PROTECTING OCCUPANTS IN ROLLOVER CRASHES: CASE EXAMPLES AND LATEST TECHNOLOGIES

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22ND ESV Conference 2011 - Paper 11-0344
Washington, D.C.

ABSTRACT

NHTSA has documented that rollover accidents account for about 3-percent of all vehicle accident in the United States, yet are responsible for about 30-percent of the deaths, plus thousands of quadriplegics (tetraplegics). The principal mechanisms of injury causation are due to roof crush and occupant ejection.

Therefore, stronger roof design is needed to prevent the buckling and crushing down of the roof into the occupants' *"survival space"*. And improved side window glazing, such as using laminated glass instead of tempered glass, will help prevent occupant ejection during rollovers, as well as in other impact modes.

Using rollover accident case examples and exemplar vehicles, detailed inspections and analysis show how and why the roof structures failed to adequately maintain the passenger compartment "survival space" and how the consequences often caused quadriplegic injuries. The history and technology of roof design shows safer alternative designs that would have made a safety difference.

It is clear that Federal Motor Vehicle Safety Standard 216 (FMVSS 216) on Roof Crush Resistance, which is a *minimum* requirement, has not ensured a reasonably safe roof in rollover accidents. Upgrades are need to ensure stronger roofs, with dynamic rollover testing to evaluate the total system of roof structural integrity, side window glazing, seatbelt restraints, side curtain airbags, and other measures that will help attain the Vision Zero compassionate goal of preventing needless deaths and injuries.

AFFIRMED: IN ROLLOVERS, ROOF CRUSH CAUSES QUADRIPLEGIA

In a rollover accident, it is imperative to maintain the occupants' "survival space". It is a well-established principle in vehicle safety and crashworthiness that a vehicle should be designed so as to prevent or minimize intrusion or penetration into the passenger compartment *"survival space"* in all types of foreseeable collisions…. including front impact, side impact, rear impact, rollover. Automakers and vehicle safety specialists often refer to the critical need to provide a strong *"roll cage"* vehicle construction to protect the passengers.

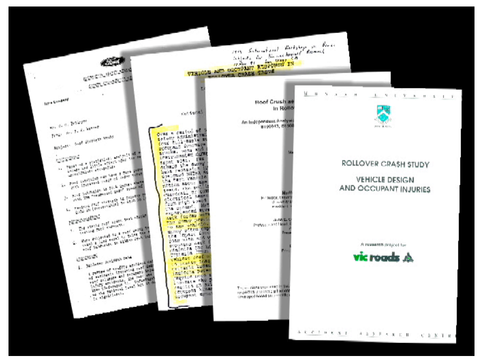


Figure 1. The mechanism of vehicle roof crush causing cervical-spinal injuries has been well-documented in the literature.

1968: Back in 1968, Ford Motor Company issued "the Weaver memo", an intra-company safety evaluation formally entitled "Roof Strength Study." With the advent of shoulder belts becoming mandatory in the late-1960's, Ford was concerned about the relationship between roof crush and lap-and-shoulder belted occupants who would be seated upright as the vehicle rolled over. As Ford noted:

> *"Roof intrusion may have a more pronounced effect on occupant injuries with increased usage of upper torso restraints. People are injured by roof collapse. The total number of nationwide deaths and injuries cannot be estimated but it is a significant number."*

In other words, Ford was concerned that the collapse of the roof onto the passengers would cause deaths and injuries to those seat belted occupants. Ford then put it all into perspective:

> *"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."*

<u>1973-74:</u> The National Highway Traffic Safety Administration, or NHTSA, issued Federal Safety Standard 216 (FMVSS 216) as the *minimal* requirement for Roof Crush Resistance. In its rulemaking notices, NHTSA stated:

> *"… serious injuries are more frequent when the roof collapses."*
> *"It has been determined, therefore, that improved roof strength will increase occupant protection in rollover accidents."*
> *"After August 15, 1977, Standard 216 will no longer be a substitute for the Standard 208 rollover test. It is expected that as of that date Standard 216 will be revoked, at least with its application to passenger cars."*

FMVSS 216 also expressed for concern about the integrity of side windows relative to occupant ejection, but no test requirement was included to ensure that side windows would not shatter out. But the anticipated rollover test was never mandated.

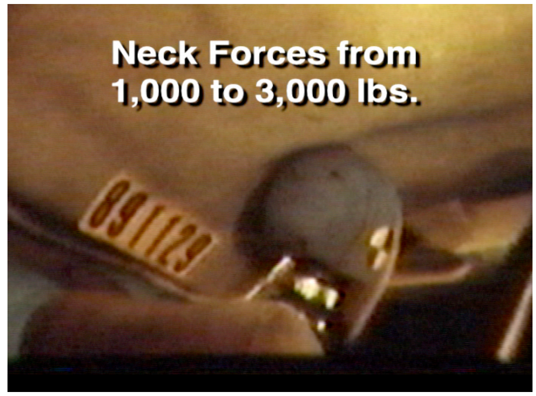
<u>1982:</u> In 1982, NHTSA issued a report on "<u>Light Vehicle Occupant Protection – Top and Rear Structures and Interiors</u>". (SAE Report 820244.) This comprehensive NHTSA analysis pointed out a significant correlation:

> *"…accident statistics show that the degree of roof intrusion is highly associated with occupant injury severity and rate."*

<u>1992</u>: In 1992, the major report "<u>Vehicle and Occupant Response in Rollover Crash Tests</u>" was issued as a coordinated effort by NHTSA and by the Armstrong Laboratory, of the Department of the Air Force. It reported on the findings from a series of 24 rollover crash tests that NHTSA had sponsored to study vehicle and occupant dynamics. Roof crush varied from about 4 to 20 or more inches. The test dummies were instrumented to measure head and neck forces. Among the report's conclusions:

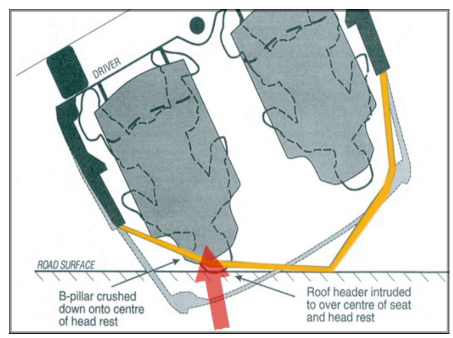
> *"Most of the tests resulted in significant roof crush. Often the body was trapped by the roof crush. In these cases, the head/neck system was vulnerable to large loads from the roof."*

In many of the rollover tests, the dummies received major compressive loads to their necks and cervical spine, with many in the 1,000 to 3,000 pounds range, sufficient to cause cervical fractures, spinal cord damage, and quadriplegia.



