ADVANCED ROOF DESIGN FOR ROLLOVER PROTECTION

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ABSTRACT

Roof strength clearly affects the probability of occupant head and neck injury in light vehicle rollovers. Despite this, most manufacturers continue to design and build vehicles with inadequate roof strength. From experimental and biomechanics evidence and rollover crash data, we present the case that weak, antiquated roof designs contribute to severe head and neck injuries. We discuss the deficiencies in modern roof designs, how they cause severe head and neck injuries, and the limitations inherent in the Federal roof crush standard, FMVSS 216. We describe cost-effective examples of materials and technologies that can provide adequate roof strength to protect occupants in most rollovers without imposing significant weight penalties. Finally, we discuss an approach to dynamic roof strength testing that is based on what occurs in an actual, serious injury-producing rollover.

INTRODUCTION

Structurally weak roofs are the primary cause of serious head, face and neck injuries (HFN injuries) to occupants who are not ejected in rollovers. This conclusion is supported by analyses of National Accident Sampling System (NASS) data; computer simulation models; and a variety of vehicle rollover and drop test experiments using cadaver, hybrid III dummy, and human subjects.

Thirty years ago, auto safety experts understood that major intrusion into a vehicle occupant's space increased the potential for serious injury. They often found that head and neck injuries in rollovers resulted from roof crush.

Crash investigations in those years (Huelke, 1973) also showed that at least half of all occupants who were seriously injured had been ejected. In more recent years, increased belt use reduced the probability of rollover ejection, leaving occupants more vulnerable to injury within the vehicle.

Despite the fact that its own research indicated the need for a stronger standard, in the early 1970s, the National Highway Traffic Safety Administration (NHTSA) promulgated a minimal, quasi-static roof crush standard (FMVSS 216). It was based on a Society of Automotive Engineers (SAE) Recommended Practice that General Motors Corp. (GM) had originally proposed.

FMVSS 216 provides a poor emulation of the conditions of actual rollovers that result in serious injury. Despite extensive evidence of the need for a stronger standard, it has never been amended except to broaden its coverage to light trucks and vans.

In 1975, Dr. Edward Moffatt, a GM engineer, published a paper that put forth the hypothesis that there was no causal relationship between roof crush and head or neck injury (the Moffatt theory; Moffatt, 1975). His theory was that head and neck injuries in rollovers occurred when a vehicle roof initially touched the ground, and that the subsequent behavior of the roof was irrelevant to such injuries. Since then, GM and other auto companies have justified inadequate roof strength by citing the Moffatt theory.

General Motors, attempted to experimentally prove the Moffatt theory in two major, rollover test programs (the Malibu I and II tests: Orlowski, et. al., 1985; Bahling, et. al., 1990). The Malibu tests provide a rich source of data on rollovers and rollover injuries despite GM's attempts to keep the data secret and to publish misleading interpretations of it.

The authors have demonstrated that vehicle roofs – including those that meet FMVSS 216 – are not passive interfaces between an occupant's head and the ground in a rollover. Rather, a weak roof can collapse and buckle in a rollover, imposing forces on an occupant's head that are substantially greater than would result from the vehicle drop itself. In a significant minority of rollovers, these amplified impacts cause severe to fatal head and neck injuries that would not have occurred if the person's head had simply struck the ground at the speed it was falling.

Friedman has documented this effect through analyses of more than two hundred rollovers in which occupants received catastrophic injury. He has shown that the purported proofs of Moffatt's theory that roof strength is not relevant to occupant injury are not valid (Friedman, various papers).

Despite the overwhelming evidence, auto makers and their experts continue to oppose open scientific discussion of rollover casualties. They make confusing and deceptive presentations to NHTSA, the courts, and the public to perpetuate three myths.

Myth #1: Vehicle rollovers are violent events in which the roof strikes the ground at high speed

A rollover is actually a low force event by comparison with major, easily survivable frontal or side impacts. Ninety percent of rollovers do not exceed one complete (360°) roll. The more serious ten percent of rollovers of more than one revolution look violent and damage major vehicle surfaces.

However, in virtually every rollover test and accident the authors and their colleagues have analyzed, the vertical velocity of the vehicle's center of gravity at roof touch down is less than about 2.5 meters/sec (8 feet/sec or 5 mph). More typically, it is half this velocity.

In a rollover, the front seat occupants move and fall with the vehicle whether they are restrained or not. The forces seen by a vehicle occupant in a rollover are only violent if the roof intrudes rapidly into the occupant's survival space. If the roof and its supporting structure are sufficiently strong that they do not deform significantly, an automobile rolls as an essentially rigid, roughly cylindrical body.

This means that the occupant's second collision (with the interior of the vehicle) is effectively at the same speed as the vehicle's collision speed with the ground. Such head impact speeds (1.2 to 2.5 m/sec) into reasonably padded surfaces (such as are now required by FMVSS 201) are easily survivable without serious head or neck injury.

