WHAT NASS ROLLOVER CASES TELL US

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ABSTRACT

This research provides new insight into the nature, causes and costs of rollover casualties; and the economic benefits of basic countermeasures. The National Accident Sampling System (NASS) is a rich source of data on motor vehicle crashes, particularly if one goes beyond the electronic files. In this work, the author reviewed every NASS case from 2002 through 2004 in which a passenger car, SUV, pickup, or minivan that was less than eleven years old rolled over and produced an AIS 3+ injury (more than 500 cases). From this, we developed a useful new classification for these crashes with AIS 3+ injury: (1) cases with complete ejections, (2) cases in which there was a head or neck injury from roof crush, (3) other rollovers in which the rollover was the most harmful event, (4) cases in which a collision before the rollover was the most harmful event, and (5) cases in which a collision or major change in elevation during the rollover was the most harmful event. We used the NHTSA "Economic Impact of Motor Vehicle Crashes" and the weighting factor for the crashes to determine the total cost of all of these crash injuries. We then estimated the effectiveness of three simple countermeasures – a strong roof, side window glazing that does not break out during the rollover, and an effective belt use reminder – in reducing the severity and cost of these injuries. The results were most dramatic for SUVs where the discounted potential savings were on the order of several thousand dollars per vehicle over its lifetime. Even for passenger cars, the savings would easily justify the cost of these countermeasures. This work demonstrates the high degree of benefit that would far outweigh the cost of the countermeasures even if the affected vehicles were equipped with electronic stability systems.

NASS ROLLOVER FILES

The National Accident Sampling System (NASS) [1], initiated by the National Highway Traffic Safety Administration (NHTSA) more than 25 years ago, is a rich source of data on motor vehicle crashes. Most analysts use only its electronic files and therefore miss the value that is contained in the crash descriptions, scene diagrams, and photographs of the vehicles and scenes that are in the NASS files.
For this work, we examined the details of more than 500 case files from accident years 2002-2004 to determine the critical conditions of rollover crashes. Based on that data, we estimated the effectiveness of countermeasures that are designed to reduce casualties in rollovers.

Specifically, we looked at *all* 2002-2004 NASS rollover cases involving passenger cars, utility vehicles (SUVs), pickups, and minivans that were ten years old or less in which there was at least an AIS 3 injury to an occupant of the vehicle that rolled over. NASS is currently between one fourth and one third of its original design size and rollover cases typically have more serious consequences than other types of crashes. Thus, we assumed that we would get reasonably representative results by combining three years of recent data.

Each rollover vehicle *occupant* who sustained an AIS 3+ injury was considered as a unit for this work. There were more than one such occupants in relatively few rollovers, and in most of those, it was because at least one of the occupants was ejected or there was a major impact either before or during the rollover. In fewer than 2 percent of all cases did we find more than one occupant who sustained an AIS 3+ injury who remained completely in the vehicle.

CLASSES OF ROLLOVERS

In looking at the NASS cases, a natural classification of rollovers suggested itself for quantitative study. We found that the traditional taxonomies were of little use in analyzing rollover injuries. The number of rolls is a valid measure of severity only in the sense that each vehicle roof impact offers additional opportunity to damage a weak roof or to eject an occupant through a failed window. The inherent forces in each roll are low regardless of the number of rolls. The classification of initiation of the rollover (trip over, flip over, climb over, bounce over, etc.) are poorly defined, often incorrectly coded, and of little practical use. Thus, we divided the rollovers into the following classes:

1. Cases where the rollover was the most serious event and an occupant with AIS 3+ injuries was unbelted and ejected.

2. Cases where the rollover was the most serious event and where any occupants were belted and received at least an AIS 3 injury to the head or spinal column.

3. All other cases where the rollover was the most serious event and an occupant had an AIS 3+ injury.

A subclass of these cases are cases where the rollover was the most serious event and where any occupant was belted and received at least an AIS 3 arm or hand injury (the maximum AIS coding for an upper extremity injury) that was due to a partial ejection of the hand or arm.

4. Cases where an initial collision was the most serious event (and the one that probably caused the most serious injury) but where there was subsequent rollover.

A subclass of this group includes cases where there were serious collisions both before and during the rollover.

5. Cases where a rollover was the initial event, but where the most serious event was a collision or a substantial change in elevation as the vehicle was rolling over (where the collision probably caused the most serious injury).

There was one case (NASS 2002-75-110) where 5 people riding in the bed of a pickup each received at least AIS 3 injuries (one was a fatal) when the pickup rolled over. We did not include this case in the analysis.

The justification for this classification is not only that rollover crashes divide into roughly equal sets among, at least for passenger cars, but that each class suggests a unique set of countermeasures as will be discussed later.

ECONOMIC CONSEQUENCES OF INJURIES: A HARM METRIC

Next, using the NHTSA estimates of the economic consequences of injury, we assigned a dollar value to each of the injuries. These values are shown in Table 1. They were determined by taking the direct economic cost of injuries to specific body areas from Appendix H in the NHTSA report, *the Economic Impact of Motor Vehicle Crashes 2000*, [2] multiplying the results by the factors in Appendix A for injury severity in that report to get the specific economic consequences. These results were updated for inflation by multiplying by a factor of 1.15 (roughly 3 percent inflation per year).

Figure 1. An example of a Class 4 NASS case where an initial collision (with a large tree) was the most serious event.

These are the essentially values that NHTSA would use in assessing the economic consequences of new motor vehicle safety standards. They include the actual medical costs associated with the injury,[3] the lost wages, and intangible consequences of injury and death which were determined from studies of people's "willingness to pay" to avoid injury or death based on "wages for high-risk occupations and purchases of safety improvement products."

CASES STUDIED

We studied all rollovers involving passenger cars, SUVs (utility vehicles), pickups, and minivans that were less than 11 years old. That is, for accident year

2004 we included all vehicles of model year 1995 and later that rolled over and had an AIS 3 or greater injury to an occupant. Each unit of study was an occupant who received an injury of AIS 3 or greater or who died as a consequence of the accident. A very substantial majority of these were front seat occupants.

Virtually all occupants who received such AIS 3 or greater injuries who were not in front seats were not restrained. Once the cases were identified, they were classified as noted above. Because of the limitations on vehicles and injuries, our data underestimates the total harm in rollovers by a factor of 1.5 to 2. We will attempt to better quantify the total harm from rollovers in follow-up work.

Figure 2. An example of a Class 5 NASS case where a collision (with a large tree) during a rollover was the most serious event.

HARM IN ROLLOVERS

Because of their total number, the largest total cost is from passenger car rollovers. However, the highest cost per registered vehicle, by a substantial margin, is for SUVs. Their comprehensive cost for AIS 3+ injuries in rollovers is nearly three times as high as for passenger cars. Pickups have about twice the comprehensive cost of passenger cars.

By dollar volume of harm, the largest numbers by far were in Class 1 rollovers of SUVs. This is partly because of the higher rollover rates of these vehicles and the lower safety belt use in them, but those factors do not fully account for the excessive ejections.

Light trucks are also overrepresented in cases where a rollover is a secondary consequence of a serious collision (class 4 rollovers). This suggests that loss of control is a greater problem for light trucks than for passenger cars. Since the rollovers in these cases were almost incidental, for this class of crashes the traditional countermeasures applied to frontal and side crashes are much more likely to be effective. The same is not necessarily true for Class 5 crashes since a significantly stronger occupant compartment and roof will help to reduce roof crush and injuries in these cases.

It is interesting to compare the proportional relations among the five classes of rollovers for specific vehicle types. For example, because of the high cost of head and cervical spine injuries, Class 2 rollovers have a proportionally larger economic impact.

These data show that *each new* SUV comes loaded with an average of at least $3,500 in discounted economic consequence costs for the rollovers they will have during their lifetime. For pickups, the added liability is at least $2,200 and for passenger cars and minivans it is at least $1,200 and $1,700 respectively.

Few if any purchasers of these vehicles are aware of this liability when they purchase a new vehicle. Furthermore, because first and third party auto insurance together pay only a trivial part of the cost of the most serious injuries and fatalities, fewer still are aware that they will bear most of these costs either directly or through non-automobile insurance systems if they are actually seriously injured in a rollover.[4] In fact, Medicaid picks up a significant part of these costs and families themselves must suffer the lost income (and the consequently reduced standard of living) and the extra personal services that are a major consequence of AIS 3+ injuries to a family member.

Table 1. Cost of injury by severity level and body part from *The Economic Impact of Motor Vehicle Crashes 2000.*

AIS	Body Part	Cost		AIS	Body Part	Cost
1	SCI	N.A.		4	SCI	$7,296,260
	Brain	$124,459			Brain	2,939,047
	Lower Extremity	13,820			Lower Extremity	1,161,530
	Upper Extremity	5,548			Upper Extremity	N.A.
	Trunk, Abdomen	10,133			Trunk, Abdomen	480,459
	Face, Head, Neck	9,734			Face, Head, Neck	869,853
2	SCI	N.A.		5	SCI	$10,210,387
	Brain	$686,992			Brain	6,826,032
	Lower Extremity	277,275			Lower Extremity	2,056,783
	Upper Extremity	117,739			Upper Extremity	N.A.
	Trunk, Abdomen	204,573			Trunk, Abdomen	860,798
	Face, Head, Neck	144,749			Face, Head, Neck	1,805,288
3	SCI	$1,506,961		6	All	$ 3,623,787
	Brain	1,306,647				
	Lower Extremity	530,725				
	Upper Extremity	235,160				
	Trunk, Abdomen	266,856				
	Face, Head, Neck	325,650				

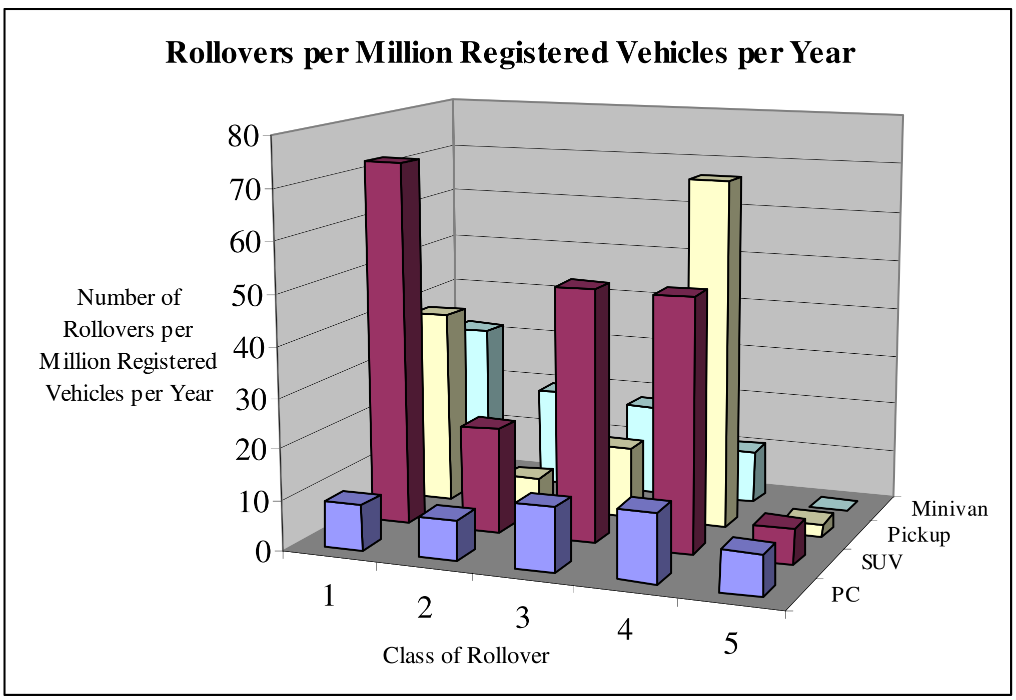

Figure 3. Estimated annual number of rollovers with AIS 3+ injuries by class and vehicle type.

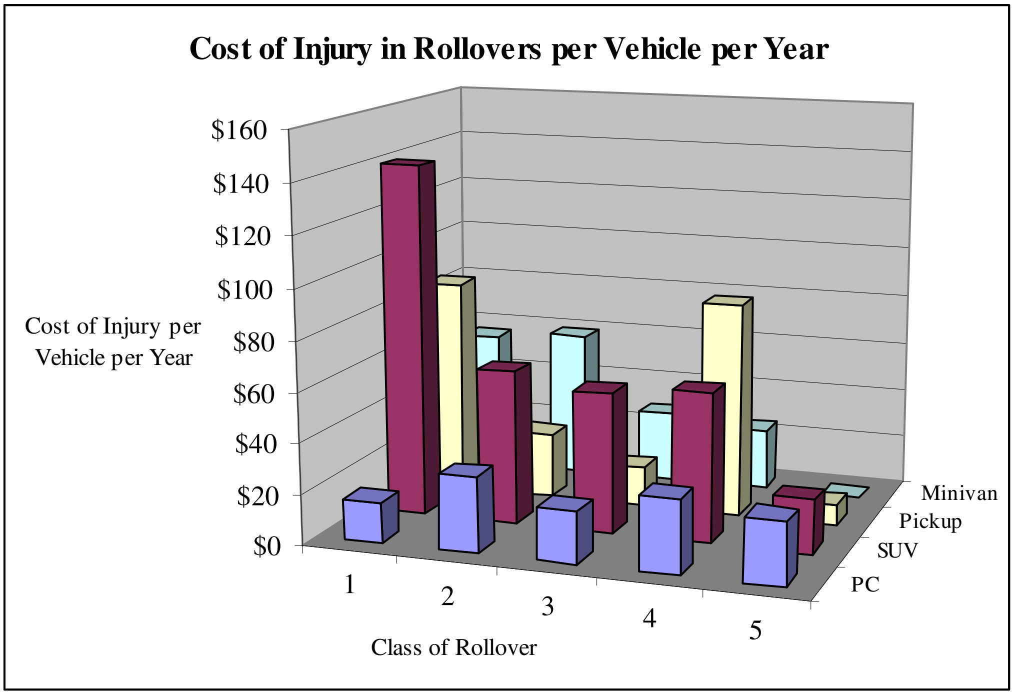

Figure 4. Cost of injury per registered vehicle by type of vehicle and type of injury.

The results of this investigation are shown in Figures 3 and 4. These graphics clearly shows the dramatic difference between passenger cars on one hand, and light trucks on the other. The total annual economic consequence of Annual AIS 3+ injuries in light vehicles in the first ten years of operation is approximately $36 billion. [5]

Figures 3 and 4 show that the spectrum of passenger car rollovers is quite different than the spectrum of SUV and pickup rollovers. The minivan figures are not as reliable because of the small number of minivan cases in the study (in the three years studied, there were only 20 rollovers involving 45 occupants with AIS 3+ injuries). It is nevertheless clear that as a class, minivans have rollover harm that is higher, per vehicle, than for passenger cars. Part of the reason for the relatively low rate of rollover harm in minivans is the demographics of those who own and use them (they are often the family station wagon for people who do not need the personal image from driving an SUV), not that they are inherently particularly safe in rollovers.

- About forty-five percent of passenger car and pickup truck rollover harm is either preceded by a collision that is the most serious event, or involve a collision or other complication during the rollover that is the most serious event (Class 4 and 5 rollovers). For SUVs, only a quarter of the rollovers met those conditions.

This result strongly suggests that about one-third of the harm attributed to rollovers should be reconsidered from the standpoint of appropriate countermeasures. That is, for cases with major collisions before or during a rollover, the traditional assumption that rollover casualties come primarily from ejection that is a consequence of the rollover or from roof crush (the justifications for the dolly rollover test in FMVSS 208 and for the roof crush requirements of FMVSS 216) should be reconsidered. However, it should be noted that some countermeasures – particularly occupant restraint – protect occupants in both circumstances.

- By far the greatest disparity is in complete ejections of occupants in rollovers. The rate of such rollover ejections where the rollover is the most serious event is nearly nine times as high in SUVs, and five times as high in pickups as in passenger cars.

This dramatic difference comes partly from the much higher rollover rates and lower belt use rates in light trucks but those factors do not completely explain the difference. The only other major factor that might account for the higher unrestrained occupant ejection rates is the larger side window openings in SUVs and pickups. It is clear that SUVs and pickups in particular should be a major target of further research and programs to reduce ejection.

The NASS photographs reviewed for this study showed that the roofs in most contemporary vehicles crush extensively in a majority of rollovers where there are serious to fatal injuries. While it is clear that an occupant is safer in a rollover with a safety belt than without, public policy that increases belt use without addressing the problem of roof crush would be irresponsible (see comments below and reference #7). This situation would be analogous to ignoring the unintended injuries that were inflicted by the first generation of air bags.

- Rollovers where a restrained occupant receives an AIS 3+ head or neck (cervical spine) injury are common in all vehicle types but are about twice as high in SUVs and minivans as in passenger cars and pickups.

This finding strongly suggests that a major increase in roof strength would have a substantial benefit in reducing these injuries to people who are taking the responsibility of wearing the available lap and shoulder belts.

RESTRAINT USE

The major disparity in complete ejections between passenger cars and light trucks initially suggested that belt use in the latter was much lower than in the former, and figure 2 confirmed that suspicion. One might expect that when looked at from the standpoint of the proportion restrained by the economic consequences of the injury, only SUVs and pickups show a significant difference which probably results in the exceptional ejection rate in these light trucks.

ROLLOVER COUNTERMEASURES

Next, we looked at the potential savings from obvious, well tested, inexpensive and effective rollover occupant protection countermeasures. The primary countermeasures we considered were the following:

1. Safety belt use which could be substantially increased by installation of a highly effective safety belt use reminder.[6] (Most critical for classes 1,3 and 4)

2. Side windows that do no fail in rollovers (such as laminated glass that is retained in its opening so that even if it breaks it continues to provide a barrier to ejection – see Figure 5). (Class 1)

3. A strong roof that is resistant to crushing during a rollover (such as has been demonstrated by the Volvo XC90 – see Figure 6). A strong roof is important not only to reduce direct injuries from roof crush, but for the protection of side windows and to ensure proper safety belt performance (upper anchorage stability). (Classes 1,2,3 and 5)

Table 2. Restraint use among occupants with AIS 3+ injuries from light vehicle rollovers.

	Belted	Not Belted	Unknown Belt Use
Passenger Car	52%	46%	2%
SUV	30%	61%	9%
Pickup	27%	70%	3%

Table 4. Proportion of harm in rollovers where there was at least one AIS 3+ injury by belt use.

	Belted	Not Belted	Unknown Belt Use
Passenger Car	46%	48%	6%
SUV	43%	49%	8%
Pickup	26%	70%	4%

The secondary countermeasures were:

4. Padding in the head impact area as now required by amendments to FMVSS 201. (Class 2 and 3)

5. Improving safety belt performance. Safety belts are notorious for developing excessive slack in rollovers and many belts have rather poor geometry to hold occupants effectively in rollovers. The best solution would probably be a seat mounted safety belt with a rollover-triggered pretensioner. However, less expensive approaches, such as cinching latch plates that keep lap belts snug or a time delay on the retractor lockup, would have some benefit. (Class 2)

6. Changes to interior design (particularly in the door and foot well areas) to reduce torso and limb injuries from contact with the interior. (Class 3 and 4)

In addition to these elements, two advanced technologies that are currently being commercialized are:

7. Electronic stability systems that will primarily reduce the probability of some of the Class 1, 2, and 3 rollovers. These systems generally reduce oversteer in vehicles so that even though the driver cannot fully control a vehicle, at least it will not yaw so that a rollover is likely. (Classes 1, 2, 3 and 5)

8. Rollover-triggered side curtain air bags. These systems deploy as a vehicle begins to roll (triggered by a combination of the roll angle of the vehicle and its roll rate) and cover the window openings so that the potential for ejection is substantially reduced. (Class 1, 3, 4 and 5)

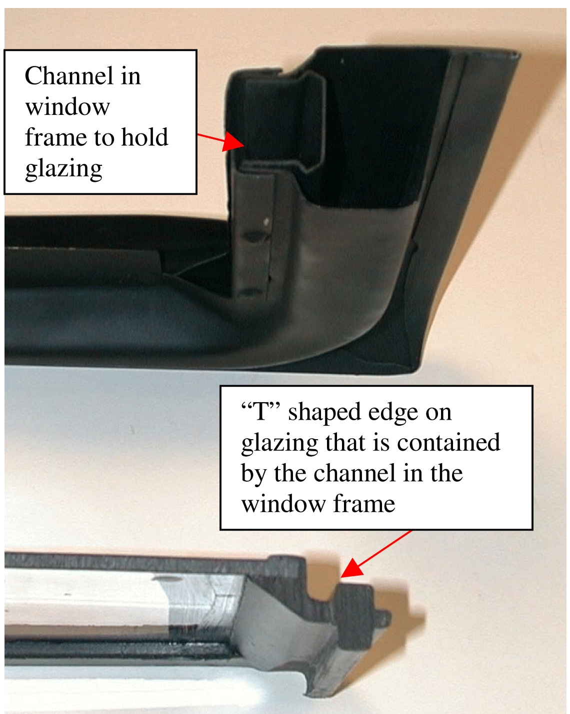

Figure 5. Side window glazing designed with channels and tracks for ejection mitigation.

It is important to note that the effectiveness of these elements may be interrelated. For example, as was pointed out by a Ford engineer in the late 1960s, "It is obvious that occupants that are restrained in upright positions are more susceptible to injury from a collapsing roof than unrestrained occupants who are free to tumble about the interior of the vehicle. It seems unjust to penalize people wearing effective restraint systems by exposing them to more severe rollover injuries than they might expect with no restraints."[7] It is also the case that even window glazing that is designed to reduce ejection will do so only if the window openings and frames are reasonably protected from distortion by a strong roof. Conversely, if the roof does not significantly distort in a rollover, it can generally protect even tempered side glazing.

Occupant ejection could be reasonably addressed by either substantially increased belt use, the use of side window glazing that will contain occupants, or rollover-triggered window curtain air bags. Belt use is the most cost-effective means, but it would not fully address partial ejections. On the other hand, belt use has major benefit in virtually all other crash modes.

Figure 6. A Volvo XC90 with a strong roof after a rollover (NASS Case 2003-79-57).

The cost and weight of the three primary countermeasures would be modest:

- Effective safety belt use reminders would add less than $25 to the retail cost of a vehicle. The added weight would be trivial.

An effective belt use reminder must go well beyond the Ford Belt Minder® system which was shown to raise belt use rates by only about 5 percentage points.[8] Effective systems have been developed in Europe and are recognized there in the European New Car Assessment Program. Highly effective belt use reminders might come about without regulatory pressure if insurance companies worked with auto makers by offering significant medical payment insurance discounts for vehicles that were equipped with them. Such discounts could easily offset the original cost of these systems.

Although belt use is critical to reducing injuries in rollovers, it must be accompanied by other countermeasures.

- Front side glazing that retains occupants (laminated glass with edge holding systems) would, according to NHTSA, have added approximately $50 to the retail price of a vehicle in 1997. Inflation would increase this to less than $65 today.

The cost-effectiveness of this technology would be greatest if it were used only in the front doors because by far the majority of occupants are ejected through these windows. If advanced glazing were used in all side windows, it would increase the retail price of a vehicle by about $140 per vehicle on average. The agency estimated that there would be no weight penalty for any of the alternative side window materials.[9] [10] We have used a compromise figure of $100 as the average increase in the retail price per vehicle for ejection control glazing.

This technology is fully developed and available for production. In its simplest form, it consists of laminated glass that has “T” shaped material glued on to the side edges that fit into channels such that the glass can move up and down, but even if the glass is broken, it cannot pull out of the channels (see Figure 5). NHTSA conducted extensive research into this product in the 1990s. The effectiveness of this countermeasure depends on the vehicle having a strong roof so that the window opening is not substantially distorted from roof impacts.

NHTSA has estimated that the effectiveness of advanced ejection-mitigating glazing in reducing rollover ejection injuries is in excess of 80 percent. It noted that the benefit would be particularly high for light trucks.[11] The 2005 Transportation legislation [12] requires that NTHSA specifically address the problem of occupant ejection.

- A strong roof would, on average, cost less than $100/vehicle.

Research has shown that the addition of well under than 100 pounds of structural material can be added to an existing vehicle to ensure very good roof crush resistance – well beyond that called for even in NHTSA’s proposed amendment to FMVSS 216. The use of high strength steels and plastic inserts at buckling points would ensure only minor weight increase for an adequately strong roof. [14] If a roof is designed to provide a high level of crush resistance in the first place, the added material and cost would be substantially less than 100 pounds and $100. Volvo has demonstrated the mass production practicability of strong roof construction.

Electronic stability systems and rollover-triggered side curtain air bags each has the potential to substantially reduce rollover casualties, but their cost in full production is substantially higher than the cost of the three basic countermeasures. Their benefit was not estimated in this work. The added retail cost of either of these technologies has been estimated to be around $250 in large scale production. The extra cost of rollover triggering of side curtain air bags that are already in a vehicle would be $25 to $50. The cost of electronic stability systems assumes that the vehicle already has anti-lock brakes.

BENEFITS OF ROLLOVER COUNTERMEASURES

The effectiveness of each primary countermeasure was assessed against the specific conditions of the crash. In no case was it assumed that the effectiveness would be above 80 percent because of uncertainties about the cases and outcomes and the fact that there might be residual, although less serious injuries even with the countermeasures. However, where there was a complete ejection in an otherwise simple rollover (without complications such as significant collisions or major changes in elevation during the rollover) it was assumed that the combination of a strong safety belt use reminder and retained side window glazing would have an 80 percent effectiveness in reducing the injury below the AIS 3 level, conservatively based on the NHTSA estimate, for example. Thus, the benefits of safety belt use and improved side glazing was high for the first class of rollovers. The benefits of a strong roof were major for the second class.

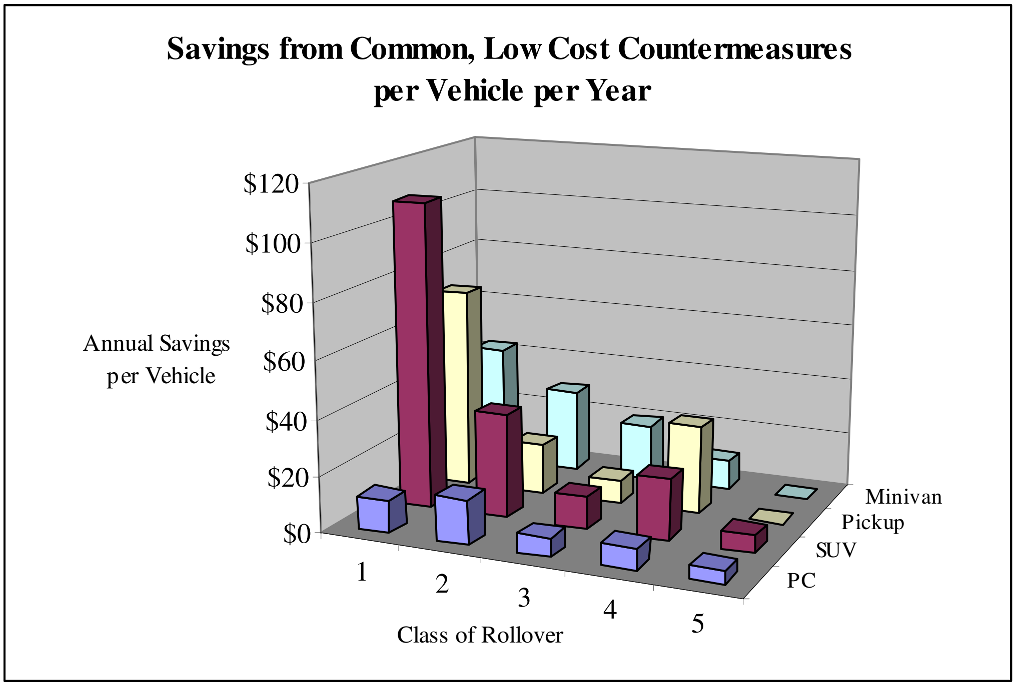

Figure 7. Benefits of basic countermeasures – a strong roof, side glazing designed to contain occupants, and effective safety belt use reminders – from the reduction of rollover AIS 3 or greater injuries. These results should be compared with Figure 4 showing the total economic consequences of AIS 3+ injuries rollovers. It does not include reductions in AIS 1 and 2 injuries.

There has been considerable reluctance to require (or for manufacturers to voluntarily offer) strong belt use reminders because of the experience with ignition interlocks in the early 1970s. We believe that manufacturers and insurance companies could develop a voluntary program, encouraged by changes in the NCAP rating system and insurance premium reductions, to offer and encourage effective belt use reminder systems in new vehicles. Such systems would have benefits well beyond rollovers. However, even in the absence of such systems, improved side glazing or rollover-triggered side curtain air bags would very substantially reduce ejections from vehicles that rollover.

It was assumed that the effectiveness of the three basic countermeasures considered here for the fourth and fifth classes of rollovers, where collisions were the primary source of injury, would be low. Exceptions would be for unrestrained and ejected occupants who were not subject to direct trauma from the collisions.

The results, which are a total saving of half of the comprehensive cost of rollover AIS 3+ injuries, are shown in Figure 5.

OVERALL COSTS AND BENEFITS

In doing this analysis, we found that making conservative assessments of the benefits yielded very high potential savings (over $17 billion per year) from the three simple countermeasures discussed above.

