

# Rollover Crash safety: Characteristics and issues

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## Abstract

This paper presents a brief overview of current issues relating to rollover safety and associated literature. It also describes the research program currently underway in Australia investigating rollover crashes. Preliminary data from investigating US NASS online data and some Australian data is revealing the highly fatal nature of rollovers caused by the consistent violation of basic crashworthy design principles when considering occupant protection in rollover crashes. The paper confirms that ejection and roof intrusion are again linked to a higher proportion of MAIS 3+ injuries suggesting that manufacturers have yet to fully address these areas in modern vehicle design related to rollover crashes.

## INTRODUCTION

While considerable advances have been made in relation to occupant protection resulting from frontal, side impact and to some degree pedestrian vehicle collisions, the same cannot be said in regards to preventing or minimising fatalities and serious head and spinal injuries resulting from rollover crashes. Around 1 in every 5 fatalities in Australia result from a rollover crash [1] whereas in the USA it appears to be even higher around 1 in every 3-4 fatalities [2, 3]. For Europe it is estimated around 1 in every 10 fatalities are rollover crash related [4].

A perspective of how dangerous a rollover crash event is becomes obvious when considering US vehicle crash data, of rollover crash fatalities, over the past decade. Linstromberg et al and Viano and Parenteau [5, 6] point out that while rollovers in the U.S. represent less than 1 in 20 of all vehicle crashes they account for approximately 1 in 3 vehicle occupant fatalities.

One of the main reasons why rollover crashes are overrepresented in vehicle occupant fatalities and particularly hazardous is there are no standards or consumer tests, in any country, that *dynamically* assess the rollover crashworthiness of passenger small and large vehicles such as cars, four wheel drive (4WD) and sport utility vehicles (SUV).

Figure 1 shows, for example, the current Australian Design Rules (ADR's) and consumer tests such as Australian New Car Assessment Program (ANCAP) dynamic crashworthiness crash tests and crash test dummies used to assess the crashworthiness of the Australian vehicle fleet.

Paradoxically, in contrast to frontal and side impacts, rollover crashes in themselves are a low severity event as the crash energy is dissipated over seconds rather than milliseconds. Thus the source of the severe injury risk and over representation lies not in the collision event itself but rather the lack of occupant protection designed into the vehicle.

This paper presents an overview of some current issues related to rollover crashes, supported by some crash tests from previous studies and preliminary rollover related crash statistics. The paper will also provide some direction in regards to what is required to mitigate injuries in vehicle rollover crashes.

## OVERVIEW OF ROLLOVER ISSUES

Crashworthiness modifications to the design of vehicles goes as far back as the early 1930s when Claire Straith influenced Chrysler to provide in their vehicles foam rubber to protect occupants against striking hard surfaces, to recess protruding knobs to reduce impalement, and to raise the dashboard to reduce knee injuries in their vehicles. Over the next two decades the major advances in understanding how human injury occurred in crashes and how to mitigate them in aircraft crashes was in large the result of Hugh De

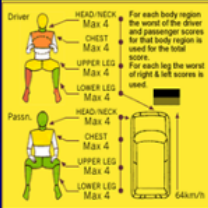


	Frontal	Side	Pedestrian	Rollover
Consumer	 <p>Hybrid III</p>	 <p>optional SID2S, EuroSID</p>	 <p>Headform, Legform</p>	<p>?</p> <p>?</p>
ADR	<p>ADR 69 ADR 73</p>	<p>ADR 72</p>	<p>?</p>	<p>?</p>

Figure 1. Current standards and consumer tests in Australia

Haven's research efforts at Cornell University. Over time this understanding was used to start to design vehicles to protect automobile occupants in vehicle crashes, and included the work of Colonel John Stapp, a colleague of Hugh De Haven. While the origins and growth of this movement was due to the input and experience of many such people, Hugh De Haven is often attributed with being the "Father of Crashworthiness principles and Research" and the person who created the original theories of crashworthy design. He adapted simple packaging principles to show its relevance to protecting occupants during automotive crashes [7,8]. These principles are:

1. The package should not open up and spill its content and should not collapse under expected conditions of force and thereby expose objects inside to damage,
2. Packaging structures which shield the inner container must not be made of brittle or frail materials; they should resist force by yielding and absorbing energy applied to the outer container so as to cushion and distribute the impact forces and thereby protect the inner container,
3. Articles contained in the package should be held and immobilized inside the outer structure, and
4. Wadding, blocks or means for holding an object inside a shipping container must transmit the forces applied to the container to the strongest parts of the contained objects.

These principles are still valid today and yet often ignored in the design of mobile structures when considering occupant protection. The authors unequivocally subscribe to the view that if first principles of crashworthiness design are ignored or violated, then it is no surprise, indeed it is axiomatic, that severe injuries will be the outcome.

While the initial focus of occupant protection systems by industry and regulators focussed on protecting vehicle occupants in frontal, side impact, and rear end crashes, and current crashworthiness research is now being broadened to consider roadside furniture and pedestrians, there is a distinct lack of

application of such sound principals as those outlined by Hugh De Haven to rollover crashworthiness design of cars and 4WD/SUV vehicles. This is despite there already existing rollover roof crush crashworthiness standards for buses and heavy industrial and farm machinery in Australia, South Africa, Europe and the USA. The ECE (Economic Commission for Europe), South Africa and Australia have a mandatory bus rollover standard which is a dynamic test. The US bus-rollover test is quasi-static [9, 10, 11]. The standards that exist for mining, industrial and farming machinery for roof crush are based on quasi static tests and are not mandatory but are usually conformed to as a result of Occupational Health and Safety legislation and litigation exposure [12, 13, 14, 15].

