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Diving versus roof intrusion: a review of rollover injury causation

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Abstract: Rollover injuries are the outcome of the inability of a vehicle's crashworthiness design, or lack thereof, to protect its occupants during a rollover crash. While countermeasures for injuries due to ejection are well established, there is still much debate ongoing regarding injury mechanisms of occupants contained in a vehicle during a rollover and hence countermeasures required to mitigate such injuries. This paper presents and analyzes the two apparently conflicting views of injury causation for contained occupants in rollovers that have been presented in research literature to date: diving versus roof intrusion. To analyze the validity of each of these theories, the basic physics behind the underlying concepts is investigated. Injury results from the General Motors (GM) rollover Malibu II test series are then used and reanalyzed in light of the findings presented in this paper. Results show that the most injurious events in the Malibu II tests are those where the roof structure was not strengthened. It was also concluded that more work needs to be carried out to establish acceptable injury mechanisms and associated injury criteria for future rollover crash testing protocols.

Key words: Rollover, neck injury, roof crush, diving, roof intrusion, Malibu.

INTRODUCTION

Rollover crashes have become the final crashworthiness frontier for researchers to focus on [1]. Detailed investigation and research into occupant protection for front and side impact collisions, pole crashes, rear-end crashes and under-run crashes, along with reducing injuries to vulnerable road users, such as pedestrians, cyclists and motorcyclists, has resulted in increased protection in each of these crash configurations. Contrary to this trend, research into the area of rollover crashes has yet to have an influence on reducing fatalities observed in this form of crash in the US and Australia. Around 20% or one in every five fatalities in Australia results from a rollover crash [2], whereas in the USA the rate is higher at around 33% or one in every three fatalities [3, 4]. For Europe, it is estimated, around one in every 10 fatalities are rollover crash related [5].

Figure 1 shows that fatalities in the USA resulting from rollover crashes have increased from 1971 to 2004 despite the introduction of two rollover crashworthiness test procedures, namely FMVSS 216 and FMVSS 208 [6, 7]. This figure is annotated with key milestones in the area of rollover research and government policy which have had little effect in reversing the increasing trend in rollover fatalities. It appears the deficiencies that are seemingly present in current day vehicle design with respect to rollover crashworthiness have yet to be addressed.

Contrary to all other crash forms rollover protection has no mandatory dynamic test in effect for any country around the world. Only three countries (America, Canada and Brazil) have a mandatory quasi-static design standard that requires a level of roof strength for passenger vehicles namely, FMVSS 216 [6]. This quasi-static test has been criticized by many researchers and professionals focused on rollover crashworthiness, as being ineffective in protecting occupants in real-world rollover crashes [8, 9]. In contrast to frontal and side impacts, the rollover crash event occurs over a much longer duration, that is, the crash energy is dissipated over seconds rather than milliseconds. However, when occupants contained within the vehicle suffer neck and head injuries the injuries occur over a relatively small duration of around 50 to 100 milliseconds. Thus the source of the severe injury risk lies not only in the collision event but the lack of occupant rollover protection designed

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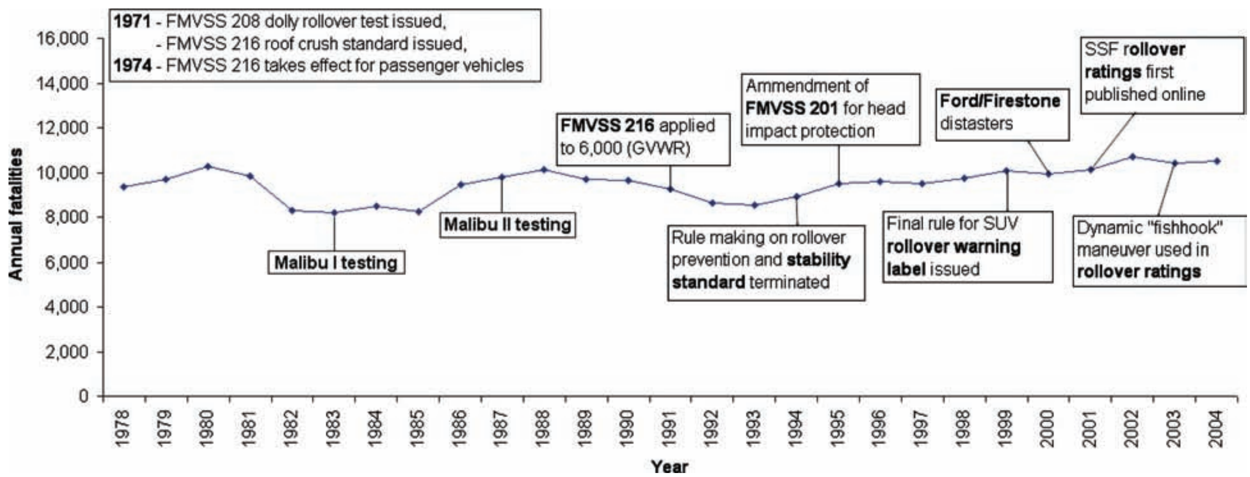

Figure 1 Annotated US rollover fatality timeline 1978–2004.

into the vehicle, exposing the occupants to short duration, injurious decelerations.

In the 1980s GM undertook a series of rollover crash tests to look for the need for stronger roofs for their 1983 Chevrolet Malibu vehicle, that is, whether the injuries to belted occupants were resulting from roof crush or diving. Two series of rollover tests were undertaken, referred to as Malibu I (1983) [10] and Malibu II (1987) [11]. Each involved eight vehicles, four with strengthened roofs and four with production roofs, which were tested using the FMVSS 208 dolly rollover test procedure. In Malibu I the Hybrid III 50th percentile dummies positioned in the front passenger's and driver's positions were unrestrained, while in Malibu II dummies were restrained with the vehicle's seatbelt systems. In Malibu II, the belts were allowed to have a slack equivalent to the static inversion of a human surrogate in the vehicle. For this study it was decided that because Australia's current seatbelt wearing rate is of the order of around 95% [12], the research work should focus on the analysis of the safety of seat-belted occupants involved in rollover crashes. For this reason only the Malibu II data involving restrained occupants was considered.

One of the key factors affecting occupant survival in all types of collisions is maintaining the integrity of the occupant's "survival space" within a vehicle during a crash. The survival space of an occupant is defined as the physical envelope in which the motion of an occupant is contained during a crash. It has been proposed 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 [13]. 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 [14, 15] appear to confirm that injuries increase when roof intrusion exceeds a level of 10 cm.

Contrasting this perspective, US vehicle manufacturers dispute that roof intrusion is not causally related to occupant head and neck injuries in rollover events and that such injuries are the result of a secondary event. It has been argued by manufacturers that roof intrusion is "*merely an indication of accident severity and that injury severity increased with accident severity*" [8, 11]. However, responding in turn to this argument, vehicle safety advocates have been producing evidence from crash tests where peak neck loads have been recorded and attributed to roof intrusion [16, 17].

The automotive industry have attempted to decouple the link between roof intrusion and injury causality by arguing that head and neck injuries in rollover crashes are caused by the torso continuing to move towards the roof, compressing the head and neck as a result of inertia, when the vehicle is upside down. Moffatt [18] first presented this view in 1975 when he contended that a misconception has occurred when people begin to discuss the roof crush issue. He refers to the fact that it is often said the roof is "pushed downward" in a rollover crash. In contrast to this, Moffatt advocated that the roof is in 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.

This paper investigates these two apparently conflicting views of injury causation for contained occupants in rollovers that have been presented in research literature to date, that is, diving versus roof intrusion.

MOFFATT'S "DIVING" THEORY

In 1975 Edward Moffatt [18] presented a view that injuries to occupants contained in vehicles during rollover crashes were not causally related to the roof intrusion experienced by the vehicle. Moffatt's contention was based on the statement:

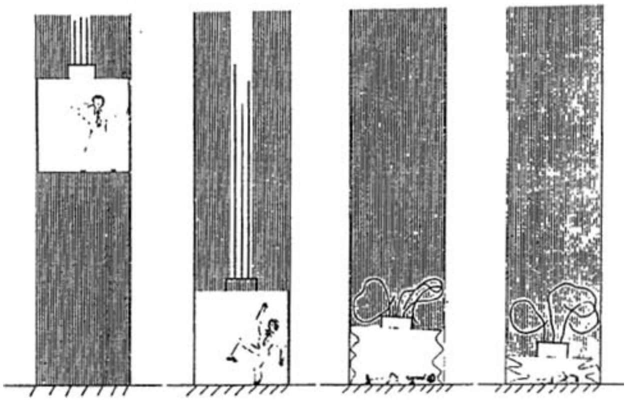

Figure 2 Copy of Figures 11(a) to 11(d) "elevator-shaft" analogy presented by Moffatt [18].

> "When the roof of the vehicle struck the ground, it essentially came to rest relative to the ground. The roof struck the ground and stopped, but the body of the vehicle continued to move towards the roof."

From this statement Moffatt went on to dispute that in contrast to a roof crushing in on an occupant during a rollover crash and loading the occupant's neck, neck injuries were caused by torso augmentation. This means that while an occupant's head stops against the roof of the vehicle during a roof to ground impact, the torso of the occupant continues to move towards the roof/ground at the same rate as the vehicle is approaching to the ground. This then loads the occupant's neck and head and causes the observed head, neck and spinal injuries in rollover crashes.

Moffat presented the view that the severe neck injuries that occur and continued to be observed in rollover crashes are related to the 'severity' of the crash. It was contended that the roof deformation would increase with severity of the rollover thus showing a correlation between severe neck injuries and roof deformation but not a causal link. This argument was presented as a parallel to the deformation observed when an elevator cable breaks allowing an elevator to fall down an elevator shaft, as presented in Figure 2. In this case Moffatt stated that

> "The occupant continues to fall until he strikes the floor of the elevator, which has stopped at the bottom of the elevator shaft. . . . The higher fall caused the increased injuries, and the higher fall caused the increased crush to the sides of the elevator."

Moffatt's arguments have been used consistently since 1975 to aid vehicle manufacturers in defending product litigation relating to injuries that occur to contained occupants resulting from rollover crashes where there is evidence of significant roof intrusion. The following points critically analyze the underlying theories and assumptions made within Moffatt's paper.

1. Moffatt's paper consistently aims to present rollover roof-to-ground impacts as high deceleration cases. This is done by presenting parallel arguments that are much higher in severity than the roof-to-ground impacts of a rollover. These parallels which will be discussed further in this section include side impacts and a falling elevator. Both of these situations take place with much higher changes in velocity (Δv) and deceleration values for the whole crash event than a rollover roof-to-ground impact.

   This means that the parallels drawn, while partially relevant, present information in such a way as to give the impression that the forces and decelerations in side impact crashes and elevator falls are somehow equivalent to those that occur in rollover roof-to-ground impacts.

2. Moffatt's underlying principle, that more severe rollovers will produce more severe injuries <u>and</u> more roof intrusion, implies firstly that injuries cannot be decoupled from the severity of the rollover crash and secondly, that all vehicle roof strengths are the same. The corollary of Moffatt's argument implies that if each of these vehicles experiences the same roof impact then a similar degree of roof deformation should be observed. Moreover, this principle is aimed at addressing the statistical evidence that shows increased roof intrusion corresponds with observed increases in frequency of high severity injuries [8, 15, 19, 20].

   For rollovers that involve more severe roof-to-ground impacts to correlate with larger roof intrusion than rollovers with less severe roof-to-ground impacts, vehicles subjected to impacts of exactly the same severity and load orientation must have very similar, if not the same, roof strength. To show why this is not the case, two examples of a theoretical drop test of three vehicles are considered below. The three vehicles considered are: a 2003 Ford Expedition; a 2003 Subaru Forrester; and a 2002 Ford Explorer. The roof strength-to-vehicle weight ratio (SWR) for the Subaru Forrester is typically much higher than for the other too vehicles. The SWR, FMVSS 216 roof crush test results and the masses of these vehicles were obtained from the National Highway Traffic Safety 215 Administration (NHTSA) Docket 22143 website [9]. It is assumed the drop test is carried out so that the vehicle is held upside down and somehow restrained with frictionless roller bearings at its perimeters so that the angular orientation of drop matches precisely the angular orientation of the FMVSS 216 static test and is maintained throughout the drop test. Furthermore, in these examples the word 'intrusion' is synonymous with the word 'crush'.

   The first example considers a drop height of 500 mm (Table 1), as this height was shown by McElhaney *et al.* [21] to match a head impact velocity corresponding to the onset of serious spinal cord injury (SCI). Obviously the roof impact velocity is the same for each vehicle if dropped from a height of 500 mm, that is, $v = \sqrt{2gh} = \sqrt{2 \times 9.81 \times 0.5} = 3.13$ m/s, where $g = 9.81$ m/s^2. After falling 500 mm, the kinetic energy of each vehicle ($\frac{1}{2}mv^2$) just prior to impact will vary depending on the mass (m) of the vehicle, i.e. being 15.348 kJ for the Ford Expedition, 9.221 kJ for the Subaru Forrester and 11.792 kJ for the Ford Explorer.

Table 1 **Roof intrusion data (drop height: 500 mm)**

Vehicle	Vehicle mass (kg)	Drop height (h) (mm)	Roof impact velocity (v) from drop (m/s)	Kinetic energy just prior to impact with ground (J)	Required amount of roof intrusion to dissipate kinetic energy (mm)
Ford Expedition	3129	500	3.13	15,348	>254
Subaru Forrester	1880	500	3.13	9,221	203
Ford Explorer	2404	500	3.13	11,792	>254

Table 2 **Roof intrusion data (roof intrusion: 240 mm)**

Vehicle	Vehicle mass (kg)	Amount of roof intrusion (mm)	Dissipated roof intrusion energy (J)	Roof impact velocity (v) to generate equivalent kinetic energy from drop (m/s)	Required drop height (h) to generate equivalent kinetic energy (mm)
Ford Expedition	3129	240	9,233	2.42	301
Subaru Forrester	1880	240	10,819	3.39	587
Ford Explorer	2404	240	7,999	2.58	339

The kinetic energy of each vehicle just prior to impact with the ground is then equated to the area under the FMVSS 216 roof intrusion load deformation curve obtained for each of these vehicles [9] up to the point where the test was stopped. In other words, the area under the FMVSS 216 load deformation curve, being the vehicle's roof intrusion dissipation energy, was summed up to a roof intrusion value that was "equivalent" to the kinetic energy of each vehicle just prior to impact. However, because the kinetic energy was larger than the area under the FMVSS 216 load deformation curve, the value for the roof intrusion required could only be ascertained as being greater than 254 mm. This is shown in Figure 3.

It should be noted that when the roof deforms, work is carried out via plastic and elastic deformation of the roof. The elastic deformation is recoverable energy, that is, there is elastic unloading or spring back of the roof intrusion. The principles of how a steel structure absorbs and dissipates kinetic energy via plastic and elastic deformation have been outlined by numerous authors, including Grzebieta and Murray [22–24]. In this example and the next one, it is assumed that the vehicle is somehow clamped in place just prior to spring back, that is, it is fixed in place at the maximum point of intrusion.

Hence, Table 1 shows the amount of roof intrusion (column 6) that would theoretically be required to absorb (roof crush dissipation) energy equivalent to the kinetic energy (column 5) a car would possess for a drop height of 500 mm (column 3). Table 1 shows the roof intrusion for the Forrester varies from the Expedition and the Explorer.

