ROLLOVER INJURY SCIENCE AND ROLLOVER CRASH TYPOLOGY

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ABSTRACT

Motor vehicle manufacturers have developed and deployed rollover roof rail mounted air bags to mitigate occupant injury and the potential for occupant ejection in rollover collisions. Some manufacturers have published information on the type of rollover collisions that are used to establish criteria and define the circumstances for rollover air bag deployment commands.

This paper examines the National Automotive Sampling System Crashworthiness Data System (NASS CDS) to characterize the type and severity of roll over collisions that occur on United States roadways and reports upon the distribution of rollover occurrence by type, and rollover injury occurrence by type of rollover event. Involvement rates are reported for light duty vehicles. Occurrence rates for roll over collision and roll over collision related injury are compared to the rollover collision types that have been identified by motor vehicle manufacturers to assess the proportion of roll over collisions and injuries that might be subject to mitigation with the installation of roof rail mounted rollover air bags.

This comparison shows, if all light duty vehicles in the new vehicle fleet applied similar deployment criteria, approximately 84% of rollover collisions and injuries could be subject to the injury mitigation effects of existing roof rail mounted roll over air bags.

MOTOR VEHICLE ROLLOVER COLLISION AND INJURY MITIGATION TECHNOLOGIES

Rollover crashes are a relatively small proportion of all collisions in the U.S. but a disproportionate share of fatal and serious injuries occur in rollover crashes. Therefore, rollover related injury has been a high priority for the National Highway Traffic Safety Administration (NHTSA). It has developed a comprehensive approach to rollover injury mitigation that involves three elements: 1) reduction of the occurrence of rollover crashes, 2) mitigation of ejections, and 3) occupant protection. The NHTSA has taken rule making action in all three dimensions.

For reduction of the occurrence of rollover crashes the NHTSA has promulgated Federal Motor Vehicle Safety Standard (FMVSS) 126 requiring improved vehicle dynamics with the installation of Electronic Stability Control (ESC) technology. The NHTSA intends to generate reductions in occupant ejections through: increased occupant use of safety belts, improved door hardware performance (FMVSS 206), and application of new ejection mitigation performance requirements (primarily) due to application of rollover activated roof rail air bags (FMVSS 226). The NHTSA addressed occupant protection with increased roof strength in FMVSS 216.

In all three areas, motor vehicle manufacturers have initiated technology insertion and/or policy actions to address these same three dimensions.

Motor vehicle manufacturers initiated application of ESC technologies in the late 1990s. Figure 1 is a bar graph of the proportion (of total models) of the new vehicle fleet (passenger cars and light trucks, herein after the “light vehicle fleet”) over the period 1998 through 2009 that were offered for sale in the U.S. with ESC available. By 2004, the NHTSA and the Insurance Institute for Highway Safety (IIHS) had examined collision data and determined that ESC effected meaningful reductions in all collisions and in single vehicle off road rollover collisions. The NHTSA initiated rule making on FMVSS 126 in September 2006, roughly at the beginning of the 2007 model year. In that year over 65% of new model vehicles had ESC available as standard or optional equipment. The NHTSA issued its final rule in April 2007, a very rapid conclusion for a very complex rule. The rule applied to vehicles manufactured after September 1, 2008 and incorporated a three year phase-in period, provided carry forward credits for vehicles that satisfy the

performance criteria, and became fully effective to light duty vehicles manufactured after August 31,

