

DATA ANALYSIS METHODOLOGY AND OBSERVATIONS FROM ROLLOVER SENSOR DEVELOPMENT TESTS

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ABSTRACT

Although rollover crashes represent a small fraction (approximately 3%) of all motor vehicle crashes, they account for roughly 22% of crash fatalities to occupants of cars, light trucks, and vans (NHTSA Traffic Safety Facts, 2005 (1)). Of the fatally injured occupants in rollover crashes, 57% were ejected (2). With the development of advanced airbag and sensing technologies, General Motors (GM) has introduced systems intended to help mitigate the risk of head and torso ejection during a rollover crash.

The implementation of these systems was preceded by the development of a suite of rollover sensor laboratory tests designed to simulate several types of rollover initiations. Many of these tests were conducted with instrumented Hybrid III 50th percentile Anthropomorphic Test Devices (ATDs) seated in the front outboard seating positions. For tests in which an Injury Assessment Reference Value (IARV) (3) was exceeded, a methodology was developed to provide a detailed summary of the vehicle kinematics, timing of ATD contacts, ATD peak responses, and film observations.

Using this procedure, GM was able to identify common trends of peak ATD responses relative to restraint use and rollover initiation type. IARVs were shown to be exceeded in all test types, with both belted and unbelted ATDs. Although exact ATD motion was unpredictable, test type did have some effect on the location of ATD contact. In addition, the location of contact by leading side ATDs was influenced more by test type than by restraint usage. IARVs were shown to be exceeded with the vehicle at a wide range of orientations. Any impact during which the motion of the ATD head was arrested prior to stopping the ATD body showed the potential for exceeding a neck compression IARV. This was true regardless of vehicle orientation, location of the head contact, or dynamic deformation of the vehicle's structure.

INTRODUCTION

General Motors first introduced rollover crash sensors in 2005 model year mid-sized sport utility vehicles and has continued to develop this technology for other vehicle model lines during subsequent model years. The introduction of these sensors was preceded by the development of a suite of rollover sensor laboratory test types and test procedures that were used to develop the sensor calibrations for production applications. (4)

GM has conducted 176 tests during the development of the suite of rollover sensor signature laboratory test methods as well as the development of production sensor calibrations for 2005 and 2006 model year vehicles. These tests were conducted to generate vehicle sensor signatures as well as ATD kinematics for sensor calibration. The test types included:

1. Trip-over:
 - a. Curb trip-over
 - b. Soil trip-over
 - c. Gravel trip-over
 - d. Friction trip-over
 - e. Curb trip-over sled
 - f. Soil trip-over sled
2. Fall-over:
 - a. Ditch fall-over with dirt slope
 - b. Ditch fall-over with high friction slope
3. Flip-over: Corkscrew ramp flip-over
4. SAE J2114 Dolly rollover
5. Other:
 - a. Half corkscrew ramp
 - b. Bounce-over

The data collected were not identical across all tests, but the majority of tests included the following:

1. ATD head accelerations
2. ATD chest accelerations
3. ATD upper neck loads and moments
4. ATD lower neck compression
5. Seat belt loads, on tests with belted ATDs
6. Vehicle accelerations and roll rates

The vehicles tested included:

1. Mid-sized sport utility vehicles
2. Full-sized sport utility vehicles
3. Cross over vehicles
4. Passenger cars

The tests were conducted with belted and unbelted Hybrid III 50th percentile ATDs in the front row

outboard seating positions. In many of the tests, nylon-fabric membranes were attached to the vehicle structure across the front side window openings. High-speed cameras were installed in the test vehicles to record the kinematics of the ATDs relative to the vehicle. In addition, high speed cameras were placed outside of the test vehicles to document the kinematics of the test vehicle.

CHARACTERIZATION OF ENTIRE DATASET

Test Type

A comparison of field statistics for the types of rollover initiations in the field to the 176 laboratory test dataset under analysis is shown in Figure 1. The trip-over tests make up the largest proportion of the laboratory dataset and reflect the majority of field rollover initiations (2001-2005 NASS-CDS, Cars + LTV's).

