UPPER INTERIOR HEAD, FACE AND NECK INJURY EXPERIMENTS

Donald Friedman
Keith Friedman
Friedman Research
United States
Paper Number 98-S8-P-11

ABSTRACT

Head, face and neck (HFN) injuries associated with upper interior contacts account for a large percentage of all serious to fatal injuries annually. In the past, many of these injuries were the result of unrestrained occupants in rollovers and side impacts. Mandatory belt use laws have helped keep the head and torso inside the vehicle, but HFN injuries in side and rollover accidents persist. Regulatory actions for side and rollover protection deal with torso injuries but head injuries have been addressed only by upper interior padding.

Rollovers have been characterized as violent events and roof crush as the natural consequence of such violence. The original claims were based in part on the "Malibu" experiments, which suggested that head and neck injuries for occupants are unavoidable even with improved roof strength and the use of production restraints.

An analytical effort to understand rollover injuries, using the field accident data of the NASS files and residual headroom as an indicator, was reported by the authors at the 1996 ESV conference in Melbourne, Australia. This work led to a revised theory of rollover head, face and neck (HFN) injury mechanisms and their relationship to, for example, roof crush, headroom, restraint excursion, padding, glazing and vehicle geometry. In an effort to investigate both the original claims and the revised theory, some additional analyses were conducted and a series of experiments were devised.

This paper briefly summarizes the previous work, describes further analyses and experimentally identifies the low crash severity, roof crush, padding and restraint relationship to HFN injury, through physical, computer, and volunteer occupant tests.

The conclusion is that a causal relationship exists between HFN injury and occupant protection system design and performance (including, for example, roof intrusion, vehicle geometry, headroom, restraint excursion, glazing, upper interior padding in combination).

INTRODUCTION

During the sixties and early seventies, the Government and most manufacturers assumed that there was a causal relationship between roof crush, accident and HFN injury severity. [1 2 3]

From the early seventies (when less than 15% of the occupants were using belts), rollover accident investigation researchers confirmed a relationship between roof crush, accident impact severity and occupant HFN injury severity; however, the researchers were inconclusive about whether the injury was a result of the impact severity or the associated roof crush.

Mackay (1970): - [The increased injury associated with increased roof crush] "does not necessarily mean that the roof collapse was the immediate cause of the increased injury; it may be that large amounts of roof collapse are an indication of large collision forces which would have led to serious injury anyway." [4]

The studies of Huelke (1973) showed that, "although roof crush is not necessarily the injury-producing mechanism in rollover accidents, there is a correlation between the amount of roof crush and the severity of injury. This seemingly contradictory finding is explained by the fact that the amount of roof crush is indicative of the impact severity, but the two are not causally related." [5]

Moffatt, (1975) wrote, "If the occupant in these illustrations had suffered neck or head injury, one might be tempted to conclude that the damage caused the injury, and overlook the true mechanics which show that the impact caused the injury and the impact caused the damage, but it was not the damage which caused the injury." [6]

Melvin (1982) wrote "Thus a severe rollover event may produce a severe roof/ground contact, and a severe occupant/roof contact, with the result that both roof intrusion and occupant injuries have occurred but are not directly related." [7]

Strother and Warner then in 1984 carried the point one step further. They pointed out that in side and rollover accidents, it was the occupant's contact velocity with the intrusion that produced the injury, not the change in velocity as in restrained frontal impacts. [8]

In 1985 a summary of 8 unrestrained rollover tests with neck instrumented Hybrid III dummies were interpreted to show "... that roof strength is not an important factor in the mechanics of head/neck injuries in rollovers for unrestrained occupants." In 1990 a similar summary of restrained occupant rollovers and drop tests were published with similar conclusions. These studies are used to demonstrate the apparent violence of rollovers and describe the frequency and mechanism of catastrophic injury to the Hybrid III dummy neck and head in production and rollcaged 1983 Malibu cars. They suggest that such injuries are inevitable and that neither stronger roofs nor restraints will do any good. In 1995 police accident data (which mis-characterizes serious injury) was analyzed in an attempt to validate the experiments and suggest that the conclusions apply to human victims of rollover accidents.[9 10 11]

