assumed that the association was causal, and stimulated the writing and introduction of FMVSS 216 nearly 20 years ago. However, they and others soon came to realise that the severity of the crash was also related to the degree of roof deformation, and proposed that it was *crash severity* that was causing the injuries, not the roof deformation as a single factor.

They also argued that there was a fundamental misconception as to the mechanism of injuries - especially head and neck injuries - in rollover. What they suggested was happening was this. During the roll, the roof contacted the ground. Because the car was inverted, the occupant's head - always near the roof in any event - would come into contact with the interior of the roof's surface, even if a seat belt was worn because of natural extension and normal geometry of the belt. After that, the head's vertical velocity was the same as that of the roof, however much the roof was crushed, and roof-to-head contact could not be causing harm. Head injury could be caused by contact with *any* interior (or exterior) surface during a roll, and that risk in turn was related to the severity of the crash. Neck injury was caused by the loading of the torso on the neck, and because test crashes had shown that the (inverted) seats did not apply pressure to the dummies, and strengthening the roof did not reduce axial neck loads, it followed that strengthening the roof would not reduce the incidence of neck injury in the real world either.

Accordingly, there was no reason to recommend stronger roofs. If this was done, the head-to-roof contacts could be more violent, the deceleration effects on all occupants worse, and the risk of rollover raised because the centre of gravity would be higher.

Nevertheless, all authors of this mind - Huelke, Mackay and Strother among others - concede that the risk of injury for the restrained occupant is raised when the intrusion of the roof is as much as 350 to 450 mm. Further, in this report we have reviewed opposing points of view from American and Australian sources that highlight the agreed association, whether "causal" or not, between

roof crush and injury to the adjacent occupant, and to the invalidity of some dummy measurements for assessing the risk of human injury in rollover. It might be noted that some manufacturers apparently also disagree with the proposition that roof strength has nothing to do with injury: for example, the Mercedes Benz, BMW, Saab and Volvo companies have all highlighted the roof strength of their vehicles at one time or another.⁵

Part of the problem is that because of the complexity of the rollover event, the dynamics of which we have reviewed at some length, the mechanisms of injury to the head and neck are equally complex and unpredictable. In some rollovers, injuries will occur with or without roof crush. Often, these are the result of partial ejection of the head and/or limbs through an open or shattered window. In others, the head will contact the roof interior with enough velocity to threaten the skull, brain and neck, and this can also be independent of roof crush. In other rollovers, with enough vertical velocity, the car continues downwards from its inverted position, the roof support structures deform, and after a certain degree of deformation the occupant is compressed between the seat and the roof, again threatening the head, neck and thorax. As Rechnitzer and Lane (1995) have shown, this crush does not have to be very extensive if the head becomes wedged in the angle between the top of the door and the interior of the roof, because if any crush or deformation then occurs it imposes flexion loads on the neck that can threaten the integrity of the spine. In yet other rollovers, the forward component of velocity will tend to cause human necks to flex, in which position they are also very vulnerable to loadings on the head that cause flexion-compression injuries, including fracture-dislocation of the cervical spine. Again, a substantial degree of roof deformation is not necessary for this to happen.

We have also argued in this report against the proposition that increasing roof strength would increase the propensity for roll, through increasing the height of the centre of gravity. First, most of the energy is absorbed by impact of the wheels, suspension and vehicle underside with the ground. Second, the extra weight due to increased roof strength would be negligible compared with overall vehicle weight.

Clearly therefore, there is more to preventing injury in rollovers than simply imposing a roof strength requirement that is already easily passed by most passenger cars.

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Volvo USA contravened advertising standards by their hyperbole in an advertisement showing a truck being driven across the tops of a line-up of several cars, with only the Volvo roof withstanding the load. The Volvo was later found to have been especially strengthened by the advertising agency.

This takes us to discussion of the results of Moffatt and Padmanaban (1995). They showed quite convincingly that roof strength, as measured by the FMVSS 216 method, was not related to roof damage to GM cars in real rollover crashes, or to the risk of occupant injury in those crashes.

As Murray (1991, 1994) has pointed out, to pass the FMVSS 216 requirement places heavy emphasis of the contribution of the windscreen, because the loading is very close to the plane of the sheet of glass. We and other authors have shown that up to two-thirds of real-world rollovers include some degree of forward, as well as sideways, motion. This imposes a rearwards loading, in pitch, on the A pillar in most cases. It is interesting that the original NHTSA proposal for the FMVSS 216 test method suggested a 10 degree pitch angle for the test platen, but this was reduced to 5 degrees because 10 degrees was seen as too severe by the industry. Although a 10 degree pitch angle would probably be more realistic, it would impose bending loads across the windscreen, which would be more likely to cause it to crack and deform, thus weakening the roof structure considerably and requiring redesign of the steel structures in order to pass the test. Also interesting is the fact that, in association with style demands for more sloping and "aerodynamic" windscreens, the test method is open to review again. This may be because even the 5 degree pitch angle on the platen is imposing these bending loads on the sloping windscreens, and the test is becoming hard to pass. Some new European cars with exceptionally sloping screens, such as the Renault Laguna, have notably thick A pillars, and these two factors may be related.

Thus, one reason that Moffatt and Padmanaban failed to find any relationship between roof strength and occupant injury is that the test method used to assess strength is unrelated to the kind of strength that is required in rollovers - particularly, resistance to longitudinal bending of the A pillars (and to some extent bending of the B pillars) after the windscreen has broken. The kind of strength that is required will be more able to withstand inverted impact in the presence of forward motion, as well as impact with the ground after end-over-end and launching rollovers, where height from the ground has been gained and the vertical velocity on impact is substantial.

