

The next paper was published in the ACRS Journal of May 2008. Unfortunately in the graphic design stage some diagrams lost clarity, limiting their usefulness. The Editor apologises for this and is therefore republishing the paper in full.

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 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 [1].

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

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

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.

	% 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%

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 the percentage of rollovers in each state is at least partially related to the amount of rural areas.

Table 3: Categorisation of rollover crashes where a fatality occurred

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

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 [2], Gugler et al [3] and Viano and Parenteau [4]. As mentioned previously, vehicles can also become involved in a rollover crash as a secondary event after it has been struck by another vehicle [5]. For single vehicle rollover crashes, one of the most common ways a rollover crash occurs involves a vehicle losing 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 [6]. 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 [7, 8] 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 [9]. 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 [10], and supported by others [11], but continues to this day to be strenuously defended by vehicle manufacturers.

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



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

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 et al [6, 7, 8, 12, 13] and other crashworthiness experts [14, 15 and 16], 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 [17] and Grzebieta et al [18]. 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 [11] 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 [18]. The following equations

$$F_{neck} = v_R \sqrt{km} \tag{1}$$

$$F_{neck} = v_d \sqrt{km} \tag{2}$$

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.

Consider the silhouette of a vehicle that is rolling over as shown in Figure 3. It rotates at a roll speed of ω 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 [6, 7] 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 [19]. During each quarter turn the corners of the roof, points B & C, and the tyres interact (touches down)

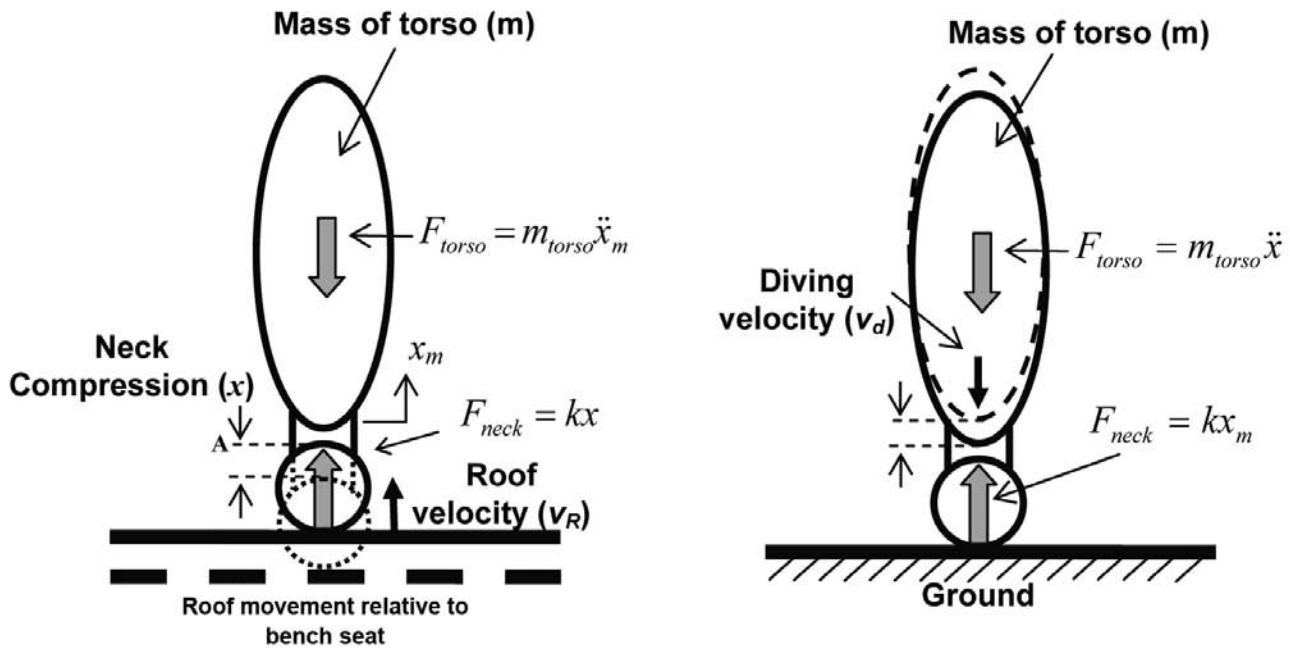


Figure 2: Single degree of freedom dynamic model representing Hybrid III dummy

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 [6, 11, 14, 20, 21].