In the second example, the roof intrusion is now restricted to only 240 mm, that is a drop height 'h' is found that will result in a maximum roof of 240 mm in each vehicle. The vehicle is restrained and dropped and then held at the maximum intrusion in the same way as example one above. This roof intrusion value was chosen as it corresponds closely to the roof intrusion limit used in the current FMVSS 216 rule, which is valid until the new rule is phased in. Again, column 4 in Table 2 shows the energy under the load-deformation graph from the FMVSS 216 test equivalent for a roof intrusion of 240 mm for each vehicle. This dissipated roof intrusion energy is equated to the kinetic energy ($\frac{1}{2}mv^2$) and in turn equated to potential energy (mgh) and solved for the velocity (v) and drop height (h). The resulting values shown in Table 2 indicated that the drop height (column 6) and hence impact velocity (column 5) varies from one vehicle to the next to result in the same amount of roof intrusion.

Tables 1 and 2 hence dispel the argument that all vehicle roof strengths are the same. These tables show that for the same roof-to-ground impact (equivalent drop height as in Table 1), assuming FMVSS 216 pitch and roll angles, the same degree of roof intrusion is not produced for vehicles of different roof strength. Indeed, to produce the same amount of roof intrusion, the stronger Forrester must be dropped from a theoretical height slightly less than twice that of the Ford (Table 2). This indicates that the amount of roof intrusion for a particular impact severity depends on the roof strength and not necessarily on the severity of the crash.

This case of similar rollover conditions but differing roof strengths was considered to some extent when GM performed the Malibu I and II series of rollover tests. Analysis of these tests [16, 19, 20, 25, 26] has indicated that occupants in vehicles with weaker roofs experienced more severe injuries than those in strengthened roof vehicles. Further evidence that this is the case will be discussed in more detail later in this paper.

3. Moffatt uses figures/images that are not representative of vehicle kinematics in actual real-world rollovers. Some of these figures are shown in Figure 4. By presenting sketches of vehicles that have significant vertical drops directly onto the top of their roofs, the reader may be persuaded that a high change in height and hence high vertical velocity are present during rollovers. The more common scenario for a vehicle to be involved in a rollover

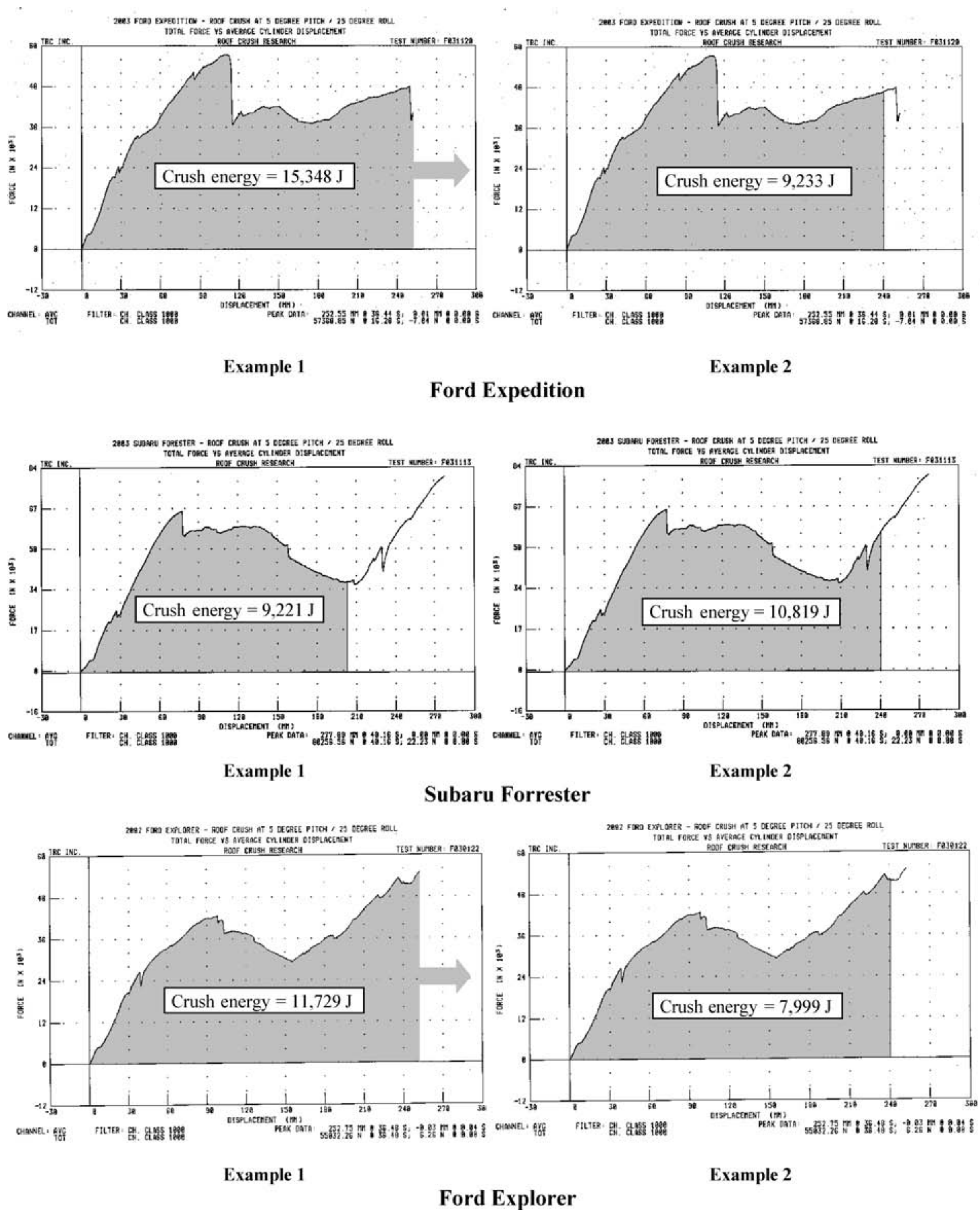

Figure 3 Intrusion (crush) energy estimated from FMVSS 216 load displacement curves.

is on level terrain and the vertical drop is often small as discussed by Friedman and Nash [16].

4. Many of Moffatt's diagrams also present the view to the reader that a vehicle is flat against the ground and roof loading is completely vertical during a rollover crash. This is rarely true, and when it is the case, loading is usually not severe as it occurs at the end of the rollover when most energy has been dissipated. Figure 5 shows that a component of the roof loading, present in the majority of rollover roof-to-ground impacts but not considered in Moffatt's paper, is lateral frictional loading.

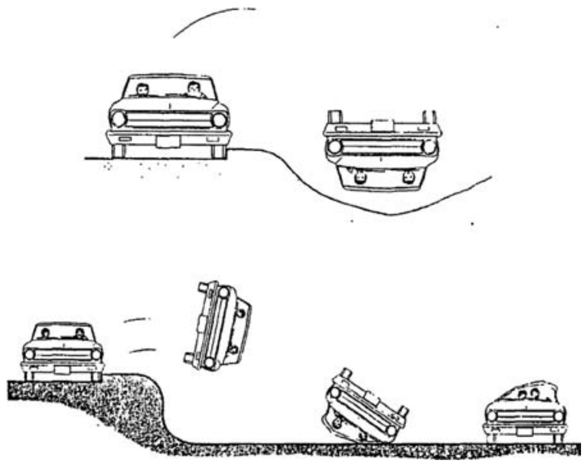

Figure 4 Figures after Moffatt 1975 [18].

While there is a vertical component of the loading on the roof of the vehicle experienced in a rollover, there is also a horizontal and rotational component of loading. The lateral and rotational forces, in addition to the roll angle of the vehicle at the time of ground contact observed in real-world rollovers and rollover tests, do not correspond to the vertical 'diving' type vehicle motion implied by Moffatt [18]. That both horizontal and rotational loading coupled with vertical loading occurred was confirmed by Bahling *et al.* [11] in their Malibu paper.

5. The fifth point to discuss is the reliability of Moffatt's paper to draw analogies between injuries sustained in rollovers and side impacts. Moffatt consistently argues that the rollover 'diving' argument is analogous to the impact of a pole to the side of a vehicle. This argument becomes puzzling when it is considered that side impact standards now exist that aim to evaluate how effectively "*a crashworthy side structure resists or slows down intrusion of contacting vehicles or objects and also contains energy-absorbing materials to cushion the impact with the occupant*" [27].

   Indeed, the arguments and current status regarding rollover safety are parallel to the views on side impact protection in the 1960s and 1970s, when quasi-static testing and a view that intrusion did not relate to injury was presented by vehicle manufacturers. This view was proved to be false and resulted in the introduction of side impact crash tests, utilizing a side impact surrogate vehicle and a pole, aimed at reducing intrusion by employing side impact protection.
6. Moffatt's proposal that increased roof intrusion is allowable directly contradicts the basis of the crashworthy design of vehicles. In 1952 Hugh DeHaven [28] presented four basic principles of crashworthy vehicle design. The first two of these principles are:
   i. 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;
   ii. 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.

   These two principles directly lead to the concept of a protective 'survival space'. If the occupant's deceleration within this survival space is managed appropriately, then injury causing decelerations should be significantly reduced. Moffatt's theories imply that providing a strengthened survival space will not reduce serious injuries to belted occupants in the case of a rollover crash. This is in clear contrast to the basic principles that have governed occupant protection and crashworthy vehicle design for the past four or more decades.
7. One diagram (Figure 2) presented by Moffatt deserves special attention. This diagram is used in the comparison Moffatt utilizes to prove roof intrusion's non-causal relationship to occupant injury in rollover. The picture is used to show the parallel this theory has to the non-causal relationship between the crush of an elevator compartment and the injuries of occupants contained within the elevator.

   This example is an oversimplification. The magnitudes of velocities and impulses experienced by an elevator in a "four floor" drop when compared with those for an occupant in a rollover are not equivalent. This oversimplification allows Moffatt to impress upon the reader that roof-to-ground contact in rollover is also severe. Henderson and Paine [8], in an evaluation of rollovers, observed that "*most of the energy absorption appears to take place when the wheels and underside of the vehicle contact the ground*". This suggests that roof-to-ground impacts during rollovers are of lower severity and less frequent than the peak decelerations experienced when the vehicle is on its wheels.

In summary, it appears arguments presented by Moffatt [18] have little support in terms of physical evidence when considering the majority of real-world rollover crashes and the associated occupant injury mechanisms. Nevertheless, the Malibu test series were commissioned in the 1980s to show that serious injuries would still occur to both unrestrained and restrained occupants with the same severity and intensity, regardless of whether the roof was strengthened or not. Dummy neck loads measured during the rollover crashes appeared to justify this position and this information has been used over the past twenty-five years to help rationalize that there is no causal link between a vehicle's roof strength and injuries to an occupant restrained in the vehicle.

In the meantime, considerable biomechanical research [29–31] has been carried out in regard to identifying what magnitudes of loading need to be applied to a vehicle occupant's neck to cause serious injury. However, the information made available from the Malibu II series tests

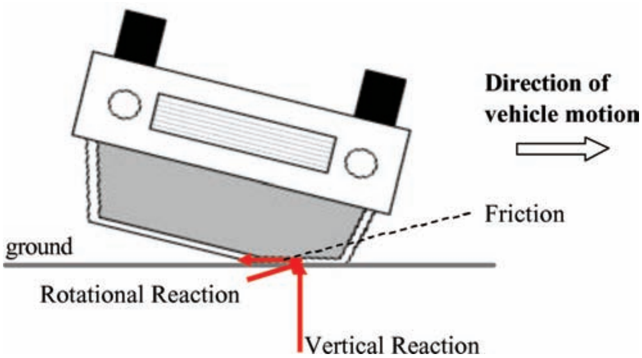

Figure 5 Loading on vehicle roof during rollover roof-to-ground impact (vectors not to scale).

have not been reanalyzed in respect to the developments in biomechanical neck injury criteria. The following reanalysis of the Malibu II data involving restrained occupants reveals an interesting outcome. The Malibu I data was not reanalyzed here as it is well accepted that restraint helps make occupants less vulnerable to another dangerous rollover injury mechanism, namely ejection [32].

MALIBU RESULTS:

Forty (40) Potentially Injurious Impacts (PIIs) were recorded in Malibu II test series which were cases where the axial (F_Z) neck load of a hybrid III dummy exceeded 2000 N. Figure 6 presents a plot of all of the PIIs recorded in Malibu II.

Malibu II tests 1, 2, 5 and 6 all used vehicles with reinforced roofs while tests 3, 4, 7 and 8 used vehicles with production (not strengthened) roofs. The Malibu II study [11] concluded that neck injuries in rollover were not causally linked to roof intrusion, using the following points:

1. The dummies in both production and roll caged vehicles had numerous potentially injurious impacts (PIIs).
2. Both the drivers and passengers in roll caged vehicles had less PIIs than those in the production vehicles, primarily due to the reduction in rail-to-ground impacts in roll caged vehicles.
3. Under similar roof-to-ground impacts there was no increase in level of protection in the roll caged vehicles over the production vehicles.

Each of these conclusions was reached on the basis that all the measured PIIs were equally injurious to the occupants, regardless of the neck load magnitude. However, in light of the developments in biomechanics related to neck injuries, the injury potential of each of the Malibu II-recorded PIIs should now be reanalyzed.

One way of doing this is to use the NHTSA [30] approved Neck Injury Criteria (N_{ij}) where

$$N_{ij} = \frac{F_Z}{F_{\text{int}}} + \frac{M_y}{M_{\text{int}}}.$$

As can be seen the factor N_{ij} takes into account both axial loading and bending moment in the neck. NHTSA documentation [29, 30, 31] suggests a limit of 1.0 for N_{ij} thus

$$N_{ij} = \frac{F_Z}{F_{\text{int}}} + \frac{M_y}{M_{\text{int}}} \leq 1.0. \quad (1)$$

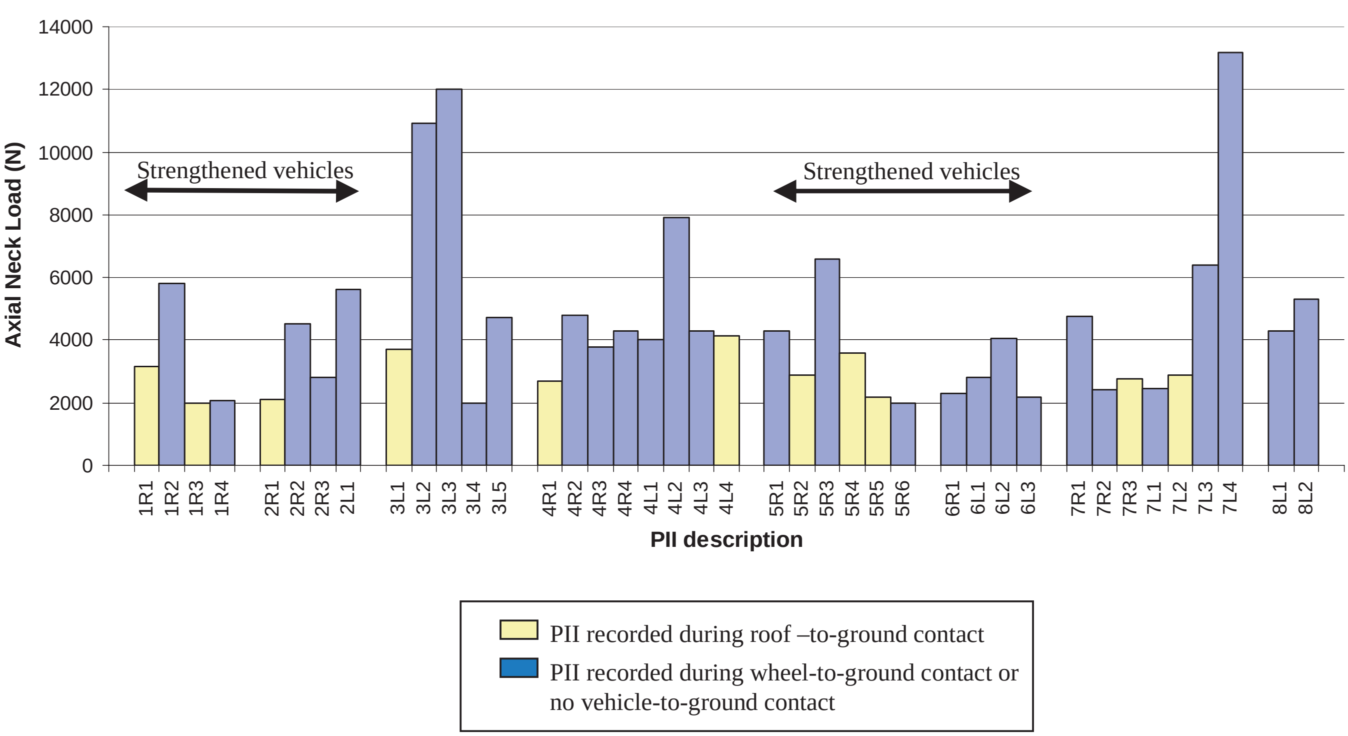

Figure 6 Human and Hybrid III torso mass and neck stiffness.