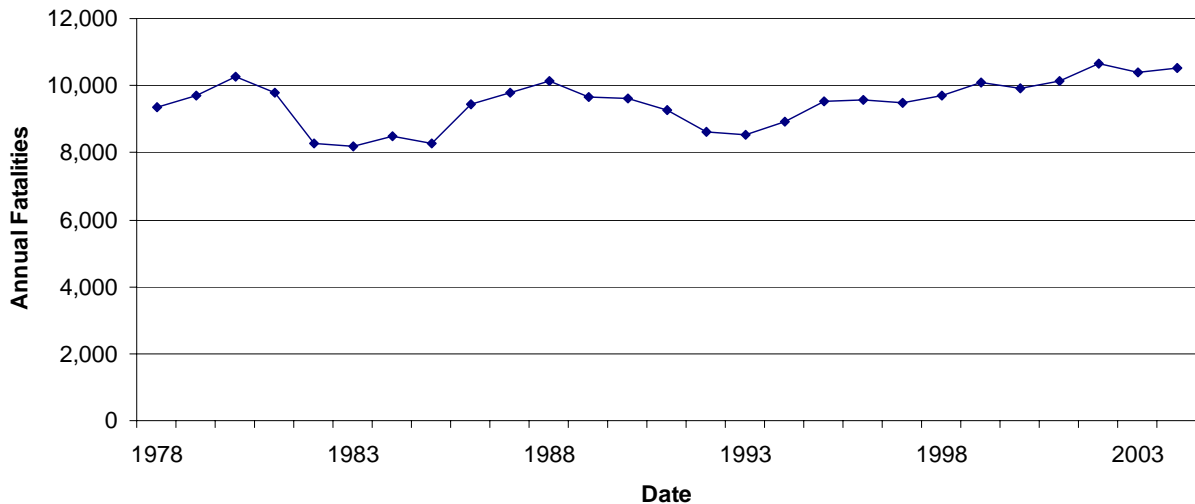
Table 1 presents a summary of the current rollover crashworthiness standards and guidelines the authors are aware of. In Australia rollover crashworthiness of busses, police vehicles, army vehicles, farm tractors, earthmoving, forestry and mining machinery are available. Yet a passenger vehicle design rule or consumer test is inauspiciously absent. Each of the standards or guidelines can be classified by the degree of compliance required. These levels appear to be;

1. *Mandatory* – Compliance is a legal requirement for the vehicle to be able to be used, publicly or privately,
2. *Best Practice* – This recommends the level of safety agreed upon by professionals, consumer groups and industry to be acceptable but is not a legal requirement for a vehicle, and
3. *Duty of care* – It is a legal requirement for an employer (e.g. a mining company) to use care to protect occupants from unnecessary risk but the guideline recommended is not mandatory.

**Table 1 – Legal requirements and design considerations for rollover safety of different vehicle types**

	Sections applicable to Rollover	Requirement	Static vs. Dynamic	Components tested	Applicable Vehicle Class	Country
ADR	59	Mandatory	Dynamic	Structural	Buses	Australia
ASA	2294	Best Practise	Static	Structural	Earth-Moving Machinery	Australia
ASA	1636	Best Practise	Static	Structural	Tractors	Australia
ISO	3471	Best Practise	Static	Structural	Earth-Moving Machinery	International
SAE	J1040	Best Practise	Static	Structural	Construction, Earthmoving, Forestry and Mining Machines	USA
OHS&E	Richardson et al [19]	Duty of care	Static & Dynamic	Structural	Army Vehicles	Australia
	Richardson et al [19]	Duty of care	Static & Dynamic	Structural	Mining vehicles	Australia
ECE	R.66	Mandatory	Dynamic	Structural	Busses	Europe
FMVSS	220	Mandatory	Quasi-Static	Structural	School busses	USA
	216	Mandatory	Static	Structural	Passenger vehicles	USA
	208	Optional	Dynamic	Occupant containment	Passenger Vehicles	USA
NCAP	Rollover Ratings	Best Practice	Static/ Dynamic	Stability	Passenger Vehicles	USA
SANS	1563	-	-	Structural	Busses (capacity>16)	South Africa

Currently the only countries to have a standard that purports to protect occupants in cars and larger vehicles (SUV's) in rollover crashes is the USA, Brazil and Canada using FMVSS216. The FMVSS 216 roof crush standard was developed in 1971 and revisions to the standard are currently being considered though there is considerable debate regarding the changes proposed [16]. Data obtained from IIHS [2] when plotted as shown in Figure 2 indicates that over the last 30 years the number of rollover fatalities in the USA seems to be rising placing into further question the adequacy of the FMVSS 216. This is despite the amount of increasing research world wide into the effects of roof crush on occupant injury during a rollover crash.



**Figure 2 – US Rollover fatalities 1978 – 2004**

Rollovers have been classified into eight categories in the US according to the National Automotive Sampling System-Crashworthiness Data System (NASS-CDS) [17, 18] based on typical rollover crash initiation scenarios. These scenarios are:

- Trip-over** - when the lateral motion of the vehicle is suddenly slowed or stopped inducing a rollover. The opposing force may be produced by a curb, pot-holes, or pavement dug into vehicle wheels. This typically happens on a country road in Australia for example when a driver momentarily has a micro sleep or becomes distracted and drifts to the side of the road onto the gravel verge. The driver is then suddenly woken up by the vibrations and/or the noise of the vehicle travelling on the gravel and jerks the wheel to steer the vehicle back onto the bitumen road. The result demonstrated by Richardson et al [19] is shown in Figure 3.
- Flip-over** - when the vehicle is rotated along its longitudinal axis by a ramp-like object such as a turned down guardrail, a concrete end terminal ramp barrier (Figure 4), on an F shape barrier or water filled barrier as demonstrated by Grzebieta et al [20], or the back slope of a ditch. The vehicle may be in yaw when it comes in contact with a ramp-like object.
- Bounce-over** - when a vehicle rebounds off a fixed object and overturns as a consequence. The rollover must occur in close proximity to the object from which it is deflected as for example demonstrated by the wire-rope barrier crash shown by Grzebieta et al [20], see Figure 5.



**Figure 3 - Vehicle motion during typical trip initiated rollover (After Richardson et al) [19]**



**Figure 4 - Tram ramp protects pedestrians but results in vehicle Flip-overs.**

**Turn-over** - when centrifugal forces from a sharp turn or vehicle rotation are resisted by normal surface friction (most common for vehicles with higher centre of gravity (COG) cornering too hard at speed). The surface includes pavement surface and gravel, grass, dirt, etc. There is no furrowing or gouging at the point of impact. Note that if rotation and/or surface friction causes a trip, then the rollover is classified as a turn-over.

**Fall-over** - when the surface on which the vehicle is traversing slopes downward in the direction of movement of the vehicle's COG such that the COG becomes outboard of its wheels (Note: The distinction between this code and flip-over includes a negative slope.).



**Figure 5 - Vehicle motion during typical longitudinal roll bounce-over initiated rollover (After Grzebieta et al) [20]**



**Figure 6 - Vehicle motion during typical End-over-end, bounce-over initiated rollover (After Grzebieta et al) [20]**

***Climb-over*** - when the vehicle climbs up and over an object (e.g. guardrail, barrier) that is high enough to lift the vehicle completely off the ground. The vehicle must roll to the opposite side from which it approached the object.