By reviewing the data on which the interpretation of results was based, the current authors published a series of papers from 1990 to 1995 refuting and casting doubt on the validity of those conclusions. In the process the authors studied the relationship between roof strength and accident severity, and the relationship between roof crush and uninjured, moderate and serious to fatal HFN injury accidents for restrained and unrestrained occupants.[12 13 14 15 16]

The Malibu experiments were also defended and challenged by cadaveric experiments with regard to the biofidelity of the Hybrid III neck for spinal trauma assessment.[17 18 19 20 21 22] Volunteer experiments indicate that the way the human head and neck is held and oriented during impact is quite different than the neck alignment provided by the Hybrid III dummy neck.

In 1995 NHTSA identified negative residual headroom with the use of production restraints as a significant indicator and cause of serious injury.[23]

In 1996 the authors, based on current NASS field accident data, demonstrated a causal relationship between roof crush and serious to fatal HFN injury for restrained occupants.[24] At the same time, Australian accident investigators at Monash University concluded that there is a causal relationship between roof crush and HFN injury, and NHTSA discussed their current research leading to petitioned revision in rollover testing.[25 26]

The authors and associates have recently completed and reported on a number of additional studies characterizing and quantifying the occupant protection factors leading to catastrophic injury in rollovers, including on-going volunteer drop testing.[27 28 29 30] Three additional volunteer drop test series are briefly described here, but separate papers are in preparation.

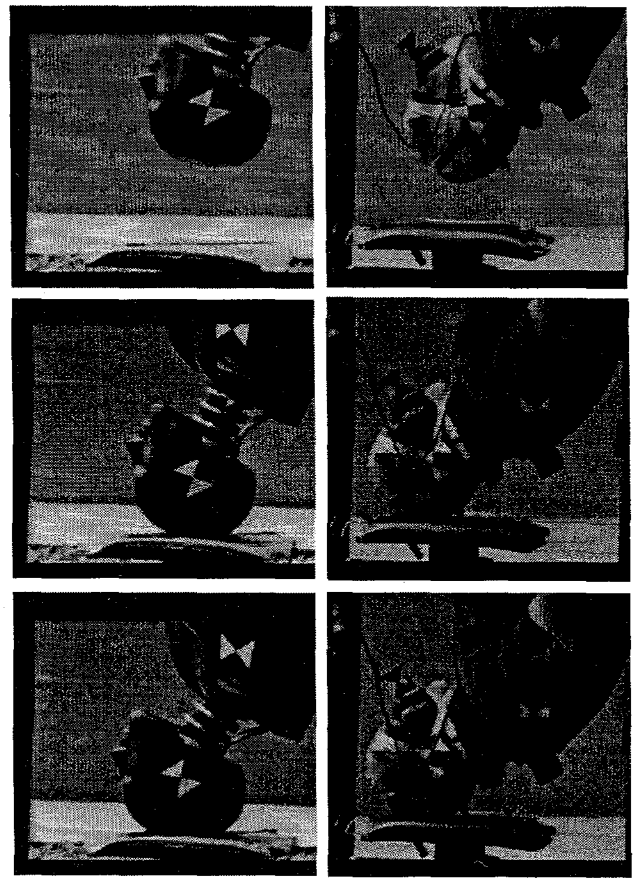
The objective of this paper is to integrate these latest human injury accident analyses, studies and experiments and supplement our previously published research into this causal relationship issue.

