

Dynamic JRS Rollover Occupant Protection Tests Of Five Contemporary Sedans using Hybrid III Dummies

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We conducted Jordan Rollover System tests of five contemporary sedans. The tested vehicles were selected from a list of cars that the National Highway Traffic Safety Administration (NHTSA) had tested using its static test as part of its rulemaking to amend Federal motor vehicle safety standard 216. The vehicles had FMVSS 216 roof crush strength-to-weight ratios (SWR) ranging from 2.3 to 5.1. The results demonstrated a rough correlation between the results of the two tests. However, the dynamic testing gave important new insights into rollover roof performance and occupant injury potential such as the role of vehicle geometry and the importance of roof strength in reducing ejections. The dynamic tests also showed that currently available sedans provide a wide diversity of rollover occupant protection performance. However, it was disappointing to find in the dynamic tests that even the two best performers sustained windshield header failures. The tests of vehicles with higher SWR also demonstrated some reduction in side window breakage, which should reduce rollover ejections. This program also provided initial confirmation of a new procedure for using a Hybrid III dummy to measure the potential for restrained occupant injury in a rollover.

Tests of contemporary sedans on the Jordan Rollover System (JRS) have demonstrated why dynamic testing should be adopted for both Federal standards and consumer information programs. Such testing shows detailed failures that could inflict serious injuries on restrained occupants from roofs that have exceptionally high strength to weight ratios (SWR) in Federal motor vehicle safety standard (FMVSS) 216. The dynamic tests also show that vehicles with similar SWR can have significantly different responses in the more realistic dynamic test conditions.

Measurements of the dummy neck bending moment over time, at the lower end of the neck where cervical injuries typically occur, showed that the greater the roof crush the higher the potential for serious neck injury.

Federal Standards on Rollover Occupant Protection

The National Highway Traffic Safety Administration (NHTSA) has issued an electronic stability control (ESC) standard, which will have a significant impact on the number of rollovers, but it will only cut rollovers by up to half. However, NHTSA has shown little enthusiasm for promulgating standards or a consumer information program to reduce rollover occupant casualties. If NHTSA issues a final rule in October 2008 as promised, it will have been seven years since the agency requested comments on the need

for upgrading FMVSS 216 and nearly twenty years since it found the current roof crush standard to have been ineffective.¹ Yet in that time, the agency has not seriously considered dynamic testing for rollover occupant protection testing. Based on its proposals, the amended standard will probably require only a trivial upgrade to a level roughly equivalent to what was originally proposed in 1970 before it was degraded at GM and Ford's urging in the final 1971 rule (see Appendix A).

Rollover occupant protection is the last major area to be addressed by NHTSA. Frontal and side impact injuries are now covered both in Federal standards and in New Car Assessment Ratings by dynamic tests using anthropometric dummies to measure injury potential. Manufacturers have responded with extensive material and technological changes to reduce the potential for injury in frontal and side impacts. At present, however, beyond the basic protection offered by safety belts and interior padding, the only rollover occupant protection standard for passenger cars and light trucks is the inadequate, static roof crush resistance standard, FMVSS 216.

In 2001, NHTSA asked for comment on how that standard could be improved, and in August 2005, after ignoring most of the comments, NHTSA proposed a minor amendment to the standard. The proposal would have raised the roof crush resistance strength-to-weight ratio (SWR) from 1.5 to 2.5 and made residual headroom a key factor in determining compliance. The result, according to NHTSA, would have saved only one out of 200 rollover fatalities. In 2008, the agency supplemented the rulemaking record with the results of 26 two sided static tests, and proposed a sequential two-sided roof test and hinted that the standard might be set above a SWR of 2.5.

The Santos/State Farm Test Program

Under a research grant from the Santos Family Foundation and using contemporary vehicles provided by the State Farm Mutual Auto Insurance Company, we selected five of the 4 door sedans that NHTSA recently tested for Jordan Rollover System (JRS) dynamic testing of rollover occupant protection performance. The sedans were a 2007 Pontiac G6, a 2006 Chrysler 300, a 2006 Hyundai Sonata, a 2007 Toyota Camry, and a 2007 Volkswagen Jetta. These vehicles all continue to be sold as 2008 models. Most, if not all, will be sold as 2009 models. We used extensive instrumentation and Hybrid III dummies restrained by three-point safety belts in the tests. The current research program also includes tests of five light trucks. The results of the first of these tests of a 2007 Honda Ridgeline are discussed in Appendix B).

It is well known that the initially trailing side is the most vulnerable seating position for a belted occupant in a rollover. The critical aspects of rollover occupant protection are a strong roof, safety belts that fully restrain occupants in a rollover, interior padding

¹ Kahane, Charles J., "An Evaluation of Door Locks and Roof Crush Resistance of Passenger Cars – Federal Vehicle Safety Standards 206 and 216, NHTSA Technical Report No. DOT HS 807 489, Washington, D.C., 1989.

in the head impact areas, and occupant compartment integrity to reduce partial or complete ejection. All of these vehicles had the padding in the upper interior as required by FMVSS 201. None of the sedans had rollover triggered safety belt pretensioners, rollover triggered side curtain air bags, or laminated glazing in the side windows.