The cost of these three would be around $3.5 billion per year for all new passenger cars, light trucks and vans; so that their benefits would be at least five times the cost. If these were applied only to SUVs and pickups, these countermeasures would yield a benefit more than eight times the cost because of the much higher rate of rollover casualties in them. However, these countermeasures would be cost beneficial even for passenger cars and minivans. Responsible manufacturers have a particular obligation to adopt these countermeasures, even in the absence of regulatory requirements, for SUVs and pickups because of their excessive rollover casualties in comparison with the passenger cars they have typically replaced.

Table 2. Total annual economic consequences of rollovers by type of vehicle and class of rollover (in millions). The sum for all light vehicles is $36.8 billion per year.

Class of Rollover	Passenger Car	SUV	Pickup	Minivan
1. Unbelted Occupant Fully Ejected	$ 2,177	$3,658	$3,359	$ 1,004
2. Belted Occupant w/Head, SC Injury	$ 4,061	$1,600	$1,016	$ 1,062
3. Other Primary Rollovers	$ 2,768	$1,461	$ 612	$ 511
4. Collision Before Rollover	$ 3,925	$1,546	$3,340	$ 439
5. Collision During Rollover	$ 3,399	$ 561	$ 311	$ 0
Total	$16,330	$8,826	$8,638	$ 3,016

Table 3. Total Savings by Type of Vehicle and of Rollover (in millions) from primary countermeasures.

Class of Rollover	Passenger Car	SUV	Pickup	Minivan
1. Unbelted Occupant Fully Ejected	$1,572	$2,822	$2,770	$ 773
2. Belted Occupant w/Head, SC Injury	$2,118	$ 961	$ 688	$ 530
3. Other Primary Rollovers	$ 902	$ 303	$ 329	$ 363
4. Collision Before Rollover	$1,015	$ 560	$1,220	$ 188
5. Collision During Rollover	$ 602	$ 163	$ 8	$ 0
Total	$6,209	$4,809	$5,014	$1,855

Table 4. Upper limit of the cost of countermeasures to reduce rollover injuries.

Countermeasure	Cost per Vehicle	Total Cost (billions)
Safety Belt Use Reminders	$25	$0.4
Improved Side Window Glazing	$100	$1.6
Strong Roof	$100	$1.6
Total	$225	$3.6

This analysis does not account for the savings of AIS 1 and 2 injuries in rollovers, for vehicles more than ten years old, or for the reduction in injuries in non-rollovers. Thus, these countermeasures would have even greater cost effectiveness than is calculated here. The belt use reminder would improve safety in all crash modes while improved occupant compartment integrity and glazing would improve side impact protection.

The total cost of AIS 3 and greater injuries in rollovers of vehicles no more than ten years old – $36.8 billion – is shown in Table 2. Note that only $13.5 billion (just over one-third) is in cases involving a collision as the most serious event, either before or during the rollover. This table does not include any losses from AIS 1 or 2 injuries nor does it include losses in vehicles more than ten years old. The total for all light vehicles is $17.9 billion.

The savings from the countermeasures described in this paper are provided in Table 3. Note that the savings from reducing ejection of unbelted occupants (primarily from improved belt use reminders, improved side glazing, or both) amounts to nearly $8 billion. This counts none of the savings in AIS 1 and 2 injuries, the other savings in non-rollover crashes from these countermeasures, or savings from vehicles more than ten years old. Those savings would probably more than double the benefits. The savings from a reduction in head and spinal column injuries to belted occupants would be over $4 billion, and would come primarily from stronger roofs and the interior padding that is now standard in all new light vehicles.

Estimates of the upper bound costs of these countermeasures, assuming that 16 million light motor vehicles are sold in the U.S. annually, are shown in Table 4.

It can be seen from Table 4 that even considering only the benefits from reductions in AIS 3+ injuries in rollovers of vehicles less than eleven years old, these countermeasures are highly cost-beneficial. Their value would be higher if one considered AIS 1 and 2 injuries, injuries from rollovers of vehicles more than ten years old, and the ancillary benefits in non-rollovers of these countermeasures. It is clear that priority should be given to making these improvements in light trucks where the losses are greatest.

FURTHER THOUGHTS: HISTORY AND POLICY

This research shows the value of the National Accident Sampling System and the NHTSA's estimates of the economic consequences of motor vehicle crashes. This work derives directly from the important work from the 1970s of the late Dr. Anthanasios Malliaris, who developed the harm concept; and Barbara Faigin who produced the first analysis of the cost of injury and Laurence Blincoe who produced the current edition. It is unfortunate that NHTSA did not carry out this type of analysis of rollover injury years ago when it could have saved thousands of lives and serious injuries in rollovers. Based on refinements of this work and on more realistic dynamic testing of vehicle rollover performance and the requirements of the SAFETY-LU legislation, we look forward to major advancements in rollover occupant protection in the near future.

We believe that NHTSA could achieve much of the benefit discussed in this paper by instituting a rollover occupant protection rating in the New Car Assessment Program that gave increasing ratings (number of stars) to vehicles that had stronger roofs and that incorporated other features that improved rollover occupant protection. A proposal has been made to NHTSA for such a rating system (see Appendix A).

When NHTSA proposed the amendment to FMVSS 216 last August, it made the very controversial comment, ". . . if the proposal were adopted as a final rule, it would preempt all conflicting State common law requirements, including rules of tort law." This comment conflicts with the statement in the National Traffic and Motor Vehicle Safety Act of 1966 which says, "Compliance with any Federal motor Vehicle safety standard issued under this title does not exempt any person from any liability under common law." NHTSA's view was based on the Supreme Court decision in *Geier v. Honda*, [15] in which the court held that NHTSA's ability to use more creative means of implementing motor vehicle safety standards involving new technologies and uncertain public acceptance would be compromised by permitting product liability claims against manufacturers that did not implement the most effective safety technology.

An alternative that addresses the highly controversial question of manufacturer liability is discussed in another of this author's publications on how automobile insurance can become a much more effective regulator of motor vehicle safety.[16] The use of consumer information under the New Car Assessment Program could also obviate this controversy.

REFERENCES

[1] Now that a politically correct NHTSA Administrator is gone, the more accurately descriptive original names of the National Accident Sampling System, the Fatal Accident Reporting System, and the Experimental Safety Vehicle Conference should be restored.

[2] Blincoe, Lawrence J., et al., "the Economic Impact of Motor Vehicle Crashes 2000,"

[3] It was suggested by NHTSA staff in a private communication that the assessment of medical costs contained in this work significantly underestimated the cost of rehabilitation following injury.

[4] Nash, Carl E., "A Market Approach to Motor Vehicle Safety . . . That Also Addresses Tort Reform," Product Safety and Liability Reporter, Bureau of National Affairs, Vol. 34, No. 8: Washington, D.C. February 27, 2006, p. 202-212.

[5] It is worth noting that NHTSA estimates that the total direct economic cost of injury today is more than $260 billion and the economic consequences would therefore be on the order of $350 billion. Rollovers account for roughly one quarter of the total loss, or nearly $90 billion annually. Thus, our estimate of the comprehensive cost of rollover casualties is conservative even if one assumes that counting AIS 1 and 2 injuries and counting injuries in vehicles more than ten years old would double our estimate.

[6] See Committee for the Safety Belt Technology Study, "Buckling Up – Technologies to Increase Seat Belt Use," Special Report 278, Transportation Research Board, Washington, D.C. 2003.

[7] Memorandum from J.R. Weaver to H.G. Brilmyer, "Roof Strength Study," Ford Automotive Safety Research Office, July 8, 1968.

[8] Insurance Institute for Highway Safety

[9] The Advanced Glazing Research Team, "Ejection Mitigation Using Advanced Glazing, a Status Report," National Highway Traffic Safety Administration, Washington, D.C.: November 1995.

[10] Willke, Donald, Stephen Summers, Jing Wang, John Lee, Susan Partyka, and Stephen Duffy, "Ejection Mitigation Using Advanced Glazing: Status Report II, National Highway Traffic Safety Administration, Washington, D.C.: August 1999.

[11] Winnicki, John, "Estimating the Injury-Reducing Benefits of Ejection-Mitigating Glazing," National Highway Traffic Safety Administration, Washington, DC. February 1996, DOT HS 808 369.

[12] Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU), enacted August 10, 2005, as Public Law 109-59. SAFETEA-LU authorizes the Federal surface transportation programs for highways, highway safety, and transit for the 5-year period 2005-2009.

[13] See, for example, Brian Herbst, Stephen Forrest, Steven E. Meyer, Davis Hock "Alternative Roof Crush Resistance Testing with Production and Reinforced Roof Structures" SAFE, LLC, Golita: SAE 2002-01-2076

[14] In its Regulatory Analysis, NHTSA estimated that increasing roof strength from 1.5 to 2.5 in the FMVSS 216 test would cost $3.45 per vehicle and result in a weight increase of 1.7 pounds.

[15] *Geier v. Honda*, U.S. Supreme Court No. 98-1811, 2000.

[16] Nash, *op cit.*

APPENDIX: **A PROPOSED NEW CAR ASSESSMENT PROGRAM RATING SYSTEM**

To supplement the basic roof crush requirement, we suggest that the best way to encourage manufacturers to offer a higher and more comprehensive level of rollover occupant protection is through a Rollover Occupant Protection rating in the New Car Assessment Program. A proposed outline for such a rating is as follows:

- ★ Meets basic requirements of all Federal motor vehicle safety standards, including those of the amended FMVSS 201 and 216, and has a (Ford-type) belt-minder level safety belt reminder system.
- ★★ Meets the requirements for one star, has a strength of 2 in the FMVSS 216 test with the pitch angle increased to 10°, and has an advanced level belt use reminder.
- ★★★ Meets requirements for two stars and provides minimal performance under a dynamic roof strength test such as the Jordan Rollover System (including no side window failures)
- ★★★★ Meets the requirements for three stars and has rollover-triggered safety belt pretensioners that minimize occupant excursion in a rollover.
- ★★★★★ Meets requirements for four stars, provides a high level of occupant protection performance in a dynamic roof strength test, and retains the full integrity of all windows in this test, and has a side curtain air bag system.

EFFECTS OF SEAT BELT LOAD LIMITERS ON DRIVER FATALITIES IN FRONTAL CRASHES OF PASSENGER CARS

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ABSTRACT

In the mid-1990s, seat belt load-limiting devices were introduced on many new passenger vehicles equipped with front airbags. These devices are intended to reduce belt-induced injuries such as rib fractures by allowing forward movement of occupants' torsos when belt loads exceed some threshold. Load limiters have been shown to reduce thoracic injury risk in controlled experiments with cadavers and in full-width rigid barrier frontal crash tests.

The Insurance Institute for Highway Safety has evaluated many vehicles equipped with load limiters in 64.4 km/h (40 mi/h) frontal offset crash tests. Results indicate that in some crash circumstances the amount of forward movement allowed by load limiters could increase the risk of head injury from contacts with vehicle interior components. Thus, although load limiters perform well in rigid barrier tests with high deceleration, short duration, and low intrusion, the forward movement they allow in crashes with longer duration and higher intrusion may increase head injury risk.

To examine the effects of load limiters on driver fatality risk in real-world crashes, the present study compared rates of belted driver deaths per vehicle registration before and after load limiters were added to seat belts. Study vehicles were restricted to models and years with no other significant design changes. Fatality rate comparisons for passenger cars with and without load limiters suggest these devices have not reduced fatality risk and even may have increased risk.

Also presented in this study is a review of a small number of cases from the National Automotive Sampling System that illustrate how increased occupant forward movement can contribute to head injury risk even in vehicles with front airbags.

INTRODUCTION

Seat belts are the single most important safety feature of any passenger motor vehicle. They have been estimated to have saved more lives since 1960 than all other crashworthiness design features combined (National Highway Traffic Safety Administration (NHTSA) 2005). However, many studies have shown that seat belts can contribute to thoracic injuries under certain loading conditions, especially among older occupants (Augenstein et al., 1999; Dalmotas, 1980; Hill et al., 1992; Niederer et al. 1977; Patrick and Andersson, 1974). Several patents filed as early as the 1950s and 1960s described methods of limiting the magnitude of belt loads to reduce the risk of these injuries (Viano, 2003). The major drawback of these technologies is that they must sacrifice occupant coupling to the vehicle by allowing forward movement of the occupant's torso, increasing the risk of head or chest contact with the steering wheel or other vehicle interior components. As a result, it was not until front airbags were installed as standard safety equipment that automobile manufacturers began to equip production vehicles with seat belt load limiters in large numbers. Although airbags provide additional occupant protection against contacts with the vehicle interior, they may not eliminate the risk associated with large amounts of increased forward movement in many serious frontal crashes.

Prior Research on Load Limiters

Cadaver tests – Cadaver testing has examined the potential of load-limiting seat belts in combination with airbags to mitigate thoracic injuries. Kent et al. (2001) conducted seven cadaver tests and found a 40 percent reduction in the average number of rib fractures for belts that limited loads to 3.5 kN compared with standard belts that did not limit loads. Cadaver subjects averaged older than 60 years and were positioned to avoid potential hard head contacts. Crandall et al. (1997) conducted six cadaver tests and found a 58 percent reduction in the average number of rib fractures for belts that limited loads to 2 kN compared with standard belts. Cadaver subjects averaged 57 years old, and although no hard head contacts were observed in tests with either standard or load-limiting belts, forward head excursion averaged 42 percent greater in tests with load-limiting belts. Kallieris et al. (1995) conducted tests with five cadavers averaging 50 years old, two restrained with a standard belt and three restrained with a 4 kN load-limiting belt. Fewer thoracic injuries per subject were observed in tests with load-limiting belts (three total rib fractures among three subjects) compared with standard belts (three rib fractures among two subjects). Differences in the amount of forward head excursion were not reported.

Field studies – Field studies also have examined the effects of load limiters on injury risk. An early field study in France examined load-limiting seat belts in Renault and Peugeot vehicles (Foret-Bruno et al., 1978). Belt stitching near the upper anchorage points in these vehicles was designed to tear under load to introduce additional webbing into the belt system. The study correlated the amount of belt load to the risk of occupant thoracic injury. Among the findings were that occupants younger than 30 could sustain belt loads of 7.4 kN without any thoracic injury, but occupants older than 50 were susceptible to injury at lower belt loads. Mertz et al. (1991) later used these data to establish risk curves for Hybrid III dummy chest compression associated with seat belt loading.

In 1995, Renault vehicles were equipped with a new type of limiter that mechanically deformed under load, limiting belt forces to 6 kN. Foret-Bruno et al. (1998) combined crash data for vehicles equipped with the new limiter with cases involving the vehicles manufactured in the 1970s. Only 6 percent of the 256 total cases involved vehicles with airbags, and head injury risk was not reported. Risk curves were established to correlate shoulder belt loads with thoracic injury risk. A very strong dependence on age was found; the risk of AIS 3+ thoracic injury reached 50 percent with shoulder belt loads of less than 4 kN for 80-year-old occupants but more than 9 kN for 20-year-old occupants. The injury risk curves also were compared with those developed from 209 cadaver sled tests conducted in the 1970s. Belt loads associated with a specific level of injury risk were 2 kN lower in the cadaver tests than in the field cases. The authors suggested that belt load thresholds developed from cadaver tests may be low, possibly due to below-average bone strength for the post-mortem human subjects. According to the injury risk curves developed from the field data, limiting shoulder belt loads to 2 kN (as suggested by Mertz et al. (1995) and used in the cadaver tests conducted by Crandall et al. (1997)) would produce less than a 10 percent risk of AIS 3+ thoracic injury for 80-year-old occupants and essentially zero risk for younger occupants.

Foret-Bruno et al. (2001) recently conducted a study based on field cases of vehicles equipped with a new 4 kN load-limiting seat belt. Results confirmed the earlier injury risk curves, finding a further reduction in thoracic injuries associated with the lower belt load threshold. The vehicles with the new load limiters were equipped with airbags, but the risk of head injury associated with increased forward excursion was not discussed.

NCAP frontal tests – Load limiters have improved test scores for many vehicles in NHTSA's New Car Assessment Program (NCAP), and this may have increased the use of such devices as manufacturers tried to achieve better NCAP ratings. NHTSA (2003) published a technical report and request for comments on the improvements in frontal NCAP scores associated with load limiters and belt crash tensioners. The Insurance Institute for Highway Safety (IIHS) identified 14 vehicle models that were structurally unchanged, added load limiters without other seat belt changes, and were retested in NCAP (Appendix A). None of these vehicles received a lower driver star rating in the retest with load limiters, and only one vehicle received a lower passenger rating (one less star). Four vehicles had unchanged ratings for both occupants, whereas the other nine improved by at least one star for either the driver, passenger, or both.

The frontal NCAP test is a full-width crash into a rigid barrier at 56.4 km/h (35 mi/h). The resulting crash pulse is very short, limiting the amount of time the dummy occupant loads the seat belt and airbag. The faster loading rate increases the effective initial stiffness of the restraint system. Furthermore, loading a vehicle across its full width limits the amount of intrusion, maintaining larger clearances in the occupant compartment. This configuration also ensures that occupant loading and rebound phases occur with minimal vehicle rotation. Because of these factors, the risk of dummy head contact with the vehicle interior is lower than in longer pulse crashes and in crashes with greater vehicle rotation or intrusion.

IIHS frontal offset tests – Since 1995, IIHS has conducted frontal offset crash tests in which only 40 percent of a vehicle's front end overlaps a deformable barrier. This configuration has a longer crash pulse than the NCAP test and is likely more representative of real-world crashes. NHTSA studies have found that about 20-25 percent of frontal crashes in the field are full width (Saunders and Kuppa 2004; Stucki et al. 1998), and many of these impacts are with objects less rigid than the NCAP barrier. The performance of load limiters in the IIHS offset test could be an important indicator of their potential effectiveness in many real-world crashes.

IIHS generally does not retest vehicles when adjustments to restraint systems are unaccompanied by structural changes, so there are no paired vehicle tests that isolate the contribution of load limiters. However, general observations can be made between vehicles with and without load limiters while recognizing that other restraint system differences exist.

As of June 2006, IIHS has evaluated 123 passenger cars in the frontal offset test that received structural ratings of good or acceptable. Comparing similar vehicles with such high ratings limits the influence that large amounts of intrusion have on dummy kinematics and injury measures and avoids issues that may arise from comparing different vehicle types. Of the passenger cars tested, 103 were equipped with load-limiting seat belts and 20 were not. Evidence from test film and dummy instrumentation plots suggest that driver dummy head excursion into the airbag resulted in steering wheel contact in 52 percent of the vehicles with load limiters and in 20 percent of vehicles without. Although many of these head contacts would be unlikely to cause serious injury, the contacts in about two-thirds of the cases produced the maximum resultant head accelerations recorded during the tests. In real-world crashes with different loading conditions or occupants of other sizes, the forces involved in these hard head contacts could be greater.

For most of the tested vehicles with load-limiting belts, the amount of webbing that spooled from the retractor during the crash was measured. Figure 1 shows the total amount of belt spool-out for the passenger cars tested with load-limiting belts. If a vehicle was equipped with belt crash tensioners, then the spool-out measurement was the amount of webbing pulled from the retractor after the tensioner activated. The average total amount of belt spool-out has been increasing in recent model years, from about 10 cm for 1997-2000 models, to 17 cm for 2003 models, and to 23 cm for the 2004-05 models for which spool-out was measured (15 tests). During the same period, many airbags were depowered and advanced airbags were introduced. These newer airbag designs are intended to reduce airbag inflation risks for out-of-position occupants, but they may permit more occupant forward movement than earlier airbag designs.

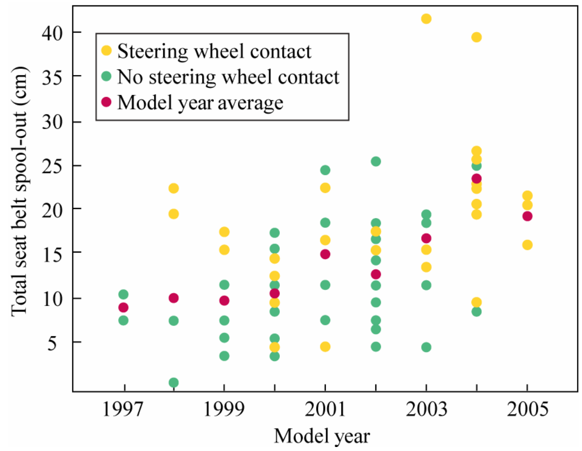

Figure 1. Total measured seat belt spool-out in passenger cars with load-limiting belt; IIHS frontal offset deformable barrier tests.

Thus, seat belt spool-out has been increasing while airbags may have been allowing more forward movement. Of 17 tests with more than 20 cm of total belt spool-out, 14 had hard contact between the dummy's head and steering wheel through the airbag.

The observations of load-limiting belts in frontal offset tests suggest that belt load thresholds that reduce measured injury risk in frontal NCAP tests could produce undesired results in longer pulse crashes. All three cadaver test series discussed earlier, as well as many of the mathematical models presented in the literature, employed crash pulses similar to those of full-width rigid barrier impacts. In addition to increasing driver head excursion through the airbag, too much belt spool-out also may increase injury risk during the rebound phase of a crash or in multiple-event crashes, including frontal impacts followed by a side impact or rollover. Front airbags provide occupant protection only during the initial loading phase of a crash, whereas seat belts have the potential to restrain occupants for the duration of a crash.

METHODS

To investigate the effectiveness of seat belt load limiters in real-world crashes, driver fatality rates for different vehicles were compared before and after load limiters were added to their designs. Vehicles with coincident changes to advanced airbags, electronic stability control, or front structure were not included. Due to these restrictions, only one vehicle model that also was equipped with belt crash tensioners could be included. Vehicle model years with unchanged front structure were identified using the same information collected by IIHS for its frontal crashworthiness evaluation program. Vehicles not tested by IIHS were not considered for study due to the limited amount of available structural and restraint system data. Only mechanical deformation-type load limiters were evaluated. Reliable model-specific information on belts with other energy management features, such as seat belt webbing with stitching that tears under load, was not widely available. The passenger cars that met the inclusion criteria are listed in Table B-1 of Appendix B.

Federal Motor Vehicle Safety Standard (FMVSS) 208 was amended in 1997 to allow compliance with frontal crash performance requirements to be demonstrated by using sled tests as an alternative to rigid barrier tests (NHTSA, 1997). In response, the airbags in many vehicles were depowered to inflate in a less aggressive manner. Because a depowered airbag could affect the performance of a seat belt load limiter, this variable also was considered in the analysis. All vehicles in the present study had depowered airbags installed at either the beginning or during the middle of the 1998 model year. To isolate the effects of load limiters, fatality rates were calculated separately for the years vehicles were equipped with depowered airbags. Any model that received depowered airbags in the middle of the 1998 model year was evaluated for 1997 and 1999 but not the year of the running change. It should be noted that the amount of airbag depowering may have varied considerably among these different makes and models.

Driver Fatality and Vehicle Registration Data

A query of the 1996-2003 Fatality Analysis Reporting System (FARS) provided the fatality counts of belted drivers in the study vehicles. FARS cases were restricted to crashes with a principal impact location of 12 o'clock. Direct frontal crashes were evaluated because load limiters are designed to have the greatest effect in this loading condition. Additionally, side impact airbags were introduced on some models as optional safety equipment during the model years that were compared, and this could confound the results for other impact locations.

Fatality rates were calculated by dividing the number of fatalities for a given model, model year, and calendar year by the number of registrations for that vehicle. Registration data were obtained from the National Vehicle Population Profile of R.L. Polk and Company. Because registration data are collected in the middle of each calendar year, the vehicles for each model year in the study were not evaluated until the following calendar year.

To test the null hypothesis that load limiters have no effect on driver fatality risk, expected fatalities were calculated for the vehicles with load limiters by multiplying the fatality rate for those vehicles before load limiters were added by the number of registered vehicle years after load limiters were installed. The number of expected fatalities then was adjusted for changes in environmental and behavioral factors using an adjustment procedure described below. Finally, rate ratios for each vehicle were obtained by dividing the observed fatalities in vehicles with load limiters by the adjusted expected fatalities. Rate ratios less than 1.00 indicate a reduction in fatal crash likelihood for vehicles with load limiters, whereas ratios greater than 1.00 suggest an increased likelihood.

Adjustment Procedure

Because driver belt use, average travel speed, vehicle fleet mix, and other factors change over time, fatality rates vary over time even for unchanged vehicle models. To control for these differences, a set of passenger car models that had no seat belt or structural changes across the same model and calendar years was identified for each study vehicle that received load limiting seat belts. The fatality rate ratios for these comparison models were used to normalize the rate ratios for the vehicles that received load limiters. Because airbag depowering also was tracked, this change was captured in the control group when the study vehicle also received depowered airbags.

For example, the Dodge Stratus and its corporate twins were structurally identical for the 1995-2000 model years and had load-limiting seat belts and depowered airbags installed beginning with 1998 models. An expected number of belted driver fatalities for vehicles with the seat belt and airbag changes was calculated based on the fatality rate for vehicles with the unchanged restraint systems. This expected value then was multiplied by the fatality rate ratio for a control group of vehicle models that also had depowered airbags installed in 1998 but did not receive seat belt or structural changes during the same model years. Finally, the rate ratio for the Stratus was determined by dividing the observed fatalities by the adjusted expected value.

Two selection criteria were established for the control vehicles in this analysis. First, vehicles older than 4 years were excluded to reduce the effect of any model-specific trends related to changes in vehicle ownership. The second criterion resulted from the fact that differing numbers of control vehicles could be used based on the range of model years for which each study vehicle was being compared. To balance the requirements for multiple vehicles in the control group and sufficient exposure for the study vehicle, the model years in each comparison were chosen to produce the most registered vehicle years for the study vehicle, provided the control group contained at least four distinct models with a minimum of 400,000 total registered vehicle years. In the few cases where no comparison existed with at least four such models, the next highest number of control vehicles was selected. Table B-2 in Appendix B lists the models used for the control groups. Several control vehicles had side airbags introduced during this time period, giving further reason to consider only those crashes with a principal impact location of 12 o'clock.

Overall rate ratios were computed by grouping vehicle models that received the same restraint system change and comparing the total adjusted expected and observed fatalities. Because depowered airbags were distinguished from earlier generation airbags, four different technology combinations were possible for the vehicles without belt crash tensioners (all but one model in the study). In a given model year, a vehicle could have depowered airbags, load limiters, both, or neither.

Ninety-five percent confidence limits were calculated for the overall rate ratios corresponding to each change in restraint technology. The limits were computed using a formula developed by Silcocks (1994):

Lower:

$$\beta_{0.025}(O, E + 1) / \{1 - \beta_{0.025}(O, E + 1)\} \qquad (1).$$

Upper:

$$\beta_{0.975}(O + 1, E) / \{1 - \beta_{0.975}(O + 1, E)\}, \qquad (2).$$

where O is the sum of the observed fatality counts, E is the sum of the expected fatality counts, and $\beta p(x,y)$ is the pth percentile from the beta distribution with parameters x and y. The expected fatality counts were those adjusted with the control group rate ratios. This method does not capture the uncertainty in the rate ratio estimates of the control vehicles themselves, making the confidence intervals somewhat narrower than they would be otherwise. Rate ratios with associated confidence intervals that do not include 1.00 are considered statistically significant.

RESULTS

Results for the groups of vehicles with similar restraint system changes are reported in Table 1. The fatality rate ratios in the first and third rows of the table are relative to the ratio for other passenger cars that had unchanged restraint systems during the same model and calendar years, whereas the fatality rate ratios in the second and fourth rows are relative to the ratio for passenger cars that received only depowered airbags. In every case, the control group of vehicles had substantially more registered vehicle years than the study vehicle with which they were compared.

The number of vehicle models and their exposure varied for each technology change. The smallest group consisted of the Chevrolet Cavalier and Pontiac Sunfire, corporate twins, which were the only vehicles that received load-limiting belts before depowered airbags (first row of Table 1). There were 18 percent fewer fatalities than expected in these vehicles after load-limiting belts were installed. This result was not statistically significant at the selected confidence level.

Fifteen different model/body style combinations received both depowered airbags and load-limiting belts, making up the largest group with a total exposure of more than 17 million registered vehicle years (second row of Table 1). There were 36 percent more fatalities than expected for these vehicles after the airbag and seat belt changes, a statistically significant finding. This increase is relative to other models that received depowered airbags at the same time as the study vehicles but that had no seat belt changes. When analyzed individually (Table 2), six of the eight vehicle platforms in this group had adjusted fatality rate ratios ranging from 1.35 to 2.55. The other two vehicle models had fatality rate ratios near 1 (1.01 and 1.04).