A rolling vehicle's lateral velocity (in relation to the ground) is likely to exceed its maximum drop speed of 2.5 m/sec. When the roof touches down, friction between the roof and the ground and gouging into the ground may impose lateral forces on the roof that are as great as the vertical impact forces. A strong roof will transmit these forces to the vehicle as a whole where they will affect the translational and rotational velocities of the vehicle. By contrast, a weak roof will simply collapse laterally and buckle.

Myth #2: Vehicle roofs that meet FMVSS 216 are adequately strong

Almost all light motor vehicles on American roads meet FMVSS 216. It requires that a roof withstand a force of up to 1½ times the weight of the vehicle. For passenger cars, this force is limited to 5,000 pounds. The force is applied at a 5^o pitch and 25^o roll angle over where the A-pillar meets the roof panel. The vehicle passes if the roof deforms less than 5 inches when the maximum force is applied.

The steel structure of most modern vehicle roofs and supporting pillars, weighs less than 3 percent of a vehicle's curb weight (the steel in a car roof typically weighs less than 100 pounds). When tested under FMVSS 216, more than 30% of a roof's static strength may come from its bonded windshield. That is, many modern vehicles could not meet FMVSS 216, if their windshields were removed.

If the force of FMVSS 216 were applied at a greater roll angle, a typical roof would be as much as 30% weaker. However, a greater roll angle more accurately simulates what occurs in a real rollover.

Dynamic roof loading in rollover almost always fractures or separates the windshield from its frame when the roof first contacts the ground. Without the strength provided by its windshield, the roof is much more likely to deform and buckle upon its subsequent impact with the ground.

A rollover often applies higher lateral forces to the roof than occur in FMVSS 216. Thus, a roof that only meets FMVSS 216 is likely to deform laterally and buckle in a highly nonlinear fashion, particularly after the windshield integrity has been lost.

The roofs buckle at weak points such as at holes and the ends of reinforcing gussets, and where welds are inadequate. The speed of a buckling roof element can be a multiple of the impact speed between the roof and the ground, amplifying the force on an occupant's head that is in its path. Such forces may be sufficient to severely injure the occupant.

Thus, the deficiencies in FMVSS 216 are that:

1. It applies the force in a manner that permits the windshield to play a significant, but unrealistic role in limiting roof deformation;
2. It applies the force at a more vertical roll angle than is typical of actual rollover forces; and
3. The total force applied is substantially less than the forces actually applied to a roof in a rollover.

Myth #3: Neck force measurements on a Hybrid III dummy neck properly measure the potential for human head and neck injury

GM's H. J. Mertz wrote a paper (Mertz, 1978) analyzing how two young, helmeted football players were injured when they were struck on the head by a spring loaded tackling block with 15 cm (6 inches) of relatively soft padding over a 25 kg (55 pound) steel core. One impact was at 4.5 m/sec (10 mph) and the other at 6.8 m/sec (15 mph). Both players received vertebral fractures at C-6 and became quadriplegic.

Mertz arranged to have a Hybrid III dummy's head struck by the same tackling block at the same speeds emulating the forces that injured the players. He measured the axial forces at the top of the neck to be 4,000 N (900 lbs) and 6,670 N (1,500 lbs).

A few years later, Nusholtz and Sances conducted a number of full body human cadaver drop tests (Nusholtz, et al, 1982; Sances, et al, 1984). They dropped cadavers from heights of 0.9 to 1.5 meters with and without neck alignment constraints. They showed that a reasonably healthy human being could survive a drop on his or her head from a height of up to one meter onto a modestly padded surface.

The impact velocity from a 1 meter drop is 4.5 m/sec (15 ft/sec). They also showed that other combinations of speed, padding and weight produced different forces and injuries, but vertebral fractures to a healthy, fairly young individual required an impact speed of at least 4 m/sec. (9 mph).

This is generally accepted as the limit impact speed above which catastrophic neck injury becomes highly likely. There is a also a consensus that the lowest head impact velocity that can fracture a human neck, is about 3 m/sec (10 ft/sec) which would be the result of a drop from 0.5 meter.

Despite this evidence, Mertz (1984) proposed a very conservative Hybrid III neck injury criteria: 4,000 N (900 lbs) at onset, declining to 2,000 N after 40 ms. He did not discuss the influence of speed, padding and impacting weight from which the forces were generated. In fact, these and other factors can alter the potential for a force to injure a human neck.

The speed of the impact, not the force, is the primary determinant of human neck injury. If the neck has time to bend and move out of the way, it is much less likely to fracture. A 2.5 mph unpadded impact to the head of a dummy can produce a 4,000 N force at base of the head, but such an impact is not likely to seriously injure a human neck.

The Hybrid III dummy has a solid rubber neck supporting a one-piece aluminum head. The dummy neck was designed to simulate the motion of a human head and neck in a frontal crash with a restrained torso. It is generally accepted that the Hybrid III neck has poor biofidelity in other respects because its construction does not permit the range of motion and response of a human neck.