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 VCOG. 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 [11] 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 possible 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

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

This expression can be rearranged to

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

and

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

and thus

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

or in trigonometric form

$$\delta = L(\cos \beta - \cos \alpha) \quad (5)$$

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 :

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

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

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

or in expanded form

$$F_{neck} = \frac{(\sqrt{L^2 - \Delta_0^2} - \sqrt{L^2 - (\Delta + \Delta_0)^2})}{\Delta} \times (V_{COG} - V_{\omega}) \sqrt{km} \quad (8)$$

or in trigonometric form

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

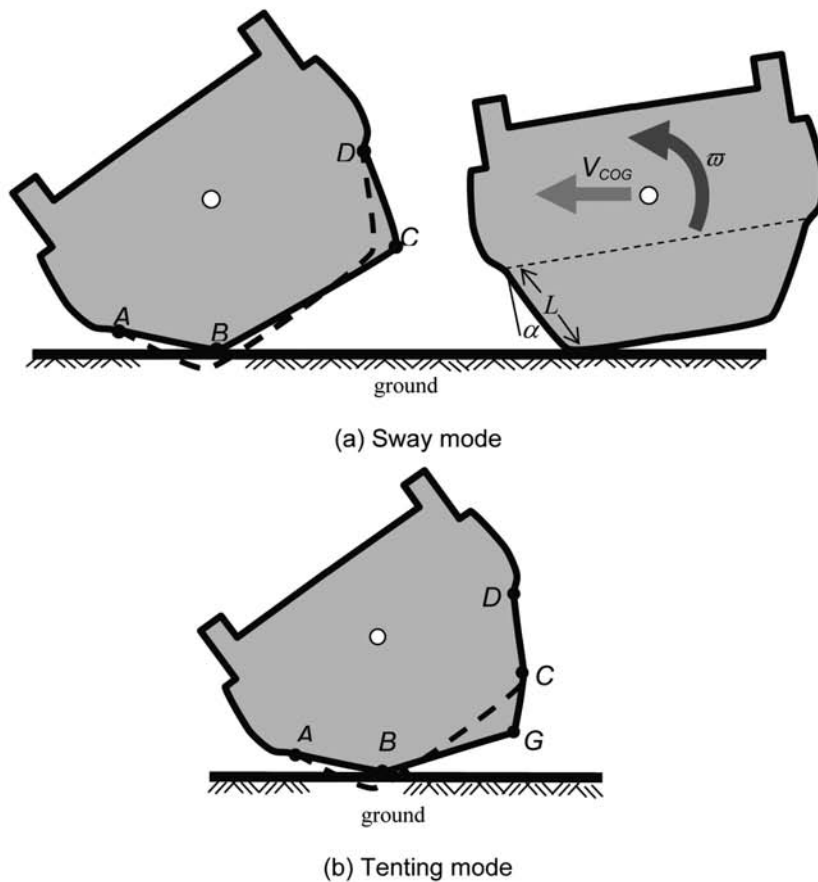


Figure 3: Sedan vehicle rolling over striking the ground on the trailing side of the roof.