The issue of whether a stronger roof will reduce injuries in rollovers has been settled in studies by NHTSA² and the Insurance Institute for Highway Safety (IIHS).³ The latter showed that for mid-sized SUVs, an increase of roof strength (SWR) from 2 to 3 would reduce the injury rate by 25 percent (the current minimum requirement is a SWR of 1.5 and the proposed amendment would set the required minimum SWR at 2.5). This injury reduction is an order of magnitude higher than the prediction by NHTSA.

A few manufacturers including Volvo, Toyota and Volkswagen have voluntarily exceeded the minimum Federal requirements in some of their vehicles by substantial margins. Nevertheless, we have thus far seen only one production vehicle that provides good rollover occupant protection: the Volvo XC90. In designing this vehicle, Volvo prepared a briefing discussing its dynamic tests to achieve the desired performance. A critical finding of the Volvo engineers is that the roof should not sustain permanent buckling or other structural failures.

Many manufacturers have substantially strengthened the B pillars and posts (where the rear of the front doors latch) and added a strong cross member between the B pillars to improve dynamic side impact performance under FMVSS 214 and the New Car Assessment Program (NCAP). This has also improved roof crush resistance in FMVSS 216, but not roof strength over the A pillars (the supports on either side of the windshield) as this is not independently tested in the current FMVSS 216 protocol (see Appendix A). In actual rollovers, most roofs are subjected to the primary impact force in the A pillar area because vehicles typically pitch forward as they roll. In the present test program, the first roll was conducted at a 5° pitch angle and the second at a 10° pitch to provide a range of roof impact test conditions that is typical of actual rollovers.

Jordan Rollover System Tests

Test Procedure. The JRS suspends vehicles on mounts at the front and rear in a manner that permits them to roll freely. The mounts are released as the vehicle is rotated and a road segment is passed underneath so that the initial roof contact is the passenger side (the initially leading or near side). Two JRS tests were conducted of each vehicle: at a pitch angle of 5° for the first roll and 10° for the second. The road speed was 15 mph and the vehicles were dropped four inches to the first roof impact at a roll angle of 145°.

² Strashny, Alexander, *The Role of Vertical Roof Intrusion and Post-Crash Headroom in Predicting Roof Contact Injuries to the Head, Neck, or Face during FMVSS 216 Rollovers*, National Highway Traffic Safety Administration, Washington, D.C.: 2008.

³ Brumbelow, Matthew L., Eric R. Teoh, David S. Zuby, and Anne T. McCartt, *Roof strength and injury risk in rollover crashes*, Insurance Institute for Highway Safety, Washington, D.C.: March 2008.

The roll rate was 160°/second at the time of first roof impact.⁴ These test conditions were derived from studies of actual rollovers and other dynamic rollover tests to emulate the conditions of actual rollovers.

Four string potentiometers were placed between the longitudinal roll axis of the vehicle and the roof structure at the top of the driver's side A-pillar and B-pillar, at the header inboard of the A-pillar and at the top of the passenger's side A-pillar. These instruments measure the amount and speed of roof intrusion to determine whether it would injure a human whose head is in the path of the intruding roof.

An instrumented, safety belted 50th percentile male Hybrid III test dummy was placed in the driver's seat (the initially trailing side in this test). For the first roll, the dummy was seated in general as specified in FMVSS 208 for frontal crash tests except that the right shoulder was tightened to prevent contact with the forward roof string potentiometers. The dummy was instrumented with string potentiometers under the seat. The dummy also had upper and lower six axis (three force and three moment) neck load cells. For the second roll, the dummy's torso was pitched forward to increase the angle of the neck axis to 10 degrees forward, and the seat was moved rearward to place it in a more realistic position for a rollover condition. Seat belt load cells were used to measure belt tension.

Six vertical and two lateral load cells were placed in the moving roadway to record the impact characteristics of the test. A string potentiometer was placed on the front fixture support tower and another on the rear tower to record vehicle vertical motion characteristics during the test. A roll encoder was placed on the cable pulley which pulls the moving roadway to record the roadway velocity throughout the test. Another roll encoder was placed on the shaft of the vehicle roll axis or in the vehicle itself to determine the vehicle roll angle and angular velocity during the test.

Rollover Occupant Injury

Table 1 provides the basic results of these tests as they relate to the potential for injury for the five vehicles tested. The roof performance measures that were used to evaluate the performance these include peak dynamic roof crush, residual roof crush, and peak crush intrusion speed.

NHTSA has concluded that if the residual roof crush (the distortion of the roof after the test is completed) leaves negative headroom for a 50th percentile male, the probability of occupant head, face or neck injury increases dramatically. As can be seen from Table 1, the peak dynamic intrusion (the maximum crush during the test) is typically 50 to 100 percent greater than the residual intrusion. The ratio of the peak road load in the first roll to the peak in the second roll decreases with increasing SWR indicating that the vehicles

⁴ The test parameters are nominal target values. Actual parameters were within a few percent of these values.

with stronger roofs respond more similarly in multiple rolls than vehicles with weak roofs.⁵ Belt loads were nominal (no more than a few hundred pounds) in all tests.

