REDUCING ROLLOVER OCCUPANT INJURIES: HOW AND HOW SOON

Donald Friedman and Carl E. Nash, Ph.D.
Center for Injury Research
United States
Paper No. 05-0417

ABSTRACT

Public release of previously confidential Malibu test data and film [1] provides the basis for this review. These are sixteen well-instrumented, definitive 32 mph dolly rollover tests of production Chevrolet Malibu sedans with unbelted Hybrid III dummies and eight with belted dummies (half of the cars in each group had roll cages to simulate strong roofs). This paper analyzes and reinterprets this material to resolve the principal motivating research question: does a strong roof reduce the potential for rollover head and neck injuries? Our findings are: (1) a rolling vehicle's center of gravity rises and falls only about 10 cm during a rollover so that its vertical velocity at roof impact is never more than 2.5 m/sec; (2) the six dummies showing the highest head and neck forces were all seated on the far side of Malibus without roll cages; (3) these high head and neck loads occurred after onset of roof intrusion from rapid roof collapse and buckling, not from occupant diving; (4) average roof impact neck forces measured by near side dummies and by far side dummies seated under roofs that did *not* contact the ground all averaged 3,300 to 3,600 N, and none was sufficient to cause serious injury; (5) the unrestrained Hybrid III dummy drop tests showed that neck loads of 7,000 N correspond to a 2.4 m/sec roof intrusion velocity while 3,500 N neck loads corresponds to a 1.1 m/sec intrusion velocity; (6) the windshields of the production vehicles broke early leaving weakened roof structures that deformed back and forth with subsequent roof impacts; and (7) the tempered side glazing of production Malibus broke far more frequently than in rollcaged vehicles facilitating partial or complete ejection. The Malibu tests provide considerable insight into the potential countermeasures that could reduce rollover injuries.

INTRODUCTION

In May 2004, General Motors finally released extensive data from the 1983-1990 Malibu tests [2,3] previously seen only in litigation. These data provide the most comprehensive information on rollover, dummy dynamics, and head and neck injury potential as a function of roof strength and occupant restraint available at this time. Because we question some aspects of the analyses conducted by the engineers who conducted the tests, we have conducted a detailed re-analyses of the Malibu data.

Two SAE papers, referred to as Malibu I and II, reported on the two test series of dolly rollover tests of 1983 Chevrolet Malibu sedans. Malibu I was conducted in 1983 and reported in papers published in 1985. In these tests, two unbelted Hybrid III dummies were in the driver and right front passenger positions in the Malibu sedans. Four of these vehicles were production models, and four had strong roll cages installed in them that emulated a strong roof, substantially limiting roof crush. Malibu II was conducted in 1987 and reported in 1990. These tests were identical to the Malibu I tests except that they were conducted with lap and shoulder belted dummies where the belts had cinching latch plates.

These are the definitive tests for understanding the role of roof performance in occupant head and neck injury. These dolly rollover tests demonstrate that:

- The most severe neck injuries (i.e. the highest axial, shear, and moment neck loads) occurred to dummies seated on the far (initially trailing) side in roof impacts of production Malibus without roll cages. Taking other evidence of human neck tolerance, only these six exceeded a conservative axial neck load criterion (7,000 N): all were in Malibus with production roofs. These are shown in Figures 1 and 2 where the forces are converted to the head to roof contact velocity by photo-analysis to an accuracy of + or – 10%. The highest HIC, 2,820, occurred from a 20 mph buckling roof intrusion in Malibu I impact 1L3 in a production Malibu (a HIC above 1,000 is considered to be indicative of a high probability of serious head injury).
- The center of gravity of a rolling vehicle does not rise or fall more than a few inches during a rollover. Thus, the vertical velocity of the center of gravity of the vehicle at roof impact is low – virtually never more than 2.5 m/sec (5 mph). This is a survivable impact speed for a human head/neck, particularly if there is padding in the roof as is now required by FMVSS 201. The basis for this claim is the production and roll caged vehicle plots in Malibu I of the motion of the CG in the vertical, horizontal and rotational directions. We have previously shown that the vertical falling velocities of the sequence of near and far side roof

rollover impacts were similar and about 1 mph in production and about 3 mph in roll caged vehicles as shown in Figures 3 and 4 [4].

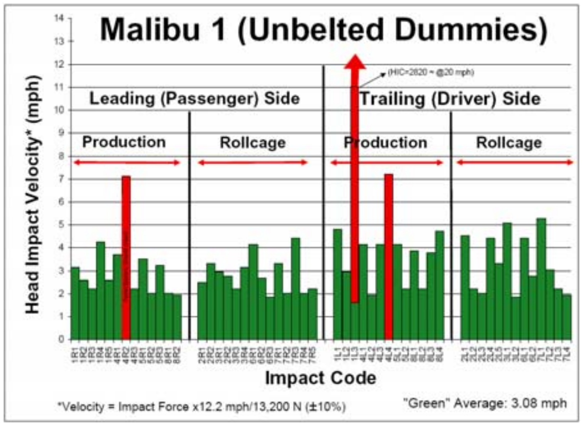


Figure 1. Malibu I neck compression velocities.

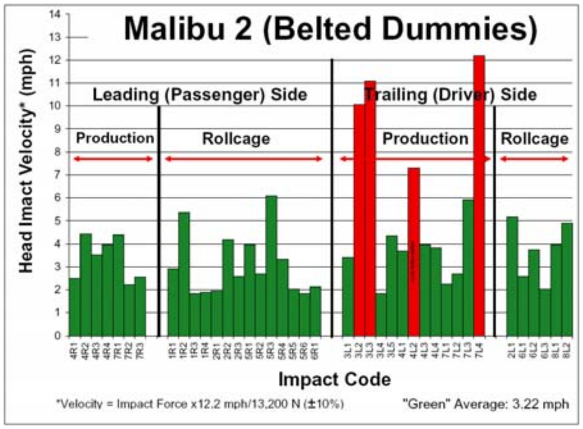
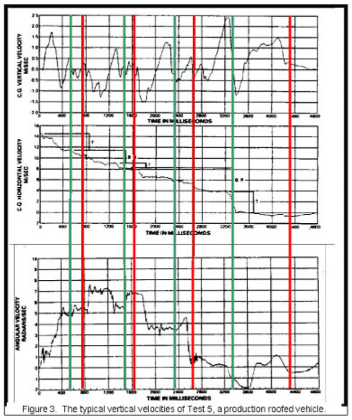


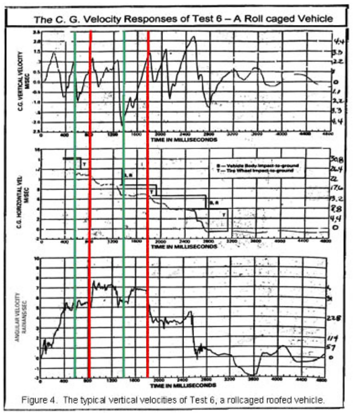
Figure 2. Malibu II neck compression velocities.

- The windshield of the production Malibus broke early in these rollovers and, as shown in film of the vehicle's interior, the roof structure was deformed laterally back and forth several times as alternate sides of the roof struck the ground. This shows that the residual deformation of the roof of a rolled vehicle does not generally represent the maximum intrusion for a vehicle that has rolled more than once, nor does it indicate the maximum intrusion velocity.
- A stronger roof tends to reduce the trailing side loading forces.
- The front door side windows (tempered glass) of the production vehicles virtually all broke out leaving avenues of partial or complete ejection for a number of the unrestrained dummies.
- High head and neck loads are from rapid roof intrusion, not from the occupant diving into the roof.
- The circumstances of a rollover involving roof collapse have been documented by GM and Xprts, LLC photo-analyses and GM electronic instrumentation in the Malibu II test series. Table 1 consists of data from four production vehicles' roof to ground impacts in the Malibu II series where a restrained dummy suffered substantial neck loading.



