A STUDY OF NASS ROLLOVER CASES AND THE IMPLICATION FOR FEDERAL REGULATION

Carl E. Nash, Ph.D.
Center for Injury Research
Allan Paskin
Xprts, LLC
United States
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ABSTRACT

NHTSA identified 273 NASS rollover crashes occurring from 1997 through 2000 in which the light vehicles had more than 6 inches of residual roof crush. The agency analyzed these cases, but we have studied them in much more detail. We found a number of important, consistent features that demonstrate conditions that produce rollover injuries, and strongly indicate how rollover casualties can be reduced using readily available technologies. We found: (1) nearly two-thirds were essentially flat ground rollovers without complications; (2) the windshield was always broken when the front of the roof was damaged; (3) virtually all had major damage over an A pillar and a substantial majority had front fender damage indicating that forward pitch in at least one roof impact was roughly 10 degrees; (4) where the vehicle executed more than ½ roll, the initially trailing side of the roof generally had the greatest crush; (5) safety belt use was critical to the pattern of injuries and ejections; (6) the type of roof damage is a function of its design and the nature of the roof impacts; (7) nearly one fifth of the occupants had MAIS 3 or greater injury to the head, face, or cervical spine; and (8) when non-ejected occupants received head, neck or upper torso injuries, they were generally seated on the initially trailing side under a significantly crushed part of the roof. Our study strongly suggests which countermeasures would best address the problem of light vehicle casualties in rollovers, discusses various candidate countermeasures, and estimates the casualty reduction that would result from them. Finally, we discuss the implications for Federal policies.

INTRODUCTION

Several years ago, the National Highway Traffic Safety Administration (NHTSA) asked the public for "views and comments on what changes, if any, are needed to the roof crush resistance standard," Federal motor vehicle safety standard (FMVSS) 216. Shortly afterward, Administrator Jeffrey Runge, M.D. said, "NHTSA plans to propose an upgrade of its roof crush standard to require roofs to allow less crush during a rollover event." As of January 2005, the agency had received 120 comments. Virtually all comments from outside the auto industry support strengthening the standard. The authors of this paper have submitted a large volume of data that should help the agency develop an effective amendment to that and related standards.

NHTSA estimates that 16,000 light vehicle occupants receive serious, non-fatal injuries and that more than 10,000 are killed in rollovers annually. Of those, NHTSA estimated that 28 percent were not ejected and were injured from roof contact (almost all were from roof intrusion); and that half were ejected. While NHTSA did not connect ejection with roof crush, the Malibu tests showed that a strong roof substantially reduced tempered glass side window breakage which would reduce ejection.

The Malibu I tests [Orlowsky] showed "All of the [4] partial ejections were through side window openings as a result of glass breakage. The only total ejection was through a windshield opening. . . . The rollcaged [strong roof] vehicles had less glass breakage than the standard roof vehicles. In the standard vehicles, 18 of the 20 side and rear windows were broken, and all were broken due to roof deformation as a result of ground contact. For the roll caged vehicles, only five of the 20 side and rear windows were broken, and one of the side windows was broken by occupant loading." All of the ejected dummies in these tests were in vehicles with weak (production) roofs, and were seated on the initially trailing, or far side of the vehicle. Thus, the need for motor vehicle safety associated with roof crush in rollovers – including for occupants who are ejected – is substantial. Furthermore, rollover casualties are becoming more numerous with the increasing use of light trucks as private passenger vehicles. SUVs, in particular, are grossly overrepresented in producing AIS 3+ injuries in rollovers.

RECENT NHTSA RESEARCH AND ANALYSIS: THE 273 NASS CASES

Last year, NHTSA released two bodies of information that it is using to develop and support an amended FMVSS 216. The first [Pack], is a list of 273 National Accident Sampling System rollover cases with significant roof crush from accident years 1997-2000. We have prepared detailed tables of these cases that are available from the authors on request (allanp@xprts-llc.com). The NHTSA authors selected these cases from the 1997-2000 NASS files involving rollovers with at least 2 quarter turns (one-half roll) of the vehicle. The vehicles were selected as 1995-2001 light vehicles that weighed 10,000 pounds or less, had no post manufacture modifications, (one case, NHTSA 2000-11-73, involved a pickup truck that had a large rack over the bed and did not meet the criterion), were not towing a trailer, *and had at least 6 inches of roof crush.*

NHTSA characterized these rollovers as "very serious rollover crashes." Their severity was apparently judged by the amount of residual roof crush which is a measure of the weakness of the roof, not the severity of the rollover. These crashes, even when they involve multiple rolls, do involve forces that are easily survivable if the occupant is reasonably protected. They sometimes have serious outcomes (AIS 3+ injuries, ejections, etc.) and may appear to be serious because of the amount of damage sustained by the vehicle, but these are both the result of failures of the vehicle's structure or its rollover occupant protection system. Furthermore, just as the agency is concerned with applying countermeasures to higher speed frontal and side crashes; it should be primarily concerned about applying countermeasures to these crashes that have serious injury consequences.

In 87 of the cases (32%), the vehicle executed only ½ roll. It executed ¾ to 1¼ rolls in an additional 80 cases (29%), and 1½ or more rolls in the remaining 106 cases (39%). A collision preceded the roll (and in most cases contributed to the onset of the rollover) in about 35 cases. In a few cases, the initial impact caused the most serious injury.

A majority of rollovers occur on reasonably flat ground and do not involve significant collisions with anything but the road or ground. Of the 273 NASS cases, 63 percent were "pure" rollovers: rollovers that were not tripped by anything more than traction with the road or ground, that involved no significant collision before the rollover, no collision with anything beyond the ground during the rollover, and no unusual contour to the ground over which the vehicle rolls. Another 14 percent involved a significant collision before the rollover (such as with another vehicle or a guardrail), and 23 percent involved other unusual conditions (collisions with trees during the rollover, or an encounter with a major change in ground elevation).

We observed windshield separation or breakage in pictures of *all* 260 of the vehicles in for which pictures were available and in which there was any significant damage to the front of the roof. The NHTSA study found that the windshield was "intact" in 66 of the cases and had a characterization of the windshield in all 273 cases. We found that in seven cases, there were no pictures or snow that made a determination of the condition of the windshield impossible. We found only 6 in which the windshields were unbroken and fully bonded, none of which involved significant damage to the front of the roof. We do not believe that the NHTSA analysts were sufficiently critical in their evaluation of windshields of these vehicles. We have observed in FMVSS 216 tests, that when the windshield breaks (typically at around 8 cm of crush) the strength of the roof declines dramatically. This has led us to conclude that once the windshield cracks or separates to any degree, it ceases to contribute to roof strength.