***Collision with Another Vehicle*** - When an impact with another vehicle causes the rollover. The rollover must be the immediate result of the impact between the vehicles. For example, this could occur at an intersection where a vehicle is struck in the side and the momentum of the struck vehicle results in a rollover.

***End-over-end***- When a vehicle rolls primarily about its lateral axis as for example demonstrated by the concrete barrier crash shown by Grzebieta et al [20], see Figure 6.

The reasons behind rollovers dangerous fatality rate can be revealed by examining the typical vehicle motion, occupant motion and structural loading, and in turn the vehicle structure (including glazing) and restraint system response associated with a rollover event. Figure 3 shows the series of photos representing the typical vehicle motion during a trip-over rollover event.

The series of events in a typical trip-over crash can be segregated into the following distinct stages:

1. Loss of control of vehicle,
2. Vehicle Yaw (travelling sideways down roadway),
3. Rollover initiated (by tripping) and
4. Vehicle rolls, with roof to ground contact.

An investigation by Grzebieta et al [20] into road barrier crashworthiness noted two rollovers initiated by barrier impact; these are shown in Figure 5 and Figure 6. The second of these two figures shows an end-over-end type of rollover. These rollovers are less frequent than longitudinal rolls and commonly require an exterior component, such as a guardrail or a ditch, to initiate this motion.

Typically the above 90% of rollover events involve rotation about the longitudinal (roll) axis of the vehicle [21] as is indicated in Figure 3. It is the motion seen in Figure 3 Figure 6 that also gives rise to the *impression* of a particularly dangerous nature of a rollover crash. Paine [22] noted that “The combination of vertical acceleration/deceleration, horizontal deceleration and rotational acceleration/deceleration generally results in complex occupant kinematics during a rollover”. Standard restraints that are designed for frontal collisions do not provide effective restraint in rollovers, and with roof intrusion, and also allow partial occupant ejection, and the risk of severe head and spinal injuries as observed. The issue of the ineffectiveness of seatbelts and role of roof crush in injury causation was highlighted by Rechnitzer et al 1994 and 1998 [23, 24]

Digges [25] observed that 50% of HARM<sup>1</sup> [26] in a rollover event is a result of brain and head injuries with neck and spine injuries accounting for a further 10%. It is these injuries that need to be addressed to reduce fatalities and the catastrophic outcomes of rollovers. Whilst the extended nature of the rollover event requires the safety system to operate far longer than in say a frontal collision, this also means that crash severity is much lower than for other crash modes. Berg et al [27] states that “Occupant protection is necessary up to 10 seconds after the rollover starts”. This extension of the time during which safety systems are expected to act in a rollover (when compared with the 60 to 100 milliseconds required in front or side collisions) requires a different design approach to that of current crash technology systems.

Many rollover investigations have observed that there are two different injury mechanisms that are prevalent during rollover crashes. These relate to the in vehicle retention of the person(s) involved in the crash. Each mechanism results in a separate injury profile for the occupants of the vehicle. These two varying rollover injury mechanisms are,

- Crashes where the occupants are maintained in the vehicle (i.e. not ejected), and
- Crashes involving partial or full ejection of occupants.

Ejection is the process by which an occupant is either partially or fully thrown from a vehicle allowing for contact with the ground and other surfaces exterior to the vehicle. This includes entrapment of the occupant and/or their limbs, head or torso between the road surface and the vehicle structure. Berg et al [27] summarised research performed in Germany that investigated these two different injury profiles. This data suggests that injuries to ejected occupants are primarily to the torso and head while injuries to non-ejected occupants are primarily to the head, skin and extremities. It can be concluded that the larger degree of torso injuries seen in cases of ejection are caused by the secondary impact of the ejected occupant to the ground or via entrapment. On the other hand injuries in the case of non-ejection seem to relate to the degree of roof crush and impact of the occupant on the interior (e.g. roof or pillars) of the vehicle. Richardson et al suggest that the best way to reduce occupant movement and ejection resulting in

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<sup>1</sup> HARM is defined as the “the sum of each injury cost multiplied by its respective frequency of occurrence”

injury is to maintain an intact survival space by reducing roof crush of vehicles coupled with effective seatbelt restraint [19].

The success of these measures is made clear when considering the severe rollovers that occur in motor racing. In these vehicles an extremely stiff (roll caged) roof structure along with an effective restraint system that dramatically reduces occupant motion leads to a pronounced increase in survivability for rollovers, when compared to real world crash scenarios. These measures result in a dramatic reduction in fatalities in these vehicles, despite the fact that this dangerous collision type constitutes nearly half of all racing crashes [23].

To provide a better understanding of how roof intrusion influences the safety of occupants during a rollover crash, these issues will be further investigated under the noted research program awarded to the authors.

### Roof Intrusion

One of the key factors affecting occupant survival in all types of collisions is maintaining the integrity of the occupant's "survival space"<sup>2</sup> within a vehicle during a crash. It has been identified that during a rollover crash, the protective structure must be capable of providing a survival space that is coupled to an effective passenger restraint system that restricts occupant movement within that space [19].

It has been observed that the integrity of a survival space during a rollover is influenced primarily by the amount of roof intrusion that is experienced by the vehicle. Two separate studies focusing on the relationship between roof intrusion and injury levels [22, 28] appear to confirm that injuries increase when roof crush exceeds the level of 10 cm.

Vehicle manufacturers (with notable exceptions) in the US propose that roof crush is not causally related to occupant head and neck injury in rollover events and that it is the result of a secondary event. It has been consistently argued that roof crush is "merely an indication of accident severity and that injury severity increased with accident severity" [29]. Contrary to this point of view vehicle safety advocates have been producing evidence from crash tests where peak neck loads have been recorded and attributed to roof intrusion. One such case is from a GM crash test, known as Malibu I, undertaken in 1985. In an investigation of the data collected during this crash test, Friedman and Nash [30] showed a link between peak neck loads exceeding human tolerances and roof intrusion. Figure 7 shows an interior view of the vehicle subjected to the rollover shown in Figure 5. It supports this finding where, as a result of roof intrusion, the roof impacts the head and compresses the neck.