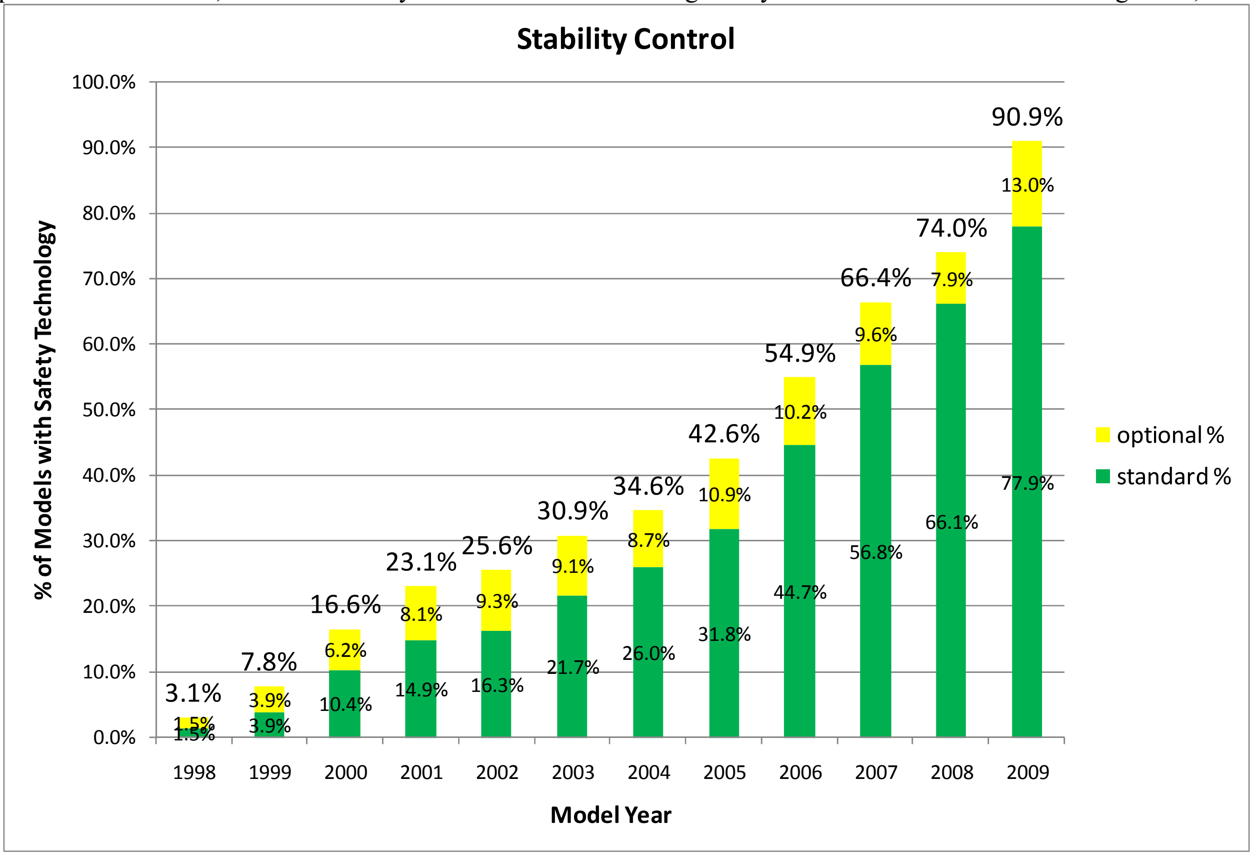

Figure 1. Optional and standard installation rates for electronic stability control as a proportion of new light duty vehicle models.

the performance criteria, and became fully effective to light duty vehicles manufactured after August 31, 2010. The NHTSA estimated that ESC as applied to satisfy FMVSS 126 will avoid 1,171 to 1,465 fatal rollover related injuries annually when fully integrated into the motor vehicle fleet [1].

Ford Motor Company installed enhanced seat belt use reminders during the mid-1990s. Survey work conducted by the IIHS reported about a five percent increase in belt use in Ford vehicles with enhanced seat belt reminders as compared to Ford vehicles not so equipped. Following publication of the Ford/IIHS study, NHTSA Administrator Dr. Ricardo Martinez encouraged all manufacturers to consider incorporation of similar enhanced seat belt use reminder systems in their vehicle designs. Virtually all major manufacturers responded affirmatively; the insertion profile for enhanced seat belt use reminder systems is shown below in Figure 2. The source of this data is the NHTSA New Car Assessment Program (NCAP) database. Note that the discontinuity in model year 2005 is because that is the first year the technology was recorded consistently. The insertion percentage increase from the mid-1990s was much smoother than Figure 2 shows.

Motor vehicle manufacturers collaborated on the public policy front to change occupant behavior regarding seat belt usage. Vehicle manufacturers created the Air Bag and Seat Belt Safety Campaign (ABSBSC) and partnered with some insurers, particularly Nationwide Insurance, to fund a ten year program to increase seat belt use in the U.S. The program was operated by the National Safety Council. The ABSBSC: 1) expanded the "Click It or Ticket" program built by the IIHS and police agencies in North Carolina across the U.S., 2) worked to improve mandatory seat belt use laws, and 3) focused public attention on seat belt use during periods of intense enforcement efforts on a regular basis. After the ABSBSC was concluded in 2007, the NHTSA has continued to organize the periodic enforcement events. During the life of the ABSBSC, seat belt use in the U.S. increased 21 percentage points from 61% to 82%.

Rollover injury science was advanced by work performed by motor vehicle manufacturers. See, for example, roof strength docket comments provided by the Alliance of Automobile Manufacturers [2] and [3]; Ford Motor Company [4], [5], and [6]; Nissan [7]; and General Motors [8], [9], and [10]. Manufacturers studied and reported upon the injury mechanisms related to compressive loading of the spine when in an inverted position due to gravitational forces that act on the thorax through the neck and are resisted by the head at rest on the ground or on vehicle structures.