GM Malibu I
Test 5
(All data from GM Discovery)
Near Side Contacts:
(Green Lines)
550 ms = 0.6 mph
1500 ms = 0.3 mph
2350 ms = 1.2 mph
3350 ms = 1.2 mph
Far Side Contacts:
(Red Lines)
790 ms = 0.6 mph
1677 ms = 0.4 mph
2662 ms = 1.2 mph
4330 ms = 0.7 mph

Figure 3. Contact Velocities in a Production Malibu.



GM Malibu I
Test 6
(All data from GM Discovery)

Near Side Contacts:
(Green Lines)
575 ms = 2.2 mph
1500 ms = 2.5 mph

Far Side Contacts:
(Red Lines)
836 ms = 2.7 mph
1802 ms = 3.1 mph

Figure 4. Contact Velocities in a Rollcaged Malibu.

- The typical vehicle roll angle of impact at the time of high roof rail intrusion velocity and injury measures was about 210 degrees. Another source of high intrusion velocity was roof panel buckling when the vehicle was at about 180 degrees.
- The typical vehicle roll angle of impact on the passenger side of these passenger side leading rolls was about 135 degrees.

- Based on unrestrained Hybrid III dummy drop tests a neck load of 7,000 N corresponds to a 2.4 m/sec (5.4 mph) impact/intrusion velocity while the average 3,867 N neck load of some 94 PIIs correspond to a 1.1 m/sec (2.4 mph) impact intrusion velocity.

In 1975, the lead engineer in these tests, Edward Moffatt, set forth the theory that occupant injury in rollovers was the result of diving into the roof rather than from the consequences of roof collapse or buckling. In this, he was supporting a position that General Motors had taken in the early 1970s when it opposed promulgation of a strong roof crush standard by the Federal government. The authors of the papers on the Malibu tests (who actually conducted the tests) claim that the Malibu tests demonstrated that high neck loads were a consequence of the occupant diving into the roof. However, the newly released test data clearly shows that the peak neck loads occurred significantly after onset of roof intrusion, and typically when the roof intrusion velocity was highest, as shown in Figure 5. Quotes and conclusions from the original paper will be referenced and discussed in view of the newly public information.

A REINTERPRETATION OF MALIBU I

The following quotations, from the Abstract of "Rollover Crash Tests – The Influence of Roof Strength on Injury Mechanics," SAE 851734, October 1985, present General Motors' views on how head and neck injuries are inflicted in rollovers. This paper reports on dolly rollover tests of four production and four roll caged 1983 Chevrolet Malibus. All of the front outboard seated dummies in these tests were unrestrained.

Table 1. Characteristics of an automobile rollover illustrating the conditions during injurious impacts in Malibu II. Time lag is the time between roof touchdown to peak neck load and the speed is the traveling speed at touchdown.

PII	Neck Load (N)	Time Lag (ms)	Speed (mph)	Roll Angle at Neck Load	Vehicle Pitch at Neck Load
3L2	10,900	28	22.1 ±2.2	210°	5°
3L3	12,000	30	20.0 ±2.1	1+ 210°	7°
4L2	7,600	28	21.9 ±3.2	1 +225°	3°
7L4	13,200	5 + 12	6.7 ±.8	3 +190°	10°

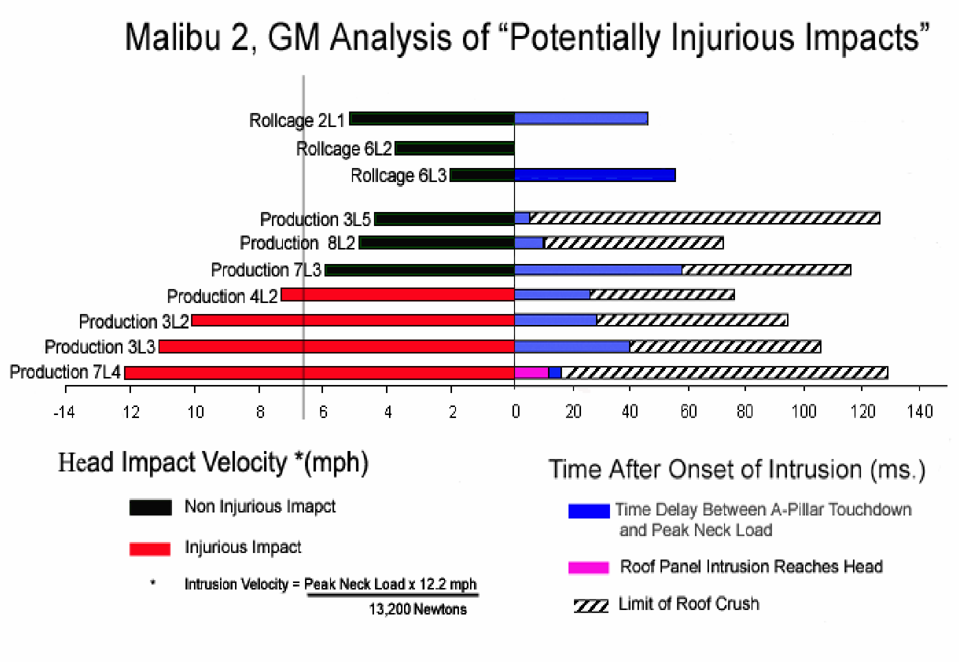


Figure 5. Head impact velocity and timing of GM selected impacts.

> "… High head/neck loads were measured when the head contacted a part of the car experiencing a large change in velocity, often that part of the car which struck the ground." (SAE 851734, p. 181)

> "… The results of this work indicate that roof strength is not an important factor in the mechanics of head/neck injuries in rollover collisions for unrestrained occupants. … There was no reduction in the incidence or severity of head/neck injuries in the roll caged cars compared with the standard roof vehicles. The roll caged vehicles incurred less glass breakage." (SAE 851734, p. 181)

In these tests only two roof impacts resulted in a "large change in velocity" of the far side roof: impacts (1L3 and 4L4). Both were in production roof vehicles. Another head-to-ground impact accompanied by a "large change in velocity" (4L2) was to an ejected occupant (one of eleven partially or completely ejected occupants). None of these, out of a total of 54 measured impacts, occurred in vehicles with roll cages.

The other 51 dummy impacts had head or neck loads averaging less than half of these three and occurred at an average impact velocity of 2.6 mph. The three serious injury measures, in two of four production vehicle rollovers, are more than would be representative of the frequency of serious to fatal injuries in the U.S. vehicle population of the time as indicated by National Accident Sampling System (NASS) data.

Although not mentioned in the paper, GM recorded roof intrusion velocities of approximately 20 mph for 1L3 and approximately 3.1 m/sec (7 mph) for 4L4. The neck load from ground contact for 4R2 was also approximately 3.1 m/sec. As with the other 11 ejections, it was the result of side window breakage (18 out of 20 side and rear windows broke in production Malibus from ground contact while only 5 of 20 broke in roll caged cars).