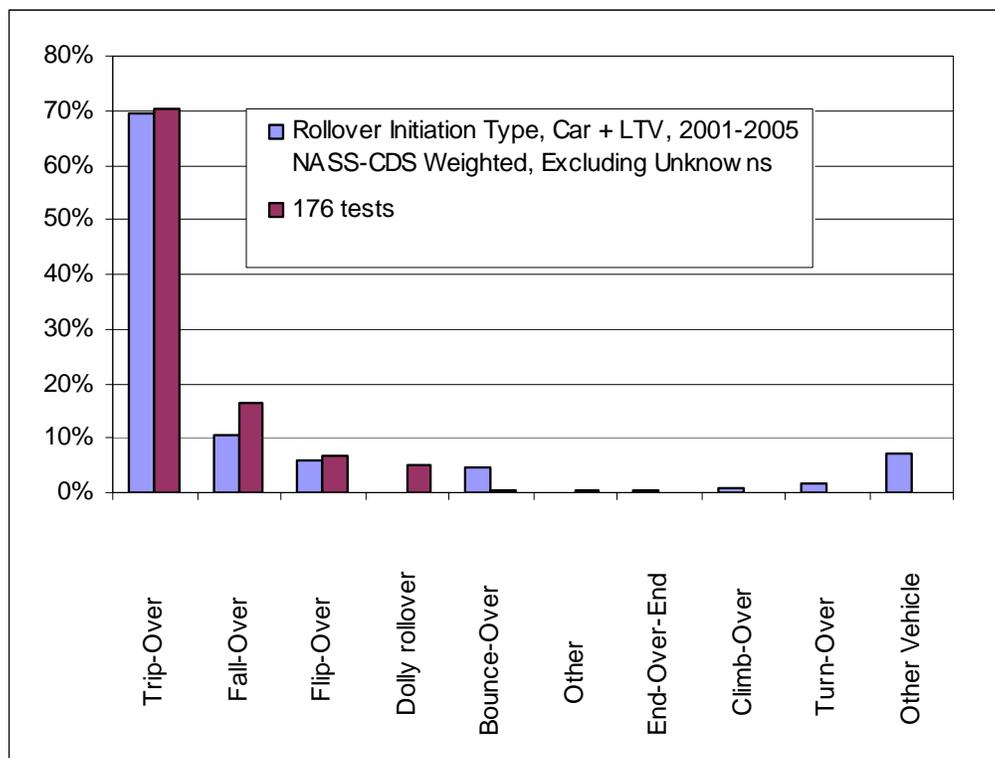


Figure 1. Distribution of test types.

Quarter Turns Achieved

Of the 176 tests under analysis, 95 resulted in a rollover of at least ¼ turn. A comparison of these 95 tests which rolled at least ¼ turn to statistics from field rollovers is shown in Figure 2. The larger

proportion of laboratory tests that rolled only ¼ turn is indicative of the objective of the rollover testing itself - to develop a rollover sensing calibration. This puts an emphasis on simulating vehicle kinematics that approach and/or exceed a "threshold" in terms of vehicle rollover.

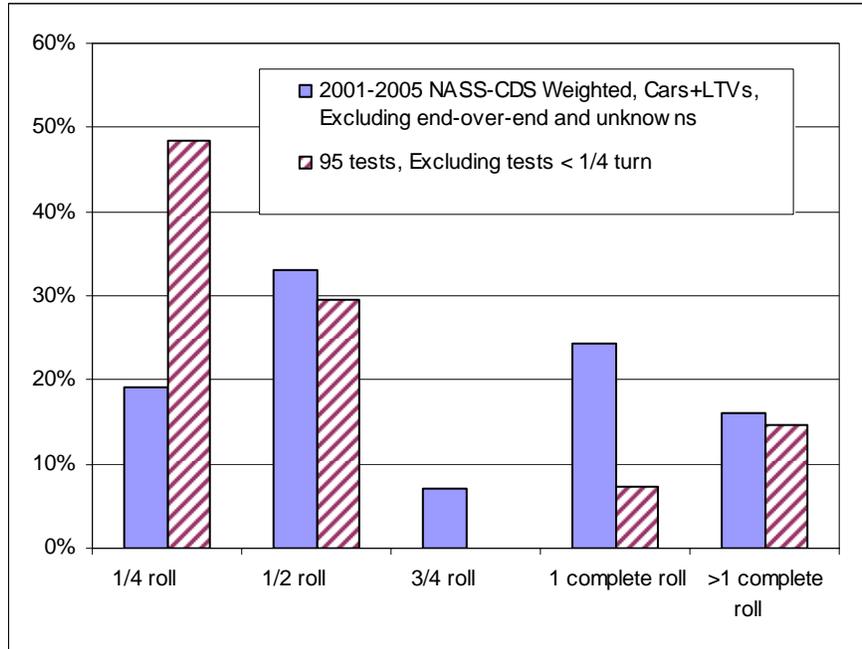


Figure 2. Comparison of field data to test data by quarter turn achieved.

CHARACTERIZATION OF TESTS WITH IARV EXCEEDED

For the 176 tests conducted, the data was subsampled for tests in which the ATD recorded injury values which exceeded IARVs. It was observed that in the 81 tests which did not achieve at least ¼ turn, no IARVs were exceeded. Of the remaining 95 tests, 48 tests had at least one IARV exceeded.