REVIEW OF RECENTLY PUBLISHED DATA

Malibu / Dummy Injury Causation

GM has recently released the Malibu[9 10] instrumentation traces and photographic analysis data. Using the data, the authors assert that rollover tests using the Hybrid III dummy are grossly flawed because injury measurements made on the dummy neck do not correlate with the forces that would be experienced by a human in the same circumstances. Perhaps more interesting, the dummy head would not have been near the roof, if the dummy had been positioned in accordance with the 208 positioning procedure. The Hybrid II and III dummies lack biofidelity for measuring HFN injury in rollovers where the acceleration loads are much lower than in frontal crashes. The measurements of neck compression injury taken from the dummy in those tests indicate neck injury at a rate more than two orders of magnitude greater than occurs in actual crashes. This alone calls into serious question the validity of injury measurement in these experiments.

Nonetheless, there are some useful comparisons between production and rollcaged vehicle driver data that can be made, circumventing the invalid neck data. For instance,if consistent with the field accident data, we assume that a human spine could easily absorb the 2000 newton PII's, but not the 4000 newton PII's, then there were nearly twice as many high energy contacts to unrestrained driver dummies in production vehicles than in rollcaged vehicles.



Furthermore, under a similar assumption there were one fifth as many high energy as low energy contacts to the restrained driver dummy overall, and five times as many in production vehicles than in rollcaged vehicles.

There were only two interior head injuries in 16 tests each involving three rolls and two dummies. That is about two in 96 opportunities, both of which occurred to unrestrained dummies.

There was only one flexion injury and that was to a restrained driver in a production car with the most roof crush at a low equivalent velocity.

Assuming a serious lateral neck flexion injury measure is similar to an extension injury measure, there were 10 such injuries to the driver dummy of production vehicle and none to rollcaged vehicle dummies.

For all 10 driver neck loads that were photographically analyzed, the A-pillar/roof rail touch down occurs typically 20 to 50 milliseconds after the neck compression loading peak, as recorded by the technician.

Rollover Injury Data

National Accident Sampling System (NASS) field accident data provides the best source of statistical injury data about real world accidents. A review of that published data shows the estimated number of rollover occupants (1,900,000) and those known to have had head or neck injuries (680,000) based on NASS data for the five year period from 1988 through 1992.[26] Each year about 140,000 (36%) of all occupants are known to have received head, face or neck injuries. Of all occupants in rollovers, more than 96+ percent (96+ %) were not coded as having a serious to fatal HFN injury. Two percent (2%) were coded as having received serious to fatal head or face injuries and one percent (1%) were coded as having received serious to fatal neck injuries. The distribution by restrained or unrestrained occupants is also described. [31] Our studies recognize that the NASS coding protocol requires that a broken neck be coded as an AIS 2 if it is not further specified. Hence those AIS 2 neck injuries in which there is cord damage, neck fracture or dislocation are included in the serious to fatal grouping.

Rollover Residual Headroom Data

NHTSA researchers concluded that there was a causal relationship between restrained HFN injury and "residual headroom," which is the difference between headroom before and after the rollover. The authors' study of "residual headroom" indicates that for unrestrained occupants with upper interior contact, there seems to be little difference (-3.3 to -5.3 cm) in negative residual headroom between minor (AIS 1-2) and severe (AIS 3-6) HFN injury.

For restrained occupants, however, the difference is dramatic. For head, face and neck injuries of AIS 2 or less, the average residual headroom is around plus 3cm (+1 in). For more serious injuries, the average residual headroom is minus 13 cm. (-5 in).

Physically Validated Computer Simulations of Vehicle Rollovers, Rollover Accident Reconstruction and Drop Tests

Using this methodology we consider the relationship between accident impact severity and roof crush and identify the impact velocities which produce the intrusion. [32] The study indicates that 3 to 7 kph (2 to 4mph) is a reasonable estimate of the impact velocities to produce about 150mm (6 in) of roof crush for many on-the-road cars and light trucks from 1988 to 1992. It is also clear that most production vehicle roofs will collapse to the window sill at 10.8 kph (6.7 mph).

