ADVANCED DESIGNS FOR SIDE IMPACT AND ROLLOVER PROTECTION

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ABSTRACT

Every year in the U.S., about 8,000 fatalities occur in side impacts, and about 9,500 fatalities occur in vehicle rollovers. Severe head trauma and spinal cord injuries are the prevalent traumatic injuries that are directly related to the extent of inward crushing or intrusion into the occupant's *"survival space"* and to the rigidity and shape of interior edges and surfaces.

Based on accident evaluations and assessment of available technologies, there are feasible and practical advanced design features for vehicle bodies and interiors that can concurrently enhance both **side-impact protection** and **rollover roof-integrity protection:**

Strengthened vehicle body by the use of rigid-foam-filled tubular members that strengthen and stiffen the vehicle body, by tripling resistance to bending and compression. Strengthened doors with full-perimeter overlap and multiple latches. Multi-layer laminated floorpans, cross-panels, and roofs of composite materials. Roof tubular members in an interconnected design, with full-length internal stiffeners and/or rigid-foam-filled. Wrap-around stronger seats with taller headrests, and integral seatbelts and belt pre-tensioners that activate in side impacts and when rollovers are initiated. Energy-absorbent closed-cell padding of interior surfaces, some with a metal-air-gap underlayer. Side airbags for torso and head protection. Side window glass-plastic glazing and perimeter bonding, to cushion head impacts and prevent occupant ejection from the vehicle.

The main objects of these safety upgrades are to (A) encourage deflection of the striking vehicle and struck vehicle away from each other, **(B) minimize intrusion** into the occupant's "survival space", **(C) reduce the velocity differential** between the struck vehicle and the occupant kinematic movements, **(D) restrain and cushion the occupant's head and torso**, or allow contact with energy-absorbing materials to maximize distribution of contact forces.

SECTION 1:

SIDE IMPACT PROTECTION

The emphasis on upgraded side impact crashworthiness has been prompted by the 1991 amendment of the United States Federal Motor Vehicle Safety Standard 214 (FMVSS 214). Beginning in the middle to late 1990's, all new cars and vans sold in the U.S. began to phase-in various side-impact features and technology in order to meet a 33.5 MPH dynamic crash test by a deformable moving barrier (DMB), with specific injury-related thresholds applicable to front-seat and rear-seat near-side Side Impact Dummies (SID).

This paper explores the novel integration of various features and technologies that will likely be the leading candidates to upgrade side-impact crashworthiness. Rather than selecting only the *minimal* features to comply with the *minimal* requirements of FMVSS 214 and its limited crash test protocol, there should preferably be an optimal application of features to maximize or optimize side-impact crashworthiness.

These side-impact crashworthiness features include:

The use of internal baffles and rigid-foam-filled tubular members to strengthen and stiffen the vehicle body.
Strengthened doors with full-perimeter overlap.
Wrap-around seats with integral seatbelt restraints.
Foam-cushion energy-absorbent padding of interior surfaces.
Side airbags for torso and head protection.
Side-window glass-plastic glazing.

Since FMVSS 214 is a performance standard, manufacturers have opportunities to be innovative in the designs they adopt in order to comply. The creative use of new vehicle designs, new features, new technologies, new materials, and new manufacturing techniques should be encouraged. From a potential product liability viewpoint, it would be prudent to design for performance levels well above the minimums cited in FMVSS 214, and to include protection for all vehicle occupants, and for a variety of side-impact collision modes.

HISTORICAL BACKGROUND

In the modern era beginning around 1960, various features and technologies have been applied in efforts to make vehicles more crashworthy, to better protect the occupants from traumatic injury in collision accidents.

In the early 1960's, General Motors adopted the full-length *"perimeter frame"* for most of its full-size and mid-size American automobiles, noting that one main function was to protect passengers in side-impact collisions:

> *"Box-section steel members form the frame sides and extend their protective strength from end to end. These husky rails act as steel barriers at the sides of the seats to give you maximum protection all around. You ride cradled within the frame!*

The concept of safely maintaining the occupants' ***"survival space",*** and the use of restraints such as seatbelts and airbags, have been major themes adopted by virtually all automakers (usually with a prod from mandatory regulations, or in response to litigation losses). When a feasible safety technology becomes available, it often takes about twenty years or so before the majority of automakers implement that technology into their mass-produced vehicles. Airbags are such an example, since they were first implemented by GM and Ford in low-volume production (in approximately 12,000 automobiles in the 1973-76 era), then abandoned by GM and Ford.

In the early 1970's, various automakers tried to comply with the initial Experimental Safety Vehicle (ESV) requirements for all prescribed crash modes, including side impacts. Extensive use of structural side-members and cross-members were typically used in a total "cage" design to stiffen and strengthen the vehicle sides and thus help reduce penetration or intrusion into the passengers' ***"survival space".***

In 1984, a U.S. Department of Transportation edict was issued to try to induce a large percentage of states to adopt their own mandatory buckle-up laws, or else passive restraints (airbags or automatic seatbelts) would be federally mandated. Another catalyst was the U.S. government decision to purchase a few thousand cars equipped with driver-side airbags, to which Ford responded with their 1985 Tempo models becoming available with a driver's airbag option. Mercedes also began in 1985 to equip their various models with airbags as standard equipment. Thus stimulated, airbags finally came into mass-production implementation by most auto manufacturers in the early-1990's.