Damage was observed on the top of at least one front fender in more than 80 percent of the cases for which there were pictures, indicating that the vehicle was pitched at least 10 degrees during at least part of the time it was inverted. This is approximately the angle formed with the horizontal by a line between the top of the roof over the A pillar and the top of the front fender of virtually all contemporary production light vehicles.

The types of roof damage varied depending on the nature of the crash, the structural weaknesses of the roof, and other factors. However, there were certain common features. The greatest damage was to the front of the roof in all but a handful of cases, for example. The initially trailing, front side of the roof sustained the most damage or both sides of the roof were seriously damaged in 187 cases (163 had major damage to the trailing side only) while 60 involved primary damage to the initially leading side of the vehicle. The remaining 24 were indeterminate or the case file did not have sufficient information. The damage to the roof was likely to have involved a collision with something other than approximately flat ground in about 65 of the cases out of the 273.

Thus, of the cases where sufficient information was available, 75 percent had major damage to the initially trailing or far side of the roof (some of which involved major damage to both sides of the roof). We observed buckling of at least one structural member of the roof in 208 of the cases – 80% of those for which there were pictures. These cases also show that many vehicles roofs are weak at the junction of the major structural elements, the post to pillar connections and the pillar to roof rail and windshield header connection.

Of the 60 cases with primary roof damage at the front on the initially leading side, 47 were less than 1½ rolls (of those, 30 were only ½ roll). Only 7 were more than 1½ roll, and there were complicating factors in most of these. For example, the investigator's reconstructions were questionable in a few of these cases and in a few it appears that the vehicle may have both rolled and yawed so that the direction of the roll changed during the accident. In several, the roof was so massively damaged, it defied easy classification. As a consequence, the estimate that 75 percent of the cases had major damage to the far side of the roof is conservative.

It is important to note that residual roof damage does not reflect the maximum deformation of the roof for two reasons. The first is that the steel from which roofs are made have some elasticity, so that they bounce back (typically 20 to 30 percent) from their maximum deformation. Second, each time the roof strikes the ground, it will deform in the direction of the force applied to it. The force on one side of the roof may force it toward the opposite side, but the force on the opposite side will tend to restore it to its original configuration. This effect was demonstrated in the Malibu tests. This conclusion comes from observation of the videotapes of the vehicle interior associated with this test program. These films are available from Docket NHTSA 1999-5572.

Table 1.
Distribution of rollovers and their casualties from the 273 NASS cases

	NASS R/O Cases with 6"+ Crush all cases	MAIS 3+ injury	2001 R/O Fatalities (FARS)	1997-2001 R/O serious, non-fatal injuries (NASS est.)
Passenger Car	95 (35%)	46 (40%)	5,343 (45%)	15,535 (52%)
SUV	101 (37%)	42 (36%)	2,142 (21%)	5,930 (20%)
Pickup	65 (24%)	25 (22%)	2,643 (26%)	6,595 (22%)
Van	7 minivans (3%) 5 full vans (2%)	3 (3%)	793 (8%)	1,600 (5%)
R/O after Collision	35 (13%)	13 (11%)	18%	(80% of rollovers are single vehicle accidents)
R/O incl. other*	67 (25%)	36 (31%)	1%	
Total	273 (100%)	116 (100%)	10,121 (100%)	29,660 (100%)

* includes collision with other vehicle, tree, or other during rollover; major drop; etc.

Table 2.
Area of primary roof damage in the 273 NASS cases and of cases with MAIS 3+ head or neck injuries

Primary Roof Damage	Total Number of Cases	Cases with MAIS 3+ Head or Neck (cervical spine) Injury
Initially Trailing Side, Front	163* (65% of those with front damage)	39 (64% of front damage cases)
Both Sides, Front	24 (10% of those with front damage)	6 (10% of front damage cases)
Initially Leading Side, Front	60 (23% of those with front damage)	13 (21% of front damage cases)
Rear, Other or Unknown	24	3

* 22 of the total cases and 6 of the cases with MAIS 3+ injury may have involved a collision between the roof and another object such a vehicle or a tree.

The NHTSA analysts spend a substantial amount of time discussing the specific nature of the roof failures (that the pillars themselves "largely remain straight" with bending "occurring at or near both ends . . ." While this is interesting, it is an artifact of the specific design characteristics of the roof. This would be interesting to vehicle designers who are committed to improving roof crush resistance, but tell little about what action is necessary to develop a better test for roof crush resistance.

The fact that in all 273 cases there was more crush than is permitted in FMVSS 216 shows that there were 273 roof failures. These failures put the occupants of the vehicles involved at risk even if they were not actually seriously injured. In fact, the serious injury rate in these rollovers was considerably higher than the rate for rollovers generally. In these cases, approximately 40 percent resulted in MAIS 3 or greater injury, or a fatality. In rollovers generally, fewer than ten percent result in such injury.

To some degree, serious injuries (or perhaps their absence) in rollovers involve a certain serendipity. Unlike severe frontal or side crashes in which major forces must be sustained by the occupants, in rollovers, the basic forces are low – the result of a change in velocity that is very rarely greater than about 2 m/sec (5 mph). Thus, when injuries are sustained, they are the result of failures: ejection of unrestrained or poorly restrained occupants, structural collapse, lack of padding, or other factors.

In their analyses, the NHTSA engineers looked at the injuries, attempting to find some correlations between roof crush that compromised headroom and injury. This discussion seems to assume that restrained occupants remain in their normal seating positions in a rollover, which they do not. Even restrained occupants are typically forced upward and outward in relation to the vehicle during a rollover because of centrifugal force, and because most safety belts do a mediocre job, at best, restraining them under rollover conditions. Unrestrained occupants can be thrown almost anywhere in, and too often outside a vehicle. The NHTSA analysts also neglected to analyze the relationship between injured occupant seating position and the location of major roof crush.

There are some correlations between roof performance and injury. For example, ejections cannot occur unless there is a path for ejection: a broken window or open door. Side windows virtually always break when there is substantial roof crush, but are often intact when the roof damage is minor. A restrained occupant's head, face or neck are likely to be seriously injured only if they are subject to extraordinary forces because of roof buckling or collapse, or because they are ejected.