Based on both experimental tests and real world crash statistics, NHTSA has established that if the neck injury criterion, N_{ij} exceeds 1 there is 15 percent probability that the occupant will suffer an AIS 3 or greater neck injury.

Pass. Car Year, Make & Model (strength-to-weight ratio – test weight)	Roll	Peak Road Load (pounds)	Peak Dynamic Crush (inches)	Peak Crush Speed (mph)	Residual Roof Crush (inches)	Peak Neck Load (N)	Neck Injury Criteria (upper)	Integrated bending moment (IBM)
2007 Pontiac G6 (2.3 – 3,179)	1	19,062	7.1	7.5	4.9	2,399	0.66	17.4
	2	33,406	6.0	13.1	7.0	1,916	0.54	14.4
2006 Chrysler 300 (2.5 – 3,941)	1	24,100	8.4	7.5	5.6	5,598	1.80	20.1
	2	43,050	10.4	10.6	7.4	1,979	0.40	15
2006 Hyundai Sonata (3.2 – 3,501)	1	17,711	4.7	5.0	2.6	4,835	0.63	13.5*
	2	31,380	6.9	7.2	N.A.	3,457	1.15	10.1*
2007 Toyota Camry (4.3 – 3,176)	1	19,242	3.4	5.0	1.6	4,211	0.78	9.9*
	2	25,038	8.3	7.5	5.5	2,669	0.76	5.1*
2007 VW Jetta (5.1 – 3,316)	1	17,362	2.7	5.7	1.0	5,158	0.96	7.2
	2	20,798	8.0	7.1	3.4	5,394	1.08	7.9

* Estimated

Table 1. Data from tests of contemporary passenger cars of varying FMVSS 216 roof crush resistance (strength-to-weight ratio – SWR)

Details of Vehicle Performance

Pontiac G6. Figure 1 shows the Pontiac G6 after the first and second rolls. Note the extensive windshield header and roof panel buckling and intrusion of the roof panel over the driver position.

The Pontiac's curb weight is 3,422 pounds and its test weight was 3,179 pounds. It has an FMVSS 216 SWR of 2.3, the lowest among the tested vehicles. It registered a maximum road impact load with the first side of the roof of 10,605 pounds and of 19,062 pounds on the second side on the first roll test. The higher road impact load in the second test occurs because of the impact between the lower body of the vehicle and the road. The total residual roof intrusion at the A pillar was 4.9 inches after the first roll and 7.0 inches (an additional 2.1 inches) after the second.

The roof of the G6 suffered major structural failure in the first roll, and the second roll increased the damage only marginally. The windshield header buckled in numerous places indicating that it is completely inadequate to ensure structural integrity in a rollover. The driver's side window broke in the first roll, but the remaining side windows survived both rolls.

⁵ In vehicles with weak roofs, the peak force on the road on the second side impact occurs when the roof has crushed and the lower body of the vehicle comes in contact with the road segment.



Figure 1. Pontiac G6 after first (left) and second roll JRS tests.

This vehicle would not comply with the weak, proposed upgrade of FMVSS 216. The roof intrusion rate on the first roll would have inflicted serious injury to a driver whose head is located in the path of maximum intrusion. The intrusion rate in the second roll was sufficient to inflict injury to a driver in virtually any position near the roof rail. This vehicle would have to be considered defective for its excessive roof intrusion and intrusion rates.

The maximum neck loads and neck injury criterion in these two tests were moderate because the safety belts permitted sufficient excursion of the dummy that friction between the head and interior headliner kept the dummy away from the roof rail area. This is partly a function of the very stiff neck of the dummy that prevented it from bending to permit the occupant to move into the path of the roof's greatest intrusion and partly a function of the poor belt restraint. The measurements of roof intrusion provided confirmation of the high injury potential of roof intrusion in this vehicle.

Chrysler 300. Figure 2 shows the Chrysler 300 after the first and second rolls. It registered a maximum road impact load with the first side of the roof of 11,604 pounds and of 24,001 pounds on the second side on the first roll test. The latter was due to the impact of the lower side of the vehicle with the road segment. The FMVSS 216 SWR was 2.5. Note the extensive windshield header buckling and intrusion of the roof panel over the driver position.

The Chrysler's curb weight is 3,726 pounds and its test weight was 3,941 pounds. The total residual roof intrusion at the A pillar was 5.6 inches after the first roll and 7.4 inches after the second. The intrusion at the roof buckle was even greater. According to NHTSA, this would significantly increase the probability of a head, face or neck injury in a rollover.

The Chrysler 300 barely met the roof crush resistance value proposed by NHTSA in 2005, and did so in its two-sided test. However, the roof showed serious performance deficiencies in our dynamic testing. We would rate the rollover occupant protection capability of this vehicle as poor based on the amount and speed of roof intrusion, and on the high peak neck load and neck injury criterion in the first roll test.



Figure 2. The 2006 Chrysler 300 after the first JRS roll test (left) and second roll.