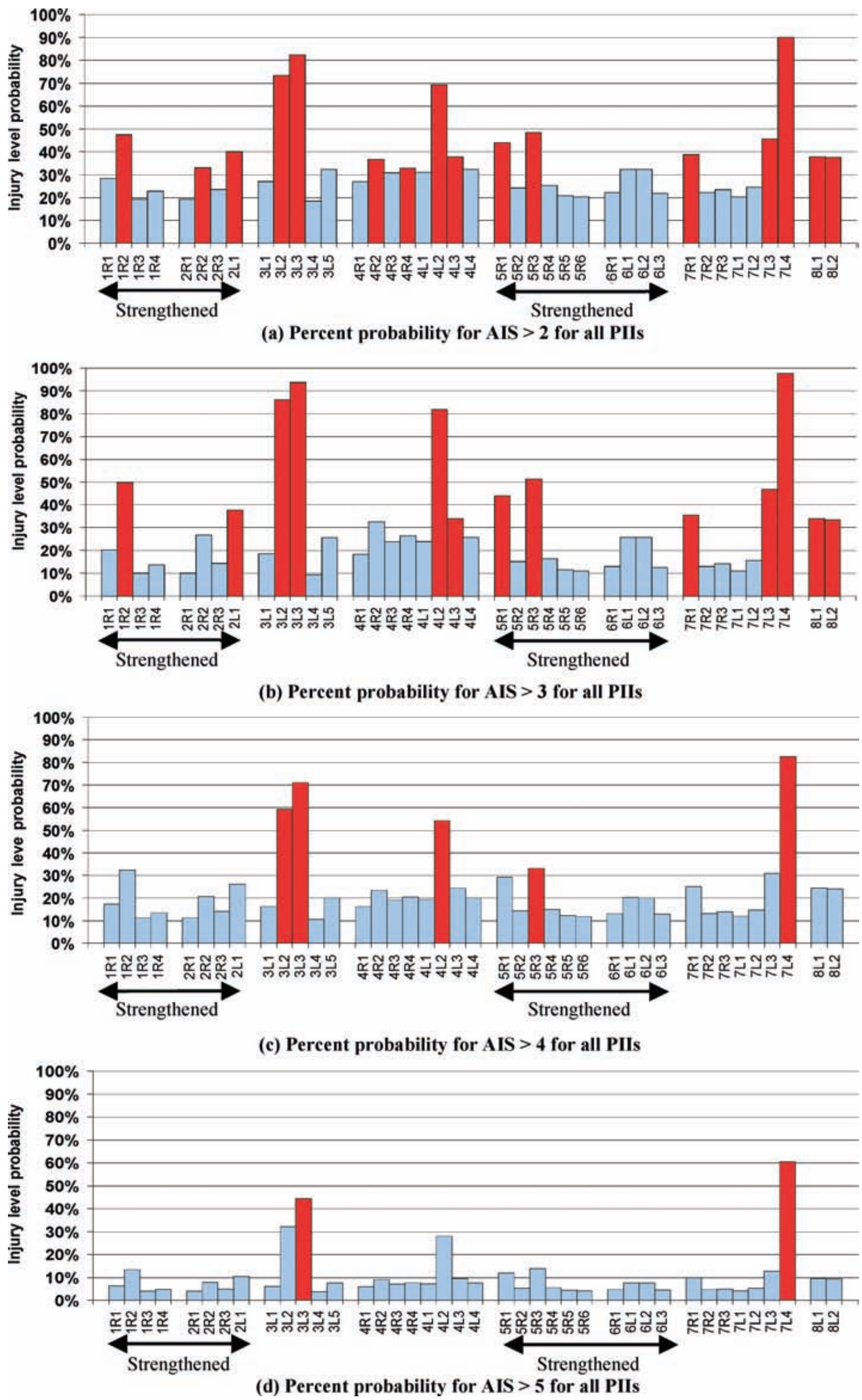

Figure 7 AIS percentage probabilities through N_{ij} analysis.

Eppinger *et al.* [30] also suggested in 1999 that the risk of a particular injury severity to the neck could be accounted for by using the following equations:

$$\Pr(AIS \geq 2) = \frac{1}{1 + e^{2.054-1.195Nij}} \tag{2}$$

$$\Pr(AIS \geq 3) = \frac{1}{1 + e^{3.227-1.969Nij}} \tag{3}$$

$$\Pr(AIS \geq 4) = \frac{1}{1 + e^{2.693-1.195Nij}} \tag{4}$$

$$\Pr(AIS \geq 5) = \frac{1}{1 + e^{3.817-1.195Nij}}. \tag{5}$$

Table 3 **Critical intercept values for use in Eq. (1) [31]**

	Axial (N)		Moment (Nm)	
Hybrid III	Compression	Tension	Extension	Flexion
5%	3880	4287	67	155
50%	6160	6806	135	310
95%	7440	8216	179	415

Table 4 **Counts for PIIs relative to $N_{ij} = 1.0$ injury level, using final March 2000 NIC rule [31]**

	Count			N_{ij}
	N_{ij} <**1.0**	N_{ij} >**1.0**	% N_{ij} >1.0	Average
All	28	12	30	0.90
Production	10	8	44	1.28
Roll caged	18	4	18	0.60

Equations (2)–(5) shown above are from the 1999 NIC criteria. Each of these statistical distributions matches an N_{ij} value with the probability that the associated loading will result in an injury of a particular AIS (Accident Injury Scale) level [30]. The most recent criteria released by NHTSA in March 2000 [31] do not contain any injury severity probability equations for the neck. To the best of the authors' knowledge, the most recent risk curves developed using the NIC criteria are those released in 1999 [30] at this stage.

The N_{ij} criterion provided by NHTSA was developed primarily through validation of the Hybrid III dummy in frontal impacts. Thus, it must be realized that while the authors propose that it can act as a measure for injury potential in compressive loads, such as experienced in the Malibu series of rollover tests, its accuracy in regard to vertical impact loading has yet to be researched and validated. Further, it is acknowledged that the results presented below may not be representative of the injury severity in regard to real-world injuries. Nevertheless, it is still believed that the analysis and resultant outputs provide a level of information indicating the increased severity of neck loading, which is biomechanically superior to the load criterion used by Bahling *et al.* [11] for the PIIs recorded in the Malibu II data. It is thus worthy of consideration until such time that Eqs. (1)–(5) can be validated for injuries resulting from rollover crashes.

Table 3 shows the critical intercept values used as the denominators in Eq. (1) from the most recent criteria released in March 2000 [31].

Using Eq. (1) and the associated limits shown in Table 3, each of the PIIs recorded in the Malibu II tests were re-interrogated. The values used to calculate N_{ij} were the axial and moment values listed in a summary report provided to the authors [33] of the PII neck load impacts measured in the Malibu II tests. The result of this re-interrogation is shown in Table 4 with counts of PIIs classified by their value relative to the N_{ij} limit of 1.0.

Table 5 **Number of injuries and ATD's (occupants) exceeding 33% probability at AIS injury levels, using the 1999 Revised NIC rule [30]**

	Total Injuries exceeding 33% probability		Number of ATD's measuring neck load exceeding 33% probability that injury will occur	
	Production	Roll caged	Production	Roll caged
AIS >2	11	5	6	4
AIS >3	9	4	5	3
AIS >4	4	1	3	1
AIS >5	2	0	2	0

Table 4 shows a correlation of increase in severe injury frequency for production vehicles when compared to roll caged vehicles, with production vehicles having twice as many $N_{ij} > 1.0$ values. Furthermore, when the raw data is analyzed it was observed that for the four N_{ij} values above 1.0 experienced in roll caged vehicles, the average N_{ij} value is 1.20. In contrast to this, the average for the eight production vehicle PIIs with N_{ij} over 1.0 is 1.64. This further supports the view that weaker roofs present an increased severe injury risk to occupants in rollover crashes, and contradicts conclusion 3 reached by Bahling et al. in their paper summarizing the Malibu II tests [11] discussed earlier.

To correlate each of the recorded PIIs to injury risk and hence real-world injuries a second reanalysis of the PII data provided to the authors [33] was carried out. This time, Eqs. (2)–(5) and the critical neck injury intercept values detailed in NHTSA's 1999 criteria [30] were used. The reason the 1999 intercept values were used in preference to those shown in Table 3 (used to calculate the values in Table 4), was that the authors felt the reanalysis should adopt historically consistent intercept and risk values.

Table 5 summarizes the results of this second reanalysis of the Malibu II results. It shows the total number of times individual injury risk counts exceeded a particular injury severity, and when it exceeded a 33% probability for each AIS level, and the number of Anthropometric Test Dummies (ATDs or occupants) that registered a neck load in excess of the particular severity level. The results of this second reanalysis are also graphically presented in Figure 7, where the percentage probabilities associated with each PII are shown. The dark bars are PIIs with a probability exceeding 33%.

This data indicates that for all AIS levels the production vehicles recorded a significantly greater number of injuries (exceeding 33% probability) than roll caged vehicles. Moreover, Figure 7(a) to 7(d) show that while both roll caged and production vehicles have injuries exceeding 33% probability at various AIS levels, the percentage probability of the injuries in the production vehicles is generally

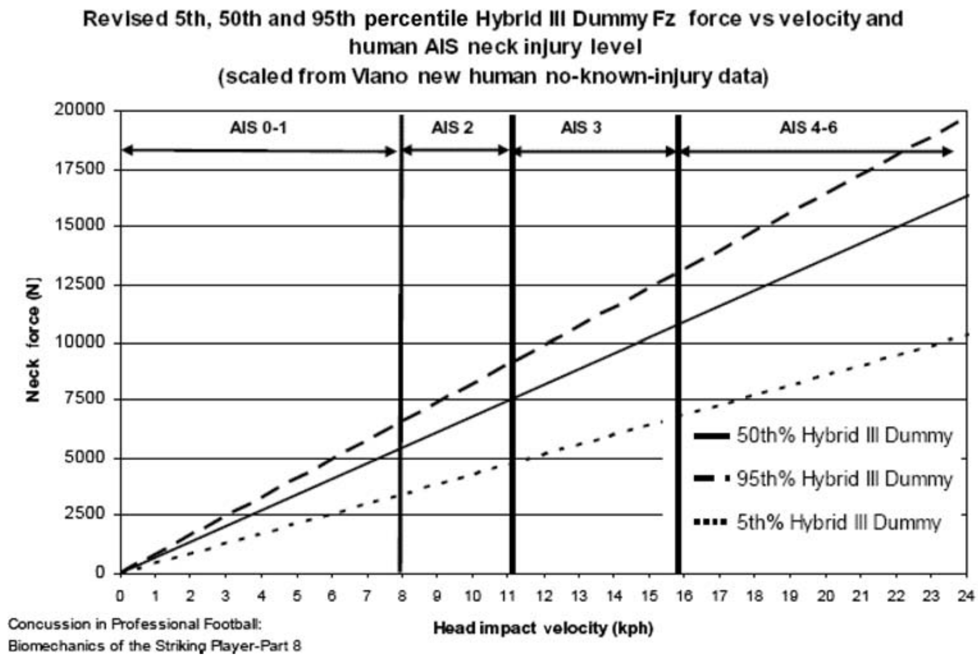

Figure 8 Dummy and human neck injury probability function by occupant size for axial compression only [37].

a lot higher (e.g., 3L3, 4L2 and 7L4) than for roll caged vehicles (e.g., 1R2, 5R1 and 5R3).

Thus it can be deduced that there must be some extra level of safety that a roll caged vehicle offers apart from a reduction in rail-to-ground impacts as inferred by conclusion 2 of Bahling et al. mentioned earlier [11]. It also shows that the 2000 N PII level appears to be too low a level for establishing a comparison of injury potential for the production and roll caged vehicles, further confirming Friedman and Nash's findings [16].

To further elaborate on whether or not there was an increase in the level of protection in the roll caged vehicles over the production vehicles for similar roof-to-ground impacts (conclusion 3 reached by Bahling *et al.* [11]), it is necessary to consider the speed at which the roof intrudes into the occupant compartment.

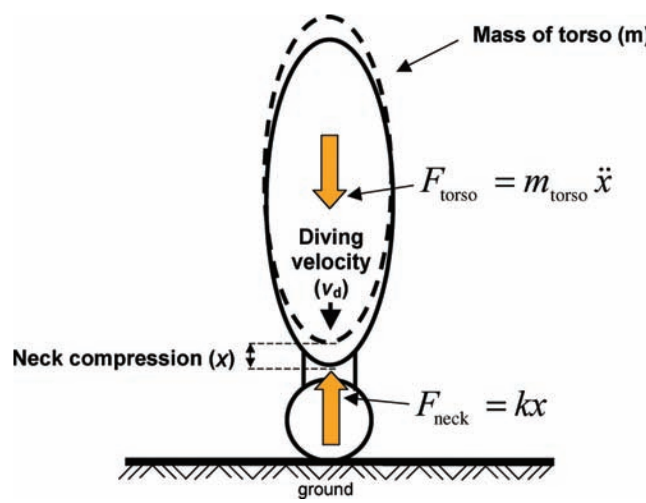

Figure 9 Neck loading of simplified Hybrid III model for pure axial compression (diving) mechanism.

Intrusion Velocity

Friedman and Nash [25] proposed in 2001 that intrusion of the roof occurs at a much greater rate than the rate at which the vehicle 'falls' to the ground during a rollover. This is contrary to the Moffatt's "diving" theory which suggests that the intrusion rate of the roof is equivalent to the rate the vehicle's centre of gravity (COG) approaches the ground. It was this increased intrusion rate that Friedman and Nash proposed as being the cause of the serious neck injuries observed in rollovers. Elevated intrusion velocity is a result of weak roof systems buckling, through various loading and failure mechanisms, onto their occupants at a rate faster than the vehicle's COG falling vertically towards the road surface.

Through analysis of the Malibu II results, in conjunction with an analysis of an investigation of head and neck injuries for NFL footballers [34] and two other studies [35, 36], Friedman and Nash produced the plot shown in Figure 8 of neck load as a function of head impact velocity. The mechanism of injury is purely axial compression where either a diving type mechanism or one where the roof directly compresses the head without bending occurs [25, 37].