The other, and related, reason why they may not have found a relationship between roof strength and injury is that roof strength as measured in the FMVSS method is at the very "weak" end of the relationship between roof strength and roof damage. A theoretically 100% strong roof would not be damaged at all. A 100% weak roof, like an open car, might as well not be there. Assuming the relationship between strength and damage is S-shaped, then all the test might be doing is relating the risk of damage to a very small

incremental increase in strength. Within the range of roof strength that it measures, there is little change in damage risk and (notionally) little change in related injury risk either. Realistically to prevent the kind of damage that threatens the head and neck in rollover requires much greater increases in strength, well outside the range measured in FMVSS 216 tests.

This would explain why substantially stronger roofs, as used in competition cars, do appear to be related to much lower rates of head and neck injury. No competition administrator has taken the risk of assuming that the lower rates of head and neck injury are merely related to better restraints and the wearing of crash helmets, and consequently relaxed requirements for strong roofs for rally and race cars. A roll cage to the specifications of the Confederation of Australian Motor Sports (CAMS) is very effective in reducing roof crush in "simple" rollovers. At a typical weight of about 10 kg for a base design, such a roll cage would have a negligible effect on rollover propensity. Such extra weight, if incorporated into the roof structure of a standard vehicle, could substantially reduce the degree of crush in rollover.

We readily accept that there would be a need for redesign and reconstruction of the steel structures supporting the roof of passenger cars to sustain a higher standard for strength. However, there are some quite simple methods - such as filling the A and other pillars with compressed foam, and strengthening the joints between the pillars and the lower structures - that are already being employed by some manufacturers. None of these modifications would be costly. Other modifications appear less realistic for the designs of today: for example, in the days of "quarter lights", vertical pillars running from the tops of the A pillars to the bottom of the side windows could help support the A pillar against bending loads.

However, in the face of the arguments proposed by Mackay, Huelke, Moffatt and others, it is very unlikely that the industry would be prepared to accept that such modifications were justified, if they were associated with more severe standards. In Australia, we face the realities of the global automobile market, which means that local administrators are to a substantial extent forced to accept overseas standards in the absence of strong justification to do otherwise.

Some of the emerging standards might provide substantial benefit in terms of the potential for head and neck injury in rollover. The US Intermodal Transportation Efficiency Act of 1991 identified several safety improvements that in the opinion of Congress should be brought into regulation by NHTSA. Among several other proposals, the Act identified the need for an *improved* roof crush protection standard, a matter that has not proceeded. However,

another of the proposed rules that has been introduced is for interior head protection, which could reduce head injuries in rollover. NHTSA has recently published its final rule amending FMVSS 201 to require passenger and multipurpose vehicles to protect occupants from head strikes against upper interior components during a crash. The current estimate for the per-vehicle cost for passenger cars is US\$33. The final rule became effective on September 18, 1995.

8.2 The main conclusions

Our main conclusion is that the FMVSS 216 is an inadequate standard, and that there would be little or no incremental benefit in introducing an Australian Design Rule based on it. Because we do not believe its introduction would reduce harm to a measurable extent, we have not attempted a formal cost-benefit analysis of the proposal.

We do believe, however, that the matter of roof strength and its relationship to occupant injury is far from settled, and that more work should be done on the matter. It was not part of our brief for this project to examine such issues, but we agree generally with Rechnitzer and Lane (1994) that vehicle design improvements should include the following:

- better integrity for the side windows;
- increasing A and B pillar strength;
- providing more energy-absorbing padding in the head-strike areas (see following discussion on the new FMVSS 201);
- modification of the framing in the door/roof region to reduce the risk of the head locking in to this angle;
- improvements in seat belt design to reduce occupant movement in rollovers;
- improvements in door integrity and side padding.

To these we would add reduction of head injury potential by redesign of roof framing to eliminate or redirect sharp welded flanges. In most cars these are directed inwards and are unprotected by any padding. Particularly when distorted, these present a cutting edge that is a real threat to the head even in the absence of significant crush.

We also recommend that through international forums the Federal Office of Road Safety should closely monitor, and where appropriate encourage, moves to update and improve the existing FMVSS 216. In the short term, we recommend that the Federal Office of Road Safety review the feasibility of introducing an Australian Design Rule based on the newly amended FMVSS 201 for head impact protection. This could cover many of the points raised above.

A less specific recommendation flows from the fact that Rechnitzer and Lane found a few cases where the occupant had been ejected despite wearing a seat belt, and the Fatality File also contains several such cases. The turbulent and sometimes destructive nature of the rollover event probably makes this occasionally inevitable. However, to the extent that inadvertent unlatching of the buckle may occur from contact with flailing limbs, and to the extent that deformation of the back and other parts of the seat and seat mountings can release the occupants from the belt, many of these ejections may well be preventable. This matter deserves early and detailed investigation, in our view.

Rechnitzer and Lane also suggest that research is required on drop tests, computer simulation and modelling, and the investigation of restraint system performance in rollover. Again, we agree.

In summary, in our opinion rollover is an important cause of injury in road accidents in Australia. We believe that improvement in roof strength (perhaps in certain key directions), along with other countermeasures, would decrease the incidence of rollover-related injuries, not only from contact with the ground during inversion but also from contact with roadside obstacles.