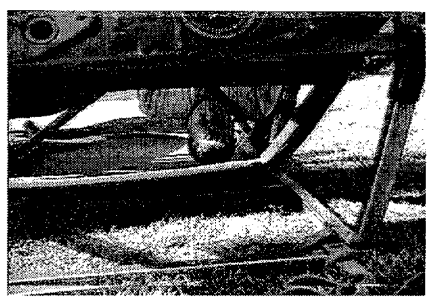
Volunteer Neck Injury Testing

Five series of volunteer tests have been conducted.

(1) The first series was in a roll fixture with a pre-depressed (no headroom) roof in which the restrained subject/author with 75 mm of restraint excursion was repeatedly inverted at 2 radians per second without discomfort.[32]

(2) The second series had the subject inverted and suspended by a lap belt in a drop fixture, with the head and neck in a pre-flexed (aligned) orientation touching the roof. The fixture was then pivoted upward and repeatedly dropped from 50 to 150 mm to a concrete floor without discomfort.

(3) The third series had the authors inverted and suspended by the production door mounted restraint (and a safety lap belt) with their heads near or just touching the non-intruding roof of a 1993 Sunbird compartment, which was then dropped to hardpacked earth from about 225 mm, 500 mm and 925 mm, without discomfort.



(4) The fourth series with high speed cameras, was conducted by dropping a fully instrumented Hybrid III dummy on its head to an instrumented plate, while restrained by a safety belt on an inverted controlled excursion seat in a drop fixture from 50 mm and 175 mm. The dummy neck compression loads exceeded the Malibu potentially injurious impact criteria. The tests were then repeated with an instrumented author/subject who was uninjured. The results were then compared.

(5) The fifth series also with high speed cameras, was conducted by simultaneously dropping from 300 mm to hardpacked earth, a fully instrumented Hybrid III dummy and a similarly sized author/subject, while they were restrained only by the production belts with their heads just touching the rigidized roof of a 1981 Malibu compartment. The dummy instrumentation recorded catastrophic neck injury while the 71 year old author/subject was uninjured.

HUMAN ROLLOVER INJURY CAUSATION

One aspect and perhaps the crux of the causal issue is whether such low severity rollover impacts generally cause severe HFN injuries as claimed by some researchers? [9,10] A second is, given such low severity impacts, can the occupant protection system do something about it?

The answer to the former question from the frequency and distribution of rollover head, face and neck injuries is NO! The answer to the latter question is yes. In investigated rollovers, 96% of the occupants are not coded as HFN seriously injured. Rollover occupant protection systems in which the elements are compatibly designed to prevent injurious contact are clearly available.

The answer to the former question from the residual headroom analysis is NO! The answer to the latter question is yes. The residual headroom analysis clearly shows that the injury probability for restrained occupants increases with reduction in residual headroom. The implication is that the elements of the rollover occupant protection system must be compatible in order to protect restrained occupants. Unrestrained occupant's injuries are preventable through the use of improved occupant protection system design.

On the basis of the five series of volunteer drop tests from as high as 925 mm (but without significant roof crush), the answer to the former question is NO and the latter is yes!

A fourth No answer to the former question and a yes to the latter question, resulted from analysis of the NASS files for restrained occupants and average roof crush. The table below confirms that the average roof crush for serious to fatal restrained head, face and neck injuries is greater than for those with lesser HFN injury.