Table 1
Passenger cars that received load-limiting seat belts; rate ratios for driver deaths in crashes with principal impact location of 12 o'clock among structurally unchanged vehicles, adjusted for change in fatality rates of other passenger cars without load-limiting seat belts in same model and calendar years

Belt load limiter and/or depowered airbag?		Pre-change		Post-change				
Pre-change	What added	Registered vehicle years	Driver deaths	Registered vehicle years	Driver deaths	Adjusted expected deaths	Rate ratio	95% confidence interval
Neither	Load limiter	765,309	12	1,644,406	29	36	0.82	(0.48, 1.37)
Neither	Both	8,825,779	126	8,632,257	148	109	1.36	(1.06, 1.76)
Depowered airbag	Load limiter	6,069,741	91	8,281,390	131	130	1.01	(0.79, 1.30)
Neither	Both (+ crash tensioners)	1,410,719	14	3,263,383	34	27	1.27	(0.74, 2.19)

Not all vehicles received depowered airbags and load limiters simultaneously. As mentioned previously, the Cavalier and Sunfire designs incorporated load-limiting belts before depowered airbags. Another subset of vehicles had depowered airbags for at least one model year before load limiters were introduced. Relative to other models that had no restraint system changes, these vehicles had 1 percent more fatalities than expected after seat belts were changed (third row of Table 1). At the model-specific level (Table 3),

Table 2
Breakdown of fatality rate ratios by make and model for vehicles that received load-limiting seat belts in combination with depowered airbags, adjusted for change in fatality rates of other passenger cars that received depowered airbags only

	Without depowered airbags or belt load limiters			With depowered airbags and belt load limiters				Adjusted using control group	
Vehicle	Model years	Registered vehicle years	Driver deaths	Model years	Registered vehicle years	Driver deaths	Expected driver deaths	Expected driver deaths	Rate ratio
Chevrolet Cavalier	1995	765,309	12	1998	1,320,263	24	21	24	1.01
Control group		3,697,812	56		2,431,750	40	35		
Dodge Stratus	1996-	1,455,193	15	1998	786,383	14	8	8	1.78
Control group	1997	11,669,667	171		4,916,952	70	72		
Ford Contour	1997	392,015	5	1999	674,760	13	9	8	1.54
Control group		2,896,644	56		2,574,133	46	47		
Ford Escort	1997	1,472,942	36	2000	274,852	11	7	4	2.55
Control group		1,567,249	30		843,361	10	16		
Ford Taurus	1997	1,952,174	23	1999	2,087,706	25	25	24	1.04
Control group		2,896,644	56		2,574,133	46	47		
Honda Civic	1997	1,179,115	12	1999	1,002,126	16	10	10	1.60
Control group		2,896,644	56		2,574,133	46	47		
Pontiac Grand Prix	1997	845,252	8	1999	1,752,665	26	17	16	1.60
Control group		2,896,644	56		2,574,133	46	47		
Saturn SL	1997	763,779	15	1999	733,502	19	14	14	1.35
Control group		2,896,644	56		2,574,133	46	47		
Study vehicle total		**8,825,779**	**126**		**8,632,257**	**148**	**110**	**109**	**1.36**

Table 3
Breakdown of fatality rate ratios by make and model for vehicles that received load-limiting seat belts after receiving depowered airbags, adjusted for change in fatality rates of other passenger cars that already had depowered airbags

	With depowered airbags and without belt load limiters			With depowered airbags and belt load limiters				Adjusted using control group	
Vehicle	Model years	Registered vehicle years	Driver deaths	Model years	Registered vehicle years	Driver deaths	Expected driver deaths	Expected driver deaths	Rate ratio
Ford Escort	1998	1,422,214	32	2000	274,852	11	6	7	1.55
Control Group		7,132,151	96		4,541,640	69	60		
Ford Taurus	1998	1,624,862	20	1999	2,087,706	25	26	34	0.74
Control Group		10,401,097	135		9,580,961	156	118		
Honda Civic (4 door)	1998	805,132	10	1999-	1,192,502	20	15	18	1.12
Control Group		7,132,151	99	2000	11,446,869	180	149		
Pontiac Grand Prix	1998	1,647,648	18	1999-	3,402,439	47	37	42	1.12
Control Group		5,159,890	73	2001	11,127,943	168	149		
Saturn SL	1998	569,885	11	1999 -	1,323,891	28	26	29	0.97
Control Group		5,159,890	73	2001	11,127,943	168	149		
Study vehicle total		**6,069,741**	**91**		**8,281,390**	**131**	**109**	**130**	**1.01**

the fatality rate decreased for one of the five models after load limiters were installed, was essentially unchanged for a second, and increased for the other three models.

Finally, the Toyota Camry was the only vehicle in the study to receive load-limiting belts, crash tensioners, and depowered airbags, all for the 1998 model year. Relative to models that received only depowered airbags in 1998, Camrys with the new restraint systems had 27 percent more fatalities than expected. The small exposure associated with studying only one model meant this finding was not statistically significant at the 95 percent confidence level. The observed increase was roughly in line with the study vehicles that received load limiters and depowered airbags without crash tensioners.

DISCUSSION

The present study attempted to evaluate the effectiveness of seat belt load limiters in reducing driver fatalities in real-world crashes. These devices now are widespread, but because they usually were integrated into vehicle designs at the same time as other crashworthiness changes, it is difficult to isolate the effects of their performance. The number of vehicle models available for study was fewer than desired, and their total exposure was too low to produce narrow confidence intervals. Although essentially all modern vehicle designs use load limiters in tandem with crash tensioners, this study could evaluate only one vehicle model with the combination of these technologies. This is due to the fact that manufacturers usually waited for substantial structural or airbag redesigns to introduce crash tensioners. Load limiters require only a new belt retractor, but pyrotechnic crash tensioners must receive a signal from the restraint system's sensing and diagnostic module based on the vehicle accelerometers. These additional structural and airbag changes confound comparisons of the belt technology.

Despite these limitations, there is unlikely to be a better opportunity to evaluate load limiters in real-world crashes. No current mainstream vehicle designs are known to be manufactured without load-limiting belts, so any changes in driver fatality rates associated with their introduction cannot be tracked in the future. Existing thresholds for belt loads will continue to be adjusted, but these modifications will be difficult to evaluate because of the proprietary nature of the information and the shorter design life of today's vehicles. For these reasons, the limited results available from the present study warrant serious consideration.

With few exceptions, the addition of load-limiting seat belts appeared to have no effect on driver fatality rates in some cases and some association with increased fatality rates in others. When the largest group of vehicles received load limiters and depowered airbags, a statistically significant 36 percent increase in fatalities was observed compared with other vehicles that received only depowered airbags. The one model that received similar technology in combination with crash tensioners had a similar increase, though not statistically significant.

In total, fifteen fatality rate ratios were calculated for different restraint combinations on nine vehicle platforms to estimate the effect of load-limiting seat belts in fatal crashes. Of these combinations, two resulted in substantially fewer fatalities than expected: the 18 percent initial reduction for the Cavalier platform (Table 1) and the 26 percent reduction for the Taurus platform (Table 3). Three results were within 4 percent of the expected number of fatalities. The remaining ten rate ratios, including one for the model with crash tensioners, ranged from 1.12 to 2.55, with an average of 1.55.

Variation in Seat Belt and Airbag Load Sharing from Frontal NCAP

The varying fatality rate changes among the different vehicle models that received load-limiting seat belts highlights an important issue. Although some variation would be expected due to the limited exposure of several models, the reduction in fatality rates observed when load-limiting belts were installed on the Cavalier and Taurus platforms is in sharp contrast to the majority of the other models with large fatality rate increases. A significant explanation for these discrepancies may be the differences in the load-limiting mechanisms and airbags themselves. Load-limiter activation thresholds vary throughout the vehicle fleet and, potentially, even in the same vehicle across different model years. The same is true of airbag designs; the amount of depowering varied among vehicles, and subsequent designs may have been modified when load limiters were installed. A more detailed understanding of how certain restraint systems were changed would supplement the observed fatality rates associated with these changes.

One source of data that can be used to quantify restraint system changes is the frontal NCAP. In most of these tests, the belt is instrumented with a transducer to measure the force generated on each occupant's shoulder belt. Table 4 lists the study vehicles with belt load data available from frontal NCAP tests for the model years tested.

Table 4
Maximum driver shoulder belt forces (kN) during tests of study vehicles in frontal NCAP; maximum forces listed by presence of depowered airbags and/or load-limiting seat belts in model year tested

	Shoulder belt loads by presence of depowered airbags and belt load limiters			
Vehicle	Neither	Depowered airbags only	Load limiters only	Both
Chevrolet Cavalier (four-door)	6.7	N/A	9.5	6.9
Dodge Stratus	8.2	N/A	N/A	5.1
Honda Civic (four-door)	8.1	12.5	N/A	7.2
Pontiac Grand Prix / Oldsmobile Intrigue	8.6	7.0	N/A	4.8
Saturn SL	5.4	5.4	N/A	3.5
Toyota Camry	6.3	N/A	N/A	5.7*

*In addition to depowered airbags and load limiters, crash tensioners were also added to the Camry restraint system.

A decrease in shoulder belt load for a vehicle tested in NCAP suggests that an increased amount of the occupant's kinetic energy is being transferred through the airbag than in the previous restraint system design. This can be accomplished by allowing more belt webbing to spool out from the retractor during the crash (as with a seat belt load-limiting mechanism), changing properties of the airbag (such as size, venting, or inflation speed), or a combination of both. As discussed previously, it is unknown what airbag modifications, if any, accompanied the installation of load-limiting belts in the study vehicles. So although a change in belt load is not necessarily a direct estimate of the effects of a load limiter, it is likely a reasonable indicator of change in the restraint system's overall balance of loads between the airbag and seat belt.

Installation of a load limiter would be expected to produce a decrease in belt loads, and this was true for all vehicles listed in Table 4 except the Cavalier. The installation of load limiters on the Cavalier platform corresponded to an increased shoulder belt load measured in NCAP and a fatality rate ratio of 0.82 in real-world crashes. When depowered airbags subsequently were installed on the Cavalier platform, the measured belt load decreased to a value similar to the original measurement. The overall change in load was only 3 percent and corresponded to a fatality rate ratio of 1.01. A reason for the atypical belt loads in the Cavalier cannot be determined from the present study, but possibilities include adjustments to the driver airbag or load limiter or the previous installation of a load-limiting device other than the type initiated by mechanical deformation. In any case, the decrease in fatality risk for the Cavalier appears associated with increased occupant loading of the belt, not a reduction. This leaves the fatality rate ratio associated with the Taurus platform as the only decrease potentially resulting from reduced belt forces among the study vehicles.

Figure 2 plots the adjusted model-specific fatality rate ratios by the changes in shoulder belt loads

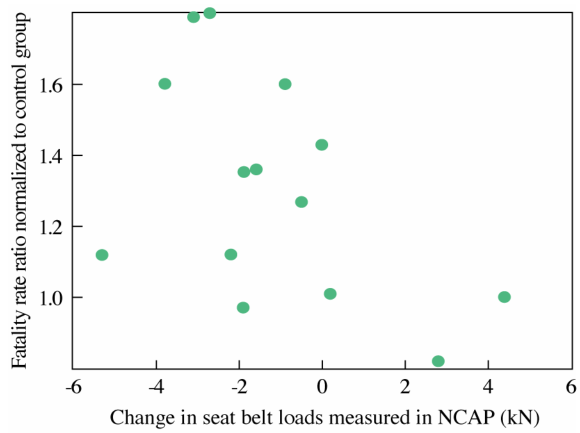

Figure 2. Belted driver fatality rate ratios in frontal crashes for passenger cars that received restraint changes, plotted by the change in belt loads in frontal NCAP tests.

measured in frontal NCAP. Restraint system changes that occurred in multiple steps are plotted for each individual step as well as the overall change. Increases in belt load suggest a greater emphasis on the seat belt in the overall function of the restraint system, whereas decreases suggest the airbag is providing more restraining force than before. The figure shows that the shifts toward lower belt loads were correlated with increased driver fatality rates; of the ten restraint system changes producing decreased belt loads, nine corresponded to increased fatality rate ratios. The three restraint system changes that produced increased belt loads were associated with fatality rate ratios less than or approximately equal to 1.

NASS/CDS Case Review

The increased fatality rates for most vehicles challenges the assumption that for models with airbags, "the increased risk of significant head injury due to the greater upper torso motion allowed by the shoulder belt load limiter…only occurs for non-deploy accidents where the risk of significant head injury is low even for the unbelted occupant" (Mertz et al., 1995). Although a complete analysis of the overall effectiveness of load-limiting belts would include a comparison of injury risk to different body regions before and after installation, reliable injury data by body region are not available at the make-model level. However, review of a small number of cases from the Crashworthiness Data System (CDS), a part of the National Automotive Sampling System (NASS), reveals that airbag deployment does not prevent injurious excursion-related contacts with interior vehicle components in many crashes. Table 5 summarizes some of the relevant data from the reviewed cases.

In certain cases, occupants also may have sustained injuries from the seat belts. It often was difficult to discern the direct source of injury; some of the injuries coded as coming from excursion contacts may have been belt induced, whereas others coded as being caused by belt loading may have been excursion related. Due to the lack of photographic evidence, it also was impossible to determine precisely the amount of belt spool-out that occurred in most cases. However, the larger point is that these cases provide evidence that excursion contacts continue to occur in vehicles with airbags. In each of the NASS/CDS cases, either there was physical evidence of excursion contact in the vehicle or an investigator's best explanation for the observed injuries was hard contact through the airbag or with other interior surfaces. All vehicles appeared to have adequate postcrash survival space such that intrusion was not likely a source of upper body injuries.

Factors such as offset loading and multiple impacts may have contributed to increased forward excursion in the NASS/CDS cases. However, the greatest insight provided by review of the cases is the reminder that numerous and complex factors are involved in each real-world crash. Laboratory tests of individual restraint system components such as load limiters may produce desirable results and be generally repeatable. Crash tests add a level of complexity because the entire system of components is evaluated in a specific configuration that may be encountered in the field. However, real-world crashes are substantially more intricate. They involve occupants of all sizes and in different positions, differing numbers of impacts with objects of various shapes and strengths, vehicle loading from any direction and for a range of durations, and potential contacts with intruding vehicle components. Although it remains impossible to design restraint systems for every potential real-world crash scenario, the present study suggests that optimizing the performance of airbags and load-limiting belts for 56.4 km/h (35 mi/h) rigid barrier tests may compromise occupant protection in many serious real-world frontal crashes.

Results of the present study in no way diminish the importance of managing belt-induced thoracic loads during crashes. However, they do imply that continued development of alternative belt technologies could have unexpected benefits. Inflatable restraints or four-point belt systems that can mitigate localized thoracic loads without substantially increasing the risk of excursion contact may prove more beneficial than the continued downward trend of belt load thresholds. Alternatively, advanced systems capable of adjusting belt restraint forces based on occupant size, position, and other crash conditions could be required (Miller, 1996).

Table 5
Sample of cases from NASS-CDS with possible excursion contacts and injuries

Case number	Vehicle	Restraint system	Possible excursion contacts	Possible excursion injuries	Contributing factors
2002-042-025	2002 Jaguar X-Type	Airbag, tensioner, load limiter	Windshield, header, front dash (passenger)	Aorta laceration, cerebral hemorrhage	Multiple impacts, possible seat movement
2003-048-228	2002 Honda CR-V	Airbag, tensioner, load limiter	Steering wheel	Cerebral hemorrhage	Front undercarriage loading
2003-049-010	2002 Mitsubishi Galant	Airbag, load limiter	Steering wheel	Loss of consciousness, facial contusions	Multiple impacts
2003-050-101	2001 Ford F-150	Airbag, tensioner, load limiter	Steering wheel	Rib and sternum fractures	Occupant mass, offset loading
2004-050-041	2002 Ford Escape	Airbag, tensioner, load limiter	Steering wheel	Loss of consciousness, facial contusions	Multiple impacts, offset loading
2004-081-007	2002 Toyota MR-2	Airbag, tensioner, load limiter	Left A-pillar	Facial fracture and lacerations	Vehicle rotating at impact
2004-082-123	2002 Toyota Camry	Airbag, tensioner, load limiter	Steering wheel	Facial fractures, loss of consciousness, pneumothorax	Offset loading

CONCLUSIONS

Laboratory tests and limited field studies have shown that load-limiting seat belts have the potential to decrease the risk of belt-induced thoracic injuries. In the past, the increased occupant forward excursion resulting from load limiters kept them from being widely installed. However, with a modern vehicle fleet equipped with standard front airbags, load-limiting belts have become an integral part of restraint systems in new vehicle designs. Low force thresholds have been proposed for these belts, with the assumption that driver airbags can provide the necessary restraining forces during the later stages of a frontal crash. This can reduce injury measures in full-width rigid barrier tests. However, tests with greater intrusion, longer crash pulses, and impact forces offset from the vehicle centerline indicate an increased risk of excursion contact, and undesirable occupant kinematics can result from excessive amounts of belt webbing spool-out. Changes in driver fatality rates associated with the installation of load-limiting belts in passenger cars suggest this restraint technology has not reduced and may have increased the risk of driver fatality in some crashes. Where corresponding model-specific changes in seat belt restraint forces are available, the data indicate reductions in belt forces usually correspond to increased fatality rates. Observations from NASS/CDS cases illustrate the possibility of excursion contacts and injuries in vehicles with airbags under certain crash conditions. The present study suggests that optimizing the performance of airbags and load-limiting belts for rigid barrier tests without regard to the dangers of increased occupant excursion does not produce the most effective restraint systems for many real-world crashes and that alternative methods for reducing localized loading of seat belts should be targeted.

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APPENDIX A

Table A-1
Vehicles tested in frontal NCAP before and after addition of load limiters; no significant structural changes were made and crash tensioners were not added between retests

Make/model	Model year	Driver stars	Passenger stars
Chevrolet Blazer	1997	3	1
	1998	4	4
Chevrolet Cavalier	1995	3	3
	1997	4	3
Chevrolet S-10	1997	3	2
(extended cab)	1998	4	4
Chevrolet S-10	1995	3	1
(regular cab)	2000	3	3
Dodge Durango	1998	2	3
	1999	2	4
Dodge Grand Caravan	1998	3	3
	1999	4	4
Ford Taurus	1998	4	4
	1999	5	5
Honda Civic (2 door)	1996	4	4
	1999	4	4
Honda Civic (4 door)	1998	4	4
	1999	4	4
Oldsmobile Intrigue	1998	4	3
	1999	4	2
Pontiac Grand Prix	1997	4	4
	2001	4	4
Saturn SL	1998	5	4
	1999	5	5
Toyota 4Runner	1996	3	3
	1998	3	3
Volvo 850/S70	1994	5	4
	1995	5	5

APPENDIX B

Table B-1
Passenger cars with load limiter introductions not associated with structural changes; actual model year spans with identical structural platforms may be larger; model years with advanced airbag features or electronic stability control are not included

Make/model	Model years with depowered airbags and/or load-limiting seat belts: Neither	Depowered airbag	Belt load limiters	Both
Buick Century/Regal	1997	1998		1999-2002
Chevrolet Cavalier	1995		1997	1998-2002
Chrysler Cirrus	1995-1997			1998-2000
Dodge Stratus	1995-1997			1998-2000
Ford Contour	1995-1997			1999-2000
Ford Escort	1997	1998		2000
Ford Taurus	1996-1997	1998		1999
Honda Civic (coupe)	1996-1997			1999-2000
Honda Civic (sedan)	1996-1997	1998		1999-2000
Mercury Mystique	1995-1997			1999-2000
Mercury Sable	1996-1997	1998		1999
Oldsmobile Intrigue		1998		1999
Plymouth Breeze	1996-1997			1998-2000
Pontiac Grand Prix	1997	1998		1999-2002
Pontiac Sunfire	1995		1997	1998-2002
Saturn SL	1995-1997	1998		1999-2002
Toyota Camry	1997			1998-1999*

*The Toyota Camry was the only vehicle that received crash tensioners in addition to load limiters and depowered airbags.

Table B-2.
Passenger cars without load limiters or that had load limiters added previously; these vehicles were used for control groups; actual model year spans with identical structural platforms may be larger

Make/model	Structurally identical model years before and after depowered airbags: Before	After
Acura RL	1996-1997	1998
Audi A6		1998-2001
Buick Park Avenue	1997	1998-2002
Cadillac Catera	1997	1999-2001
Chevrolet Lumina	1995-1997	1998-2000
Chevrolet Malibu	1997	1998-2002
Chevrolet Prizm		1998-2002
Dodge Neon	1995-1997	1998-1999
Honda Accord		1998-1999
Hyundai Sonata	1995-1997	1998
Lexus LS400		1998-2000
Lincoln Continental	1995-1997	1998-2002
Mercury Tracer	1997	1998
Mitsubishi Galant	1994-1997	1998
Mitsubishi Mirage	1997	1998
Nissan Sentra		1998-1999
Oldsmobile Cutlass	1997	1998-2002
Plymouth Neon	1995-1997	1998-1999
Subaru Legacy	1995-1997	1999
Toyota Avalon		1998-1999
Toyota Camry		1998-2001
Toyota Corolla		1998-2002
Volkswagen Passat		1998-2000
Volvo S70		1998-2000

INJURY ANALYSIS OF LAMINATED AND TEMPERED SIDE GLAZING

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Paper Number 07-0101

ABSTRACT

The injury characteristics of tempered and laminated side glazing during collisions are analyzed. This study is based upon a comprehensive literature review, fundamental design analysis, and the results of numerous statistical studies with particular emphasis on the injury rates associated with the tempered and HPR laminated windscreens that were used concurrently in Europe in the late 1960s and 1970s. Comparative aspects of laceration, ejection, impact, eye injury, and entrapment are detailed. It is shown that the occupant is most seriously threatened by partial or complete ejection which can be effectively mitigated by laminated glazing. It is also shown that the most common glazing-related injury is laceration, the incidence of which is also reduced by laminated glazing. Injury statistics conclusively demonstrate that for each injury mechanism studied, laminated side glazing offers superior occupant protection. The relative merits of the two glazing materials are discussed from the cost, security, and comfort/convenience perspectives. The results of testing of currently marketed side glazing technology are also presented. The study is limited by the disproportionate use of tempered side glazing in vehicles on the roadway at the time of writing, and that instances of laminated side glazing preventing ejection related serious injuries are not fully reported. New contributions include the comprehensive nature of the study, testing, and analysis.

INTRODUCTION

Automobile side glazing is generally composed of 4 to 5 mm thick sheets of either tempered safety glass (TSG) or laminated safety glass (LSG). It usually demonstrates simple (single axis) or complex (multiple axes) curvature. The majority of passenger vehicles on the roadway today come equipped with tempered side glass, but recently laminated side glass has increasingly been used for its safety and convenience benefits [21].

The American regulation governing automobile glazing is found in 49 CFR Ch. V, 571.205; *Glazing Materials* [1], which indicates that the purposes of the standard are to:

1. "Reduce injuries resulting from impact to glazing surfaces
2. "Ensure a necessary degree of transparency in motor vehicle windows for driver visibility
3. "Minimize the possibility of occupants being thrown through the vehicle windows in collisions."

The federal regulation incorporates by reference a non-governmental standard, ANSI/SAE Z26.1, last revised in 1996 [5], which provides for material performance. Neither the FMVSS 205 nor the ANSI Z26.1 governs the overall safety performance of the glazing system.

The rise in popularity of sport utility vehicles (SUVs) has brought about serious occupant safety issues. With their relatively high center of gravity and narrow track width, these vehicles roll over much more easily than do sedans. Thus, ejections through window openings have also risen. Even with a significant rise in national seat belt usage, the fatal ejection rate has not proportionately diminished [39]. The National Highway Traffic Safety Administration (NHTSA) has recently investigated the requirement for occupant retention side glazing within automobiles in positions other than the windshield and ultimately decided against mandating this technology [15;39;40;42;43]. Within their analysis, NHTSA did not look at injuries such as laceration, entrapment, and eye trauma. This present research analyzes previous NHTSA work, compares injury mechanisms not investigated by NHTSA within their advanced glazing work, and presents the results of new testing. Statistical analyses focus on 1999, the last year for which data was available at the time of making the decision not to implement occupant retention side glazing across the US fleet.

LAMINATED GLASS

Laminated glass is the original *safety glazing material*. Automotive "safety glazing material" was first defined in 1938 by the American National Standards Association, which wrote, "Specifications and methods for safety glazing material (glazing material designed to promote safety and reduce or minimize the likelihood of personal injury from flying glass material when the glazing is broken) as used for windshields, windows, and partitions of land and marine vehicles and aircraft (emphasis added) [4]. This definition was subsequently altered, and the most recent revision defines "safety glazing materials as, "A product consisting of organic and/or inorganic materials so constructed or treated to reduce, in comparison with annealed sheet, plate, or float glass, the likelihood of injury to persons as a result of contact with these safety glazing materials when used in a vehicle, whether they may be broken or unbroken, and for which special requirements regarding visibility, strength and abrasion resistance are set-forth" [5].

Factory automotive laminated glass is almost universally of "trilaminate" construction featuring two plies of solar-tinted soda-lime glass sandwiching a sheet of polyvinyl butyral (PVB) that provides the impact toughness that the glass cannot. In the early 1960s, the formulation of laminated automotive glazing (principally for the windshield) was fundamentally changed for the US market to improve its safety properties [3]. The PVB interlayer thickness was doubled to 0.030" (0.76 mm), and controlled adhesion of the plies replaced maximum adhesion. Impact testing of HPR (High Penetration Resistant) laminate shows that full penetration with a 10 kg (22 lb) headform are uniformly high, e.g. 44 kph (28 mph) [49], and 48 kph (30 mph) [47]. This design requires approximately three times the kinetic energy for a blunt impactor to penetrate compared to a tempered lite [14].

Besides the safety advantages that are described herein, laminated glass demonstrates numerous ancillary advantages [11]. These include reduced ultraviolet transmission and associated fabric fade, noise attenuation, security (intrusion resistance), higher optical quality, superior visibility when broken, replacement ease, and infra-red load reduction with proper interlayer coating. A trade group, the *Enhanced Protective Glass Automotive Association* (EPGAA) [21] promotes the usage of LSG for its desirable safety, comfort and convenience properties.

TEMPERED GLASS

Tempered glass is the dominant glazing for automotive side lites, and has been since the early 1960s when it almost completely displaced laminated glass in these positions for economic reasons [56; 57]. The American Society for Testing and materials (ASTM) standard C1048-04 [6] specifies two basic levels of surface compression as a result of thermal treatment, types FT and HS. Type FT (fully tempered) generally has a minimum surface compression of at least 69 MPa (10,000 psi) or an edge compression of at least 67 MPa (9,700 psi). Fully tempered glass is generally considered to be four times as strong as annealed glass. Moveable monolithic side window glazing is always fully tempered glass. Type HS (heat strengthened) glass has a surface compression of 24-52 MPa (3,500-7,500 psi). Heat strengthened glass is approximately twice as strong as annealed glass, and has similar fracture characteristics. Most laminated side glazing in fixed window positions retains at least some heat strengthening as consequence of the forming process (that is, it is not annealed back to a stress free state after bending).

When properly constructed, the majority of fragments created during controlled fracture of tempered glass are relatively small and blocky. The pertinent federal standard, Federal Motor Vehicle Safety Standard (FMVSS) 205, *Glazing Materials* [1], requires that, post fracture, no piece away from the periphery or crack initiation site remains uncracked or has a weight exceeding 4.25 g (0.15 oz). However, uneven tempering, bending, or twisting of the lite prior to fracture can produce splines, which are fragments with large aspect ratios. If the crack produced by the tensile separation within the glass during the fracturing process does not extend to the surface, then large, internally cracked fragments remain, and are more potentially injurious than are blocky fragments.

The principal advantages of tempered glass are its reduced cost compared to laminated and its strength in compression and bending. Its strength provides lower scrap rates in production and increased blunt impact and shock performance. Further, its properties are temperature independent. It can be thinner and lighter than laminated side glass, and does provide some modest level of occupant ejection mitigation. Unlike HPR laminated glass, tempered glass cannot be used within the vehicle without restriction; tempered glass may not be used within the windshield, either alone or as one or more plies of the laminated construction.

GLAZING-RELATED INJURY STATISTICS FOR MAJOR ACCIDENTS

According to the NHTSA publication, "1999 Traffic Safety Facts [41] for the year 1999, there were 6,279,000 accidents recorded, of which 2,990,000 were towaway [17] and 277,000 of those towaway accidents involved rollover [41]. Figures 1 and 2 provide side-glazing related serious and non-serious injury estimates for towaway accidents based upon a variety of sources detailed herein. There were approximately 227,500 injuries due to flying tempered glass fragments, making this the dominant injury mode [17]. Flying tempered glass fragments cause almost exclusively non-serious injuries, with only one serious chest injury recorded within the 1999 NASS-CDS database. The "head/neck impact" category indicating ~41,300 non-serious and 740 serious injuries refers to non-lacerative contact injuries (i.e., concussion, contusion, dislocation, fracture, sprain and strain). For side glazing, the lacerative injuries were estimated to be 20,000, all of which were non-serious [17].

Side glazing related serious injuries and deaths are totally dominated by ejection, with approximately 13,100 instances in 1999 coupled with an additional ~18,800 ejection-related minor injuries [42]. The national estimate of glazing-related ocular injuries gives 2,030 occurrences. All of these were coded as minor (non-serious), as almost all eye injuries including total blindness are considered to not be life-threatening [17]. By using historical data [28;17], instances of permanent vision degradation from glazing (including windshields) can be estimated at approximately 520 for 1999. The estimate done for this research of true instances of glazing-related entrapment (not injury) that is shown in Figure 1 is 600, based upon the number of towaway accidents recorded for 1999 and historic data [17;12]; note that entrapment does not necessarily indicate injury. The statistics cited indicate that, excluding ejection, 99.5% of side glazing related injuries are not serious.

By comparison, HPR windshields yielded 99,015 total laceration injuries in 1999, of which only 202 were serious or fatal. This represents 0.2% of interactions [17]. The incidence of windshield ejection was approximately 4,420 averaged over 1995-1999 [40] using fatalities as adjusted to the 1999 FARS. Approximately 8.6% of glazing ejections are through the windshield, while frontal collisions represent well over 50% of collisions [41].