Figure 8 shows three lines which relate changes in head velocity to neck loading for Hybrid III dummies subjected to compression only. The raw data analyzed by Friedman was relevant for a 50th percentile dummy. This data was then scaled to obtain the 95th and 5th percentile dummy lines. This scaling was achieved using a ratio of NHTSA's axial neck loading injury criteria between the 50th percentile and other dummy sizes.

To further investigate the characteristics of Figure 8 and its implications related to the Malibu II test series, the simplified theoretical model shown in Figure 9 was also considered, where the mechanism of injury is assumed as diving with only axial compression. The model constitutes a body with a torso mass, m, traveling towards the roof at a diving velocity, v_d, and as a consequence the neck compresses by an amount x. This process results in a compressive load being experienced by the neck.

To analyze this model simple Newtonian equations of motion can be used. However, the following assumptions must first be made, namely:

1. All movement of the head and/or torso is absorbed through compression of the neck, that is, the torso-neck-head interaction is effectively a single degree of freedom system subjected to an imposed vertical motion applied as a result of the torso mass moving at a constant velocity towards a rigid surface and then compressing a spring neck;
2. No damping of the force occurs due to impact with the head.
3. As is suggested in Moffatt's diving theory, all loading on the neck is produced by the inertia of the dummy's torso (torso augmentation).
4. The roof which is impacted by the head is stationary and does not intrude towards the occupant.
5. Deceleration occurs at a constant rate.
6. Force is constant throughout the neck, that is, the same force at the top of the neck, C1 position, and the base of the neck, C7 position.
7. The head and neck stay aligned as shown in Figure 9 for the duration of loading, resulting in a purely compressive load.

To determine the neck load, energy of the single degree of freedom system is assumed to be conserved, that is,

$$E_k = E_s$$

where E_k is the kinetic energy of the torso and E_s is the stored energy that is absorbed by the Hybrid III's neck, modelled as a linear spring of stiffness k.

Thus,

$$\frac{1}{2} m_{\text{torso}} v_d^2 = \frac{1}{2} k x^2 \tag{6}$$

Rearranging Eq. (6) it can be readily shown that

$$x = v_d \sqrt{\frac{m}{k}} \tag{7}$$

Using Eq. (7) the force in the neck can thus be expressed as

$$F_{\text{neck}} = kx = v_d \sqrt{mk} \tag{8}$$

Table 6 shows a series of values for m and k for differing dummy sizes and neck constraints that can be used to determine forces using Eq. (8). This data was obtained from an investigation of the effect of end constraint of neck stiffness performed by Nightingale [38] and Hybrid III component masses quoted by First Technology Safety Systems [39]. Table 6 also quotes values for the masses of the upper torso of each size Hybrid III ATD. The justification for using only the upper torso weight of the Hybrid III comes from work performed by Nightingale [40] where it is stated that the upper torso is an "*estimate of the fraction of the torso mass which acts on the neck during dynamic injury*".

Using Eq. (8) and Table 6, calculated values of neck forces are plotted together with the Friedman and Nash curves from Figure 8 and are shown in Figure 10. This diagram indicates that the theoretical formula corresponds well with Friedman's practical analysis [37] of Viano's [34] and others' [35, 36] data when the neck stiffness assumes rotational constraint. Both the 95th and 50th percentile results are within experimental variation quoted by Friedman. However the 5th and 95th percentile dummy results compared in Figure 10 do not show the same precision that the 50th percentile dummy values do. This may be due to the method of scaling chosen by Friedman, the choice of Hybrid III rotationally restrained neck stiffness for the theoretical model and/or other model assumptions. Nevertheless, this difference does suggest that either Friedman's work and/or the theoretical model require further investigation to determine the actual trend in the case of the Hybrid III 5th percentile results.

Having established a method of correlating neck loading to velocity change applied to the neck, the next step is to reassess the results from the Malibu II tests. The two contrasting injuries chosen for comparison are PIIs 7L4 (production roof) and 2L1 (reinforced roof), which are predominantly axial compression loading of the ATD neck.

For the 7L4 result (fourth PII to the left (driver) side dummy in the seventh test), the axial neck load was 13,200 N. This injury occurred 3787 ms into the test when the vehicle roof started intruding into the occupant compartment. Figure 11 shows exterior views leading up to and including 7L4 and in particular how the vehicle finished on its roof after 3½ rolls. 7L4 has the largest axial neck loading recorded in the Malibu II test series. The mechanism is a predominantly axial compression loading of the neck. As a result of this fact, 7L4 has been heavily scrutinized by both automotive safety advocates and vehicle manufacturers alike. One such analysis performed by Friedman and Nash and presented in 2005 [16] shows a plot of the roof intrusion above the driver's side dummy's head over the period of time that 7L4 was recorded.

To understand the nature of the head impact velocities and accelerations experienced by the Hybrid III dummy subjected to 7L4, an analysis of the roof intrusion was carried out. Slow motion film recordings of test number

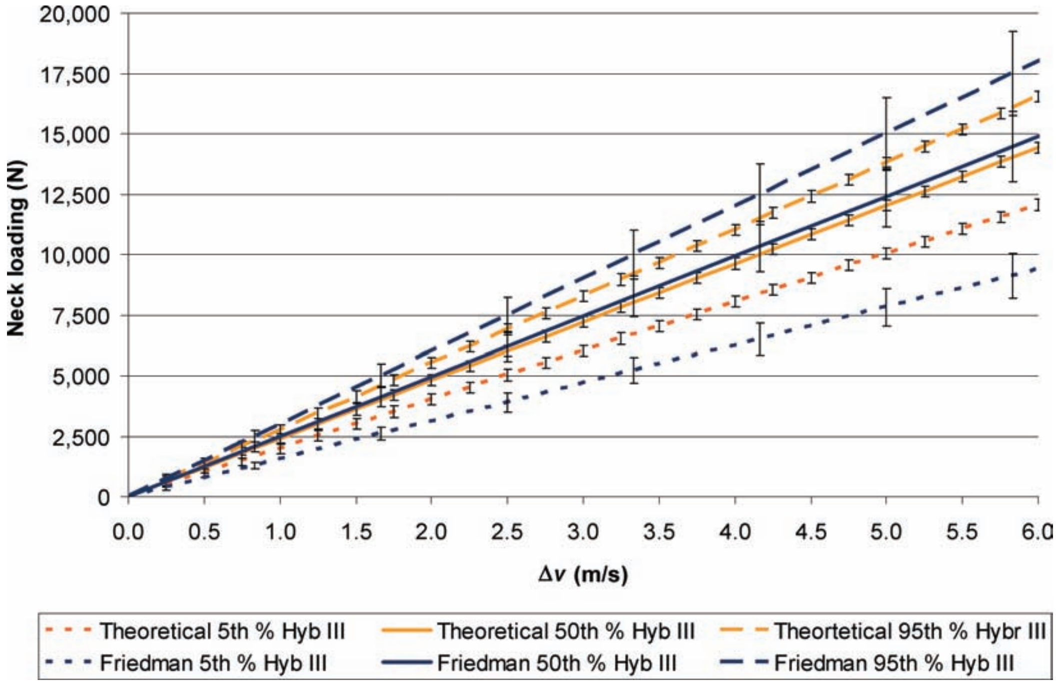

Figure 10 Theoretical (±225 N) and practical (±10%) neck loading for axial compression only by change in velocity of head-neck-torso system, neck stiffness of 3.36 kN/cm (rotational constraint).

Table 6 **Human and Hybrid III torso mass and neck stiffness**

	Factor	End condition	5th percentile	50th percentile	95th percentile
Hybrid III	k [39] (kN/cm)	Unconstrained		1.69	
		Rotational Constraint		3.36	
		Full Constraint		4.17	
	m (kg) [40]	N/A[1]	11.99	17.19	22.58
Human	k [40] (kN/cm)	Unconstrained		0.003 ± 0.001	
		Rotational Constraint		0.028 ± 0.016	
		Full Constraint		0.041 ± 0.032	
	m (kg) [40]	N/A[1]	11.99	17.19	22.58

1 Mass data for Hybrid III 5th percentile dummy has a quoted variation of ±0.30 kg. This was assumed a constant variation for all ATDs for the purpose of model variation analysis.

7 were investigated in detail. Reference lines were drawn along the top of the seat back as shown in Figure 12 and appropriately scaled from known dimensions of the vehicle and dummy. The length of a line drawn from the horizontal and vertical reference lines to an identifiable point on the roof above the ATD's head, a point at the top of the 'b-pillar', to the ATD's head, and the ATD's shoulder were measured in each of the approximately 3 millisecond frames for neck load 7L4. A line was also drawn from the shoulder to the head and measured in each frame to obtain neck compression data. A filtering program DPlot[a] was utilized to smooth the curve, using a smoothing interval of 10.

Whilst the values obtained are only as accurate as can be measured from each high-speed film frame and thus subject to measurement and scaling errors, they do provide a basis on which an understanding can be reached of how the load is applied to the ATD's neck during the 7L4 injury measurement. The analysis also further explains what the measurements made by Bahling *et al.* [11] mean and explains how the results should be interpreted from the recent analysis by Chirwa *et al.* [41] of the intrusion curve of Bahling et al.

Figure 13 shows the displacement versus time curve obtained of the roof intrusion of a point above the ATD's head. Figure 14 shows the movement of the various parts of the ATD relative to the neck loading and the reference lines. Figure 15 compares the intrusion deformation versus time curve shown in Figure 13 to the curve of Bahling *et al.* [11] from their Figure 13, to Friedman and Nash's curve [16] from their Figure 24, and to the vertical deformation of the top of the 'b-pillar'. Figure 16 shows the vertical deformation versus horizontal deformation for the 7L4

[a]Available as an add-in to Microsoft Excel from: http://69.65.110.213/index.htm

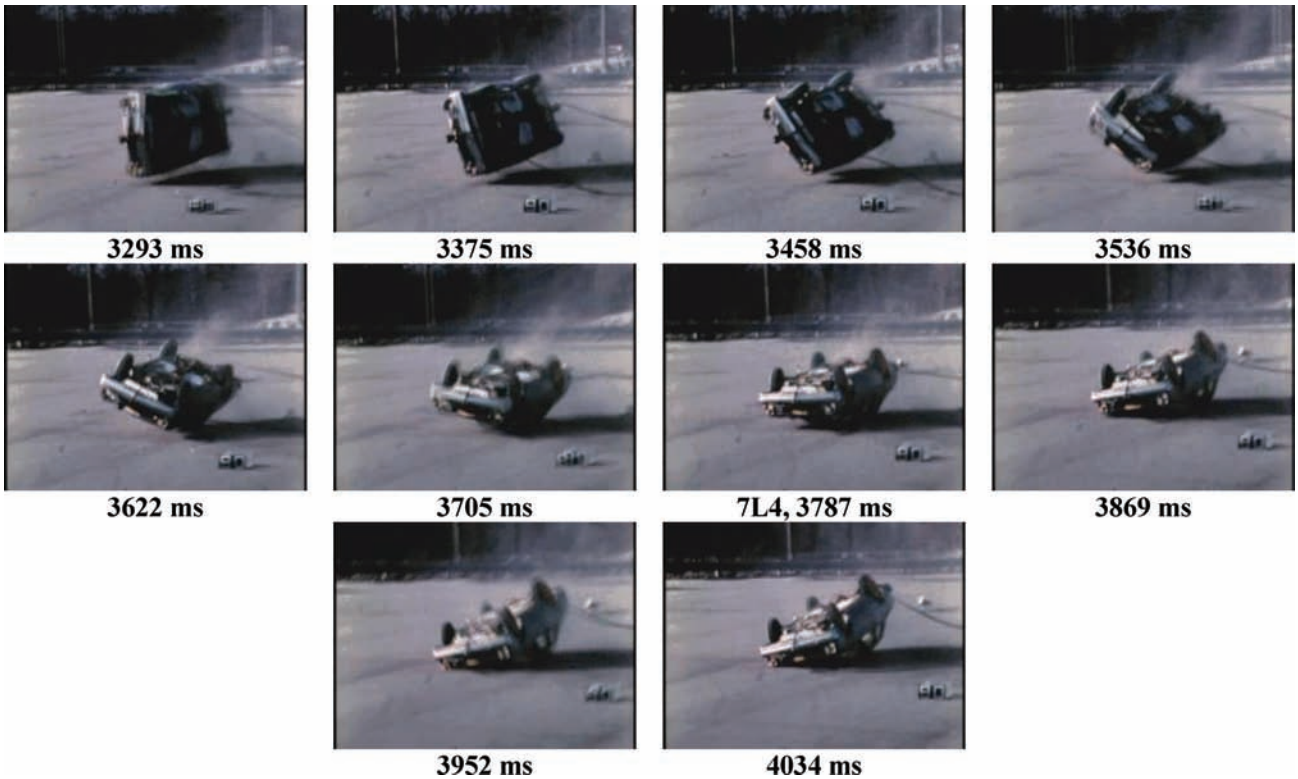

Figure 11 Exterior vehicle views leading up to and including PII 7L4, Malibu II.

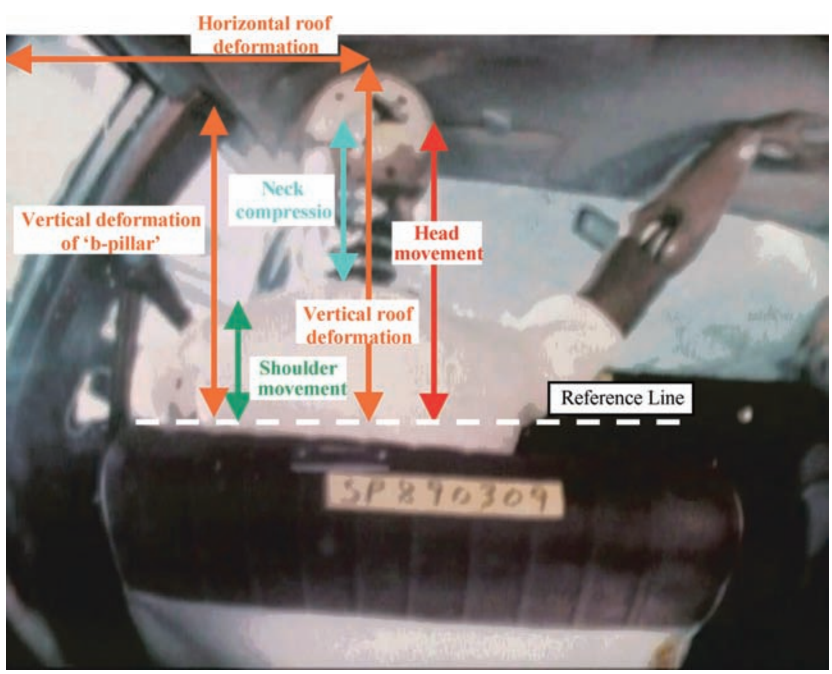

Figure 12 Lines measured during each (approximately 3 ms) frame.

injury compared to the 3L3 injury, where a similar frame-by-frame line length analysis was carried out. Figure 17 shows the intrusion velocity and acceleration of the roof immediately above the ATD's head.