Presently for their 1996 models, virtually all vehicle manufacturers equip all or most of their production cars, pickups, vans, and multi-purpose vehicles with airbags, for the driver and often for the right-front pasenger.

SIDE IMPACT MEASURES STIMULATED BY FMVSS 214, LITIGATION, AND THE ESV PROGRAM

Side impact crashworthiness upgrades are now being implemented in response to the recent amendment of U.S. Federal Motor Vehicle Safety Standard 214 (FMVSS 214). Finally, FMVSS 214 requires dynamic crash testing and measured test dummy loads. A Thoracic Trauma Index (TTI) in the 85-90 g's range for rib, lower spine, and pelvis accelerations, is measured on the Side Impact Dummy (SID). This dynamic test supercedes the "slow push" minimal test which most vehicles met by installing an inner-door beam or tubular member.

Side impact fatalities account for about 32 percent of all vehicle occupant fatalities per year. NHTSA examined accident data from the 1978-1990 era, and concluded that side impacts caused an average of 7,730 fatalities per year, plus an average of 68,600 AIS 3-to-5 level injuries (serious to critical injuries) per year.

Stimulation for auto manufacturers to improve side impact measures has come from a combination of:

- The upgraded FMVSS 214, with its 33.5 MPH side-impact crash test, etc.
- Incentives from product liability cases, which prompt manufacturers to try to design out potential design defects.
- Feasible improvements that have been demonstrated in the Experimental Safety Vehicle (ESV) Program, from 1971 through the present. (The ESV Program has recently been renamed as the *Enhanced* Safety Vehicle Program.)

PERIMETER AND LATERAL STRUCTURAL DESIGN TO MINIMIZE INTRUSION AND ENCOURAGE DEFLECTION

It is important to interconnect virtually all vehicle body structural members so as to efficiently distribute collision loads throughout multiple members and avoid the overload on any one or a few. Structural discontinuities such as hole cutouts, notches, dimpling, overlaps, and spotweld spacing patterns should be minimized to avoid weak zones that would tend to buckle when collision stresses are directly or indirectly applied.

The structural members must take into account the need to **encourage deflection** of the subject vehicle away from other vehicles or stationary objects, as well as to **minimize intrusion** into the subject vehicle's *"survival space*".

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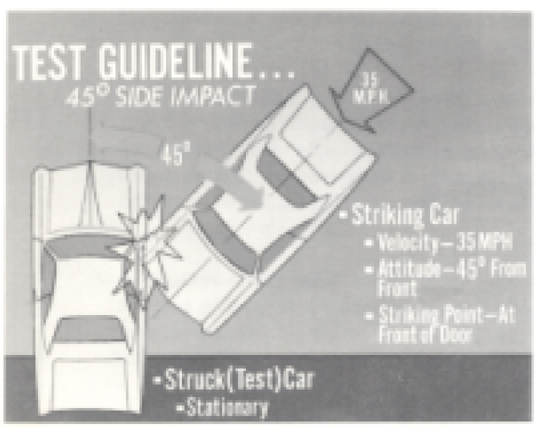
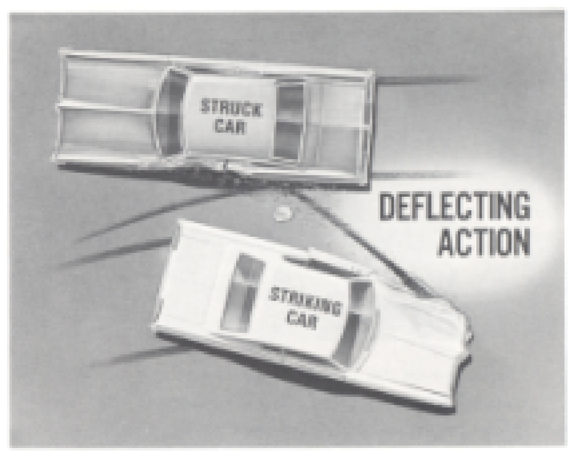
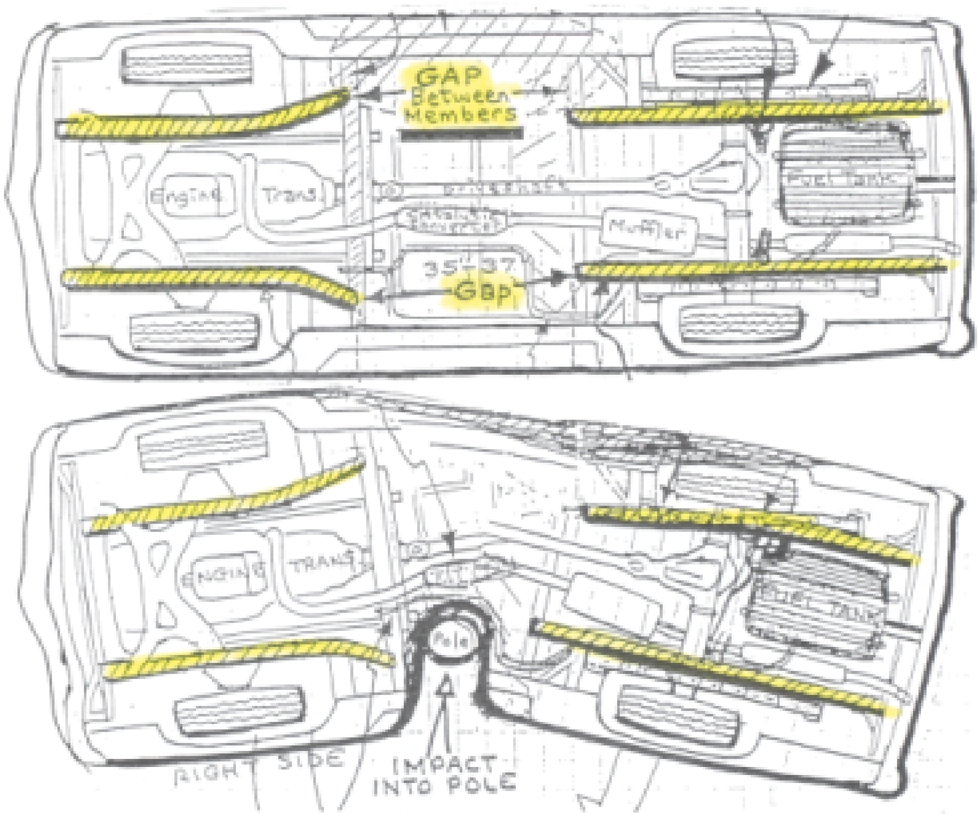
One of the earlier articles about the merits of perimeter strengthening was in *"Side Impact Structures",* part of the proceedings of the 1968 General Motors Automotive Safety Seminar. The article included the GM illustration that appears below, illustrating the desired principle of delecting one vehicle away from the other. GM's design was essentially a low-weight, high-strength steel corrugated beam that was placed horizontally about mid-way up within the door, along with reinforced structures for further support. GM introduced their inner door beam design into production cars beginning with some 1968 models.