The Hybrid III neck is far stiffer than the relatively flexible human neck. When a live human is dropped on his or her head, the neck and body tend to flex and crumple in ways that are not emulated by a Hybrid III dummy. Thus, the force transmitted to a live human from an impact to the head is virtually never axial.

The force sensor at the top of the dummy's neck measures the force at the top of the head plus a small factor to accelerate the head. This and the unrealistic stiffness of the Hybrid III neck and torso mean that, for a given head impact, the force levels measured by the neck sensor are considerably higher than the forces that would be felt at one of the middle cervical vertebra of an actual human neck. These are the vertebra that are typically injured in a rollover.

In summary, measurements made at load cells at the top of a Hybrid III dummy neck are roughly double what would be experienced by the cervical joints in a human neck under similar test conditions. The upper limit of human tolerance is roughly 4,000 N which would result from dropping a human from a height of approximately 0.8 meter on to a solid or moderately padded surface. By comparison, the load cell at the top of a Hybrid III dummy neck, under the same test conditions measures a force of about 8,000 N. These limits are important for use in research, but a compliance standard would use more conservative injury criteria to ensure a margin of safety.

COMPARISON OF HUMAN AND DUMMY RESPONSES IN DROP TESTS

Friedman (1999 a, b, c) conducted drop tests with a Hybrid III dummy and a human volunteer in a reinforced-roof Malibu automobile buck with production cinching latch plate restraints. These tests, conducted under survivable conditions, demonstrate the difference in spinal flexibility, belt reaction, and time phasing of motion of the human compared to the standing and seated pelvis Hybrid III dummies. Table 1 shows the comparison of belt loads in the virtually identical 0.3 m (12"), 2.4 m/sec (5.4 mph) drop tests. The human subject absorbed most of the impact load through the lap belt.

These tests illustrate the fact that a safety belt can play a critical role in reducing head and neck injuries in rollovers. If the roof is sufficiently strong that it does not intrude into the occupant survival space in a rollover, a properly tensioned belt can keep the occupant's head away from the roof or can reduce the force and velocity of a roof strike. Even if the Moffatt theory were correct, a strong roof a reasonable amount of head room, and well-designed safety belts equipped with either cinching latch plates or preferably with pre-tensioners that are triggered by a roll, will prevent serious head and neck injuries.

	Production Belted Standing Pelvis Dummy	Production Belted Seated Pelvis Dummy	Production Belted Iliac Crest Pelvis Human
Lap Loop Load	2,136 N	5,106 N	8,432 N
Head Force Z	6,915 N	4,255 N	(not measured –lightly struck roof)
Total Force	9,051 N	9,361 N	> 8,432 N

Table 1. Head forces and belt loads for dummies and human subjects in body buck drop tests.

THE MALIBU TESTS

The Malibu tests consisted of four sets of four tests in each set. For each test dummies were placed in the front outboard seating positions. Four tests were conducted with unbelted dummies in cars with unmodified, production roofs. Four tests were in the same cars but with belted dummies. The remaining eight tests were conducted in Malibus with roofs that had been strengthened with roll cages: four with unbelted and four with belted dummies.

GM has never released the raw data from these tests, providing only summary descriptions of the results of these tests. Some of the raw data and film became available only from discovery in product liability litigation. As a consequence, we had to conduct photo analyses from the videotape to determine some of the details from the tests.

In the Malibu tests with a rollcaged roof vehicle and unbelted dummies (GM's 1985 Malibu I, Orlowski, Moffatt and Bundorf), GM determined (and we confirmed) that the roof typically struck the pavement at about 1.5 m/sec from a drop of less than 0.25 m (0.75 ft). In none of the Malibu tests was the roof impact speed more than about 2.5 m/sec.

The Malibu roofs with rollcages did not deform significantly in these tests. The maximum force on any of the dummies' heads in the rollcaged cars was 4,500 N which (based on Sakurai test data that is described below) is equivalent to falling at about 1.5 m/sec, and would have been insufficient to injure a human. By comparison, the production Malibu roofs collapsed substantially during the rollovers.

In the first series of eight tests (Malibu I), the only catastrophic head and neck injury occurred with unrestrained dummies in cars without roll cages. The videotape of 1L3 shows that the 13 inches of roof crush proceeds from the near side of the roof to its far side to produce a HIC of 2,820. The videotape of 4L4 shows that the 7 inches of roof crush proceeds from the near side of the roof to its far side to produce the neck injury force measure of 7,750 N.

The rapid roof crush and intrusion produces the injury, not the rate at which the dummy falls or dives into the roof. The videotape shows precisely when the roof struck the head. It took just ten milliseconds for the roof to force the head into the neck. During that time, the torso barely moved. This confirms that the falling or diving velocity is not responsible for the injury measurement in the dummy.