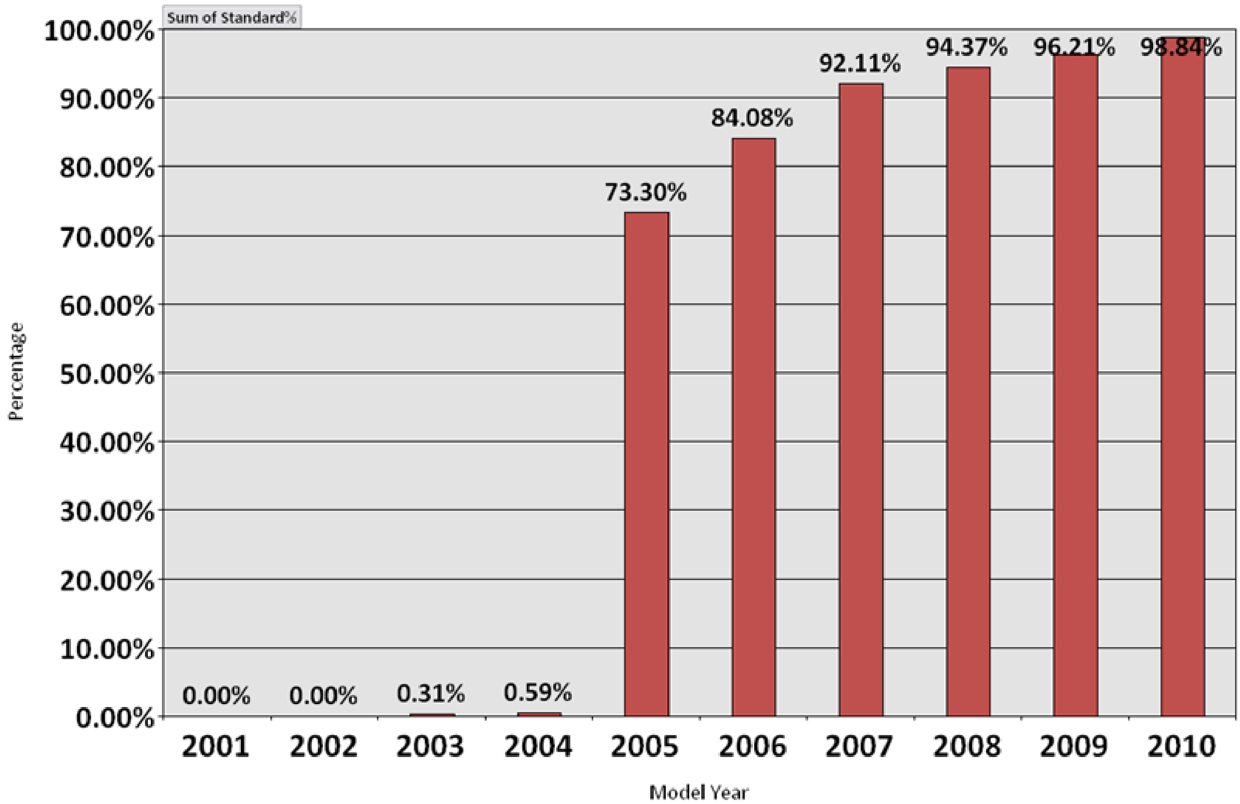

Figure 2. Installation rate for enhanced seat belt reminder systems. Data was not consistently recorded prior to 2005.

Applying this injury control science, manufacturers developed and implemented rollover activated roof rail air bags. Ford Motor Company first introduced this technology in the middle of the 2002 model year. Figure 3 shows the technology insertion progression for rollover roof rail air bags. The technology is anticipated to reduce occupant ejection in rollover and also may provide a counter measure for some types of non-ejection rollover related occupant injuries related to head strikes to ground or to vehicle structures covered by the inflated air bag at occupant contact.

The NHTSA has finalized its performance requirements in FMVSS 226 (ejection mitigation) [11]. The standard imposes an energy absorption requirement and excursion limits in response to an impulse insult from a guided linear impactor. The rule was finalized in January of 2011, first required implementation is September 1, 2014 but early compliance credits can be earned starting after February 2011, and carry forward credits can be earned with early applications so as to smooth and match phase in proportions to manufacturers' individual portfolio change plans. The phase in period ends August 31, 2017 save for altered vehicles and those manufactured in more than a single stage. The NHTSA forecasts that application of the technologies necessary to satisfy these performance requirements will reduce rollover related occupant fatal injuries by 373 annually when fully applied.

ROOF STRENGTH RULE MAKING

The technical literature is rich in studies examining the relationship between vehicle characteristics and occupant injury outcomes in rollover crashes. This paper will not attempt to survey or report upon the nature and conclusions various authors have published regarding that matter. However, two studies performed by the NHTSA are critical to an understanding of the NHTSA's rule making action on the vehicle parameter of roof strength [references12 and 13]. Both studies used NASS CDS data for rollover crashes to collect belted occupant injury outcomes and roof profile data over the occupants of interest to look for relationships between head, face and neck injury from roof contact and roof deformation. The roof included the roof panel and all surrounding structures, pillars, headers, etc. Austin et al. [12] found a dichotomous relationship between post crash headspace (positive or negative value) and injury severity. Strashny [13] found a statistically significant relationship between the maximum severity injury to the head, face or neck, and the amount of roof deformation measured as roof deflection or residual headspace. Neither Strashny nor Austin claimed that the statistical correspondence they found established a causative relationship between roof deformation and occupant injury. In addition to the statistical relationships, both NHTSA researchers found over 99% of rollover crash involved occupants that experience head, face, or neck contact with the roof are not seriously injured and register a maximum head, face, or neck AIS injury level of 0, 1, or 2. This would indicate vehicle structures and restraint systems have been well balanced to provide good occupant protection in rollover crashes for belted occupants.