The appropriate conclusion is that there were two high head/neck loads from a rapid roof intrusion on the trailing side and one high neck load from a near side partial ejection and ground contact in production vehicles while there were *none* in roll caged vehicles. The test engineers recorded a total of 50 other minor head impacts (none of which would have resulted in serious injury). These head impacts included 10 other near side partial ejections; one total ejection and one head impact on the unpadded roll bar). Except for the ejections, these low injury potential impacts were about equally distributed among production and roll caged cars.

Dummy Head Impacts 1L3 and 4L4

In the same Malibu I paper, GM presented an explanation of two particular head impacts with high injury measures.

> "In impacts 4L4 and 1L3 the left dummy head was against the roof panel in an area which struck the ground. …It was not the displacement of the roof relative to the seat but, rather, the increased area of contact between the roof panel and the ground which defined this specific injury mechanism." (SAE 851734, p. 193)

Figures 6 and 7 show a sequence of frames from the photographic documentation of 1L3 and 4L4 that demonstrate that the injury mechanism was, in fact, the roof displacement..

Figure 6 shows Malibu I Impact 1L3 in a sequence of interior views (at 4 ms timing per frame) of the driver dummy during roof intrusion of 12 inches at 20 mph velocity taking place over 32 ms. This roof intrusion produced a HIC of 2,820 to the dummy that is against the roof (from centrifugal force) and driven inward and towards the seat cushion. Notice the checkered seat back reference is stationary so that the path of the head can be followed by the sequence of yellow dots which locate the dummy's chin.

Figure 7 shows the Malibu I Impact 4L4 sequence of interior 4 ms frames of the driver being struck by a traveling buckle in the roof panel moving from the passenger side towards the driver side. The loading occurs in frame 6 when the neck is seen compressed and the dummy is subsequently driven towards the seat.

Shown below in Figures 8 and 9 are the vehicles at rest showing the extent of lateral roof crush to the vehicles in these tests.

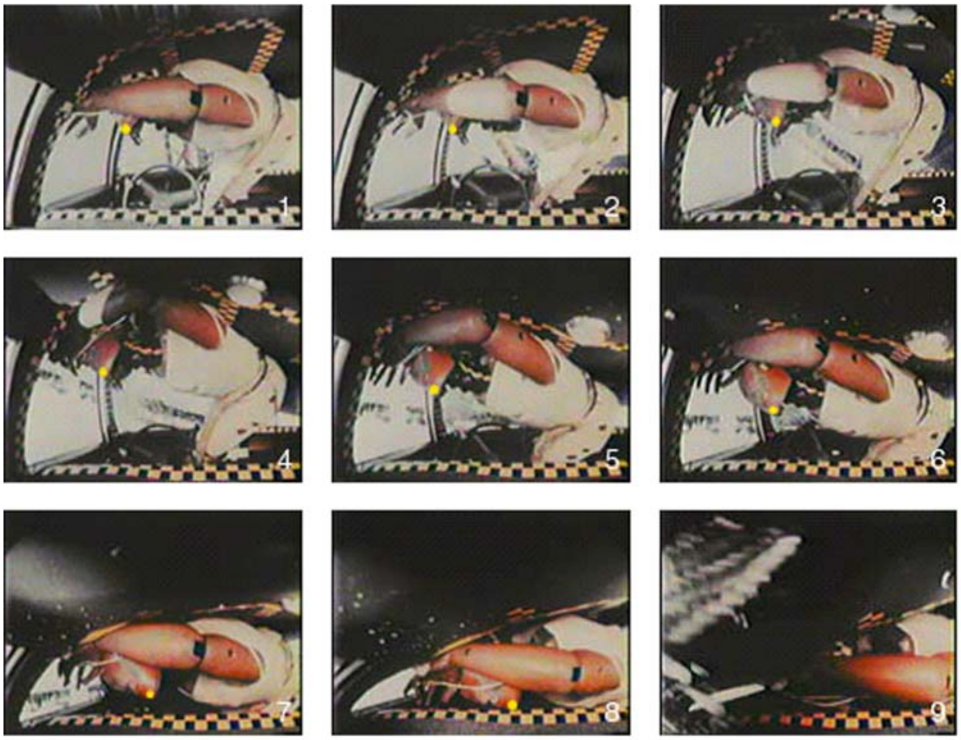


Figure 6. A sequence of frames from Malibu I, Impact 1L3.

Figure 7. A sequence of frames from Malibu I Impact 4L4.

A REINTERPRETATION OF MALIBU II

The following quotations present General Motors' views on various aspects of occupant injury in rollovers. They are from "Rollover and Drop Tests-The Influence of Roof Strength on Injury Mechanics using Belted Dummies," SAE 902314, November 1990. This paper reports on dolly rollover tests conducted with four production and four rollcaged 1983 Chevrolet Malibus. All of the front outboard seated dummies in these tests were restrained by lap/shoulder belts that had cinching latch plates.

Neck Loads and the Neck Injury Criterion

The engineers who conducted the Malibu tests stated:

> "In order to compare the injury mechanics in the roll caged vehicles with those of the standard roof vehicles, it was necessary to make a judgment as to which were the significant impacts to the head and neck." … *The performance of the two types of vehicles were studied by comparing the number of* "potentially injurious impacts" *measured by the dummies*. (SAE 902314, p. 191, emphasis added)

GM states that the conclusions about injury should be based on injury potential, but theirs are not. Rather, GM elected to use an unrealistically low neck injury criterion of 2000 N. Such an impact would be produced by striking the head at only 2 mph (a very slow walking speed) which they said would produce "Potentially Injurious Impacts."

Figure 8. Malibu I Test 1 vehicle at rest with residual driver side intrusion.

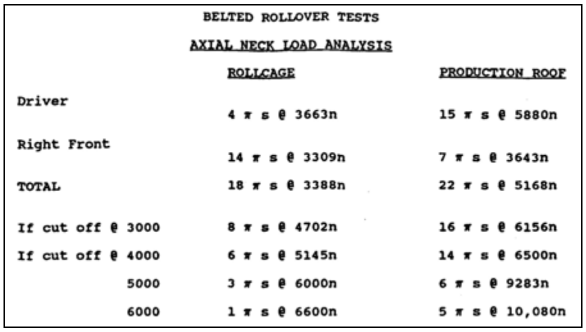
The Advantage of a Strong Roof

The GM engineers concluded:

> "The roll caged vehicles did not have any increased level of protection over the standard roof vehicles in these tests. The number of potentially injurious impacts for the roll caged vehicles was 28 compared to 26 for the standard roof vehicles. The average neck load measured in the roll caged vehicles was 3318 N compared with 3688 N in standard roof vehicles." (SAE 902314, p. 194)

Figure 9. Malibu I Test 4 vehicle at rest with residual front seat intrusion and tenting.

The following chart, Figure 10, of Malibu II shows that even using their reasoning, as the potentially injurious neck injury level is raised to 6,000 N the number of injuries was substantially lower in roll caged vehicles. This chart was generated by GM, but was not included in the paper.