Quarter Turns Achieved

Tables 1 and 2 show the distribution of the 176 tests conducted with and without an IARV exceeded by test type and by number of quarter turns achieved. The dataset shows 46% (81) of the tests rolled less than ¼ turn, which again reflects the objective to develop a rollover sensor calibration. Although the data shows that an IARV can be exceeded in a rollover of only ¼ turn, the majority of IARVs were exceeded in tests with multiple ¼ turns.

Table 1. Number of quarter turns achieved – IARV not exceeded

	Number of Quarter Turns Achieved													Total
	IARV not Exceeded													
	0	1	2	3	4	5	6	7	8	9	10	11	12	
Trip-over	68	26	3	0	1	0	2	0	1	0	0	0	0	101
Fall-over	12	5	3	0	0	0	0	0	0	0	0	0	0	20
Flip-over	0	2	2	0	0	0	0	0	0	0	0	0	0	4
Dolly	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Other	1	0	0	0	1	0	0	0	0	0	0	0	0	2
All	81	33	8	0	2	0	2	0	1	0	0	0	1	128

Table 2.
Number of quarter turns achieved – IARV exceeded

	Number of Quarter Turns Achieved IARV Exceeded													Total
	0	1	2	3	4	5	6	7	8	9	10	11	12	
Trip-over	0	9	7	0	3	0	2	0	2	0	0	0	0	23
Fall-over	0	2	7	0	0	0	0	0	0	0	0	0	0	9
Flip-over	0	2	6	0	0	0	0	0	0	0	0	0	0	8
Dolly	0	0	0	0	2	0	0	0	1	1	1	0	3	8
Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0
All	0	13	20	0	5	0	2	0	3	1	1	0	3	48

Restraint Condition

Direct A-to-B comparisons of specific tests were not possible due to the underlying test objective, variation in vehicle models and rollover test types, and the inherent non-repeatability of rollover testing.

Therefore, observations focused on the dataset of 95 tests (190 ATDs) in which a rollover of at least ¼ turn was achieved. Table 3 and Table 4 show the distribution of restraint usage for the various test types in tests which rolled at least ¼ turn.

Table 3.
Leading side ATD in tests which rolled at least ¼ turn

	Unbelted		Belted	
	IARV Not Exceeded	IARV Exceeded	IARV Not Exceeded	IARV Exceeded
Trip-over	7	6	41	2
Fall-over	2	3	7	5
Flip-over	0	1	7	4
Dolly	0	3	4	2
Other	0	0	1	0
All	9	13	60	13

Table 4.
Trailing side ATD in tests which rolled at least ¼ turn

	Unbelted		Belted	
	IARV Not Exceeded	IARV Exceeded	IARV Not Exceeded	IARV Exceeded
Trip-over	3	10	33	10
Fall-over	2	3	11	1
Flip-over	0	1	5	6
Dolly	0	3	1	5
Other	0	0	1	0
All	5	17	51	22

For this dataset, 14 of the 44 unbelted ATDs did not have an IARV exceeded, while 111 of the 146 belted ATDs did not exceed an IARV. Therefore, 68% of the unbelted ATDs and 24% of the belted ATDs exceeded an IARV. This suggests the likelihood of an ATD exceeding an IARV decreases with the use of belts, which is consistent with observations of rollover field data (5).

The seat belt types included all-belts-to-seat (ABTS) as well as belt-to-pillar configurations. Retractor pretensioners or buckle pretensioners were included in some belted tests. However, the small size of the dataset precludes analysis of the effects of seat belt configuration, anchor location, and pretensioner type.

DATA ANALYSIS METHODOLOGY

A summary chart was created for each ATD in the 48 tests that had at least one IARV exceeded. This involved a total of 26 leading side ATDs (13 belted, 13 unbelted), and 39 trailing side ATDs (22 belted, 17 unbelted). An example summary chart is shown in Figure 3.

The chart is a tool used to develop a one-page summary of the rollover test. The x-axis represents time in milliseconds, while the y-axis reflects the roll angle of the vehicle. The time at which a peak value occurred is plotted on each chart, along with the

appropriate data label. Data labels in bold show peak ATD loads that exceeded the IARV, while those in italics show observations estimated from film. Film observations may include items contacted by the ATD, as well as estimated timing of dynamic vehicle upper structure deformation. Pictures of the vehicle and ATD orientation at the time at which an IARV was exceeded are also included.

In Figure 3 for example, two IARVs were exceeded on the trailing side ATD during a single impact -- head contact to the leading side B-pillar. At this point in the rollover, the vehicle has achieved only 52 degrees of roll angle.