Of the 65 cases with MAIS 3+ or fatal injuries to the head, face or neck (cervical spine), 25 were belted, and 25 involved occupants who were not ejected (some of whom were not belted). Three were not front seat occupants. Five were belted occupants who were partially ejected. The partial ejection and injury to a belted occupant's head is unlikely unless there is substantial distortion of the roof. This occurs typically when there is matchboxing of the roof in the direction away from the occupant's seating position. In such a case, the occupant does not typically go outside the vehicle. Rather, the envelope of the vehicle moves so that it no longer contains the occupant. In 23 of the cases, the vehicle had a significant collision before or during the rollover, and nine occupants in these cases were belted, but received MAIS 3+ head or neck injuries.

Fifty-one cases had MAIS 3+ or fatal injuries to parts of the body other than the head and neck. All but a few of these injuries to belted occupants, were to extremities rather than to the thorax. Many cases with MAIS 3+ trunk injuries involved collisions before the roll. The total number of AIS 3+ is higher than the overall numbers for injuries presented in NHTSA's October 2001 Notice. This is probably a function the fact that NHTSA selected only cases with at least 15 cm (6 inches) of roof crush.

Table 3.
Area of MAIS 3+ injury in 273 NASS cases

Area of Injury	Number of MAIS 3+ Injuries
Head, Face or Cervical Spine only	58 (18 belted, non-ejected occupants)
Head, Face or Cervical Spine plus Other Injury	7
Torso	34 (4 to thoracic spine)
Extremity	15

Table 4.
Ejected occupants by injury in 273 NASS cases

Injury	Not Ejected	Partial Ejection	Complete Ejection
MAIS 3+ or fatal head or neck injury	23+	12	27
Other MAIS 3+ or fatal injury	26+	6	23
MAIS 1 or 2 non-fatal injury	139+	8	15

Note: many vehicles had more than one occupant so this table underestimates non-ejected occupants.

Approximately 91 occupants in these cases were ejected. Of these, 39 received MAIS 3+ or fatal head or neck injuries. The most seriously injured occupants (24 of which were MAIS 1 or 2 injuries) were partially or fully ejected. Most were not belted, but there were some injuries to extremities among belted occupants.

Among the 39 cases where an occupant with an MAIS 3+ or fatal head or neck injury was ejected, 27 involved more than one half roll. Only 2 had primary damage to the near side of the roof or complicating factors. Only 13 of these rollovers involved passenger cars, 8 of which had at least 1½ rolls.

Three cases with MAIS 3+ head or neck injuries involved collision with another vehicle or object before the rollover and another 20 collided with something during the rollover, complicating the accident. In four cases, the occupant suffered MAIS 3+ thoracic spine injuries, but only two (both ejected) did not involve complicating or unusual factors. Six fatally injured occupants were coded as MAIS 1 or 2. Although an AIS 6 is virtually always a fatality, and fatalities are somewhat likely with AIS 4 or 5 injuries, a fatality may occur with lower AIS level injuries. In some cases, however, limited information may result in a fatality being coded as AIS 1 or 2.

Among the occupants in the 273 cases selected, 173 who suffered the most serious injury in the rollover were coded as wearing safety belts while 114 were coded as not wearing them. A few were coded "unknown" or were not coded. There was not a particularly strong correlation between non-use of safety belts and the number of rolls in the crash. The rate of safety belt use in this file is not consistent with other data that indicates only about half of all occupants involved in rollovers are belted. According to NHTSA (1) "Seventy-eight percent of the people who died in single-vehicle rollover crashes were not wearing the vehicle safety belt, and 64 percent were partially or completely ejected from the vehicle (including 53 percent who were completely ejected)."

CONCLUSIONS FROM THE 273 ROLLOVERS

From these data, we can draw the following conclusions concerning regulatory approaches to countermeasures:

- Increasing safety belt use is critical to reducing AIS 3+ injuries to the thorax and lower extremities.
- Belt use is critical to reducing occupant ejections. However, injuries to occupants' arms that have gone outside the vehicle's envelope can be controlled only by reducing side window breakage. In a few cases, partial ejection was coded for a head or neck injury where the occupant did not move significantly from his or her normal seating position. In these cases, the roof distorted so that its envelope no longer contained the occupant's head. In 1968, Ford engineer J.R. Weaver stated "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." The Malibu tests confirmed that belted occupants have increased probability of severe head or neck injury.
- Any roof crush test that does not result in windshield failure in most contemporary vehicles *before* compliance is determined (either breakage or separation from the body) is not applying sufficient or realistic forces.
- A realistic test of roof crush resistance, whether quasi-static or dynamic, must be conducted at a pitch angle of at least 10 degrees.
- A test of roof crush resistance, whether quasi-static or dynamic, must reasonably emulate the conditions of an initially trailing side roof impact to address a substantial majority of AIS 3+ head and neck injuries. This includes application of the force at a roll angle significantly greater than 25° as occurs with the initially trailing side of the roof in a majority of rollovers.
- Although passenger cars are a substantial proportion of the vehicles that roll over, SUVs are highly overrepresented in rollovers and particularly in rollovers with AIS 3+ injuries. Pickups are also overrepresented, but to a smaller degree. Thus, any test of roof crush resistance must address the particular geometric and roof strength issues of light trucks.
- A substantial increase in roof strength has the potential to reduce AIS 3+ head and neck injuries to non-ejected occupants by 50 to 80% depending on the degree of increase under far side impact conditions and the performance of the vehicle's restraints.
- Roughly half of all other AIS 3+ injuries – mostly ejections – that are not a consequence of a collision with another vehicle or an external object would be reduced with a stronger roof if it significantly reduced side window failure. This would be enhanced by attention to the design of side window systems (perhaps including laminated side glazing) to close ejection portals.
- The minority of cases in which there are major vehicle collisions before or during the rollover are among those most difficult to address. However, the traditional approaches – occupant compartment integrity, crash energy management, good occupant restraint, and appropriate interior padding – should improve occupant safety in such conditions.

QUASI-STATIC TEST RESULTS

NHTSA released the results of a number of quasi-static tests of roof crush resistance in May 2004 [VRTC]. These tests were generally conducted according to the procedures of FMVSS 216, but NHTSA tested three pairs of identical vehicles with the platen being forced into the vehicle through a stroke of 254 mm (10 inches) rather than the 127 mm specified in the standard. One of the pair of vehicles was tested at the 5º pitch and 25º roll specified in the standard while the second was tested with the pitch angle increased to 10º and the roll angle increased to 45º. The vehicles were a mid-sized SUV (2002 Ford Explorer), a mid-sized pickup (1998 Chevrolet S10 pickup) and a minivan (1997 Dodge Grand Caravan). The platen is driven by two rams, one over the front roof contact point and one toward the rear.