SAFETY DEFECT: A Structural "Gap" or Weak Zone

Too many passenger cars have inadequate versions of "unitized bodies", especially in their failure to include side impact protection. Many vehicles have a structural "gap" between the front and rear subframe members, causing a weakened body in the mid-region of the vehicle where the passengers are located. Thus, another striking vehicle or a tree or pole can excessively intrude directly into the passengers' *"survival space"*, rather than being deflected safely away with minimal intrusion.



DOORS WITH FULL-PERIMETER OVERLAP

FMVSS 214 first became effective in January 1973 as a requirement for "Side Door Strength - Passenger Cars". It required a "slow push" into the side of the vehicle door so that an inward deformation of no more than 5 inches occurred when the slowly-applied load reached one-and-a-half times the weight of the car, or 5,000 pounds, whichever was less. There was no crash test, no use of instrumented test dummies, nor any specified measure of intrusion into the passenger ***"survival space"***. Most manufacturers met this minimal requirement by adding an inner door beam, typically by a sandwich of corrugated sheetmetal panels, or a steel tube. Too often, such inner door beams were inadequately connected or "floated" within the door.

Improved door structures have typically increased the strength of the door hinges, added stronger door latches (and sometimes a second interlock pin), and strengthened the mid-body B-pillar. Some designs also ***significantly overlap the door*** over the lower rocker section, so that the bottom edge of the door could not be easily pushed inward

The upgraded version of FMVSS 214, retitled as *"Side Impact Protection",* had a phase-in period from September 1993 (10% of an automaker's production fleet) through September 1996 (100% of the fleet) for compliance. The previous static test ("slow push") has been superceded by more stringent loads applied to the doors, to measure initial, intermediate, and peak crush resistance (not less than three and one half times the vehicle curb weight or 12,000 pounds, whichever is less), required to deform the door inwardly over the initial 6 inches, then 12 inches, then 18 inches of crush.

There is also a new dynamic test in which a deformable moving barrier impacts the side of the target vehicle at 33.5 miles per hour, to measure acceleration loads imparted to seated anthropomorphic test dummies. The basic criterion is the Thorcic Trauma Index (TTI), based on measured acceleration data from the ribs, spine, and pelvis of the test dummy. The calculated TTI shall not exceed 85 g's for 4-door passenger cars, nor 90 g's for 2-door models.