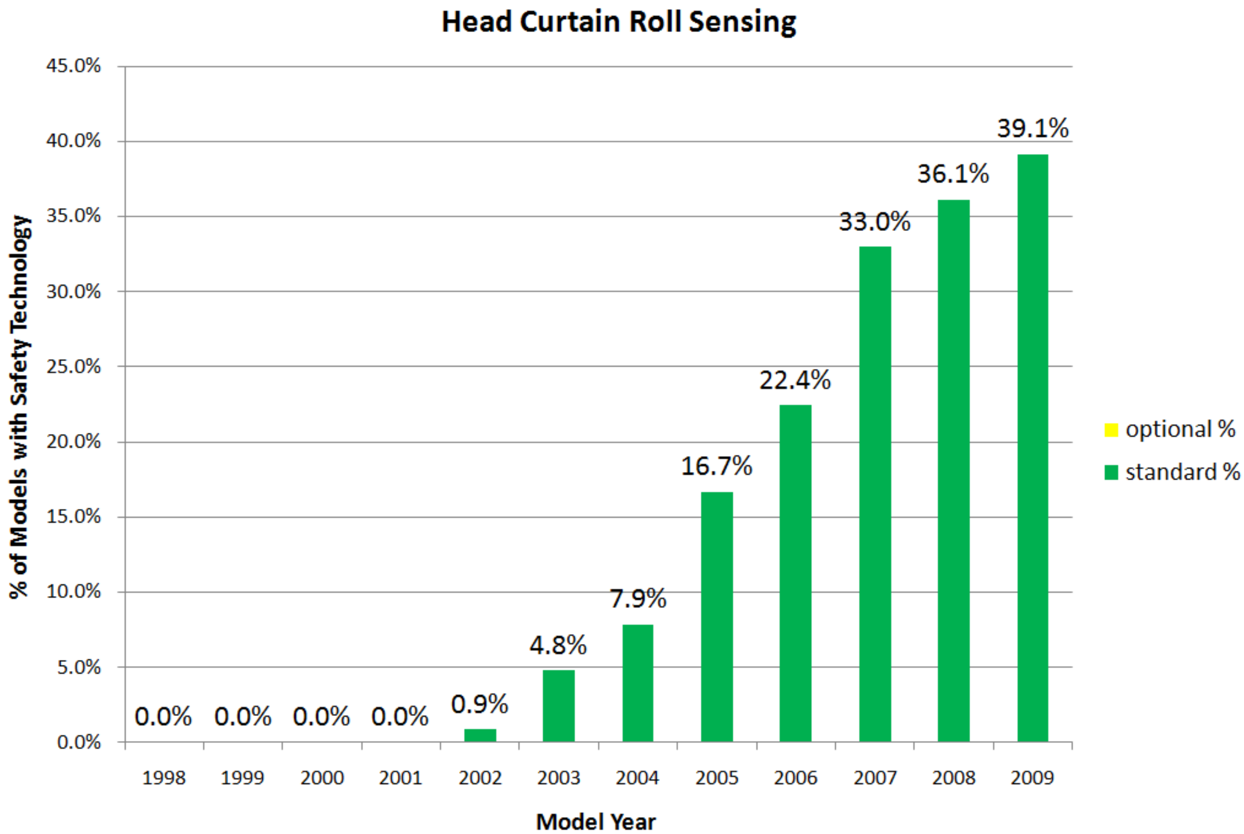

Figure 3. Installation rate for rollover deployed roof rail air bags.

The NHTSA applied the findings of statistical significance in promulgating its roof strength standard, FMVSS 216 [14], published as a final rule in May 2009. The new standard refined many elements of the existing FMVSS 216 test procedure; it added new acceptance criteria for roof contact with a seated occupant, increased the load requirement acceptance criteria as a proportion of vehicle mass, maintained the basic test orientation and load application device from the then existing rule, and applied a new requirement for sequential testing of both sides of an individual vehicle for compliance.

The NHTSA forecast a small reduction in rollover related fatal injuries to occupants of 135 annually after full application.

ROLLOVER INJURY SCIENCE

As is the case for roof crush and injury, the literature is rich with regards to the science of rollover injury causation. A comprehensive discussion of that body of literature is beyond the scope and length of this paper but two more recent studies bear review to add clarity and context to the current state of knowledge.

In 2008, Exponent reported results for a series of dolly rollover tests it had performed using a 2003 Subaru Forester as the research tool. Exponent explained that the Subaru Forester was selected as the test subject as it was a vehicle with a high roof strength to vehicle weight ratio (the strength to weight ratio or SWR); the SWR for the Subaru Forester is about 4.8. Three test vehicles were instrumented to record pillar displacements and one of the tests was also fitted with instrumented Anthropomorphic Test Devices (ATD or crash test dummies) in the front outboard seating positions that recorded injury measures throughout the test [15].

Two tests were conducted without ATDs; as the tests continuously recorded roof deformation, for the first time in rollover injury research, engineers could examine the time history of roof deformation in a severe rollover crash, and compare the post crash roof condition to the deformations that obtained during the rollover event itself. Exponent observed there was little correspondence between post crash roof deformation and the time history displacement of roof components during the rollover.

One rollover test was conducted with instrumented pillars and instrumented ATDs in the front outboard seating positions. The most interesting observations from this test is the time history correspondence between neck compression for the ATD at first ground strike and the structural response measured as pillar displacement (roof deformation) following the first ground strike while the vehicle was inverted and continuing in the rollover sequence. The ATD maximum neck compression occurred early in the ground strike as roof deformation was just initiating. Maximum roof deformation did not occur until later in the ground strike event and by that time, the ATD neck load had gone from compression into tension indicating that the ATD torso was no longer loading the neck due to spinal alignment. These successive events are depicted in Figures 4 (maximum neck compression) and 5 (maximum roof pillar deformation) and shown below. These are Figures 7 and 8 in [15].