The interpretation of these tests provided by Donald Willke of NHTSA was:

- No trend in energy absorbed
- No trend in far side lateral crush
- More vertical crush in 5 x 25 deg.
- Any differences were very subtle
  - Not distinguishable in subjective evaluation of photographs of roof damage

We disagree substantially with these conclusions based on the test results themselves. These tests produced residual crush that was different from that observed in real-world rollovers in NASS (see Figure 1), for example, and that were somewhat different from each other reflecting the angle at which the platen was forced into the roof (note particularly the differences in A and B pillar damage). The force on each hydraulic ram used to press the platen into the roof was separately recorded, and the force displacement curves in these two cases are substantially different in all three pair of tests.

In the tests of the 2002 Ford Explorer conducted at 5º pitch and 25º roll, failure of the windshield resulted in a substantial reduction in the vehicle's roof crush resistance, as measured by the forward ram (see curve at left side of Figure 3), from a peak at about 85 mm (3.3 inches) displacement of 24,000 N (5,400 pounds) to about 10,000 N (2,250 pounds) at 130 mm (5 inches) displacement. At that point the rear ram was supporting 24,000 N (because the platen was fully engaged with the B pillar and rear roof structure. However, the force on the rear ram went down to less than 4,000 N (900 pounds) after the B and C pillars had failed at about 210 mm (8 inches).

Although the roof was able to sustain a maximum force of 55,000 N, this does not realistically represent roof crush resistance in a range of roof crush that would be likely to cause injury. The vehicle would have passed FMVSS 216 at about 70 mm of ram travel, yet the roof was clearly failing during this test. Very little was learned by continuing the test beyond 125 mm (5 inches) of platen travel except that the B and C pillars failed as the force on them increased. Furthermore, in an actual rollover, the injury and window failures would probably have occurred well before the roof had crushed 254 cm.

Figure 1. The NHTSA test vehicles: at 5º pitch and 25º roll at top and at 10º pitch and 45º roll at bottom. The damage is similar only in that the damaged roof's contour follows the shape and angle of the platen used in the test.

Because of the roof's tumblehome, the platen in the Explorer 10º pitch and 45º roll test almost immediately engaged the base of the A pillar which conveyed substantial force resistance. Although it is difficult to tell from the photograph (page 30, VRTC report), it also appears that the platen was not properly positioned on the Explorer's roof. The longitudinal centerline of the lower face of the platen is supposed to be located "on the initial point of contact" with the roof, while the photograph makes it appear that it is at least 5 cm below that point. This placement is critical. Had the platen been moved up somewhat, it would probably not have engaged the top of the door directly. The results would not have been much different, given that the platen engaged the A pillar just above its connection with the A post so that the lower body provided a substantial part of the platen's resistance. Nevertheless, even if the test had been properly conducted, its results could not be taken seriously. We avoided this problem in our tests by using a 305 mm wide platen. In this test, the rear ram (curve at right side of Figure 3) did not exceed 3,000 N (675 pounds) until the roof had crushed about 170 mm (6.5 inches), and never exceeded 11,000 N. The front ram increased virtually monotonically to a peak of about 50,000 N at 170 mm at which time instrumentation problems caused a loss of further data.

In the tests of the Dodge Caravan and the Chevrolet S-10 at 10º pitch and 45º roll, the rear ram picked up virtually no force in either test. Most of the crush resistance appeared to come from the base of the A pillars in both of these tests.

The width and placement of the platen in the tests at 10º pitch and 45º roll meant that this primary resistance was provided by the vehicle body (through the base of the A pillar), not the roof, so that these were not tests of roof crush resistance at all. Our own tests, in which the roof crush resistance is only about half of what is measured in tests at 5º pitch and 25º roll, are conducted with a 30 cm wide platen that applies the force only to the roof itself. Furthermore, we test at 10º pitch and 50º roll only after we have conducted a test on the first side of the roof at 10º pitch and 25º roll to a deformation of 127 mm. Our tests show lower roof strength on the second side because the windshield has already failed in the first side test and because the roofs we have tested show poor lateral shear resistance.

Since part of the rationale for increasing the roll angle is that lateral friction forces on the roof tend to move the force vector more laterally, simply rotating the large (76 cm wide) platen around to 45 degrees, as was done in this case, causes it to unrealistically engage the lower body structure rather than putting a realistic lateral shear force on the roof itself.

Figure 2. Four NASS 2002 Explorer case vehicles (2002-078-143, 2002-12-168, 2002-011-129, and 2001-11-048).

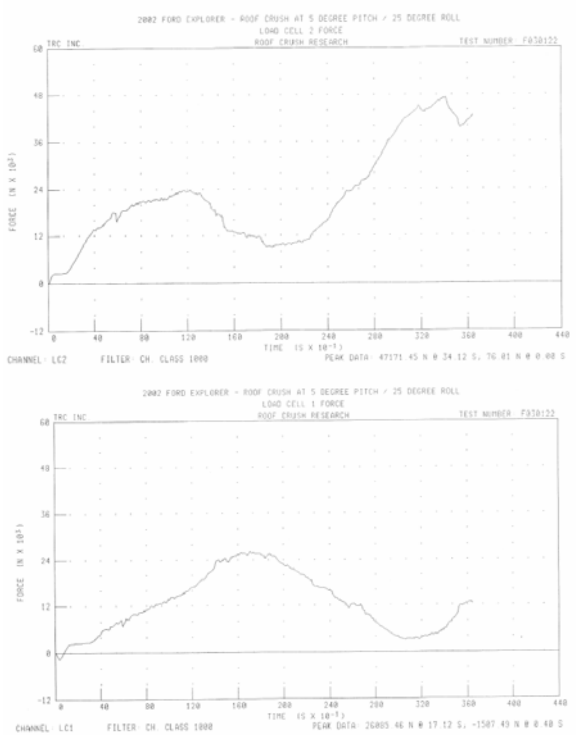

Figure 3. Curves of Force versus time (which is proportional to displacement) for the 2002 Ford Explorer in NHTSA's test at 5º pitch and 25º roll under FMVSS 216 test conditions carried out to 254 mm of displacement. The upper curve is the force at the front of the platen while the lower curve is the force at the rear of the platen.

In each of these NHTSA tests, the roof flattened against the platen rather than collapsing and buckling as is typical of vehicles in dynamic rollovers (See Figure 1). For comparison, we looked at 10 NASS cases involving 2001 and 2002 Explorers with significant rollover roof damage but no complicating factors (four of which are shown in Figure 2). The damage to these roofs was more complex, involving buckling, greater rearward or lateral displacement of the roof panel, and other features. There were three other 2002 Explorer rollovers in NASS, two of which resulted in little or no roof damage, and one of which was catastrophic.