<u>1994</u>: In "<u>Rollover Crash Study on Vehicle Design and Occupant Injuries</u>" researchers at Monash University of Australia analyzed many actual vehicle rollover accidents, and correlated the extent of roof crush with the causation of cervical spinal injuries. Among their findings was this correlation:

> *"In mass data and other crash collections, the weight of evidence is in agreement with a relationship between roof crush and occupant injury. There is a convincing relationship between rollover and spinal cord injury. Finally, there is strong evidence of a connection between local roof crush and spinal cord injury."*



<u>2005</u>: In 2005, a study by Bidez, Cochran, and King evaluated "<u>Roof Crush as a Source of Injury in Rollover Crashes</u>." The authors evaluated the data from instrumented dummies in a series of rollover tests of Ford Explorer SUVs, as conducted by Autoliv. Their conclusions included the following:

> *"Roof crush into the survival space of restrained dummies was the direct cause of neck loads, which were predictive of catastrophic neck injury in rollover crashes."*
>
> *"In the absence of significant roof crush into the occupant survival space, no dummy neck loads predictive of catastrophic injury were observed in this test series."*

2005: In 2005, at the urging of the US Congress, the National Highway Traffic Safety Administration (NHTSA) was required to amend FMVSS 216, which had been essentially the same since the mid-1970's, to increase the requirement for stronger roofs that would offer greater protection in rollover accidents. In its Notice of Proposed Rulemaking, NHTSA noted that:

> *"In sum, the agency believes that there is a relationship between the amount of roof intrusion and the risk of injury to belted occupants in rollover events."*

2009: Researchers at the Insurance Institute for Highway Safety (IIHS) correlated roof strength with injury risk in actual rollover accidents. Eleven midsize SUV roof designs were crushed using the slow-push test protocol of FMVSS 216. Applied forces were measured and the amounts needed to achieve crush of 2, 5, and 10 inches were recorded, and compared with the fatal or incapacitating injuries to drivers in single-vehicle rollover accidents. The analysis showed that *"Increased vehicle roof strength reduces the risk of fatal or incapacitating injury in single-vehicle rollover crashes."*

The strongest roof of the studied SUVs had a strength-to-weight ratio up to 3.16, with roof excursions from 3.2 to 7.3 inches before the roof contacted the test dummy's head. Thus, vehicles with stronger roofs and different headroom clearances could have an even more profound effect. For example, for a taller driver in a car with 2 inches of headroom, a roof would need a greater SWR of perhaps 4.0 to 5.0 or greater to reduce the roof crush risk of fatal or quadriplegic injuries. There would be thus be safety advantages to a stronger roof, whatever the headroom clearances and sizes of the drivers and passengers.

These many authoritative studies cited above, and others, all point out and affirm the causal relationship between roof crush and spinal cord injuries. And they clearly contradict the proponents of the so-called *"diving theory"* who claim that roof crush does not cause cervical spinal injuries, but that such injuries are caused when the driver dives headfirst into the roof as the roof touches the ground. If one were to accept such a diving theory, then where are any efforts by the proponents to make safer seatbelts that will tighten up at the beginning of rollovers so as to prevent seat-belted occupants from any such unsafe diving? Of note, many of the diving theorists show up as defense experts in court cases to explain why the allegedly-weak roof that buckled and crushed downward so excessively wasn't really the cause of the quadriplegic injuries after all.

THE HISTORY AND TECHNOLOGY OF ROOF STRUCTURE IN ROLLOVERS… and FMVSS 216

A vehicle roof is supposed to stay upright and safely maintain the occupant's ***"survival space"***. The roof structure is generally described as an interconnected network of essential elements:

The windshield pillars, also called A-pillars.
The mid-body pillars, also called B-pillars.
The rear window pillars, also called C-pillars.
The windshield header, which extends laterally across the top of the windshield.
Roof siderails, along the outer sides of the roof.
Roof cross-members, laterally across the roof, in varying locations, including B-pillar to B-pillar.
Corner gussets, to interconnect the junctions where the various roof members meet each other.

All together, it is the strength of these elements and how they are reinforced and connected, that determines the overall strength of the roof.

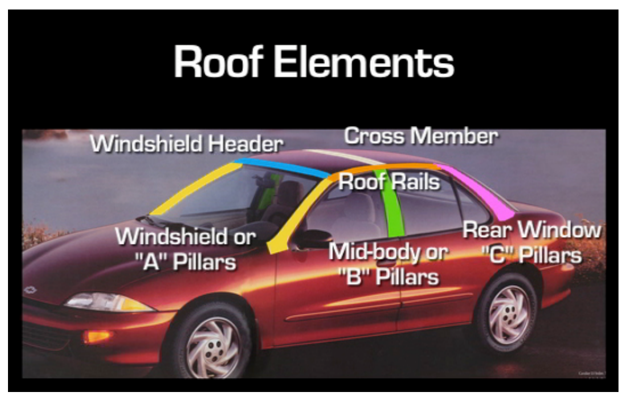


Figure 2. Roof elements are the typical structural members that interconnect to support the roof.

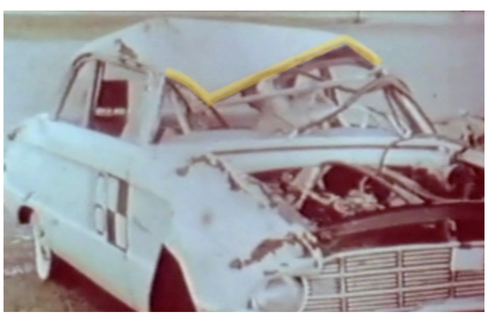
1950's: General Motors (GM) conducted dynamic rollover tests back in the 1950's, in *50 miles per hour rollovers* that GM referred to as the *"supreme test"* as noted in the adjacent GM illustration.

The 1955 Chevrolet's roof structure, with its closed-section or box-section windshield header, and its mid-body roof bow and center pillars, was shown by GM to be strong enough to prevent roof buckling and collapse. Sufficient roof strength and its performance in actual dynamic rollover testing was demonstrated.

<u>1960</u>: In 1960, Ford conducted Crash Test 116, a dynamic rollover test of a 1960 Ford Falcon passenger car. This ramp-type rollover test at 34 miles per hour was conducted in order to evaluate the Falcon's roof structure. The design of the Falcon's windshield header was a *"hat section"* – an open section design that's very similar to many of the windshield header designs in cars and SUVs throughout the 1970's to the present. *After two and one-half rolls, the Ford Falcon's roof had buckled and crushed downward… very much like what happened to the roofs in many rollover accidents over the past decades.*

In their report, Ford stated:

> *"The roof structure proved inadequate. The front of the roof collapsed. The hat section reinforcement at the very front of the roof was insufficient to withstand the load."*



That kind of roof-buckling failure in a 34 miles-per-hour rollover certainly means the roof structure is inadequate and insufficient in its design and performance.