In the Malibu II tests with belted dummies, four roof impacts produced neck force measurements of 7,750 N (1750 pounds) or more. The average force of these impacts was 11,000 N, measured between the base of the skull and the neck. The complete results are shown in Table 2.

Test Pii	Force on the head	Time after touch down	Traveling speed	Change in speed(ΔV)	Vehicle Orientation rolls + angle	pitch
3L2	10,900 N (2,500 lbs)	28 ms	25 kph (15 mph)	2 kph (1.2 mph)	210^o	5^o
3L3	12,000 N (2,700 lbs)	30 ms	26 kph (16 mph)	4 kph (2.4 mph)	1 roll +210^o	7^o
4L2	7,600 N (1,700 lbs)	28 ms	17 kph (10 mph)	8 kph (5 mph)	1 roll +225^o	3^o
7L4	13,400 N (3,000 lbs)	5 ms	13 kph (8 mph)	4 kph (2.4 mph)	3 rolls+190^o	10^o

Table 2. Vehicle circumstances at the time of each of the four injurious Malibu II head impacts.

All of these impacts would have severely injured a human occupant. It is easy to see in the videotape when the intrusion of the roof produces a blow or force to the head. It first compresses the neck and the neck then pushes the torso into the seat.

The maximum force occurred at an average of 23 milliseconds (ms) after the roof hit the ground. The impacts occurred at an average roll angle of 29^o beyond one-half roll. Table 2 shows that in the time between the initial roof contact with the ground and the time of maximum force on the head, the torso's momentum moved it only 1.4 cm toward the head and roof. The vehicle as a whole fell vertically only 3 to 4 cm but moved laterally at least twice that far.

The roof and head on the other hand, move towards the torso between 6 and 12 cm in the same time period. Thus, the roof forces the head toward the torso 5 to 10 times faster than the torso moves towards the roof. The roof was never flat on the ground when the injury-level forces occurred.

When the production Malibu roof contacted the ground, the roll rate and friction between the roof and the ground produced a high horizontal force that exceeded the magnitude of the vertical force on the roof from the ground. The roof pillars buckled and bent at a speed much greater than the change in speed of the vehicle as a whole. In fact, the change in velocity at the contact point – typically the roof rail at the A-pillar is closer to the vehicle's lateral (or rotational) speed than to the net change in vertical velocity of the vehicle due to the impact with the ground. This imposes an impact force on the dummy's head that would be sufficient to catastrophically injure a person – a situation that did not occur in any of the reinforced roof vehicle tests.

The highest force to any dummy's head in the rollover of a Malibu with a roll cage was only 5,800 N (1,300 pounds). The videos of these contacts provide a good comparison to the standard roof impacts in which the dummy measured the potential for serious injury. Clearly, the strength of the roof determines the rate of speed and the magnitude of the resulting force of the roof or roof rail on the head.

After an accident or a test crash, the residual damage – which is less than the maximum extent of deformation because of steel's restitution characteristics – is what remains. If that damage location is in the area of an occupant's head (which can generally be determined from witness marks in the interior), it most likely produced the injury.

In some of the Malibu tests, the production roofs produced impulsive forces that were transmitted directly to the dummies' heads, pushing them violently toward their torsos so fast that the torsos barely moved. The neck is between the proverbial rock and a hard place. This phenomenon is similar to what happens in most rollovers.

THE SAKURAI/MITSUBISHI TESTS

In 1991, T. Sakurai, a Mitsubishi research engineer, published a paper with neck force measurements from inverted Hybrid III whole body drops (Figure 1, Sakurai, et al., 1991). The results

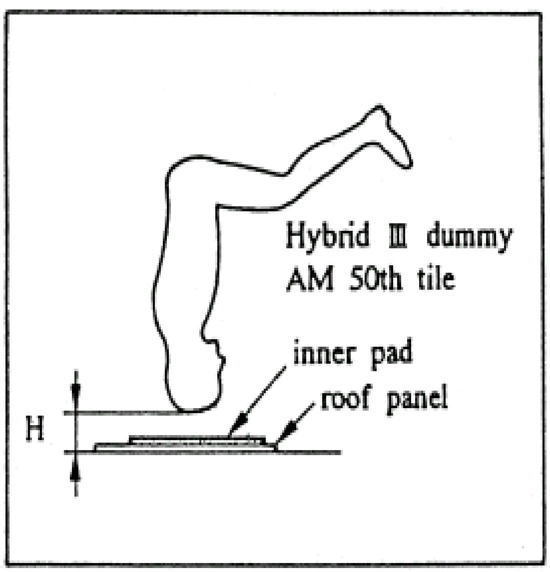


Figure 1. Hybrid III test as conducted by Sakurai.