The automotive industry have attempted to decouple the link



**Figure 7– Screen captures of interior occupant motion of Toyota Echo rollover and high level of neck compression due to the roof deformation**

<sup>2</sup> The survival space of an occupant is defined as the physical envelope in which the motion of an occupant is contained during a crash.

between roof crush and injury causality by proposing that head and neck injuries in rollover crashes are caused by a “diving” mechanism. Moffatt [31] first presented this view in 1975 when he proposed a misconception has occurred when people begin to discuss the roof crush issue. He refers to the fact that people often say the roof is “pushed downward” in a rollover crash. In contrast to this, Moffatt suggests that the roof is in actual fact stationary against the ground and it is the body of the car and the occupant that continue moving causing the occupant to strike the roof. This injury mechanism is likened to the neck injury that occurs when a person dives into shallow water in a pool, river or lake.

The so called diving theory is a misrepresentation of what actually occurs in most rollovers, in that the roof does not stop but continues to move as it is part of a rolling vehicle. In effect the corners of a roof (if not adequately strengthened) are being ‘wiped off’ resulting in an intrusion velocity towards the head of the occupant. Similarly the occupant does not typically dive into the roof but moves with a rolling vehicle. This is evident from examination of the Malibu test videos. It is also evident from a comparison of the lower neck loads experienced by the dummies in the roll caged vs production vehicles. Moffatt’s lift shaft analogy although used to justify his diving theory that the roof move towards the occupant, has little to do with a rolling vehicle yet has been presented to be so.

To contrast the view that the diving mechanism causes severe head and neck injuries in rollover, regardless of level of roof intrusion at the time of injurious impact, Friedman and Nash [32] introduce the concept of head impact velocity. In analysis of the movement of vehicle’s centre of gravity (COG) during a typical rollover crash, Friedman and Nash [30] observed that a vehicle’s COG only rises and falls by around 10 cm corresponding to a vertical velocity at roof impact of around 2.5 m/sec (5.6 mph). A similar value of vertical vehicle COG of 2 m/sec (4.5 mph) was proposed by Henderson and Paine [29]. Friedman and Nash [33] further conclude that the impact speed of 2.5 m/s corresponds to an AIS 2 level injury and that it hence is survivable.

As a result of such observations, the question that needs to be posed is; why are head and neck injuries observed to be of a higher severity than those corresponding to a head impact velocity occurring if the occupant is falling at the same rate as the vehicle’s COG at 2.5 m/s? Friedman and Nash [34] suggested that when a vehicle’s roof experiences severe roof crush or buckles, the rate of intrusion of the roof occurs “with an amplification factor of 3” compared to the vertical velocity of the vehicles they examined.

This is contrary to the view of Moffatt [31], where it is believed that the contact velocities for cars that experience roof crush/buckling is the same as cars that do not experience roof crush. Further investigation by Friedman and Nash [35] supports this initial general observation where they concluded that: *“the only severe head and neck injury measures in the measures in the Malibu tests came from situations where the roof intruded into the occupant compartment at speeds well in excess of the speed at which the rolling vehicle was falling to the ground”*. Thus the reduction in injury severity lies in minimizing roof intrusion.

The importance of intrusion minimization is further highlighted, in the observations from the recent edition of the IIHS Status Report [36] looking at the advances in Frontal Crashworthiness. The study identified that one of the major factors leading to the observed improvements in frontal crashworthiness over the past 14 years was the reduction and prevention of deformation and intrusion of the occupant compartment or safety cage. That is, the manufacturers have designed their vehicles to minimise occupant compartment deformation in frontal collision tests.

When these observations are considered in the light of the crashworthiness principals pioneered by Hugh De Haven [37] some 60 to 70 years ago, roof intrusion appears to violate his first principal, i.e. *“The package.... should not collapse under expected conditions of force and thereby expose objects inside to damage.*

## **Ejection**

Partial and complete ejection of occupants in rollover collisions is the most predominant cause of serious injuries, with 36 % of annual rollover fatalities ejected through the side window [38]. Berg et al [27] observed that almost 50 % of ejected occupants obtained AIS 5+ injuries compared with less than 5 % for non-ejected occupants. Digges observed that the relative HARM for an ejected occupant was 6.2, compared with a value of 0.5 for non-ejected occupants [25]. Ridella et al [39] further supported this observation indicating that 40 % of all ejected occupants in their study were injured fatally. Hence, there appears to be a dramatic increase in severe injuries when an occupant suffers an ejection during a rollover.

The leading factor that is related to ejection is the lack of appropriate restraints. These include either standard 3-point lap-sash belt or multipoint harness belt and a side curtain airbag. Eigen [40] identified that while 70 % of injured non-ejected occupants were recorded as using belts the figure was much lower for partially (51 %) and fully (3 %) ejected occupants.

Research work in the USA is suggesting that there may be issues with the effectiveness of current restraint systems in rollover crashes. For example, Turner [41] noted that the average belt use in US fatal rollover collisions is only 21% compared to 36% belt use for other fatal crash types. Both of these figures are significantly lower than the national US statistic that around 80 % of occupants in vehicles wear belts [42]. Turner and others [41, 43] have presented a view that such lower seatbelt use rate by occupants killed in rollover crashes as a result of ejection than in other crash types, may be indicating that in some cases seatbelts are failing during the crash. They identified spool-out, inertial unlatching, and improper fit due to deformation of vehicle pillars moving belt anchorage points during the crash as possible mechanisms of such seat belt failure.

Indeed government data presented by Public Citizen [43] indicates that 17% of belted fatally injured occupants in rollovers were either partially or fully ejected. This figure rises to 25% for SUV rollovers. Thus it must be concluded that while seatbelt use in a rollover is a key countermeasure in reducing fatal and serious injuries it is essential that restraint systems must become more effective. Table 2 summarises the various ways to increase the effectiveness of seat belts, and associated restraint systems to reduce occupant injuries in rollover crashes.

## **STATISTICAL ANALYSIS**

To further understand the how the issues discussed above relate to serious injuries and fatalities in rollovers, a statistical investigation of US NAS-CDS and Australian rollover crashes is currently being undertaken. This investigation will sample a total of around 200 rollover crashes from online NASS-CDS database from the years 1997 to 2004 in addition to rollovers crashes obtained from Victorian and NSW Coroner's fatal crash files and de-identified rollover crashes obtained from DVExperts Pty Ltd. To date 57 cases have been analysed in detail. Some preliminary results from that study are presented here. While this small sample size may have limited accuracy in regards to any conclusions at this stage, some useful trends are evident.