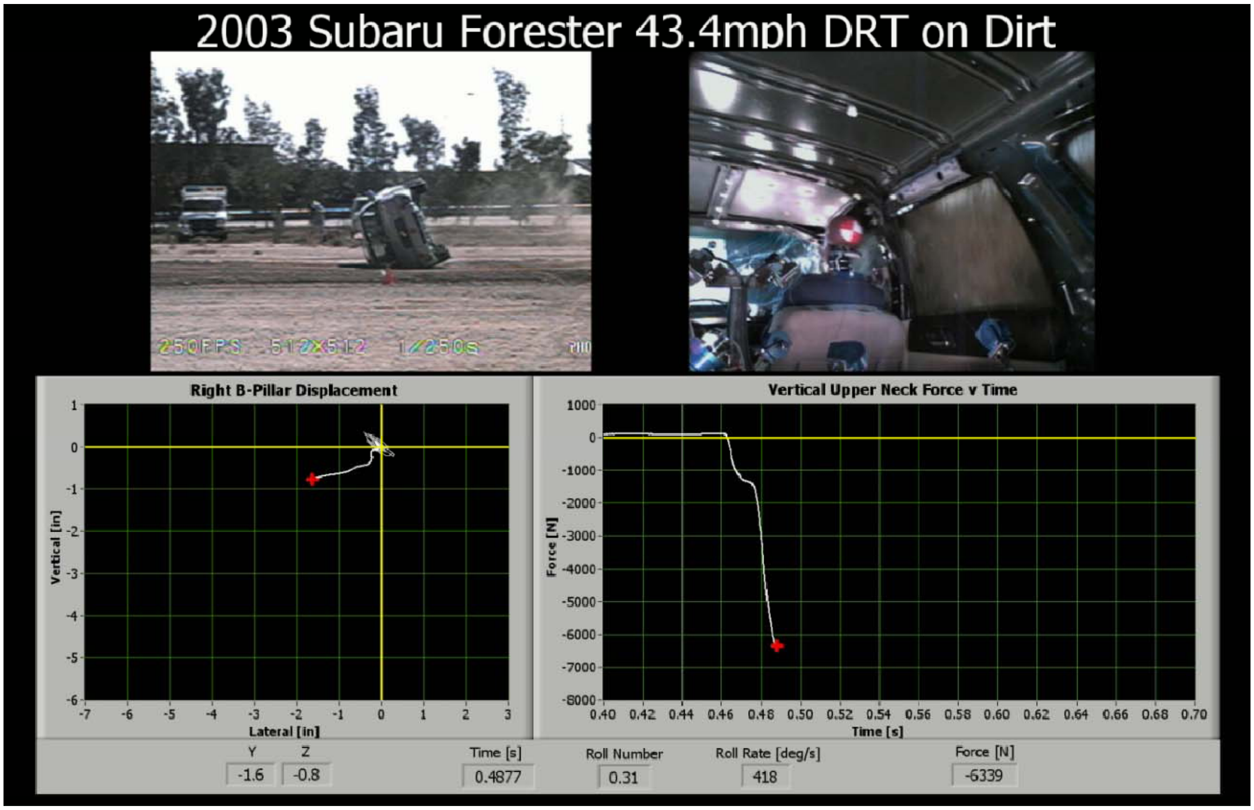

Figure 4. Captured frame from the synchronized data with composite video of the passenger-side B-pillar displacement at the time of passenger ATD peak compressive upper neck load during the first passenger side (near-side) roof rail impact (above).

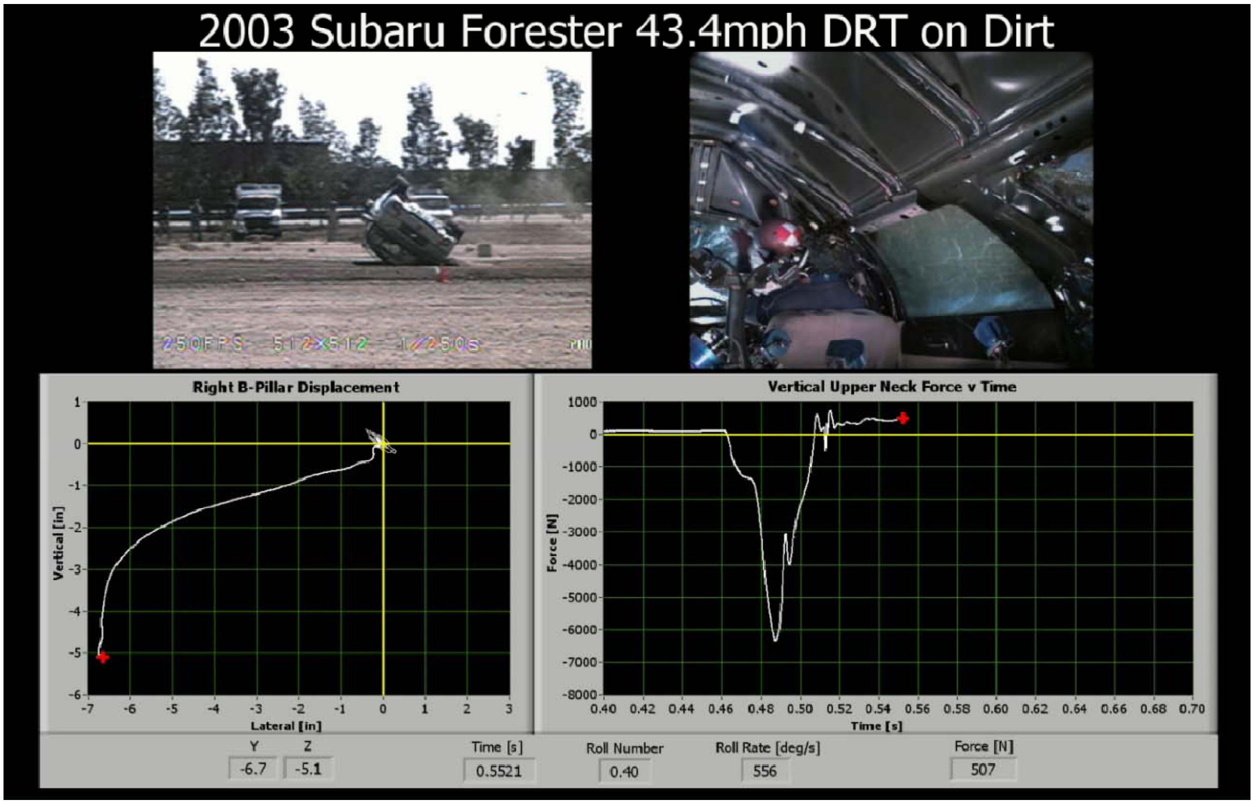

Figure 5. Captured frame from the synchronized data with composite video of passenger ATD axial upper neck load at the time of peak passenger-side B-pillar displacement during the first passenger-side (near-side) roof rail impact.

Of equal interest is a research paper GM issued concerning observations it made during development of its rollover roof rail air bags for occupant injury control in rollover [16]. GM conducted some of its rollover sensor signature development tests with instrumented ATDs and in O'Brian-Mitchell [16] GM reported the test configurations and ATD test outcomes in which IARV values were exceeded.

One hundred seventy-six of the GM sensor signature rollover tests were conducted with Hybrid III 50th percentile male ATDs in the front outboard seating positions. Some tests were conducted with belted ATDs and some with unbelted ATDs. The test configurations GM used were: 1) trip-over (curb trip-over, soil trip-over, gravel trip-over, friction trip-over, curb trip-over sled, and soil trip-over sled); 2) fall-over (ditch fall-over with dirt slope and ditch fall-over with high friction slope); 3) flip-over (corkscrew ramp flip-over); 4) SAE J2114 dolly rollover; and 5) other (half corkscrew ramp and bounce-over). In many tests, the side window openings were covered with a fabric membrane to record ATD loadings at the window openings; those loads were then later used to develop the performance criteria (energy capacity, force limits, and excursion limits) for rollover roof rail air bags [17]. ATD kinematics during the rollover were recorded using onboard high speed cameras.

GM examined the ATD injury measure test records for all of the tests. It evaluated events in which the IARVs were exceeded and reported ATD injury measures exceeding IARV limits due to ATD head strikes with: vehicle structures (leading side pillars, roof rails, and trailing side overhead structures), the other ATD, ground, door beltline, and with the window membrane. GM did not report any ATDs were ejected. Belted and unbelted ATDs recorded injury measures exceeding IARVs.