<u>1971</u>: The NHTSA report *"<u>Test for Vehicle Rollover Procedure</u>"* was based on a series of dynamic lateral rollover tests of a variety of vehicles. The abstract noted that "The tests proved the adequacy of this procedure to produce repeatable rollovers and to demonstrate the applicability over a large range of vehicle sizes and configurations."

<u>1960s – 1970s</u>: The state-of-the-art in the 1960's and 1970's was for roof structures that utilized closed-section or box-section members, as was often described in the automakers' literature.. General Motors said the roof was stronger, including *"its rugged box-section windshield header."* Ford said the roof construction on all models has "*rigid box-section rails at the sides and at the front and back window headers."* Chrysler said their *"uni-body construction was strong and tight, with its box-section windshield pillars and header."*

The state-of-the-art for decades has been that windshield headers should be a closed-section or box-section design for sufficient strength.

<u>1971</u>: When NHTSA was in proposed rulemaking for Roof Intrusion Protection (Docket 2-6, Notice 4), General Motors was critical of the proposed static roof crush test up to 5,000 lbs. with a maximum ram travel of 5 inches, noting *"we know of no safety relationship correlating such a laboratory procedure with occupant protection in rollovers"* GM then proposed that the test be based on maintaining a vehicle interior *"non-encroachment zone"* of sufficient headroom that would not be intruded into by roof crush.

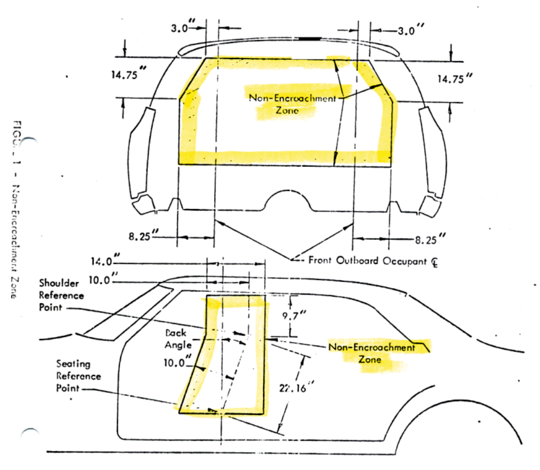


Figure 3. GM 1971 submission to NHTSA docket.

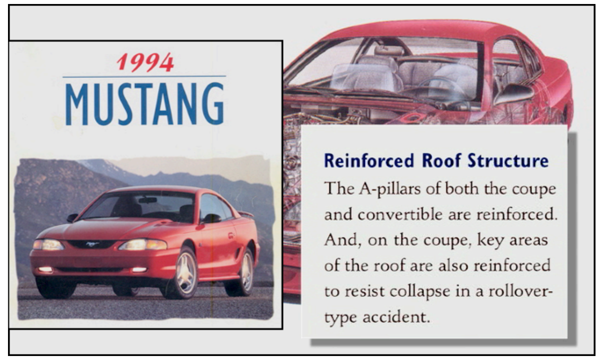
<u>1974</u>: Most of the world's automakers actively participate in the International ESV Conference held every two years, beginning back in 1971. Many of the ESV papers over the years have shown how to design and test safer roofs for enhanced protection in rollovers. As an example, in 1974 Honda presented a technical report about ensuring *"Survival Space"* and showed how a strong roll cage construction, with roof cross-members, would help maintain the passenger compartment from being crushed during a rollover accident.

European automakers, especially, showed the merits of dynamic rollover testing to evaluate roof performance. They likely believed the NHTSA projection in 1973 that the FMVSS 216 *"slow push"* compliance test (as a *minimum*) would soon be superceded by a dynamic lateral rollover test at least at 30 mph, per FMVSS 208, beginning in 1977. However, the *"slow push"* test continued, and the rollover test requirement was not phased in.

However, in too many vehicles through the late '70s into the '90s and early-2000's, too many automakers opted to compromise and short-change roof strength, doing just enough to meet the FMVSS 216 minimum requirement of 1.5 times the weight of the vehicle. Thus, too many of their vehicles were designed with weaker open-section windshield headers with large hole cut-outs and A-pillars that were not fully reinforced. Yes, the roof complied, but performed terribly in real-world rollover accidents.

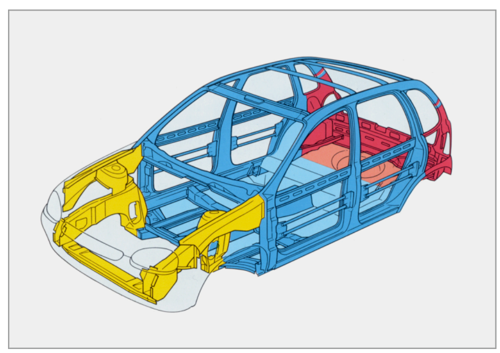
<u>1994</u>: Another example pointing out the need for closed-section windshield headers is found in Ford's candid information when they introduced the 1994 Mustang:

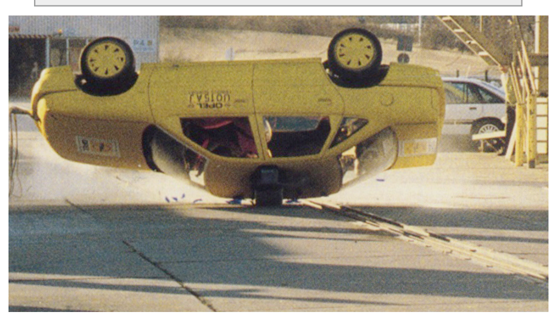
> *"Reinforced Roof Structure ... ... key areas of the roof are also reinforced to resist collapse in a rollover-type accident."*
>
> *"In the previous-generation Mustang coupe, roof members were formed with open sections. Significant gains were made in the stiffness of the 1994 by incorporating box-section roof headers and rails."*



<u>1994</u>: General Motors in Europe is known as Opel. Opel's cars are designed with a full safety-cage construction. Here's what GM-Opel said back in 1994 about rollover protection.

> *"Developments in safety at Opel also take into account occupant protection in roll-over accidents. The bodies of Opel cars are notable for their high degree of roll-over safety. Crash tests at the Technical Development Center prove the point: in a lateral rollover accident with a throw speed of 50 km/h the occupant cell suffers no critical deformation…."*





<u>1998:</u> In 1998, a paper published by the Society of Automotive Engineers, or SAE, focused on *"<u>Strength Improvements to Automotive Roof Components</u>"*. Using various alternative structural designs for roof headers, the researchers conducted axial-load compression tests and three-point bending tests to compare production roof elements versus reinforced designs. The comparisons included a production header of an open-section design, similar to the design in many production vehicles.