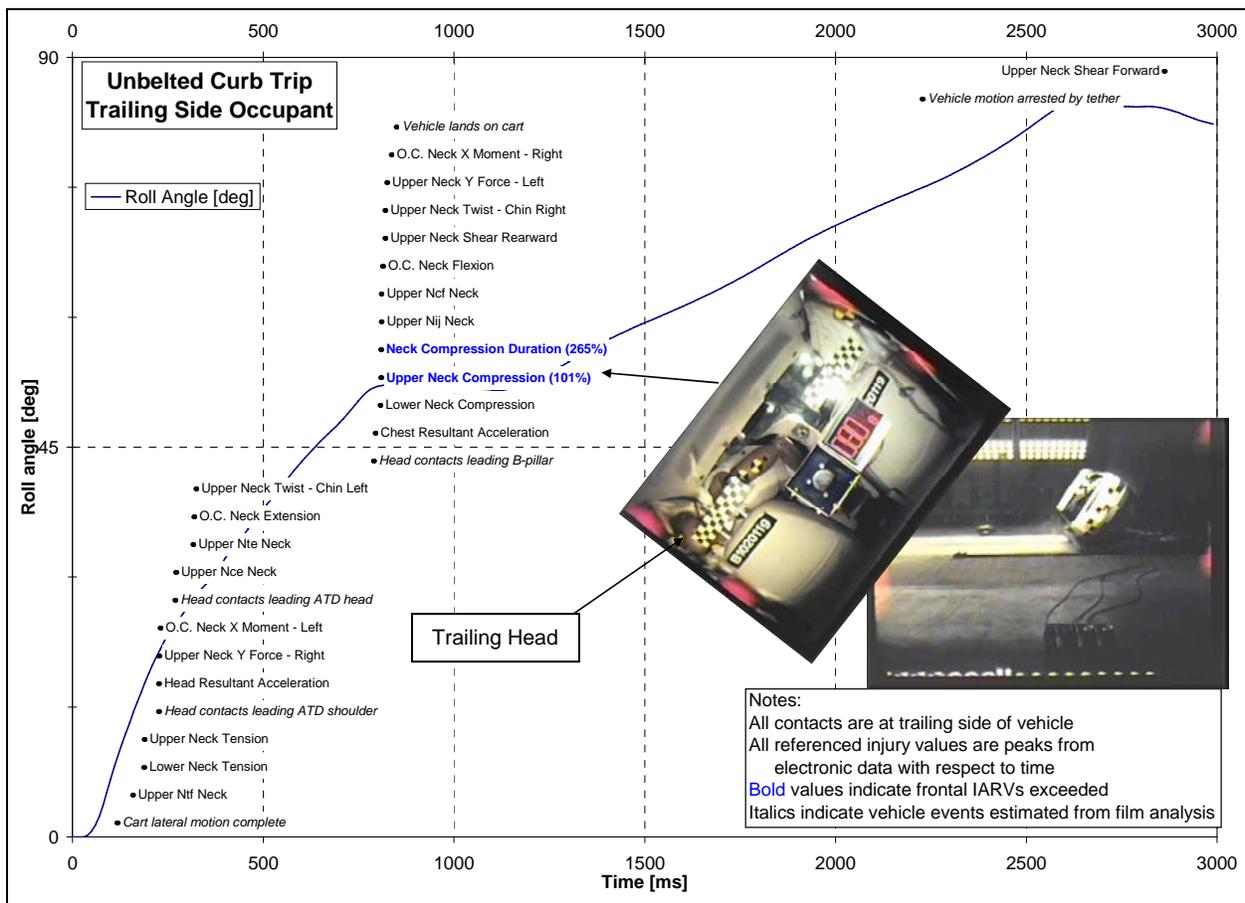


Figure 3. Sample summary chart.

DATASET OBSERVATIONS

The 48 tests with at least one IARV exceeded were analyzed by IARV type, ATD contact location, test type, and restraint usage.

IARV type

The distribution of types of IARVs exceeded on leading side and trailing side are shown in Figure 4 and Figure 5, respectively. For these tests, the following IARVs were grouped as follows:

1. One upper neck compression IARV was 'counted' if an ATD response exceeded the peak upper neck compression IARV and/or the peak upper neck compression time duration IARV.
2. One lower neck compression IARV was 'counted' if a peak lower neck compression IARV was exceeded.
3. One Nij IARV was 'counted' if one or more Nij (i.e. Ntf, Nce, Nte, Ntf) were exceeded.
4. One HIC IARV was 'counted' if a test exceeded the 15ms and/or 36 ms HIC.
5. The 'Other Neck IARVs' included upper neck shear rearward, upper neck occipital condyle moment left, upper neck occipital condyle flexion and upper neck occipital condyle extension.