BELTED ROLLOVER TESTS

AXIAL NECK LOAD ANALYSIS

	ROLLCAGE	PRODUCTION ROOF
Driver	4 π s @ 3663n	15 π s @ 5880n
Right Front	14 π s @ 3309n	7 π s @ 3643n
TOTAL	18 π s @ 3388n	22 π s @ 5168n
If cut off @ 3000	8 π s @ 4702n	16 π s @ 6156n
If cut off @ 4000	6 π s @ 5145n	14 π s @ 6500n
5000	3 π s @ 6000n	6 π s @ 9283n
6000	1 π s @ 6600n	5 π s @ 10,080n

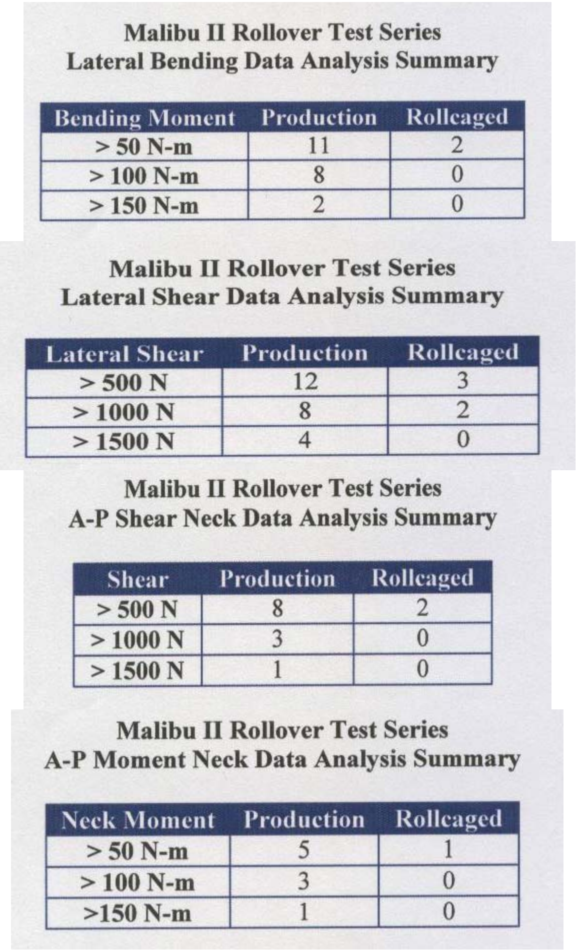
Figure 10. GM's analysis of axial neck loads from the Malibu II test series.

The potential for injury comes not only from axial compression. When considering the trailing side occupant (the driver in the Malibu tests), the tables of Figure 11, show the substantially higher risk of injury from lateral bending moments, lateral shear forces, A-P Shear forces and A-P Moments in production as compared to rollcaged vehicles.

Kinematics of Rollovers

The GM engineers correctly observed that the passenger side of the roof contacted the ground first, followed by the driver side. They also observed:

> "The difference in leading rail deformation between production and roll caged roofs resulted in the roll caged car rolling higher above the ground." (SAE 902314, p. 105)



Malibu II Rollover Test Series
Lateral Bending Data Analysis Summary

Bending Moment	Production	Rollcaged
> 50 N-m	11	2
> 100 N-m	8	0
> 150 N-m	2	0

Malibu II Rollover Test Series
Lateral Shear Data Analysis Summary

Lateral Shear	Production	Rollcaged
> 500 N	12	3
> 1000 N	8	2
> 1500 N	4	0

Malibu II Rollover Test Series
A-P Shear Neck Data Analysis Summary

Shear	Production	Rollcaged
> 500 N	8	2
> 1000 N	3	0
> 1500 N	1	0

Malibu II Rollover Test Series
A-P Moment Neck Data Analysis Summary

Neck Moment	Production	Rollcaged
> 50 N-m	5	1
> 100 N-m	3	0
>150 N-m	1	0

Figure 11. The numbers of impacts in which neck shear and bending moments exceed various limits in the Malibu II tests. (Reproduced from GM documents from the Malibu tests.)

> "As its trailing rail approached the ground, this change in elevation, combined with the vehicle geometry, usually resulted in the trailing rail lightly striking or missing the ground in the roll caged car, whereas, for the production car, it usually struck the ground with greater severity. This slight change in elevation on the inverted vehicle resulted in a substantial increase in the velocity and duration of the roof to ground impact of the trailing roof rail of the production vehicle as compared to the roll caged vehicle." (SAE 902314, p. 105)

> "In these tests, slight differences in the vehicle height above the ground resulted in major differences in the frequency and severity of the trailing roof rail impacts." (SAE 902314, p. 105)

> "This higher frequency and severity of neck loads to the driver dummy in production vehicles was the result of the increased number and severity of trailing rail-to-ground impacts as explained previously in the vehicle kinematics section." (SAE 902314, p. 106)

We found it interesting that a secondary advantage of a strong roof – and one that perhaps should be considered when determining the benefits of strong roofs – is that it reduces the severity of ground impacts. However, a more important advantage of a stronger roof is that it reduces the frequency and severity of the trailing side roof impact loading, intrusion, intrusion velocity and therefore injury potential. In the FMVSS 216 test of the production Malibu, the average strength-to-weight ratio (SWR) of the trailing side as measured by our survey tool, was only 0.6:1 [5]. The roll caged Malibu had a SWR in excess of 7:1 in the FMVSS 216 test.

Figure 12 is a sequence of frames of the Malibu II Test 3 video showing the trailing side structure and driver dummy's head and shoulders. It has been annotated with the sequential location of the intersection of the roof rail and B-pillar. The numbers 1, 3, 5, 7 and 8 show the roof after near side impacts while 2, 4, 6, and 9 show the roof after far side impacts. In this 3½ roll event, the trailing B-pillar rebounds elastically as well as from restoring forces from near side impacts. At position 8, just before the vehicle came to rest on its roof, the roof has virtually been restored to its original position. This behavior shows that residual roof crush, as used in statistical studies (without a detailed investigation of individual cases), can be misleading.

Comparisons between Production and Roll caged Roof Performance

The GM Engineers selected Malibu II impacts 3L5 (production) and 2L1 (rollcaged) for comparison. Specifically, they said:

> "To analyze the effect of roof strength on neck loading, comparable driver dummy impacts were identified. The last one-half roll of test 2 (roll

> caged) and test 3 (production) showed very similar roof-to-ground impacts, with the production car having significant roof crush. In the roll caged car which had no roof deformation, the driver dummy had an axial neck load of 5600 N. In the production roof vehicle, which had approximately 280 mm of roof crush, the driver dummy had an axial neck load of 4,700 N. In both instances the dummies were in very similar positions, the roof-to-ground impacts were of similar severity, with the ground impact velocities of 6.2 mph for the roll caged car and 6.8 mph for the production car. The neck loads were also similar despite the roof crush. Photo analysis of this impact reveals that the neck load measured by the dummy occurred when the roof hit the ground and the dummy head was on the inside of the roof panel." (p. 106)

> "The roof crush which is seen in the films is actually the vehicle body moving closer to the roof, which occurred after the peak force on the neck; consequently, this deformation had no effect on the severity of the head-to-roof impact. Figure 12 from Malibu paper (here shown as Figure 13) illustrates that the dummy neck loads occurred prior to vehicle roof crush." (SAE 902314, p. 106)

> "The PII's with relatively higher neck loads in the production roof tests were studied using film analysis in conjunction with instrumentation data to determine when the loading was experienced by the dummy. This analysis confirmed that the peak load occurred at the roof to ground impact prior to the roof deformation." (SAE 902314, p. 106)