We do not believe that either of NHTSA's tests, and particularly the tests conducted at 10º pitch and 45º roll, represent realistic loading. The 5º pitch and 25º roll platen applies the force at too shallow an angle to represent an initially trailing side roof impact which is the dangerous side for an occupant in a rollover. In the 10º pitch and 45º roll test, the wide platen engaged the A pillar base early in the test.

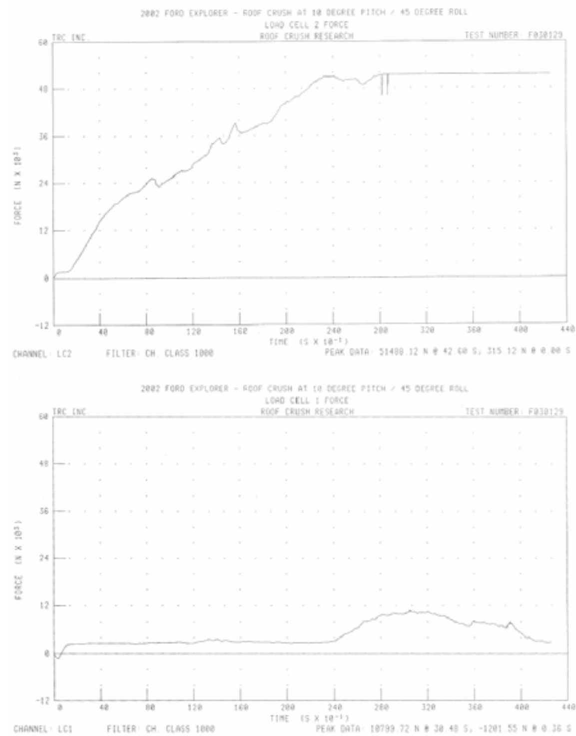

Figure 4. Curves of Force versus time (which is proportional to displacement) for the 2002 Ford Explorer in NHTSA's test at 10º pitch and 45º roll under FMVSS 216 test conditions carried out to 254 mm of displacement. The upper curve is the force at the front of the platen while the lower curve is the force at the rear of the platen.

We completely disagree with the conclusion of the NHTSA test engineer that they produced similar results. The tests conducted at 5º pitch, 25º roll show a substantial loss of roof crush resistance after the failure of the windshield, particularly as measured by the forward ram. This behavior is not observed in the 10º pitch and 45º roll test of the Explorer, for example. In the latter tests, virtually all of the resistance to the platen comes from the forward ram. It appears that much of that resistance comes from the lower body, not the roof. The final damage in the two cases reflects the angle of the platen in the test, and is not representative of damage observed in actual rollover accidents.

It is useful to compare the NHTSA test program with a test program conducted by General Motors twenty years ago [Arums]. In those tests, GM was attempting to determine the impact of various windshield adhesives. The GM tests, conducted at a roll angle of approximately 50º, show the importance of a well-bonded windshield in meeting FMVSS 216 and the importance of the roll angle in determining a roof's strength-to-weight ratio. In these tests, the GM engineers also found that at between 160 and 200 mm of crush, the crusher picked up the lower end of the A-pillar and the crush resistance consequently rose substantially.

We do not necessarily reject the quasi-static test to show minimum roof performance. However, the test must be conceived to ensure that it measures roof crush resistance realistically. Continuing the test to 254 mm (10 inches) of crush provided little new information about the performance of the weak roofs that were tested by NHTSA. A well-designed roof should not be capable of crushing to this extent in a typical flat ground rollover.

CRITERIA FOR A ROOF CRUSH TEST

In his research, Willke measured the headroom in the various vehicles he tested. He used the FMVSS 208 dummy seating criteria, which is highly unrealistic for his purpose in several respects:

- It represents only the 50th percentile male.
- The seat track position at mid-point is far ahead of the position a 50th percentile male would use in actually driving or riding in a vehicle.
- The static seating position does not take account of the degree to which safety belts permit excursion in rollovers. This excursion comes from the basic geometry of the belts, the point in a rollover at which the retractor reel is locked up, the degree to which belting spools from the retractor, and other factors.

We are not convinced that headroom is a useful measure for purposes of a roof crush standard. Furthermore, it is a serious complication of this test and its interpretation that adds little or nothing to its validity. Because roof crush should be minimal under any circumstances where the roof contributes to occupant protection, short of conducting a dynamic test that includes head and neck injury criteria, we suspect that a measure of roof intrusion such as is in the present standard may be sufficient for a quasi-static test of roof intrusion.

AMENDED STANDARD REQUIREMENTS

If the roof crush resistance standard is amended, it must meet the requirements of the National Traffic and Motor Vehicle Safety Act of 1966 (as amended):

- The standard must meet "the need for motor vehicle safety" (rollover casualties are one-third of all motor vehicle occupant fatalities and severe injuries, so the need is clear).
- It must be "practicable" (i.e. it must not seriously compromise vehicle function, it must be possible to design and build production vehicles that comply, and the cost of compliance must be consistent with the benefits that will result. The practicability of countermeasures that would enhance rollover occupant protection – a strong roof, and rollover triggered safety belts and window curtain air bags – has been demonstrated in the Volvo XC90 and other vehicles that have one or more of these features).

- A standard "provides objective criteria" (that is, a compliance test must be repeatable, reproducible, and that it not be unreasonably difficult or costly to determine compliance).
- The standard governs "the performance of motor vehicles" to which it is applied and protects "against unreasonable risk of death or injury to persons in the event that accidents do occur."

AMENDING THE ROOF CRUSH STANDARD

There are four steps that must be completed in a program leading to the development of a new or amended Federal motor vehicle safety standard:

1. Assess how roofs of current vehicles perform in real world crashes. This is investigated by looking at both particular rollovers (to understand roof failure modes and how they occur) and at crash data bases, such as National Accident Sampling System (NASS) cases, to determine how common are roof failure modes that are associated with serious to fatal injury.
2. Determine the consequences of poor roof performance: how does a poorly performing roof injure occupants both by directly striking an occupant's head and by opening ejection portals. This is investigated by looking at the consequences of actual rollovers (also using, for example, NASS cases), particularly on human injury and ejection. We have done the assessment of roof performance and its consequences using the 273 NASS cases that were identified by NHTSA, and the results are reported below. Research and testing are necessary to emulate the actual conditions of rollovers (such as with the Malibu tests, and testing conducted on Jordan Rollover System [JRS], and Controlled Rollover Impact System [CRIS]) to determine actual conditions that produce injury or other critical failures, and what performance improvements can reduce injury potential. There needs to be a similar criterion for neck injury in rollover crashes.