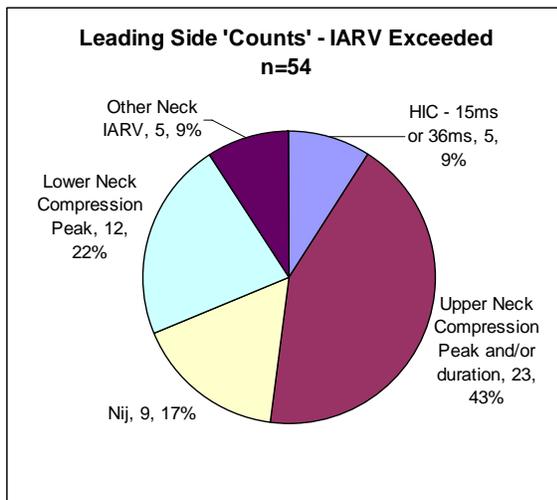


Figure 4. Leading side 'counts' – IARV exceeded.

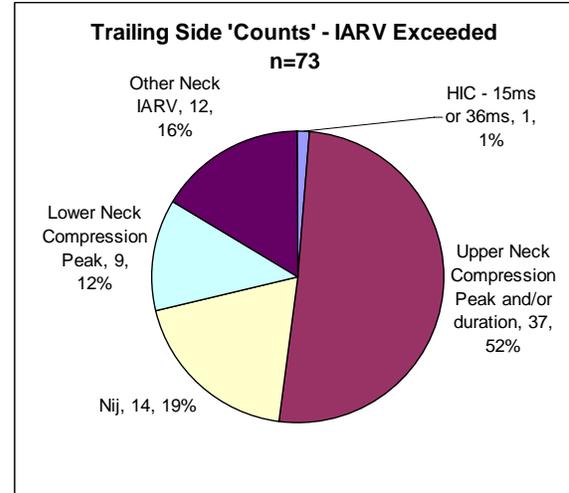


Figure 5. Trailing side 'counts' – IARV exceeded.

Of the 96 ATDs in the 48 tests, 65 ATDs had at least one IARV exceeded for a total of 127 'counts'. The distribution of exceeded IARVs is similar between leading and trailing side ATDs except for Head Injury Criteria (HIC), which has a larger proportion on the leading side. The lone example of a HIC IARV being exceeded by the trailing side ATD was the result of ATD to ATD contact.

ATD Contact Location

A description of the categories used to describe the locations of contact, with associated example photographs showing vehicle orientation and ATD orientation relative to the ground, is as follows:

1. Head contact to leading side door at beltline: The unbelted leading side ATD moved toward the trailing side and then moved back toward the leading side resulting in head contact to the leading side door (Figure 6).



Figure 6. Head contact to leading side door at beltline.

2. Head contact to ground - convertible: The head of the belted ATD contacted the ground through

the open convertible roof. The convertible roof was not in a closed position for the tests.

3. Head to leading/trailing side structure at event arrest: These tests were corkscrew ramp flip-over tests where the vehicle was arrested by contacting a row of jersey barriers that were placed in front of the building wall. The time at which the vehicle contacted the jersey barriers is considered to be the event arrest.
4. Head contact to ground or ground/roof rail on leading side: The head of the leading side ATD either contacted the ground through the leading side window membrane (a more lateral outboard motion) or the contact was to the ground with the head in contact with both the leading side roof rail and membrane (a more vertical outboard motion) (Figure 7).

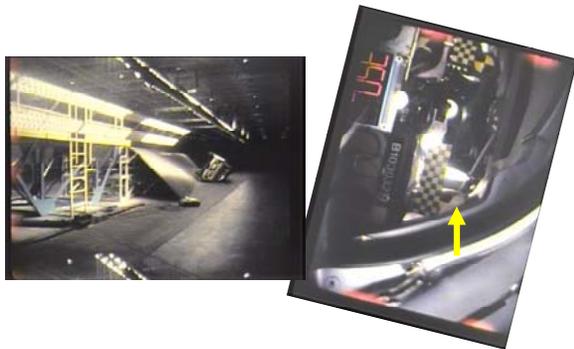


Figure 7. Head contact to ground/roof rail.

5. Head contact to leading/trailing side structure: The head contacted the roof rail, door frame, roof etc. on the leading/trailing side of the vehicle (Figure 8).

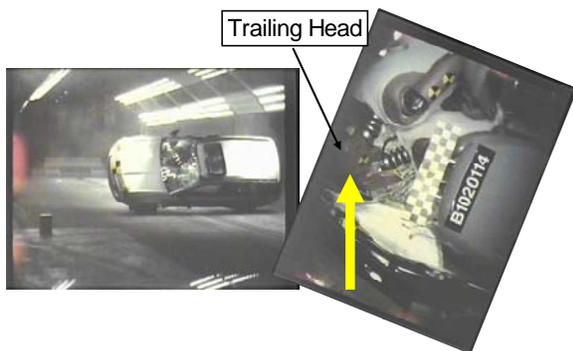


Figure 8. Head contact to leading side structure.

6. Head contact to ground through leading side membrane: The unbelted trailing side ATD moved toward the leading side and contacted the leading side window membrane which was in

contact with the ground due to vehicle orientation. (Figure 9).