However, we do not believe that the introduction of an ADR based on FMVSS 216 would have more than a minimal effect among such countermeasures, and thus its introduction cannot be justified in its present form.

9 REFERENCES

Attewell R G and Traficante R (INTSTAT Australia), *Federal Office of Road Safety Serious Injury Database: 1993 tabulations*, Report OR18, Federal Office of Road Safety, Department of Transport, 1995

Bahling G S, Bundorf R T and Moffatt E A et al, *Rollover and drop tests: the influence of roof strength on injury mechanics using belted dummies*, SAE 902314, in Proceedings, 34th Stapp Car Crash Conference, Society of Automotive Engineers, 1990

Bahling G S, Bundorf R T, Moffatt E A and Orlowski K F, The influence of increased roof strength on belted and unbelted dummies in rollover and drop tests, *Journal of Trauma*, 38(4) : 557-563, 1995

Cohen D, Digges K and Nichols H, *Rollover crashworthiness classification and severity indices*, in Proceedings, 12th International Technical Conference on Experimental Safety Vehicles, 1989

Council F M and Reinfurt D W, *Safety issues related to mini-cars from a roadway perspective*, SAE 870233, in Proceedings, SAE International Congress and Exposition, Society of Automotive Engineers, 1987

Crash Kings, *Rallying*, Duke Videos, 1994

Digges K H, Malliaris A C, Ommaya A K and McLean A J, *Characterisation of rollover casualties*, in Proceedings, International IRCOBI Conference on the Biomechanics of Impact, International Research Council on the Biomechanics of Impact, 1991

Digges K and Klisch S, *Analysis of factors which influence rollover crash severity*, in Proceedings, 13th International Technical Conference on Experimental Safety Vehicles, 1991

European Transport Safety Council, *Reducing Traffic Injuries Through Vehicle Safety Improvements: The Role of Car Design*, European Transport Safety Council, November 1993

Friedman D and Friedman K D, *Roof collapse and the risk of severe head and neck injury*, in Proceedings, 13th International Technical Conference on Experimental Safety Vehicles, 1991

Garrett J W, *A study of rollover in rural United States automobile accidents*, SAE 680772, in Proceedings, 12th Stapp Car Crash Conference, Society of Automotive Engineers, 1968

Gillespie T D, *Fundamentals of Vehicle Dynamics*, Society of Automotive Engineers, Warrendale PA, 1992

Habberstad J L, Wagner R C and Thomas T M, *Rollover and Interior Kinematics Test Procedures Revisited*, SAE 861875, in Proceedings, 30th Stapp Car Crash Conference, Society of Automotive Engineers, 1986

Henderson M, *An overview of crash data and countermeasure implications*, in Proceedings, Rural Road Safety: Focus for the Future, National Road Trauma Advisory Council seminar, Wodonga, Victoria, April 1995

Hight P V, Siegel A W and Nahum A M, *Injury mechanisms in rollover collisions*, SAE 720966, in Proceedings, 16th Stapp Car Crash Conference, Society of Automotive Engineers, 1972

Huelke D F and Compton C P, Injury frequency and severity in rollover car crashes as related to occupant ejection, contacts and roof damage: an analysis of National Crash Severity Study data, *Accident Analysis and Prevention*, **15**, 395-401, 1983

Huelke D F, Compton C and Studer R M, *Injury severity, ejection and occupant contacts in passenger car rollover crashes*, SAE 850336, in Proceedings, International Congress and Exposition, Society of Automotive Engineers, 1985

Huelke D F, Lawson T E and Marsh J C, Injuries, restraints and vehicle factors in rollover car crashes, *Accident Analysis and Prevention*, **9**, 93-107, 1977

Kahane C J, *An evaluation of door locks and roof crush resistance of passenger cars*, DOT HS-807-489, National Highway Traffic Safety Administration, Department of Transportation, Washington DC, 1989

Kalspeck W D, McLaurin R L, Harris B S, and Miller J D, The national head and spinal cord injury survey: major findings, *Journal of Neurosurgery*, **53**, S19-S31, 1980

Mackay G M and Tampen, *Field studies in rollover performance*, SAE 700417, in Proceedings, International Automobile Safety Conference, Society of Automotive Engineers, 1970

Mackay G M, Parkin S, Morris A P and Brown R N, *The urban rollover: characteristics, injuries, seat belts and ejection* , in Proceedings, 13th International Technical Conference on Experimental Safety Vehicles, 1991

Malliaris A C and DeBlois J H, *Pivotal characterisation of car rollovers* , in Proceedings, 13th International Technical Conference on Experimental Safety Vehicles, 1991

Malliaris A and Digges K, *Crash protection offered by safety belts* , in Proceedings, 11th International Technical Conference on Experimental Safety Vehicles, 1987

McElhaney J H and Myers B S, *Biomechanical Aspects of Cervical Trauma, in Accidental Injury: Biomechanics and Prevention* , Nahum A M and Melvin J (editors), Springer-Verlag, New York, 1993

Mertz H J and Patrick L M, *Strength and response of the human neck* , SAE 710855, in Proceedings, 15th Stapp Car Crash Conference, 1971

Moffatt E A and Padmanaban J, *The relationship between vehicle roof strength and occupant injury in rollover crash data* , in Proceedings, 39th Annual Conference, Association for the Advancement of Automotive Medicine, Chicago, 1995

Monash University Accident Research Centre, *Feasibility of Occupant Protection Measures*, Report CR 100, Federal Office of Road Safety, June 1992