There are no required measurements or criteria in FMVSS 214 for potential head injury, potential neck/spinal injuries. Yet, severe to fatal head and neck/spinal injuries are frequently caused in side-impact collisions, when the occupant's head strikes a tree, pole, or intruding vehicle, or the interior B-pillar or roof-rail or other rigid object. Thus, there is an urgent need to amend and upgrade FMVSS 214 to include such criteria concerning potential injury to the head and neck. Such an upgraded FMVSS 214 should correlate with the new Upper Interior Impact Protection requirements for head injury protection within the recently amended FMVSS 201

INTERNAL BAFFLES AND RIGID-FOAM-FILLED TUBULAR MEMBERS: TRIPLE THE STRENGTH

Most modern-era automobile bodies are of "unitized" design, whereby strategic stampings of sheetmetal are welded into various shapes and interconnections to allow sufficient torsional strength and beam strength. The use of ***internal baffle plates***, to essentially make one larger tube into two smaller tubes by means of a full-length internal partition, adds significantly to the bending resistance and overall strength of that reinforced tubular member.

This strengthening technique can be applied to the roof pillars, roof siderails, windshield header, roof crossmembers, rocker sections, and elsewhere throughout the vehicle body structure, for both side-impact protection as well as for roof strength. These various body elements are, or should be, interconnected to each other, so as to more efficiently distribute any localized forces over a multiplicity of elements, to thereby avoid overloads that would tend to buckle or crush the individual elements. Reinforcing gussets should be used at the junctures where various elements interconnect.

General Motors, Toyota, and Renault tested hollow tubular members that were filled with a rigid polyurethane foam. The technology is basically the insertion of the polyurethane liquid within the thin-sheetmetal tubular structure, then allowing the liquid to expand and fill all voids as it hardens.

Such foam-filled members showed an increase of about three times their original bending strength and compressive strength, at a very negligible weight increase. Various models by Ford (Windstar minivan, Falcon in Australia), Toyota (Lexus LS400), Infiniti, and Nissan (Altima) have utilized such foam-filled members to increase the strength of roof support pillars.

In Australia, the Ford Falcon literature notes:

"Strengthened Door Pillars. The A and B pillars are reinforced with a composite material which sets like concrete, and strengthens roof construction."

"Strengthened Roof Construction. Roof crush strength significantly exceeds stringent USA requirements."

FOAM-CUSHION PADDING OF INTERIOR SURFACES

The data and observations from accident injury evaluations as well as from instrumented anthropomorphic dummies in crash tests, show that expected **traumatic injury levels can be reduced by foam padding, typically supported by yielding sheetmetal beneath the padding**. The basic goals are to distribute loads to the occupant over a broad surface area, and to cushion or lengthen the time of impact deceleration or acceleration experienced by the occupant's head, chest, or entire body. The padded instrument panel upper surfaces, the padded rear-facing backrests of front seats, and the padded knee bolster beneath the instrument panel, are examples of the merits of load-distributing and energy-absorbing padding.

The density of the foam padding, its depth, the area covered, and the underlying denser foam and sheetmetal, are all factors that affect potential injury. Too soft or too shallow a padding, and the protection is progressively reduced and minimal as the crash speeds increase. A novel type of energy-absorbing padding called *"Dynapad"* has been described as closed cells, each with an orifice or other restrictor for the entrapped air to escape as the occupant loads into the padding and compresses the cells and the air within.

Vehicle interior surfaces that need padding include the windshield pillar (A-pillar), the mid-body pillar (B-pillar), the rear window pillar (C-pillar), windshield header, rear window header, and roof siderails. Led by Saab, more vehicles have included complete padded liners for virtually the entire roof.

For enhanced side impact protection, the door itself can utilize semi-rigid foam padding, particularly at the pelvic level and at the shoulder level. Ford used an approximation of such door pads in their 1985 Mondeo-Contour-Mystique vehicles. Many automakers now use foam padding within the doors to enhance side-impact protection, particularly to reduce injuries to the pelvic and torso regions.

STRONGER WRAP-AROUND SEATS WITH INTEGRAL BELT RESTRAINTS

Wrap-around contouring of the front and rear seats can help to restrain the occupant from lateral movement, as well as to offer protection from intrusion or penetrating objects coming from the side. Such wrap-around contouring of the seat backrest would stop at about shoulder height so as not to interfere with the driver's vision to the left and right. Approximations of such contoured seats have occasionally appeared on sportier models by various automakers.

It would be advantageous to integrate the lap and torso seatbelts directly within the seat structure. Thus, the seatbelts would have a better, closer fit to the occupant, without any appreciable gaps as there are with shoulder belts that have their upper mount attached to the mid-body pillar (B-pillar). There are recent or current models from BMW, Mercedes, Chrysler (Sebring convertible, Durango SUV, Ram extended-cab pickup), and some Buick models that have such integrated seatbelts within the strengthened seat.

It is a reflection of the inadequacies of FMVSS 207 on Seating Systems, that too many seats are so weak that they cannot structurally withstand the loads of seatbelts fastened to them. FMVSS 207 requires that a static-load be slowly applied to the seat equal to 20 times the weight of the seat itself, with no dummy on the seat, nor any dynamic test, nor any crash test of the seat mounted in the vehicle. Clearly, it is long overdue the time to significantly upgrade FMVSS 207 to require a dynamic crash test with a seated anthropomorphic test dummy in each seated position of all bucket-style and bench-style seats of the subject vehicle.