An open section roof member was modified by closing it along one flange to approximate a closed section, plus the insertion of an inner tubular support. Other alternative designs were also tested. In all cases, the alternative designs all proved significantly stiffer and stronger than the open-section production header… up to 5 times the peak strength in axial testing.

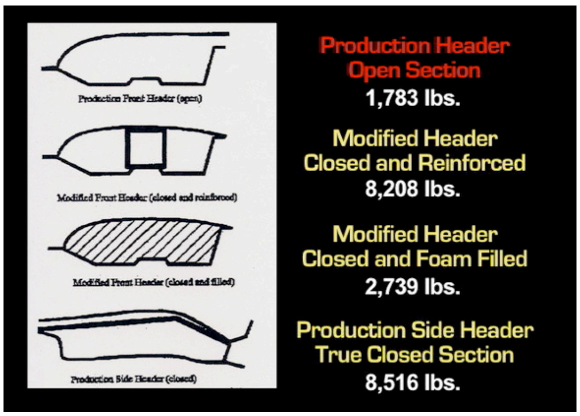


Figure 4. Simple upgrades increase roof strength.

In other words, there have been feasible and economical alternative designs that could have greatly strengthened the roof members, and such alternative roof element designs and the basic principles have been well-known for decades.

To further point out the failure of the Federal Safety Standard, FMVSS 216, to ensure safe roofs, note that the toll in rollover accidents in the U.S. has recently been in excess of 10,000 fatalities per year. In 2005, the United States Congress passed legislation that included a mandate to NHTSA to upgrade the roof crush standard to make it more effective. That resulted in NHTSA rulemaking from 2005 through 2009 that increased the strength-to-weight ratio (SWR) from an ineffective 1.5 to one, to become 3.0 to one.

It is important to note that FMVSS 216 is only a ***minimum*** requirement and, while somewhat of an improvement over its predecessor's terribly weak requirement, will likely not be strong enough nor require the dynamic testing that would more sufficiently ensure that vehicle roofs will perform safely in actual rollover accidents.

TEMPERED SIDE WINDOW GLASS SHATTERS COMPLETELY OUT AND ALLOWS UNSAFE OCCUPANT EJECTION IN ROLLOVERS

As commonly happens in rollover accidents, the side windows' tempered glass easily shatters into hundreds of small glass particles when the roof crushes down, or the occupant strikes it. This creates a large window opening through which the occupants, whether belted or unbelted, may be partially or completely ejected -- and suffer severe impact trauma with the road and the rolling vehicle.

In a rollover accident when the side window glass shattered out, a seat-belted woman in the rear seat was partially ejected and suffer fatal trauma. She was found with the seatbelt still fastened, with her legs protruding outward through the window opening.

Rather than tempered glass which shatters out much too easily, the side windows should have instead used the safer alternative of laminated glass…. a 3-layer laminate sandwich of glass-plastic-glass.

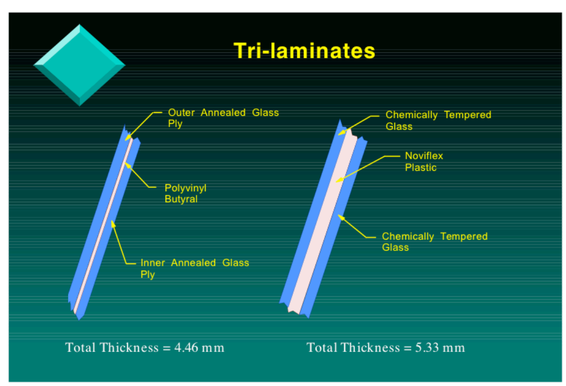
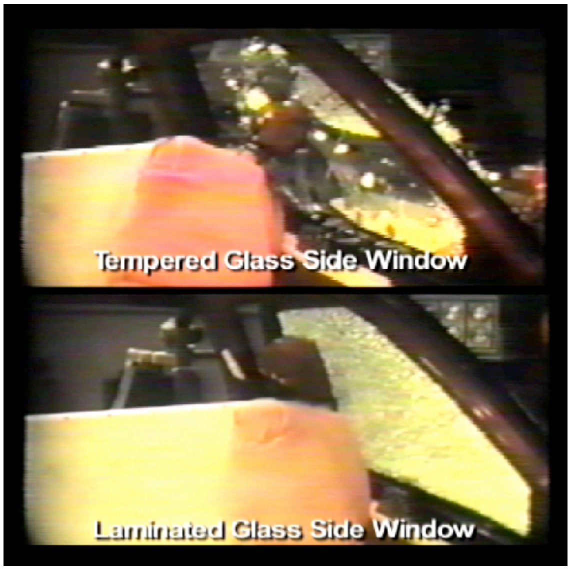


Figure 5. Laminated glass stays intact and serves as a "life net" to prevent occupant ejection.

As demonstrated in NHTSA's comparison tests, the ***tempered*** glass shatters out completely and allows the occupant to be ejected through the opening, while the safer ***laminated*** glass may break but still stays intact and serves as a *"life net"* to keep occupants safely within the vehicle. Note that ***the front windshield*** of all vehicles is made of ***laminated*** glass, a three-layer sandwich of glass-plastic-glass that is analogous to what could and should have also been utilized for the side windows.



The U.S. National Highway Traffic Safety Administration (NHTSA) has regularly issued recommendations for vehicle manufacturers to utilize safer glass-plastic side windows to help prevent the occupant ejection hazard.

In 1996, NHTSA summed up the findings of its advanced glazing research team, which again examined the window glazing opportunities to reduce occupant ejection… a subject that had been on-again and off-again for 20 or more years. NHTSA showed that from 1988 through 1993, the annual average of severe injury for occupant ejection through window glazing was about 3,700 per year, plus over 3,500 fatalities.

Over the past 30 years and currently, some automakers have opted for laminated side windows in various models. Recent and current models that have laminated side windows, either as standard or optional, include: Buick LaCrosse, Chevy Malibu, Ford Taurus, Hyundai Genesis, Lexus GS, Volvo S-80, and many others. There continues to be a re-adoption and resurgence in using laminated side window glass for its many advantages, including the prevention of occupant ejection.

As just one accident case example, the right-rear tire of a Ford 15-passenger van lost its tread, and the van went out of control and rolled over. There were ten occupants in the van, and three were fully ejected when the large side window tempered glass completely shattered out.