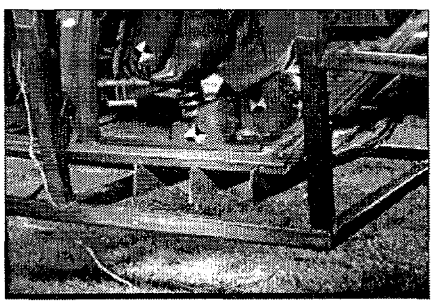
Restrained Occupant Injuries	Average Roof Crush		Average Impact Velocity	
	cm	in	kph	mph
None	4.67	1.84	3.0	1.9
No Head, Face, or Neck	6.12	2.41	3.5	2.2
Head, Face and Neck @ AIS 1-2	9.80	3.86	4.5	2.8
Neck @ AIS 2-6	18.38	7.24	6.5	4.0
Head and Face @ AIS 3-6	26.69	10.51	8.5	5.3

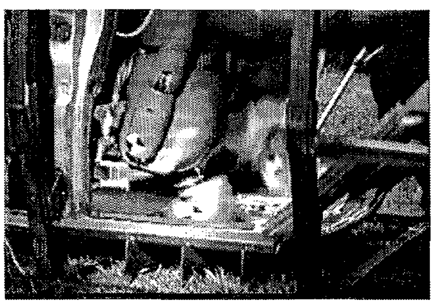
HUMAN VOLUNTEER INJURY MECHANISM DEMONSTRATIONS

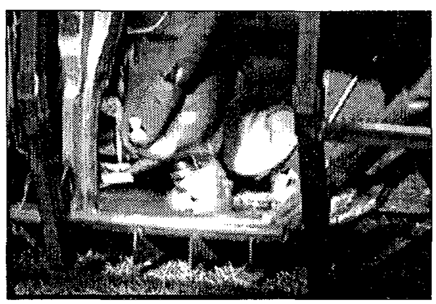
While those analyses establish that rollover roof impacts are not violent or severe events and that the impact velocities are low, we have developed a basis for explaining why, and demonstrating that the risk of neck injury is reduced with limited roof crush and or reduced belt excursion.

The first series of human volunteer [32] experiments were conducted to illustrate alternative rollover roof crush HFN injury mechanisms in a spit test device. The volunteer is restrained in a spit test machine which is pitched and can be rotated. The machine has a complex pivoted roof structure which can intrude while displacing laterally, intrude while displacing forward and backward, and intrude along a longitudinal crease over the occupant's head from a single sided lateral displacement.

The machine has been used to demonstrate the static energy absorbing, flexing capabilities of the spine with 10 cm (4 in) of roof intrusion without volunteer HFN injury. Those results have recently been extended to demonstrate 14cm (5.5 inches) of intrusion without injury. At the same time it becomes obvious that production restraints are effective in compensating for roof crush. Serious head or face injury is







demonstrated as unlikely as is neck injury, unless the roof and/or the restraint prevents the head, neck and spine from flexing.

A second demonstration mode is the mostly lateral dynamic impact and roof rail displacement with roof panel buckling. Here the roof rail scrubs the ground stopping momentarily from the traveling velocity and a roof buckle is formed and intrudes at twice the speed or more. Serious head and/or face injury is likely unless the roof rail and roof are padded. Similarly, neck or thoracic injury is likely depending on the depth of the buckling roof panel and particularly if the roof keeps the head, neck and spine from flexing.

A third demonstration mode is an impact which results in some roof crush and a rapid change in the rotational velocity. Serious head and/or face injury is likely unless the roof rail and roof are padded; however, neck injury is unlikely.

A fourth demonstration mode is the restrained volunteer dynamic drop tests in a non crushing roof compartment, with and without the head in contact with the roof. These tests correspond to the dummy drop tests conducted in conjunction with the 1985 Malibu paper but not published until 1990. They also correspond to a number of biomechanical drop test studies of unconstrained cadavers and documented studies of head/spinal impacts in sporting events with injurious and non injurious results.

HFN INJURY ROLLOVERS

The following observations provide a foundation for understanding HFN injuries in rollovers:

Most rollovers involve a number of short, low velocity impacts which incrementally scrub off the initial horizontal trip speed and support the rolling vehicle vertically. Occupant contact with the interior of a vehicle as it rolls are also typically benign. As a consequence, the vast majority of occupants in rollovers are HFN uninjured or receive only minor to moderate HFN injury.