Most significantly, some of the ATD head strikes that generated Head Injury Criteria (HIC) or neck compression injury measures that exceeded the IARV limits occurred when the vehicle was not inverted. In those events, it is obvious that roof strength and roof deformation were decoupled from the head strikes that generated the injury potential, reference Table 1 (Table 7 in [17]). It is noteworthy that in the GM test series there was a greater frequency for IARV exceeded contact events while the test vehicles were not inverted, than when the test vehicles were inverted. Application of rollover roof rail air bags may offer some potential for mitigation of some of these potential injury events (head strikes to structure covered by the bags and head strikes to ground) as well as provide potential to mitigate rollover ejection, the intent of the NHTSA's FMVSS 226 rulemaking.

Table 1.
Restraint condition, ATD seating location, and vehicle orientation at events in which an IARV was exceeded

	Restraint usage - Contacts by vehicle orientation			
	On wheels	On leading side	On roof	On trailing side
Unbelted Leading Side	1	10	2	1
Belted Leading Side	0	11	3	0
Unbelted Trailing Side	3	15	2	0
Belted Trailing Side	1	3	19	0
Sum:	5	39	26	1

ROOF STRENGTH AND ROLLOVER INJURY SCIENCE

There is a physical relationship that explains the statistical associative relationship noted by NHTSA researchers Austin and Strashny. Roof deformation consequent to a rollover event is a function of three primary variables: the energy demand that is placed upon the vehicle structure in the rollover (E), the orientation of the vehicle structure at application of the ground strike impulse (O), and the strength properties of the vehicle structure in the orientation at ground strike (S). Consider the primary variables that determine occupant injury potential when a vehicle is inverted and striking the ground in rollover; these variables are: the energy demand that is placed upon the occupant in the ground strike event (e), the orientation of the occupant as related to head, neck, and spine alignment (o), and the strength properties of the occupant head/neck/spine in the orientation at ground strike (s). Both rollover event outcomes are dependent upon the same set of variables although the specific values that obtain each instant during the rollover event are obviously unique to the vehicle and any occupant. As the variables are similar, it is not surprising that one would find an associative correspondence between occupant injury likelihood and post crash roof deformation. High energy events are similarly challenging for both vehicle structures and rollover involved occupants.

ROLLOVER TYPOLOGY

Exponent used NASS CDS to characterize rollover crashes by type to compare the resultant profile to the rollover types engineered in the GM rollover sensor. The NHTSA has already reported that its review of rollover sensor performance in real world collisions has been appropriate and therefore it declined to specify rollover air bag actuation criteria in FMVSS 226 [11].

Data was extracted from the NASS CDS database for the years 2000-2009 to investigate the circumstances surrounding vehicle rollover and the injuries resulting from this type of vehicle crash mode. Exponent considered rollover crashes recorded in 2000 to 2009 NASS years for all light duty vehicles (passenger cars, sport utility vehicles, pickup trucks, and vans) for vehicle model years 1998 to 2010 for which occupant injury level was known. The nature of rollover crashes was characterized by: the number of quarter turns, roll initiation source, roll location relative to the roadway, and extent of roof intrusion. Rollover exposed occupants were examined by distribution of MAIS and safety belt usage. The analysis considered all rollover types defined in NASS CDS.

The proportion of rollover crashes where the occupant injury level is known is shown in Figure 6 below. The analysis also reports on the distribution of belted occupant injury severity by rollover type in Figure 7 below. Data was extracted from the NASS CDS database using the SAS database query software. NASS CDS weighting factors were applied. This allows the cases sampled by NASS CDS to be projected to the national estimates . These weighting factors are applicable to general characteristics of each case.

We can match NASS CDS rollover types with the rollover tests that served as the basis for GM's sensor engineering. We can first observe that an on road "Turn Over" event is a relatively rare rollover occurrence, 1.6% of the population studied. GM's sensor test matrix does not comprehend several of the NASS CDS categories: "End-Over-End", "Unknown Rollover Initiation Type", "Other Rollover Initiation Type," and "Collision With Another Vehicle." Thus the sensor was not engineered to explicitly recognize about 16% of rollover crashes. Perhaps the sensors can register some of these as rollover independent of