Motor Transport Group, Australian Transport Advisory Council, *A review of the Australian vehicle regulatory system*, October 1982

Murray N W, *Reports on roof crush tests of Holden 1990 VN Commodore 4-door sedan (April 1991), Ford 1991 EA Falcon 4-door sedan (June 1991), 1990 Ford EA Falcon 4-door sedan (June 1991), Nissan Pulsar 5-door hatchback (July 1991), 1991 Toyota Camry 4-door sedan (June 1991), and 1991 Mitsubishi Magna 4-door sedan (December 1991)* Department of Civil Engineering, Monash University, 1991

Murray N W, *When It Comes to the Crunch: The Mechanics of Car Collisions*, p 48ff, World Scientific Publishing Company Pte Ltd, USA and UK, 1994

O'Connor P J and Trembath R F, *Road injury in Australia 1991* , Road Injury Information Program Report Series No. 4, National Injury Surveillance Unit, Australian Institute of Health and Welfare, 1995

Orlowski K F, Bundorf R T and Moffatt E A, *Rollover crash tests: the influence of roof strength on injury mechanics*, SAE 851734, in Proceedings, 29th Stapp Car Crash Conference, Society of Automotive Engineers 1985

Partyka S, Sikora J, Surti J and Vandyke J, *Relative risk to car and light truck occupants*, SAE paper 871093, in Proceedings, Government Industry Meeting and Exposition, Society of Automotive Engineers, 1987

Partyka S, *Fatal accidents in the first 15 months of NCSS*, in Proceedings, 23rd Conference, American Association for Automotive Medicine, 1979

Plastiras J K, Lange R C, McCarthy R L and Padmanaban J A, *An examination of the correlation between vehicle performance in FMVSS 216 versus injury rates in rollover accidents*, SAE 850335, in Proceedings, International Congress and Exposition, Society of Automotive Engineers, Detroit, 1985

Rains C R and Kianianthra J N, *Determination of the significance of roof crush on head and neck injury to passenger vehicle occupants in rollover crashes*, SAE 950655, in Proceedings, International Congress and Exposition, Society of Automotive Engineers, Detroit, 1995

Rally Hits, Volume 2, Rallysport Promotions, undated

Rechnitzer G and Lane J, *Rollover Crash Study: Vehicle Design and Occupant Injuries*, Report No. 65, Monash University Accident Research Centre (for VICROADS), December 1994

Robinette R D and Fay R J, *Empirical and pictorial results of vehicle tip-over impact tests*, SAE 930664, SAE International Congress and Exposition, Detroit, 1993

Strother C E, Smith G C, James M B and Warner C Y, *Injury and intrusion in side impacts and rollovers*, SAE 840403, in Proceedings, International Congress and Exposition, 1984

Syson S R, *Occupant to roof contact: roll-overs and drop tests*, SAE 950654, in *Advances in Occupant Protection Technologies for the Mid Nineties*, SAE SP-1077, Society of Automotive Engineers, 1995

Terhune K W, *The contribution of rollover to single vehicle crash injuries*, Calspan report No 7881/1, AAA Foundation for Traffic Safety, March 1991

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- Thurman D J, Burnett C L, Beaudoin D E, Jeppson L and Sniezek J E, Risk factors and mechanisms of occurrence in motor vehicle related spinal cord injuries, Utah, *Accident Analysis and Prevention*, **27**, 411-415, 1995
- Vehicle Regulatory Review Team, *A Review of the Australian Vehicle Regulatory System*, ATAC Motor Transport Group, Commonwealth Department of Transport and Construction, October 1982
- Wigglesworth E C, Motor vehicle rollovers and spinal cord injury, *International Journal of Vehicle Design*, **12**, 609-617, 1991
- Yoganandan N, Haffner M, Maiman D J et al, *Epidemiology and injury biomechanics of motor vehicle related trauma to the human spine* , in Proceedings, 33rd Stapp Car Crash Conference, Society of Automotive Engineers, 1989

**FEDERAL MOTOR VEHICLE
SAFETY STANDARD
(49 CFR PART 571)**

MVSS 216

**ROOF CRUSH RESISTANCE
PASSENGER CARS**

ORIGINAL: F.R. Vol. 36 No. 236 - 08.12.1971 and amended to January 1994

Amended subsequently:

F.R. Vol. 60 No. 49 - 14.03.1995

**ISSUE: 2
Apr/1995**

MVSS 216

ORIGINAL: FEDERAL REGISTER Vol. 36 No. 236 - 08.12.1971

§ 571.216 Standard No. 216; Roof crush resistance-passenger cars.

S 1. *Scope.* This standard establishes strength requirements for the passenger compartment roof.

S2. *Purpose.* The purpose of this standard is to reduce deaths and injuries due to the crushing of the roof into the passenger compartment in rollover accidents.

S3. *Application.* This standard applies to passenger cars, and to multipurpose passenger vehicles, trucks and buses with a GVWR of 6,000 pounds or less. However, it does not apply to -

(a) School buses;

(b) Vehicles that conform to the rollover test requirements (S5.3) of Standard No. 208 (571.208) by means that require no action by vehicle occupants; or

(c) Convertibles, except for optional compliance with the standard as an alternative to the rollover test requirements in S5.3 of Standard No. 208.