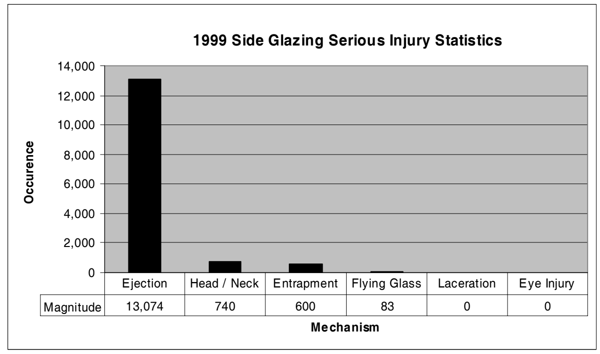

Figure 1: Estimates of side-glazing related serious injury occurrence by type.

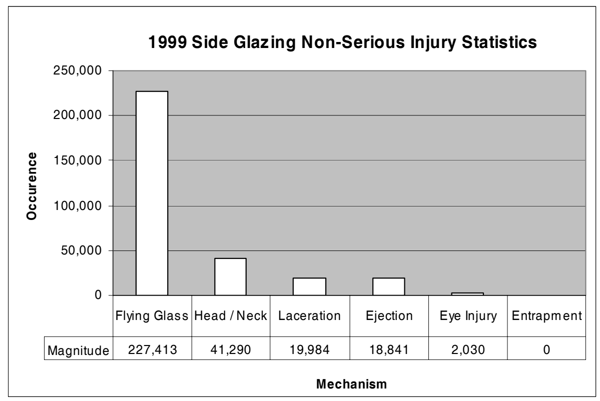

Figure 2: Estimates of side-glazing related non-serious injury occurrence by type.

INJURY MECHANISM ANALYSIS

Injury from glazing contact has long been of concern. Both tempered and laminated glazing designs of today produce fewer injuries than did previous formulations. Fewer vehicles produced today contain laminated side glass than do tempered; it is not possible at this time to conduct a robust statistical analysis of injuries in rollover collisions comparing the two, but current and previous work is sufficient to give a relative injury comparison.

Digges and Eigen [20] showed that in multiple-roll rollovers the rate of injury, even for unrestrained occupants, is less than 5% regardless of the number of rolls, Figure 3. For ¼-roll collisions, approximately 94% of the severely injured occupants received their injuries either from impact with another vehicle or from impacts with fixed objects (e.g., trees, poles) either before or during the rollover. The injury rate for one quarter-turn collision involved vehicles that do not impact other vehicles or fixed objects is less than one per 100 exposed.

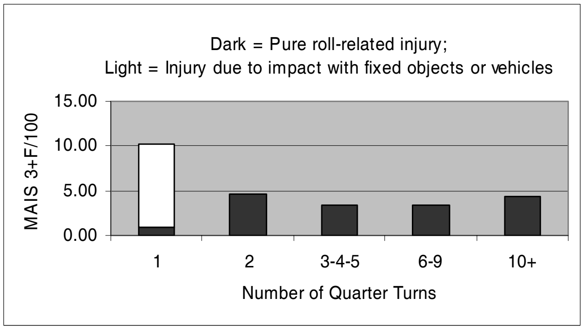

Figure 3: Injury rate of unbelted non-ejected front seat age 12+ occupants with serious injuries in rollovers by number of quarter-turns [20].

Partial and Complete Ejection

The greatest risk of serious occupant glazing-related injury is associated with ejection through the window. Previous work [8;9] has detailed the failure mechanisms of side glazing facilitating ejection. Window size is also important; ejection through glazing from 2-door cars is twice as likely as it is with 4-door vehicles [19]. This is the reason that side window sizes of school buses are restricted. Three-point passive safety belts are principally designed for frontal impact injury mitigation, particularly those with B-pillar mounted D-rings. During the chaotic motion generated by highway speed rollovers, even initially properly-belted occupants can be partially or fully ejected, Figure 4. Seat belts are not a panacea. Digges showed that although a consistent majority of rollover fatalities were determined or believed to have not been wearing their seat belts, a substantial 28% were, in fact, restrained but died anyway [18]. If ejected, the chances of serious injury and fatality increase. Estimates of the increased risk of MAIS 3+ injury due to ejection range up to 40 times as high for ejected vs. non-ejected occupants [36;39].

The study presented in Table I indicates the percentage of serious injuries and fatalities to occupants who remained in their vehicles during light vehicle rollover [16]. The findings indicate that approximately 4% of unbelted occupants incur severe injury or death in rollovers when completely contained. For those occupants who remain belted throughout the rollover accident, the percentage declines to less than 3%.

Figure 4: Sport utility vehicle rollover with sunroof ejection, probable 3 complete rolls [29].

Table 1: Percentage of serious injuries (MAIS 3-5) and fatalities sustained by occupants in light vehicles during rollover [16].

Restraint	No Ejection	Complete Ejection
Unbelted	4.2	34.9
Belted	2.5	40.8

It has long been recognized that tempered side glass is brittle and contains little or no inherent energy-absorbing capability [56]. Once broken at any point, it can no longer offer any occupant containment and in fact becomes more hazardous than a moveable window that has been retracted. As early as 1968, HPR laminated side glazing has been described as "state of the art" for energy absorption and occupant containment [26]. Significantly, the "P" in HPR refers specifically to occupant ejection mitigation, rather than impact protection from outside objects [47]. The change to the HPR windshield in the mid 1960s occurred after the domestic auto industry exchanged laminated side glazing for tempered in the early 1960s, and therefore the entire vehicle did not take advantage of this new technology.

Occupant retention side glazing for passenger vehicles has been effectively demonstrated by Clark and Sursi [13], who used 8 dolly rollover tests to show 100%

effective occupant containment, even for those 6 tests with unbelted first row anthropomorphic test dummies (ATDs). A set of pictograms currently applied to many St. Gobain laminated glass side windows is shown in Figure 5, indicating its energy absorption capability, showing occupant retention at lower left, and intrusion resistance at lower right.

Figure 5: Laminated side glazing pictograms signifying "occupant containment" (left) and "exterior impact resistance" (right).

The proof of the efficacy of laminated glass is shown in the two photographs of Figure 6. The top photo shows an ATD impact into a Volvo S80 right rear door at an initial inclination angle of approximately 17^o at a nominal 16 kph (10 mph). The second photo at bottom shows a laminated S80 front door with two surface chips indicating a foiled entry attempt.

Statistical work by Batzer, et al. [10] indicates that vehicles with commercial first row moveable laminated side glazing that is not optimized for occupant retention still produce fewer occupant ejections than do equivalent vehicles with tempered first row side glazing. Other technologies are available to rollover collision injuries. The most promising seems to be electronic stability control to prevent such accidents and side curtain airbags that are purpose-designed to contain occupants rather than to only provide impact amelioration. Laminated side glass provides a reaction surface for these airbags, increasing their effectiveness.

Figure 6: Volvo S80 glass impact performance - containment (top); security (bottom).

Occupant to Glazing Impact

Historically, the vast majority of neck and head injuries in automobile crashes result from contacts with relatively rigid structures such as the pillars and rails [45]. To address this, the FMVSS 201, *Occupant Protection in Interior Impact*, requires energy absorbing materials on various components. As part of their occupant retention glazing analysis [39;40;42], the National Highway Traffic Safety Administration (NHTSA) conducted a study including the scope of current injury rates, technical feasibility, cost, tradeoffs, and potential benefits and disbenefits, particularly for ejection injuries prevented and possible increased occupant-to-glazing contact injuries. Various side glazing materials were studied including monolithic tempered as the baseline, HPR trilaminate, a non-HPR trilaminate, polycarbonate (monolithic rigid plastic), and glass-plastic bilaminate. NHTSA conducted free-motion headform tests to measure HIC (head injury criterion) indicating potential brain injuries, side impact sled tests to measure potential neck injuries, and virtual rollovers of human models capable of giving injury data.

For a frontal barrier crash at 48 kph (30 mph), the FMVSS 208 [2] sets the maximum permissible HIC (Head Injury Criteria) level at 1000 for 36 ms (HIC 36) as defined by:

$$HIC = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a \, dt \right]^{2.5} (t_2 - t_1) \qquad (1)$$

where: a is the resultant head acceleration; t_2-t_1 = 36 ms; and t_2 and t_1 are selected to maximize HIC. It should be noted that, then as now, no injury criteria in side impacts to the head for either HIC or other injury mechanisms are generally agreed upon by NHTSA. During side impacts and rollover collisions, the head and shoulders can hit virtually any portion of the glazing. Two points, the upper rear corner of the glazing and the approximate geometric center were chosen by NHTSA for study, Figure 7:

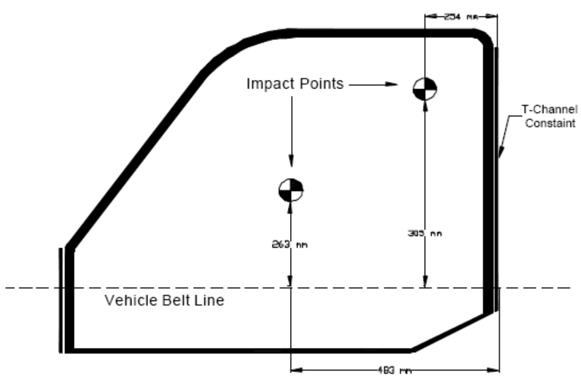

Figure 7: NHTSA targeted glazing impact locations [40].

NHTSA's free motion headform tests indicated that head and brain injury are both unlikely with any side glazing formulation considered. A combination of hits to the geometric center of the glazing and the upper rear corner were used; their averages are shown in Figure 8. Note that for this and the following NHTSA graphs, the number of individual tests per glazing type is included in parenthesis.

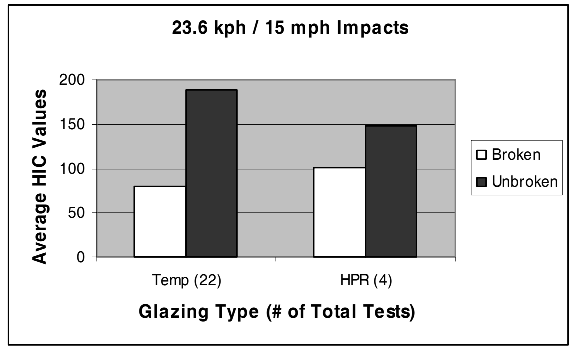

Figure 8: Average of center and corner impact HIC values for 23.6 kph strikes [40].

As expected, unbroken lites produce a greater injury potential than do broken lites that fail to completely retain the headform. The increased rigidity of the tempered lites ensured a higher HIC when unbroken. However, when broken, the HPR lites, with their greater retention capability showed a higher HIC value. None of the testing of tempered or HPR side lites showed values close to 1,000, which is an agreed to threshold for serious injury.

NHTSA also performed HYGE sled tests, moving doors containing experimental lites at speeds of up to 24 kph (15 mph) into the ATDs. To determine the maximum neck injury potential of such impacts, the dummy was tilted to about 26^{o} toward the glazing to help ensure that initial contact was by the head, rather than the shoulders, maximizing neck loading, rather than realism. In actual rollover collisions, occupant to glass loading is generally substantially less than 24 kph [10], and in side impact collisions the shoulders typically impact the window prior to the head, affording head and neck protection. The rigidity of the Hybrid-III neck ensured the neck orientation remained as desired. The values determined for the tests using the experimental glazing panels are given in the Figures 9-11. Note that there were not, and are not, neck injury criteria for side impacts that are generally accepted by NHTSA researchers. The criteria given by NHTSA in two different 1999 publications [22;40] differ significantly.

Figures 9-11 show five individual data points per set of tests; 2 tempered, 3 HPR. The white portion within the center of the bars shows the minimum, mean, and maximum values of the test. Again, the number of tests performed is shown in parenthesis on the horizontal axis. The dark band which extends past the maximum and minimum values gives a confidence interval of the mean, by assuming that occupant to glazing impacts are Gaussian (normally) distributed.

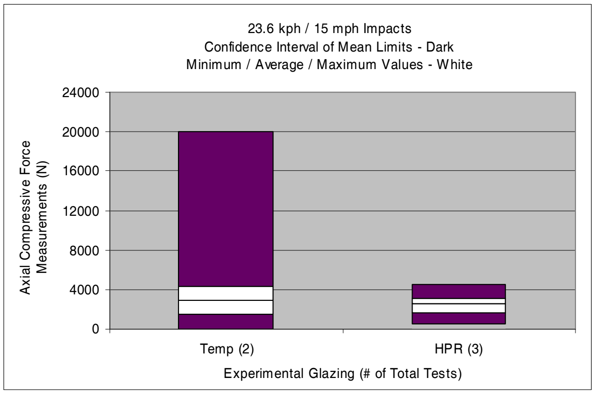

Figure 9: Axial compressive force [40].

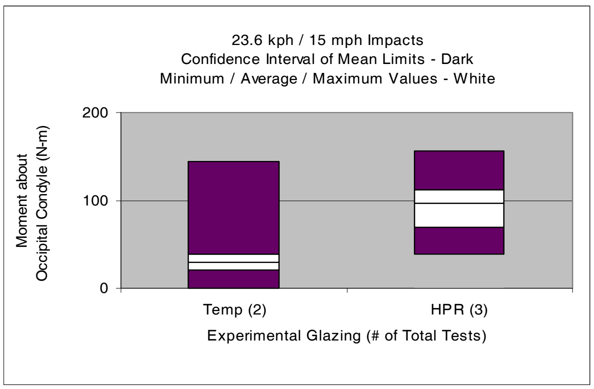

Figure 10: Moment about occipital condyle [40].

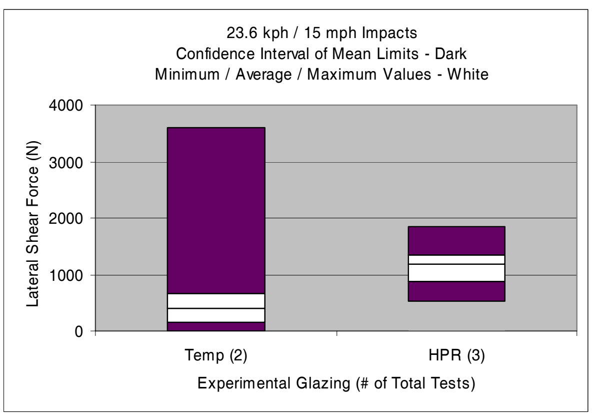

Figure 11: Lateral shear force [40].

As is shown, significant variability was measured in lateral neck shear loads, axial compression, and moments about the occipital condyles. Further, the dearth of measurements (2 tempered tests, 3 HPR laminate tests) ensures that the confidence intervals of the mean are very broad and overlap for the two glazing materials for each injury mechanism. It was observed that occupant to glazing impacts were, in general, more severe with HPR laminated than tempered for the limited data set presented. However, the occupant usually does not strike tempered glass in rollover collisions with sufficient force to cause fracture, as the glazing is already broken out due to body flexure and ground impact forces [16;36].

NHTSA's experimental work demonstrated that currently available HPR glazing used in side positions is capable of retention, has low HIC values and probably does not exhibit a potential for head or neck injury for healthy occupants at likely rollover impact velocities. In fact, NHTSA declared, "…even if there can be small increases in low level neck injury, it is anticipated that the fatality prevention benefit of advanced glazing would likely greatly outweigh any such disbenefits" [40].

NHTSA's work has confirmed previous insights. When tempered glazing was being compared to the old style, non-HPR laminated glazing in the 1960s, the similarity in impact trauma was recognized. Patrick stated in his 1995 SAE paper [46] "Laminated side glass would not be hazardous from an impact standpoint (except for laceration) when struck with the glass in its normal position."

A further comparison can be made with non-HPR to HPR type windshields. The resistance to penetration dramatically increased with this newer technology, and could presumably have caused more blunt impact trauma. According to Kahane [30], "With pre-HPR glazing, there was a 50 percent probability that an unbelted occupant would penetrate the windshield in a frontal crash with a Delta V of 14 miles per hour. With HPR glazing, the likelihood of penetration does not reach 50 percent until the Delta V is 31 mph." The difference between these two velocities for a fixed occupant mass is 120% greater momentum and 390% greater kinetic energy. Kahane continues, "HPR windshields had little or no observed effect on injuries characteristic of blunt impact trauma: concussions, contusions and complaints of pain."

Rushworth, et al. [50], agree with Kahane. They estimated in the late 1960s that tempered windshields outnumbered laminated windshields in Australia by 8:1. Further, these 6 mm (quarter inch) nominal thickness tempered windshields required up to 9,100 N (2,050 lbs) to fracture. Yet, "…no serious closed head injuries from impact with the windscreen alone have been encountered by us…this aspect appears to be unimportant." Sances, et al., showed through drop testing of Hybrid-III dummies that the potential for neck injury due to impact into laminated side glazing is low in rollovers [51;52].

Entrapment

Testing and experience show that neither tempered nor laminated glazing is easy to penetrate without tools. Quasi-static pushout tests of moveable side lites show production tempered glass to take over 500 lbs of force without fracture. While laminated glass can be kicked through with multiple impacts, tempered glass will not progressively damage, and will resist most human attempts at fracture.

The Cornell Aeronautical Laboratory studied regarding automobile glazing as an injury factor in accidents [12]. They indicated that entrapment was extremely rare, and requires all of the following conditions to be true (emphasis in original text):

- "All car doors jammed shut or otherwise blocked, <u>and</u>
- "All windows rolled up, <u>and</u>
- "All windows jammed such that they could not be rolled down, <u>and</u>
- "All glass surfaces intact."

Additionally, the occupant(s) must have survived the initial accident to make egress relevant. The researchers studied 30,000 accidents, of which only 755 cases presented a situation in which escape through the doors was not possible. "In only 12 of these was there a need for immediate escape because of fire or immersion. In none of the 12 was there a clear-cut indication that egress depended upon the necessity for breaking a glass surface. Three hundred of the 755 were studied individually and the indications were that egress would have been possible without resorting to breaking glass in most, and perhaps all, cases…it stated with confidence that the number is extremely small."

The findings of the Cornell report were supported by the *Submerged Vehicle Safety* study [31]. This report listed as its purpose, "to determine the sequence of events when automobile is suddenly submerged in water deeper than the vehicle itself, what passengers can do to save themselves, and how passengers can be rescued". Four passenger cars were used for data acquisition and three others were used for test feasibility studies. A total of forty-nine tests were run using a 4 meter deep pool. The recommendations regarding proper actions required 20 pages of text and a 20-minute film in explanation. Escape recommendations included:

> "Following impact, for a vehicle entering on its top, the occupant can escape by keeping his head against the floorboard, inhaling deeply, and leaving the vehicle through the open windows which are under the surface.
>
> "If the occupant is unable to escape through the front windows after impact, he should position himself to the rear of the passenger compartment in the existing air so as to provide more time to plan his escape, as the vehicle will descend to the bottom on its top, engine first. Escape at this time can be accomplished through an open window, or by opening a door."

According to Morris, et al. [38], "whether using laminated side and rear glass would in fact make it difficult for an entrapped occupant to escape can only be speculated at this stage since field data is not available to allow conclusions to be drawn." They conclude, "In summary, we have shown that ejection is an undesirable outcome and that retention is more desirable. Introduction of any alternative security glazing material in the side and rear windows would be welcome, especially as it is anticipated that it would reduce the incidence of ejection."

Patrick's analysis of available glazing materials [46] affirmed that laminated glass gives a slight performance edge over tempered in entrapment situations. However, he felt that this was not even of concern in Holland, which has a high number of canals along the roadways. Hassan, et al. [25] studied the implications of laminated side glazing for occupant safety, and determined that "occupant entrapment is not likely to be a major problem."

Laceration

The dominant glazing injury mechanism, by far, is that of laceration [46;57]. By studying the leading automobile accident mode, the frontal collision (representing ~60% of all accidents for passenger vehicles and light trucks [44]), it is possible to gain insight into the lacerative potential of windshields, and by extension, tempered and laminated side glazing. The contact mechanics are comparable, and in Europe, tempered windshields were produced side-by-side with HPR-formulated windshields for years. Field experience has led Western Europe to follow the United States in requiring HPR laminated glazing for all windshields of passenger vehicles.

Patrick, et al. [48], wrote that, "Severe lacerations resulted in all impacts in which tempered glass broke. Less severe lacerations were found for the laminated windshield impacts at comparable speeds." They go on to indicate that the consensus of German researchers in the 1960s was that penetration of tempered windshields caused severe facial lacerations and eye injuries ranging from minor to total loss of sight. They recommended the usage of laminated over tempered windshields due to the disproportionate number of injuries, particularly laceration, caused by tempered glass.

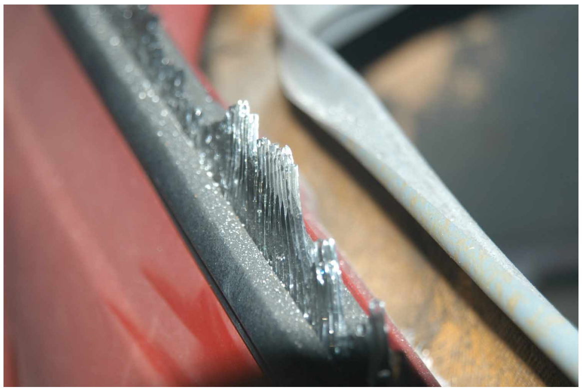

Figure 12: Laceration source from tempered glass fragments, fractured fixed quarter lite.

The superiority of HPR windshield glass over the previous formulation is universally recognized, "HPR windshields have already been informally evaluated. The dramatic reduction in the demand for facial plastic surgery following the introduction of HPR made it clear to the safety community that [the requirement for] HPR has been, perhaps, more successful than any other standard [30]." The slicing and soft tissue laceration commonly seen in pre-HPR glazing was replaced by "relatively minor scrape-like abrasions," some pitting injuries, and fewer concussive brain injuries [27;55].

In multiple-roll rollovers, the possibility exists for multiple impacts against laminated occupant-retention glazing. Batzer, et al. [7], found that the laceration potential did not substantially increase in multiple impacts against EPG style laminated side glass with multiple impacts without through-glass penetration, Figure 13.

The lacerative potential of tempered glass fragments depends upon how it is handled. Casual, low-pressure handling of "dice like" fragments of tempered glass gives an unrealistic impression of their danger. Such fragments contain points and edges which are sharp, not rounded as is sometimes claimed.

Figure 13: Blunt impactor testing of EPG style laminated side glazing.

Severy and Snowden [54] conducted glazing tests and reported that, "Subsequent examination of high speed movies of these experiments revealed that tempered glass fragments may move as clusters, an inch or two across the long axis, so that the comment concerning hazard arising from tempered glass weight should be modified. It was also observed in collecting the fragments that while many particles are cube-like, as described by other investigators, most were by no means free of sharp points or edges, making them very difficult to handle without cutting one's hands." Yudenfriend and Clark [57] found in door impact testing that 20-40% of the glass fragments flew inward toward the occupant survival space, and that they entered that space at velocities as high as 23 km/hr (14 mph). The speed, size, shape, and sharpness of tempered glass fragments explain why some shards have been found to penetrate skin and skull and even enter the brain [57]. Citations regarding skull penetration of glazing fragments refer exclusively to tempered fragments, rather than to the annealed fragments produced by laminated glass [50;24].

Ocular Injuries

When tempered glass shatters in collisions, it is usually stressed under the conditions of bending or shock loading, and can shower fragments into the occupant space. Laminated glazing spalls and creates small, even dust-like, fragments. However, the quantity of laminated glass fragments detaching from the polymer laminate is, in general, less than 1% of that from tempered glazing. In one side collision with fractured tempered glazing, a woman complained to her physician of persistent eye irritation. This lead to an X-ray examination that indicated that a fragment was lodged behind the eyeball itself and rested against the optic nerve. This can be explained by gross inertial deformation of the eye during the crash pulse that caused a separation between the ball and the surrounding tissue, allowing introduction of the fragment.

HPR laminated versus tempered windshield ocular injury was investigated by Langwieder [32], who found only one eye injury from HPR laminated glass from those 228 occupants who had head injuries. Tempered windshields induced about 17 cases of eye injury from 545 head injuries. This represents a sevenfold increase in injury rate for tempered windshields over laminated.

Figure 14 Fractured tempered back lite after rear impact. Driver penetrated window and was blinded in left eye.

Both McLean and Mackay, et al., discussed the severe injuries that occur from the tempered fragments that remain at the frame around the windshield opening [37;35]. The ANSI Z26.1 standard does not regulate the size or shape of fragments at the periphery of the window.

The higher injury rate associated with tempered windscreens when compared to HPR laminated windshields was also investigated by Mackay [34]. He concluded that, "Eye injury from toughened glass windscreens is a substantial problem reflected in the clinical literature from at least 12 countries. By contrast, countries which use HPR laminated glass report no incidence of eye injuries from the windscreen of any consequence."

Huelke studied a 27-month period of National Crash Severity Study data (January 1977-March 1979) comprising 106,000 passenger vehicles involved in towaway crashes [28]. The data included vehicles with pre-HPR windshields. No single occupant of the 106,000 accidents studied had been totally blinded, but there were 29 occupants who received serious ocular injuries. Various objects within and outside of the vehicle caused the various eye injuries, but the predominant agents (~64%) were the windshield and side glazing.

The mechanism of increased laceration and ocular injuries produced by tempered over laminated HPR glazing is illustrated in the photographs given in the Figure 15. Note that these vehicles are not equipped with first row airbags. The vehicles were directed into a frontal impact with a fixed barrier at 12 o'clock. The unrestrained right-side dummies moved forward and impacted the dashboard with their knees and chests, and against the windshields with their heads.

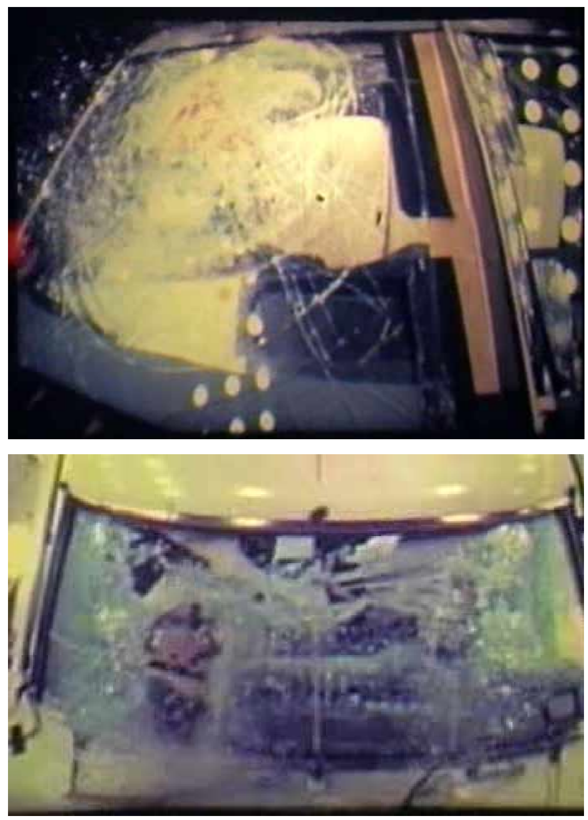

Figure 15: Passenger (right) side dummy impact against an HPR laminated windshield (top) and a tempered windshield (bottom) [23].

The impact against the HPR laminated windshield (top) shows typical performance. The glass fractures but largely remains adhered to the polymer interlayer. Spalled fragments are shown from the exterior glass ply against the dark background. The dummy's head does not show significant relative downward motion (scrub) against the inboard glass ply that would have presented an enhanced laceration hazard. The impact against the tempered windshield produces progressive fracture of the glass, with maximized laceration. That is, the glass does not break and fly away in a single instant. It largely retained its planar shape and presented progressively formed edges against the dummy's face as the head moved forward and downward toward the dashboard.

In 1975, UK researcher G. Murray Mackay wrote, "It is of note that all papers reporting eye injuries originate from countries where the windscreens of cars are made from toughened glass [33]."

ANALYSIS AND CONCLUSIONS

The injury mechanisms of both laminated and tempered automotive side glazing constructions have been compared. This study confirms and supports with new research the body of 30 years of work in a comprehensive manner. The mechanisms of injury for automotive side glazing are identical to that of the windshield, of which has been written, "The principal finding of this field study of accidents is that tempered glass is inferior, from the viewpoint of producing injury, than the 0.030" interlayer laminated glass" [35].

The greatest serious injury threat to both belted and unbelted occupants is that of complete or partial ejection. If the side window portal is kept covered in a collision, occupant containment can be realized. The greatest non-serious injury mechanism is that of laceration, principally through flying fractured tempered safety glass. Ocular injuries are shown to be relatively rare, and other injuries, such as entrapment-induced injury, are even rarer. The safety benefits of the major two types of side glazing are listed in Table 2 below.

Table 2: Side glazing injury attributes
most beneficial glazing marked "X"

Attribute	Tempered	Laminated
Airbag Assistance		X
Containment		X
Entrapment		X
Eye Injury		X
Fire Protection [53]		X
Impact Blunt Trauma	Neither	
Laceration		X
Skull Penetration		X

Significantly, LSG has been shown to be the superior material for addressing the two injury causation mechanisms (impact and ejection) given as purposes for the FMVSS 205. For the third purpose, providing driver visibility, LSG is also superior, as it does not vacate the portal when fractured or pixelize. Thus, for each of the three stated FMVSS205 purposes, laminated safety glazing has been shown to be the superior material for side window applications when compared to tempered safety glazing.