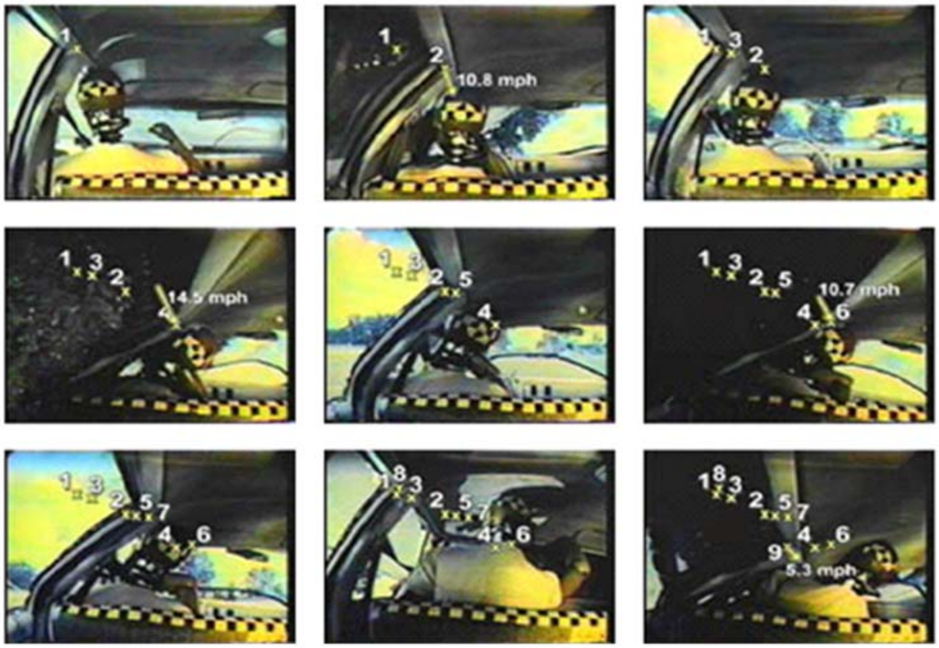


Figure 12. Malibu II Test 3 sequence of the intrusion position of the trailing side roof.

The pair 3L5 and 2L1 are not the only ones that can reasonably be compared. But GM's photo analysis of the potentially injurious impacts (the first page of which is shown in Figure 14) and the summary charts of all analyzed impacts, Figure 15, show that the roof crush that produced the neck load occurred after a significant delay from the adjacent A-pillar ground contact: on average about 27 ms. after the roof began to crush.

To analyze the effect of roof strength on neck loading, many comparable driver dummy impacts were identified in addition to 3L5 v 2L1. Of the 10 analyzed by GM (See Figures 5 and 14) they include 3L3 v 6L1 and 7L4 v 2L1. GM deliberately chose a pair that had the same low neck load to suggest that there is no added protection from a strong roof vehicle.

The second roll of test 3 (3L3) and test 6 (6L1) showed very similar roof-to-ground impacts, but the production car suffered substantial roof crush from that roof impact. In the roll caged vehicle, which had no roof deformation, the driver dummy had an axial neck load of 2,800 N. In the production roof vehicle, which had 225 mm of roof crush, the driver dummy had an axial neck load of 12,000 N. In both instances the dummies were in very similar positions, the roof-to-ground impacts were of similar severity. The neck loads however were vastly different because of the difference in roof intrusion velocity which was 6.3 m/sec (14 mph as determined from the initial slope of the roof crush versus time graph) for test 3 but only 2.2 m/sec for test 2; and roof crush which was 23 cm (9 inches) for test 3 but less than 3 cm for test 6 (see Figure 16, 17, and 18).

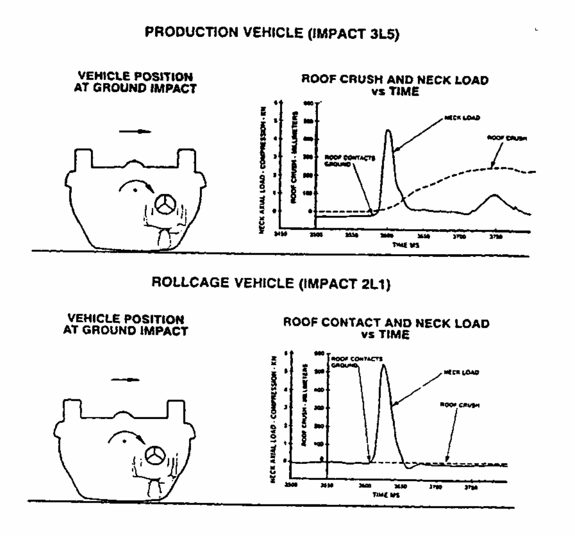
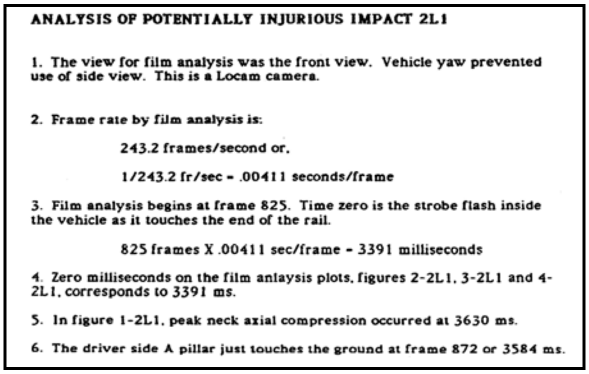


Figure 13. (Figure 12 in the Malibu II paper.) Roof Crush and Neck Loads versus Time from a GM Comparison between 3L5 (production) and 2L1 (roll caged).

Photo analysis of these impacts reveals that the production vehicle neck load measured by the dummy occurred approximately 26 ms after the roof hit the ground and the dummy head was on the inside of the roof panel. The first four inches of high speed roof crush intrusion, which is seen in the films, occurs before the peak force on the neck. The maximum (or residual) deformation had no effect on the severity of the head-to-roof impact. Figure 16 illustrates that the high dummy neck loads occurred after the initial four inches of high speed intrusion but before the maximum roof crush.

The last roll of test 7 (7L4) and test 2 (2L1) showed very similar roof-to-ground impacts, with the production car having substantial roof crush. In the roll caged vehicle, which had no roof deformation, the driver dummy had an axial neck load of 5,000 N (which would not produce serious injury). In the production roof vehicle, which had 225 mm (9 inches) of roof crush, the driver dummy had an axial neck load of 13,200 N. In both instances the dummies were in very similar positions, the roof-to-ground impacts were of similar severity. The neck loads however were vastly different because of the difference in roof intrusion velocity which was 6.3 m/sec (from the buckle moving from right to left) for test 7, and 1.4 m/sec for test 2; and roof crush which was 23 cm for test 7, and 3 cm for test 2.


ANALYSIS OF POTENTIALLY INJURIOUS IMPACT 2L1

1. The view for film analysis was the front view. Vehicle yaw prevented use of side view. This is a Locam camera.

2. Frame rate by film analysis is:

   243.2 frames/second or,

   1/243.2 fr/sec - .00411 seconds/frame

3. Film analysis begins at frame 825. Time zero is the strobe flash inside the vehicle as it touches the end of the rail.

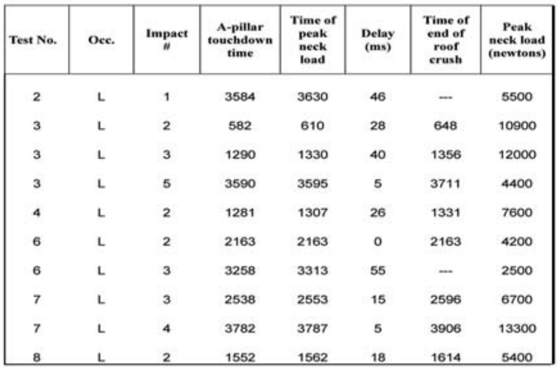
   825 frames X .00411 sec/frame - 3391 milliseconds

4. Zero milliseconds on the film anlaysis plots, figures 2-2L1, 3-2L1 and 4-2L1, corresponds to 3391 ms.

5. In figure 1-2L1, peak neck axial compression occurred at 3630 ms.

6. The driver side A pillar just touches the ground at frame 872 or 3584 ms.

Figure 14. The first page of the 2L1 set of the 10 sets of photo analysis.