3. Determine the appropriate human head impact and neck tolerance for use as injury criteria in a standard. There is a substantial body of biomechanics research that shows human head and neck tolerance levels or injury criteria under various impact conditions. The Head Injury Criterion (HIC) is generally accepted as a measure of the potential for closed head injury. We have advocated that an axial neck force loading of 7,000 N be adopted as the neck injury criterion for this purpose. A neck shear and a moment tolerance would also be useful.
4. Develop a test or tests that reasonably emulate the critical aspects of roof performance under highly controlled conditions of rollover that currently produce serious to fatal head or neck injury. Identify the salient features of rollovers that can be repeatedly and reproducibly tested on vehicles at reasonable cost. The test must reasonably discriminate between roofs that provide good occupant protection in the field and roofs that inflict or contribute to occupant injury in rollovers.

There are several aspects of the process of developing a compliance standard that are critical. The results of any compliance test must be compared with performance under actual rollover conditions of a vehicle that can pass the test to ensure that passing the test is consistent with good rollover occupant protection performance. Similarly, vehicles that perform poorly under actual rollover conditions (which include virtually all contemporary vehicles) must also fail the compliance test. Another way of looking at this question is that if a proposed test is conducted on a vehicle that has a stronger roof (such as a Volvo XC 90 and a 2003 Subaru Forrester that Willke showed could sustain significantly more than four times its weight in force on its roof to 150 mm (6 inches) of roof crush in a FMVSS 216 test.) and a poor or marginal performer (most other contemporary vehicles) the former should be able to pass the test while the latter should not.

FMVSS 216 has used a quasi-static test for decades. There are serious questions about the degree to which a quasi-static test can fully deal with the question of rollover occupant protection, but there are good theoretical and practical reasons for using such tests for a minimum standard to represent a dynamic phenomenon. However, quasi-static tests have limitations. For that reason, NHTSA abandoned its original quasi-static side impact test in favor of a dynamic test.

We have previously reported on our Jordan Rollover System, a repeatable dynamic rollover test device that has the flexibility and the precision to determine the adequacy of a quasi-static roof strength test. We have found that a roof with a strength-to-weight ratio that is as high as 3.5, when measured according using the FMVSS 216 procedure, is unlikely to ensure reasonable rollover occupant protection performance. We strongly suspect that it would require a strength-to-weight ratio of at least 4.5 to 1 in this test to ensure such protection. As we have said before, a major problem with FMVSS 216, which makes such high strength to weight ratios necessary, is that the test angles are too shallow to emulate realistic rollover conditions, and it tests only one side of the roof.

The experimental evidence demonstrates that the injury mechanism in rollovers is from the speed of intrusion of the roof into an occupant's head that results from structural failure, and is not directly related to residual crush. The intrusion amplitude at the dummy's head (wherever the head is likely to be) must be at least several inches and the maximum intrusion velocity for a neck injury must be more than 14 ft/sec to injure most healthy individuals. For a head injury the velocity must be at least 22 ft/sec. Because modern, lightly loaded vehicles roll with as much as 10 degrees of pitch (as evidenced by front fender contact when inverted) the rapid intrusion begins after the windshield has fractured or separated, when the front, initially trailing side of the roof sustains an increasingly lateral force from its contact with the ground.

Under these conditions, the ground contact region of a weak roof will deform toward the vehicle's center of gravity in either a matchbox motion or with buckling of the roof's structural elements and panel. The structural buckles are the result of bending at their ends, or toward the center as a result of end loading. A structure that is buckling near its mid-point moves transversely at 3 to 4 times the speed of the end that is sustaining the buckling force, and can inflict serious injury to or through an occupant's head that is in its path. Much of the tempered side glazing also fails when structural elements surrounding it buckles, opening avenues for partial or complete ejection.

While a quasi-static test can verify a strong roof's strength, it is unlikely to show the dynamic failure mechanism of a weak roof, particularly if the load is applied in a direction that is not representative of the forces that the roof will encounter in an actual rollover. If a roof's structure were essentially elastic, the correspondence between the quasi-static and dynamic test would be fairly good, but actual roof structures behave in a highly non-linear fashion, with major losses in strength when the windshield fails and when key structural elements buckle. It is this behavior that may not be adequately demonstrated by a test such as FMVSS 216, even if the force criterion were raised substantially.

On the other hand, quasi-static testing at a more realistic angle could provide a better picture of a roof's ability to resist the actual forces of a rollover impact with the ground. Under these conditions, a force as low as 2.5 times the vehicle's weight would be likely to ensure good rollover occupant protection.

We have confirmed that a roof that can sustain a load of 2.5 times the vehicle weight in a two-sided roof crush test at realistic loading angles can sustain loading from a dynamic rollover tests on the Jordan Rollover System without roof intrusion velocities that would inflict head or neck injuries. Our analysis of NHTSA's selected case files confirm, from an occupant protection perspective, what a quasi-static roof strength test must achieve. If the agency does not substitute a dynamic rollover test for FMVSS 216, it must at least confirm the effectiveness of the test procedure and criteria it proposes with a dynamic rollover test that measures the intrusion velocity at the occupants head.

It would be unscientific and unconscionable to promulgate a revised standard without confirming its effectiveness under dynamic conditions using one of the available dynamic test procedures to confirm the tests validity. We have offered our Jordan Rollover System and our other test equipment for this purpose.

ALTERNATIVES TO REGULATION

The imposition of an FMVSS is not the only mechanism for improving motor vehicle safety performance. NHTSA has used the New Car Assessment Program (NCAP) with some success to improve frontal and side crash performance as well as rollover resistance of new vehicles. The advantages of a consumer information program such as NCAP are that they (1) impose no requirements on automakers, (2) impose no lead time for achieving particular performance levels, (3) can specify multiple levels of safety performance rather than just a minimum, and (4) have been reasonably effective in encouraging manufacturers to strive for higher levels of safety performance.

It is unfortunate that manufacturers generally do not compete on safety in the absence of high quality, widely-disseminated consumer information. There are some interesting exceptions, however. Volvo has a somewhat deserved reputation for making safer vehicles. Certain safety equipment, such as electronic stability systems and side curtain air bags, has been voluntarily offered as standard equipment on luxury vehicles and as optional on others. Some equipment, such as side impact air bags and safety belt pretensioners, is not required but can help manufacturers meet some FMVSS.