ACKNOWLEDGEMENTS

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CRASHWORTHINESS ANALYSIS OF THREE PROTOTYPE AMBULANCE VEHICLES

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ABSTRACT

This paper is an evaluation of the predicted safety performance of three USA prototype ambulance vehicles with aftermarket structural modifications. Expected safety performance was analyzed using existing and established automotive safety principles. Information on design and construction of the vehicles was identified, and evaluated via application of basic engineering crashworthiness principles and laws of physics, with a specific focus on countermeasure design for reducing harmful loading and injury causation potential in crashes or sudden decelerations. Data sources used for the analysis included: vehicle specifications, inspections, photographs, crash tests and published crashworthiness and injury mitigation literature.

Results demonstrated poor vehicle structural integrity and crashworthiness for these aftermarket modified ambulance vehicles. Assessed crashworthiness performance and occupant protection do not appear optimized even for the minimally structurally modified van. Current interior design features (seat design, patient transport device design, head strike zones and restraint systems) and layout, demonstrated predictable serious crashworthiness and occupant protection hazards.

These are projected findings, rather than actual crashworthiness tests – however this is the first comparative automotive safety evaluation of prototype ambulance vehicles. This is key information for a major fleet of vehicles globally which has had minimal automotive safety attention or input to date.

From this study it appears there are major deficiencies in safety design of these prototypes. Emphasis on a passenger compartment that has crashworthy features, effective seat design, based on existing literature and a clear focus on occupant human factors and equipment location and anchors, could provide for major safety enhancements for ambulance vehicles. There is need for vehicle safety researchers, ambulance industry and vehicle designers to recognize and apply these existing principles to reduce current failures in an important and essential service that appears to have a poor safety record, considerably below that of other passenger (Maguire 2003, Ray 2005, Levick 2006) and also other commercial vehicles (FMCSA).

INTRODUCTION

Emergency Medical Service (EMS) vehicles, ambulances, are an unusual vehicle in the transportation system for a number of reasons – they carry passengers in a number of orientations, are part of an emergency response system, are built primarily as aftermarket modifications to existing vehicles or have a 'box' secured to a light or heavy truck chassis (all conducted outside of the existing automotive safety infrastructure), and are also occupational environments for the EMS providers. However, in the USA ambulance vehicle safety is addressed outside of the Federal Motor Vehicle Carrier Safety Administration system – in regards to crash events and outcome data collection and hence do not share the same comprehensive safety oversight of other commercial vehicles.

Capture of safety performance of these vehicles is at best scant – and rudimentary at a national level and has been demonstrated to be incomplete (McGuire 2003). The data that has been published highlights that ambulances are associated with high crash fatality and injury rates per mile traveled and that compared to other emergency vehicles (Becker 2003) have high occupant fatality rates and that also compared to trucks have almost double the percentage of occupant fatalities. It is recognized that the hazards are greatest for occupants of the rear compartment (Becker 2003).

Given this background and the existing, albeit scant, biomechanical and crashworthiness data that have been published – the issue of identifying crashworthiness and occupant hazards has been raised in a number of sectors.

One response to this safety performance challenge has been for a spectrum of people to attempt to address the occupant safety and crashworthiness of these vehicles and largely on an individual level . However, as well intentioned as these initiatives have been , they have primarily involved small teams of Emergency Medical Service end users and after market manufacturers and had very minimal, if any, input from key and recognized automotive safety expertise, and very minimal application of in depth understanding of automotive safety and crashworthiness principles.

EMS is a relatively new industry, an industry that has an unusual history of beginnings within the mortician industry. The first modern ambulances were hearses, usually a Cadillac station wagon, a vehicle in which an occupant could be transported in the recumbent position. Proximity and access to the patient was not a challenge in that environment, which was very compact. However over the past 50 years ambulance vehicles in the USA have become larger and larger – and transitioned from the intact automotive passenger vehicle to the truck chassis with an after market 'box' or a modified van with an aftermarket elevated roof. What should be kept in mind is that these vehicles, related largely to how they are operated, are vehicles at high risk of crash and thus it would seem prudent that the safety and crashworthiness of these vehicles be optimized.

How safe are EMS vehicles and to what standards are they designed and tested? Despite the large strides that the general automotive industry has made in the last 30 years in the safety of passenger vehicles, this expertise has not yet been translated substantively to the safety of ambulance vehicles. There are few safety standards and no crash safety test procedures or guidelines that provide occupant protection in ambulance vehicles in the USA. Limited safety testing requirements were established in Europe in 1999 (CEN 1789). Australia has had the ambulance restraint standard ASA 4535 in place since 1999, and it is the most stringent globally (AS/NZS 4535). Thus ascertaining the safety of EMS transport vehicles (and products in that environment in the USA) remains limited largely to sparse expert opinion and peer evaluation, often by non automotive safety engineering expertise and in a piecemeal fashion.

EMS has been generally demonstrated recently to be a dangerous profession, and vehicles crashes have been shown to be the most likely cause of a work related fatality in EMS (Maguire 2003). The most dangerous part of the ambulance vehicle has been demonstrated in both biomechanical and epidemiological studies to be the rear patient compartment (Becker 2003, Levick 2000-2006), which currently is a part of the ambulance vehicle that is also largely exempt from the USA Federal Motor Vehicle Safety Standards (FMVSS). Also, unfortunately, no reporting system or database exists specifically for identifying ambulance crash related injuries and their nature, so specific details as to which injuries occurred and what specifically were the mechanisms which caused them are scarce, and there is not yet a national system for this data capture in the USA.

What we do know is that ambulances have high crash fatality rates per mile, well above those of passenger vehicles, or even when compared to similar sized vehicles (Ray 412).- and there is approximately one ambulance crash fatality per week in the USA, and a number of serious injuries for each fatality, with over 4,000 reportable crashes per year (Becker 941).

There has been a limited number of peer reviewed automotive safety engineering tests conducted for the EMS environment in Sweden (Turbell 1980), Australia (Best 1993, Levick 1998), and the USA (Levick 2000-2001). That which has been conducted has clearly identified some predictable and largely preventable hazards, particularly pertaining to intersection crashes and the hazards of the rear patient compartment, demonstrating the benefit of use of existing restraints for occupants, the importance of over the shoulder harnesses for the recumbent patient and firmly securing all equipment (Best 1993, Levick 1998-2006). These studies also identify hostile and hazardous interior surfaces of the rear compartment, as well as a need for head protection.

Many fatal and injurious ambulance crashes occur at intersections – either with the ambulance being struck with a side impact (more likely on its right side) or frontal impact. Failure to stop at an intersection for all vehicles is an extremely high risk practice. Lack of use of seatbelts by EMS personnel is cited frequently in the literature as a predominant cause for the high injury and fatality rates for occupants in EMS crashes (Becker 2003). The hazards resulting from the failure to secure equipment in the patient compartment, which has also been found to cause serious injury in the event of a collision has also been documented. This is supported by the engineering data from ambulance safety research involving crash tests (Levick 2001), as well as insurance and litigation records. With ambulance crashes being identified in the USA as the highest cause of patient adverse event mortality and serious morbidity (Wang 2007).

The very recently developed American National Standards Institute/American Society of Safety Engineers Z15.1 Fleet Safety Standard (ANSI/ASSE 2006) is possibly the only nationally approved fleet safety standard that is now applicable to the safety management of EMS vehicle fleets. It requires that the vehicles be crashworthy and safe – yet, in the USA there are no crashworthiness standards for these vehicles. The only USA guideline is the GSA KKK purchase specification, which does not provide for guidelines for dynamic crash testing – rather simply static tests. It is likely that the implementation of ASSE/ANSI standard will enhance the data collected regarding EMS vehicle safety, and hopefully provide more emphasis on EMS vehicle safety generally and assist in bringing EMS vehicle safety more inline with state of the art automotive safety practices.

Complexity of the Vehicle

A primary challenge to determining a dynamic safety testing profile in EMS is that of a spectrum of occupant orientations and structural crashworthiness performance of the rear compartment. The rear compartment is an environment containing a combination of occupant positions, for health care providers and the patient and any family members and also a large amount of different types of medical equipment, such as cardiac monitors and oxygen cylinders.

Complexity of the Activities in the vehicle environment

The rear compartment is also an environment where health care activities, access to equipment and communications are all undertaken. So that the design and crashworthiness features need to consider these activities – even though it has been described that emergency life saving procedures are only required in less than 5% of EMS transports.

Crashworthiness and Occupant Protection Systems

The principles of crashworthiness and occupant protection have been well described in foundation papers such as the original Dehaven publications (DeHaven 1952) and more recently Tingvall's landmark vision zero paper (Tingvall 1998). There is extensive engineering literature on the principles behind crashworthiness and occupant protection. These principles are reviewed in both the Rechnitzer (Rechnitzer 2000) and Grzebieta (Grzebieta 2006) papers which address these fundamental approaches that underpin the analysis undertaken in this paper.

Design Principles for Injury Mitigation upon Impact

i. Reduce the exchange of energy -
ii. Provide energy absorption (maximize the stopping distance) –
iii. Ensure compatible interfaces –
iv. Manage the exchange of energy –
v. Provide a survival space

Based on the above design principles, and the extensive body of automotive safety literature and existing real world ambulance crash data, in addition to any dynamic or impact test data for similar ambulance design and performance – an analysis of the anticipated crashworthiness performance strengths and weaknesses of the selected prototype vehicles was conducted by the multidisciplinary team. The analysis is one based on these principles and is supported by evidence from the real world and crash test data that is available.

ANALYSIS OF THE THREE AMBULANCE PROTOTYPES BASED ON THESE FUNDAMENTAL PRINCIPLES OF AUTOMOTIVE IMPACT MECHANICS

Approach

The three vehicles used in this study reflect a spectrum of the vehicles that have been designated by their designers as safety prototypes for ambulance transport in the USA. They were developed and designed essentially by end users and after market manufacturers, with limited, if any input, from key recognized automotive safety expertise and infrastructure. Expected safety performance was analyzed using existing and established automotive safety principles in addition to relevant published crashworthiness literature. Information on design and construction of the vehicles was identified, and evaluated via application of basic engineering crashworthiness principles and laws of physics, with a specific focus on countermeasure design for reducing harmful loading and injury causation potential in crashes or sudden decelerations. Data sources used for the analysis included: vehicle specifications, inspections, photographs, actual real world crash information for similar vehicle construction, crash tests and published crashworthiness and injury mitigation literature.

<u>The Three Vehicles</u> – All three vehicles have been developed by end users with support of an after market ambulance manufacturer, of which there are some 56 in the USA, largely all members of the NTEA (ref)

Vehicle X - A modified van, with an elevated roof
Vehicle Y - A chassis with aftermarket box
Vehicle Z - A chassis with aftermarket box

The vehicle X - is a standard van which had undergone structural modifications to the body and interior modifications to the seating and some equipment anchors, in addition to some change in arrangement of cabinetry and some additional electronics for collision avoidance.

Vehicle Y – is a truck chassis with an aftermarket box – and a spectrum of seating arrangements, with a spectrum of restraint approaches. This vehicle also has and some additional electronics for collision avoidance.

Vehicle Z - is also a truck chassis with an aftermarket box – and a spectrum of seating arrangements, with a spectrum of restraint approaches.

The following types of features were evaluated for each vehicle, and rated by the multidisciplinary team on a 5 level scale of estimated safety or protective performance based on the fundamental principles of crashworthiness - a score of five stars being the best expected performance and a score of one star being the lowest expected performance. There were no negative score designations. One star was the lowest score achievable. Features analyzed included: Rear passenger compartment construction, Seating design Squad bench design, Head strike areas, Hostile interior structures, Restraint systems, Netting and any Impact tested components

Study Findings

Results demonstrated poor vehicle structural integrity and crashworthiness for these aftermarket modified ambulance vehicles both theoretically and the related vehicle crash data and from the controlled crash test data. Assessed crashworthiness performance and occupant protection do not appear optimized even for the minimally structurally modified van.

The real world crash data demonstrated some complete disruption of the rear compartment 'box' in the type Y and Z vehicles (Figs 1a and 1b) , and some disruption of the vehicle compartment integrity related to the aftermarket modifications to the roof of the vehicle of the type X style.

Figure 1a. and 1b. Examples of real world crash outcomes for the rear passenger compartment (EMS Network)

Figure 1b. Image of the ambulance's right side (EMS Network)

Published crash test data confirmed these findings for both frontal and side impacts (Figs 2a and 2b.).

Figure 2a. and 2b. An example of crash test outcome at 44 miles/hr closing speed for a chassis/box configuration. Figure 2a. Immediately after impact, chassis/box ambulance on its side.

Figure 2 b. The struck vehicle has been righted to demonstrate the intrusion to the rear passenger compartment. (crash and impact test photos provided by the author)

For vehicles Y and Z there were also concerns raised regarding the nature of the attachment of the 'box' to the chassis and the potential for the rigidity this system to increase the transfer of energy to the rear compartment occupants.

Additionally, there was liberal use of netting in a these vehicles – even though no testing of the nature of the netting material or its performance under impact conditions was referenced by any manufacturer. In studies conducted by the project SUPPORT team and the author – the characteristics of appropriate netting structure and dynamic impact performance has been evaluated, as well as an optimal design to allow for adequate human factors issues. (Fig 3.)

Figure 3. Dynamic testing of a netting device, by Project SUPPORT design team and the Author

Regarding the layout of the vehicles – Patient (P) was recumbent toward the left side of center of each vehicle, Occupant (A) was in the rear facing Captains chair, Occupant (B) and (C) were on the squad bench positions, and Occupant (D) was in an alternate position on the left hand side of the rear compartment or at the forward end of the squad bench. The

Figure 4. Interior cabinetry and seating design

Evaluations of the anticipated crashworthiness of these components are outlined in Table 1. below, with the 1 to 5 scale representing the anticipated degree of crashworthiness, one being the lowest score and 5 being the highest achievable score.

Table 1. Features analyzed

	Vehicle X	Vehicle Y	Vehicle Z
Rear passenger compartment construction	***	*	*
Seating design	***	**	**
Squad bench design	*	*	*
Head strike areas Patient –P Occupant- A Occupant- B Occupant –C Occupant -D	 *** ** ** ** **	 *** ** ** ** **	 *** ** ** ** **
Hostile interior structures	***	**	**
Restraint systems	**	**	**
netting	**	**	**
Impact tested components	*	*	*

DISCUSSION

The features described in these study vehicles had numerous concerns – the five major area of concern.

1. For study vehicles Y and Z - being a non crashworthy structure of the rear passenger box, with non crashworthy connections of the passenger box to the chassis and in the setting of vehicle X, the van, compromising the potential integrity of the passenger compartment by removing and replacing the roof.

2. The persistence of the 'squad bench' in all vehicles with minimal if any occupant protection related to this structure and of variable degrees of potential failure of occupant protection based on its design and construction.

3. An interior environment where access to the equipment or the patient was severely limited due to the layout of the rear compartment with many hostile surfaces

4. All vehicles were designed using harness systems in side oriented seating positions in the rear passenger compartment, even though there is published literature suggesting that this is hazardous (Richardson et all 1999, Zou et al 1999). Additionally, there was no evidence that any of these harnessing systems had undergone any meaningful, if any, dynamic impact testing.

5. Rear compartment interior design features, (Fig. 4) particularly in and around the seating positions, where there were cabinetry and rigid structures that were potential hazards to seated occupants, and arm rests where there were potential hazards of a side facing occupant being struck in the liver or spleen region in a frontal impact.

By contrast there are some excellent examples of vehicles that are in use in EMS outside of the USA. The vehicles used by NSW Ambulance in Australia (NSW Ambulance) or the vehicles used in Sweden and Norway – some of which are similar to the Australian vehicles – are essentially retrofitted intact automotive industry manufactured vans without any structural modifications performed and with close involvement of the original automotive manufacturing expertise – rather than primarily being performed by an aftermarket manufacturer and in relative isolation of the automotive safety engineering industry. Neither the Australian vehicles nor the Swedish or Norwegian vehicles have a squad bench nor the after market structural vehicle modifications that can potentially decrease crashworthiness integrity that were seen in study vehicles X, Y and Z.

It remains a sad irony that the design and crashworthiness features and occupant protection for the rear compartment of vehicles carrying laundry and packages is essentially little different from a dynamic impact crashworthiness perspective than for these chassis box combination or retrofitted ambulance vehicles carrying our emergency providers, patients and next of kin in the USA.

The failure to address the design of these vehicles based on accepted published and peer reviewed automotive safety literature, and in isolation of the extensive global expertise in automotive safety, human factors and ergonomics, remains a serious concern for this aspect of the EMS system.

CONCLUSIONS

Ambulance vehicle design and crashworthiness features should be driven by accepted automotive safety principles, practice and science. In the USA in a setting of high crash rates, documented high rear occupant compartment injury and fatality rates, a complex occupant and emergency care environment, and the absence of prescribed dynamic crashworthiness test procedures for ambulances – a comprehensive application of existing knowledge in vehicle impact dynamics and automotive safety performance principles should be applied by appropriately skilled experts in the field of crashworthiness and automotive safety. These findings in this study are projected findings, rather than actual crashworthiness tests – however this is the first comparative automotive safety engineering evaluation of prototype ambulance vehicles by recognized automotive safety expertise.

This is key information for a major fleet of vehicles globally which has had minimal automotive safety attention or input to date. Clearly the optimal approach to ascertain crash performance of these vehicles in addition to inspection of real world vehicle crash sites and vehicles is to conduct appropriate vehicle crash tests – with crash test dummies, anthropomorphic test devices (ATDs) which are properly configured for the unusual occupant positions that are routine in the ambulance environment and also – given the high frequency of 'roll-over' of these vehicles in crash situations to conduct rollover tests of these vehicles in addition to side impact testing (Levick 2000-2006) which would demonstrate the impact performance and any failures of these vehicles.

From existing published USA research, and crash information - side impact crash performance for the box style vehicles (vehicle Y and Z) is very poor, and frontal impact also results in poor occupant protect for the rear compartment of these vehicles. From this study it appears there are major deficiencies in the safety design of these prototypes. The issue of placing occupants in a non automotive safety engineered 'box' construction for a passenger compartment is fundamentally unacceptable given the current knowledge in automotive safety design and performance and the existing data on crash out comes for these vehicles.
Emphasis on effective seat design, based on existing automotive safety literature and a clear focus on occupant human factors and equipment location and anchors, could provide for major safety enhancements for ambulance vehicles. There is need for vehicle safety researchers, ambulance industry and vehicle designers to recognize and apply these existing principles to reduce current system failures in an important and essential service that has a poor safety record well below that of passenger vehicles and other commercial vehicles.

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HEAD AND NECK INJURY POTENTIAL IN INVERTED IMPACT TESTS

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ABSTRACT

NHTSA has concluded that there is a relationship between roof intrusion and the injury risk to belted occupants in rollovers [1]. Roof crush occurs and potentially contributes to serious or fatal occupant injury in 26% of rollovers [2]. The inverted drop test methodology is a test procedure to evaluate the structural integrity of roofs under loadings similar to those seen in real world rollovers. Drop test comparisons have been performed on over 20 pairs of production and reinforced vehicles representing a large spectrum of vehicle types. The structural modifications in the reinforced vehicles maintained the occupant survival space and seat belt geometry. This paper analyzes inverted drop testing performed on several production and reinforced matched vehicles with restrained Hybrid III test dummies. Review of neck load data indicates that reduced roof crush results in a direct reduction in neck load, thereby increasing occupant protection. Restraint loading and performance, relating to roof structure integrity, is also evaluated.

INTRODUCTION

The probability of injury in rollovers is increased with roof crush as shown by Rains [4], Rechnitzer [5], Summers [6] and the U.S. Federal Register [7]. It is estimated that roof intrusion occurs and potentially contributes to serious or fatal occupant injury in approximately 26% of rollovers [8].

Previous testing on many different vehicle types indicates that damage consistent with field rollover accidents can be achieved through inverted drop testing from small drop heights [9]. Drop test comparisons were performed on over 20 pairs of vehicles representing a large spectrum of vehicle types. Each vehicle pair included a production vehicle and a vehicle with a reinforced roof structure dropped under the same test conditions. Several examples of post-production reinforcements to roof structures that significantly increased the crush resistance of the roof were given. The modification methodologies are well-accepted practices in the industry, which have been published in previous research and/or incorporated in production vehicles. The basic approach was to close open-section components, add internal reinforcements and/or void fill components with structural foam or epoxy [10,11,12,13,14]. The results of these modifications indicated that roof crush could be dramatically decreased, as roof crush was reduced by 44 – 96% with only a 1–3.1% increase in vehicle weight.

Previous work by the authors demonstrates that the HYBRID III neck lacks biofidelity in rollovers [15]. The Hybrid III neck has been reported to be up 50 times stiffer than the human neck in compression [16]. Due to its extreme stiffness, the Hybrid III neck holds the dummy head straight up which nearly eliminates flexion and guaranties high neck axial compression loads. The human neck on the other hand, is very flexible, and usually experiences flexion injuries instead of compression injuries. The flexing motion of the head can dramatically increase the available survival space of the occupant [17,18]. The Hybrid III dummy is essentially predisposed to produce significant axial neck injuries well before a human neck would experience flexion injuries. Although the HYBRID III dummy has many limitations, it can still be a useful tool. If the dummy neck does not record an axial neck injury in an inverted drop test, then the likelihood of a flexion injury to a human would be eliminated.

Understanding the known limitations of the Hybrid III, several pairs of dummy-equipped inverted drop tests were conducted to further investigate the relationship between roof crush, survival space and neck injury potential. The dummy axial neck loads were analyzed and compared in each of the drop test pairs.

DROP TESTING COMPARISIONS

The vehicles tested for this paper were inverted and dropped from a predetermined height and orientation based upon damage sustained by similar vehicles in a real world accident scenario. Initial drop conditions used were from 12 – 24 in of height, 16 – 25 degrees of roll angle, and 5 – 7 degrees of pitch angle. The production drop test vehicles sustained roof damage consistent with those sustained by real-world rollover accident vehicles. An equivalent production vehicle was structurally modified based on the deformation patterns and failure modes seen in the corresponding real-world accident vehicles and production drop test vehicles. The modifications were limited to reinforcing the existing structure without significantly impacting the interior compartment or exterior styling. Each reinforced vehicle was then subjected to the same drop test environment as the production vehicle with differences in structural performances as discussed.

Inverted Drop Test Setup

<u>1996 Ford Escort With Hybrid III Dummy</u> - A pair of 1996 Ford Escort passenger cars, each equipped with a test dummy, were subjected to inverted drop tests. One of the cars was a production vehicle and the other vehicle had a reinforced roof. The angles and drop height for this test set were chosen based upon an analysis of a real world rollover, resulting in an initial drop height of 18 inches, 16 degrees of roll angle and 7 degrees of pitch angle. The initial contact point was the top of the driver's side A-pillar. For these tests, a Hybrid III 50th Percentile ATD with a modified lumbar spine (which reduced the seated height by 2 inches) was placed in the right front passenger's seating position and the restraints were normally applied (See Table 1).

The reinforced Escort roof was strengthened by inserting internal steel reinforcements and by filling the steel cavities with structural foam. The additional vehicle weight added by the reinforcements was 26.3 lb (117 N). All of the reinforcements were internal to the existing roof structure and the entire production roof structure was retained. In addition to the reinforced roof structure, this vehicle's upright survival space was increased by approximately 3 inches (80 mm), which was accomplished by lowering the seat base frame. The additional survival space could also be achieved through any combination of lowering the seat, increased roofline and/or improvement the presence of a pretensioner or other device that could draw the occupant into the seat.

Table 1.
1996 Ford Escort Drop Test Conditions

Test Conditions	Production Ford Escort	Reinforced Ford Escort
Drop Height	18.1 in (460 mm)	18.1 in (460 mm)
Impact Speed	6.7 mph (10.8 kph)	6.7 mph (10.8 kph)
Pitch Angle	7 degrees	7 degrees
Roll Angle	16 degrees	16 degrees
Test Weight	585 lb (1,294 kg)	585 lb (1,294 kg)
ATD	Modified Hybrid III	Modified Hybrid III
Restraint Use	Production 3 Point Passive Restraint	Production 3 Point Passive Restraint
Roof Structure	Production	Tubular and Structural Foam Reinforced
Upright head-to-roof Clearance	Production (approximately 3.4 in or 86 mm)	80 mm greater than production (approximately 6.5 in or 165 mm)
Inverted head-to-roof Clearance	Production (approximately 2.2 in or 57 mm)	Modified (approximately 6.0 in or 152 mm)

<u>1998 & 1999 Ford Econoline E-350 15-Passenger Van With Hybrid III Dummy</u> - A pair of Ford E-350 Econoline 15-Passenger Vans, each equipped with a test dummy, were subjected to inverted drop tests. One of the vans was a production vehicle and the other van had a reinforced roof. The vehicles were set up using the same load application angles as those specified in the federal roof strength test, FMVSS 216, namely 25 degrees of roll angle and 5 degrees of pitch angle. The initial contact point was the top of the driver's side A-pillar, which is consistent with real world rollovers. A 12-inch drop height was chosen as appropriate to produce a degree of roof crush consistent with real rollover accidents (See Table 2). For these tests, a Hybrid III 50th Percentile ATD with a modified lumbar spine (which reduced the seated height by 2 inches and weight by

15 pounds) was placed in the driver's seating position and the restraints were normally applied. The test weight for the production vehicle was 6,528 lb (2,960 kg). The test weight for the reinforced vehicle was 6,690 lb (3,034 kg).

Table 2.
1998 & 1999 Ford Econoline Drop Test Setup

Test Conditions	Production Ford Econoline	Reinforced Ford Econoline
Drop Height	12 in (305 mm)	12 in (305 mm)
Impact Speed	5.5 mph (8.8 kph)	5.5 mph (8.8 kph)
Pitch Angle	5 degrees	5 degrees
Roll Angle	25 degrees	25 degrees
Test Weight	6,528 lb (2,960 kg)	6,690 lb (3,034 kg)
ATD	Modified Hybrid III	Modified Hybrid III
Restraint Use	Production 3 Point Passive Restraint	Production 3 Point Passive Restraint
Roof Structure	Production	Tubular and Structural Foam Reinforced
Inverted head-to-roof Clearance	Production (approximately 8.5 in or 216 mm)	Production (approximately 8.5 in or 216 mm)

The reinforced Ford E-350 roof was strengthened by inserting internal steel reinforcements and by filling the steel cavities with structural foam. In the reinforced vehicle, all of the modifications were internal to the existing roof structure and interior. Production restraint systems were used in both vehicles.

<u>1999 Ford F-250 F-series Crew Cab Pickup With Hybrid III Dummy</u> - Dummy-equipped inverted drop tests were conducted on a pair of Ford F-250 Crew Cabs, one production vehicle and the other with a reinforced roof. The test set-up for the pair is presented in Table 3 below. The load application angles used were the same as those specified in FMVSS 216, the federal test for roof strength. In order to evaluate the front roof structure, the top of the driver's side A-pillar was chosen as the initial impact location. The 12-inch drop height was chosen to produce the approximate roof crush of a real world rollover involving a similar vehicle. The Hybrid III 50th Percentile Male was placed in the driver's seat, which was set to its middle position for both tests. The adjustable D-ring was also placed in its middle position for each test. In the production test, the dummy was belted normally using the provided OEM 3-point restraint. In the reinforced test, the dummy was 3-point belted with a pretensioned restraint system, consistent with belt activation prior to the first quarter turn in a rollover [19].

Table 3.
1999 Ford F-series Drop Test Setup

Test Conditions	Production Ford F-series	Reinforced Ford F-series
Drop Height	12 in (305 mm)	12 in (305 mm)
Impact Speed	5.5 mph (8.8 kph)	5.5 mph (8.8 kph)
Pitch Angle	5 degrees	5 degrees
Roll Angle	25 degrees	25 degrees
Test Weight	6,131 lb (2,780 kg)	6,373 lb (2,890 kg)
ATD	Standard Hybrid III	Standard Hybrid III
Restraint Use	Production 3 Point Passive Restraint	Pretensioned 3 Point Passive Restraint
Roof Structure	Production	Tubular and Structural Foam Reinforced
Inverted head-to-roof Clearance	Production (approximately 4.75 in or 121 mm)	Production (approximately 6.75 in or 172 mm)

The reinforced Ford F-250 roof was strengthened by inserting internal steel reinforcements and by filling the steel cavities with structural foam. In the reinforced vehicle, all of the modifications were internal to the existing roof structure and interior. In addition to the strengthened roof structure, the reinforced vehicle test employed a belt pretensioner, which removed 4 inches of the belt with 60-70 lb of resulting belt load prior to inversion.

<u>1986 Ford Econoline E-150 Van With Hybrid III Dummy</u> – In addition to the previous three drop test pairs, a single reinforced drop test was conducted on a 1986 Econoline E-150 Van. A standard Hybrid III test dummy was placed in the front seat compartment and was restrained with the production 3-point belt system. The vehicle was inverted and orientated such that the pitch angle was 5 degrees, the roll angle was 16 degrees, and the initial point of contact was the driver's side A-pillar. The vehicle was then dropped from a height of 24 in (610 mm) (See Table 4).

Table 4.
1986 Ford Econoline Drop Test Setup

Test Conditions	Production Ford Econoline	Reinforced Ford Econoline
Drop Height	N/A	24 in (610 mm)
Impact Speed	N/A	7.7 mph (12.4 kph)
Pitch Angle	N/A	5 degrees
Roll Angle	N/A	16 degrees
Test Weight	N/A	6,373 lb (2,890 kg)
ATD	N/A	Standard Hybrid III
Restraint Use	N/A	Production 3 Point Passive Restraint
Roof Structure	N/A	Tubular and Structural Foam Reinforced
Inverted head-to-roof Clearance	N/A	Production (approximately 6.0 in or 152 mm)

The reinforcements incorporated in the drop test vehicle included a B-pillar area tubular reinforcement and structural foam filling. In this test, the production restraints were applied in a fashion consistent with normal occupant use. The vehicle was then inverted via a vehicle rotational mechanism and the occupant was allowed to move towards the roof to the degree permitted by the restraint system prior to drop.