The integrated seatbelts should include a **pre-tensioner** that automatically snugs or tightens both the lap and torso belts at the onset of a crash, thereby eliminating dangerous slack or looseness that can allow the occupant's torso to bypass the shoulder belt and impact the steering wheel, the windshield pillars, or other hard edges and surfaces. A belt **force-limiter** should be included to ensure that maximum tolerance belt loads are not exceeded.

The 1997 Cadillac Catera (imported from GM's European Opel operation) featured seatbelt pre-tensioners, as do most of GM's Opel and Vauxhall models in Europe. Yet, the rest of GM's domestic U.S. vehicles lag behind in implementing these more effective seatbelts. The Ford Mondeo cars in Europe have featured seatbelt pre-tensioners since their introduction back in 1994, yet their subsequent U.S. equivalent Ford Contour and Mercury Mystique models do not include seatbelt pre-tensioners.

The delay in adopting seatbelt pre-tensioners in American domestic vehicles is noteworthy and puzzling since GM and Ford had obtained patents for various versions in the 1970's and 1980's, and have been aware of their safety benefits from the ESV program and their own research for about twenty years.

It may have something to do with the tens of millions of GM and Ford cars still on the road with the so-called *"windowshade"* slack-inducing feature that causes the shoulder belts to get dangerously looser as you drive, making such seatbelts less safe and effective in a crash. How do you explain away the alleged merits of those slack-inducing *"windowshade"* seatbelts, while now promoting the safety advantages of *pre-tensioners* that automatically tighten your lap and shoulder belt at the start of a crash?

Clearly, it is important for the lap and shoulder belt to hold the occupant snugly in a side-impact collision situation, to help keep any lateral movements of the torso and head to a minimum. This is necessary for both the collision's near-side occupants as well as for the far-side occupants across the car. This will also help keep the occupants from slamming into each other.

SIDE AIRBAGS FOR TORSO AND HEAD PROTECTION

Automatically inflatable airbags have become widely accepted and utilized for frontal impact protection. Most auto manufacturers refer to airbags as being *"supplemental"* restraints to complement seatbelts, further noting that airbags afford added protection for the head and upper torso in the more severe collisons. These airbags are installed (or stored) within the center of the steering wheel, and in the right-half portion of the instrument panel.

The latest airbag application is for side impact protection. Volvo began utilizing side airbags in 1995, with the airbag installed within the outboard portion of the driver's seat and the right-front passenger's seat. Thus, the Volvo airbag protects the adjacent occupant's torso, and helps keep their head from being impacted by inward intrusion or lateral displacement. The latest Volvo design features a "side curtain" airbag system that inflates downward from the roof-rail, to offer instantaneous protection for the front seat and rear seat occupants.

BMW has recently shown their version of **airbags for side-impact protection**, including the mounting of one airbag within the upper door structure and another tubular-shaped airbag that inflates to offer protection from the windshield pillar to the mid-body pillar. Thus, this second or upper airbag more directly protects the head of the adjacent occupant.

Various side-impact airbags from Volvo, BMW, Mercedes, and Ford show alternatives for mounting the airbag... within the outboard portion of the front seat, or within the door just below the window level, or along the roof siderail (essentailly between the windshield pillar and the mid-body pillar).

The BMW design, first implemented in some of its 1997 models, is especially meritorious in having an upper-level tubular-shaped airbag that protects the head of the driver and right-front passenger. The front anchorage is at the windshield pillar, and the rear anchorage is at the top of the B-pillar. Once inflated, this head-protecting side airbag commendably stays inflated for a prolonged interval to help continue its effectiveness throughout what could be a more complex accident scenario.

It is apparent from crash testing demonstrations and from actual accidents involving Volvo's equipped with side airbags, that reasonable levels of injury reduction can be attained with side impact airbags. The technology is now available to have side impact airbags inflate within 20-to-30 milliseconds of the onset of a side impact to the subject vehicle. There are various storage cavities for the airbags that can be available by feasible redesign of the the seat, the door, or the roofrail. The crash sensors and gas generators have response and actuation times to ensure airbag inflation in sufficient time (e.g., within about 10-to-20 milliseconds).

Side impact airbags for front seat (and also rear seat) occupants are feasible in various designs.... as inflatable protective cushions for the pelvic, torso and/or head regions, as supplemental to lap and torso seatbelts, which may have to be integrated within the front seat (rather than attached to the mid-body pillar) so as to not interfere with the inflating aide-impact airbags.

SIDE-WINDOW GLASS-PLASTIC GLAZING

In a side-impact collision, the tempered side window glass typically shatters or disintegrates into hundreds or thousands of small pebbles. The side window tempered glass is a single sheet, rather than a three-layer sandwich of glass/plastic/glass like the front windshield. Thus, the side window glass does not have any plastic interlayer such as high-penetration-resistant (HPR) butyl plastic to absorb the impact forces of the occupant's head striking it.