Note the particles of tempered glass still embedded to the adhesive and rubber molding strip of the large side windows.

CASE EXAMPLES OF ROLLOVER ROOF CRUSH AND QUADRIPLEGIC INJURIES

In my analysis of many rollover accidents across the United States, I often inspect the vehicle at-issue and exemplar vehicles, to evaluate roof design characteristics, including how and why the roof buckled and crushed during the rollover. In most cases, the roof had been designed very poorly, with only minimum features that enabled the vehicle to comply with the *"slow push"* test of FMVSS 216. That test requires a slow push at a downward angle to the side of the roof, with a force of 1.5 times the vehicle weight, or 5,000 lbs, whichever is less, with no more than 5 inches of roof crush allowed. This is known as a strength-to-weight ration (SWR) of 1.5 to one.

But in real-world accidents, the weak roof performed poorly, resulting in excessive crush into the driver's and passenger's survival space, often causing fatal or quadriplegic injuries. Yet, all of these poorly-designed and unsafely-performing vehicles had complied with the US Federal Motor Vehicle Safety Standard 216, which is only a minimum requirement by law. Such compliance with the "safety standard" did not ensure a reasonably safe roof. Yet, that FMVSS 216 *"safety standard"* had been in effect since 1973 through to the present, and has only recently been moderately strengthened to apply to future vehicles.

The following rollover accident case examples are intended to show the symptomatic weak roof designs and their failure in rollover accidents, illustrating ineffective roof structures that are all-too-common among many cars, pickups, vans, and SUVs made by many automakers over the past 40 years and currently.

Rollover Case A: 1989 Ford Escort Hatchback

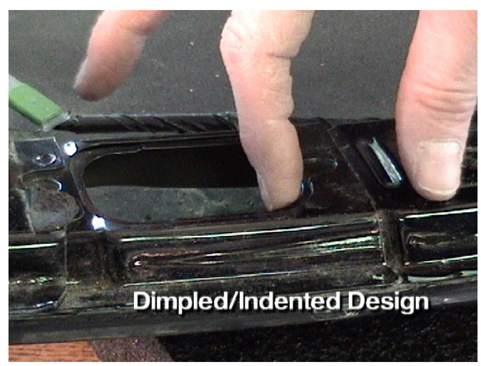
This rollover accident occurred when the driver of a 1989 Ford Escort 2-door hatchback tried to avoid another vehicle that had cut into his lane, and rolled over at about 35 mph on a grassy center median. The seat-belted driver was rendered a quadriplegic.

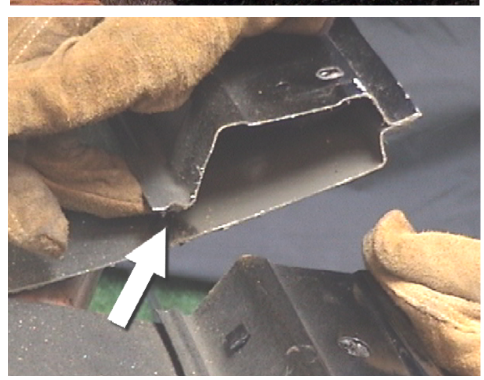
The Escort's roof design was very minimal. The windshield pillar was internally reinforced with a baffle plate, but only in its lower 6 inches, and that's where it bent over in the rollover. The windshield header was a flat channel, a weak open-section, and was further weakened by many large hole cutouts, and the roof buckled in those predisposed weak zones. Yet, despite its minimal design and poor performance, the Ford Escort's roof had complied with FMVSS 216.

Rollover Case B: 1999 Toyota SUV

This rollover accident occurred when a 1999 Toyota RAV4 SUV was impacted by an adjacent vehicle, and rolled over on the road. The seat-belted right-front passenger was subjected to the roof crush and was rendered a quadriplegic, while the driver was only moderately injured.

The RAV4 windshield header was an open-section shallow channel design, with many large hole cutouts and dimpled contours, and the corner gussets overlap only a short distance onto the header. In the rollover, the roof buckled and crushed down in these predictable weak areas.





The RAV4 had an "*open section*" design for the windshield header, basically a flat channel that's spot-welded along the roof's forward edge. In contrast, in the same 1999 model year, the Toyota Camry utilized a "*closed section*" design, a rectangular-shaped tube that was stiffer and stronger in resisting bending and compressive loads.

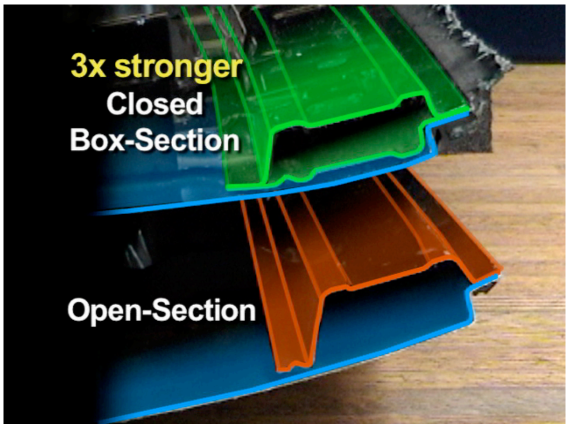


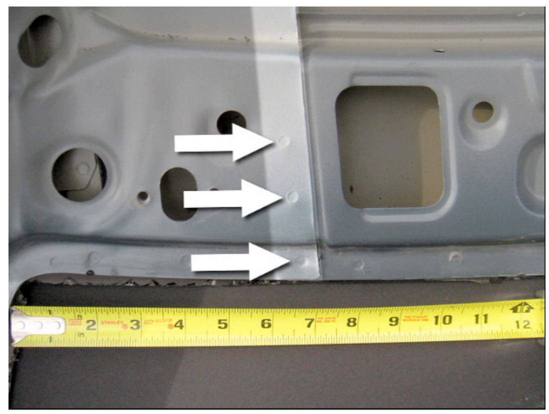
Figure 6. Closed box-section roof headers are about 3 times stronger than open-section headers.

Yet, despite its weak roof and poor performance, the RAV4 roof had complied with FMVSS 216, again indicating that compliance with the *minimum* force requirements of its unrealistic *"slow push"* test does not ensure a reasonably safe roof.

Rollover Case C: 2000 Daewoo Leganza

In the course of the vehicle rollover, the Daewoo Leganza sedan's roof buckled and crushed down into the "survival space" of the driver. Photos at the scene show the seat-belted driver still positioned upright in the seat. He had suffered fractures of his cervical vertebrae, and was rendered a quadriplegic.