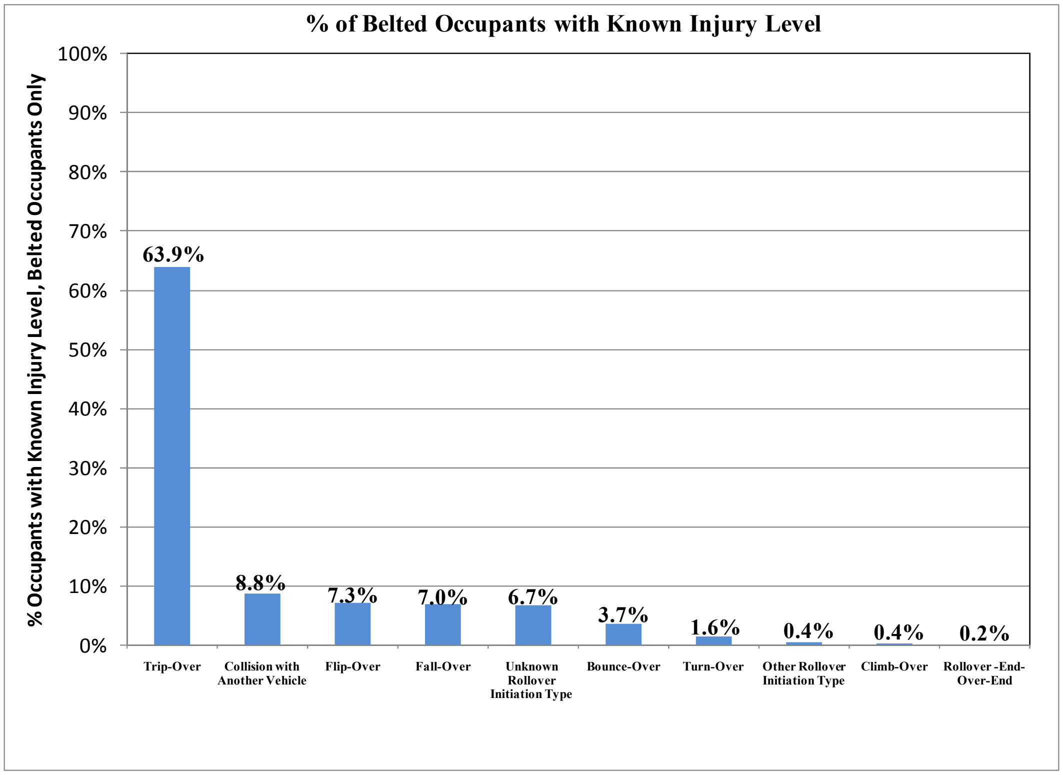

Figure 6. Distribution of belted occupants with known injury level by rollover type in NASS CDS.

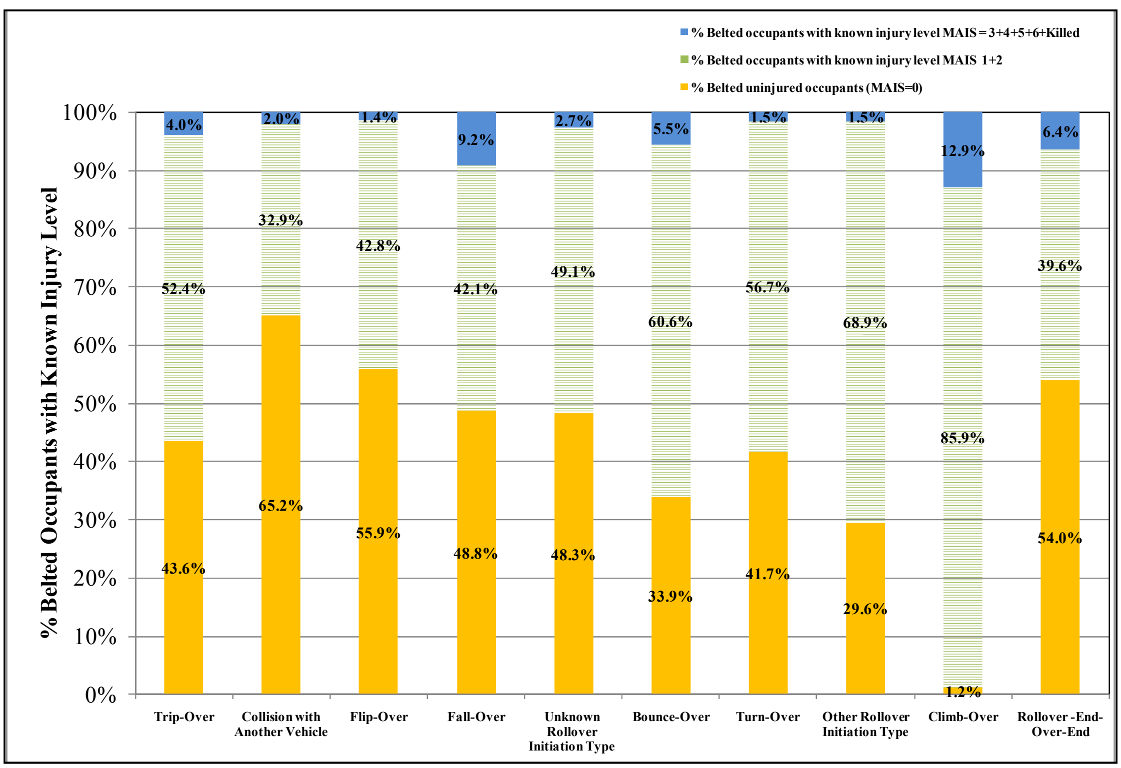

Figure 7. Belted rollover occupant injury severity by NASS CDS defined rollover type.

the initiating cause so in some of these types, perhaps

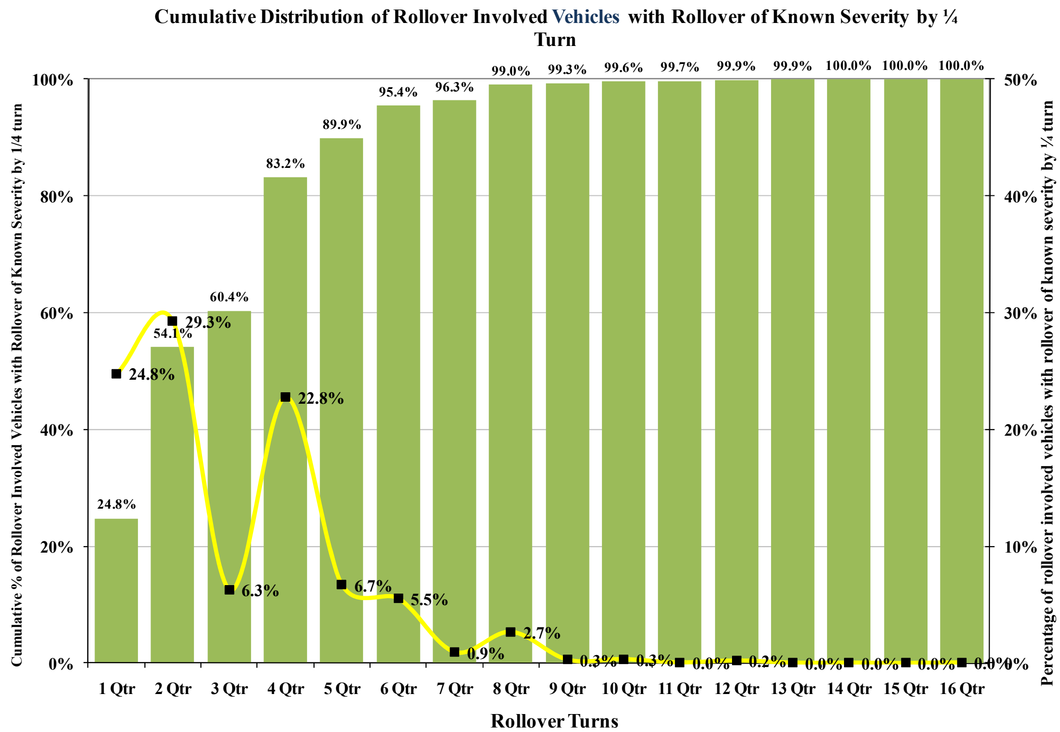

Figure 8. Rollover crash severity frequency by quarter turn and cumulative frequency.