Test No.	Occ.	Impact #	A-pillar touchdown time	Time of peak neck load	Delay (ms)	Time of end of roof crush	Peak neck load (newtons)
2	L	1	3584	3630	46	---	5500
3	L	2	582	610	28	648	10900
3	L	3	1290	1330	40	1356	12000
3	L	5	3590	3595	5	3711	4400
4	L	2	1281	1307	26	1331	7600
6	L	2	2163	2163	0	2163	4200
6	L	3	3258	3313	55	---	2500
7	L	3	2538	2553	15	2596	6700
7	L	4	3782	3787	5	3906	13300
8	L	2	1552	1562	18	1614	5400

Figure 15. The summary chart of the 10 photo analysis showing that there is a significant delay between the beginning of crush (A-pillar touchdown) and peak neck load.

Photo analysis of these impacts reveals that the production vehicle neck load measured by the dummy occurred approximately 200 ms after the near side roof hit the ground and a roof panel buckling wave (what GM called a contact patch in Malibu I, but did not mention in Malibu II) struck the dummy's head which was pressed against the inside of the roof panel. The first four inches of high speed roof crush intrusion, which is seen in the films, occurs before the peak force on the neck; although the maximum (or residual) deformation had no effect on the severity of the head-to-roof impact. Figures 19, 20 and 21 illustrate that the high dummy neck loads occurred after the initial four inches of high speed intrusion but before the maximum roof crush.

In the case of impact 7L4, the GM engineers opined:

> "Figure 13. [Impact 7L4, shown as figure 22 here] … First the load on the dummy neck is the result of the dummy head stopping against the roof when the roof is against the ground. When the dummy head stops, the dummy torso continues to move toward the head, causing high axial forces in the neck. The neck measurements indicate that the peak of the force pulse occurred approximately 10 ms after the adjacent roof panel struck the ground, which was before any significant roof crush occurred." (SAE 902314, p. 106)

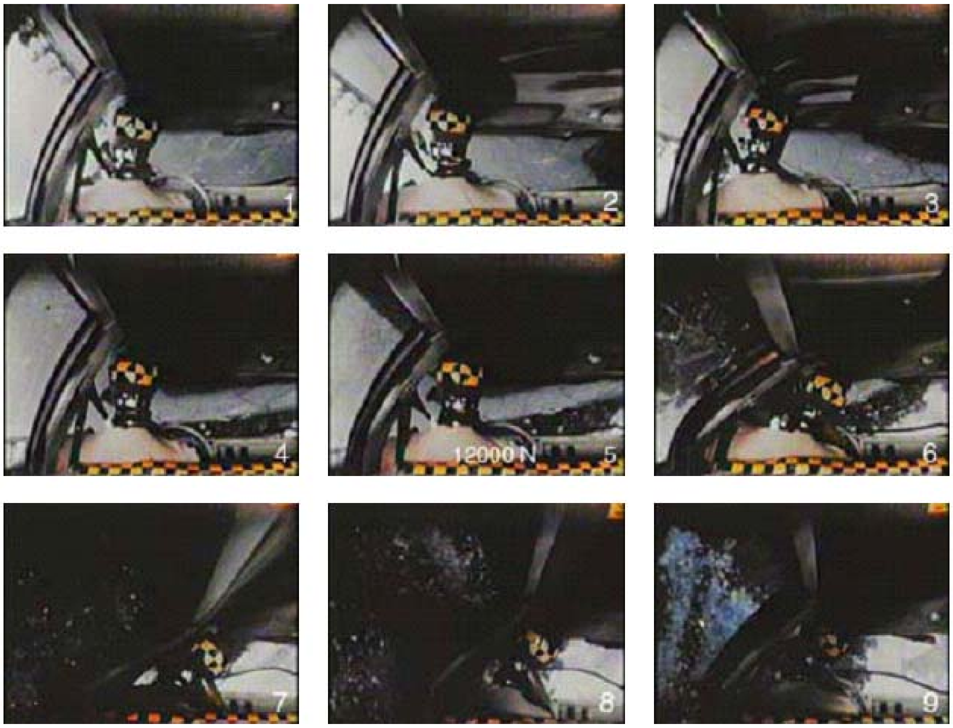


Figure 16. A sequence of frames from Malibu II Impact 3L3.

Impact	3L3	6L1
Roll Angle	217°	225°
B-Pillar Displacement	16.7 in	0 in
Peak Neck Load	12,000 N	2,800 N
Vehicle Rotation Rate	407°/sec	500°/sec
B-Pillar Velocity	10.7 mph	0 mph

Figure 17. Comparison of Malibu II Impacts 3L3 (Production) and 6L1 (Roll caged).

We have redrawn their Figure 13 from the Malibu II paper as Figure 23 here to reflect detailed measurements of right and left B-pillar acceleration, the interior intrusion and intrusion velocity. With the original film there is sufficient resolution to track the motion of the roof directly above the dummy's head.

The load on the dummy neck is the result of the dummy head being contacted by the deformation of the roof panel from the near side ground contact and intrusion. That contact also forms a traveling buckle in the roof panel starting on the near side and traveling across the vehicle roof to merge with the trailing side contact and intrusion. The traveling buckle has an amplitude of about 4 inches and is off the ground and intrudes on the dummy head at 12 mph, causing the peak neck load over about 12 ms.

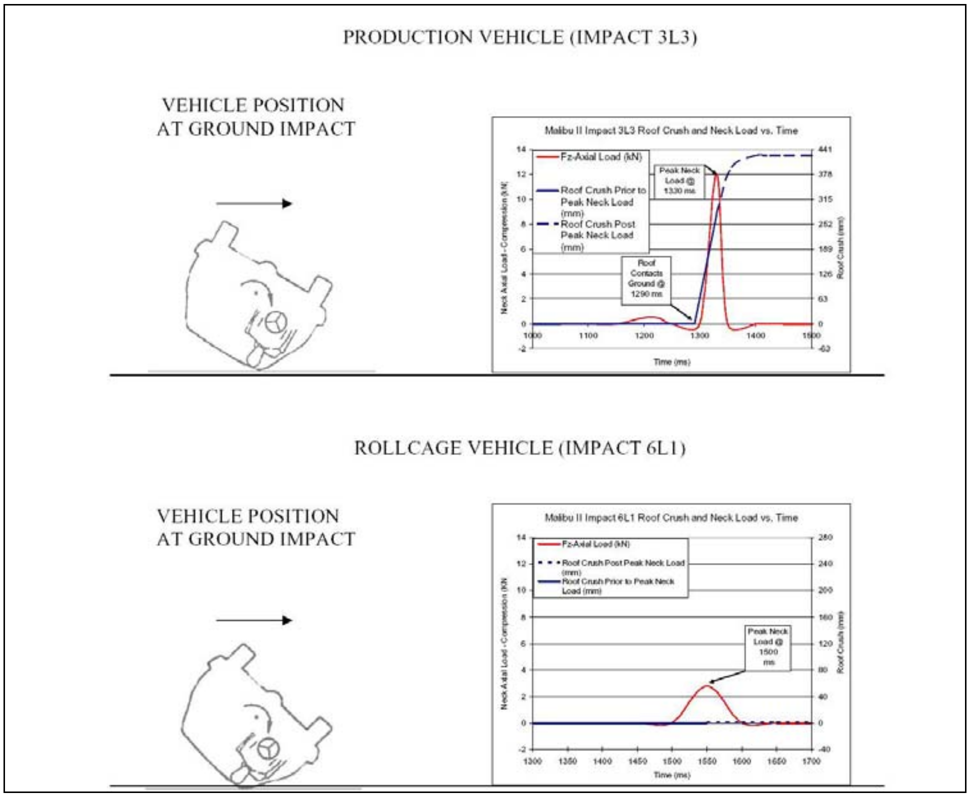


Figure 18. Roof Crush and Neck Loads v. Time for Impacts 3L3 (prod.) and 6L1 (roll caged).