Figure 9. Head contact to ground through leading side membrane.

7. Head contact to leading side window membrane: The unbelted trailing side ATD moved toward the leading side and was arrested by the leading side window membrane when the leading side of the vehicle was not in contact with the ground (Figure 10).



Figure 10. Head contact to leading side window membrane.

8. Head contact to leading side ATD: The head of the trailing side ATD contacted the leading side ATD (Figure 11).



Figure 11. Head contact to leading side ATD.

9. Head contact to ground/roof rail on trailing side: The trailing side ATD contacted the trailing side roof rail and window membrane which were in contact with the ground.
10. Insufficient film length/No onboard lights: In some tests, the onboard camera ran out of film prior to the ATD contact or the onboard lights were lost for the entire test, so ATD contacts were not visible.

A summary of the locations of contact for a leading side ATD impact during which an IARV was exceeded is shown in Figure 12. The summary for the trailing side is shown in Figure 13. It should be noted that multiple contacts during which an IARV was exceeded occurred in some tests, resulting in 71 contacts during which IARVs were exceeded for the 65 ATDs.

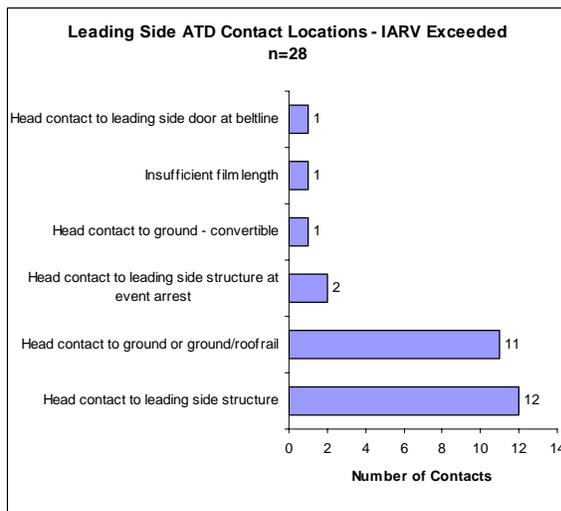


Figure 12. Leading side ATD contact locations – IARV exceeded.

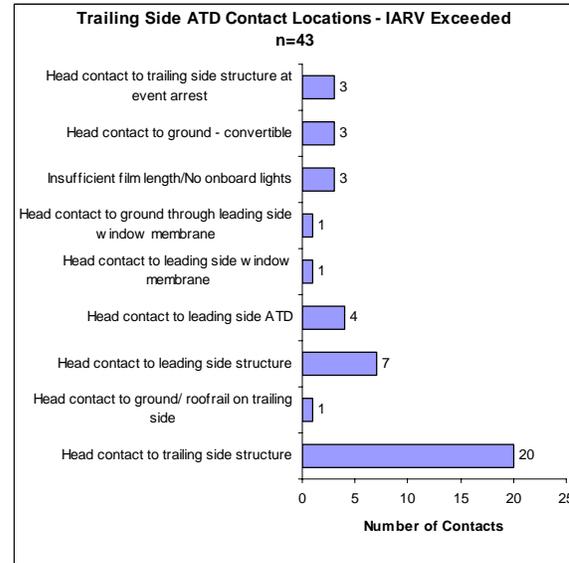


Figure 13. Trailing side ATD contact locations – IARV exceeded.

Figure 12 and Figure 13 demonstrate the complex nature of ATD motion in a rollover. Although 82% of leading side ATD contacts were with structure and/or ground, the location of contact varied. For instance, in one test, the ATD head contact was to the leading side door at the belt line, with the vehicle on its wheels (Figure 6). On the trailing side, 63% of trailing side ATD head contacts occurred with the leading or trailing side structure. IARVs were also exceeded through contact to the leading side ATD and through restraint provided by the leading side window membrane.

ATD Contact Location by Test Type

Table 5 shows the leading side ATD contacts during which an IARV was exceeded for each rollover initiation type.

Table 5. Leading Side ATD contacts during which an IARV was exceeded – by test type

	Trip-over	Fall-over	Flip-over	Dolly rollover
Head contact to leading side structure	4	0	3	5
Head contact to ground or ground/roofrail	3	8	0	0
Head contact to leading side structure at event arrest	0	0	2	0
Head contact to ground - convertible	0	0	1	0
Insufficient film length	1	0	0	0
Head contact to leading side door at beltline	0	0	0	1

All of the fall-over tests involved ATD head contact to ground or ground/roof rail. This was due to the relatively low vehicle angular rate that is characteristic of this test methodology. In these tests,

ATD motion is influenced largely by gravity, leading to motion that is primarily lateral with respect to the vehicle. In contrast, the relatively high angular rates associated with flip-over and dolly rollover tests

resulted primarily in ATD head contact with the leading side structure as the ATD moved upward and outward.