When interrogating the data in regards to pre-roll and rollover initiation, Figure 8 and Figure 9 respectively show that 57.9 % of rollovers were initiated by a trip-over and almost half of all rollovers (47.4 %) occurred in rural areas. These two results display similar trends to previous investigations into pre-roll characteristics [21, 25, 27, 44] suggesting initially that the small sample examined may be a reasonable representation of the greater population of rollovers.

**Table 2 – Suggested measures to increase seatbelt effectiveness in rollover crashes**

<b>Counter measure</b>	<b>Description [43]</b>	<b>Failure addressed</b>
Rollover pretensioners	Pretensioners generate a tension force in the shoulder and/or lap belt removing belt slack in the initial stages of a crash.	Spool-out & inertial unlatching
Emergency locking retractors	Such retractors lock when a rollover is sensed to prevent spool out before the belt system is loaded by occupant movement	Spool-out
Integration of belts into seat	By integrating seatbelt anchorage points into the seat: <ul style="list-style-type: none"> <li>• crash energy (loading) is decoupled from the occupant,</li> <li>• a better seat belt fit is achieved, and</li> <li>• the effect of any pillar deformation does not influence occupant restraint</li> </ul>	Lack of fit
Inflatable safety belts	Inflatable Tubular Torso Restraints (ITTR) possesses an integrated section of belt in the shoulder belt that inflates when triggered.	General reduction in motion
Use of four point belt restraints	These systems similar to those employed by motor racing drivers firmly restrain a driver during a rollover crash.	General reduction in motion
Side curtains	Cover possible exit portals [broken side windows]	Partial ejection
Rollover sensors	Rollover sensors enable the vehicle restraint systems (e.g. pretensioners, retractor locks, aircurtains) to fire and respond	Various

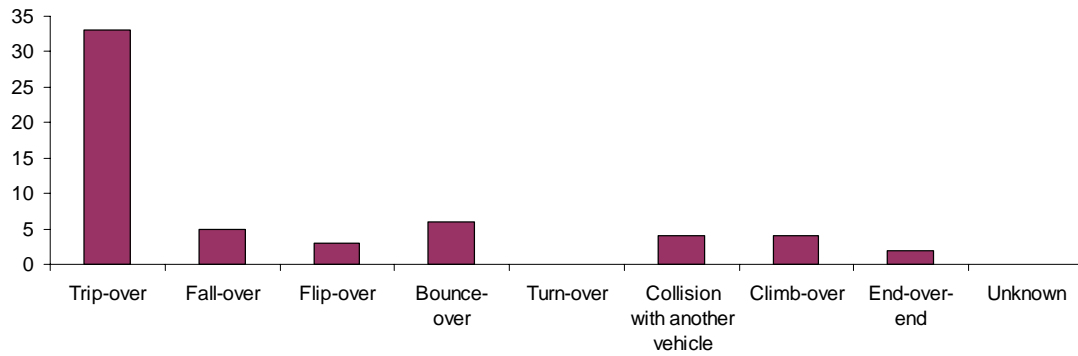
The data was also investigated to identify crash characteristics. These include; the number of rolls the vehicle experiences, the ejection characteristics, belt use, injury sources and post rollover roof crush profiles.

Figure 10 shows the distribution of quarter turns noted in each case. Notable peak values occur at two and four quarter turns. Around half of the crashes identified with the largest peak at 2 quarter turns appear to contain a high proportion of rollover crashes involving more than one event, e.g. impact with a tree or concrete barrier or a rollover initiated by collision with another vehicle. For those vehicles experiencing four quarter turns, being the next largest peak, the vehicle finishes its rollover sequence on its wheels.

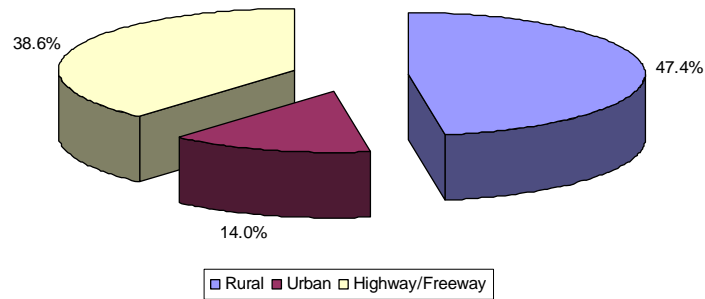
Figure 11 shows ejection and belt use details for this series of rollover cases. The results display some differences when compared to previous statistical analyses of rollover crashes. For example, the proportion of non-ejected occupants in this data set is 76.4 % which is lower than that found by other investigators [25, 40, 45]. Digges and Eigen found in their studies complete and partial ejection occurs in only 10 % of all rollover crashes. Two reasons for this anomaly may be firstly only 57 cases have been investigated to date, and secondly a lower value of belt use was recorded being 55 % when compared with other studies, i.e. 74 % identified by Digges [45]. Figure 11 also identifies that the ejection path appears to be primarily through front side glassing (76.2 %) with the majority of occupants ejected travelling through the left front window of the vehicle (47.6 %).

The roof crush profiles that the vehicles underwent and resulted from the rollover crash were also investigated here. The six profiles identified by Berg et al [27] and shown in Figure 12 were added to the roof crush profiles shown in Figure 13 (a) to (h). Figure 14 (a) shows the count of profiles according to Berg et al's profile types. Figure 14 (b) shows the distribution of roof crush profiles for the left and right sides of the vehicles according to the profile classification in Figure 13.