RESULTS & DISCUSSION

The primary differences between the production and reinforced tests were the amount of roof crush and seat belt loading, which resulted in different dynamic occupant excursion and neck loading. The reduction in neck load in the reinforced vehicle was due to increased dynamic head-to-roof clearance resulting from reduced roof crush and in some cases improved restraint performance (See Figures 1 through 4).

Production 1996 Ford Escort

Reinforced 1996 Ford Escort

Figure 1. 1996 Ford Escort Drop Test Pair Comparison Post Test

Production 1998 Ford Econoline 15 Passenger Van

Reinforced 1999 Ford Econoline 15 Passenger Van

Figure 2. 1998 & 1999 Ford Econoline Drop Test Pair Comparison Post Test

Production 1999 Ford F-250 Crew Cab

Reinforced 1999 Ford F-250 Crew Cab

Figure 3. 1999 Ford F-250 Crew Cab Drop Test Pair Comparison Post Test

Reinforced 1986 Ford Econoline Van

Figure 4. Reinforced 1986 Ford Econoline Van Post Drop

The results from the seven inverted drop tests are summarized in table 5 below.

Table 5.
1999 Ford F-series Drop Test Setup

Vehicle	Static A-Pillar Crush	Neck Load	Belt Load
Production 1996 Ford Escort	5.3 in (134 mm)	2,187 lb (9,727 N)	N/A
Reinforced 1996 Ford Escort	3.5 in (89 mm)	288 lb (1,281 N)	N/A
Production 1998 Ford Econoline	11.2 in (284 mm)	820 lb (3,647 N)	117 lb (520 N)
Reinforced 1999 Ford Econoline	0.6 in (15 mm)	49 lb (218 N)	394 lb (1,753 N)
Production 1999 Ford F-series	8.7 in (221 mm)	1201 lb (5,342 N)	162 lb (721 N)
Reinforced 1999 Ford F-series	0.9 in (23 mm)	-61 lb (271 N)	475 lb (2,113 N)
Reinforced 1986 Ford Econoline	1.5 in (38 mm)	271 lb (1,205 N)	550 lb (2,446 N)

As shown in this summary table, the injurious neck loads experienced by the dummies in the production vehicle are directly correlated to the high levels of vehicle roof crush. Similarly, the dummies in the reinforced vehicle drop tests consistently recorded neck loads well below the artificially low injury value of approximately 450 lb (2,000 N) used in the Malibu Study. The neck loads are significantly lower in the reinforced vehicles because the survival space was maintained during the inverted drop tests. This phenomenon is illustrated in Figure 5 below.

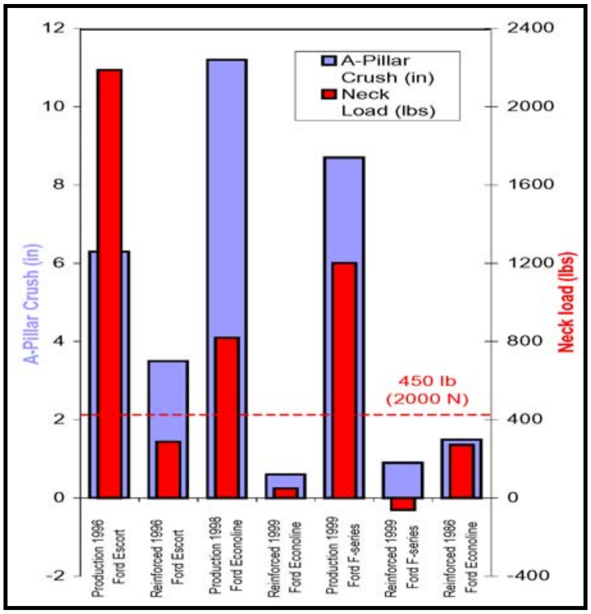

Figure 5. Inverted Drop Test Comparisons With Hybrid III Dummies: A-pillar Crush and Neck Load

The lap belt loads for the inverted drop test matrix were analyzed and compared to the Hybrid III neck loads that were recorded. Lap belt data was not recorded for 1996 Ford Escort drop test pairs, so this drop test was not included in this analysis. As shown in Figure 6 below, neck loads are inversely correlated to the amount of force transferred into the belt system.

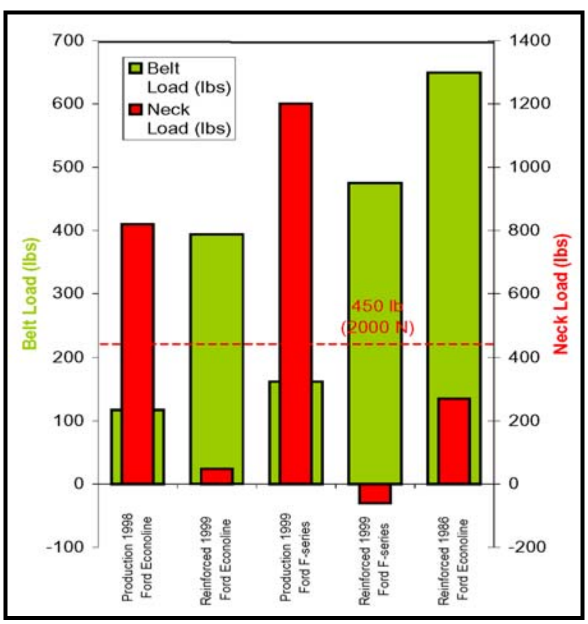

Figure 6. Inverted Drop Test Comparisons With Hybrid III Dummies: Belt Load and Neck Load

In order to further understand the relationship between roof crush, belt loads, and neck injury, the data was normalized and plotted on the same graph for comparison (See Figure 7). This was accomplished by taking the highest value in each of the three categories and setting it to 1.0 and then by expressing the other values as a percentage of that highest value. While this figure does not reflect any numerical data, it allows for a relative comparison between the data.

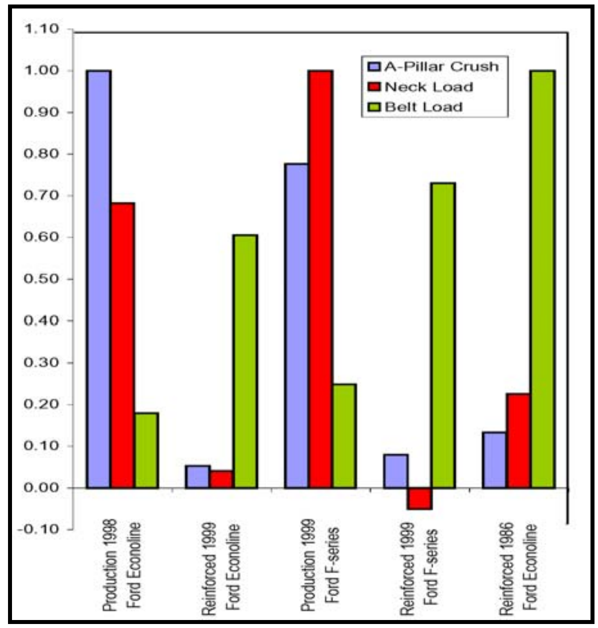

Figure 7. Inverted Drop Test Comparisons With Hybrid III Dummies: Normalized A-pillar Crush, Neck Loads, and Belt Loads

As shown in Figure 7, the production drop test vehicles both experienced high levels of roof crush, high neck loads, and low belt loads. In contrast, all of the reinforced vehicles experienced low levels of roof crush, low neck loads, and high belt loads. The belt loads are high in the reinforced drop tests because the strengthened roofs were able to maintain the occupant survival space and allow the restraints to be loaded dynamically with the occupant weight. Even though the belt loads were much higher in the reinforced drop tests, it does not necessarily reflect the quality of the restraint system. For example, the 1998 & 1999 Ford Econoline drop test pair both utilize the same production restraint system, yet the forces generated in the reinforced drop test are about three times higher than in the production drop test. This is because in the production drop test the survival space was compromised due to roof intrusion before the belt system could effectively restrain the occupant. However, in the reinforced Econoline drop test, the strengthened roof maintained the survival space, allowing the restraints to be loaded dynamically with the occupant weight.

Analysis of the test videos and data have demonstrated that the combination of a small amount of initial inverted head to roof clearance, a high degree of roof crush, and significant occupant excursion results in significant neck loads. In all three of the production drop tests the roof crush clearly preceded the initial compression neck loading, the peak neck loading, and occupant vertical displacement (See Figures 8-10).

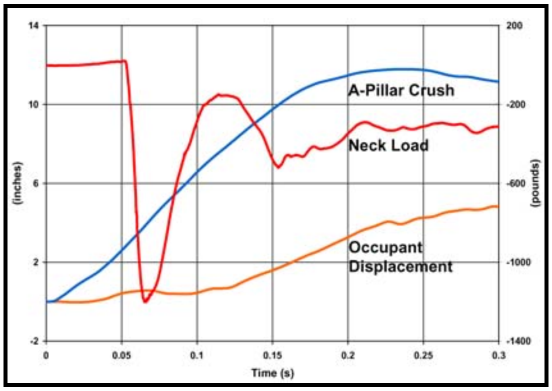

Figure 8. Production 1999 Ford F-250 Time Phasing

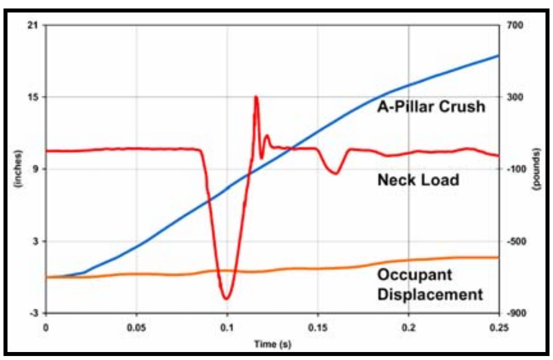

Figure 9. Production 1998 Ford Econoline Time Phasing

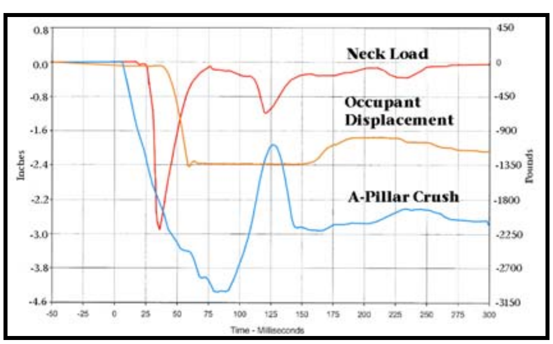

Figure 10. Production 1996 Ford Escort Time Phasing

CONCLUSIONS

- Several inverted drop tests from 12 to 24 in (305 to 610 mm) with corresponding contact speeds of 5.5 to 7.7 mph (8.9 to 12.4 kph) produced significant roof crush in typical production vehicles.
- Roof crush proceeds initial compression neck loading, peak neck loading, and occupant vertical displacement.
- Structural reinforcements to the roof structures resulted in significantly reduced roof crush and low compression and flexion force levels in Hybrid III dummies.
- High Hybrid III neck compression and flexion loads were produced in the production vehicles due to a compromise of occupant survival space and ineffective occupant restraint.
- Significant neck compression and flexion forces only occur when the survival space is compromised by significant roof crush and/or when occupant excursion reduces the effective head-to-roof clearance.
- The degree of neck axial compression and flexion loads in the Hybrid III dummy and therefore, potential for injury, is a function of the initial head-to-roof clearance, the restraint effectiveness and the extent of roof crush.
- Strong roofs along with adequate initial headroom can maintain occupant survival space and will result in increased belt loads and reduced neck loads well below injury thresholds.

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PARAMETRIC ANALYSIS OF ROLLOVER OCCUPANT PROTECTION USING A DEFORMABLE OCCUPANT COMPARTMENT TESTING DEVICE

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ABSTRACT

Occupant kinematics during rollover inverted impacts has been the subject of significant research. Controlled experiments have utilized complete vehicles, partial vehicles and seat/restraint systems attached to various platforms. The Deformable Occupant Compartment Impact Tester (DOCIT) was developed to incorporate functions similar to previous methods, but has added a roof capable of deforming under impact. These roof deformation characteristics can be reset without the destruction of a complete vehicle. The DOCIT simulates an occupant compartment (roof, seat, restraint system) in which an ATD is placed and subjected to a repeatable inverted dynamic impact environment. Several test series are reviewed, in which standard of value tests, based upon real-world rollover accidents, are compared with alternate design systems under the same impact environments. 5th and 50th percentile Hybrid III ATD's are utilized to assess neck and head injury criteria. Alternate designs for roof structures and restraint systems are tested to determine the effectiveness of each.

The DOCIT accommodates rapid parametric analysis of occupant injury criteria relative to various occupant, restraint and roof configurations in a dynamic loading environment and enables evaluation of restraint system performance and injury potential under impacts with controlled initial/residual head clearance and repeatable pre-determined roof profiles. Test variations in restraint systems or roof performance can be correlated with other component and full vehicle tests without the need for the destruction of many vehicles.

This research indicates that for reasonably restrained occupants, roof crush preceded head to roof contact and peak neck forces. Reducing roof crush also reduced neck injury measures and therefore neck injury potential. In many cases, reducing roof crush and optimizing restraint designs eliminated interaction with the roof and provided correspondingly negligible injury measures.

INTRODUCTION

In an effort to understand rollover injuries and their relationship to roof crush, many rollover occupant experiments have been conducted with a variety of surrogates, both human and ATDs. Inverted drop tests have been conducted using production and reinforced vehicles utilizing Hybrid III Anthropometric Test Devices (ATD) to examine the relationship between roof crush and neck injury potential. Several inverted drop tests with water-ballast dummies reported additional dynamic occupant excursion during impact. Smaller adjustable test fixtures have also been used to study occupant kinematics and excursion in rollovers and inverted drops.

Arndt studied the effects of belt geometry and slack in a single seat drop cage with Hybrid III ATDs in 91 cm drop tests with 5g decelerations. Herbst developed an adjustable single seat and restraint system buck, capable of being rotated about its roll axis and examined live subject occupant kinematics and excursion. Further studies with this adjustable buck documented production restraint system occupant excursions as well as the effect of alternatively designed restraint systems. Cooper analyzed occupant kinematics under angular roll rates comparable to some rollover crashes with the Head Excursion Test Device. Pywell developed a rollover fixture that was controllable, repeatable and easily modified to study occupant kinematics with various restraint types. The Rollover Restraint Tester (RRT) was developed by the National Highway Traffic Safety Administration (NHTSA) to test restraint effectiveness in rollover conditions and employed a shock tower which simulated roof to ground impacts. Friedman studied the potential for neck injury with Hybrid III dummies and live human subjects in a non-crushable production vehicle compartment dropped from heights up to 91 cm. Several studies investigated the Hybrid III 50th percentile male's response to free fall impacts in drop heights approaching 122 cm.

The Deformable Occupant Compartment Impact Tester (DOCIT) is designed to simulate an occupant compartment including a roof, seat, and restraint system (Figure 1). An ATD is placed normally in the

DOCIT seat and restraint system, which is then inverted and subjected a repeatable impact environment. The roof panel is attached to a series of vertical and lateral pneumatic cylinders, which define the motion of the roof. Adjustable stops and variable pressure relief valves on the pneumatic cylinders can control the extent and resistance to deformation. This configuration allows for controllable roof crush in lateral and vertical directions, and therefore the roof crush is repeatable and defined. The versatility of the DOCIT allows for the examination of the relationship between occupant injury potential and roof crush with a variety of vehicle configurations and occupant protection systems.

Figure 1. Typical DOCIT configuration.

METHODOLOGY

DOCIT testing is often performed as part of a thorough rollover accident analysis. A detailed accident reconstruction analysis is conducted in order to understand the kinematics of the vehicle throughout a rollover, including the various impacts along its trajectory. Structural analysis is then employed to quantify the forces and energy imparted to the vehicle's roof structure during the rollover impacts as well as the orientations of the vehicle at the time these impacts occurred. Physical testing, such as inverted drop testing or tip-over testing, can be used as part of the structural analysis to quantify impact conditions required to induce damage consistent with an accident vehicle. The vehicle impact conditions ascertained from analysis and testing can then be utilized to establish the appropriate orientation and drop height (Figure 2) for the DOCIT tests. The DOCIT ties together elements of the accident reconstruction, structural analysis and biomechanical analysis while allowing for testing of the key components that influence occupant protection in rollovers, specifically occupant survival space, occupant restraint and roof crush.

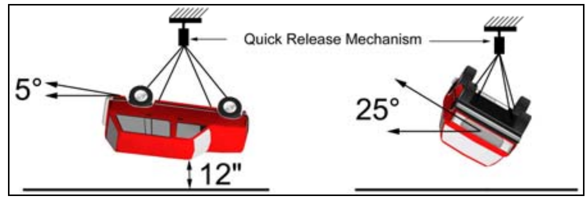

Figure 2. Typical inverted drop test configuration.

The occupant compartment geometry, including the locations of the seat, restraints and roof, can be documented with a survey tool for both the accident vehicle and an exemplar. These digitized measurements are then used as a template for the locations of the various DOCIT components. The D-ring anchor for the retractor system is attached to the roof rail of the system, and therefore would move in conjunction with the roof system when it displaced or crushed under impact, as would be the as case in a real-world rollover accident. The motion of the D-ring during roof crush has the effect of inducing slack into the restraint system and limits its ability to contain the occupant. This effect is important to understand the effects of roof crush on occupant kinematics and injury measures.

In each DOCIT test series, a baseline test is conducted to establish the test conditions under which the comparisons are to be made. The baseline test impact conditions are set based upon the reconstruction, structural and biomechanical analyses and result in injury measures, which are consistent with the occupant injuries. Once the configuration for baseline test has been established, the test device can quickly be reset between tests by righting the device, recharging the pneumatic cylinders and replacing the roof panel. Once it has been reset, a single test parameter change, such as variations in roof crush or alternate restraint system characteristic, can be made. The biomechanical effects of these parametric changes to the test setup are then easily analyzed by comparing the resulting ATD injury measures.

Hybrid III ATDs can be used as occupant surrogates, which can be tailored with spacers and ballast to more accurately represent occupants of various sizes. The ATD is instrumented to record head acceleration, upper neck forces and moments. The DOCIT fixture is instrumented to record roof crush displacement data and occupant excursion through displacement transducers, as well as lap belt loads and compartment accelerations. The ATD is placed within the DOCIT fixture seat and the restraints are normally applied. The restraint system can also be pretensioned at this point, depending on the nature of the experiment. Pre-test head-to-roof clearance and restraint measurements are made prior to inversion. Once the ATD is in place and restrained, the DOCIT is raised from the ground via a floor lift. The fixture is inverted by a set of internal pivots and attached to a quick-release mechanism from its underside. Once the test height is set, post inversion measurements are made which indicate the static excursion of the ATD within the restraint system relative to the compartment roof and other interior components. The fixture is then released and allowed to impact the floor. High speed and real-time video document the impact. Data is collected and filtered according to SAE J211 from the ATD and test fixture at a rate of 10,000Hz.

TEST RESULTS

Four test series using this DOCIT fixture and methodology are reviewed in this paper.

TEST A Results

Test series A was based on a model year 2000 domestic SUV rollover accident in which the driver suffered a cervical neck fracture resulting in quadriplegia. The DOCIT was assembled to approximate the restraint and seating systems of this accident vehicle as well as the approximate shape and extent of roof crush experienced.

The roof panel in the DOCIT was specifically constructed to allow for the formation of a longitudinal buckle by placing two hinge points at the perimeter of the roof panel support frame (Figure 3). A piece of undeformed sheet metal was placed within this hinged frame. At impact, the downward and inward motion of the impacting corner created a longitudinal buckle over the occupant.

A Hybrid III 50th percentile ATD was used during Test series A, which had the lumbar spine replaced with a lighter and shorter assembly. This modification adjusted the Hybrid III ATD to approximate a 71 kg occupant that had a seated height of 83.8 cm and would stand approximately 162.6 cm tall. The DOCIT had a pre-impact configuration of 20 degrees of roll from inverted, 0 degrees of pitch and a drop height of 30.5 cm.

The baseline test resulted in significant interaction between the occupant and the intruding roof. The injury measures resulting from the baseline test conditions (Table 1) are consistent with the injuries to the real world occupant. In the baseline test, the ATD registered 7527 N of neck compression when it impacted the intruding roof.

Table 1.
Results from test series A

	Restraints	Roof Crush (cm)	Belt Load (N)	Nij	Neck Force Z (N)
Baseline	Production	18.7	1143	1.37	-7527
Alt. 1	Production	0.6	2334	0.14	-176
Alt. 2	Pretension	0.9	2200	0.25	-291

The neck injury criteria, Nij, used by the National Highway Safety Administration, is a linear combination of tension-compression and flexion-extension moments which are normalized by the critical limits established for each ATD type. A Nij value of greater than 1.0 is generally viewed as a critical threshold. The baseline test measures resulted

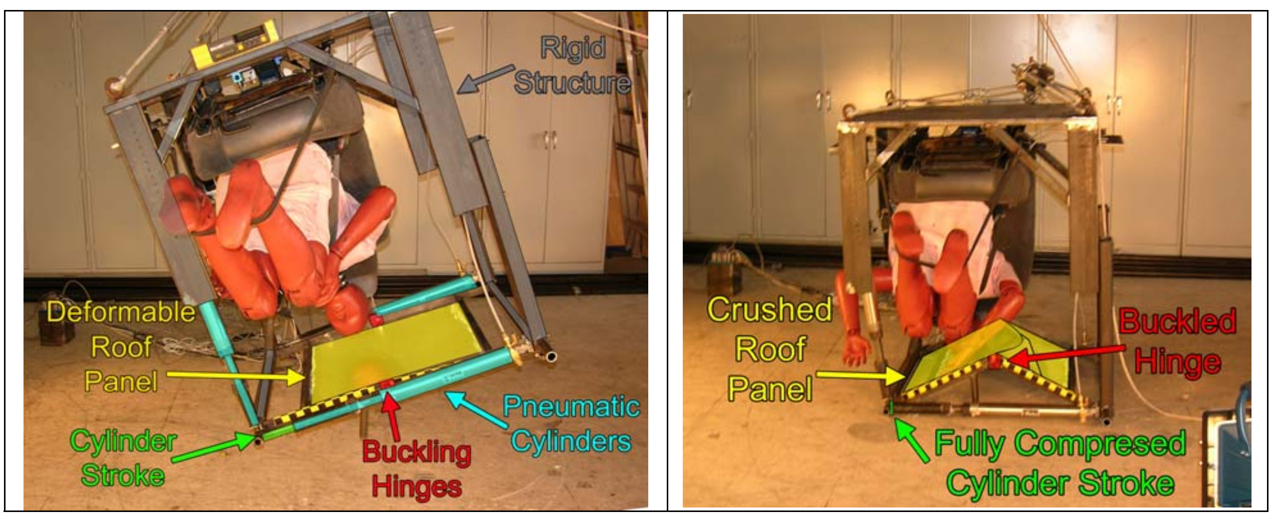

Figure 3. Pre-impact (left) and post-impact (right) photos of DOCIT baseline test series A.

in a Nij of 1.37 (based upon 50th percentile male criteria).

Two tests were conducted for comparison to this baseline test. Alternate system 1 is a parametric test comparison in which the influence of reducing roof crush is analyzed relative to the ATD injury measures. In this test, the pneumatic roof cylinders were locked out allowing only minimal dynamic flex in the roof system. Under these conditions, the occupant interaction is greatly attenuated, with the occupant only slightly touching the roof during impact. The critical neck injury measures are reduced by more than 90%, with a resultant Nij of 0.14 and a compression load of 176 N.

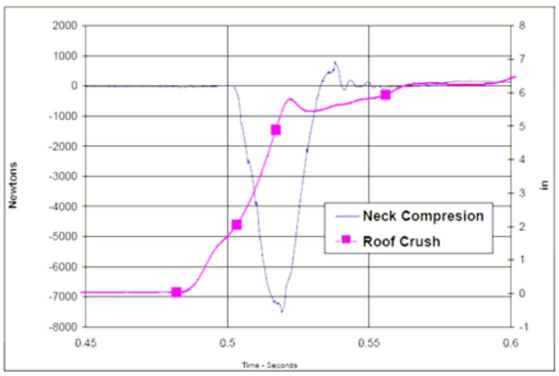

Figure 4. Roof crush vs. neck compression for baseline test series A.

A second alternate design is test in which the roof is set as in alternate design 1, but the restraints are pretensioned to 355- 375 N prior to testing. Under these circumstances, the Hybrid III ATD did not contact the roof during impact, and the resulting injury measures are below all the critical criteria. During analysis of the test data and video, it was clear that the roof crush occurred prior to the ATD's interaction with the roof and prior to the peak neck loading (Figure 4).

Both alternate systems demonstrate the potential to significantly reduced ATD injury measures and even eliminate contact. Both of these alternate systems can be compared to current production designs or designs which are technologically feasible. Pretensioners, including rollover activated pretensioners, are available in many production vehicles on the road today.

TEST B Results

Test series B involved the rollover of a 1990's small four door sedan. The injured occupant was a small female located in the driver's seat at the time of the accident, who suffered a neck fracture with resulting quadriplegia. A 5th percentile female ATD was used as the surrogate in these DOCIT tests. A 2.54 cm steel spacer was placed at the top of the lumbar spine and 11.3 kg lead ballast was attached to the ATD's legs and torso. This ATD configuration approximated a small female weighing 56.6 kg, with a seated height of 81.3 cm in. and would stand approximately 154.9 cm tall. The DOCIT had a pre-impact configuration of 20 degrees of roll from inverted, 0 degrees of pitch and a drop height of 30.5 cm.

The roof panel in the DOCIT was specifically constructed to allow for the formation of a longitudinal buckle as in Test series A. (Figure 5) The DOCIT had a pre-impact configuration of 19 degrees of roll from inverted, 0 degrees of pitch and a drop height of 45.7 cm.

Figure 5. Roof buckle formations in accident vehicle and DOCIT fixture.

The baseline test in series B, the ATD registered 5820 N of neck compression and a Nij measurement of 2.0 (based upon 5th percentile female criteria) (Table 2). Three tests were conducted for comparison to this baseline test. Alternate system 1 is a parametric test comparison in which the influence of reducing roof crush is analyzed relative to the ATD injury measures. In this test, the pneumatic roof cylinders were locked out allowing only minimal dynamic flex in the roof system. Under these conditions, the occupant interaction is greatly attenuated, with the occupant only minor contact with the roof during impact. The critical neck injury measures are reduced by approximately 85%, with a resultant Nij of 0.3 and a compression load of 839 N.

A second alternate design was tested in which the roof is set as in alternate design 1, but the restraints are pretensioned to 311 N prior to testing. Under these circumstances, the Hybrid III ATD did not contact the roof during impact, and the resulting injury measures are below all the critical criteria.

Table 2.
Results from test Series B

	Restraints	Roof Crush (cm)	Belt Load (N)	Nij	Neck Force Z (N)
Baseline	Production	19.6	891	2.0	-5820
Alt. 1	Production	4.1	3201	0.3	-839
Alt. 2	Pretension	4.7	2701	0.2	-121
Alt 3	BIS/ABTS	3.1	2596	0.12	-359

The third alternate design was tested in which the roof was set as in alternate design 1 and the seat and restraint were replaced with a production belt-in-seat or all-belts-to-seat design. Under these conditions, the occupant made light contact with the roof during impact. The critical neck injury measures are reduced by approximately 85%, with a resultant Nij of 0.12 and a compression load of 359 N. As in the previous test series, it was clear that the roof crush occurred prior to the ATD's interaction with the roof and prior to the peak neck loading (Figure 6).

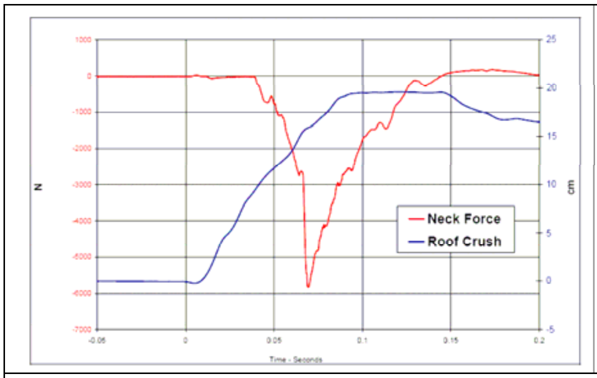

Figure 6- Roof Crush vs. Neck Compression for Baseline Test Series B

TEST C Results

Test C tests examine the injury potential of a Hybrid III 5th Female ATD restrained in the DOCIT configured to approximate the driver's seat location of a 1992 sedan in a 30.5 cm drop. The DOCIT fixture had no roll or pitch angles and the roof crush was allowed to intrude uniformly in the vertical direction. The roof was decelerated by crushable foam blocks rather than the pneumatic valves of Tests A and B. Reductions in roof crush and pretensioned production restraints are separately assessed to identify their ability to reduce injury potential.