In trip-over tests, leading side ATD contact location was more varied. At trip initiation, the deceleration of the vehicle is primarily lateral, leading to lateral motion of the ATD relative to the vehicle. As the vehicle's lateral motion is converted to angular rotation, ATD motion becomes more upward and

outward. For some tests, this resulted in ATD head contact to the leading side structure, while in others the ATD struck the ground or ground/roof rail.

Table 6 shows the trailing side ATD contacts during which an IARV was exceeded by test type. The various angular rates associated with the different test methodologies again played a role in the amount of upward and outward motion of the ATD.

Table 6.
Trailing Side ATD contact locations during which an IARV was exceeded – by test type

	Trip-over	Fall-over	Flip-over	Dolly rollover
Head contact to ground - convertible	2	0	1	0
Head contact to trailing side structure	8	1	4	7
Head contact to ground/ roofrail on trailing side	1	0	0	0
Head contact to trailing side structure at event arrest	0	0	3	0
Head contact to leading side structure	2	3	0	2
Head contact to leading side ATD	4	0	0	0
Head contact to leading side window membrane	1	0	0	0
Head contact to ground through leading side window membrane	1	0	0	0
Insufficient film length/No onboard lights	2	0	0	1

ATD Contact Location by Restraint Usage

Figure 14 and Figure 15 show a comparison between belted and unbelted leading side ATDs in terms of their contact locations. The distribution of contact locations does not appear to be affected by belt usage for the leading side ATD.

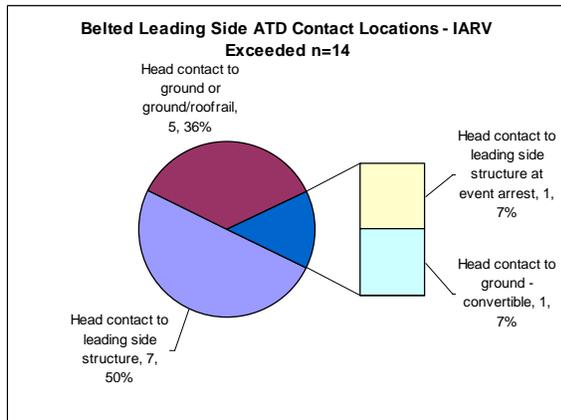


Figure 14. Belted leading side ATD contact locations with IARV exceeded.

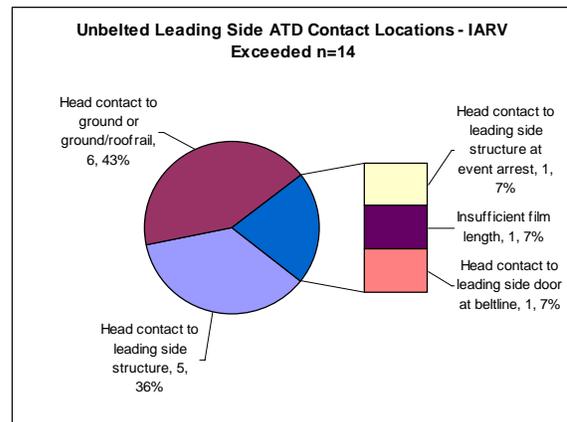


Figure 15. Unbelted leading side ATD contact locations with IARV exceeded.

Figure 16 and Figure 17 show the distribution for contact locations for belted and unbelted trailing side ATDs demonstrating that belt usage strongly influenced the trailing side ATDs contact location.

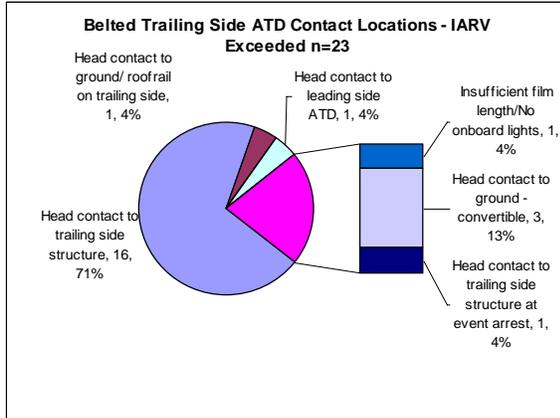


Figure 16. Belted trailing side ATD contact locations with IARV exceeded.