Despite the severity of roof crush, the side windows survived both rolls, apparently because the side window frames retained their shape and did not twist excessively. The left side window frames were bent toward the center of the vehicle but were not distorted. The rear roof panel suffered significant weld failures as seen in Figure 11.

Hyundai Sonata. Figure 3 shows the 2006 Hyundai Sonata after the first and second rolls. It registered a maximum road impact load with the first side of the roof of 12,955 pounds and of 17,711 pounds on the second side on the first roll test. The FMVSS 216 SWR was 3.2. The damage to the initially leading side of the roof increased substantially in the second roll, which is somewhat unusual in both JRS tests, and indicates that the damage to the second side in the first test substantially weakened the roof overall.

The Sonata's curb weight is 3,266 pounds and its test weight was 3,501 pounds. It registered a maximum road impact load with the second side of the roof of 17,711 pounds during the first roll and 31,380 during the second. The side windows survived the first roll, but the driver's window broke in the second roll.



Figure 3. The 2006 Hyundai Sonata after the first JRS roll test (left) and second roll.

The residual roof intrusion at the A pillar was 2.6 inches after the first roll and could not be measured after the second because of interference between the dummy and the string potentiometer. Although the intrusion over the driver position was reasonable, the

tenting of the windshield header and damage to the roof on the passenger side indicate problems with the overall structural integrity of the roof of this vehicle.

The Sonata would meet NHTSA's proposed roof crush resistance criteria with a SWR greater than 2.5 in the FMVSS 216 test, but its performance showed serious structural weakness in the JRS test and a significant probability of injury to the driver in these rollover tests. We would rate the rollover occupant protection performance of the Hyundai Sonata as marginal to poor based on the peak neck load and neck injury criterion in the first roll test, the peak roof intrusion speed in the second roll, the excessive intrusion of the passenger side roof, and the driver's side window failure.

Toyota Camry. Figure 4 shows the 2007 Toyota Camry after the first and second roll tests on the JRS.⁶ The Toyota's curb weight is 3,260 pounds and its test weight was 3,176 pounds. Its FMVSS 216 SWR is 4.3. It registered a maximum road impact load with the first side of the roof of 14,188 pounds and of 19,242 pounds on the second side on the first roll test. The vehicle looked fairly good after the first roll test (although there was incipient damage at the left end of the windshield header), but developed significant buckles in the windshield header in the second roll. Toyota uses high strength steel in the pillars and roof rails at the side of the roof of its Camry and Corolla models, but they have weak windshield headers as demonstrated in this test.



Figure 4. The 2007 Toyota Camry after the first roll JRS test (left) and the second.

Viewing the videotape and the traces from the string potentiometers on the fixture support towers showed that the impact with the near side of the roof virtually halted the fall of the vehicle's center of gravity (with a much higher road impact load than the vehicles with weaker roofs) so that the far side roof impact was less severe than with the weaker roofed vehicles. This indicates that one important benefit of a strong roof is its ability to sustain high loading in the first side impact so that the far side impact is less severe.

⁶ The front end damage to this vehicle occurred before these tests were conducted. The vehicles were donated by State Farm Mutual Auto Insurance Company after they were declared a total loss by the insurer. Detailed inspection of all vehicles tested in this program revealed no damage to the relevant occupant compartment structures.

Unfortunately, the first roll test sufficiently weakened the roof structure that on the second roll, this effect was much weaker. On the second roll, the Camry registered a maximum road impact load with the first side of the roof of only 7,506 pounds but of 25,088 pounds on the second side on the second roll test because the roof crush permitted substantial contact between the lower body of the vehicle and the road segment. High strength steel is used in the side structure of the roof, but not the windshield header. It protected the side windows from breakage in both rolls on the JRS, a major plus in reducing the potential for occupant ejection.

It registered a maximum road impact load with the second side of the roof of 19,242 pounds on the first roll test and 25,038 pounds on the second. The residual roof intrusion at the A pillar was 1.6 inches after the first roll and 4.7 inches after the second. The intrusion at the roof buckle was somewhat greater. This vehicle had only marginal headroom after the second roll test according to NHTSA's headroom criterion.

The Toyota Camry substantially exceeded NHTSA's proposed roof crush resistance criterion of a SWR of 2.5. However, the performance of its windshield header shows that performing well in the FMVSS 216 test does not guarantee good dynamic rollover performance. Attachment B is a paper by Nash that shows that this weakness affects the performance of various Toyota vehicles in actual rollovers captured by the National Accident Sampling System (NASS).

We would rate the rollover occupant protection of the Camry as fair. The good side structure of the roof is compromised by the weak windshield header that permitted high roof intrusion speed in the second roll test. The real world performance of the Camry gives little confidence that the Camry's rollover performance is much better than average. These test results show why the conditions of the current FMVSS 216 test, even if repeated on the second side, are not adequate to ensure good roof crush resistance.

Volkswagen Jetta. Figure 5 shows the Volkswagen Jetta after the first and second rolls. Despite its very high FMVSS 216 SWR, the windshield header suffered significant damage in the second test.