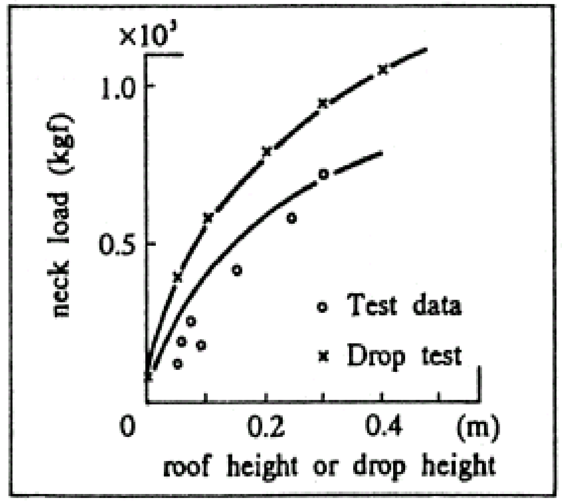
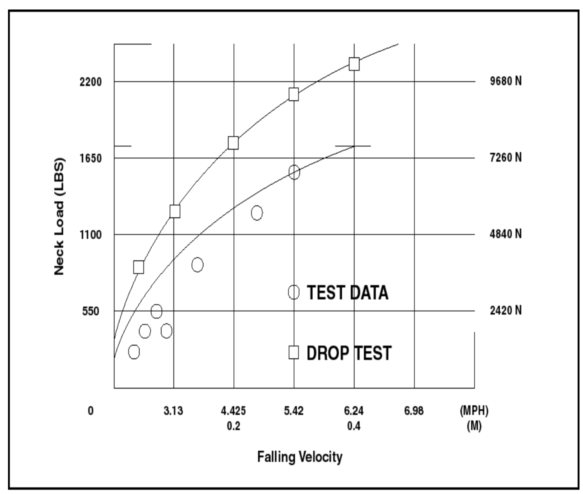


Figure 2. Hybrid III neck loads versus drop heights (Sakurai).

are shown in Figure 2, which also shows the peak neck loads in seven of his 12 vehicle ramp rollover tests. Sakurai discounted the latter results, however, because he thought the tests were too variable.



COMBINATIONS OF THE DROP HEIGHT AND THE NECK LOAD OF DUMMY IN THE INSETS OF FIGURE 11.

Figure 3. Neck Load vs. Impact Velocity

Figure 3 shows the same data converted into neck load versus impact velocity. It shows that a drop from only 0.1 m (2.5 inches) produces a Hybrid III neck force of 2,000 N, showing that this injury criterion, which was used by the GM engineers to evaluate the Malibu data, is far too conservative. In Sakurai's tests, an easily survivable human drop from only 0.5 m produced a neck load of around 8,000 N on a Hybrid III dummy supporting the use of this criterion for neck injury research.

Our analysis (Friedman, 2000) of dummy neck compression velocities in ten of the Malibu II tests, taken from videotapes of high-speed camera film is plotted in Figure 4 along with the Sakurai data. The differences in these data reflect the fact that the Malibu data come from the dynamic intrusion of a roof panel while the Sakurai data were taken from a dummy that was dropped on to a stable surface.

The Malibu and Sakurai rollover test data clearly show that neck force is a function of the speed at which the roof contacts the dummy's head, regardless of whether it is in contact with the ground at the dummy head location. The background shading in Figure 4 indicates our estimate of the probability of human injury. It is clear is that neck compression loads of 4,000 to 5,000 N measured on the Hybrid III dummy during rollovers represent dummy head strike velocities of 2 to 4 mph. These impacts were not sufficient to seriously injure a human head or neck.

From the Malibu tests and other evidence, we conclude the following:

1. Severe injury impacts from roof contact occur after the windshield glass has separated from the windshield pillars and header. The windshield separation usually occurs on the first roll.
2. Severe injury from roof impacts occur when the roof contacts the ground at approximately 180 + 25 degree of the second or later roll.
3. Bonded windshields contribute 30% of FMVSS 216 roof strength.
4. FMVSS 216 particularly fails to adequately test the lateral component of roof strength.
5. The strength of a roof structure determines both the intrusion rate and extent.
6. Severe injury impacts occur when the roof intrusion rate is 4.5 m/sec (10 mph) or more.
7. Brain damage occurs from head impact forces oriented peripherally, while spinal (mostly cervical) injuries occur from forces to the top of the head that are more aligned with the neck.
8. With weak roofs, restraints do little to reduce the forces on the spine. Restraints can be highly effective if a vehicle has a strong roof and adequate headroom.
9. When tested in accordance with FMVSS 216, a rollcaged roof (which can sustain more than 100,000 N or 24,000 lbs) is stronger than necessary to adequately protect occupants in most rollovers.
10. A production roof on the second roll (after the windshield has broken or separated) is only about half as strong as its FMVSS 216 strength.