The windshield header was an *"open section"* shallow channel-type design, which is much weaker and less safe than a *"closed-section"* tubular design, which is about 3 times stiffer and stronger. The header design had many *"Swiss cheese"* hole cut-outs and minimal overlaps, and was only .030-inch thin, all factors contributing to its weakness in rollovers.

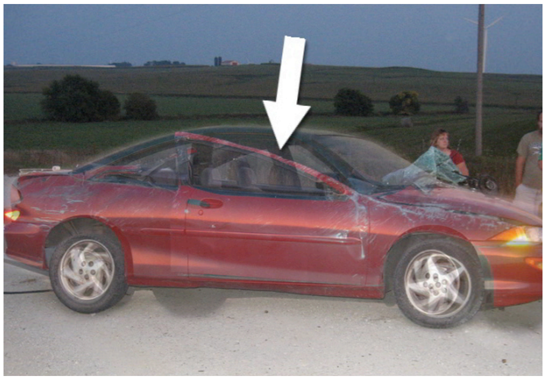


Note the predictable weak zone where the roof buckled in the accident…. as shown in the photo below. It's in this area about 6 to 8 inches inboard from the windshield pillar… where there's only a minimal overlap of only about one inch, and just three spotwelds, where two pieces of thin sheetmetal overlap each other, adjacent to a large hole cutout. That's the critical *"weak zone"* where the windshield header buckled, allowing the roof to distort laterally and downward.

Here again, even though the roof complied with FMVSS 216, its design was needlessly weak, and its performance in the rollover accident failed to protect the driver.

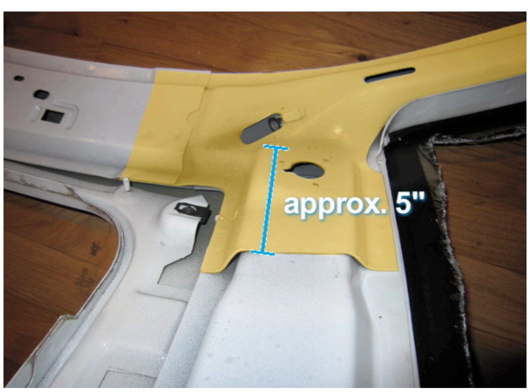
Rollover Case D: 1996 Chevrolet Cavalier Coupe

The rollover accident car was a 1996 Chevy Cavalier 2-door coupe, and the roof buckled and crushed down on the right-front passenger, a young man wearing his seatbelt. He suffered cervical spinal injuries that rendered him a quadriplegic, and paramedics cut off the roof in order to extricate him. The driver, seated where there was virtually no roof crush into her area, was essentially uninjured.



A key design defect in the Chevy Cavalier roof is the windshield header, a thin flat-channel design, an “open section” minimal design that is very weak that is easy to buckle and lacking in stiffness and strength.

The roof structure is further weakened by the short corner gusset that only overlaps about 5 inches, rather than continuing completely across the header from A-pillar to A-pillar, which would add more strength.

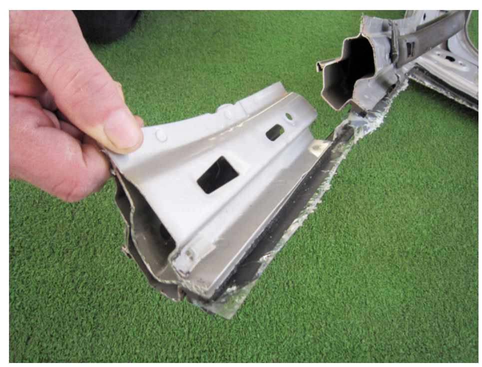


In contrast to this weak open-section design, the “closed section” or “box section” design… which looks like a rectangular tube, is about three times stiffer and stronger, and is much less likely to buckle. This design is used in many other production vehicles competitive to the Chevy Cavalier.

The opposite side windshield header also reacted by buckling upward in the weak area where the short corner gusset ended, about 5 inches inboard from its juncture with the A-pillar. When the windshield header buckles, whether upward or downward, it has thereby failed to maintain the structural stiffness that helps support the other interconnected elements.

Rollover Case E: 1994 Toyota 4Runner SUV

The Toyota 4Runner of the 1989-1995 era is known as Generation 2. The windshield header was an open-section flat-channel design with an additional strip of thin sheetmetal down the center. The header had many large hole cutouts, and the material was only about 30-thousandths. The corner gussets were very short, and ended adjacent to large hole cutouts, creating structural weak zones that are predisposed to buckling when loads are applied onto the roof in a rollover accident.



The windshield pillar had an internal reinforcement, but it only extended upward about 7 inches from the bottom. The roof siderail had a short reinforcement that ended about 8 inches back from the A-pillar. Thus there were weak zones where these structural discontinuities were located in the A-pillar and roof siderail, making them susceptible to deformation and buckling.

Inspection of the 4Runner showed that roof had buckled in those weak zones, including the A-pillar acting as a hinge at the location 7 inches from the bottom where the inner baffle reinforcement ended.

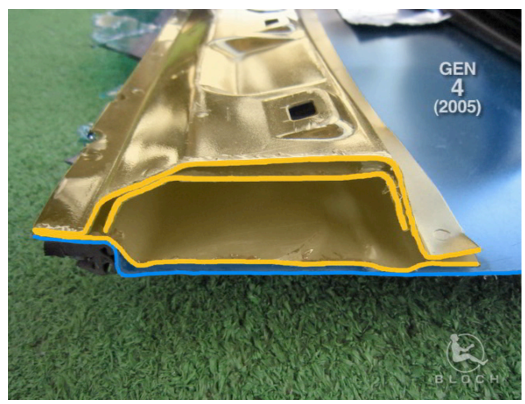
The open section flat-channel design of the windshield header, with its many large hole cutouts and minimal gusset overlaps, also proved inadequate in the rollover. Lacking in stiffness and strength, the windshield header deformed and buckled, predictably in the areas of large hole cutouts and structural discontinuities.

The combined buckling of the A-pillar and header and siderail allowed more extensive downward and lateral deformation and crush of the roof into the driver's *"survival space"* thereby causing cervical spinal loads that rendered the seatbelted driver into a quadriplegic.

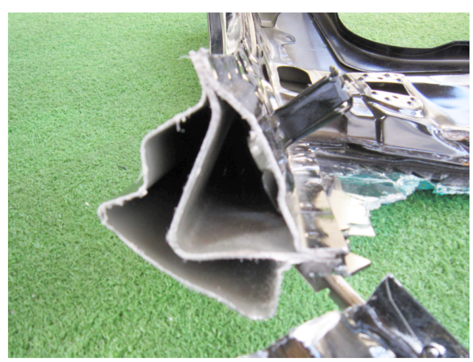
The 4Runner 3rd generation (1996-2002) adopted the well-known closed-section or box-section design for the windshield header. Though of the same thin 30 thousandths of an inch, the box-section design is about three times stiffer and stronger than the open-channel design that was used previously. Again, the short corner gussets and large hole cutouts were additional weaknesses that needlessly compromised the box-section design of the windshield header.