The Jetta's curb weight was 3,272 pounds and its test weight was 3,316 pounds. Its FMVSS 216 SWR is 5.1. It registered a maximum road impact load with the first side of the roof of 16,501 pounds and of 17,362 pounds on the second side on the first roll test. This vehicle shows the same effect seen in the first Camry roll: the strength of the roof in the near side roof impact moderated the force in the second side impact. As with the Camry, the damage from the first roll reduced the near side strength so that the road impact loads in the second roll were 10,312 and 20,798 pounds, respectively. The windshield header buckled significantly in the second roll, but moved outward so that there was only modest roof intrusion in the second roll.



Figure 5. Volkswagen Jetta after first (left) and second roll JRS tests.

At a SWR of 5.1, the Jetta had the highest SWR in FMVSS 216 testing seen in any production vehicle. Nevertheless, the dummy had moderately high neck loads in the VW tests because the dummy's head was in the direct path of maximum roof intrusion, and the roof showed significant buckling in the tests. The duration of the high loads was relatively short suggesting that a human neck would not have been seriously injured under the same conditions. We would rate the Jetta's rollover occupant protection performance as fair to good.

High FMVSS 216 SWR is Not Sufficient

It is useful to compare the performance of the two vehicles with the highest FMVSS 216 SWR with the Volvo XC90 (Figure 6) which has a lower SWR (around 4.6). After two tests at 5° pitch, the 2004 Volvo XC90 showed insignificant residual structural failures. Both the Toyota Camry and the Volkswagen Jetta showed modest structural damage in the first test and more substantial structural failures in the second roll. These results show that although Toyota and Volkswagen have successfully reduced the potential for ejection in these two vehicles, their manufacturers should address the design or materials of the windshield header to achieve a high level of occupant protection.



Figure 6. Interior views of the Jetta (above left) and Camry (above right) show buckled windshield headers after the second roll test. The G6 (below left) windshield header performed particularly poorly. The Volvo XC90, after two roll tests at 5° pitch on the JRS (below right), shows no structural failures.

Conclusions

These results show that some manufacturers continue to make vehicles that provide very poor rollover occupant protection while others have made major improvements in aspects of roof structures. However, even the best of the sedans we tested could be improved. This work also shows the importance of realistic dynamic testing to show (1) the dynamic response to realistic roof impacts in a rollover, (2) the roof failure modes, and (3) the consequences of multiple roof impacts that occur in multiple rollovers. Most serious to fatal injuries in rollovers are in multiple rollovers.

The responses of the Hybrid III dummies used in these tests only partially track the potential of the roofs of vehicles to inflict injury. The relationship between the location of the head and roof crush, and the lack of biofidelity of the Hybrid III dummy, conspire to give results that, for the most part, do not directly track the critical roof performance elements: the degree and rate of roof intrusion over a restrained, far side occupant.

One exception is what has been defined as the integrated bending moment (IBM) which is shown in the last column of Table 1. This is a measure of the product of the bending moment at the base of the neck (where most neck injuries in rollovers occur) over time where the moment is significant. The IBM, as measured when the occupant is leaned modestly forward as an occupant would be in an actual rollover, seems to provide a good measure of the potential for a neck injury from flexion in a rollover.

A flat ground rollover is a relatively benign type of crash if a vehicle is designed to provide good occupant protection. Racing cars with strong roll cages, excellent restraint systems, and padding for head impact provide virtually foolproof protection to drivers in rollovers that are far more severe than typical public road rollovers. These three features can be provided in production cars with a strong roof, a restraint system with good geometry and rollover-triggered pretensioners, and appropriate padding in the head impact area.

Volvo has shown the importance of having the roof structure respond elastically (bending like a spring rather than buckling) to ground impacts, in addition to reasonable roof crush resistance, to ensure good performance in multiple rollovers. Such a response has a higher probability of protecting side windows to reduce the potential for ejection.

Various JRS tests of vehicles with FMVSS 216 SWR equal to or less than 2.5, including the Chrysler 300, have sustained at least 127 mm (5 inches) of residual crush in all but one case (which was only slightly less than 127 mm). These tests, which were summarized in a recent Center for Injury Research (CIR) docket submission, show that setting a FMVSS 216 performance level of 2.5, whether in a one or two-sided test, would not be adequate to reduce rollover injuries significantly.

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Appendix A. FMVSS 216, Roof Crush Resistance

Federal motor vehicle safety standard 216 was originally proposed in 1970. The engineer who was responsible for the proposal intended that it be a non-destructive test because the roof strength would be sufficient to resist a force of 1½ times the vehicle's weight without significant damage to the vehicle.⁷

The original test applied a force to the front corner of the roof at a roll angle of 25° and a pitch angle of 10° using a padded (to protect the vehicle's paint) 1 foot square platen. If the vehicle could resist with a force of at least 1½ times the vehicle weight before deforming 5 inches, and could do so sequentially on the second side of the roof, it would pass the standard.

After strong objections from the U.S. automakers, NHTSA agreed to adopt the test conditions defined in Society of Automotive Engineers (SAE) Recommended Practice J374 which reduced the pitch angle to 5°, extended the platen well rearward beyond the B pillar, and required testing on only one side of the roof. Whereas virtually none of the vehicles currently in production could meet the proposed standard, most could meet the revised version that was issued as FMVSS 216 in 1971.