Table 3.
Results from test Series C

	Restraints	Roof Crush (cm)	Belt Load (N)	Nij	Neck Force Z (N)
Baseline	Production	15.8	1152	1.77	-6260
Alt. 1	Production	2.3	2242	0.25	-876
Alt. 2	Pretension	15.8	1027	1.19	-4263

The 30.5 cm inverted drop resulted in 15.7 cm of roof crush and 5.9 cm of occupant excursion. With only 7.5 cm of pre-impact headroom, the extent of roof crush and occupant excursion resulted in an occupant impact with the roof. The baseline test had neck injury measures of 6260 N of neck compression and a Nij of 1.77. Alternate test 1 had the same test parameters as the baseline test except for a reduction in roof crush from 15.8 cm to 2.3 cm. This roof crush reduction lowered peak neck compression by 86% to 876 N and lowered Nij 86 % to 0.25. Alternate test 2 had the same test parameters as Test 1 except that the belt was pretensioned to 356 N prior to static inversion. The pre-impact headroom was increased to 17.1 cm and dynamic occupant excursion was reduced to 1 cm. This lowered peak neck compression 32% to 4262 N and lowered Nij 32% to 1.19, when compared to the baseline test.

TEST D Results

Test C tests examine the injury potential of a Hybrid III 50th Male ATD restrained in the DOCIT configured to approximate the driver's seat location of a 2003 pickup in a 30.5 cm drop. A 2.54 cm steel spacer was placed above the ATD's lumbar spine to bring the overall seated height up to 91 cm. The DOCIT fixture had 10 degrees of roll and no pitch angles. The roof crush was allowed crush vertically and laterally in a planar manner without any roof buckles. The roof was controlled by pneumatic cylinders as in Tests A and B. Reductions in occupant excursion through restraint improvements are assessed to identify its ability to reduce injury potential.

Table 4.
Results from test Series D

	Restraints	Roof Crush (cm)	Belt Load (N)	Nij	Neck Force Z (N)
Baseline	Production	8.6	1287	1.46	-8368
Alt. 1	Pretension ABTS	7.7	4092	0.16	+676

The 30.5 cm inverted drop resulted in 8.6 cm of roof crush and 10.2 cm of occupant excursion. With only 2.0 cm of pre-impact headroom, the extent of roof crush and occupant excursion resulted in an occupant impact with the roof. The baseline test had neck injury measures of 8368 N of neck compression and a Nij of 1.46. Alternate test 1 had the same test parameters as the baseline test except for the seat was replaced with an ABTS (all belts to seat or integrated seat belt) with the belts pretensioned to 280 N. This improved restraint performance resulted in pre-impact headroom increasing to 13.3 cm and dynamic occupant excursion was reduced to 2.7 cm. The ATD did not contact the roof at all during impact, thereby eliminating any neck compression due to head to roof contact.

DISCUSSION

The DOCIT fixture allows for rapid parametric analyses of various occupant, restraint and roof systems. The test variations in restraint systems or roof performance can be correlated with other component or full vehicle tests without the need for the complete destruction of many vehicles to achieve the same result.

In the four test series performed, the following conclusions were drawn:

- Roof crush preceded head to roof contact as well as peak neck forces.
- Reducing roof crush correspondingly reduced neck injury measures and therefore neck injury potential.
- In many cases, reducing roof crush and pre-tensioning restraints or ABTS to a reasonable level eliminated interaction with the roof and with correspondingly negligible injury measures.
- Feasible roof and restraint design alternatives can significantly reduce the likelihood of neck injury in inverted impacts such as rollovers.

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ROLLOVER CRASHES: DIVING VERSUS ROOF CRUSH

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ABSTRACT

A rational analysis of the two apparently conflicting views of neck injury causation for contained and belted occupants in rollover crashes that have been presented in research literature to date, i.e. torso augmentation (diving) vs. roof intrusion, is presented. The validity of each of the views and associated injury causation mechanisms and underlying concepts are investigated using basic Newtonian laws of physics.

Through the analysis of General Motors Malibu II rollover test series, the authors show how roof crush at high intrusion velocities results in high neck loading. Equations are developed that demonstrate how roof intrusion is integrally linked to neck loading and hence is the main causal factor of serious neck injuries in rollover crashes. The paper also shows how roof intrusion compounds torso augmentation resulting from rollover kinematic motion.

Discussions are also presented regarding the "lift shaft" analogy proposed by Moffatt and used to explain how serious head and neck injuries occur in rollover crashes. The authors show that analogy is inappropriate by at least an order of magnitude in terms of the crash severity it suggests.

INTRODUCTION

31,041 passenger vehicle occupants were killed in the US in 2005 of which 10,608 died in crashes where their vehicle rolled over [1]. This includes passenger car, pickups, utilities & vans. **Figure 1** shows that there has been a steady rise in such fatalities over the past decade despite the introduction of a number of injury mitigation initiatives by NHTSA. In contrast, **Figure 1** indicates non-rollover related vehicle occupant fatalities have been steadily declining.

The most likely reason for the downward trend in non-rollover related crash fatalities is vehicles are subjected to both government and consumer dynamic crash testing using Anthropomorphic crash Test Dummies (ATD) for both frontal offset and side impact crashes. There is no equivalent mandated or consumer dynamic crash test being carried out to rate vehicle rollover crashworthiness. There only exists a mandated quasi-static test FMVSS216 [2]. This test has been shown to be ineffective in protecting occupants in real world rollover crashes by a number of researchers and professionals concerned about rollover crashworthiness [3, 4, 5].

It will be interesting to monitor over the next five or so years whether rollover related fatalities will decrease as a result of the introduction of electronic stability control. In the mean time it is clear there must a considerable ramping of effort to enhance the roll-over crashworthiness of vehicles. This paper deals with a number of the issues currently being debated in the US concerning vehicle rollover crashes.

Injuries to seat belted occupants involved in rollover crashes were investigated by the authors in preceding papers [5, 6]. A number of issues relating to the debate concerning whether injuries result from diving or roof intrusion were discussed and the GM rollover Malibu II test series were analysed. This paper further elaborates on some of the issues discussed and presents additional analysis of some of the Malibu II test series.

DIVING MECHANISM

In an attempt to explain why injuries were occurring in vehicle rollover crashes, Moffatt proposed in 1975 that such injuries resulted from a mechanism analogous to diving. He argued that when the roof contacts the ground, it can be considered to be stationary against it, with the body of the car and the occupant continuing to move towards, and eventually striking, the

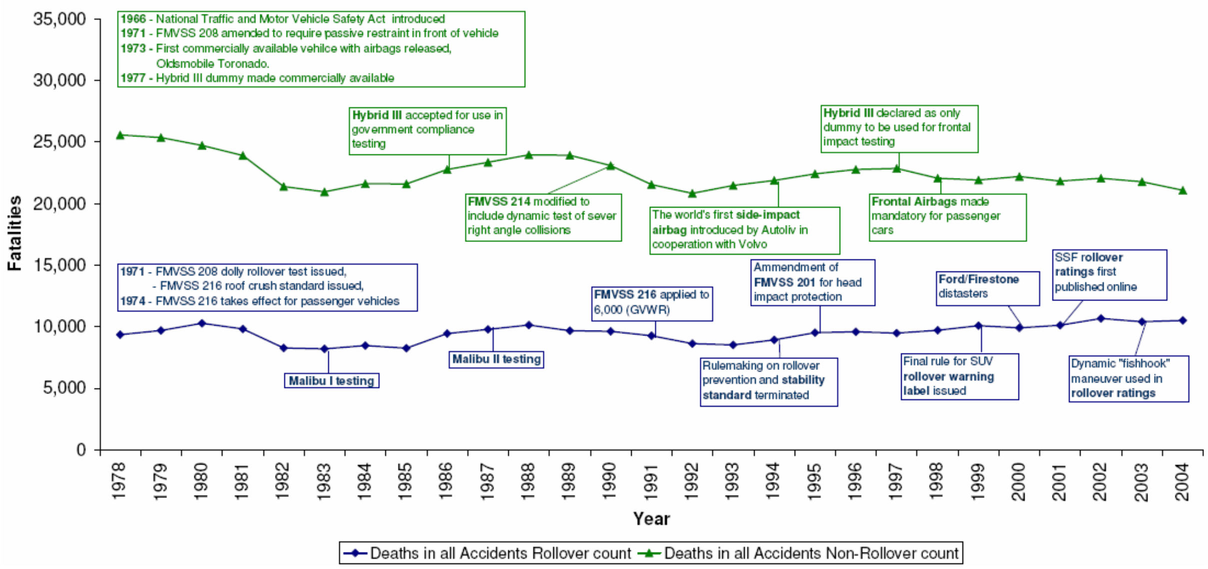


Figure 1: US Rollover related vehicle fatalities compared to all other vehicle crash fatalities.

ground/roof surface. The injury mechanism resulting from this strike was likened to the neck injury that occurs when a person dives into shallow water in a pool, river or lake.

Moffatt also contended that the injuries were not causally related to the roof intrusion, i.e.

> *"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."*

Evolving from this rationalisation of how rollover injuries occur was the concept of torso augmentation. In other words, when 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 towards the ground. The occupant's neck and head is thus loaded, resulting in head, neck and spinal injuries. Moffatt drew an analogy between the injury mechanism he described that occurs in a rollover crash to one that would occur to a person inside a lift where a cable brakes resulting in the lift falling down a lift shaft as depicted in his sketch in **Figure 2**. He further elaborated:

> *"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"*

The authors discussed this issue in a previous paper [6]. However this analogy requires further analysis. The elevator shaft defence has been used consistently by industry since 1975 to aid in product litigation related to injuries to contained occupants resulting from rollover crashes where there is evidence of significant roof intrusion.

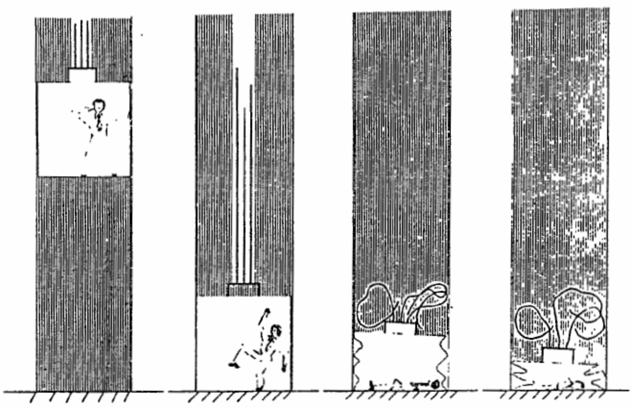


Figure 2 – Copy of Figures 11a to 11d "lift-shaft" analogy presented by Moffatt [8].

The image shown in **Figure 2** indicates a lift dropping approximately 3 stories in a lift well, i.e. around 6 metres. In contrast, Friedman and Nash (2005) on analysing GM rollover Malibu II test data found that

> "*The center of gravity of a rolling vehicle does not rise or fall more than a few inches during a rollover. Thus, the vertical velocity of the centre of gravity of the vehicle at roof impact is low – virtually never more than 2.5 m/sec (5 mph).*"

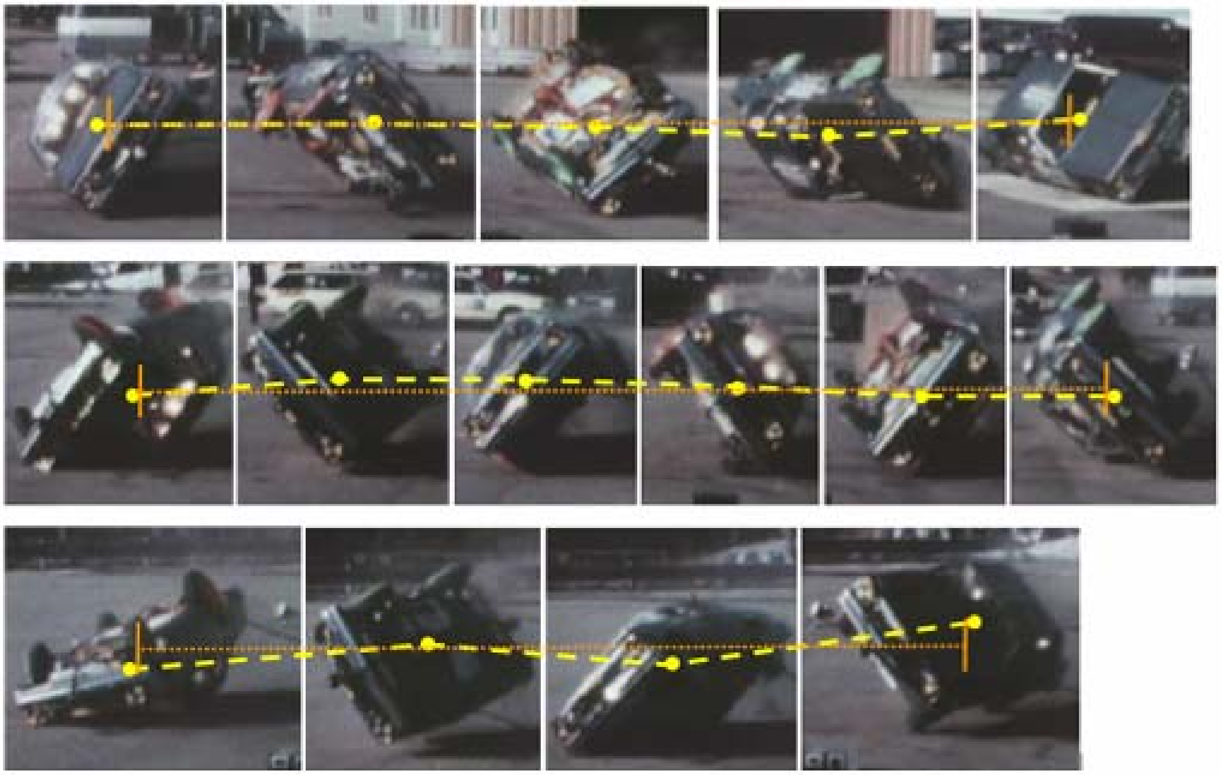


Figure 3: Frame sequence from GM rollover Malibu II test number 7 showing how the height of the vehicle's COG does not vary significantly during the rollover event.

Figure 3 shows how the height of the Centre of Gravity (COG) varies over the duration of a FMVSS 208 rollover crash test. The frames were obtained from a high speed film of GM's Malibu II test number 7. It was in this particular test that the highest neck loading of 13,200 N on the driver (7L4) was recorded [6, 9]. The orange end bars shown in **Figure 3** represent a length of approximately 61 cm (2 ft). The 7L4 neck loading occurred 3.787 seconds into the test when the vehicle roof contacted the ground. This also happened to be the last quarter turn of the crash event (last two frames in **Figure 3**).

If the falling lift analogy proposed by Moffatt is adopted, it would appear that the vertical drop height observed in the last two frames of **Figure 3** would be around 30.5 cm (1 ft). The vertical velocity from rotation was around 1.9 m/sec (Young et al [6]) Using Newtonian laws of physics, the velocity 'v' the vehicle could reach if it were to drop through such a height 'h' would be around

$$v = \sqrt{2gh} + 1.9 \qquad \ldots (1)$$

$$= \sqrt{2 \times 9.81 \times 0.0305} + 1.9 \approx 2.7 \text{ m/sec}$$

or around 9.6 km/hr or 6.0 mph. This is a very low impact velocity.

Carrying out the same calculations for a lift dropping through 6 metres as depicted by Moffatt in **Figure 2**, the impact velocity reached by the lift just prior to impact would be around 10.8 m/sec (39 km/hr or 24 mph). Hence, Moffatt's "lift shaft" analogy grossly over estimates the severity of the rollover event by at least one order of magnitude. It thus presents an inaccurate representation of the roof crush and subsequent injury process.

A question that is worth considering when contemplating Moffatt's "lift shaft" analogy, is what engineering changes would need to be carried out on the lift that would allow the person inside to survive such a 6 metre drop. One only needs to visualise the image of the lift shaft with the lift replaced by a car attached inside as shown in **Figure 4. W**ith the occupant held in the seat with a tensioned harness belt, it becomes obvious that the 6 meter fall is readily survivable. Indeed at a crash speed of 39 km/hr the occupant would most likely walk away from the fall.

Another way the Moffatt "lift shaft" scenario can be visualised as survivable is to place an aircushion at the bottom of the lift shaft. The cushion would decelerate the lift at a uniform rate of deceleration. Accepting that a person can survive a deceleration of around 10 g's it is possible to estimate the distance over which the lift would need to be decelerated in order for the person inside to survive. The fundamental equation that governs the behaviour of all decelerating objects is

$$v^2 = 2as \qquad \ldots (2)$$

where 'a' is the deceleration and 's' is the distance over which the body is decelerated. Thus the thickness of the air cushion would need to be

$$s = \frac{v^2}{2a} = \frac{10.8^2}{2 \times 10 \times 9.81} \approx 0.6 \text{ m}$$

Thus to decelerate the lift so that the person inside survives with no or minor injury from which he/she can recover, an air cushion of only 0.6 metres would be required as shown in **Figure 5**.

Figure 4: Car hung in lift shaft with occupant strapped into tensioned seat belt.

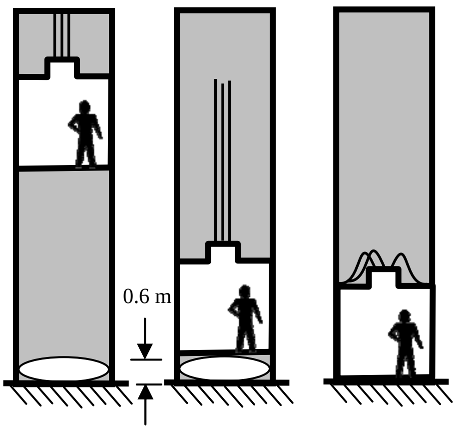


Figure 5 Energy absorber at base of lift that decelerates lift falling from 3 stories to 10 g's.

Note that equation (2) is independent of mass. This means equation (2) can be used to determine what minimum distance is required to slow a vehicle down and its occupants restrained inside so that they do not suffer a major injury. This equation was formulated in the early nineteenth century, i.e. almost 200 years ago.

Of course, because the severity of rollovers is an order of magnitude less than the lift falling three floors, the distance required to safely decelerate an occupant within the vehicle that has a strong roof structure will be accordingly far less. Nevertheless, what is more important to realise is that the deformation mechanism proposed by Moffatt in **Figure 2** bears no comparison to a 'real world' crash test shown in **Figure 3**.

To try to understand how non-ejected seat belted occupants are injured in rollover crashes, the authors have focussed on further analysing the results of the General Motors (GM) Malibu II rollover crash tests.

MALIBU II CRASH TESTS & ROOF STRIKE

GM undertook a series of FMVSS 208 dolly rollover crash tests of their 1983 Chevrolet Malibu vehicle, with seat belted occupants, in 1987. 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 Hybrid III 50th percentile 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. The rollover crashworthiness performance of the strengthened roll cage vehicles was compared to the production vehicles by Bahling et al [10].

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. **Figure 6** shows a graph of the PII's recorded [6] where it has been noted whether or not the PII was during roof-to-ground contact.

The authors have discussed the maximum PII load 7L4 recorded in test number 7 in a prior paper [6]. This paper looks in more detail at neck loads 3L2 and 3L3 and the associated roof deformation mechanisms.

Slow motion film recordings of test number 3 were investigated in detail. Reference lines were drawn along the top of the seat back and vertical from the seat back to the middle of the rear view mirror as shown in **Figure 7**. The length of a line drawn from the horizontal and vertical reference lines to an identifiable point on the roof at the B-pillar (roof deformation) and to the ATD's head (head movement) as well as the length of a line from the

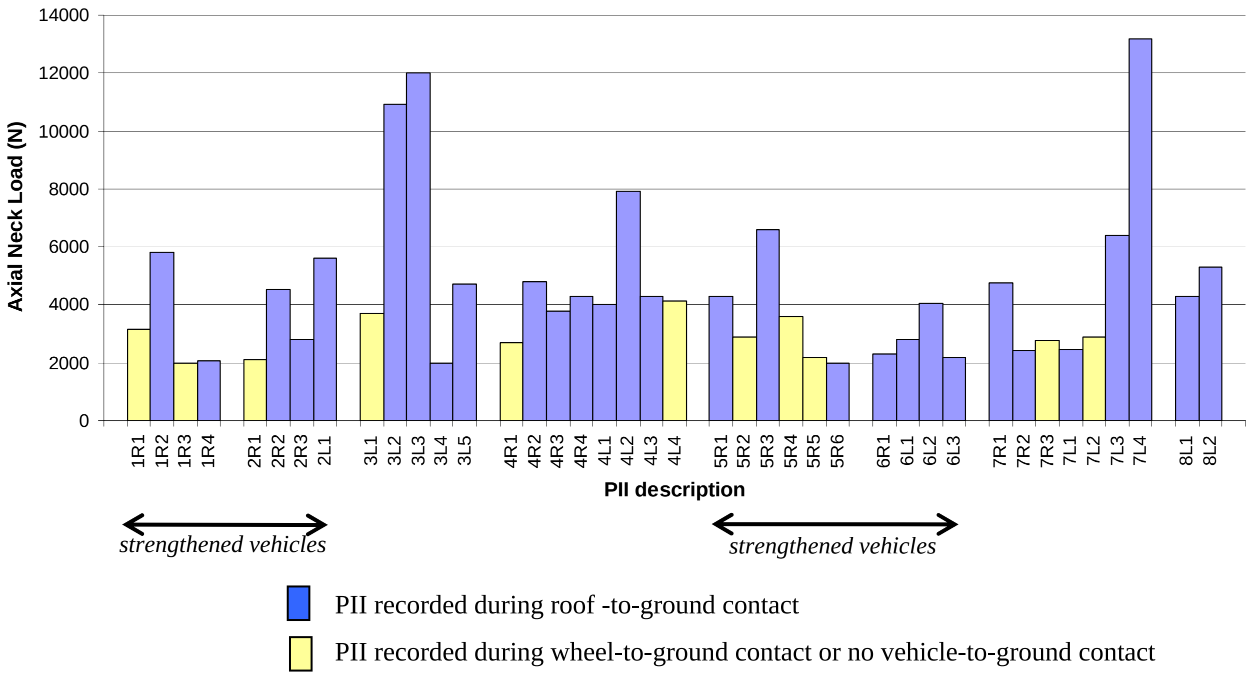


Figure 6: - Malibu II PII axial neck loads

head to the ATD's shoulders (neck compression) was measured in each of the 3 millisecond frames for neck loads 3L2 and 3L3. The data obtained is plotted in **Figures 8** & **9**. Whilst the values obtained are only as accurate as can be measured from each high speed film frame, they do provide a basis on which an understanding can be reached of how the load is applied to the ATD's neck during a rollover crash.

It is clear that in PII 3L2 the neck load occurs at the moment where the slope of the roof displacement versus time curve rises rapidly as indicated in **Figure 8 (b)**, i.e. where the vertical roof intrusion velocity is at its highest. What is interesting to note is the horizontal displacement is approximately twice the magnitude of the vertical displacement (**Figure 8 (a)**). Taking into account both vertical and horizontal displacement the resultant roof intrusion velocity at the moment 3L2 was recorded is around 5 m/sec (18 km/h or 11.2 mph).

Another interesting point to note from **Figure 8 (c)** is the ATD's shoulder does not move relative to the seat back until well after the neck had been loaded, i.e. at 625 ms. Once the load is imparted onto the ATD's head from the intruding roof, the neck is compressed as a result of the torso's inertia preventing it from immediately moving in unison with the roof crush and head. The shoulder starts to move at 625 ms and eventually catches up with the forced displacement (roof & head movement).

Figure 9 shows the comparable graphs for PII 3L3. Similar characteristics can be noted here as well, i.e.

- the horizontal deformation is around twice the vertical deformation
- the roof intrusion velocity relative to the seat back and torso is again around 5 m/sec (18 km/h or 11.2 mph)
- the torso begins to move well after the neck has been loaded and then unloaded
- the head movement is closely coupled to the roof intrusion

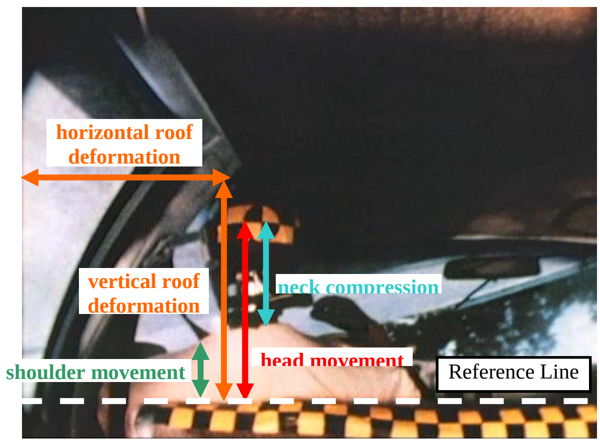
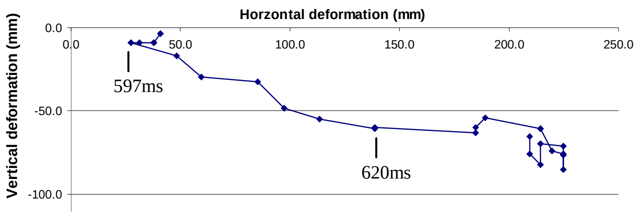
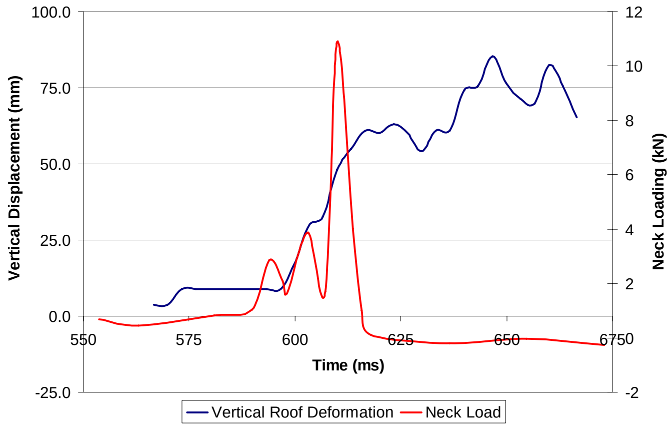


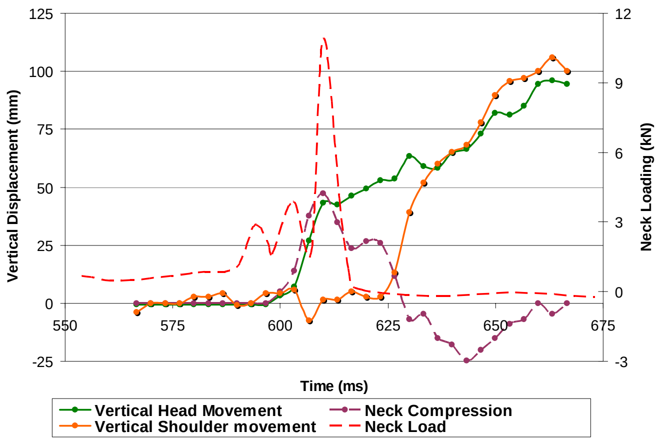
Figure 7 Lines measured during each 3 millisecond frame.



(a) PII: 3L2 Horizontal versus vertical roof deformation



(b) PII: 3L2 Vertical roof deformation and neck load versus time.



(c) PII: 3L2 Vertical head & shoulder movement and neck compression versus time compared to neck loading versus time.

Figure 8: Vehicle roof crush & ATD neck loading, head movement, shoulder movement & neck compression for Malibu II 2L2.

This is a similar result to that obtained by Freidman and Nash [9] for the 3L3 PII though the magnitude of roof crush appears to be different. The main reason for this is that only the vertical displacement is graphed in **Figure 8** whereas it is not clear what measure was used by Freidman and Nash [9] to plot roof crush. From the high speed films it appears the B-pillar and A-Pillar intrude a considerable distance sideways into the occupant compartment.

It is worth noting that Friedman and Nash [9] calculated a value of 10.1 mph for the B-pillar intrusion. This confirms the accuracy of the value calculated is reasonable considering the methodology chosen to obtain the graphs shown in **Figures 8** & **9**. Indeed, frame images from Malibu test 3 confirm the torso moves after the neck has been compressed as shown in **Figures 10** & **11**. In PII 3L2 compression is predominantly axial whereas in PII 3L3 the neck loading appears to be subjected to combined axial and shear.

The torso moves somewhat similar as would a single degree of freedom mass reacting against a compressed spring at one end and then pulling on the spring subjecting the neck to tension (**Figures 8(c)** & **9(c)**).

In regards to the Moffatt [8] diving analogy, i.e. when the vehicle's roof contacts the ground, the occupant's head stops against the roof, and then the torso of the occupant and vehicle (visualise bench seat back in **Figures 11** & **12**) continues to move towards the roof/ground at the same rate, it appears at first glance that the information in **Figures 7, 8, 11** & **12** confirms the mechanism he proposed. However, to better understand what is actually occurring in terms of the head-torso interaction with the vehicle roof and the issue of diving versus roof crush, a mathematical model characterising the occupant dynamics and neck loading needs to be considered. Such a model was proposed and analysed by the authors in a previous paper [6]. The analysis of that model is extended further here.