The 4Runner Generation 3 windshield pillar design was similar to the previous Generation 2 version, with the internal reinforcement too short, extending upward from the base only a few inches, rather than continuing the full length of the pillar.

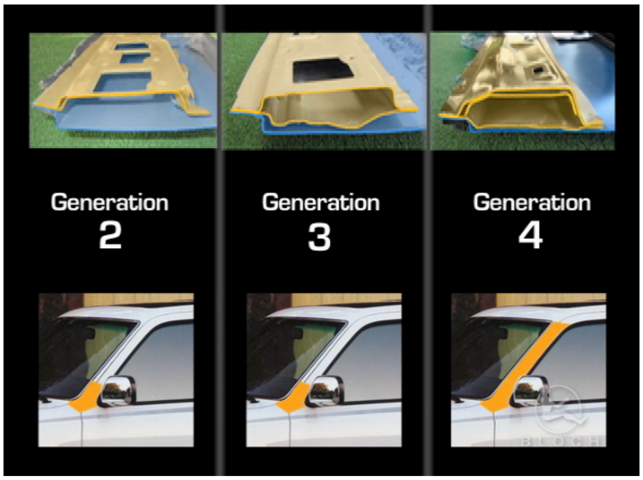
The 4Runner 4th generation (2003-2009) adopted a totally-new design for the roof structure. The previous thin sheetmetal of the windshield header was increased to 60 thousandths. A doubler plate of similar 60-thousandths thickness was also added, and there were notably less hole cutouts. The design was now a more robust thicker material, and had an internal reinforcement and taller vertical walls.



The Generation 4 windshield pillars were of thicker metal, with internal reinforcements continuing all the way from the base to the top of the pillar.



This comparison chart shows the successive revisions of the roof's structural elements from Gen 2 with its weak open-section windshield header with large hole cutouts, and only minimal lower reinforcement of the A-pillar… to Gen 3 which adopted the well-known box-section windshield header… to Gen 4 with a reinforced box-section header and full-length internal reinforcement of the A-pillar all the way from its base to the roof.



The roof structure of the 1994 Toyota 4Runner SUV was well-below the state-of-the-art. Critical roof elements were designed as minimum structures that would just comply with the minimum requirements of FMVSS 216 and its *"slow push"* test. But such a weak roof does not ensure a safe roof in real-world rollover accidents. The roof buckles and crushes down onto the occupants and cause fatal or severe injuries, including quadriplegia.

UNSAFE ROOF DESIGNS WERE NEEDLESS, WHILE SAFER ROOF DESIGNS HAVE BEEN KNOWN FOR DECADES

From my analysis of the roofs of vehicles that had been in rollover accidents, many with resulting fatalities and quadriplegics, there are patterns of needlessly-compromised designs that were well below the state-of-the-art that has existed for decades. Here's a review of the unsafe designs versus safer alternatives:

Windshield Header: If the windshield header is an open-section flat channel or shallow channel design, it will be much too flexible and subject to buckling. The header will be further weakened if there are large hole cutouts, as was often noted in production vehicles where the roof had buckled and crushed down. **Safer Designs:** The windshield header should be a closed-section or box-section design, with an internal baffle and/or doubler plate running the entire length of the windshield header, from Left A-pillar to right A-pillar. To further stiffen and strengthen the header, rigid foam can be used, which can triple the compressive and bending strength of the closed-tube member.

Windshield Pillars: Too many windshield pillars (A-pillars) had an internal baffle-type reinforcement at only the bottom 5 to 8 inches of the pillar. After the rollover accident, the A-pillar was often seen to have buckled or bent at that location right where the internal reinforcement ended, with the pillar then acting much like a hinge that allowed the roof to matchbox and crush laterally and downward. **Safer Designs:** The windshield pillars (A-pillars) should be internally reinforced their full length, from the base all the way upward to where it meets the windshield header and roof side-rail. The use of rigid foam-filling and composite plastic inserts (bonded to the metal) are also effective and economical ways to increase stiffness and strength.

Roof Siderail: Too many siderails are hollow sections with a series of short internal baffles, some of which overlap each other. With hole cutouts and minimal overlaps, the side-rails often buckled downward and thereby failed to help support the roof structure. **Safer designs:** The roof siderails should have internal baffles and doubler plates that are longer and have more substantial overlaps. . As with other tubular roof members, the use of rigid foam filling and composite-plastic inserts can add to the strength of the roof structure.

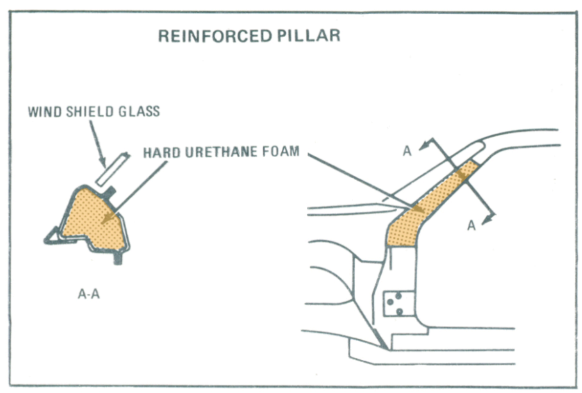


Figure 26

Figure 7. Nissan showed in the 1970's that hard urethane foam made roof pillars much stronger.

It is clear from analyzing the design and performance of roof structures that have failed in rollover accidents, that there are design characteristics that are weak and ineffective. It is apparent that too many automakers have failed to adequately test their vehicle roofs during development, to test to failure, then analyze how and why those failures occurred… and then correct them with a stronger roof.

As a tragic result of such needless compromises in roof design, there has been an epidemic of death and quadriplegia and other severe injuries that have occurred in rollover accidents. In the United States alone, the death toll in rollovers has reached about 10,000 per year.

Yet, if the Federal Safety Standard had been sufficiently strong these past four decades, including a requirement for rollover testing at 50 mph, or at least requiring a strength-to-weight ration of at least 5.0, and with laminated glass for side windows, that toll of death and injury would have been dramatically reduced toward zero.