In the course of a side-impact collision accident, the easily-shattered side window tempered glass also thereby exposes the occupant's head into being directly impacted by the intruding or striking vehicle.

Among the pioneering advocates for side window glass-plastic glazing was Carl Clarke, who helped demonstrate its merits in a series of comparative crash tests (for both side window and rear window applications). Head injury levels were reduced, as was occupant ejection.

SIDE IMPACT - CONCLUSION

In their efforts to comply with the newly upgraded FMVSS 214 and its dynamic crash test, some automakers will likely utilize stronger side impact structures (door beams, lateral stiffeners in the cowl and floorpan, etc.), semi-rigid or rigid foam blocks strategically located within the doors and pillars, plus a mix of interior energy-absorbing foam padding.

Some manufacturers are obviously going beyond the minimal requirements, such as those that are including side airbags, at the torso level. The latest systems also include a separate side airbag that is critically located at the head level for the driver and passenger.

Rather than settle for compliance with the *minimal* requirements of FMVSS 214, the automakers' efforts should focus on a more comprehensive goal... to ***maximize*** side impact protection for all vehicle occupants, in a ***variety*** of side impact collision modes, and at speeds higher than the prescribed 33.5 MPH.

As demonstrated since the early-1970's in the *Experimental Safety Vehicle (ESV) Program*... now the *Enhanced Safety Vehicle Program*... many automakers have demonstrated feasible means to achieve excellent crashworthiness and occupant protection in 50 mph side impacts. That level of performance, or even higher, should be implemented as each new vehicle is designed and mass produced.

SECTION 2:

ROOF CRUSH IN ROLLOVERS

Every year in the U.S., about 9,500 fatalities occur in vehicle rollovers. Severe head trauma and spinal cord injuries are the prevalent AIS-4/5/6 injuries, and are directly related to the extent of inward and downward crushing or intrusion into the occupant's *"survival space"* and to the rigidity and shape of interior edges and surfaces.

Based on accident evaluations and assessment of available technologies, there are many needless defects and deficiencies in the roof structures of many vehicles. I have personally inspected and evaluated a variety of cars, pickups, and vans that had been involved in rollover accidents. Despite whatever vehicle miscontrol or collision had initiated the rollover, there was extensive buckling and crushing down of the roof. The occupants had often incurred severe to fatal injuries, including severe brain trauma, quadriplegia, and paraplegia.

ROOF STRUCTURE DESIGN DEFECTS

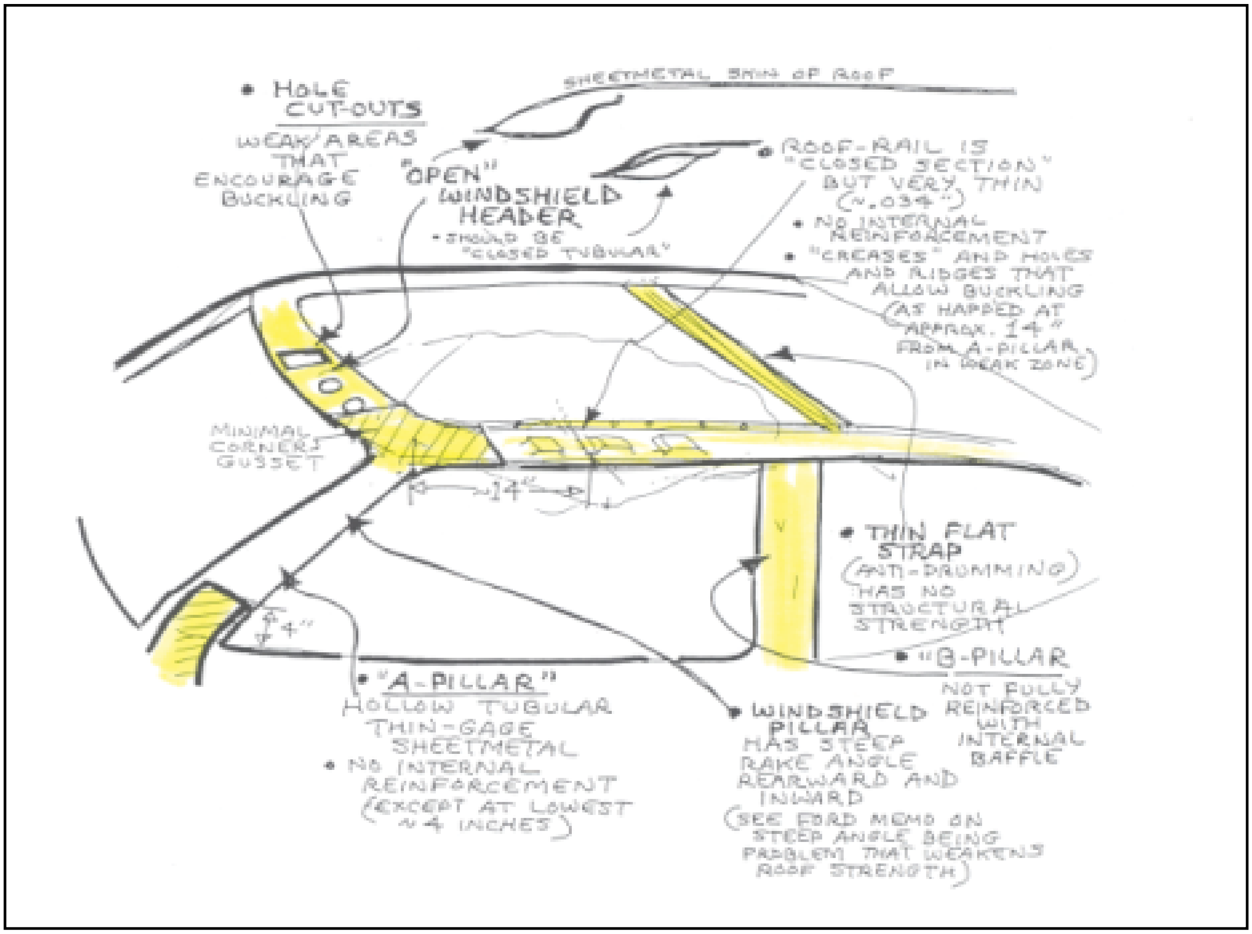
When I personally inspected the accident vehicle's roof structure, I often noted the extensive intrusion into the occupants' "survival space", with the roof having buckled and crushed downward and laterally. The vehicle's upper body and roof strength is essentially a function of the strength and rigidity of the roof pillars and crossmembers and how they all interconnect. Yet, I observed that too many of these vehicles had needless compromises that weakened the integrity of the roof structure.