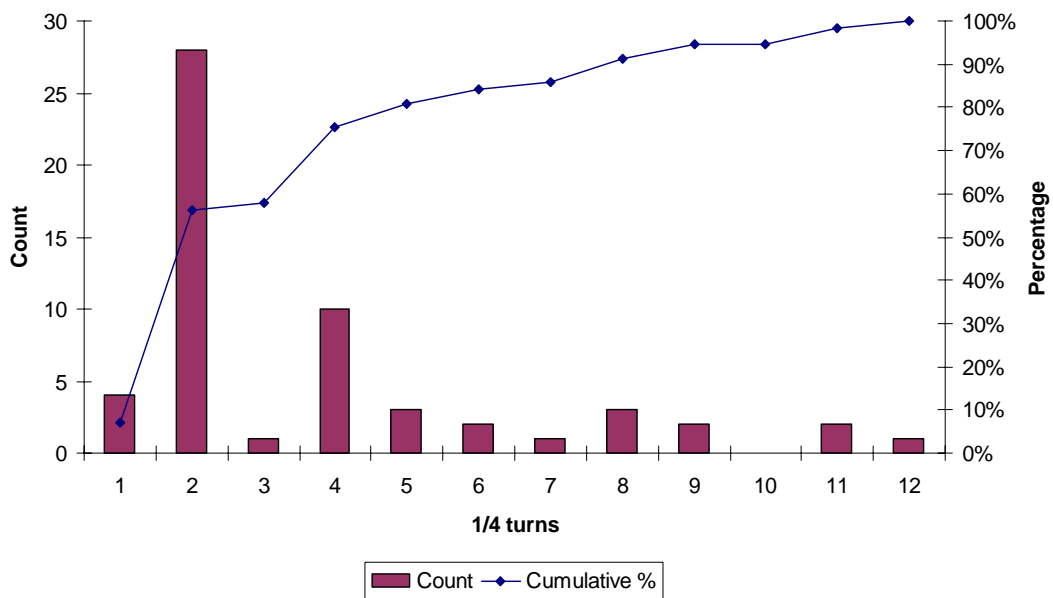
The two sets of results shown in Figure 14 indicate that the majority of roof damage occurs to the front of the roof. Damage counts were relatively similar between the left and the right side of the vehicle with



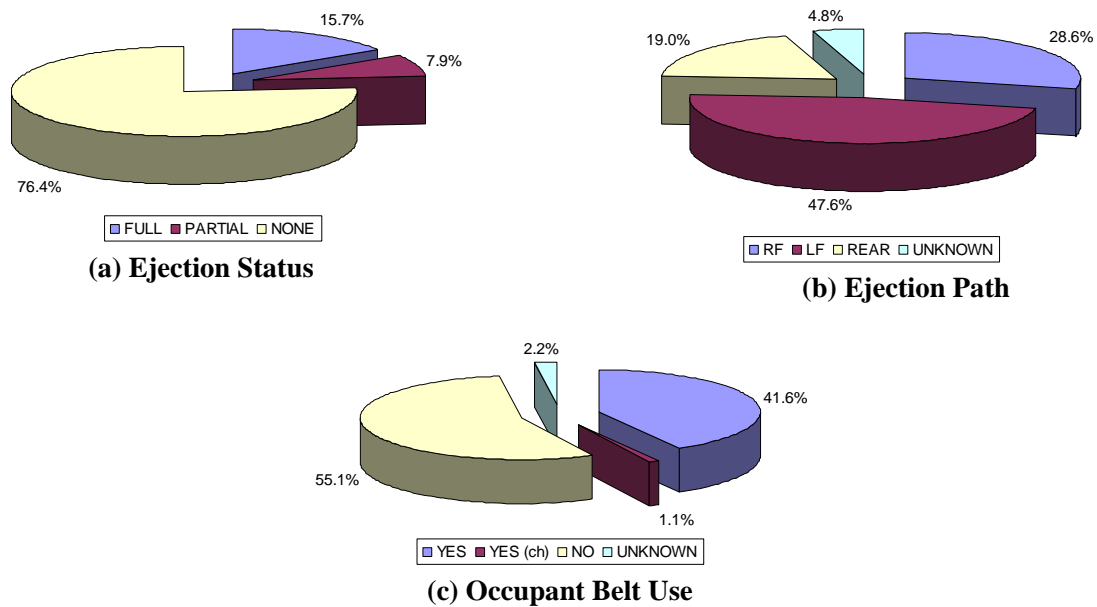
**Figure 8 – Rollover initiation type (Total 57)**



**Figure 9 – Rollover Location characteristics (Total 57)**



**Figure 10 – Number of Quarter turns experienced during rollovers (Total 57)**



**Figure 11 – Occupant ejection detail and belt use detail (Total 89)**

similar counts in all of the seven profiles observed. Figure 14 shows that when roof damage occurs deformation Types 3 & 5 and Profiles 1, 2 & 7 occur most frequently.

Figure 15 shows that the average roof crush observed in the sample was 240 mm with the majority occurring between a value of 20 and 240 mm. Figure 16 shows that the distribution of AIS 3+ head and neck injuries, normalised with respect to the number of vehicles, displayed an increase in the ratio of AIS 3+ injuries when roof crush exceeded 240 mm. This data suggests a correlation exists between roof intrusion and severe injury.

Figure 17 and Figure 18 further support the link between roof crush magnitude and injury severity. Figure 17 shows the sources of all MAIS injuries by body region and injury source, i.e. region of the vehicle interior contacted. A noted peak for head and neck injuries attributed to roof contact is clearly evident. Peaks in upper body and other regions (such as extremities) when they impact other areas of the vehicles interior (e.g. dash, steering wheel etc) are also evident. Another peak in neck injury is observed in the other group. This group included unknown injury sources in addition to non-contact injury sources. This indicates that a lot of neck injuries resulted from occupant motion that did not involve contact, e.g. whiplash.

To investigate the significance of the peaks discussed above the data was further interrogated to reveal injury sources for MAIS 3+ injuries. The most obvious change in the plot when this adjustment is made is the increase in the share of injuries caused by areas exterior to the vehicle (such as the ground) This is no doubt due to the significant role ejection plays in causing serious injury. A notable absence from exterior contacts is significant neck injuries with no MAIS 3+ neck injuries attributed to ground contact.

## CONCLUSIONS

Research currently being undertaken in regards to analysing how injuries occur in rollover crashes is revealing that the principles set out by Hugh De Haven over half a century ago are being violated when considering the rollover crashworthiness of vehicles, particularly larger SUV and 4WD vehicles.