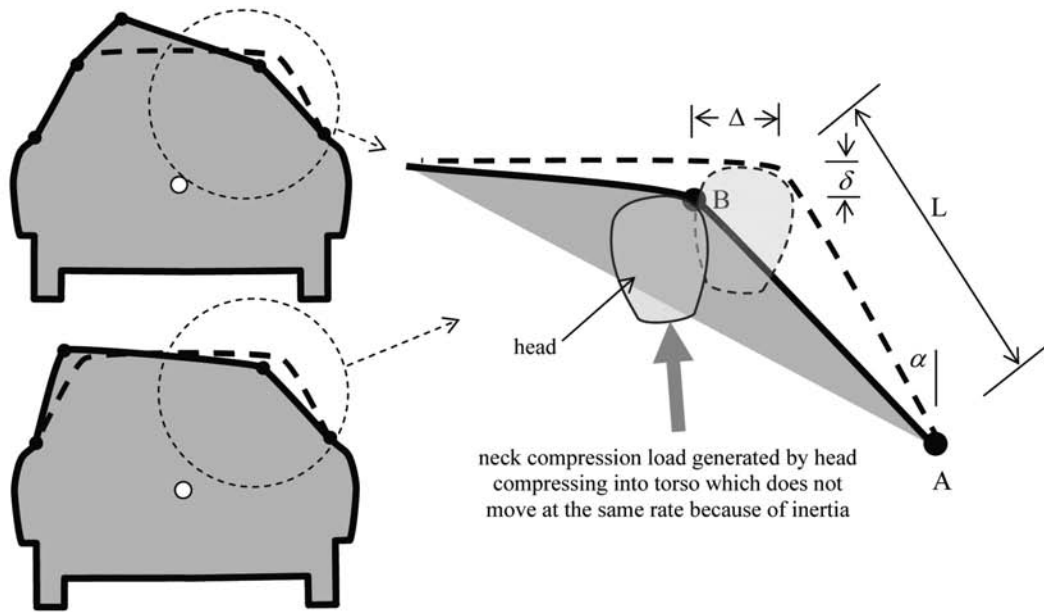


Figure 4: Deformed 'weak roof' vehicle with head placed at intersection of side pillar and roof

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 6 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 [19] albeit the COG height change is small as indicated by Friedman and Nash [6].

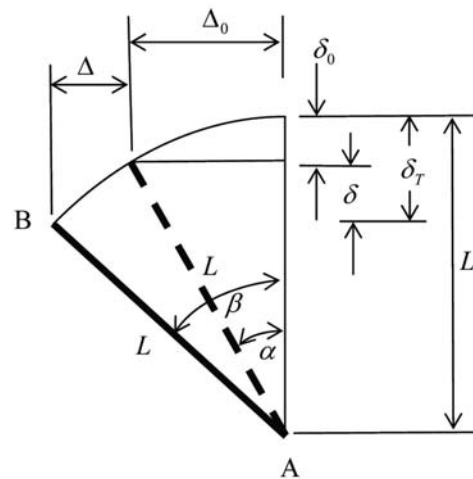


Figure 5: Displacement of pillars sideways

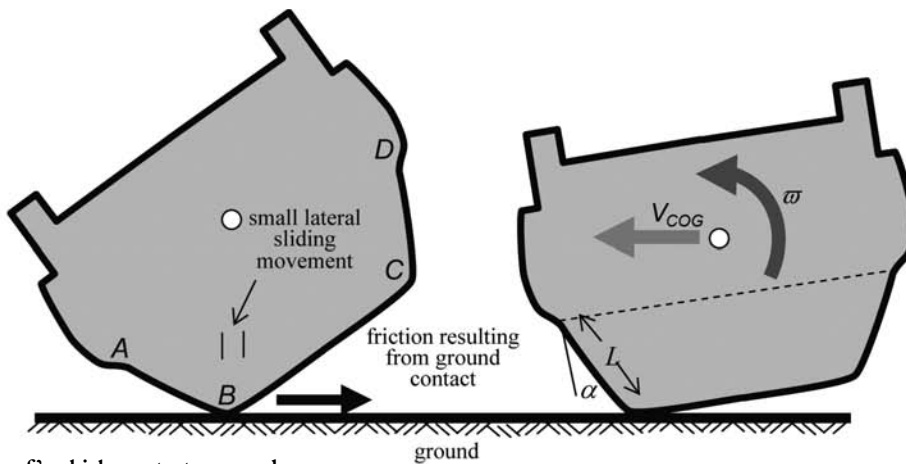


Figure 6: 'Strong roof' vehicle contacts ground

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

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

where ‘*f*’ is the deceleration drag factor, ‘*g*’ is 9.81 m/sec² 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 [22]. 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 ω , the distance R_0 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

$$V_d = \omega R_0 + \sqrt{2gh} \quad (11)$$

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.

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

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

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

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 [2, 6, 17 and 18] 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 7. Details of the test rig are provided by Jordan & Bish [23] and Friedman et al [7 & 8]. 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 7: Photograph of the JRS Test Rig [8]

Real world crash analysis by Friedman et al [7 & 8] 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 rear 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 [7 & 8]. The neck loads measured in the ATD are plotted against the speed of roof intrusion relative to the ATD and is shown in Figure 8. Theoretical values calculated using Equation (1) are also plotted using values of neck stiffness and mass as detailed by Young et al [17] and Grzebieta et al [18]. 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 8 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.

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 [24] and Myers et al [25] to influence both the risk and severity of neck injuries in experimental crown impacts to the head. In parallel, Sakurai et al [26] and Sances et al [27] showed that measured Hybrid III peak neck loads also correlated with the impact velocity for a given impact scenario (see also Figure 8 for the present study). In particular, Hybrid III reconstructions of injurious events presented by Mertz et al [28] or Pintar et al [29] 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 [6, 7, 8 and 13], and based on recent results by Viano and Pellman [30], 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 air curtains, 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.