The windshield pillar (A-pillar) was a thin sheetmetal tube, with either an abbreviated too-short internal reinforcement baffle, or none at all. The mid-body pillar (B-pillar) and rear window pillar (C-pillar) were only moderately reinforced with partial internal baffles, if at all.

In contemporary vehicle design, the windshield pillars are swept back rearward and also angled laterally inward. Such a severe leaning angle reduces the ability of the windshield pillar to support the roof, and thus requires a stronger, stiffer, reinforced pillar with even more reliance on its interconnection to other roof members to better distribute the loads encountered in a rollover accident.

The windshield header (across the top of the windshield), the rear window header, and roof sidemember (along the outboard sides of the roof) were often an "open C" in cross-section, rather than a "closed O" in cross-section. Structurally, a closed tubular section is much stiffer and stronger than an open semi-tubular section.

Further aggravating the roof integrity situation are designs that include too many holes, cutouts, notches, dimples, creases, and other discontinuities… plus a minimal number of widely spaced spotwelds, often poorly located along minimal flanges. Because of these needless design defects, the roof is structurally pre-disposed to buckle and collapse.



There is often also minimal interconnection and reinforcement of the roof structure elements. Too many vehicles have only a thin sheetmetal flat strap from B-pillar to B-pillar, serving only as a minimal pseudo stiffener to keep the broad sheetmetal from undulating as the wind rushes across it at highway speeds. Preferably, there should instead be a closed-section rectangular tube structure laterally across the roof from the top of one B-pillar to the other B-pillar. Where the various pillars interconnect with the windshield header and roof siderails, there should also be reinforcing gussets.

FMVSS 216 -
ROOF CRUSH RESISTANCE

The U.S. Federal Motor Vehicle Safety Standard (FMVSS) No. 216 is entitled "Roof Crush Resistance - Passenger Cars", and went into effect in August 1973. The purpose of FMVSS 216 is "to reduce the liklihood of roof collapse in a rollover accident" and futher notes that "available data have shown that for non-ejected front seat occupants in rollover accidents, serious injuries are more frequent when the roof collapses."

FMVSS 216 prescribes only a minimal compliance test, which requires a slowly applied load be applied on a slight angle to the front upper corner of the car's roof… and that the test device shall not move more than 5 inches (downward) with an applied force of one and one-half times the vehicle weight, or 5,000 pounds, whichever is less. There is no dynamic vehicle rollover crash test, nor any use of an instrumented anthropomorphic test dummy.

FMVSS 216 was supposed to be initially just a temporary alternative until August 1977, when it would be supeceded by the dynamic rollover crash test required as part of FMVSS 208, entitled "Occupant Crash Protection". The dynamic rollover crash test required the complete vehicle (tilted at 23 degrees), on a moving dolly or sled, to be propelled laterally along a track at 30 miles per hour. The test vehicle would then be released or catapulted off the sled, and it would then laterally roll multiple times on the pavement. With a front seat anthropomorphic test dummy, this dynamic rollover test more closely simulated real-world rollover accidents than does that FMVSS 216 "slow push" to a portion of the roof.

Of interest, virtually all European automakers, including GM-Europe and Ford-Europe, have long conducted and continuously still conduct such dynamic rollover tests per FMVSS 208, as well as the static test of FMVSS 216. U.S. automakers and most Japanese automakers have instead designed their roof structures in accordance with the FMVSS 216 requirements only.