Right A-Pillar Touch Down 3641ms
Start of Buckle 3720ms
Buckle Moving Towards Driver 3757 ms
Left A-Pillar Touch Down 3768ms
Peak Neck Load 3787ms
3794ms
3835ms
3918ms
End of Event

Figure 19. Nine frames from impact 7L4 with timing referenced.

Impact	**7L4**	**2L1**
Roll Angles	176°	184°
B-Pillar Displacement	9.8 in	0 in
Peak Neck Load	13,200 N	5,600 N
Vehicle Rotation Rate	172°/sec	184°/sec
Vehicle Horizontal Velocity	6.7 mph	6.5 mph

Figure 20. Comparison of Malibu II Impacts 7L4 (Production) and 2L1 (Roll caged).

The GM engineers did not consider the pitched roof A-pillar being in contact with the ground and, as a consequence of the lateral compression of the roof panel, forming a traveling buckle that intrudes rapidly into the compartment. The continuation of the trailing side roof intrusion then drives the dummy toward the seat, after the neck injury. The traveling buckle is very much like the panel motion in Malibu I 4L4, that the GM authors called a “contact patch” as we explained earlier. Figure 24 depicts the sequence of sample frames shown in Figure 22, starting at the near side contact, then the three frames during which the buckle compresses the neck at an intrusion speed of 12.2 mph and the merging of the buckle with the far side roof crush driving the dummy towards the seat.

Drop Test Results – Vehicle Kinematics

As an additional part of the Malibu test series, the engineers dropped vehicles onto their roofs with standing pelvis (pedestrian) dummies restrained in them. They concluded, “The roll caged vehicles had no perceptible crush on impact.” (SAE 902314, p. 109) They added, “Overall, in these drop tests, roof crush did not appear to adversely affect the neck loads to the unbelted or belted dummies which were seated in the area of impact.

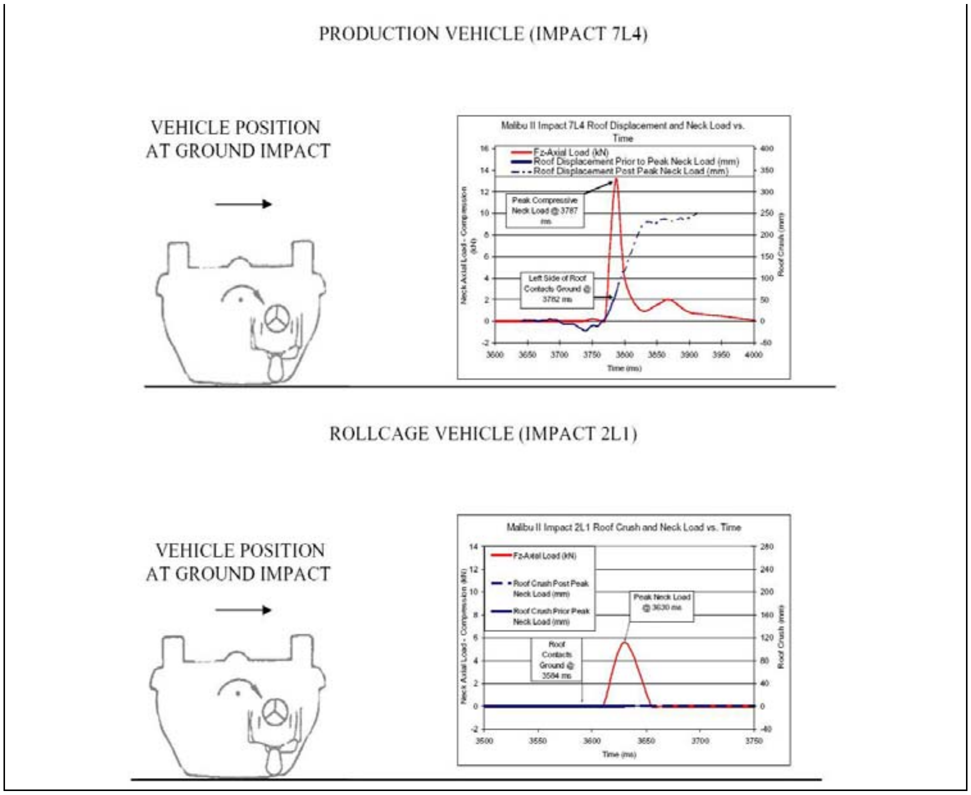


Figure 21. Roof Crush and Neck Loads v. Time for Impacts 7L4 (prod.) and 2L1 (roll caged). The roof displacement in 7L4 is measured over the driver dummy’s head.

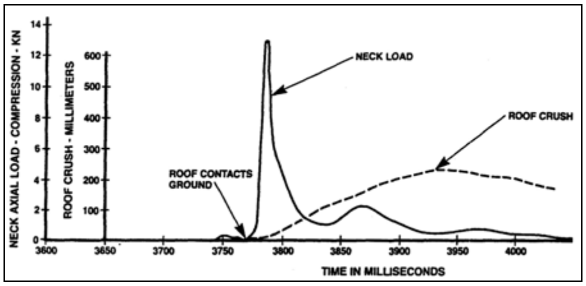


Figure 22. Figure 13 of the Malibu II paper.

Figure 25 from the roll caged drop test demonstrates that at touchdown, indicated by the flash, the roll caged vehicle drops two inches (as shown by the arrow) while deforming the crown of the roof at the dummy head contact point prior to the roll caged structure engaging the ground. As a result the production and roll caged vehicles performed identically (with the same dummy).

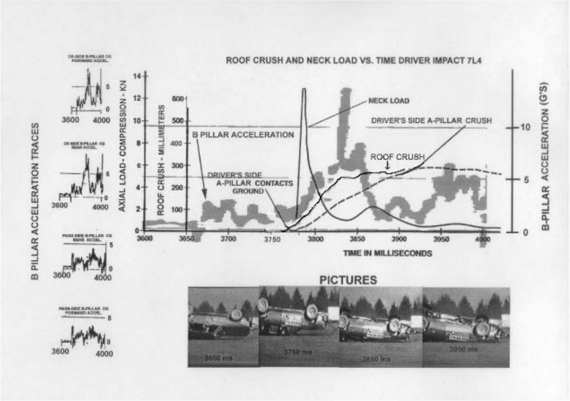


Figure 23. 7L4 redrawn to reflect the correct timing perspective and the timing of the B-pillar accelerometer traces.