The Center for Injury Research has constructed its own static test device called the M216. In tests of a number of production vehicles using the M216 using essentially the originally proposed test conditions, it was found that the crush resistance of a roof when measured at a 10° pitch angle is roughly only half that when measured at a 5° pitch angle. This is because at 5°, the resistance comes roughly equally from both the A and B pillars whereas at 10°, the A pillar area must provide virtually all of the crush resistance.

If NHTSA adopts a two-sided test at 5° pitch and 25° roll, with a minimum crush resistance of 3 times a vehicle's weight, that would be roughly equivalent to the original requirement of 1½ times a vehicle's weight at 10° pitch and 25° roll. If NHTSA issues the amended standard with these minimal test conditions, it would mean that we have made no progress from the standard proposed nearly 40 years ago.

⁷ Chu, William H.K., Letter to Rae Tyson, National Highway Traffic Safety Administration, Rochester Hills, Michigan: April 20, 2004 (Docket NHTSA-1099-5572-96).

Appendix B. Test of the Honda Ridgeline Pickup.

The first of the light truck tests under the Santos/State Farm grant was of a 2006 Honda Ridgeline pickup. This test series will include the 2007 Jeep Grand Cherokee, the 2007 Volvo XC90, the 2006 Honda CRV and the 2006 Chevrolet Tahoe. The Ridgeline is somewhat unusual in that it uses a more modern unit body construction rather than the body-on-frame construction of typical pickups. Nevertheless, it showed poor roof crush performance that is typical of other light trucks.

Figure B1 shows the Honda Ridgeline after the first and second rolls. Note the extensive windshield header and roof panel buckling and intrusion of the roof panel over the driver position and the catastrophic damage after roll 2.



Figure B1. The Honda Ridgeline after first (left) and second roll JRS tests.

The Ridgeline's curb weight is 4,453 pounds and its test weight was 4,467 pounds. It has an FMVSS 216 SWR of 2.4. It registered a maximum road impact load with the first side of the roof of 13,544 pounds and of 20,385 pounds on the second side on the first roll test. The total residual roof intrusion at the A pillar was 5.0 inches after the first roll and 10.9 inches after the second.

Pass. Car Year, Make & Model (strength-to-weight ratio – test weight)	Roll	Peak Road Load (pounds)	Peak Dynamic Crush (inches)	Peak Crush Speed (mph)	Residual Roof Crush (inches)	Peak Neck Load (N)	Neck Injury Criteria (upper)	Integrated bending moment (IBM)
2006 Honda Ridgeline (2.4 – 4,467)	1	20,385	9.4	13.7	6.3	10,006	1.64	24.1
	2	33,023	10.2	15.0	13.2	4,685	1.19	28.9

Figure B1. Basic results from the Honda Ridgeline JRS test

The roof of the Ridgeline suffered substantial structural distortion in the first roll. The structure failed catastrophically in the second roll such that the top of the A pillar intruded below the beltline of the vehicle. The dummy's head was forced outside the

envelope of the Ridgeline because of the extensive distortion of the roof, and it is clear that had a human been subjected to these conditions, the result would have been a fatal injury. It is ironic that this situation would have been coded a partial ejection by NHTSA although the dummy did not move significantly from its normally seated position. Rather, the envelope of the vehicle was so distorted that it no longer contained or protected the head of a normally seated occupant.

This vehicle would nearly comply with the weak, proposed upgrade of FMVSS 216, but its rollover performance is, in our opinion a serious safety defect that should result in a safety defect recall. The roof intrusion rate on the first roll would have inflicted serious injury to a driver whose head is located in the path of maximum intrusion. The forces on the dummy in the second roll would have had a high potential to have fatally injured an occupant subjected to the same forces under this defective roof.

In addition to the major roof intrusion in this vehicle, several side windows broke in the JRS rollover tests.

The results of this test should be compared with the results of the Chrysler 300 test discussed above. Both vehicles had similar FMVSS 216 performance, and the 300 performed poorly, but the Ridgeline had a catastrophic roof failure in its second roll that was far more hazardous than the roof intrusion of the Chrysler 300. Furthermore, none of the Chrysler's side windows broke in its JRS tests while one of the Ridgelines left side windows broke in the first test and another broke in the second roll opening major avenues for occupant ejection.

It is clear that the FMVSS 216 test cannot differentiate between poor performers and disastrous performers while the JRS test shows in detail the failure modes of vehicle roofs and the mechanism of potential injury in a rollover.

Appendix C. Does a High Strength to Weight Ratio in FMVSS 216 Necessarily Mean Good Rollover Performance?

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In recent government roof crush resistance tests of light motor vehicles (Federal motor vehicle safety standard 216) the vehicles of one manufacturer, Toyota, stood out. Figure 1 gives a summary of the results of these tests plus the results of a test of the Toyota Corolla. These tests show exceptionally high strength-to-weight ratio SWR values for Toyota's vehicles. These high numbers generally carry over to the second side when tested using the same procedure.