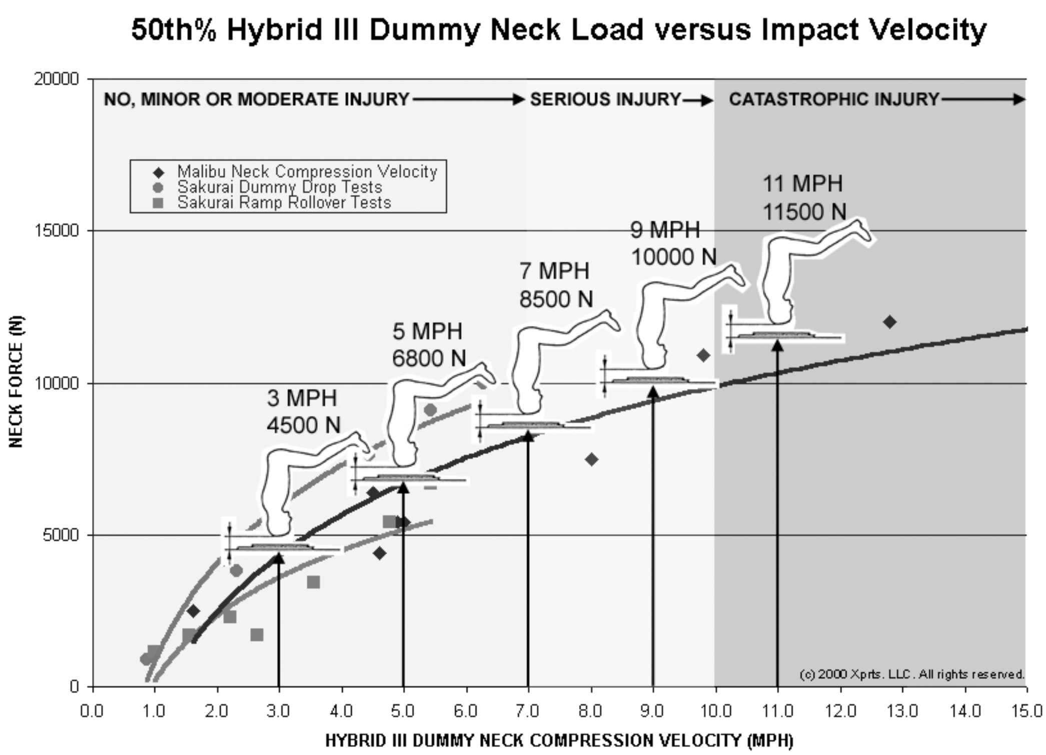


Figure 4. Dummy Neck Load and human injury probability v Compression Velocity

ANALYSIS OF A TYPICAL REAL-WORLD ROLLOVER WITH SEVERE NECK INJURY

Friedman investigated a 1985 Chevrolet Blazer rollover crash. The driver suffered a broken neck that rendered him quadriplegic. We inspected the crash vehicle with the headliner removed to expose the underlying roof structure and found two witness marks. One, originally observed when the headliner was still in place, was on the bottom of the roof rail on the driver's side about 20 cm forward of the B pillar. The roof rail witness mark was a small concave dent in the sheet metal that could have been made when the roof rail struck the driver's head. GM determined, in a series of tests, that the depression was produced by an impact at about 4.5 m/sec (10 mph) between the driver's head and the roof rail.

The other witness mark was about 28 cm rearward if the windshield, inside the roof rail and just behind a deep buckle in the roof panel. Given the nature of the injury and the dynamic analysis of the crash, it is much more likely that this was produced by the head strike that produced head and the neck injuries.

Accident Reconstruction and Injury Mechanism

Reconstruction of this case indicates that the Blazer rolled and probably touched down on its roof 3 times. The roof of this vehicle collapsed about ten inches at the driver's side A-pillar and roof rail. For comparison, another virtually identical vehicle was dropped from 15 cm (6 inches) on to a 15 cm thick pile of sand bags. It was falling at 1.4 m/sec (3 mph) when it struck the pile at a roll angle of 30 degrees and a pitch of 7.5 degrees. The damage to the crash and test vehicles is very similar. Since the crash vehicle had the accumulated damage from several roof touchdowns, it could not on any touchdown, have fallen faster than 1.4 m/sec.

Despite the fact that the vehicle roof struck the ground at less than 1.4 m/sec, GM's tests show that the roof rail intruded and struck the driver's head at a speed of approximately 4.5 m/sec. This higher impact speed was a consequence of the non-linear behavior of the roof. When it contacted the ground, vertical and lateral forces caused the pillars, header and roof rail to buckle and collapse at near the rotational speed into the interior, a speed much greater than the vehicle's change in speed.

In a comparable test to the one mentioned above, GM dropped an inverted 1986 Blazer from a height of 28 cm on to sandbags that were 15 cm thick. The Blazer was rolled 30 degrees and the front was pitched down 7 degrees before it was dropped. Accelerometers located on the B pillars showed that:

- The A-pillar holds at 1g (with a force of 15,500 N) for about 30 ms during which time the roof displaces 5 cm (at 1.5 m/sec).
- The A pillar then resists with a force of 9,800 N for 100 ms during which time the roof displaces approximately 20 additional centimeters.
- The B pillar and the top of the front fender then halt the vehicle's fall.