This comparison of curves relative to the neck load measured by Bahling *et al.* shows that intrusion above the ATD's head begins around 25 milliseconds earlier relative to the neck load than was plotted by Bahling *et al.* [11] in their Figure 13. Figure 14 shows that the ATD's shoulder does not move until the neck load peaks. This means that the torso's inertia is resisting movement somewhat similar to the model presented in Figure 9. Figure 16 further confirms this in that the deformation of the roof above the ATD's head is predominantly vertical, particularly when

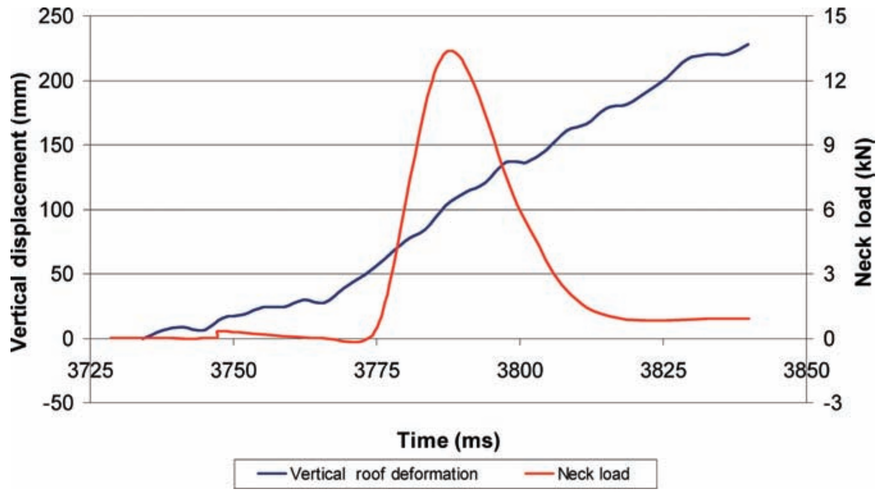

Figure 13 Roof intrusion of point above ATD's head.

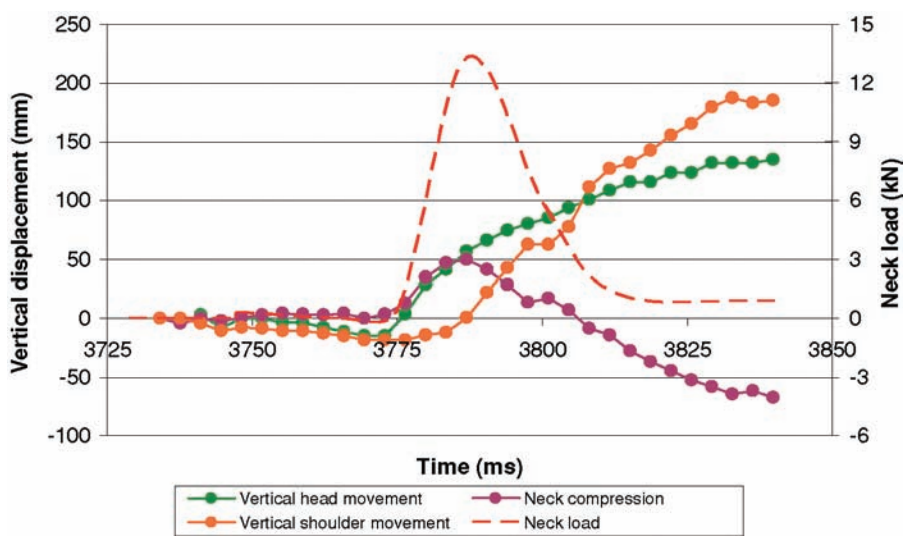

Figure 14 Movement of various parts of the ATD relative to the reference lines.

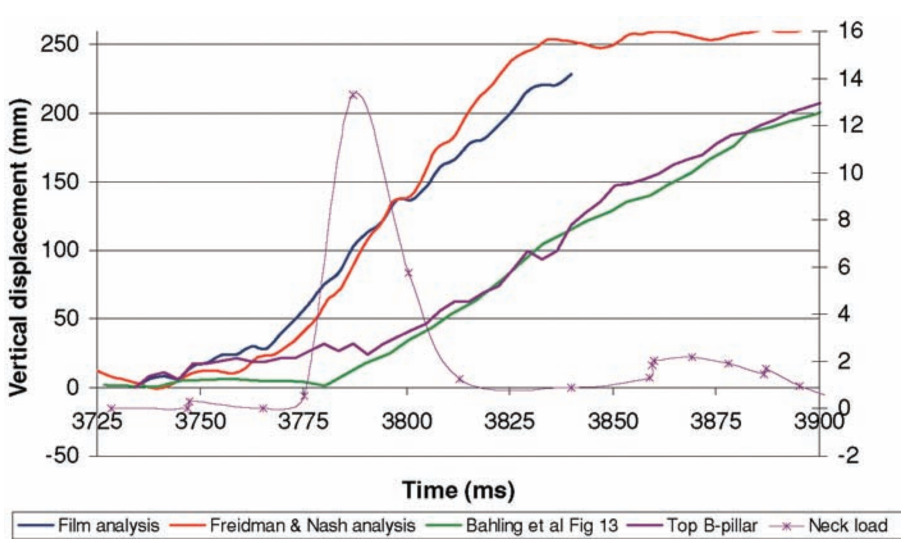

Figure 15 Comparisons of roof intrusion measured by different researchers and at different points in the vehicle for 7L4 injury.

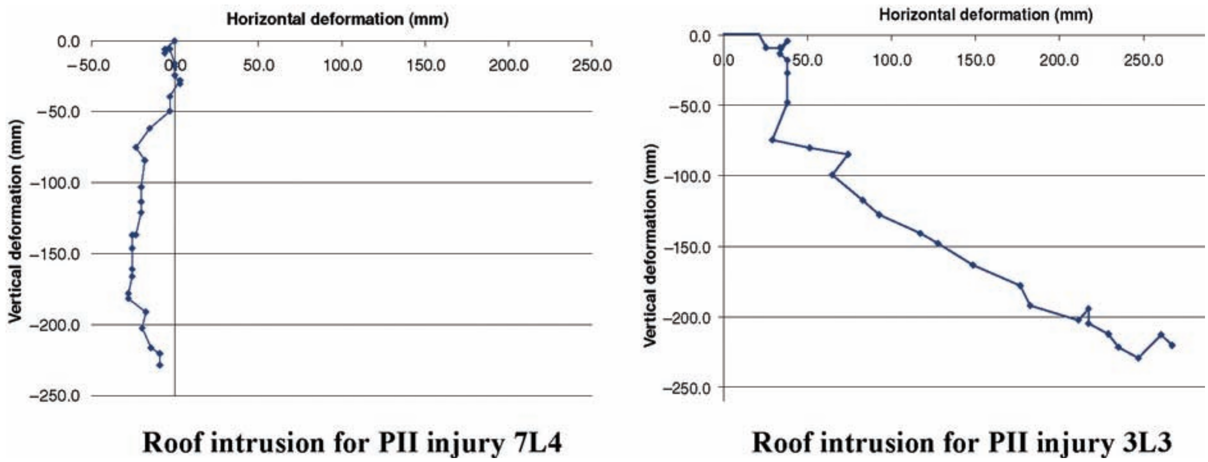

Figure 16 Vertical versus horizontal deformation for PII injuries 7L4 and 3L3 demonstrate roof intrusion in 7L4 is predominantly vertical.

compared to the 3L3 injury which resulted from the roof laterally swaying or 'match boxing' rather than buckling vertically. In regard to the Friedman and Nash [16] curve (in their Figure 24), Figure 15 shows that the curve from the film analysis in Figure 13 matches their curve with respect to timing, neck loading, magnitude of intrusion and most important rate of intrusion. What is interesting to note is that when the vertical deformation of the 'b-pillar' is compared to the Bahling et al. intrusion curve in Figure 15, the similarity in terms of timing and magnitude is close. This comparison of curves is quite revealing in terms of how the Bahling et al. curve was obtained and why it does not adequately characterize the roof intrusion and hence the roof intrusion velocity of the roof above the ATD's head at the time the peak neck load was measured.

The displacement curve presented by Bahling *et al.* [11] (in their Figure 13) was obtained from accelerometers placed at the base of the 'b-pillar' at the intersection of the rocker panel. Obviously there is a timing delay in terms of the accelerometer reading that can be clearly discerned and similarly the rate of deformation is significantly less. Friedman and Nash [16] rightly identified that a traveling buckle in the roof precipitated by the leading (near) side ground strike has compressed the ATD's neck well before the 'b-pillar' has had an opportunity to move. This can be readily ascertained from the high-speed film footage where it is clear the shoulder of the dummy and the top of the 'b-pillar' moves well after the head has moved. This indicates the roof structure is compressing the head against the torso which is not moving because of inertia.

Using the same technique used by Chirwa *et al.* [41], the curve shown in Figure 13 has been differentiated to obtain the intrusion velocity and then differentiated a second time to obtain acceleration. The results are shown in Figure 17. The results from Chirwa *et al.* [41] (in their Figure 14), of the differentiation of the Bahling *et al.* [11] intrusion versus time curve (in their Figure 13), indicate an intrusion velocity of only around 0.87 m/sec at the moment the peak neck load is measured and the intrusion velocity reaches a maximum of only 2.1 m/s. However, in order to obtain a neck load of around 13.2 kN, Friedman and Nash suggest that the intrusion velocity must reach around 5.4 m/sec as indicated in Figures 8 and 10. Figure 17 shows that the neck load peaks when the roof velocity peaks at 5.4 m/sec. Substituting this value and the values of $k = 3.36$ KN/cm for the Hybrid III's neck stiffness and $m = 17.19$ kg for the torso mass from Table 6 into Equation (8), a value of 13 000 N is obtained.

The question arises as to why the velocity is so low in the Chirwa *et al.* [41] plots. The answer is quite obvious when considering Figure 15 and viewing the high-speed film footage. The Bahling *et al.* [11] curve was measured at the base of the 'b-pillar' rather than directly above the head of the ATD. This point has been made by Friedman and Nash [16]. Hence, while Chirwa *et al.* rightly calculated that the peak deceleration of the roof occurs when the neck load peaks, their estimates of the magnitude of the velocity were heavily damped. This is because they differentiated a curve that characterizes the movement of a point remote to a point on the roof immediately above the ATD's head. In other words, the accelerometers could not have measured the moving buckle that was precipitated by a leading (near) side strike. Instead the accelerometer, whilst providing the correct magnitude of calculated displacement, provided a delayed and much slower rate of roof crush than actually occurred directly above the ATD's head, because it measured the b-pillar's response and not the roof buckle.

An additional difference between Figure 17 and the work presented by Chirwa *et al.* [41] that should be discussed is the timing of the peak roof acceleration. Chirwa et al. noted that the peak roof acceleration from their analysis of Bahling *et al.* [11] occurred at the same point in time as the peak ATD neck load. Contrary to this finding, Figure 17 shows the peak roof acceleration occurs before the peak neck load is reached. The reason for this difference in timing for Figure 17 is that this plot monitors the

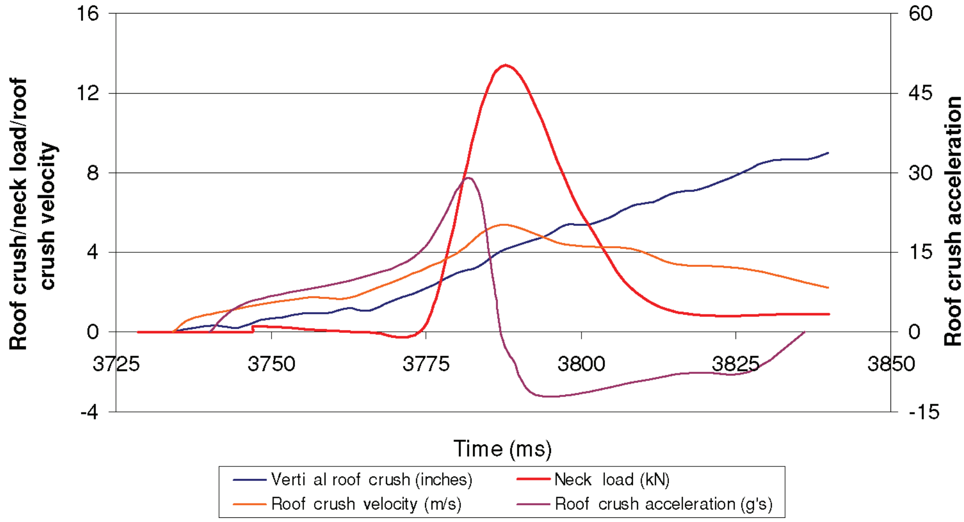

Figure 17 Roof intrusion velocity and acceleration velocity.

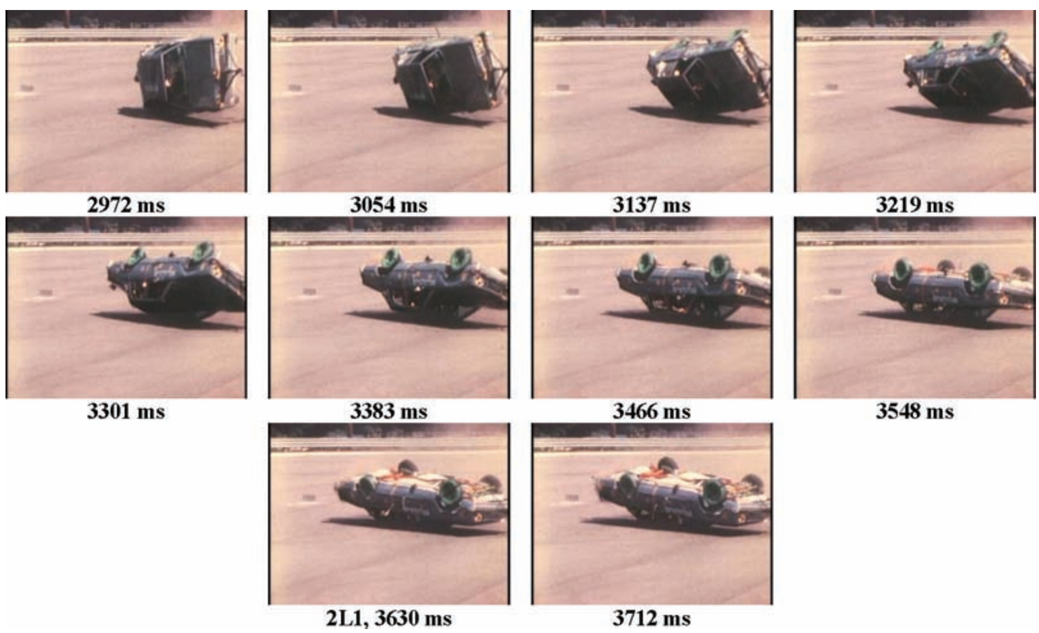

Figure 18 Exterior vehicle views leading up to and including PII 2L1, Malibu II

acceleration of the roof of the vehicle. For the peak of the acceleration to match the peak neck load, the movement, and hence velocity and acceleration of the head and/or torso of the ATD experiencing the neck load, would need to be analyzed. It is reasonable that when the roof impacts the ATDs head, there is a slight time lag (typically up to 10 ms from observations of the Malibu II video footage) until the ATD's head begins to move. Considering this time lag along with the data shown in Figure 17 shows that the timing of the peak acceleration of the head would correspond closely to the timing of the peak neck load recorded during 7L4.

Based on the results shown in Figure 13 to Figure 17, this analysis indicates that the peak neck load is causally linked to the roof intrusion velocity of the production vehicle after the roof immediately above the ATD was subjected to its maximum acceleration.