Year	Model	First Side SWR	Second Side SWR
2007	Scion tC	4.6	4.3
2007	Takoma (pickup)	4.4	3.9
2007	Camry	4.3	4.7
2007	Yaris	4.0	3.4
2006	Corolla	4.2	---

Figure 1. Strength-to-weight ratios of a selection of recent model Toyota light vehicles in Federal motor vehicle safety standard 216 static tests of roof crush resistance.

The Center for Injury Research has tested two Toyota passenger cars, the Corolla and the Camry, on the dynamic Jordan Rollover System (JRS). In those tests, a weakness in the structure of the tested vehicles became obvious: the windshield header is weak and likely to buckle under dynamic loading (see Figure 1).



Figure 1. Photographs of a 2007 Toyota Camry roof after one roll and after two rolls in a JRS test showing the buckling of the windshield header in this vehicle. The Toyota Corolla showed similar buckling in a JRS test.

In order to see whether the performance found in these tests carry over to vehicles in actual rollovers, we searched 2002-2006 National Accident Sampling System (NASS) files for all rollovers of Toyota, Scion, and Lexus models from 2003 through the present model year. We eliminated cases where the roof struck a tree or other object that caused massive crush during the rollover, cases where there was no vehicle inspection, and one case where a fire rendered the vehicle nearly unrecognizable. We found a total of 34 Toyota cases and 3 Lexus cases. The cases are generally described in Tables 1 and 2. Only injuries greater than AIS 1 were noted.

Except for a couple of cases, we found that Toyota roofs generally looked good after a rollover except that in many cases the windshield header buckled. This behavior mirrors the results of the JRS tests.

Because NHTSA's weighting factors are probably not reliable for analyses of these rollover cases, we were not able to determine the statistical significance of results of these cases. Nevertheless, a number of general conclusions can be drawn from them.

- About half of the vehicles that rolled over were passenger cars.
- We estimate that up to 27 of the rollovers involved either a collision before the rollover or conditions where electronic stability control (ESC) would have been unlikely to have prevented the rollover. Passenger cars were more likely to have had their rollovers initiated by a collision or other factors that ESC would not have prevented.
- Only six of the rollovers involved more than one roof impact with the ground (i.e. 6 or more quarter rolls).
- Three belted occupants – two in light trucks – suffered moderate (AIS 2) head injuries from contact with the roof. One, a restrained driver in a Corolla, suffered severe (AIS4) head injuries from partial ejection (2005-78-45). The vehicle had major roof crush over the driver position that repositioned the driver's side window frame so as to facilitate the partial ejection. This was the only vehicle in this study that suffered major roof crush (other than header buckling) from a flat ground rollover.
- Five other occupants suffered AIS 2 injuries, only one of which was to the head, face or neck. That one was a restrained driver whose injury came from contact with the steering system. Three occupants suffered AIS 3 arm or leg injuries, some of which were from partial ejection. One 75 year old occupant suffered a fatal neck injury from a side impact by a motorcycle before the rollover and another suffered a fatal thoracic injury from a side impact by a van.
- Although there was surprisingly little buckling or other serious damage to the A, B, or C pillars or to the roof rails, 19 of the vehicles had some intrusive buckling or tenting damage to the windshield header. In many of these cases, the header damage caused buckling of the roof panel.

NASS Case No.	Year	Model	No. of ¼ Rolls	Description of Roof Damage	Other Factors
2004-9-56	2004	Camry sedan	15	Minor header tenting	Greater tenting over rear window - unbelted rear seat pass. ejected - moderate injuries
2005-42-122	2005	Camry	2	Minor header buckle	
2005-43-169	2004	Camry	6	Minor	Unbelted 75 y.o. occ. had a serious neck injury
2006-42-140	2005	Camry	2	Minor	Minor collision first – mod. sternal fracture
2006-72-93	2004	Camry	4	Header tented	Moderate collision first
2006-72-104	2004	Camry	2	Header buckled	Moderate collision first serious arm & leg inj.
2004-03-150	2004	Corolla sedan	2	Header buckled	Minor collision first restrained driver had moderate shoulder inj.
2004-43-99	2003	Corolla	6	Header buckled	Serious arm injury
2004-48-103	2003	Corolla	2	Very minor	Minor collision first
2004-48-285	2005	Corolla	4	Header buckled	Hit guardrail first
2005-47-37	2005	Corolla	3	Header buckled	Up small embankment unknown injuries
2005-78-45	2005	Corolla	6	Major roof crush over driver	Partially ejected driver had severe head injury
2006-41-207	2005	Corolla	2	Header buckled	Side MC impact before caused fatal head inj.
2006-43-86	2006	Corolla	2	Header buckled	Collision first
2006-78-119	2006	Corolla	9	Minor	Moderate face inj. from steering
2004-82-60	2004	Prius sedan	2	Minor	Minor collision first
2004-75-194	2005	Scion tC coupe	2	Very minor	Major collision first moderate head injury
2005-79-75	2006	IS-300 sedan	4	Minor	Hit guardrail first

Table 1. NASS cases (through 2006) involving relatively simple rollovers of 2003 and later Toyota cars.