Integrating the displacement versus time of target marks observed in a videotape of the roof crush yields their velocity. This shows that the body of the vehicle continues after the time of touchdown to drop at a speed of nearly 1.8 m/sec (its speed upon initial contact). At the same time, the roof rail intrudes with an amplification factor of 3, but in the plane of the camera at 2.7 m/sec relative to the vehicle body.

The Blazer structure is so weak that 1983 to 1994 models without glazing and loaded laterally on the A-pillar, roof rail, header intersection cannot support their own weight.

CRASH DATA ANALYSES OF THE EFFECT OF ROOF CRUSH

Rains and Kanianthra (1995) published an analysis of rollover cases in the National Accident Sampling System (NASS) files demonstrating a relationship between the compromise in residual headroom and injury. This research showed that the probability of neck injury in a rollover increased substantially when roof crush was greater than the normally available headroom for an occupant.

Keith and Donald Friedman (1996) completed a more extensive analysis of 1988 to 1992 NASS injury files and found that catastrophic head, neck and face injuries to restrained and unrestrained occupants were associated with interior contact under roofs averaging more than six inches of deformation.

ADVANCED ROOF DESIGNS

The auto industry has never contended that it cannot design stronger roofs. Its prevailing view that roof strength is not related to occupant rollover safety, has meant that roof strength is not a priority. In investigating large numbers of rollover accidents we often see pillar bending and seldom see axial (vertical) pillar compression. Apparently because of the front weight bias of virtually all modern vehicles A-pillars typically bend at their root on the A-post and cowl intersection. Open section headers and roof rails typically buckle, particularly at the end of an intersection reinforcement or gusset. Obvious means of increasing the strength of columns, headers and rails are to close those sections, extend reinforcements, and avoid putting holes in key structural components.

Many current structures rely on windshield bonding for strength in FMVSS 216. However, the unnecessarily square upper and lower corners of the windshield could be filled with more effective gussets to enhance roof strength.

Glass strength can be substantially increased with the addition of a bonded plastic liner. BMW has incorporated such a liner in its Seven series security system. Stronger glazing and glass bonding would also reduce occupant ejection.

To provide better rollover performance, designers could use lateral roof hat section cross vehicle supports and filets between those hat sections and pillars. Increasing the lateral cross section of the B-pillar would have little impact on driver vision since B-pillars are usually located behind the driver.

The GM Experimental Safety Vehicle of 1972 showed how stronger B pillars could work. It had a two-panel roof separated by 1½ inch deformable spacers, that cantilevered forward of the B-pillar to the windshield. The GM ESV roof deformed only 3.9 inches in a two-foot drop test. In a 30 mph dolly rollover test, none of the six dummies were injured.

The Minicars Research Safety Vehicle (Friedman 1977) used high-density foam in large section, thin wall box sections to achieve a very high level of roof strength. The 1985 Fisher Body Concept Car of the GM Vehicle Safety Improvement Program, developed a composite structural foam that used the same approach but substantially improved the strength to weight ratio. Although recent papers have argued that such techniques are little better than the equivalent weight in steel, no author has suggested that there is a practical limit as to how strong we could make these roof and pillar structures.

The Calspan /Chrysler Research Safety Vehicle substituted high strength steels and reinforcements on the base Simca structure for improved strength.

Finite element models are routinely used to design vehicle structures. A recent study, (K. Friedman, 2001, in preparation) used such a model to show that if material thickness and section sizes were changed in a modern production vehicle, the roof strength could be increased by an order of magnitude. He also found that for a given B-pillar design, doubling the bending strength can decrease the bending velocity by a factor of 4. Finally, he demonstrated that a buckling structural element can intrude at as much as 5 times the velocity of the A-pillar/roof rail column contact with the ground.

ROOF STRENGTH TESTING

It is clear from the GM tests that the strength of the Malibus with roll cages is beyond what is necessary to provide reasonable occupant protection. The roll cage increased the roof strength, as would be measured in FMVSS 216, to about seven times the weight of the vehicle. We believe that a factor of four would be adequate, but it would have to be applied at greater roll and pitch angles, perhaps a roll angle of 45 degrees and a pitch angle of 7.5 degrees. NHTSA research and previously confidential GM data could support the establishment of revised test conditions and criteria for use in a more adequate quasi-static test such as FMVSS 216.

We believe that a dynamic test would provide a more objective performance standard for roof strength. The problem with the rollover test procedure in FMVSS 208 is that it is not repeatable, and therefore, under present rules, cannot be used as a compliance test of occupant protection in a rollover.

Despite this, the FMVSS 208 rollover test provides a substantial amount of useful information on a vehicle's rollover performance for research and developmental testing of vehicles.