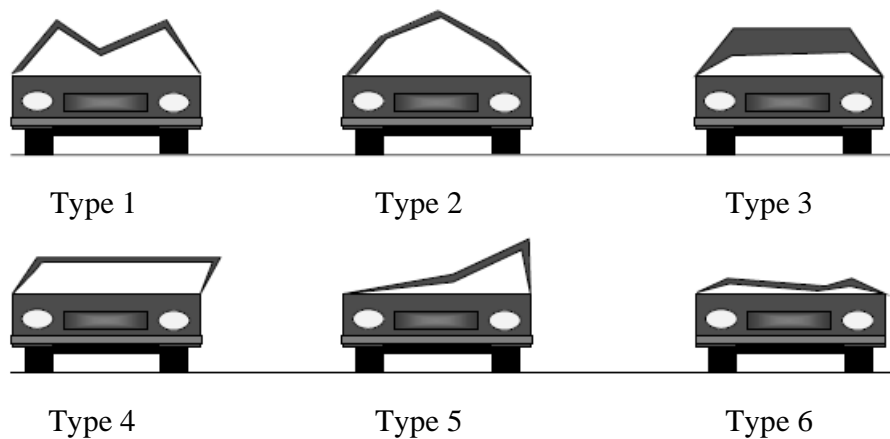


Figure 12 – Front and rear roof deformation patterns [27]

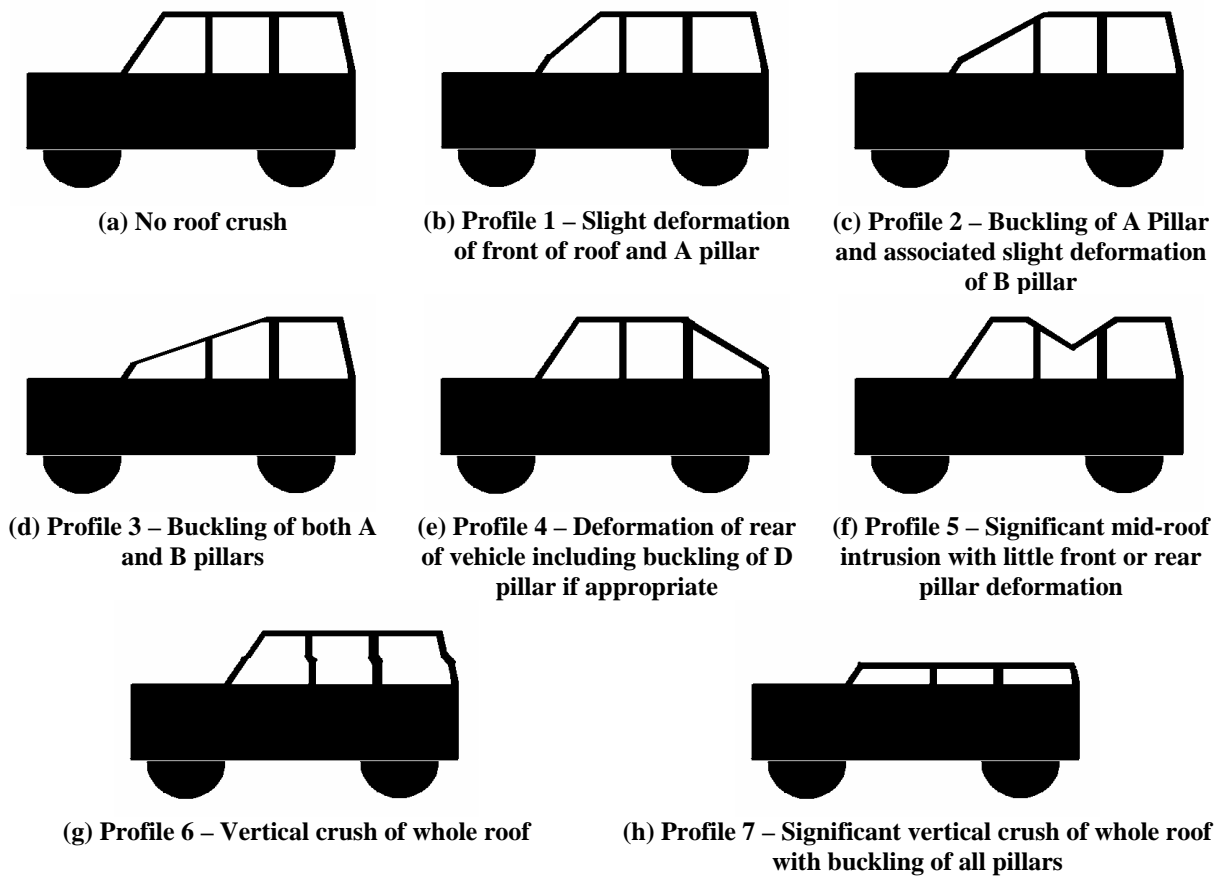
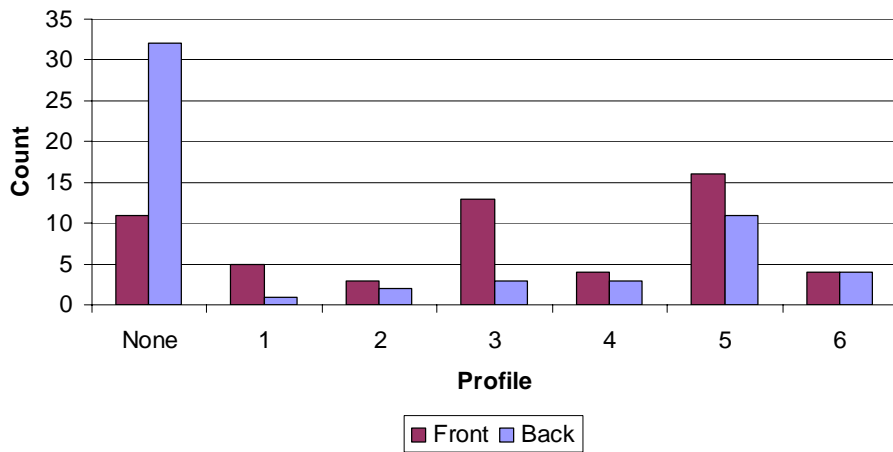
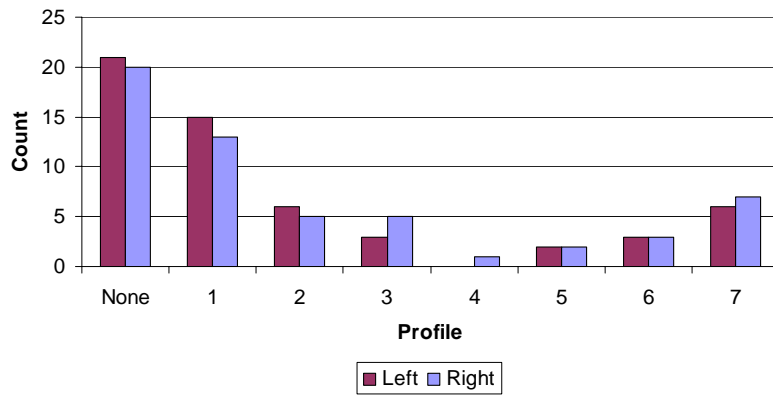