NASS Case No.	Year	Model	No. of ¼ Rolls	Description of Roof Damage	Other Factors
2005-43-180	2006	RX-400 Hybrid	4	Header buckled	Collision first
2006-75-154	2004	RX-330 SUV	4	Minor	Hit very small trees
2003-48-48	2003	Highlander SUV	2	Header buckled	Unbelted driver had AIS 2 head injury
2005-50-154	2005	Sequoia SUV	3	Minor	Minor collision first
2006-48-40	2004	4Runner	2	Moderate RF corner crush	Minor side impact first
2005-48-12	2005	Scion XB van	2	Minor	Minor collision first
2006-82-44	2006	Scion XB	4	Moderate	Major collision first ejected pass. died

NASS Case No.	Year	Model	No. of ¼ Rolls	Description of Roof Damage	Other Factors
2003-76-151	2003	Tacoma pickup	4	Header tented	
2004-9-142	2004	Tacoma	2	Header buckled	Minor collision first
2004-43-145	2003	Tacoma	6	Header buckled	Moderate head injury
2004-43-335	2004	Tacoma	4	Minor	
2004-76-146	2003	Tacoma	2	Header buckled	
2005-48-30	2003	Tacoma	4	Minor header buckle	Moderate collision before - mod. foot injury
2005-75-21	2004	Tacoma	3	Header buckled	Not flat ground R/O
2005-79-111	2003	Tacoma	2	Header buckled	Minor collision at end
2006-43-33	2006	Tundra pickup	5	Minor	Major side impact first – fatal thoracic injury to unrestrained pass.
2006-48-197	2004	Tundra	4	Moderate RF corner crush	Towing large trailer
2006-78-39	2003	Tacoma	3	Minor	Moderate arm injury
2006-79-14	2004	Tacoma	1	Minor	Moderate collision first serious arm injury

Table 2. NASS cases (through 2006) involving relatively simple rollovers of 2003 and later Toyota SUVs, vans and pickups.

- Belt use was more common in these rollovers than in rollovers generally, although this may be typical of relatively new vehicles. In eight of the rollovers at least one occupant was not wearing a safety belt. Three of those occupants were completely ejected. All of the unbelted occupants suffered at least an AIS 2 injury. Four belted occupants suffered partial ejections, three suffering an AIS 2, an AIS 3 and an AIS 4 injury.

If these cases are reasonably representative, the rollover experiences of the Toyotas captured in NASS investigations does not appear to be substantially different from what would have been found from a similar sample of late model cars and light trucks in most respects. The obvious weakness of the windshield headers in these vehicles is troublesome, however.

A Toyota corporate representative⁸ recently stated that the company added reinforcements to improve the Corolla's performance in the Insurance Institute for Highway Safety (IIHS) frontal offset crash test, not to improve rollover roof crush resistance. Toyota added or substituted about 7 pounds of high strength steel to the base of the A-pillar, the roof rails and the B-pillar for this purpose as shown in Figure 5. They did not strengthen the open section windshield header which buckled in our tests of this vehicle.

Inspections of the Toyota Corolla and Camry that were tested on the Jordan Rollover System showed strengthened B pillars and posts and a stronger roof bow between the B pillars. These structures prevent intrusion and transfer the load from side to side in dynamic side impact testing. They also greatly improve FMVSS 216 peak values because the platen engages the B pillar area early in that test. By contrast, the windshield header is very weak and poorly designed to absorb loads that are concentrated at the top of the A pillar.

Toyota could have substantially improved roof performance in rollovers by making the windshield header a closed section and perhaps by using the same higher strength steel that was used in the pillars and roof rails. The FMVSS 216 test is a poor test of roof crush resistance because it does not stress the windshield header in a manner that would show the weakness of the Toyota windshield header.

Not surprisingly, the recent model Camry has 5 star New Car Assessment Program ratings for both front and side impacts, and the Corolla has 5 star frontal crash ratings and 4 star side impact ratings. The Camry got a "good" rating in the IIHS offset frontal and (if equipped with side impact air bags) in the side impact tests. The Corolla also got a "good" rating in the offset frontal tests but only an "average" rating even when equipped with side impact air bags.

A stronger windshield header would have prevented the buckling in two of the cases where there was an AIS 2 head injury (2003-48-48 and 2004-43-145), and would have

⁸ Deposition of Motoki Shibata, taken on October 26, 2006 in *Basco vs. Toyota Motor Company*.

reduced the crush in case 2005-78-45 which would have substantially reduced the severity of the injury in that case. Three head injuries of these severities is about what one would expect from a representative sample this size.

Most, if not all of the vehicles in this study probably exceeded any level of performance being considered by NHTSA for a one or two-sided FMVSS 216 test at 5° pitch and 25° roll such as a strength-to-weight ratio of 3.5. This is why it is important that if there is a static test of roof strength, it must include a second side test at a pitch of 10° and a roll angle of 40° to realistically stress all parts of the roof structure. Structural buckling of any kind has the potential for inflicting occupant injury and for increasing the potential for window failure and partial or complete ejection. A dynamic test such as the Jordan Rollover System test or the FMVSS 208 dolly rollover test would more realistically test the structural integrity of a roof.

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