Data from the U.S. Fatal Accident Reporting System (FARS) and elsewhere affirmed there was a strong relationship between injury severeity in rollover accidents and the extent of roof crush. A 1982 SAE Report entitled "Light Vehicle Occupant Protection - Top and Rear Structures and Interiors" by Fan and Jettner, both of NHTSA, urged that further efforts be undertaken and that "it is projected that a high safety benefit could be expected when both the roof crush resistance and the roof interior padding are upgraded simultaneously."

Since then, NHTSA established Docket No. 91-68 in 1991, for rulemaking, and has established new requirements for Upper Interior Head Protection within FMVSS 201. The 5-year phase-in begins September 1998. There is currently proposed rulemaking to expand requirements for Dynamic Head Protection Systems such as airbags.

VEHICLE ROLLOVER TESTING

Commencing in 1983, through 1990, NHTSA conducted some 24 full-scale rollover crash tests to investigate vehicle dynamics and and occupant kinematics. Various recent-vintage cars, pickups, and vans were tested, mostly in sled-propelled lateral rollovers at 30 miles per hour, with a fully-instrumented test dummy seated in the front seat. Some were restrained by the existing seatbelt, while others were unrestrained.

In their late-1991/1992 report entitled "Vehicle and Occupant Response in Rollover Crash Tests", by Obergefell, Kaleps, and Johnson, the authors note among their 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. These loads did not always result in high head accelerations; therefore, it is important that neck loads be measured in rollover testing."

"These tests provide greatly needed data on vehicle and occupant dynamics during automobile from three different testing procedures. They demonstrated the variability of rollover results, the difficulty of controlling the test conditions, the tendency for significant roof crush, and the danger to the head and neck region of the body."

This 1983-1992 project by NHTSA again pointed out what has been clearly and repeatedly demonstrated for at least the past 27 years: that roof crush in rollover accidents can obviously cause severe head and neck injuries. The tested vehicles either had to comply with the FMVSS 216 "slow push" partial-roof test, or in the case of pickups and vans, they were even exempt from that minimal 216 test. Compliance with FMVSS 216 didn't seem to help when those same vehicles were rollover tested. Again, the point must be emphasized that it is imperative to test roof structures in dynamic rollover crash tests, with instrumented test dummies.

Historically, a 1968 Ford Motor Company memo is most revealing on this issue:

"A significant number of accidents result in roof damage."

"People are injured by roof collapse."

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."

A SAFER ROOF STRUCTURE

The quest for a safer roof structure must include the automaker's commitment to fully demonstrate and validate the planned vehicle's injury-reduction capabilities by dynamic rollover testing with instrumented anthropomorphic test dummies.

The entire roof structure should be designed as an integrated cage structure that will maximally protect the occupants' *"survival space"* wthin. The appropriate place to begin is with the proverbial *"clean sheet of paper"* when the particular car, sport-utility-vehicle (SUV), van, or pickup truck is initially conceived. The integrity of maintaining the passenger compartment *"survival space"* must be a mandatory design and performance requirement from the inception, rather than by subsequent piecemeal efforts to correct various structural weaknesses.

The various design defects that are discussed earlier should all hopefully be eliminated from the vehicle's very beginnings. Open-section windshield headers and roof siderails should become closed-section designs, with internal baffle reinforcements. Analogously, the A, B, and C pillars should all be closed-section tubular members that are reinforced their full length, with internal baffles and with rigid foam if needed. The roof lateral crossmembers should be closed-section structural members, not just thin flat straps. The interconnnections should be reinforced with gussets that strengthen and stiffen all joints.

Various design innovations should be devised and developed to enhance roof strength and eliminate buckling and crushing downward. Many different approaches have been proposed, some have been implemented, and others that are feasible have yet to be fully developed.

One concept uses full structural arches that span laterally across the vehicle. This is similar to the Republic Industries Safety Car of the late-1960's, then revisited and refined by many others… the Honda ESV, the General Motors ESV, the Minicars RSV, and many other variations on the theme of multiple interconnected arches to form a strong roll-cage construction.

In the early-1970's, many General Motors passenger cars utilized a double-layer roof construction. This design was essentially a sandwich type construction that combined an outer roof with a novel inner roof. While GM boasted of its strength abilities, there was undoubtedly a weight consideration that probably helped alter GM roofs back to single-layer designs, particularly as weight reduction and fuel efficiency became major influences in the mid-1970's.

Interestingly, many GM passenger cars of the early-1970's era featured padded windshield pillars, in a proclaimed effort to help reduce head injuries in a crash, and possibly foreshadowing the anticipated requirements of the then-pending FMVSS 208 for Occupant Protection. By the mid-1970's, the padded windshield pillars were abandoned, and were replaced with various renditions of hard-surface windshield pillars without any energy-absorbing foam.

The need for upgraded crashworthiness measures for side impact protection, and roof crush resistance in rollover accidents, is clear. The continuing epidemic of deaths and severe injuries warrants a dedicated commitment by vehicle safety professionals, automakers, and government agencies worldwide.

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