S4. *Requirements.*

(a) *Passenger cars.* A test device as described in S5 shall not move more than 5 inches, measured in accordance with S6.4, when it is used to apply a force of 1½ times the unloaded vehicle weight of the vehicle or 5,000 pounds, whichever is less, to either side of the forward edge of a vehicle's roof in accordance with the procedures of S6. Both the left and right front portions of the vehicle's roof structure shall be capable of meeting the requirements, but a particular vehicle need not meet further requirements after being tested at one location.

(b) Multipurpose passenger vehicles, trucks and buses with a GVWR of 6,000 pounds or less, manufactured on or after September 1, 1994. For multipurpose passenger vehicles, trucks and buses with a GVWR of 6,000 pounds or less, manufactured on or after September 1, 1994, a test device as described in S5 shall not move more than 5 inches, measured in accordance with S6.4, when it is used to apply a force of 1½ times the unloaded vehicle weight of the vehicle to either side of the forward edge of a vehicle's roof in accordance with the procedures of S6.

S5. *Test device.* The test device is a rigid unyielding block with its lower surface formed as a flat rectangle 30 inches x 72 inches.

S6. *Test procedure.* Each vehicle shall be capable of meeting the requirements of S4 when tested in accordance with the following procedure.

S6.1 Place the sills or the chassis frame of the vehicle on a rigid horizontal surface. Fix the vehicle rigidly in position, close all windows, close and lock all doors, and secure any convertible top or removable roof structure in place over the passenger compartment.

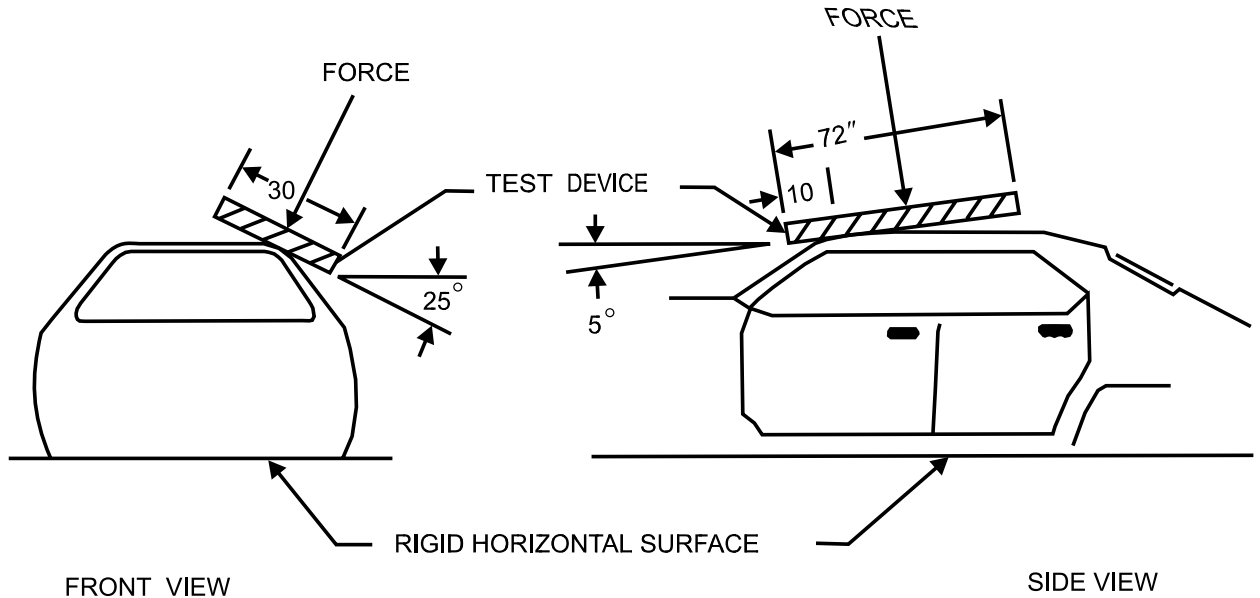
S6.2 Orient the test device as shown in Figure 1, so that -

(a) Its longitudinal axis is at a forward angle (side view) of 5° below the horizontal, and is parallel to the vertical plane through the vehicle's longitudinal centerline ;

(b) Its lateral axis is at a lateral outboard angle, in the front view projection, of 25 ° below the horizontal;

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- (c) Its lower surface is tangent to the surface of the vehicle; and
- (d) The initial contact point, or center of the initial contact area, is on the longitudinal centerline of the lower surface of the test device and 10 inches from the forwardmost point of that centerline.



TEST DEVICE LOCATION AND APPLICATION TO THE ROOF

Figure 1

S6.3 (a) *Passenger cars.* Apply force in a downward direction perpendicular to the lower surface of the test device at a rate of not more than one-half inch per second until reaching a force of 1½ times the unloaded vehicle weight of the tested vehicle or 5,000 pounds, whichever is less. Complete the test within 120 seconds. Guide the test device so that throughout the test it moves, without rotation, in a straight line with its lower surface oriented as specified in S6.2(a) through S6.2(d).

(b) Multipurpose passenger vehicles, trucks and buses with a GVWR of 6,000 pounds or less, manufactured on or after September 1, 1994. For multipurpose passenger vehicles, trucks and buses with a GVWR of 6,000 pounds or less, manufactured on or after September 1, 1994, apply force in a downward direction perpendicular to the lower surface of the test device at a rate of not more than one-half inch per second until reaching a force of 1½ times the unloaded vehicle weight of the test vehicle.

S6.4 Measure the distance that the test device moves, i.e., the distance between the original location of the lower surface of the test device and its location as the force level specified in S6.3 is reached.