Concern over product liability or bad publicity has apparently caused some manufacturers to include certain safety features or performance that goes beyond what is required. Manufacturers, fearing bad publicity, formed a committee to write voluntary guidelines for crash compatibility between SUVs and passenger cars. A similar committee on SUV rollover safety was promised, but was never formed.

THE SCIENCE OF ROLLOVER OCCUPANT PROTECTION

A critical factor in the debates over what happens to occupants in rollovers and over whether and how occupants might be protected is the lack of a comprehensive attempt to apply scientific methods to these questions. In fact, there has been little serious debate aimed at resolving these questions within a proper scientific forum.

Much of the research and testing that has been done within the industry, such as the development of and testing conducted with the Controlled Rollover Impact System (CRIS), has been aimed at trying to prove the thesis that a strong roof cannot improve the survivability of rollovers. While the testing conducted by General Motors, generally referred to as the Malibu tests, has given us an important and valuable data source on the subject, it required a massive effort to get the company to release the detailed data and film from these tests. Furthermore, some of the interpretation provided in scientific papers by those who conducted the tests has been misleading and highly controversial at best.

A major exception is the unpublished and (unfortunately) confidential work conducted by Volvo in its development of the XC90 utility vehicle. In essence, Volvo recognized the obvious: if there is no major impact between an occupant's head and the vehicle roof, there can be no head or neck injury. From this principle, Volvo developed a stronger roof structure and restraint system, with rollover triggered pre-tensioners that reduces the severity of, or prevents such contact.

NHTSA has conducted only limited testing and analysis to assess rollover occupant protection. However, some of this work has been inconclusive and its research design has been questionable (see discussion of recent NHTSA testing above). Furthermore, NHTSA has devoted little of its biomechanics resources to developing a well-accepted neck injury criterion. We have attempted to conduct research and testing to resolve these issues, but lack of funding has limited what we can achieve. The only other major institution that might have the resources to enter this debate, the Insurance Institute for Highway Safety, has neglected any significant research or testing in this field.

There have been papers presented in various meetings and journals discussing aspects of the question ranging from the biomechanics of head and neck injury to analyses of rollover crash data. However, even the refereeing of these papers and discussions following such presentations have not ensured that the best science on the subject has gained prominence and general acceptance.

Using the NHTSA [Blincoe] study as a basis, we estimate that the direct economic cost of rollover occupant injuries and fatalities is conservatively well over $20 billion (and the public's willingness to pay for eliminating a majority of rollover casualties approaches $100 billion per year). Thus, the potential for even a modest reduction in such casualties would justify a major investment in research, development and testing. Once we have found reasonable, practicable performance goals, the cost of these losses would further justify a significant expenditure in improving the rollover occupant protection performance of motor vehicles. It is a great tragedy – certainly equivalent to other major public health challenges – that our society has yet to make commitments to proper scientific resolution of these issues, and investments that would halt this unnecessary loss of life and limb.

EVIDENCE IN THE RULEMAKING DOCKET

A major body of test data, research and other information exists that should be used to shape and support an amendment of FMVSS 216. The authors have submitted massive amounts of information and analysis to the docket (NHTSA-1999-5572) to help the agency in this work. Perhaps the most critical information was the following:

- The General Motors Malibu tests from the 1980s. These fully instrumented FMVSS 208 dolly rollover tests compare the performance of production 1983 Chevrolet Malibu sedans with the performance of similar vehicles that have had a strong roll cage installed within them. Tests were conducted both with unrestrained Hybrid III dummies in the front seats and with dummies restrained by three-point belts that have cinching latch plates to limit excursion. The extensive photographic documentation and instrumentation used in these tests provides an excellent source of detailed information on what happens in rollovers, and particularly on the effect of a strong roof on rollover occupant protection.
- Extensive biomechanics research conducted on both cadavers and on Hybrid III dummies that gives good evidence on human neck injury tolerance and what injury criteria should be used for the Hybrid III in testing. We have consolidated the results of these papers [Nusholtz, Nusholtz, Sances] and have determined that a head impact speed of between 7 and 10 mph (which corresponds to a neck load in excess of 7,000 N on a Hybrid III dummy) is the threshold for cervical spine injury to a normal human being.
- Numerous internal research and test documents, primarily from General Motors Corp. and the Ford Motor Co. that show that these companies understood far more about their vehicles' performance under both quasi-static test conditions and actual rollovers than they revealed in their docket comments in FMVSS 216 rulemaking. In particular, there are documents showing that the strength of their roofs in FMVSS 216 tests was highly dependent on windshield integrity and that the strength of their roofs under the more lateral loading that is typical of far side roof impacts was substantially less than under the loading specified in FMVSS 216. Many of these documents have been included in the submissions by the authors to Docket NHTSA-1999-5572.

CONCLUSIONS

Analyses of the NASS crash data can be combined with rollover test data to develop a realistic test for roof crush resistance and to determine what other countermeasures that would produce a substantial reduction in rollover occupant injuries. The specific considerations we found in our analysis of the available data include the following:

- An effective safety belt use reminder, as recommended by the Transportation Research Board of the National Academy of Sciences, Committee for the Safety Belt Technology

Study, should be part of any program of rollover occupant protection. Of course, this would have benefits far beyond protection in rollovers.

- The primary roof damage, and occupant head and neck injury occur on the initially trailing side of the vehicle where the roll angle of the force is greater than 25º. Thus, a test conducted by simply increasing the force criterion in FMVSS 216 will not accurately capture the critical aspect of roof performance under actual rollover conditions. It is important to recognize that the roll angle at which a significant force is applied to the roof continues to increase as a weak roof contacts the ground and the roof collapses. The Malibu tests have shown that strong roof tends to contact the ground for a shorter period of time so that the mean roll angle of the force is lower for a stronger roof.
- A minimum requirement for roof crush resistance must test the roof at a pitch angle of 10º and under conditions of initially trailing side roof impacts. These impacts are at roll angles substantially greater than the 25º roll angle specified in the present FMVSS 216 standard.
- A test conducted by simply increasing the angles in FMVSS 216 without making some provision to ensure that the force is applied primarily to the upper part of the roof will not accurately measure roof crush resistance.
- Some attention must be given to the need for preserving the integrity of side windows (particularly the front side windows) in a rollover. There is strong evidence from the Malibu rollover tests that tempered side glazing breakage can be reduced by a strong roof. More attention in vehicle design to preserving the integrity of side glazing under rollover conditions will reduce both partial and full ejection of occupants in rollovers. This would be particularly important for reducing partial ejection of responsible occupants who are wearing safety belts.
- The excessive roof damage observed on light trucks strongly suggests that their roof geometry – width, flatness, and the distance of the corners of the roof from the vehicles' principal axis of rotation – play a role in determining roof crush resistance even at the same force levels. Thus, a test of roof crush resistance should take this geometry into account in some way. Testing at an angle significantly greater than 25º may help to address this question.
- A quasi-static test of roof crush resistance applied to a strong roof will give similar results regardless of the details of its application. Thus, it is important that the test be designed in such a way that the weaker roofs of most contemporary light vehicles will fail, but strong roofs will crush relatively little – and will not collapse or buckle – under application of realistic forces. In particular, the test should ensure that the windshield cannot be used as a major contributor to roof crush resistance if it will routinely fail in an actual rollover.