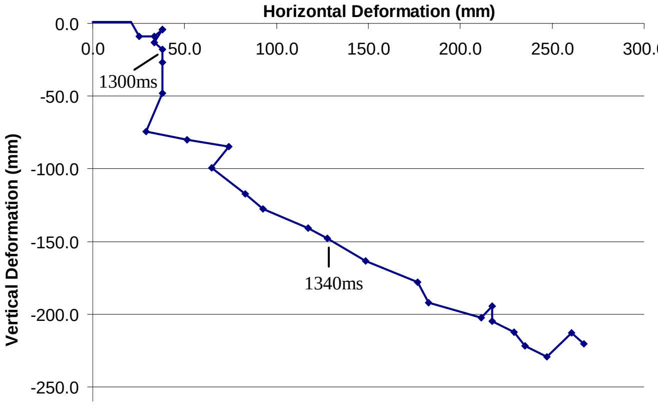
NECK-TORSO SIMPLIFIED MODEL

Figure 10 shows two simplified single degree of freedom dynamic models representing the Hybrid III dummy's torso, neck and head shown in **Figures 11** & **12**. There are three possible scenarios in which the neck in this model can be loaded; **Figure 10 (a)** Roof crush; **Figure 10 (b)** Diving; and a combination of diving and roof crush.

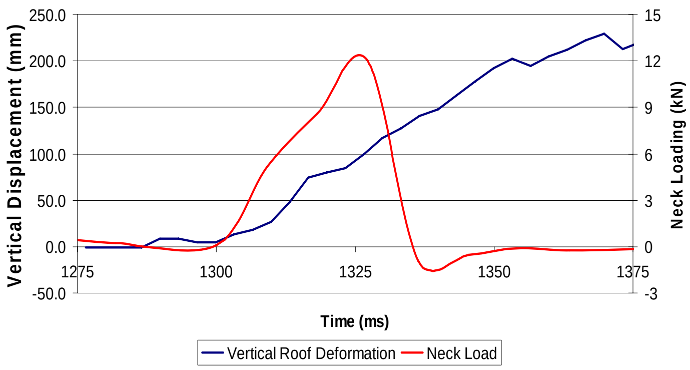
To analyse this model, the following simplifying assumptions must be made first namely:

- All movement of the head and/or torso is absorbed through compression of the neck. In other words, the torso-neck-head interaction is a single degree of freedom system subjected to an imposed vertical motion. The motion is applied as a result of either the roof striking the head and moving the head towards the torso or the torso mass moving at a constant velocity towards a rigid surface roof/ground.
- No damping of the force occurs due to impact with the head.

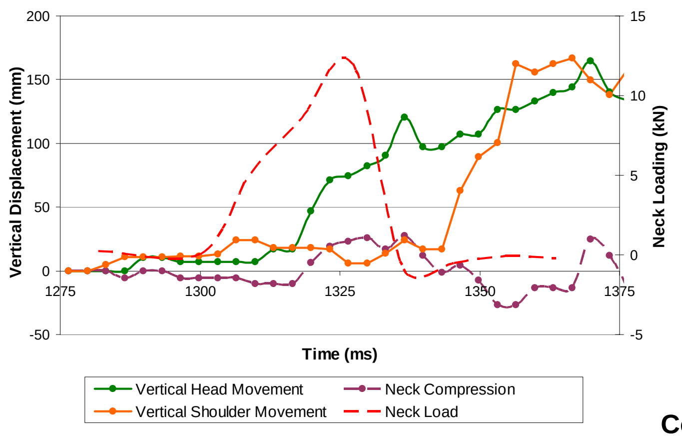
- As is suggested in Moffatt's diving theory all loading on the neck is produced by the inertia of the dummy's torso (torso augmentation).
- Deceleration/acceleration occurs at a constant rate.
- Force is constant throughout the neck, i.e. same force at the top of the neck, C1 position, and the base of the neck, C7 position.
- The head and neck stay aligned as shown in **Figure 10** for the duration of loading, resulting in a purely compressive load.



(a) PII: 3L3 Horizontal versus vertical roof deformation



(b) PII: 3L3 Vertical roof deformation and neck load versus time.



(c) PII: 3L3 Vertical head & shoulder movement and neck compression versus time compared to neck loading versus time.

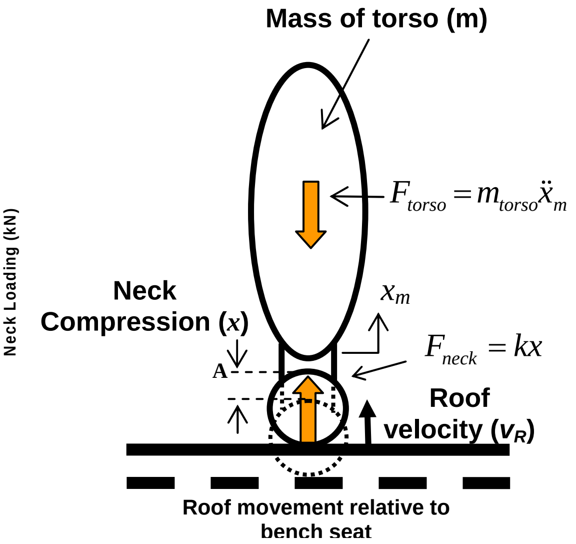
Figure 9: Vehicle roof crush & ATD neck loading, head movement, shoulder movement & neck compression for Malibu II 3L3.

Roof Crush:

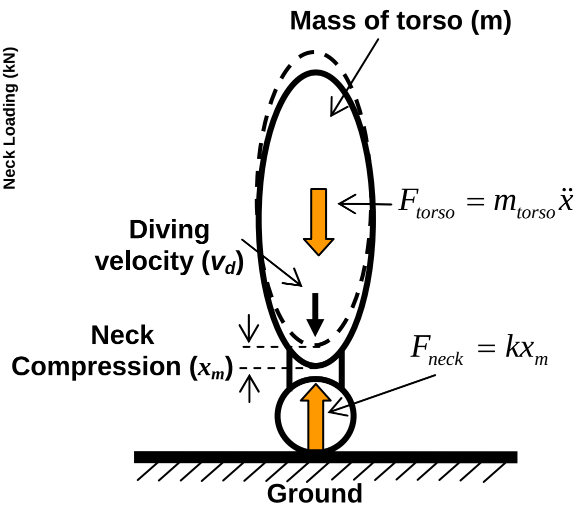
Using **Figure 10 (b)** the equation of motion, i.e. equilibrium of mass at any instant is

$$k\left(x - x_m\right) = m\ddot{x}_m \qquad \ldots (3)$$

where k is the ATD's neck stiffness, x the neck compression, x_m the displacement of the torso, m



(a) **Roof crush**



(b) **Diving**

Figure 10: Single degree of freedom dynamic model representing Hybrid III dummy


Head under side rail near B-pillar. Note three neck rings visible.


Neck compressed. Note only two neck rings visible and sensor cable flatter.


Torso now moving and three neck rings just visible. B-pillar has move laterally inwards.


Torso moved lower relative to seat back. Neck is now longer.

Figure 11: Kinematics of PII 3L2


Head under side rail near B-pillar. Note three neck rings visible.


Neck compressed and head moved side ways. Note small “v” in T-shirt neck line left of centreline of head when compared to frame above.


Torso now starting to catch up with neck and head


Torso moved lower and across relative to seat back.

Figure 12: Kinematics of PII 3L3

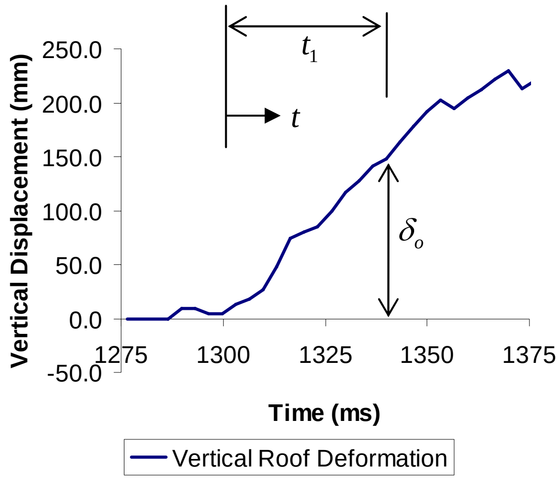


Figure 13: Roof crush versus time from PII 3L3.

the mass of the torso and $\ddot{x}_m$ the acceleration of the torso. Thus the governing dynamic equation is

$$m\ddot{x}_m + kx_m = kx \qquad \ldots (4)$$

Roof crush appears to linearly vary with time as indicated in **Figure 13**. Hence,

$$x = \delta_0 \frac{t}{t_1} \qquad \ldots (5)$$

where t is the time from the start of neck loading, t_1 is the time over which neck loading occurs and δ_0 is the magnitude of displacement at the end of the loading phase. Thus substituting into right hand side of Equation (4)

$$m\ddot{x}_m + kx_m = k\delta_0 \frac{t}{t_1} \qquad \ldots (6)$$

Equation (6) is a well known 2nd order non-homogenous differential equation with constant coefficients. It's solution is composed of a general solution being the complimentary solution x_c and the particular solution x_p. Thus

$$x_c = A\sin\omega t + B\cos\varpi t \qquad \ldots (7)$$

where A and B are integration constants and

$$\varpi = \sqrt{\frac{k}{m}} \qquad \ldots (8)$$

is the circular frequency.

The displacement during the phase over which loading occurs (t_1) can be determined using Equation (5). The particular solution for this loading is

$$x_p = \delta_0 \left(\frac{t}{t_1} \right) \qquad \ldots (9)$$

Thus the full solution for the movement of the torso is

$$x_m = x_c + x_p = A\sin\varpi t + B\cos\varpi t + \delta_0 \left(\frac{t}{t_1} \right) \qquad \ldots (10)$$

and its velocity is

$$\dot{x}_m = A\varpi\cos\varpi t - B\varpi\sin\varpi t + \frac{\delta_0}{t_1} \qquad \ldots (11)$$

and its acceleration

$$\ddot{x}_m = -A\varpi^2\sin\varpi t - B\varpi^2\cos\varpi t \qquad \ldots (12)$$

From initial conditions we know that at $t = 0$ the torso has not moved and thus its displacement is assumed to be zero, i.e. $x_m = 0$. Thus using Equation (10)

$$A\sin(\varpi \times 0) + B\cos(\varpi \times 0) + \delta_0 \left(\frac{0}{t_1} \right) = B = 0 \qquad \ldots (13)$$

and also at $t = 0$ the velocity of the torso is assumed to be zero, i.e. $\dot{x}_m = 0$. Hence substituting into Equation (11) results in

$$A = -\frac{\delta_0}{\varpi t_1} \qquad \ldots (14)$$

Thus substitution and rearranging terms the displacement of the torso for the loading phase when the roof is crushing in is

$$x_m = \frac{\delta_0}{t_1}\left(t - \frac{\sin\varpi t}{\varpi} \right) \qquad \ldots (15)$$

and its velocity is thus

$$\dot{x}_m = \frac{\delta_0}{t_1}(1 - \cos\varpi t) \qquad \ldots (16)$$

and its acceleration

$$\ddot{x}_m = \frac{\delta_0\varpi}{t_1}\sin\varpi t \qquad \ldots (17)$$

From **Figure 10 (a)** the load in the neck of the ATD can be expressed as

$$F_{neck} = k(x - x_m) \qquad \dots (18)$$

Hence using Equation (15) and Equation (5)

$$F_{neck} = kx - k\frac{\delta_0}{t_1}\left(t - \frac{\sin \varpi t}{\varpi}\right) = k\frac{\delta_0 t}{t_1} - k\frac{\delta_0}{t_1}\left(t - \frac{\sin \varpi t}{\varpi}\right)$$

… (19)

which simplifies to

$$F_{neck} = \frac{k\delta_0}{t_1}\frac{\sin \varpi t}{\varpi} = \frac{\sqrt{km}\ \delta_0 \sin \varpi t}{t_1}$$

… (20)

Using Equation (5), the velocity at the interface between the head and the neck (point A in **Figure 10 (a)**) is

$$\dot{x} = \frac{\delta_0}{t_1} \qquad \dots (21)$$

thus

$$F_{neck} = \dot{x}\sqrt{km}\ \sin \varpi t$$

The load varies over time. This means that the load in the dummy's neck is largest when

$$\frac{\partial F_{neck}}{\partial t} = 0 = \ddot{x}\sqrt{km}\ \varpi \cos \varpi t$$

Thus when the acceleration is zero the neck loading is a maximum and when $\cos \varpi t = 0$, $\varpi t = \frac{\pi}{2}$.
Substituting this and Equation (21) into Equation (20) results in $F_{neck} = \dot{x}\sqrt{km}\ \sin\frac{\pi}{2}$ and when simplified and replacing the term $\dot{x} \equiv v_R$ is

$$\boxed{F_{neck} = v_R\sqrt{km}} \qquad \dots (22)$$

Thus knowing the velocity of the roof crush, the stiffness of the ATD's neck and the mass of the torso, the peak axial force in the neck can be determined.

Diving:

To determine what the neck load would be in the situation where the torso and head move towards the ground the model in **Figure 10 (b)** is now considered. In this instance equilibrium of forces at any instant is

$$kx_m = m\ddot{x}_m \qquad \dots (23)$$

resulting in the following governing equation

$$m\ddot{x}_m + kx_m = 0 \qquad \dots (24)$$

Equation (24) is a 2nd order homogenous differential equation with constant coefficients.

The solution to **Equation (24)** is the same as the general solution for a single degree of freedom mass subjected to undamped vibration, i.e. Equations (7) & (8). Thus the velocity in this instance is

$$\dot{x}_m = A\varpi \cos \varpi t - B\varpi \sin \varpi t \qquad \dots (25)$$

and acceleration is the same as Equation (12).

From initial conditions at $t = 0$ the displacement of the torso is assumed to be zero, i.e. $x_m = 0$. Thus using Equation (7)

$$A\sin(\varpi \times 0) + B\cos(\varpi \times 0) = B = 0 \qquad \dots (26)$$

and also at $t = 0$ the velocity of the torso is assumed to be constant during neck loading, i.e. $\dot{x}_m = v_d$ (see Figure 12 in Young et al [6]). Hence substituting into Equation (7)

$$A\varpi \cos(\varpi \times 0) - 0 = A\varpi = v_d \qquad \dots (27)$$

resulting in

$$A = \frac{v_d}{\varpi} \qquad \dots (28)$$

Thus the final governing equations for the loading phase when the torso and neck are diving into the roof/ground is

$$x_m = \frac{v_d}{\varpi}\sin \varpi t \qquad \dots (29)$$

and the velocity is thus

$$\dot{x}_m = v_d \cos \varpi t \qquad \dots (30)$$

and acceleration

$$\ddot{x}_m = -v_d \varpi \sin \varpi t \qquad \ldots (31)$$

From **Figure 10 (b)** the load in the neck of the dummy is expressed as

$$F_{neck} = k x_m \qquad \ldots (32)$$

Hence using Equation (29)

$$F_{neck} = k \frac{v_d}{\varpi} \sin \varpi t \qquad \ldots (33)$$

which can also be expressed as

$$F_{neck} = v_d \sqrt{km} \sin \varpi t \qquad \ldots (34)$$

The load varies over time. This means that the load in the dummy's neck is largest when

$$\frac{\partial F_{neck}}{\partial t} = 0 = v_d \sqrt{km}\ \varpi \cos \varpi t = k v_d \cos \varpi t$$

This means $\varpi t = \dfrac{\pi}{2}$ or $t = \dfrac{\pi}{2\varpi} = \dfrac{\pi}{2}\sqrt{\dfrac{m}{k}}$

Thus substituting into Equation (34) for ϖt

$$\boxed{F_{neck} = v_d \sqrt{km}} \qquad \ldots (35)$$

This is exactly the same equation as Equation (22), i.e. there is no mathematical difference between roof crush and diving from a engineering dynamics perspective.

Combined roof crush and diving:

In this instance the roof is crushing in at a velocity of v_R as shown in **Figure 10 (a)** while at the same time the torso is moving towards the incoming roof at v_d as shown in **Figure 10 (b)**. In this case the equilibrium of forces is the same as for roof crush alone, i.e. Equation (3). Thus the governing equation is Equation (4).

Roof crush will still vary linearly during the load phase. Hence Equation (5) is still valid for the neck compression and Equation (6) is the governing dynamic equation. The solution to this equation is represented by Equations (10), (11) and (12). However this is where the mathematical similarity to roof crush ends.

The initial conditions are different in this case, i.e. at $t = 0$ the displacement of the torso is adopted as zero such that $x_m = 0$. Thus using Equation (12)

$$A \sin(\varpi \times 0) + B \cos(\varpi \times 0) + \delta_0 \left(\frac{0}{t_1}\right) = B = 0 \qquad \ldots (36)$$

but at $t = 0$ the velocity of the torso is constant, i.e. $\dot{x}_m = v_d$. Hence substituting into Equation (11)

$$A \varpi \cos(\varpi \times 0) - 0 + \frac{\delta_0}{t_1} = A\varpi + \frac{\delta_0}{t_1} = v_d \qquad \ldots (37)$$

resulting in

$$A = \frac{1}{\varpi}\left(v_d - \frac{\delta_0}{t_1}\right) \qquad \ldots (38)$$

Therefore the dynamic equations for the loading phase when the roof is crushing towards the occupant and the occupant is diving into the roof is

$$x_m = \frac{1}{\varpi}\left(v_d - \frac{\delta_0}{t_1}\right) \sin \varpi t + \delta_0 \left(\frac{t}{t_1}\right)$$

and after rearranging terms is

$$x_m = \frac{v_d}{\varpi} + \frac{\delta_0}{t_1}\left(t - \frac{\sin \varpi t}{\varpi}\right) \qquad \ldots (39)$$

and the velocity is the same as Equation (16) and acceleration is the same as Equation (17)

The load in the neck of the dummy is the same as Equation (18). Hence using Equation (39) and Equation (5)

$$F_{neck} = kx - k\left[\frac{v_d}{\varpi} - \frac{\delta_0}{t_1}\left(t - \frac{\sin \varpi t}{\varpi}\right)\right]$$

$$= k\frac{\delta_0 t}{t_1} - k\frac{v_d}{\varpi} - k\frac{\delta_0}{t_1}\left(t - \frac{\sin \varpi t}{\varpi}\right)$$

which simplifies to

$$F_{neck} = k\left(\frac{v_d}{\varpi} + \frac{\delta_0}{t_1}\frac{\sin \varpi t}{\varpi}\right) = \sqrt{km}\left(v_d + \frac{\delta_0 \sin \varpi t}{t_1}\right) \qquad \ldots (40)$$

From Equation (5) the velocity at the neck head interface is

$$\dot{x} = \frac{\delta_0}{t_1}$$

Thus

$$F_{neck} = \sqrt{km}\left(v_d + \dot{x}\sin\varpi t\right) \quad \ldots (41)$$

The load varies over time. This means that the load in the dummy's neck is largest when

$$\frac{\partial F_{neck}}{\partial t} = 0 = \ddot{x}\sqrt{km}\ \varpi\cos\varpi t$$

Thus when the acceleration is zero the neck loading is a maximum as all other terms are non-zero regardless of the speed of the torso's initial diving velocity.

Again if $\cos\varpi t = 0$. This means $\varpi t = \frac{\pi}{2}$ or

$$t = \frac{\pi}{2\varpi} = \frac{\pi}{2}\sqrt{\frac{m}{k}}$$

Thus substituting into Equation (41)

$$F_{neck} = \sqrt{km}\left(v_d + \dot{x}\sin\frac{\pi}{2}\right)$$

and finally after replacing the term $\dot{x} \equiv v_R$, results in

$$\boxed{F_{neck} = \sqrt{km}\left(v_d + v_R\right)} \quad \ldots (46)$$

This means that the roof crush and the diving components combine together resulting in an increase in load to the neck. That this is the case has been shown by the authors in a previous paper for injury 7L4 (Young et al [6]). However, only the diving component of the impact was calculated and shown to be around half the neck load measured where roof crush was evident. Equation (46) shows that the intrusion velocity of the roof needs to be added to the diving velocity of the ATD to obtain the correct value of the neck load.

NECK LOAD CALCULATIONS

To calculate the torso velocity, the high speed film was digitised into single frame images and the rotational and vertical movements for a given time period were noted. The rotational velocity (ω) and vertical velocity (v_v) was calculated. This was then used to determine the respective rotational and vertical velocity changes of the vehicle where the time period was started when the driver's side or passenger side roof rail touched the ground until the peak neck load was observed. The period was around 20 - 40 ms.

The equivalent change in tangential velocity (Δv_ω) the dummy would be subjected to as a result of rotation was determined using the position of the dummy and the rotational velocity change of the vehicle. The distance from the dummy's COG to the vehicle's COG, which in turn was assumed to be at the centre of rotation, was the lever arm length used to convert rotational velocity. The tangential and vertical velocity changes were then added because both were essentially in the vertical direction (i.e. down) at the time of roof to ground contact. Thus the overall vertical velocity change Δv_d that the dummy's torso would be travelling at was calculated.

Finally, using Equation (35) and the calculated velocities, the theoretical neck load in the case of torso augmentation ("diving") was estimated. **Table 1** shows the rotational, vertical and total (equivalent "diving") velocity change for each vehicle and the resulting theoretical neck load that could be expected as a result of this torso movement. The final column in **Table 1** lists whether the calculated loads minus the measured loads were within estimated calculation errors.

It is clear that using the velocity from rotation and vertical drop only (**Figure 3**), where there is significant roof intrusion (3L2, 3L3 & 4L7), results in an underestimate of the neck load measured in the ATD.

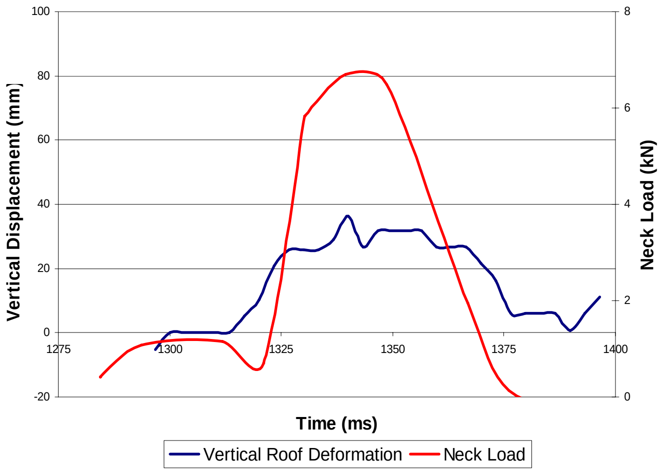
When Equation (22) and the intrusion velocity for 3L2 and 3L3 of 5 m/sec is used, a neck load value of around 12 kN is obtained compared to measured values of 10.9 kN and 12 kN respectively. A neck stiffness of 3.36 kN/cm and a torso mass of 17.19 kg were used to calculate these values (Young et al [6]). The calculated neck loads are within measurement tolerance. Hence this confirms that the neck load is closely coupled with the roof intrusion.

Figurers 8 & **9** show that the torso is not moving relative to the seat back until after the neck load has peaked. The captured images in **Figures 11** & **12** demonstrate that the torso only begins to move well after the neck has been loaded and then unloads.

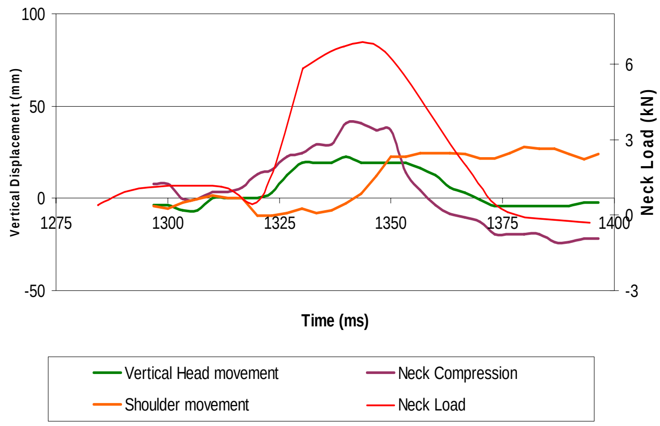
When injury 5R3 is considered, being the highest neck load for a reinforced vehicle, measurements of shoulder and head movements shown in **Figure 14** indicate the ATD's shoulder is moving earlier and

Test	Roof Support	Injury	Position	Δω (rad/Sec)	Lever arm to COG (m)	ΔV_ω (m/sec)	ΔV_v (m/sec)	ΔV_d (m/sec)	Theoretical Load (N)	Hybrid III Load (N)	Difference (N)	Inside errors?
2	Reinforced	2L1	Far-side	2.4±0.2	0.46	-1.1±0.1	-1.3±0.9	2.4±1.0	5,700±2,400	5,600	-100	Yes
5	Reinforced	5R3	Near-side	1.4±0.3	0.65	-0.9±0.2	-1.7±1.2	2.6±1.4	6,200±3,300	6,600	400	Yes
3	Production	3L2	Far-side	2.6±0.1	0.56	-1.6±0.1	-1.1±1.5	2.7±1.6	6,400±3,800	10,900	-4,500	No
3	Production	3L3	Far-side	2.6±0.1	0.53	-1.3±0.1	-0.5±1.3	1.8±1.4	4,400±3,300	12,000	-7,600	No
4	Production	4L2	Far-side	2.6±0.3	0.69	-1.8±0.2	-0.7±1.2	2.5±1.4	5,900±3,300	7,900	-2,000	Yes
7	Production	7L4	Far-side	2.9±0.2	0.63	-1.9±0.1	-0.9±0.9	2.8±1.0	6,700±2,400	13,200	-6,500	No

Table 1: Theoretical ATD neck loads calculated using Equation (35) compared to measured loads.



(a) PII: 5R3 Vertical roof deformation and neck load versus time.



(b) PII: 5R3 Vertical head & shoulder movement and neck compression versus time compared to neck loading versus time.

Figure 14: ATD neck loading, head movement, shoulder movement & neck compression for Malibu II 5R3.

within the neck loading phase. Hence in this test, neck compression appears to be resulting from a component attributed to torso movement within the reinforced vehicle. Moreover, when the internal views of the ATD for each of the PII's are viewed for the reinforced vehicles, the footage shows the roof and roll cage moving relative to the seat back. **Figure 14 (a)** clearly shows the reinforced roof moving 35 mm vertically downwards relative to the vehicle's seat back. The intrusion velocity is around 2.5 m/sec. Using Equation (22) a value of around 6 kN neck load is obtained. Thus, some form of small roof intrusion is still occurring albeit small and can be observed for most of the PII injuries in the reinforced vehicles.

All of the Malibu II film footage of the reinforced vehicles was also carefully investigated to identify if a PII injury measure existed where there was clearly no roof deformation but torso augmentation was clearly visible. **Figures 15** & **16** show that injury 6L2 matches such a characteristic. **Figure 16** shows the torso moving towards the roof during a near-side impact and no roof deformation on the far-side above the dummy could be perceived in the film. The measurement of the movement of the roof relative to the seat back is graphed in **Figure 15**. It deformed only a few millimetres. The measured neck loading resulting from this diving mechanism, characterised in **Figure 10 (b)**, is graphed in **Figure 15**. The velocity of the torso just prior to the neck being loaded was of the order of 1.7 m/sec. Again using Equation (35) a value for the neck load of around 4 kN is obtained.

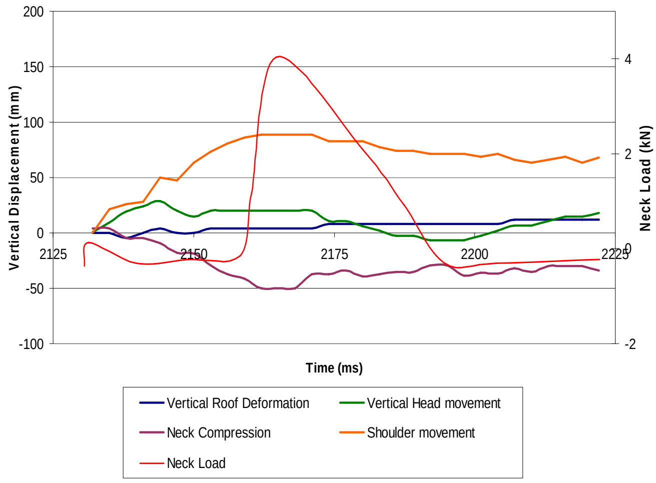


Figure 15 ATD neck loading, head movement, shoulder movement & neck compression for Malibu II 6L2.

CONCLUSIONS

The following conclusions were reached on the basis of the work presented in this thesis.

The "lift shaft" analogy used by Moffatt [8] to describe how injuries occur in rollover crashes does not reflect the measured injuries in real world FMVSS 208 dolly rollover crash tests nor for that matter real world crashes. The magnitude of injury severity in a rollover would be inaccurate by at least an order of magnitude compared to the severity of a lift dropping 3 stories down a shaft and crashing. Similarly, the kinematics of a rollover crash are not comparable to the kinematics of a lift dropping three stories down a lift shaft.

Dissipating the kinetic energy of a lift dropping down a lift shaft three stories in order to prevent anyone inside the lift being injured, only requires an aircushion approximately 0.6 metres deep.

Because the severity of a rollover crash is an order of magnitude less severe than a lift falling three stories, a much smaller energy dissipater such as padding or an air curtain is require to mitigate occupant injuries.

Roof crush increases the severity of neck injuries in rollover crashes.

The neck loading is closely coupled to the velocity of the roof intrusion. This can be proven mathematically using Newtonian laws of physics.

Injurious neck loads would be significantly reduced in rollover crashes if vehicles roofs were strengthened to prevent intrusion at critical velocities.

Vehicle just prior to touch down on near side. Note position of torsorelative to seat back.

Torso moves towards roof (diving into roof) during near side touch down resulting in 6L2 injury measure.

Figure 16 Kinematics of PII 6L2.

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