U.S. SUPREME COURT HAS RULED THAT COMPLIANCE WITH FMVSS IS NOT SUFFICIENT

In the United States, the National Traffic and Motor Vehicle Safety Act of 1966 created NHTSA and the Federal Safety Standards. That law defines safety standards as *minimum* standards for motor vehicle performance. A key provision states that *"Compliance with any Federal motor vehicle safety standard issued under this title does not exempt any person from any liability under common law."*

The U.S. Supreme Court recently issued a unanimous 8 to 0 opinion (one justice was recused) in February 2011 in the case of *Williamson versus Mazda*. A key issue focused on whether a FMVSS 208 permissible option of a lap-belt-only for a middle-row aisle seat in a minivan was a significant objective of the federal safety standard. The Supreme Court ruled that it was not, so that Mazda could be potentially held liable in a state lawsuit for its failure to include a shoulder belt. NHTSA had encouraged inclusion of shoulder belts, which Mazda had failed to implement.

Applying this Supreme Court ruling to rollover roof crush cases, an automaker could be held liable even if its roof complied with FMVSS 216. Not only is the FMVSS 216 only a *minimum*, but NHTSA has consistently pointed out and encouraged that roofs be made stronger. So if a vehicle roof at-issue complied with the so-called *"safety standard"* yet was a weak roof structure with a *"defective design"* that was well below the state-of-the-art, the manufacturer could be held liable in a state court case. The risk of such potential liability also serves as a constructive incentive for automakers to make stronger roofs well beyond the minimum requirements, and that will help prevent future deaths and injuries.

Reflecting back on the case examples cited earlier, a roof that had a windshield header that was a weak open-section shallow channel design with large hole cutouts, and a partially reinforced A-pillar, could not escape liability by claiming the roof complied with FMVSS 216.

The directive for auto safety professionals and for automakers is to design roofs so they won't buckle and crush down in rollover accidents, to avoid causing injury-causing intrusion into the survival space of tall adult test dummies. This will require roofs well above a SWR of 1.5 or the latest 3.0 minimum (with many production roofs already well above 4.0 and some above 5.0).

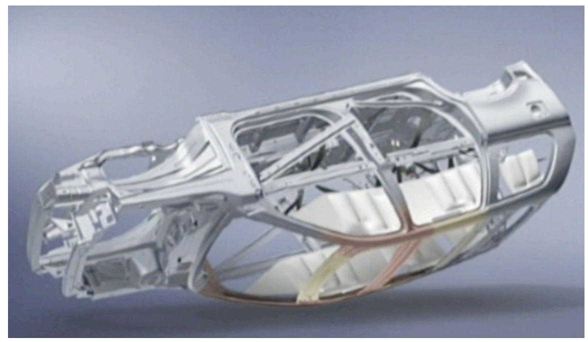


Figure 8. Volvo illustrates how strong roof structural integrity, side curtain airbags, and seatbelt pre-tensioners enhance safe performance in dynamic rollover testing.

Automakers must also conduct dynamic rollover testing at sufficient levels (e.g., at least at 50 mph) to validate the safe performance of the roof, the seatbelts, the side window glass, the side curtain airbags, and other features. The issue is no longer whether there is precisely-exact repeatability in rollover testing, but rather reasonable repeatability in testing that simulates what happens in real-world accidents.

The compassionate goal must be to eliminate deaths and quadriplegic injuries in rollover accidents. As discussed above, including the illustrative case examples, this may well require roofs with a SWR well above 5.0 and dynamic rollover testing with instrumented test dummies at 50 mph or higher.

CONCLUSIONS

FMVSS 216 has been ineffective as a "safety standard" and does NOT ensure a safe roof to protect occupants in rollover accidents. Recent upgrading of the *"slow push"* compliance test requirement for a strength-to-weight ratio (SWR) from 1.5 to the new requirement of 3.0 is far too minimal… with many production vehicles already well above 4.0 and some above 5.0.

Analysis of many roofs has shown that, for the past 40-plus years, automakers have been needlessly compromising roof strength by using open-section headers, partial reinforcement of A-pillars, minimal gussets, and other structural weaknesses.

Instead, roofs should use closed-section or box section headers with internal reinforcements, with A-pillars internally reinforced from bottom to top, with more substantial gussets, and with the use of rigid foam filling and composite plastic strengtheners, and other innovative designs and technologies that can significantly increase roof strength.

There is ample evidence that affirms that roof crush causes cervical spinal traumatic injuries and resulting quadriplegia, a cumulative body of authoritative research that is well supported by dynamic rollover tests with instrumented test dummies, and extensive bio-mechanical and bio-medical assessments.

In defending their weak roof that too easily buckle and collapse, some automakers and their defense experts have theorized a *"diving theory"* as the mechanism of injury, rather than such fatal and cervical spinal injuries being caused by roof crush.

What is needed is a strength-to-weight ratio (SWR) of at least 4.0 with a phased-in upgrade to 5.0, and a dynamic rollover test with instrumented dummies at 50 MPH and a phased-in upgrade to 60 MPH.

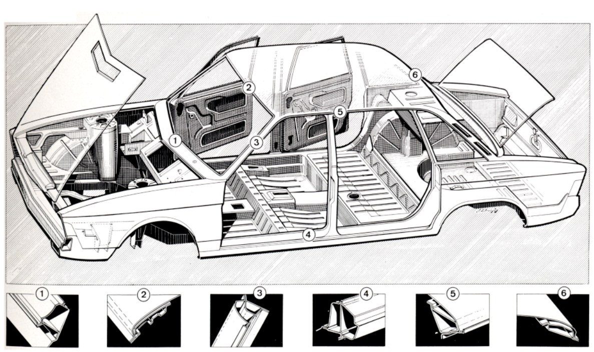


Figure 9. NSU-Volkswagen K-70 illustrated in 1969 how reinforced box-section roof members interconnect to help maintain structural integrity.

Safer designs have reinforced roof pillars with *full-length* internal baffle plates and/or are filled with *rigid foam* (which can *triple* their strength), and closed-section (like an " O ") rather than open-section (like a " C ") tubular windshield headers and roof siderails, plus lateral side-to-side cross-members, and reinforcing gussets at the connections.

Thus, stronger roofs will help minimize the downward and lateral roof crush that causes head and cervical injuries, and will safely maintain the *"survival space"* or *"non-encroachment zone"* for the driver and passengers.

Safer roof designs have been documented since the 1950's when automakers conducted dynamic vehicle rollover tests and then again in the Experimental (Enhanced) Safety Vehicle Program that began in the early 1970's. In addition to stronger roofs, the use of laminated glass-plastic side-window glass, side curtain airbags, and energy-absorbing padded vehicle interiors can all reduce occupant injuries during rollovers.

In striving to attain the compassionate goal of Vision Zero… the elimination of fatal injuries due to the motor vehicle… it is imperative to innovate, design, develop, test, and produce vehicles that offer optimal crashworthiness in frontal, side, rear, and rollover accidents.

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