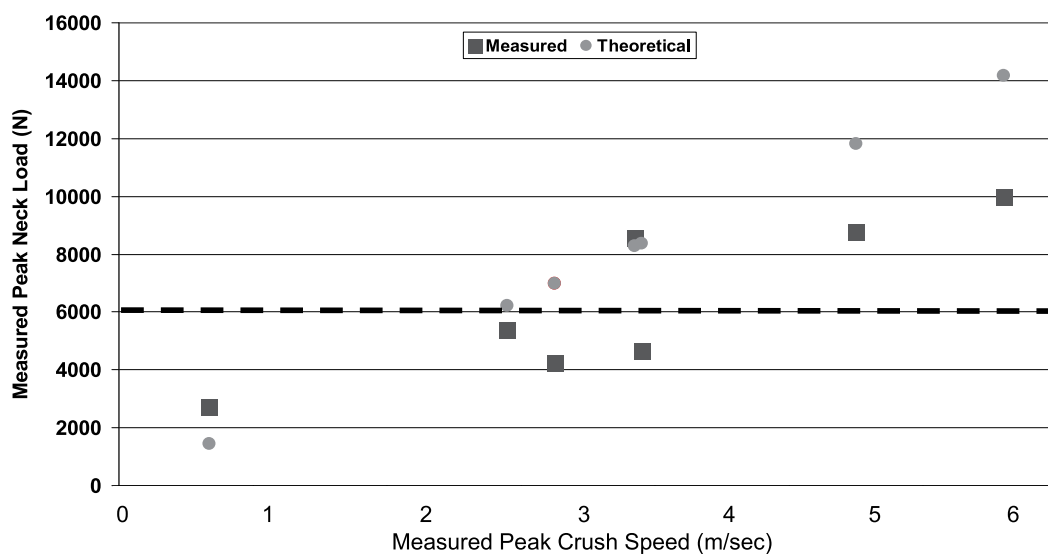


Figure 8: Peak Neck Load v. Peak Crush Speed

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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References

1. NHTSA, Traffic Safety Facts 2005, A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System and the General Estimates System, US Department of Transportation (<http://www.fars.nhtsa.dot.gov/Main/index.aspx>).
2. Young D., Grzebieta R.H., Rechnitzer G., Bambach M. & Richardson S., Rollover Crash safety: Characteristics and issues, Proceedings 5th Int. Crashworthiness Conf. ICRASH2006, Bolton Institute U.K., Athens, Greece, July 2006.
3. Gugler J., Steffan H., Lutter G. & Fleischer S. Rollover Scenarios in Europe, Improvement of Rollover Safety for Passenger Vehicles, European Community -R&TD-Project – 5, Framework-Programme "Growth", Results of Work Package 2 "In Depth Accident Analysis", 2004.
4. Viano D.C. and Parenteau C.S., Rollover Crash Sensing and Safety Overview, SAE Paper No. 2004-01- 0342.
5. Digges K. and Eigen A.M., Injuries in Rollovers by Crash Severity, 20th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Paper Number: 07-0394, Lyon, France, Paper Number 07-0236.
6. Friedman, D. & Nash, C. E. Reducing Rollover Occupant Injuries: How and How Soon, 19th International Conference on the Enhanced Safety of Vehicles. Washington DC, USA, 6 - 9 June 2005.
7. Friedman, D., Nash, C.E., Bish, J., “Observations From Repeatable Dynamic Rollover Tests”, International Journal of Crashworthiness 2007a, Vol. 12, No. 1, pp. 67-76.