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METRIC CONVERSION

The following changes are effective from March 14, 1996 , optional early compliance is permitted beginning March 14, 1995.

§ 571.216 [Amended]

Section 571.216 is amended by revising S3; revising S4; revising S5; revising in S6.2, paragraph (d); and revising S6.3 to read as follows:

§ 571.216 Standard No. 216, Roof crush resistance-passenger cars.

* * * * *

S3. *Application.* This standard applies to passenger cars, and to multipurpose passenger vehicles, trucks and buses with a GVWR of 2722 kilograms or less. However, it does not apply to-

- (a) School buses;
- (b) Vehicles that conform to the rollover test requirements (S5.3) of Standard No. 208 (§ 571.208) by means that require no action by vehicle occupants; or
- (c) Convertibles, except for optional compliance with the standard as an alternative to the rollover test requirements in S5.3 of Standard No. 208.

S4. *Requirements.*

(a) *Passenger cars.* A test device as described in S5 shall not move more than 125 millimeters, measured in accordance with S6.4, when it is used to apply a force in newtons equal to 1½ times the unloaded vehicle weight of the vehicle, measured in kilograms and multiplied by 9.8 or 22,240 newtons, whichever is less, to either side of the forward edge of a vehicle's roof in accordance with the procedures of S6. Both the left and right front portions of the vehicle's roof structure shall be capable of meeting the requirements, but a particular vehicle need not meet further requirements after beina tested at one location.

(b) *Multipurpose passenger vehicles, trucks and buses with a GVWR of 2,722 kilograms or less, nwnmanufactured on or after September 1, 1994.* For multipurpose passenger vehicles, trucks and buses with a GVWR of 2,722 kilograms or less, manufactured on or after September 1, 1994, a test device as described in S5 shall not move more than 125 millimeters, measured in accordance with S6.4, when it is used to apply a force in newtons equal to 1½ times the unloaded vehicle weiahrt of the vehicle, measured in kilograms and multiplied by 9.8, to either side of the forward edge of a vetiicle's roof in accordance with the procedures of S6. Both the left and right front portions of the vehicle's roof structure shall be capable of meeting the requirements, but a particular vehicle need not meet further requirements after being tested at one location.

S5. *Test device.* The test device is a rigid unyielding block with its lower surface formed as a flat rectangle 762 millimeters x 1829 millimeters.

* * * * *

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S6.2 * * *

(d) The initial contact point, or center of the initial contact area, is on the longitudinal centerline of the lower surface of the test device and 254 millimeters from the forwardmost point of that centerline.

S6.3(a) *Passenger cars.* Apply force in a downward direction perpendicular to the lower surface of the test device at a rate of not more than 13 millimeters per second until reaching a force in newtons of 1½ times the unloaded vehicle weight of the tested vehicle, measured in kilograms and multiplied by 9.8 or 22,240 newtons, whichever is less. Complete the test within 120 seconds. Guide the test device so that throughout the test it moves, without rotation, in a straight line with its lower surface oriented as specified in S6.2(a) through S6.2(d)

(b) *Multipurpose passenger vehicles, trucks and buses with a GVWR of 2,722 kilograms or less, manufactured on or after September 1, 1994.* For multipurpose passenger vehicles, trucks and buses with a GVWR of 2,722 kilograms or less, manufactured on or after September 1, 1994, apply force in a downward direction perpendicular to the lower surface of the test device at a rate of not more than 13 millimeters per second until reaching a force in newtons of 1½ times the unloaded vehicle weight of the tested vehicle, measured in kilograms and multiplied by 9.8. Complete the test within 120 seconds. Guide the test device so that throughout the test it moves, without rotation, in a straight line with its lower surface oriented as specified in S6.2(a) through S6.2(d).

* * * * *

Section 571.216 is amended by revising Figure 1 at the end of S6.4 to read as follows:

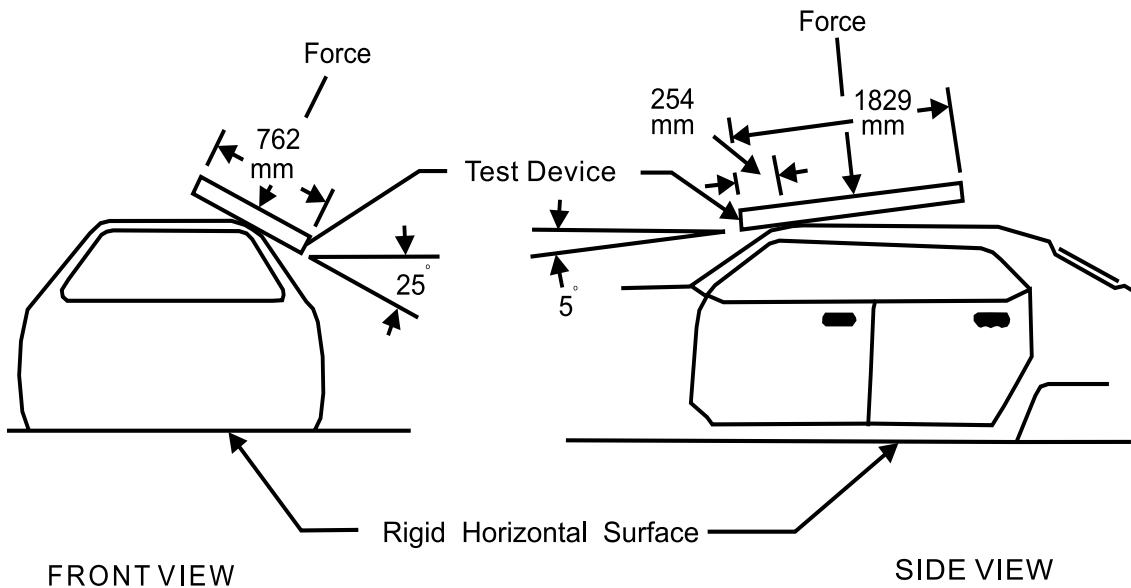


FIGURE 1

TEST DEVICE LOCATION AND APPLICATION TO THE ROOF

APPENDIX 2

CASES FROM THE FATALITY FILE

This appendix includes narrative summaries of the cases extracted from the Fatality File of the Federal Office of Road Safety. In all these cases seat belts were reportedly worn by the fatally injured occupant.

The numbers are the Fatality File ID numbers.

332.1 VIC. Ford 1988. Fatalities: 1. Rolled onto roof. Unable to release seat belt. Fire followed.

387.1 SA. Subaru 1982. Fatalities: 1. Rural road. Veered across road, hit a group of trees. Rolled down embankment. Came to rest on roof. Estimated speed 113 to 138 km/h. Photos: major impact to top rear. Possible pitch-over, landing on roof and boot. Front of roof relatively intact but side-sway of roof may have contributed to injury. Deceased was found suspended by seat belt, touching roof. Extensive bruising to left side of head. Fracture to base of skull.

412.1 SA. Holden Commodore 1986. Fatalities: 1. Rural road. veered off road, hit fence, rolled several times across a paddock. High speed crash. Photo: Major impact to right side of bonnet and roof. Possibly a corkscrew rollover. Possibly similar loading direction to FMVSS 216. Deceased driver had frontal skull fracture. Possibly struck forehead above windscreen. This region was crushed inwards slightly.

442.1 SA. Toyota 1976. Fatalities: 1. Rural arterial. Off road, skidded, rolled and hit tree with roof against tree. Roof on driver's side was pushed back towards centre of vehicle. Intrusion of tree main factor. Head of deceased came into contact with tree. Body protruded outside vehicle from shoulders up. Possible side-sway.

467.1 SA. Ford Escort 1971. Fatalities: 2. Highway (2 lane). Off road, over-corrected and rolled. Photos: Main damage to passenger side of vehicle. Some side-sway. AIS report indicates ejected driver was not wearing a seat belt. Left front passenger died from trauma associated with a skull fracture to right side. Possible partial ejection but was restrained by seat belt. Passenger in rear seat had minor injuries.

637.1 NSW. Nissan 1981. Fatalities: 1. Rural highway. Lost control. Off road and rolled. Front left passenger trapped. Severe head and body injuries.

642.1 NSW. Nissan Pintara FWD 1990. Fatalities: 1. Rural highway. Off road, collided with small trees and embankment. Overturned a number of times. Driver survived with unspecified lacerations. Left front passenger died from "massive head injuries". Also sustained broken ribs.

643.1 NSW. Ford Falcon. Fatalities: 1. Outback highway. Tyre blow-out. Lost control, off road. Came to rest on roof. Driver had spinal and neck injuries and fracture at base of skull.

683.1 NSW. Nissan Skyline 1988. Fatalities: 1. Rural road. Off road and down embankment. Rolled several times. Rear seat passenger died from severe head injuries.

693.1 NSW. Ford Meteor/Laser 1985. Fatalities: 1. Off road. Hit pole (possible 1/4 roll and roof hit pole). Severe intrusion.

745.1 NSW. Holden 1983. Fatalities: 1. Highway. Lost control Fish-tailed. Rolled a number of times.

773.1 NSW. Mitsubishi Sigma 1980. Fatalities: 1. Rural road. Off road and down embankment.

775.1 NSW. Ford Falcon 1984. Fatalities: 1. Rural intersection. High speed. Vehicle rolled after being impacted on left side. Driver was killed.

793.1 NSW Mazda 323 1983. Fatalities: 1. Off road at bend. Hit tree and culvert causing vehicle to roll. Landed back on the roadway. Rear seat passenger died from head injuries.

825.1 NSW. Nissan 1985. Fatalities: 1. Rural road. Lost control, off road down embankment.

838.1 NSW. Toyota Camry 1991. Fatalities: 1. Freeway. Veered onto dividing strip. Hit several small trees, coming to rest on roof.

846.1 NSW. Holden Commodore 1987. Fatalities: 1. Freeway. Veered off road, hit rock cutting, climbed 6 m up rock face then rolled end-over-end for 80 m. Driver partially ejected and decapitated. Passenger survived.

853.1 NSW. Holden Nova 1991. Fatalities: 1. Suburban road. Veered off bend. "Sailed over" creek and landed on embankment.

907.1 NSW. Ford Fairmont 1973. Fatalities: 1. Rural highway. Off road in wet. Glanced off rock cutting and overturned. Driver received non-lethal head injuries. Front left passenger severed fingers. Rear seat passenger killed.

923.1 NSW Subaru 1990 Fatalities: 1 Rural highway. Swerved to avoid collision. Off road, hit pipe and rolled. Driver received fractured ankle and lacerated scalp. Front left passenger killed.

965.1 NSW. Holden Nova 1990. Fatalities: 1. Suburban arterial. Off road, coming to rest on roof in a creek. Possible impact with pole.