To contrast the loading mechanism of the production vehicle with a test where the vehicle roof was strengthened and subjected to a similar roof-to-ground impact, test result 2L1 was chosen (second test and first PII). The axial neck load for the left driver's side dummy in this case was 5,600 N. Similar to 7L4, the injury occurred 3630 ms from the beginning of the second test in the last quarter turn, with the vehicle finishing on its roof after $3\frac{1}{2}$ rolls. Screen captures of test 2 leading up to and including 2L1 are shown in Figure 18. These screen captures show that the motion of the vehicle is very similar to that which was experienced by the vehicle in test 7 leading up to 7L4. The only difference between the two vehicles' motions

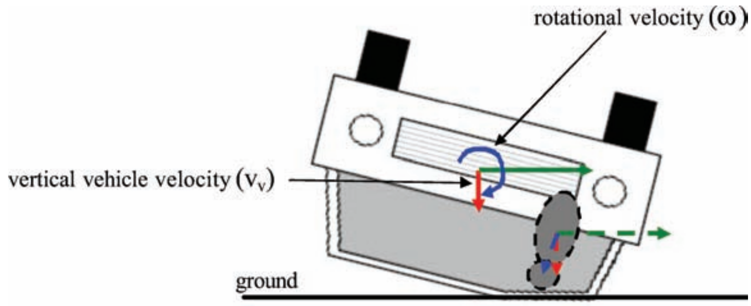

Figure 19 Transfer of vehicle velocities to occupant during rollover roof-to-ground impact (not to scale).

(Figures 11 and 18) lies in the observation that leading up to 2L1 the reinforced vehicle shown in Figure 18 is rotating about the vertical (yaw) axis, in addition to the longitudinal y-axis and with little lateral motion.

To compare the results of 2L1 with 7L4, each rolling vehicle's rotational and falling velocities (Figure 19) were calculated to determine the change in velocity the relevant dummy occupant contained in each vehicle would be subjected to, that is, diving velocity, v_d. Using this velocity change and the theoretical model shown in Figure 9, a neck loading was calculated based entirely on vehicle kinematics where roof intrusion was ignored (i.e., $v_r = 0$ and thus $\Delta v = v_d$).

There were two reasons why the 7L4 and 2L1 PIIs were chosen for comparison.

- Firstly, both measurements occur at the end of the rollover sequence. Thus the majority of the vertical and rotational kinetic energy (and associated velocity) before the roof-to-ground impact occurred is dissipated when the roof impacts the ground and the vehicle comes to 'rest'. This greatly assisted in simplifying the calculation of the change in rotational and vertical velocity components that are associated with neck loading.
- Secondly, two PIIs were measured when the vehicle motion most 'closely' correlated to Moffatt's assumed vehicle kinematics, that is, the vehicle drops onto the far side of the roof causing intrusion as indicated in Figure 4. In other words, these two PII measurements constitute the extreme-case scenarios where a torso augmentation (diving) type injury could be theorized to occur.

Thus, using digitized single-frame images of the tests' videos (Figures 11 & 18) and noting the rotational and vertical movements for a given time period, the rotational velocity (ω) and vertical velocity (v_v) versus time was calculated. This was then used to determine the respective rotational and vertical velocity changes of the vehicle. The change in both rotational and vertical velocities was taken over the time period starting when the driver's side roof rail touched the ground until the peak neck load was observed. This was noted as having occurred over a period of around 20–40 ms. Because the vehicle did not continue to roll after this impact and the vehicle landed more or less directly on its roof, the rotational component was assumed to be parallel to the vertical component of occupant motion. Furthermore, change in horizontal velocity was assumed to be negligible and not included in any calculations. This assumption was based on the fact that change in horizontal velocity of the vehicle/occupant would only be due to friction against the road surface. Because the peak neck loading in Malibu II tests was generally recorded 20–40 ms after roof impact with the ground, the time where peak neck load was recorded, the change in horizontal velocity was estimated to be less than 0.30 m/s. It was thus felt this was insignificant in the context of velocity change applied to the occupant's head (generally vertical).

Using the position of the dummy and the rotational velocity change of the vehicle, the equivalent change in tangential velocity (Δv_ω) the dummy would be subjected to as a result of rotation was determined. The length of the lever arm used (630 mm for 7L4 and 460 mm for 2L1) to convert rotational velocity was the distance from the dummy's COG to the vehicle's COG, which in turn was assumed to be at the centre of rotation. Using the sum of the tangential and vertical velocity changes, as both were essentially in the vertical direction (i.e., down) at the time of roof to ground impact (Figures 11 and 18), the overall vertical velocity change Δv_d that the dummy would be subjected to was calculated. Finally, using Eq. (8) and the calculated velocities, the theoretical neck load expected as a result of torso augmentation was determined. Table 7 shows the rotational, vertical and total velocity change for each vehicle and the resulting theoretical neck load that could be expected as a result of torso augmentation. The final column in Table 7 lists the measured loads.

Data in Table 7 correlates well, within an acceptable error band, for neck loading measured in 2L1 and yet the experimentally measured neck loading of 7L4 far exceeds the theoretical load calculated for the same PII using this method of analysis.

This suggests that the axial neck load recorded for 2L1 can be attributed to a 'diving' type torso augmentation (i.e., $v_r = 0$). However, for 7L4 a diving type occupant motion does not provide an adequately high enough impact velocity to account for the 13,200 N load recorded. When Figure 13 to Figure 17 are considered, along with the fact that the area of roof above the occupant's head was not in contact with the ground at the time 7L4 was recorded, it

Table 7 **Vector analysis of Malibu II neck injuries**

Injury	$\Delta\omega$(rad/s)	Δv_ω (m/s)	Δv_v (m/s)	Δv_d (m/s)	Theoretical Load (N)	Malibu II Load (N)
7L4	2.9 ± 0.2	-1.9 ± 0.1	-0.9 ± 0.9	2.8 ± 1	$6{,}700 \pm 2{,}400$	13,200
2L1	2.4 ± 0.2	-1.1 ± 0.1	-1.3 ± 0.9	2.4 ± 1	$5{,}800 \pm 2{,}400$	5,600

becomes obvious that 7L4 is a case where roof intrusion has caused the noted injury to the Hybrid III dummy, with little to no contribution from the occupant's 'diving' motion (i.e., $v_d \approx 0$ so $\Delta v \approx v_r$).

Finally, when 2L1 is carefully scrutinized, some roof deformation of the roll cage can be perceived. Whilst theoretical calculations in relation to the 2L1 can account for the neck load using the diving model shown in Figure 9, it appears from the film footage that the neck load is more likely resulting from roof intrusion of the roof and roll cage structure. This will be further investigated and discussed in subsequent papers.

Hence, contrary to conclusion 3 reached by the Malibu II authors, it appears that under similar roof-to-ground impacts there is indeed an increase in the level of protection in the roll caged vehicles over the production vehicles.

CONCLUSIONS AND FURTHER RESEARCH

This paper discussed and analyzed two apparently conflicting views of injury causation for contained occupants in rollovers, namely torso augmentation, more commonly known as the diving mechanism, and roof intrusion. It is concluded as follows:

1. It appears arguments and analogous crash scenarios presented by Moffatt [18] have little support in terms of physical evidence, when considering the majority of real-world rollover crashes and the associated occupant injury mechanisms.
2. The roll caged vehicles in the Malibu II series tests offer a significant extra level of safety based on current NHTSA neck injury criteria and probability of an injurious event.
3. The 2000 N PII level measured in the Malibu II test series was set too low for establishing a comparison of injury potential for the production and roll caged vehicles.
4. The amount of roof intrusion for a particular impact severity depends on the roof strength. In other words, for the same severity of roof-to-ground impact, the degree of roof intrusion varies from one vehicle to the next because of their different roof strengths.
5. The theoretical and practical neck loading related to roof intrusion velocity can be readily characterized using simplified physical equations based on Newtonian physics.
6. Occupants in vehicles with weaker roofs experienced higher severity injuries than those in strengthened roof vehicles. Results show that the most injurious events in the Malibu II test series are those where the roof structure was not strengthened.
7. Torso augmentation due to a "diving" mechanism does produce neck loading but these loads were found to be significantly lower than the loading required to produce serious neck injuries.
8. More work needs to be carried out to establish acceptable injury mechanisms and associated injury criteria for future rollover crash testing protocols.
9. Proximity of the occupant's head to high-speed roof deformation due to intrusion of a vehicle's roof structure, be it from buckling or otherwise, increases the danger of severe neck injuries.
10. There is a direct causal link between roof intrusion velocity and neck injury.
11. Maintaining adequate survival space and adherence to DeHaven's original crashworthiness principles [28] appears to be the key process in reducing injuries during rollover crashes.

To further investigate the issue of rollover crashworthiness, further research should focus on: buckling mechanisms of current vehicle roof structures; the neck injury response that occupants' and ATD's heads and necks have to varied levels of axial and bending loads; and the validity of utilizing a dynamic rollover testing fixture, such as the Jordan Rollover System (JRS), in testing these phenomena.

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ROLLOVER CRASHWORTHINESS: THE FINAL FRONTIER FOR VEHICLE PASSIVE SAFETY

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ABSTRACT

Fatalities and injuries to seat belted occupants resulting from rollover crashes is of considerable concern to road safety advocates around the world. Rollover crashes in Australia account for around 1 in every 6 road fatalities, in Europe approximately 1 in every 10, while in the USA it is an alarming 1 in every 4. Recent detailed analysis of the Australian National Coronial Information System fatalities for the year 2005 has revealed that almost 1 in every three vehicle (excluding motorcycle, bicycle and pedestrian fatalities) occupant fatalities (29%) can be attributed to a rollover crash and that of those crashes 16% occur in urban environments whereas 84% are rural crashes. Moreover, vehicle roll-overs are among the most common cause of spinal cord paralysis injury in Australia. Yet there still is no government mandated or consumer dynamic rollover test that protects occupants in such crashes. The main reason for this is considered to be two fold. Firstly, vehicle manufacturers continue to contend that there is no causal link between roof crush and occupant injuries and in particular neck injuries. Secondly, government and consumer groups are presently focussed on prevention of rollover via assessment and ranking of a vehicle's stability characteristics and promotion of electronic stability control.

This paper provides a brief summary of research work carried out and findings to date of an Australian Research Council (ARC) project "Protecting Occupants in Vehicle Rollover Crashes". It includes: the mechanisms that lead to neck injury and fatalities in rollover crashes; the causal link between serious head and neck injuries and excessive roof crush for seat belted occupants; and a proposed rollover crashworthiness testing device called a Jordan Rollover System (JRS) test rig; some preliminary results of a number of vehicles tested using the JRS test rig and a proposal of how vehicle rollover crashworthiness could be rated using the JRS test rig.

AUSTRALIAN ROLLOVER CRASHES FOR 2005

Approximately 1268 of a total of 1627 road fatalities recorded for year 2005 were investigated using the Australian National Coroners Information System (NCIS). The remaining 359 fatalities were still associated with open files and hence could not be accessed. This meant that a total of around 77% of all road fatalities in 2005 were accessible. **Table 1** shows the breakdown in percentage of all fatality cases accessible via NCIS in each state.

Out of this total (accessible) of 1268 road fatalities in 2005, 742 were vehicle occupants. This excludes motorcyclists, cyclists and pedestrians. Of the 742 occupant fatalities, 216 were in a vehicle involved in a rollover crash where around 63% were in cars, 30% in 4WD vehicles, 6% in trucks and the remainder were non-typical road vehicles such as tractors, etc. From a another perspective, nationally, around 29% of vehicle occupants killed were in a vehicle that was in a rollover crash, i.e. a little less than 1/3rd of vehicle occupants (excluding motorcyclists and cyclists). This figure is not dissimilar to the proportion of vehicle fatalities in the USA that are rollover crash related. Around 11,519 fatalities from a total of around 33,041 vehicle occupant fatalities (excluding motorcyclists and cyclists) occurred in the USA in 2005 that were rollover related, i.e. 1 in every three vehicle occupant deaths can be attributed to a rollover crash mode [NHTSA, 2005].

	% data accessible
ACT	100%
NSW	62%
NT	93%
QLD	76%
SA	92%
TAS	98%
VIC	82%
WA	68%
Total	**77%**

Table 1: Percentage of all road fatalities for each state accessible using NCIS.

	% rollovers (vehicles only)	Rollover % rural divide
ACT	27%	0%
NSW	13%	89%
NT	74%	79%
QLD	29%	89%
SA	32%	96%
TAS	22%	63%
VIC	26%	76%
WA	45%	95%
Total	29%	84%

Table 2: Percentage of vehicle only crashes where it was identified the vehicle rolled over and percentage of the rollover related crashes that were rural.

Of the 29% of vehicle occupants involved in a rollover crash around 42% were in a vehicle that is involved in a secondary collision, and 58% were in a single vehicle crash. The secondary collision vehicles were either vehicles struck by another vehicle prior to or after rolling over, or the vehicle hit a fixed object such as a tree, pole, road side barrier, etc, prior to or after rolling over. **Table 2** shows the percentage breakdown of vehicle occupant fatalities involving a rollover crash occurring in each state. It is worth noting that rollover related crash fatalities are over represented in Western Australia and the Northern Territory.

The rollover occupant fatalities were also analysed and segregated into rural and urban associated fatalities. The division of rural versus urban was based on assessing postal codes and using maps and assessing whether the crash occurred in an urban built up environment or not. **Table 2** again shows the percentage rural rollover occupant fatalities for each state. **Table 2** also shows that rollover associated fatalities predominantly occur in the rural divide at around 84% nationally but varies greatly and clearly percentage of rollovers in each state is at least partially related to the amount of rural areas.

Ejection		Seatbelt Usage	
Yes	43%	Yes	19%
No	32%	No	35%
Partial	6%	Unknown	46%
Unknown	20%		

Table 3: Categorisation of rollover crashes where a fatality occurred.

Occupants who were killed in a vehicle that rolled over were further investigated for seat belt usage and ejection. This data is summarised in **Table 3**. It is interesting to note that 49% of the fatalities that occurred were either fully or partially ejected during rollover and around 35% of occupants killed were found to be not using a seat belt. Unfortunately, little can be said about the 46% of occupants killed involving a rollover crash where seatbelt usage is unknown. However, the authors suspect a large proportion of these occupants may not have been wearing seat belts. Thus significant gains in terms of injury reduction could be made by ensuring occupants wear seat belts and that systems are developed to ensure the occupants are contained within the vehicle during the rollover event.

ROLLOVER CRASH MECHANISM

The different ways in which a single vehicle rollover crash occurs has recently been described by Young et al (2006), Gugler et al (2004), Viano and Parenteau (2004). As mentioned above, vehicles can also become involved in a rollover crash as a secondary event after it has been struck by another vehicle [Digges and Eigen, 2007]. Of those rollover crashes described for single vehicle rollover crashes, one of the most common ways a rollover crash occurs involves a vehicle loosing steering control, yawing sideways, and eventually “tripping” because of excessive tyre resistance to yaw sliding. Analyses of crash scenarios have revealed to date that this can either occur:

- because of excessive speed during a cornering manoeuvre inducing the yaw;

- as a result of the driver falling asleep at the wheel allowing the vehicle to drift onto the soft gravel shoulder, suddenly waking and then oversteering the vehicle in an attempt to guide it back onto the bitumen;
- from an excessive swerving steering manoeuvre to avoid a collision into another vehicle or object;
- or from an impact with a roadside concrete barrier or dirt mound.