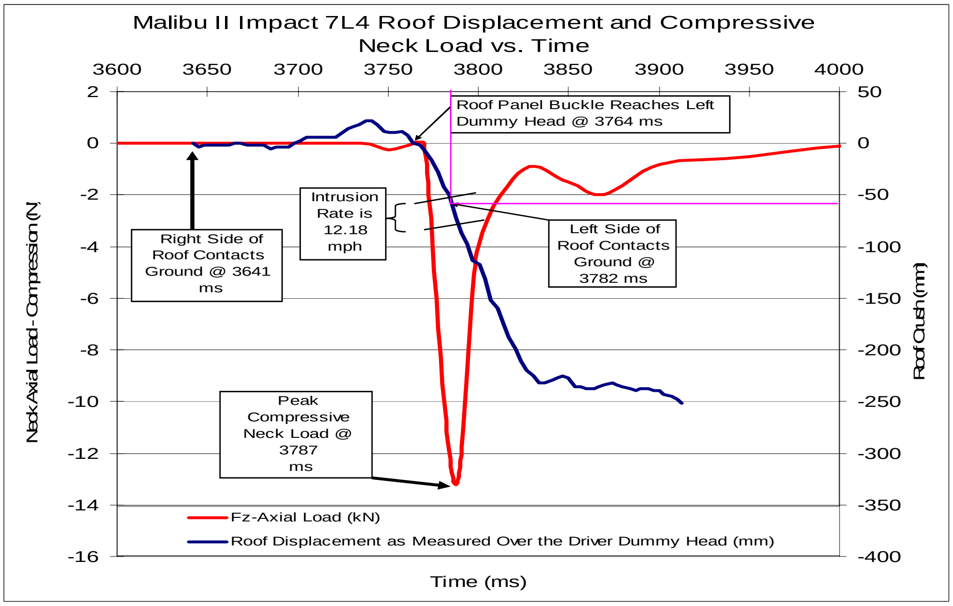


Figure 24. The motion of the roof above the driver dummy's head relative to a reference line.

Although not stated in the paper, the dummies used in these tests were standing, not seated pelvis dummies (with the probable exception of the belted driver in the production vehicle drop test). A subsequent test conducted by one of the authors with the same vehicle, with a production belted human and a seated pelvis dummy in a rigid roll caged vehicle showed a major difference in neck loading, Figures 26 and 27.

The Mechanism of Neck Injury

The Malibu II data show clearly that:

- During a rollover, the vehicle drop height is insufficient to cause a neck injury. The impact speed of the head with the vehicle roof when the roof does not collapse is less than a normal human walking speed.
- The mechanism of neck injury in rollovers is roof crush where the low falling speed of the occupant is substantially exacerbated by the rapid intrusion

of the collapsing roof to produce excessive neck loads.

- The results of Figure 10 show that even using their methodology, as the potentially injurious neck injury level is raised to 6,000 N, the number of potentially injurious impacts would be substantially lower in roll caged vehicles. In fact, if the cut off were raised to 7,000 N, a value that is shown by Hybrid III biomechanics research to be a threshold for dummy neck injury, there would have been no potentially injurious impacts in the roll caged vehicles.

Figure 25. Sequence of photos from roll caged Malibu drop test.

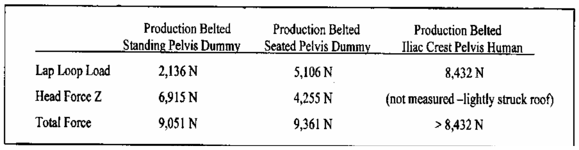
Despite this evidence, the engineers who conducted these tests insisted that:

> "Neck loads resulted from "diving" type impacts where the head stops and the torso momentum compresses the neck, with the magnitude proportional to the impact velocity" (SAE 902314, p. 111)

In both of the GM Malibu papers, the authors present a theory that the occupants have high neck loads because they are diving into the ground as the vehicle rolls. In their view, the injury occurs when the roof comes into contact with the ground and the occupant's head, which is in close proximity to the roof, also strikes the ground through the roof. As a consequence, the vertical motion of the occupant's head is stopped. The claim is that at that point the occupant's body is still moving downward and imposes an injurious force on the neck because the neck is compressed between the head and the body. This is similar to what happens to a person who dives into a shallow pool.

* Property of Friedman Research Corporation

Figure 26. One of the authors (Friedman) and a Dummy in a 5.4 mph Malibu Drop Test in which roof crush was precluded.



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

Figure 27. A comparison of data from Seated vs. Standing Dummies and a human subject.

GM's theory may at first glance seem reasonable, but at the time a strong roof strikes the ground, the motion of the occupant's head (and body) is mostly horizontal. Thus, the speed with which the occupant's head strikes the ground (through the roof) is about the same as the falling velocity of the CG (3 mph) and is insufficient to cause a diving type injury.

The Malibu Figures of 16 and 19, above, taken from the package shelf behind the rear seat offer no perspective of the fore and aft position of the dummy head. In reality the dummy neck is stiff compared to a human and gives the impression that the head does not bend. In rolling, with a Malibu cinching latch plate belt a human person typically does not 'dive' into the roof (provided the rate of roll is sufficient) but is certainly not tightly in the seat at all times.

View of the wonder wheel

Side 0 degrees

Side view 45 degrees

Side view 90 degrees

Side view 135 degrees

Side view 180 degrees

Side view 225 degrees

Side view 270 degrees

Side view 315 degrees

Side view 360 degrees

Figure 28. A human volunteer wearing a seat belt in the "Wonder Wheel"[6] that is rolling through 360 degrees. The occupant of this rotating fixture does not experience diving into the roof because his motion is essentially circular so that when the occupant's head is nearest to the ground, it is traveling parallel to the ground.

We have illustrated this point with the "Wonder Wheel," a device that simulates the motion of a rolling vehicle cab but with no roof crush or intrusion velocity. A human volunteer test subject is shown in Figure 28. His head moves to about the middle of the roof rail (even without vehicle pitch) and rises and falls about 4 inches (in relation to the vehicle interior) during the rollover sequence.

CONCLUSION

The Malibu tests were well-designed and conducted, and provided a wealth of excellent data and film that has provided considerable insight into the mechanisms of occupant injury in rollovers. Furthermore, these tests show the value of a strong roof as a countermeasure to prevent severe head and neck injuries in rollovers.

It is unfortunate that the engineers who conducted these tests misinterpreted the results and that General Motors refused for two decades to release the raw data so that other scientists could review the validity of their interpretation. The consequences were that proper peer review of this work was impossible, and that the misinterpreted results were used to delay the provision of adequate rollover protection in new vehicles.

It is critical that other scientists conduct further review of this data to ensure that all scientists and engineers in the auto safety community understand and derive a consensus on the importance of strong roofs for rollover occupant protection.

REFERENCES

[1] NHTSA Docket 1999-5572, (dms.dot.gov).

[2] Bahling, G.S., Bundorf, R.T., Kaspzyk, G.S., Moffatt, E.A., Orlowski, K.F., and Stocke, J.E. "Rollover and Drop Tests – The Influence of Roof Strength on Injury Mechanics Using Belted Dummies." SAE 902314, 1990. A more complete set of documents and films from this research has been placed in Docket NHTSA-1999-5572.

[3] Orlowski, K.F., Bundorf, R.T., and Moffatt, E. A. "Rollover Crash Tests – The Influence of Roof Strength on Injury Mechanics." SAE 851734, 1985

[4] NHTSA Docket 1999-5572 (dms.dot.gov) CFIR Comment 10, April 2003.

[5] Friedman, D. and Nash, C. E., 2003, "Measuring Rollover Roof Strength for Occupant Protection," IJCrash 2003, Vol. 8, No. 1, pp 97 – 105.

[6] Bish, J., Honikman, T., Sigel, J., Nash, C.E., and Friedman, D., "Human Response to Dynamic Rollover Conditions," ASME IMECE 2003.