the initiating cause and the sensor would recognize and command deployment of the air bags.

It would appear that the balance of the NASS CDS rollover types correspond to some element of the sensor engineered performance set and the rollover roof rail technology may potentially apply to about 84% of the class of rollover crashes studied.

We also plotted the rollover severity distribution measured by number of quarter turns, Figure 8, and the distribution of occupant injury level by quarter turns in Figure 9. Figure 9 illustrates the point that the likelihood of severe injury increases with rollover crash severity generally although the trend is not monotonic.

DISCUSSION

The NHTSA developed a comprehensive plan for rollover injury control with three elements: collision avoidance, occupant protection, and occupant containment from ejection. It has completed rule making in all three domains. On an individual basis, motor vehicle manufacturers have undertaken to engineer vehicles to performance criteria in all three domains as well; manufacturers' actions preceded rule making.

REFERENCES

[1] Federal Motor Vehicle Safety Standards. Electric Stability Control. Controls and Displays. FMVSS 126 49 CFR Parts 571 and 585.

[2] Alliance of Automobile Manufacturers comment dated February 27, 2006; Docket Number NHTSA-2005-22143.

[3] Alliance of Automobile Manufacturers comment dated March 27, 2008; Docket Number NHTSA-2008-0015.

[4] Ford Motor Company comments dated October 19, 2005; Docket Number NHTSA-199-5572.

[5] Ford Motor Company comments dated November 18, 2005; Docket Number NHTSA-2005-22143.

[6] Ford Motor Company comments dated July 10, 2008; Docket Number NHTSA-2008-0015.

[7] Nissan comments dated May 10, 2007; Docket Number NHTSA-2006-26555.

[8] General Motors Corporation comments dated August 16, 2002; Docket Number NHTSA-1999-5572.

[9] General Motors Corporation comments dated June 16, 2005; Docket Number NHTSA-1999-5572.

[10] General Motors Corporation comments dated March 20, 2008; Docket Number NHTSA-2008-0015.

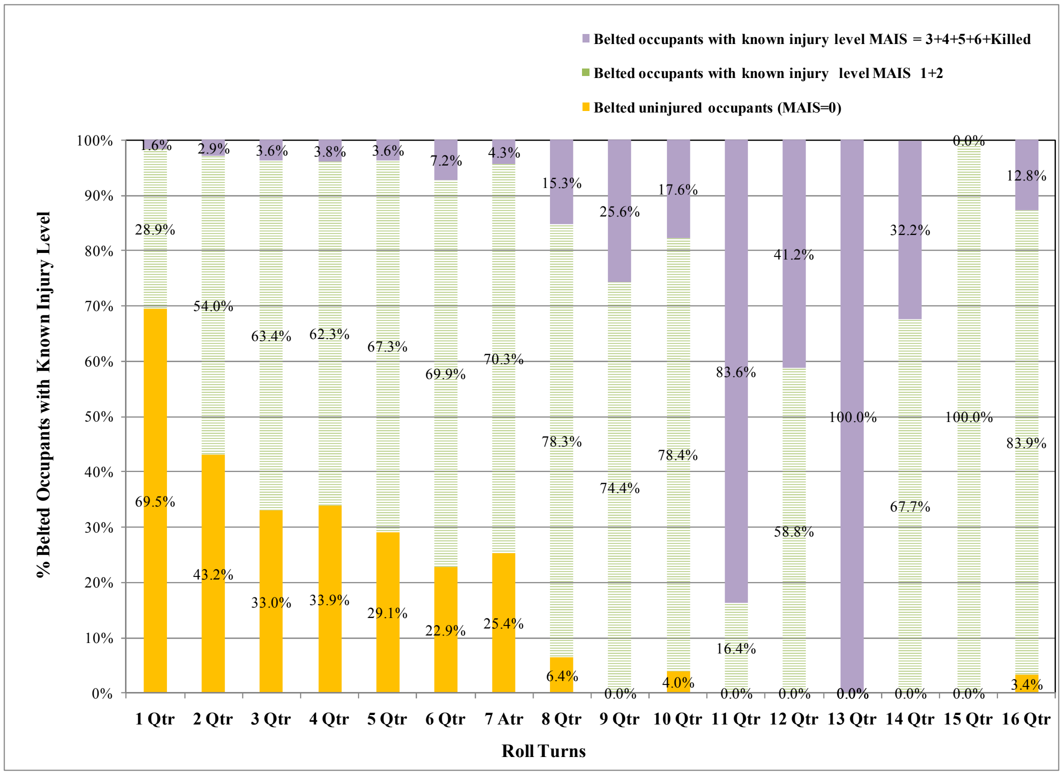

Figure 9. Belted occupant injury level by rollover collision severity as measured by number of quarter turns.

[11] Federal Motor Vehicle Safety Standards. Ejection Mitigation. FMVSS 226 49 CFR Parts 571 and 585.

[12] Austin, Rory et al. "The Role of Post-Crash Headroom in Predicting Roof Contact Injuries to the Head, Neck, or Face During FMVSS No. 216 Rollovers." Docket Number NHTSA-2005-22143.

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