Regardless of how vehicle tripping was induced, once the vehicle begins its rollover sequence, the safety of the occupants depends on the structural integrity of the roof, the seatbelt restraint and side air-curtain system. The majority of rollovers usually occur on flat terrain where there is little rise or fall of the vehicle during the rollover event (Friedman, 2005). Newton's first law of physics governs that any objects within the vehicle are usually thrown to the outside away from the centre of rotation of the vehicle unless they are restrained in some manner. The restrained occupant is held within the seat area by forces applied primarily by the seatbelt. If the occupants are not restrained, there is no air curtain and the vehicle's side windows are compromised and fractured as a result of roof crush, ejection of the occupants is most likely. If the roof structure is weak and readily collapses, then the internal survival space is compromised to a point where both the occupant's head and neck cannot fit under the roof structure unless the neck is broken as is obvious for the vehicle shown in **Figure 1**.

The vehicle shown in **Figure 1** underwent two rollovers (two complete revolutions). Friedman et al (2007a, 2007b) have shown that around 90% of rollover crash related fatalities occur within 2 complete 360 degree rolls, i.e. 8 one quarter (90 degree) turns. In other words, the authors believe that the vehicle's roof structure should be built to withstand at least 2 rollovers without intrusion into the occupant compartment. A strong roof also helps significantly reduce breakage of side and/or front glazing which in turn mitigates ejection (which constitutes a large proportion of rollover fatalities and serious injuries).

INJURY MECHANISM

This paper focuses on injuries to seat belted occupants. A large number of papers have been published analysing how such occupants are injured during a tripping rollover event. It has been established that a seat belted person suffers serious, potentially fatal neck injuries, as a result of loading to the head which in turn loads the neck. Hence the large number of spinal injuries resulting from vehicle rollover crashes [Cripps, 2005]. In other words, the head appears to be driven into the torso of the occupant.

Effectively there appear to be two different hypotheses in regards to how occupants are injured in this way. One proposes that the occupant "dives" into the roof during the rollover when the roof strikes the ground. This view was introduced by Moffat in 1975, but continues to this day to be strenuously defended by vehicle manufacturers [Bahling et al, 1990].

Figure 1: Tenting roof crush and pillar deformation leaves little room for survival

The basis on which the “diving” hypothesis is defended dates back to a series of FMVSS 208 dolly rollover tests carried out in 1987 by General Motors of their 1983 Chevrolet Malibu vehicle, with seat belted Hybrid III 50th percentile crash test dummies (ATD). The series is referred to as the Malibu II rollover crash tests. Eight vehicles were tested. Four vehicles had roofs strengthened with a ‘roll cage’ and four ‘production’ vehicles had no strengthening. The ATD’s were restrained with the vehicle’s seatbelt systems. The belts were fitted to the ATD’s with slack equivalent to the static inversion of a human surrogate in the vehicle. ATD neck loads were measured. Any neck load above 2000 N was identified as a Potentially Injurious Impact (PII). There were forty (40) such PII’s recorded from the test series.

An alternate view, mostly promulgated by Friedman (1998, 2001, 2005, 2007a, 2007b) and other crashworthiness experts [Nash & Paskin, 2005, Rechnitzer & Lane, 1994, and Chirwa et al, 2006], states that roof crush is causally linked to fatal and serious head and neck injuries resulting from rollover crashes.

In an attempt to resolve the argument and hence fill a knowledge gap, the authors have analysed in detail the principles on which the "diving" hypothesis is based. A discussion of this can be found in two papers by Young et al (2007) and Grzebieta et al (2007). Essentially the authors have developed equations based on a single degree of freedom dynamic model of an occupant that directly relates the magnitude of neck load to either the intrusion velocity of a roof and/or the velocity of the occupant "diving" into the roof. Further analysis of General Motors (GM) Malibu II vehicle rollover crash tests [Bahaling et al, 1990] was also presented in these papers illustrating how high neck loads in production (non-reinforced) vehicles cannot be attributed to "diving" alone. It was concluded that these significant forces must be resulting from roof crush and in particular the velocity at which the roof intrudes. **Figure 2** shows the model used [Grzebieta et al 2007]. The following equations

$$F_{neck} = v_R \sqrt{km} \qquad (1)$$

and

$$F_{neck} = v_d \sqrt{km} \qquad (2)$$

relates the velocity of roof intrusion V_R and the "diving" velocity V_d to the neck loading where k is the ATD's neck stiffness, x the neck compression, x_m the displacement of the torso, m the mass of the torso, and $\ddot{x}_m$ the acceleration of the torso.

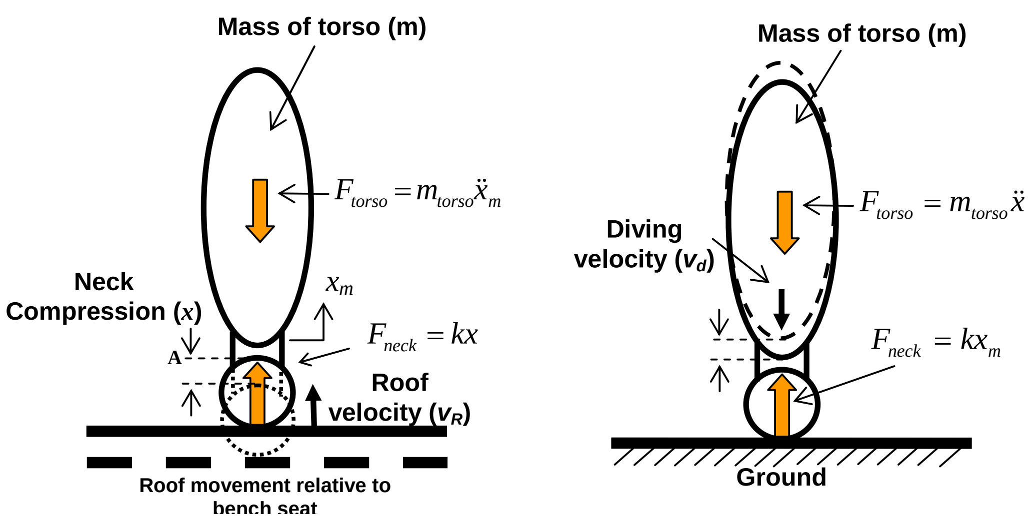


Figure 2: Single degree of freedom dynamic model representing Hybrid III dummy

Consider the silhouette of a vehicle that is rolling over as shown in **Figure 3**. It rotates at a roll speed of ϖ degrees per second and its Centre Of Gravity (COG) is travelling sideways at a velocity of V_{COG}. The rollover can be thought of as a smooth cylindrical barrel roll. Friedman and Nash (2005) on analysing the GM rollover Malibu II test data found that the COG of the vehicle does not rise or fall more than 4 to 5 centimetres such that the vehicle's COG vertical velocity at roof impact is never more than 2.5 m/sec. Thus each complete rollover can also be considered as being made up of four quarter turns where a small portion of the vehicle's kinetic energy is dissipated during each quarter turn (Bahling et al (1990), Richardson et al (2001)). During each quarter turn the corners of the roof, points B & C, and the tyres interact (touches down) with the road surface. Between each touchdown the vehicle can be assumed to be airborne.

We now assume that the roof and pillars are weak and will distort typically as an unbraced frame with weak joints at positions A, B, C & D. In other words, we assume the pillar AB sways sideways. The pillar on the non-struck side can also sway in a mechanism commonly referred to as 'match-boxing' or 'side sway' if pillar CD is weak in rotation (**Figure 3(a)**). In the case of the vehicle shown in **Figure 1**, the roof 'tented' rather than deform the opposite pillar as depicted by line DC in **Figure 3(b)**. Note that the force in the opposite non-struck side pillar resolves in a direction that provides maximum resistance to any loading from the struck side impact. Hence, the roof 'header rail' at the front windscreen tends to deform instead because it provides a weaker resistance to movement than the far side pillar. **Figure 3 (b)** shows how the deformation mechanism and weak roof can result in an extra hinge point G forming in the header rail.

Regardless of how the opposite side pillar distorts, the occupants head is close to the struck pillar when contact occurs as shown in **Figure 4**. This occurs as a result of plastic deformation hinges forming at points A, B, C & D as shown in **Figure 3(a)** or at A, B, C, G & D as shown in **Figure 3(b)**. Position A represents a hinge formation at the intersection of the 'a'-pillar and side roof rail and/or at the 'b'-pillar and side and header roof rails. We also assume this occurs when the trailing side at point B strikes the ground. That the trailing side usually distorts as a result of adverse load paths generated by rollover forces, as opposed to the leading side that better resist the forces, has been confirmed by a number of investigators [Bahling et al (1990), Parenteau et al (2001), Friedman and Nash (2005), Nash and Paskin (2005) and Chen et al (2007)].

Consider now in isolation pillar AB, e.g. the 'b-pillar', manufactured at an inclined angle α. If the pillar roof connection is very weak in bending then as a result of striking the ground the pillar will distort sideways as it moves horizontally by an amount Δ. This deformation occurs at the speed at which the vehicle is moving laterally, i.e. at a velocity V_{COG}. Geometry and kinematics then dictates that the roof rail drops down a distance of δ at a velocity directly related to the horizontal velocity. Bahling et al (1990) found in their rollover crash tests of the Malibu vehicle where the occupants were seat belted that: *"As a result of this rotational velocity, dummies moved upwards and outward to the extent which the lapbelt and vehicle side interior would allow. They tended to remain with their heads adjacent to the outboard roof siderail while constrained by the lapbelt and door and moved away from that point only by vehicle-to-ground impacts."*

This means that the head when in contact with the siderail near point B would undergo a vertical displacement of δ when the line AB ('b-pillar' and/or 'a-pillar' together) rotates sideways. Thus by calculating δ it is possibly to determine the vertical intrusion velocity of the roof onto the occupant head that causes both a vertical and lateral displacement of the head.

Weak Roof

The relevant dimensions for length AB in isolation are shown in **Figure 5** where the length of the 'b-pillar' is adopted as L. From this sketch when element AB is rotated the following relationship is obtained

$$\delta_T = \delta_0 + \delta = L - \sqrt{L^2 - (\Delta_0 + \Delta)^2} \tag{3}$$

This expression can be rearranged to

$$\delta = L - \sqrt{L^2 - (\Delta_0 + \Delta)^2} - \delta_0$$

and

$$\delta = L - \sqrt{L^2 - (\Delta_0 + \Delta)^2} - \left(L - \sqrt{L^2 - \Delta_0^2}\right)$$

and thus

$$\delta = \sqrt{L^2 - \Delta_0^2} - \sqrt{L^2 - (\Delta_0 + \Delta)^2} \tag{4}$$

or in trigonometric form

$$\delta = L(\cos\beta - \cos\alpha) \tag{5}$$

At point B touchdown if the roof is a weak structure, the 'b-pillar' can potentially reach the vehicle's COG horizontal velocity minus the velocity due to vehicle rotation at point B. Thus

$$V_R = \frac{\delta}{\Delta} \times (V_{COG} - V_{\varpi}) \tag{6}$$

Substituting Equation (1) for the neck force from roof crush, the expression for the neck loading resulting for a vehicle with a weak roof is

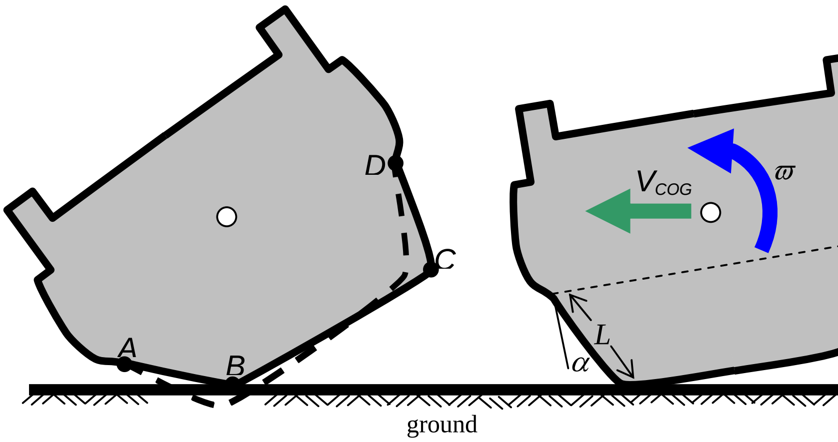
$$F_{neck} = \frac{\delta}{\Delta} \times (V_{COG} - V_{\varpi})\sqrt{km} \tag{7}$$

or in expanded form

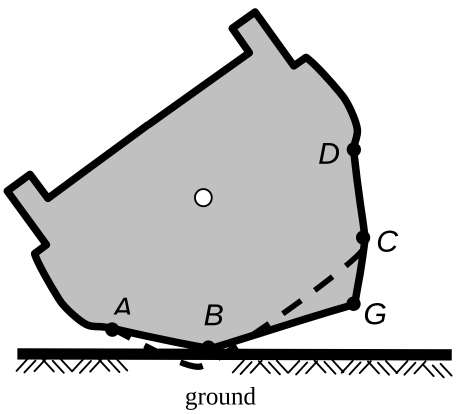
$$F_{neck} = \frac{\left(\sqrt{L^2 - \Delta_0^2} - \sqrt{L^2 - (\Delta + \Delta_0)^2}\right)}{\Delta} \times (V_{COG} - V_{\varpi})\sqrt{km} \tag{8}$$

or in trigonometric form

$$F_{neck} = \frac{L(\cos\beta - \cos\alpha)}{\Delta} \times (V_{COG} - V_{\varpi})\sqrt{km} \ . \tag{9}$$



(a) Sway mode



(b) Tenting mode

Figure 3: Sedan vehicle rolling over striking the ground on the trailing side of the roof.