Figure 13 – Side view roof deformation patterns and descriptions



(a) Front and rear profile counts



(b) Side profile counts

Figure 14 – Roof deformation profile classification counts (Total 56)

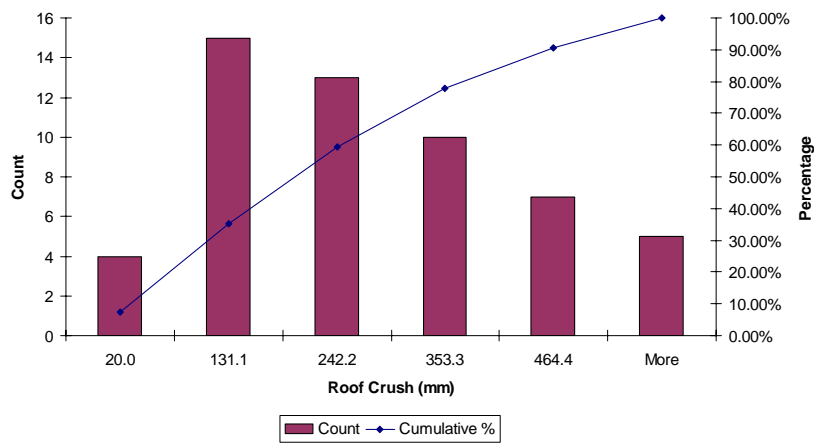
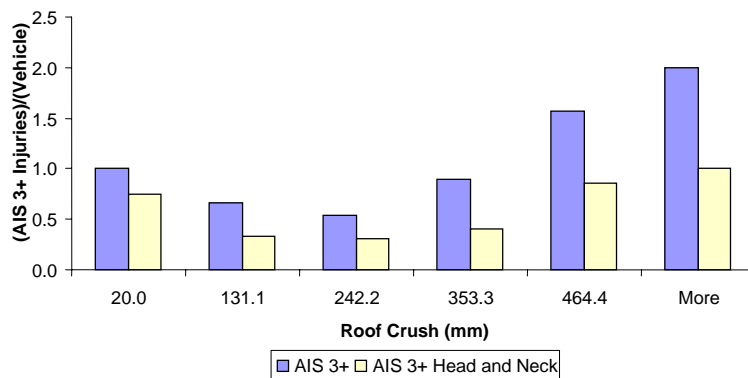
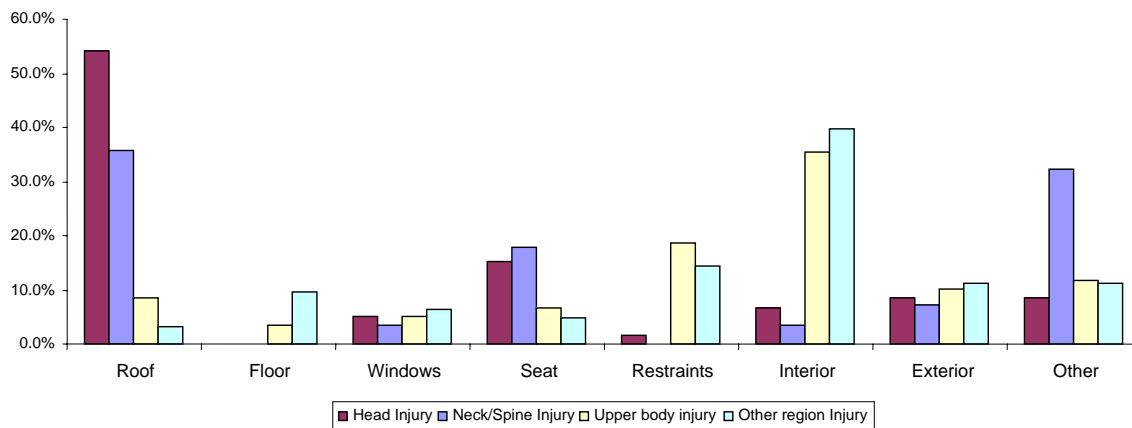


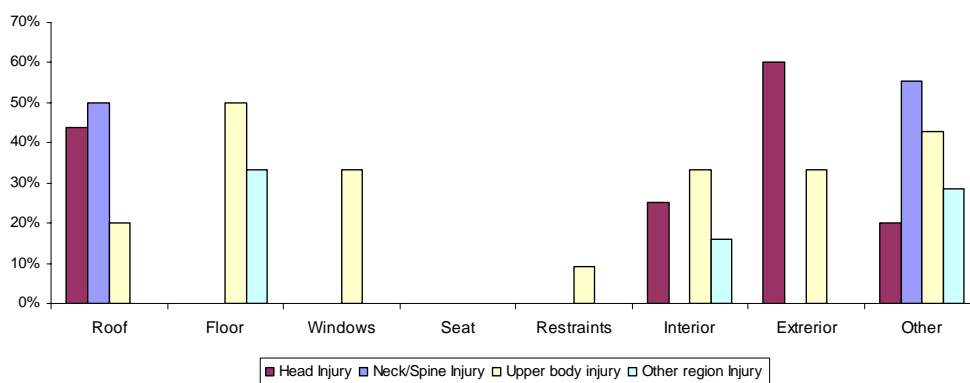
Figure 15 – Distribution of degree of roof crush (Total 54)



**Figure 16 – AIS 3+ injuries for varying degrees of roof crush (Totals 51 and 27)**



**Figure 17 – Injury source by body region (Total 209)**



**Figure 18 – Injury source by body region for MAIS 3+ injuries (Total 53)**

An investigation of the issues concerning rollover crashes and a preliminary statistical analysis on a small group of rollover crashes supports the following conclusions regarding rollover crashes:

- Rollover crashes are particularly hazardous for occupants as injuries resulting from such crashes are overrepresented in regards to frequency of crash categories
- Fatalities resulting from vehicle rollover crashes appear to be increasing. This is thought to be mainly the result of there being no regulatory or consumer dynamic test requirements protecting occupants in such crashes
- The “diving” mechanism proposed by various researchers (Moffatt et al) and vehicle manufacturers (with some exceptions) as the causal factor of neck injuries is not supported by rollover crash tests or real world experience such as on race tracks and in rallying
- Ejection and roof intrusion appear to be major sources of occupant injury
- Neck and head injury severity of occupants are linked to magnitude of roof crush.

This study will be enhanced by the addition of more rollover cases from Australian coronial files to further assess the validity of the above conclusions.

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