The human skull can withstand most such impacts that occur in rollovers without major HFN injury. The remainder of the body—particularly the neck and torso—are highly flexible and resilient. Thus, they can accommodate most of the contact forces and even some intrusion in a rollover.

Rollover tests using Hybrid II and III dummies produce misleading results due to the lack of biofidelity in the flexibility of the dummies' neck and torso.

There are two primary mechanisms of HFN injury to restrained occupants from rollover, and they occur relatively independently of each other.

- Severe head injuries typically occur in rollovers where the head strikes either a rigid part of the interior (such as an unpadded roof rail) or a rigid surface outside the vehicle (such as the road) where the relative speed between the head and the roof or the road is relatively high (6 to 12 ms). This occurs in the interior as a result of roof contact causing lateral intrusion and an abrupt change in roll rate.

- Severe neck compression-flexion injuries typically occur in rollovers in which there is a substantial and rapid reduction in headroom. However, the head, neck and torso, considered as a unit, can flex and foreshorten while absorbing energy. Exceeding the spine's tolerance for such energy absorption may result in injury to the neck—the most vulnerable component of this unit—as it is bent beyond its limits. The bone and ligament structure of the neck is mechanically damaged and consequently can damage the spinal cord.

Rollovers are not inherently violent crashes: that is, the forces generated by most rollovers are within human tolerance limits. Relatively minor modifications to vehicles could substantially reduce the probability of these types of injuries to restrained occupants in rollovers.

THE EFFECT OF THESE STUDIES

Roof to ground contacts in rollovers are foreseeable but not violent events, to a restrained occupant as measured by roof strength, intrusion and/or deformation. Restrained occupant interior contacts in rollovers are in general so low in speed, and so low in force on the head, neck or torso, that the natural compliance of the body resists injury. Catastrophic injury only occurs when the occupant protection system design and/or one of its elements allow excessive interaction between vulnerable body parts and the interior.

Based on these experiments and analyses the claim that catastrophic injury for restrained occupants is the result of diving or torso augmentation and that roof strength or restraint excursion doesn't matter appears to be invalid.

CONCLUSIONS

There is a clear causal relationship between HFN injury and the design and performance of the rollover occupant protection system (including roof crush, vehicle geometry, headroom, restraint excursion, retained side glazing and padding functioning in combination).

REFERENCES

[1] *GM's Comments in Response to NPRM Roof Intrusion Standards (FMVSS 216), 1971.*

[2] *Ford Experimental Safety Vehicle, Final Report 1972, Contract No. DOT-OS-20005.*

[3] *GM Experimental Safety Vehicle, Final Report - 1972, Contract No. DOT-OS-00095.*

[4] *Mackay G.M. and Tampen, I.D., Field Studies of Rollover Performance, 1970.*

[5] *Huelke D.F., Injury Causation in Rollover Accidents, 1973.*

[6] *Moffatt E.A., "Occupant Motion in Rollover Collisions," 1975.*

[7] *Melvin, J.W., Discussion of SAE 820244, Crash Protection, SAE SP-513, 1982.*

[8] *Strother and Warner, "Injury and Intrusion in Side Impacts and Rollovers," SAE 840403, 1984.*

[9] *Orlowski K.F., Bundorf R.T., Moffatt T., and Edward A., "Rollover Crash Tests - The Influence of Roof Strength on Injury Mechanics," SAE 851734, 1985.*

[10] *Bahling G.S., Bundorf R.T., Kaspzyk G.S., Moffatt E.A., Orlowski K.F., and Stocke J.E., "Rollover and Drop Tests -- The Influence of Roof Strength on Injury Mechanics Using Belted Dummies," SAE 902314, 1990.*

[11] *Moffatt E.A. and Padmanaban J., "The Relationship Between Vehicle Roof Strength and Occupant Injury in Rollover Crash Data," October 18, 1995.*