8. Friedman D., Nash C.E., Caplinger J., Results From Two Sided Quasi-Static (M216) And Repeatable Dynamic Rollover Tests (JRS) Relative To Fmvss 216 Tests, International Technical Conference on the Enhanced Safety of Vehicles (ESV), Paper Number 07-0361, 2007b.
9. Cripps R. A., Spinal cord injury, Australia, 2003–04, Injury Research and Statistics Series Number 25, Adelaide: AIHW (AIHW cat no. INJCAT 77), 2005.
(http://www.healthinsite.gov.au/topics/Spinal_Cord_Injuries)
10. Moffatt, E.A., Occupant Motion in Rollover Collisions, in 19th Conference of the American Association of Automotive Medicine. 1975: San Diego, California, USA.
11. Bahling, G. S.; Bundorf, R. T., and Kasprzyk, G. S.; Moffatt, E. A.; Orłowski, K. E., and Stocke, J. E., "Rollovers and Drop Tests- The Influence of Roof Strength on Injury Mechanics Using Belted Dummies," SAE Paper No. 902314, 34th Stapp Car Crash Conference Proceedings, pp. 101-112, 1990.
12. Friedman, D. & Friedman, K., Roof crush versus occupant injury from 1988 to 1992 NASS. Detroit, MI, USA, 1998, SAE, Warrendale, PA, USA.
13. Friedman, D. & Nash, C. E., Advanced Roof Design for Rollover Protection, 17th International Technical Conference on the Enhanced Safety of Vehicles. Amsterdam, The Netherlands, 2001.
14. Nash, C. E. & Paskin, A. A Study of NASS Rollover Cases and the Implication for Federal Regulation. 19th International Conference on the Enhanced Safety of Vehicles, Washington DC, USA, 6-9 June, 2005.
15. Rechnitzer, G. & Lane, J. Rollover Crash Study - Vehicle Design and Occupant Injuries. Monash University Accident Research Centre, 1994.
16. Chirwa E.C., Mao M., Chen T. & Latchford J., Flaws in Malibu I and II interpretation of test results that have influenced many poor rollover roof designs, Proceedings 5th Int. Crashworthiness Conf. ICRASH2006, Bolton Institute U.K., Athens, Greece, July 2006.
17. Young D., Grzebieta R.H., McIntosh A., Bambach A. & Frechede B. Diving vs Roof Intrusion: A Review of Rollover Injury Causation, International Journal of Crashworthiness, Vol. 12 No. 6 pp. 609–628, Dec. 2007.
18. Grzebieta R.H., Young D., Bambach M. and McIntosh A., Rollover Crashes: Diving Versus Roof Crush, 20th International Technical Conference on the Enhanced Safety of Vehicles (ESV), Paper Number: 07- 0394, Lyon, France, June 2007.
19. Richardson S, Grzebieta R.H. and Bellion P., Proposed ¼ turn metric to simulate rollover crashes, 17th International Conference on the Enhanced Safety of Vehicles Conference, Paper No 01-S6-W-99, Amsterdam, Netherlands, June 2001.
20. Parenteau C, Gopal M and Viano D, 'Near and far-side adult front passenger kinematics in a vehicle rollover', SAE Tech Paper Ser, 2001-01-0176, 2001.
21. Chen T, Chirwa E C, Mao M and Latchford J, Rollover far side roof strength test and simulation, IJCrash, Vol. 12 No. 1, pp. 29–39, 2007.
22. Baker, J. and Fricke, L., Traffic Accident Investigation Manual, Topic 862 Drag Factor and Coefficient of Friction in Traffic Accident Reconstruction (Northwestern University Traffic Institute, 1986).
23. Jordan A. and Bish J., Repeatability testing of a dynamic rollover test fixture, 19th International Conference on the Enhanced Safety of Vehicles, Paper Number 05-0362, Washington, DC, 2005.
24. Alem, N.M., Nuscholtz, G.S., and Melvin, J., 1984, Head and neck response to axial impacts. Paper 841667, 28th Stapp Car Crash Conference.
25. Myers, B. and Nightingale, R., 1997, The Dynamics of Head and Neck Impact, and its role in injury prevention and the complex clinical presentation of cervical spine injury. Proceedings of the 1997 IRCOBI Conference.
26. Sakurai, T., Takigawa, Y., and Ikeno, H., 1991, Study on Passenger Car Rollover Simulation. Paper 91-S6-O-10, Proceedings of the 13th International Technical Conference on Experimental Safety Vehicle, Paris, France.
27. Sances A, Carlin F, Kumaresan S, Biomechanical Analysis of Head-Neck Force in Hybrid III Dummy During Inverted Vertical Drops, 38th Biomedical Sciences Instrumentation Conference, 2002.
28. Mertz, H.J., Hodgson, V., Thomas, M., and Nyquist, G., 1978, An Assessment of Compressive Neck Loads Under Injury-Producing Conditions. The Physician and Sport Medicine, 6(11): p. 95-106.
29. Pintar, F.A., Sances Jr, A., Yoganandan, N., Reinartz, J., Maiman, D.J., Suh, J.K., Unger, G., Cusick, J.F., and Larson, S.J., 1990, Biodynamics of the total human cadaveric cervical spine. Paper 902309, 34th Stapp Car Crash Conference, Orlando, FL, USA.
30. Viano D.C. and Pellman E.J., Concussion in Professional Football Player: Biomechanics of the Striking Player – Part 8, Neurosurgery 56 pp. 266-280, 2005.