It is clear from the cases in the NASS file provided by NHTSA that vehicle roofs are performing very poorly under typical rollover conditions. Some automakers, and particularly General Motors, have argued that head and neck injuries to occupants in rollovers are not related to roof crush. GM Safety Executive Robert C. Lange, for example, recently said, "There is no relationship between roof strength and the likelihood of occupant injury given a rollover." NHTSA has also suggested that ejected occupants would not be helped by having greater roof strength. In the analysis presented in their 2001 notice [NHTSA (2)], the 13,374 "Ejected Seriously Injured Occupants in Light Vehicle Rollover Crashes" were essentially dismissed as if roof crush was not relevant to those injuries.

We strongly disagree with both of these conclusions. The 273 NASS cases make the point that head and neck injury – particularly to restrained occupants – correlate highly with roof crush; and that a majority of such injuries occur on the initially trailing side. Furthermore, both partial and complete ejections strongly correlate with roof crush and the consequent destruction of side glazing. Rollovers involve crash energy management (absorption) rates that are an order of magnitude lower than the rates for survivable frontal and side crashes. (The requirements of FMVSS 208 involve absorption of the kinetic energy of a 30 mph barrier impact, the energy of which is the square of the vehicle speed. FMVSS 214 defines the side impact requirement from a barrier moving at 33.5 mph, but with the energy absorption being somewhat lower because a rigid barrier is not involved. A rollover involves roof impacts at speeds of less than 5 mph.) If occupants can be contained within the vehicle and if the occupant compartment can keep its basic integrity, a good restraint system and roof padding should keep occupants' heads from roof contacts that produce head and neck injuries.

If NHTSA wants to reduce injuries in rollovers, and intends to comply with Federal administrative law, it has ample evidence on which to propose amendments to its standards. Compliance with strong roof crush requirements will substantially reduce serious rollover occupant injuries and will not be particularly costly or difficult to meet. There is little excuse for failing to understand and use the available evidence to propose effective amendments to its standards that will dramatically reduce rollover casualties.

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APPENDIX A

Inter-Organization

Milford Proving Ground
Current Product Engineering
General Motors Corporation

Date: June 27, 1984

Subject: Cab Roof Crush - Rollover Simulation

From: I. Arums, Safety & Crashworthiness Systems

To: ✓J. D. Green, Safety & Crashworthiness Systems
D. Millittelo, Truck & Bus

Engineering judgment, based on viewing of rollover accident damage patterns, indicated first cab contact with the ground to be either the front or rear corner of the cab at the roof to door junction.

A single test simulation of these loadings was developed using the SRDL static crusher against an angled cab with 1' x 3' plywood-faced load cells measuring the cab's reaction forces. Since rotation of the cab onto its roof, as in a rollover, was not feasible, a test endpoint was defined as either door side glass breakage or load cell contact with the door handle.

Seven cabs - held at 38 to 41 degrees - were tested; analysis of the data is attached as Figures 1 through 20. Figures 21 - 27 are photographs showing the general deformation of each cab.

CONCLUSIONS

1. Door side glass does not fracture because of door frame deformation in this test mode. (Test #L18019 applied 200 mm. of crush at top of door frame without side glass fracture.) The tempered glass fractures if contacted by the load cell edge or bolts on load cell.

2. Bonded backlites, as well as bonded windshields, are structurally significant. They interact with the roof so that localized buckling instead of translation occurs.

3. Bonded backlite together with bonded windshield eliminated most of the deformation in the "A" and "B" pillars on the side opposite the load. BONDING of BOTH REDUCED by a FACTOR OF TWO the "MATCHBOXING" of the cab; the translation of the roof as an unbent panel (see Figure 7). BONDING of BOTH INCREASED by a FACTOR OF TWO the LOAD carrying ability of cab (see Figure 10).

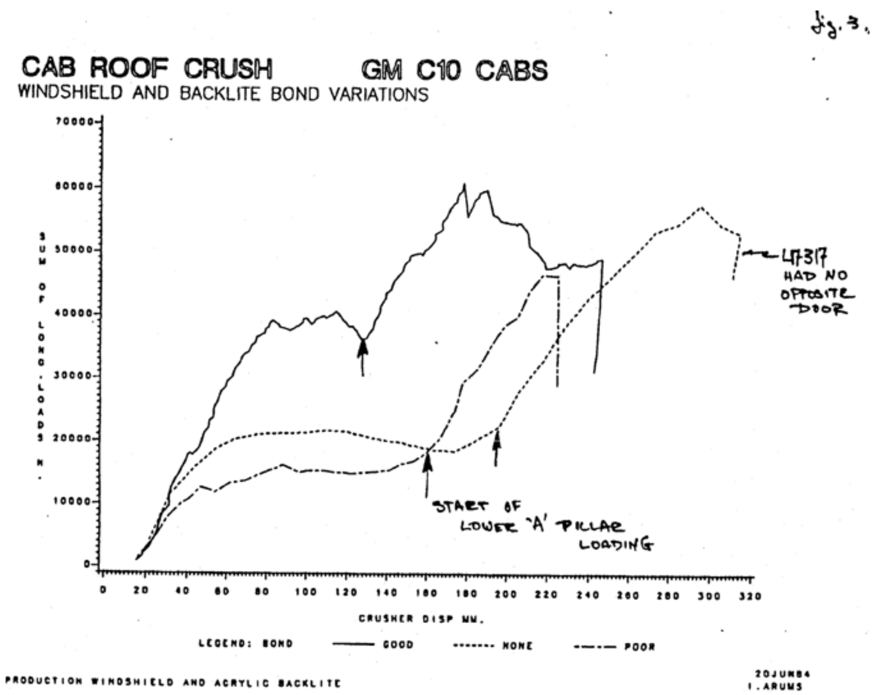

Figure A1. GM Memorandum on the role of windshield glazing in roof crush.