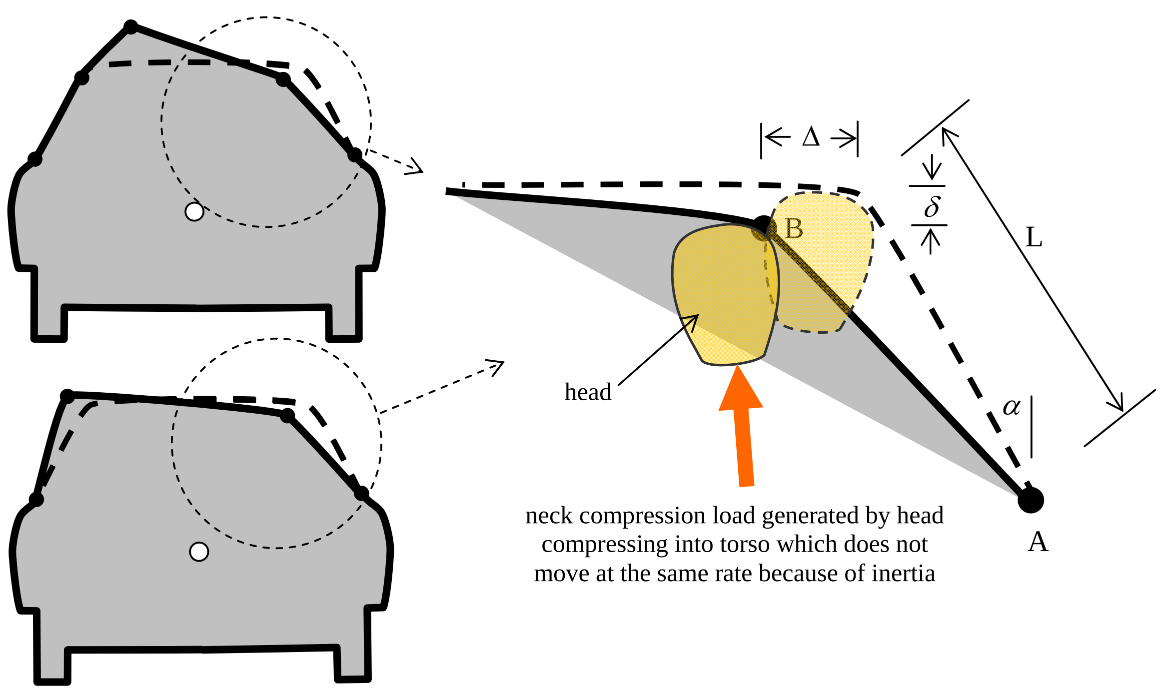


Figure 4: Deformed 'weak roof' vehicle with head placed at intersection of side pillar and roof

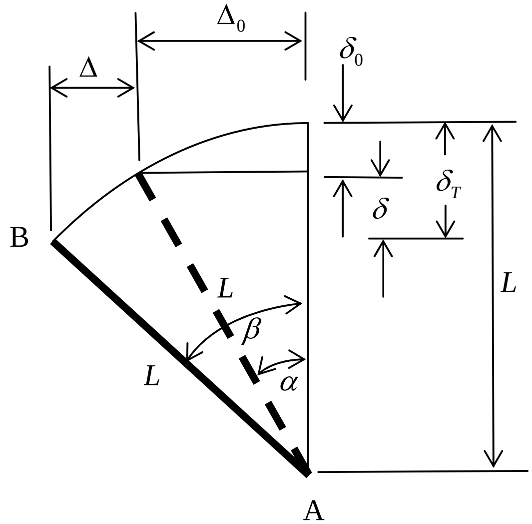


Figure 5: Displacement of pillars sideways

Strong Roof

It is now assumed that the vehicle is subjected to an FMVSS 208 dolly rollover crash test on a bitumen surface and the roof is very strong. In general, for an FMVSS 208 dolly rollover crash test, the height of a vehicle's COG does not change significantly. If the roof is now so strong that it does not deform during contact with the ground, the vehicle effectively skids along the road surface each time contact is made in quarter turn. In other words, the steel-bitumen and tyre-bitumen contact surfaces slide against each other as shown in **Figure 4** and a certain amount of energy is dissipated. It is for this reason scratch or gouge marks left in the road or gravel surface are often noted by crash investigators and reconstructionists, as points of contact and sliding, identifying how the vehicle rolled. It should be noted that rollover energy is also dissipated by the raising and lowering of the vehicles COG [Richardson et al, 2001] albeit the COG height change is small as indicated by Friedman and Nash (2005).

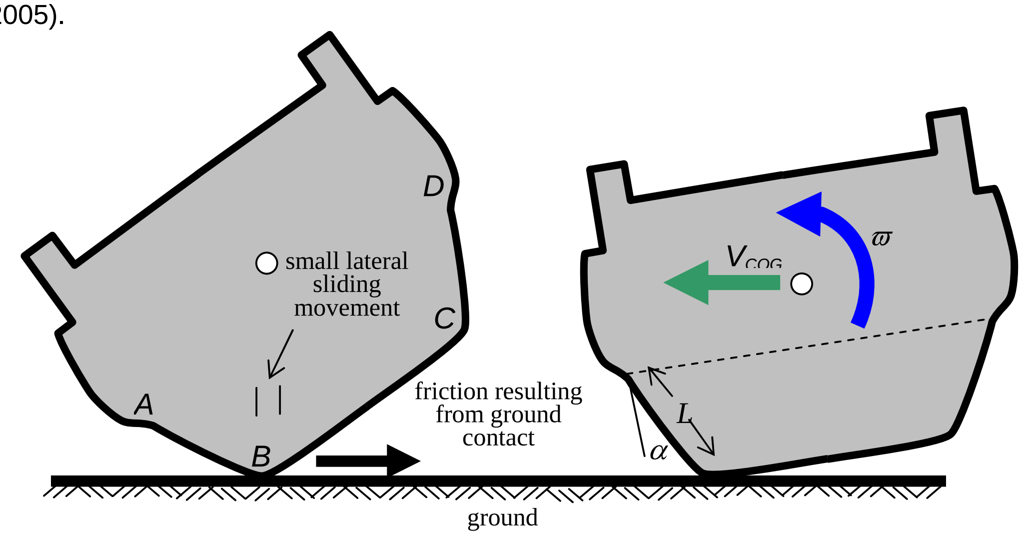


Figure 5: 'Strong roof' vehicle contacts ground.

The car body can be considered as a rotating shell surrounding the occupant, slowing down each time it makes contact and the steel roof corner or tyres skid on the bitumen surface. To determine how much the vehicle decelerates each time touchdown occurs, the following equation based on Newtonian laws of physics governing the deceleration or acceleration of a body can be used

$$V^2 = 2fgd \qquad (10)$$

where 'f' is the deceleration drag factor, 'g' is 9.81 m/sec^2 being the earth's gravitational constant and 'd' is the distance over which a body decelerates, can be used. Equation (10) has been used by crash reconstructionists for over twenty years [Baker, J. and Fricke, L. (1986)]. The key variable is the drag factor 'f'. Coefficients of friction for steel against bitumen and for tyres against bitumen range from 0.55 to 0.7. In this instance a value of around 0.6 will be adopted.

The "diving" velocity of an occupant inside the vehicle can be calculated, knowing the rate of angular roll ϖ , the distance R_o from the occupants COG to the vehicle's COG and the vertical drop height 'h' through which the vehicle's COG drops as it rolls along. Thus

$$V_d = \varpi R_0 + \sqrt{2gh} \qquad (11)$$

However the rate of angular roll can be directly related to the change in velocity of the vehicle structure in each quarter turn as it strikes the bitumen, i.e.

$$V_d = \frac{R_0}{R_{COG}}\sqrt{2fgd} + \sqrt{2gh} \qquad (12)$$

Again Equation (2) for "diving" velocity can be adopted in place of the roof crush velocity to be used to estimate the neck load. Thus

$$F_{neck} = \left[\frac{R_0}{R_{COG}}\sqrt{2fgd} + \sqrt{2gh}\right]\sqrt{km} \qquad (13)$$

Equation (13) shows that the main factor that influences the severity of a rollover crash and the velocity at which an occupant will dive into a strong roof during each quarter turn is the height of vertical fall *'h'*. However, the authors and others [Friedman and Nash 2005, Young et al 2006 & Grzebieta et al 2007] have shown that the vertical drop height is small for a rollover on level ground in the case of a rollover FMVSS 208 crash test.

What is interesting to note about Equation (13) is it is independent of the velocity at which rollover commences. Thus it should be irrelevant of the vehicle starts to rollover at 100 km/h freeway speed or 52 km/h as in the case of a dolly rollover crash test, so long as the vertical drop height '*h*' is not large and consistent between the two events. The outcome will be that the occupant "diving" velocity will always reach a threshold value that is directly related to the coefficient of friction between the vehicle's steel body and tyres and the road surface. It also means that if the coefficient of friction becomes higher, i.e. ploughed earth, or the drop height becomes larger, the neck load will increase unless the occupant is firmly secured in a seat belt with adequate clearance between the head and the roof. The research work to confirm this finding is currently under way.

JORDAN ROLLOVER TEST RIG AND ROLLOVER CRASH TESTING

To confirm the validity of Equation (1), the authors requested results of measured neck loads from Hybrid III dummies placed into vehicles that were subjected to a repeatable, dynamic rollover test using the Jordan Rollover System (JRS) test rig as shown in **Figure 6**. Details of the test rig are provided by Jordan & Bish (2005) and Friedman et al (2007). The test vehicle or occupant compartment only buck is supported by two drop towers along its longitudinal roll axis at the vehicle's COG. The vehicle can be positioned at any pitch or yaw angle. A mobile roadbed segment moves under the vehicle and is synchronised with the vehicle's roll so as to simulate the rate at which the vehicle's COG is moving as it rolls. When the test starts the vehicle is rotated and allowed to free fall to the roadway. The vehicle moving freely, strikes the near side and far side of the roof on the road bed. The vehicle is then caught by the towers as the road bed progresses through and beyond the towers so that the vehicle does not suffer any further damage. The vehicle, roadbed and Hybrid III Crash Test Dummy (ATD) are instrumented to record: vertical and lateral vehicle impact loads; roof displacement and roof intrusion velocity during roof impacts at several roof locations inside the vehicle; and dummy neck loads. High speed and real-time cameras record movement of the vehicle and ATD.

Figure 6: Photograph of the JRS Test Rig [Friedman et al, 2007b]

Real world crash analysis by Friedman et al (2007) indicates that the most appropriate set up for the vehicle in the JRS is: a pitch angle of 5°; a yaw angle of 10°; a rotation speed of around 190 degrees per second; a free fall of 10 cm; and a roadbed speed of 24.1 km/h (15 mph). Under these conditions the vehicle strikes the near side of the roof at a roll angle of 135°.

A selection of US vehicles have been tested in the JRS under the initial test conditions outline above by Friedman et al (2007). The neck loads measured in the ATD are plotted against the speed of roof intrusion relative to the ATD and is shown in **Figure 7**. Theoretical values calculated using Equation (1) are also plotted using values of neck stiffness and mass as detailed by Young et al (2007) and Grzebieta et al (2007). Correlation between theory and test is considered reasonable, indicating that peak neck loads appear to be linked to the speed of roof intrusion. The values at the far right of the plot in **Figure 7** are instances where the vehicle roof was known to be weak, whereas the point on the far left of the plot where the load was around 2000 Newtons was a vehicle that was known to have a strong roof. In the instance of the two 'weak roof' vehicles, the ATD head was found to be to one side of the point in the vehicle roof where the intrusion and its velocity was a maximum, accounting for the underestimate in peak neck load for these tests. Suffice to say that many more tests need to be carried out to assess the validity of the above equations. This is one of the current tasks of the Australian Research Council (ARC) Discovery Project rollover grant research team.

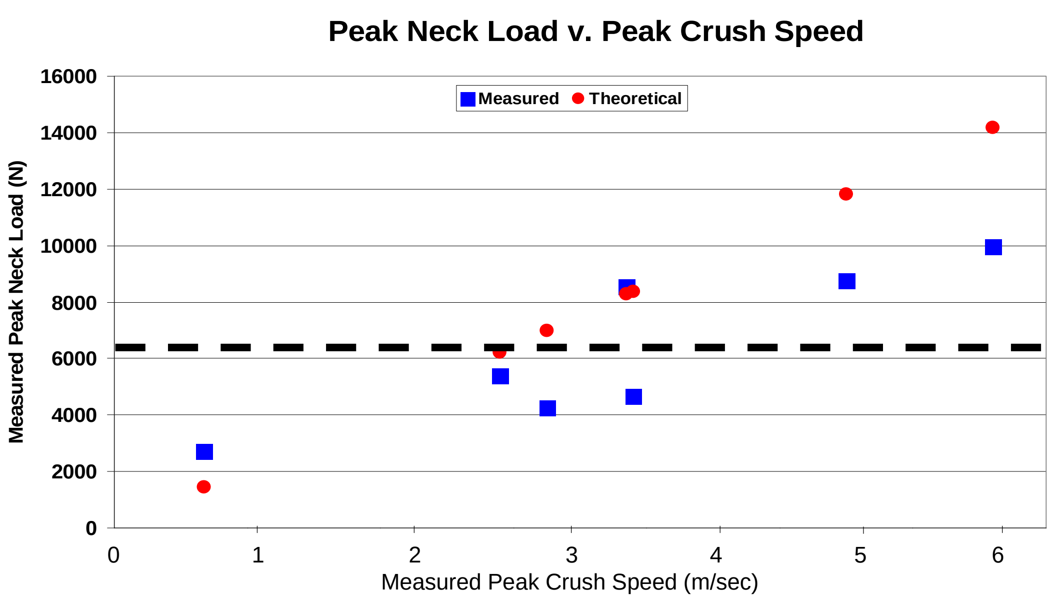


Figure 7

Considerable biomechanical research has been carried out in regards to identifying what magnitudes of axial loading need to be applied to a vehicle occupant's neck to cause serious injury, and how ATD measurements relate to these injury levels. The impact velocity was shown by Alem et al (1984) and Myers et al (1997) to influence both the risk and severity of neck injuries in experimental crown impacts to the head. In parallel, Sakurai et al (1991) and Sances et al (2002) showed that measured Hybrid III peak neck loads also correlated with the impact velocity for a given impact scenario (see also **Figure 7** for the present study). In particular, Hybrid III reconstructions of injurious events presented by Mertz et al (1978) or Pintar et al (1990) showed that severe injuries to the neck start to occur at compressive loads between 4000 to 6000 Newtons (N) measured on this ATD. However, as raised by Friedman et al (2001, 2005, 2007a and 2007b), and based on recent results by Viano and Pellman (2005), the current 4000 N Injury Assessment Reference Value may be underestimated for the Hybrid III. Therefore, it is considered more work is needed in order to precisely define the peak load/impact velocity combination that may be associated with a given injury level.

The above raises the issue of using the JRS rollover rig to assess the crashworthiness of vehicles and rate them in terms of protection for seat belted occupants. The JRS test rig is also capable of assessing the on-board safety restraint systems such as an aircurtains, pretensioners and seat belts. For example, a possible five star rated vehicle could be one where the neck load is less than its Injury Assessment Reference Value (IARV), the vehicle is installed with pretensioners and curtain airbag, and the roof deformation is such that no window rupture occurs.

CONCLUSIONS

The following conclusions have been drawn so far from the research work carried out to date:

1. Statistical data clearly indicates that rollover crashes are dangerous events and should be a priority in terms of mitigating injuries occurring to occupants;
2. Occupant protection in rollover crashes are not currently being addressed by design rules. There is an urgent need to introduce a system that will ensure seat belted occupants are adequately protected in a rollover crash;
3. It appears that the vertical load imparted to the neck of a seat belted occupant inside a vehicle that is rolling over, where the roof strength is weak, is directly related to the amount of lateral roof “match boxing” distortion a vehicle undergoes at the moment of touchdown;
4. In the case of a weak roof that can readily deform, the vertical intrusion velocity is directly related to the velocity of the lateral displacement of the roof and/or roof pillars. This deformation is in turn directly related to the velocity at which roof touchdown occurs with the ground surface which is directly related to the speed at which the vehicle’s COG is moving laterally;
5. If the vehicle roof is weak, the higher the lateral travelling velocity of the vehicle’s COG, the higher the speed of vertical intrusion and hence the greater the severity of injury to the occupants;
6. If the roof is strong enough to resist lateral and vertical movement during each quarter turn touchdown, the maximum “diving” velocity an occupant will be subjected to will be limited to the resistance to rollover afforded by friction between the vehicle’s roof structure, its tyres and the road surface (around 0.6 drag factor) and the height of drop the vehicle’s COG undergoes from one quarter turn to the next.
7. If the roof is strong, each quarter turn touchdown will slow the rotating vehicle approximately 4 km/h being a consequence directly related to the roof to ground friction coefficient of around

0.6 and the movement of the COG vertically – this movement is a non-injurious change in roll rate for a seat belted occupant;

8 If the roof is strong enough to resist lateral and vertical movement during each quarter turn touchdown, theoretically there should not be any difference in crash severity to a seat belted occupant between a vehicle being tripped at 100 km/h and 52 km/hr so long as the vehicle's COG remains within 3-5 centimetres or so of vertical displacement and the occupant is adequately restrained. This fact has been proven time and again in racing cars that rollover where the roof has been substantially strengthened and the occupant is held in a full harness seat belt. Again the coefficient of friction between the vehicle's body and the road surface is the main factor governing this outcome.

9 The Jordan Rollover System (JRS) test rig can adequately assess the rollover crashworthiness of a vehicle. A JRS test rig should be built in Australia for research and crashworthiness rating purposes.

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