It is clear that additional research is necessary to develop an objective, repeatable test of occupant protection in rollover accidents. Among the considerations are:

- The test should permit safety belt use only if the vehicle has a proven, effective belt use inducement system built into it.
- The test should not constrain design choices and should encourage innovations.

For example, it should encourage such things as safety belt pre-tensioners and window curtain air bags that deploy when a vehicle rolls over. Autoliv is testing window curtain bags for Ford SUVs, but has not announced what evaluation criteria it is using.

The standard could also encourage auto makers to find a way to make the windshield and its mounting an effective part of the roof strength throughout a multiple rollover. This could be done by initially inverting the vehicle and dropping it from a height of about .2 m on it’s A-pillar at a roll angle of 30 to 35 degrees and a pitch angle of 5 to 10 degrees. This would be sufficient to break or separate the windshield of a conventional contemporary vehicle. The test of rollover occupant protection would then proceed.

- The test should define the occupant survival space as a function of the original headroom within the vehicle, the performance of the occupant restraints, and the amount of roof intrusion into the occupant compartment.

The occupant survival space could be defined by placing a Hybrid III dummy in the driver’s seat and restraining it as called for in FMVSS 208. The vehicle could then inverted, and any devices that would be deployed when the vehicle is rolled (such as belt pre-tensioners) would be deployed. The head of the dummy could then moved fore, aft, and laterally so that the top of the dummy's head defines a surface within the vehicle's interior. After the dummy is removed, the surface defined by the dummy's head, which represents the occupant's survival space, can be emulated in a rigid plastic foam insert placed in the front seat.

- The test must ensure roof strength to the extent that the roof neither collapses at a speed that is significantly greater than the speed at which the vehicle lands on the ground, nor does it intrude substantially into the occupant survival space.
- The test must emulate what happens to a vehicle in a multiple rollover such as occurs in the FMVSS 208 rollover test.
- The test must ensure that unbelted occupants are not ejected from the vehicle in a rollover.
- The test must be objective and repeatable.

CONCLUSIONS

The error in the Moffatt theory is that it assumes that a vehicle's roof is a passive interface between the ground and the occupant when it strikes the ground in a rollover. Moffatt assumed that when the roof strikes the ground, it lays flat against the ground and slides with low friction across the ground, neither buckling nor deforming laterally. Actual production roofs behave in a highly non-linear fashion because they are complex shapes with discontinuities in their structure from holes, gussets, non-box section elements, and incomplete welding.

The problem with torso augmentation – the industry's theory of how a human neck is injured in a rollover – is that neck injuries occur in about ten milliseconds. In that time, the torso moves toward the head less than 2 cm: far less than would be necessary to injuriously compress a human neck.

The non-linear collapse of the roof of a rolling vehicle imposes velocities and forces on an occupant's head that are far greater than an occupant would experience solely from his or her dropping at the vertical velocity of the vehicle's center of gravity.

Interpreting the results of testing with a Hybrid III dummy requires an understanding of the differences between a human and the dummy. The key problems are the stiffness of the dummy's neck (and of the dummy generally) and the placement of the neck force sensor at the top of the dummy's neck.

The Hybrid III can provide useful information on the potential for rollover injuries. It could be used in a safety standard with a conservative injury criterion. However, but for research, the injury criterion should be more realistic. It is well-known that the probability of human neck injury increases substantially at loads above 4,000 N. However, it is clear from subjecting humans and human cadavers to the same tests as the Hybrid III that measurements on the dummy are roughly twice as high as measurements made on a human neck. Thus, a realistic dummy neck injury criterion for research purposes is roughly 8,000 N.

Inadequate roof strength *is* the cause of most serious to fatal injury of vehicle occupants who are not ejected in rollovers. Manufacturers have thus far refused to acknowledge the limitations and weaknesses of the Moffatt theory. They have continued to build motor vehicles with weak roofs that can severely injure the heads and necks of occupants in rollovers.

The consequence is that during the past ten years, more than 50,000 motorists have suffered serious to fatal head, face, and neck injuries that could have been prevented with good roof design. We estimate that they saved less than $20 per vehicle produced for use in that period by ignoring roof strength, for a total of less than $2.4 billion. This amounts to less than $50,000 per serious injury, a very poor bargain, indeed.

Good vehicle design for rollover protection requires the following:

- An effective safety belt use inducement [Ford is currently using a belt use inducement that repeats the 4 to 8 second warning until an occupant dons the belt, but this system has not yet been evaluated for its effectiveness.]
- A strong roof that will not deform substantially under the conditions of a multiple rollover.
- Interior geometry that provides adequate head room to keep a well-restrained occupant's head away from an undeformed roof.
- A well-designed safety belt system equipped with pre-tensioners that trigger when a vehicle rolls over.
- Effective interior padding in the head impact areas, such as is required by FMVSS 201.
- Doors and door latches that prevent ejection in a rollover, and possibly window curtain air bags that are triggered by a rollover to prevent ejection through side windows (and to keep an occupant's head away from the roof rail area after the side windows break).

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