[12] *Friedman D. and Friedman K., "Roof Collapse and the Risk of Severe Head and Neck Injury," 13th Experimental Safety Vehicle Conference, 1991.*

[13] *Friedman D., "Mitigation of Head and Neck Trauma," ASME Biomechanics of Trauma Conference, 1993.*

[14] *Friedman D, et al., "Enhanced Safety for Light Trucks and Vans," 14th Enhanced Safety Vehicle Conference, 94-S10-W-24, May 1994.*

[15] *Friedman D. and Friedman K., "The Causal Relationship in Rollover Accidents Between Vehicle Geometry, Intrusion, Padding, Restraints and Head and Neck Injury," Submitted in support of Comments to NHTSA Rollover Prevention Docket No. 91-63; Notice 03, August 16, 1994.*

[16] *Friedman D, Light Truck and Van (LTV) Rollover Safety, Appendix C attached to comments to Docket No. 91-68; Notice 03, re Rollover Prevention, August 16, 1994.*

[17] *Yoganandan N., Sances A., Maiman D., "Spinal Injuries with Vertical Impact, Mechanisms of Head and Spine Trauma," Aloray Publisher, Goshen, New York, 1986.*

[18] *Pintar, Yoganandan, Sances, Reinartz, Harris and Larson, "Kinematic and Anatomical Analysis of the Human Cervical Spinal Column Under Axial Loading," SAE 892436, 1989.*

[19] *Yoganandan N., Maiman D., Pintar FA, Sances A., "Cervical Spine Injuries from Motor Vehicle Accidents", J. Clin Eng 1990*

[20] *Nightingale R, McElhaney J, et al. The Dynamic Response of the Cervical Spine: Buckling, End Conditions and Tolerance in Compressive Impacts, SAE 973344..*

[21] *Sances A Jr., Voo LM: Biofidelity of the Hybrid III Neck for Spinal Trauma Assessment, ASME Adv. Bioeng, 1997.*

[22] *Syson S.R., "Occupant to Roof Contact: Rollovers and Drop Tests," SAE 950654, 1995.*

[23] *Glen C. Rains and Joseph N. Kanianthra, "Determination of the Significance of Roof Crush on Head and Neck Injury to Passenger Vehicle Occupants in Rollover Crashes," SAE 950655, Detroit, Michigan, February 27-March 2, 1995.*

[24] *Friedman K., et al., "Improved Vehicle Design for the Prevention of Severe Head and Neck Injuries to Restrained Occupants in Rollover Accidents," Paper Number 96-S5-O-14, ESV Conference, Melbourne, Australia, 1996.*

[25] *Rechnitzer G. and Lane J., "Rollover Crash Study — Vehicle Design and Occupant Injuries," published as a Monash Univ. report 1994, and at the 15th Technical Conference on Enhanced Safety of Vehicles, May 17, 1996.*

[26] *Summers S., Rains G.C., Wilke D.T., "Current Research in Rollover and Occupant Retention," 15th Technical Conference on Enhanced Safety of Vehicles, May 17, 1996.*

[27] *Meyer, Steven E., "The Effects of Pretensioning of 3-point Safety Belts on Occupants in Rollover Crashes," National Association of Forensic Engineers, 1997.*

[28] *Herbst, et al., "Strength Improvements to Automotive Roof Components," SAE 980209..*

[29] *Friedman, K., "Vehicle Structural Design Utilizing Optimized Finite Element Modeling," SAE 981013.*

[30] *Friedman, D., "Human Subject Experiments in Occupant Response to Rollover with Reduced Headroom," SAE 980212.*

[31] *Friedman, D., "Roof Crush Versus Occupant Injury from 1988 to 1992 NASS," SAE 980210.*

[32] *Friedman, D., "The Relationship Between Vertical Velocity and Roof Crush in Rollover Crashes," SAE 980211.*