1106.1 NSW. Peugeot 1980. Fatalities: 1. Gravel road. Lost control. Over-corrected. Rolled a number of times. Driver died from broken neck and severe head injuries.

1120.1 NSW. Holden Commodore 1987. Fatalities: 1. Rural highway. Off road, hit dirt mound, became airborne, hit small tree and landed on roof. Driver died from chest injuries after 10 days.

1149.1 NSW. Ford Cortina 1976. Fatalities: 1. Rural road. Lost control on bend. Veered across road, over embankment and hit tree. Came to rest on roof. Driver died from massive head injuries. Two passengers survived.

1160.1 ACT. Ford Telstar 1984. Fatalities: 1. Rural road. Lost control. Slid sideways, mounted earth mound, rolled over, coming to rest on roof in a small culvert. Driver survived. Front left passenger died from head injuries. Driver claims to have unfastened seat belt of the deceased.

1182.1 QLD. Mitsubishi Colt. Fatalities: 1. Off road, through ditch, hit tree stump, flipped over, hit small tree, came to rest on roof.

1191.1 QLD. Ford Falcon. Fatalities: 2. Rural highway. Off road, through table drain, overturned several times. Came to rest on side. Total of 5 occupants. Driver died from head injuries. Front left passenger ejected and died. Other passengers survived.

1235.1 WA. Holden Commodore 1989. Fatalities: 1. Speeding. Failed to take bend. Off road and rolled. "Lurched down on driver's side before rolling". Driver ejected and killed. Evidence of sea belt being worn. Noted that seat was adjusted to rear - possibly allowing sash to be loose.

1246.1 WA. Holden Commodore 1978. Fatalities: 1. Unlikely that the ejected driver was wearing a sea belt. Passengers received minor injuries.

125.1 VIC. Subaru 1988. Fatalities: 1. Rural highway. Lost control on bend, off road, hit tree. Possible 1/4 roll and roof hit tree (intrusion).

1263.1 WA. Holden Statesman 1973. Fatalities: 1. Off road, over embankment. Rolled several times. Came to rest on wheels. Damage report: extensive damage. All "turrets" bent and forced inwards. Motor wrenched from vehicle. Driver survived. Front left passenger died from fracture of base of skull. Dirt on face indicating direct contact with ground.

1268.1 WA. Saab 1989. Fatalities: 1. Swerved. Slid sideways. Off road, onto side and hit tree with roof.

1305.1 WA. Hyundai 1992. Fatalities: 1. Off road. Rolled onto side and hit tree with rear of roof. Driver and front left passenger survived. One rear seat passenger was ejected and crushed. Other died from broken neck. Intrusion.

1327.1 WA. Toyota Corolla 1988. Fatalities: 1. Swerved and lost control. Off road and down verge, tripped and came back onto road. Probably rolled four times. Came to rest on wheels. Drivers head struck bitumen on three occasions. Possible "rag doll" effect.

1357.1 WA. Holden Commodore 1980. Fatalities: 1. Off road. Hit embankment and rolled onto driver's side. Came to rest with roof against power pole. Intrusion?

1359.1 WA. Ford Falcon 1992. Fatalities: 1. Off road, rolled several times and hit tree. Severe impact to left rear quarter. Five occupants. Deceased child was ejected but evidence of wearing lap portion of lap/sash seat belt (was sash portion in place?).

1379.1 WA. Ford Laser. Fatalities: 1. Lost control. Veered across road, hit small tree 2 m above ground. Came to rest with roof against a tree. Intrusion on passenger side. Driver died from broken neck - unclear how this occurred. Front left passenger survived despite intrusion.

1413.1 QLD. Holden Commodore 1982. Fatalities: 1. Driver had heart attack. Off road, roof hit tree. Front left passenger died from crushed head - probably intrusion.

1431.1 QLD. Subaru. Fatalities: 1. Rural highway. Driver distracted. Lost control Off road. Came to rest on roof. Driver survived. Front left passenger died from massive head injuries and fractured neck. Was still wearing seat belt but appears to have been partially ejected, possibly due to reclined sea .

1434.1 QLD. Ford Cortina. Fatalities: 1. Off road at intersection. Hit table drain and tree. Rolled onto roof. Photo: massive roof deformation over front seats. Unclear how driver survived. Front left passenger partially ejected and died.

1472.1 QLD. Mitsubishi Sigma 1981. Fatalities: 1. Off road. Over-corrected. Rolled a number of times and hit a tree 2.5 m from ground. Massive intrusion on passenger side. Front left passenger partially ejected - came into contact with tree or ground.

1547.1 QLD. Toyota Corolla 1985. Fatalities: 1. Rural highway. Off road, over-corrected, veered across road and down embankment. Rolled end-over-end several times. Extensive damage to all panels. Driver was ejected through rear window. Seat squab "bent" and recline - possibly during an impact. Seat belt was still fastened.

1608.1 QLD. Mazda 1974. Fatalities: 1. Rural highway. Fell asleep. Off road, over-corrected. Down embankment.

1615.1 QLD. Toyota. Fatalities: 1. Vehicle seen to b fish-tailing. Veered to wrong side of road and overturned. Driver died from head injuries.

1705.1 QLD. Holden Commodore. Fatalities: 1. Veered across road. Hit culvert and somersaulted completely. Then rolled sideways and came to rest on roof. Driver apparently partially ejected. Head crushed under vehicle. Still in seat belt.