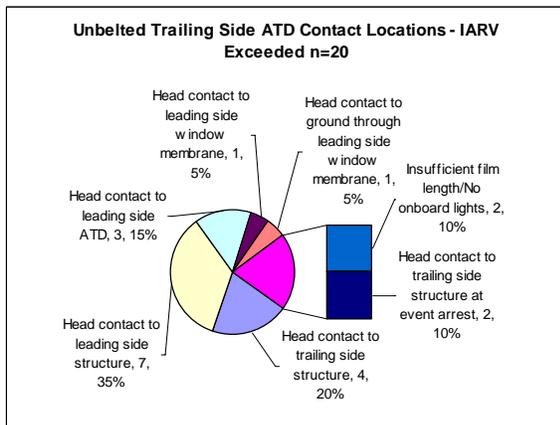


Figure 17. Unbelted trailing side ATD contact locations with IARV exceeded.

For the belted ATDs, contact occurred primarily to the trailing side structure, although belt usage did not preclude head contact with the leading side ATD (Figure 18).



Figure 18. Belted ATD head contact to leading side ATD.

For the unbelted trailing side ATDs, 60% of the contacts occurred on the leading side of the vehicle, while only 20% were to the trailing side structure.

Table 7 shows the number of quarter turns and vehicle orientation for the contacts, summarized by restraint usage. For the leading side ATD, the vehicle orientation at the contact did not show a significant difference for belted or unbelted ATDs. For the trailing side, however, the trend differs. The unbelted trailing side ATDs show the majority of contacts when the vehicle is on the leading side, as the unbelted ATD moves from the trailing side to the leading side, whereas the majority of belted contacts occurred when the vehicle was on the roof.

Table 7. Restraint condition and ATD location in contacts with IARV exceeded by vehicle orientation

	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

HIC and ATD Contact Location

For leading side ATDs, HIC IARVs were only exceeded during fall-over tests as a result of head to ground contact. However, head to ground contacts occurred during other tests without the HIC IARV being exceeded. In addition, one test demonstrated that it is possible that the HIC IARV could be exceeded without exceeding any additional IARVs.

On the trailing side, the HIC IARV was exceeded once, due to belted trailing side ATD head contact with the shoulder of the leading side ATD (Figure 18).

Upper Neck Compression and ATD Contact Location

As shown in Figure 4 and Figure 5, approximately 1/2 of the IARVs exceeded were due to upper neck

compression loading. Figure 19 and Figure 20 show the distribution of contact locations during which the upper neck compression IARV was exceeded.

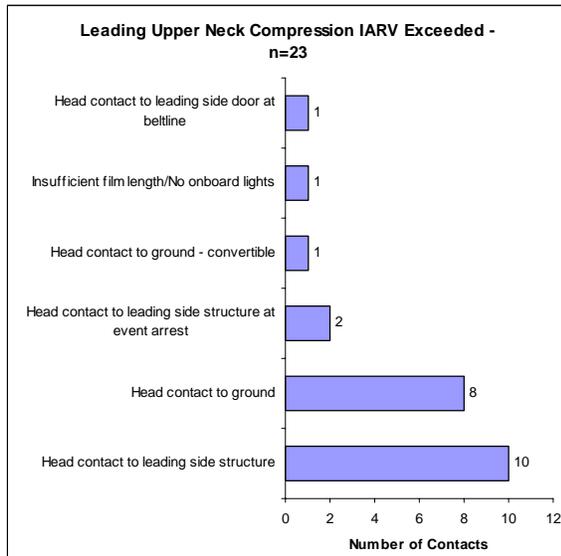


Figure 19. Leading side ATD upper neck compression IARV exceeded – ATD contact location.

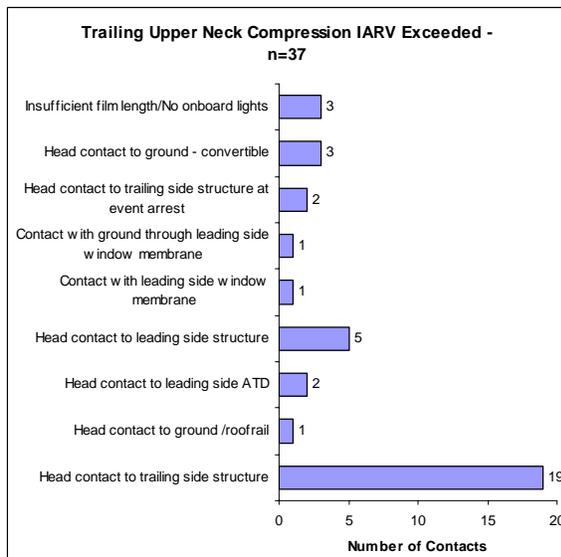


Figure 20. Trailing side ATD upper neck compression IARV exceeded – ATD Contact Location.

Table 8 shows the vehicle orientation for tests during which the upper neck compression IARV was exceeded. As demonstrated in Figure 19 and Figure 20, upper neck compression IARVs were exceeded through contact with the ground, door, roof rail, roof, window membrane or the other ATD. Any contact

during which the motion of the ATD head was arrested prior to stopping the ATD body showed the potential for exceeding a neck compression IARV. This was true regardless of vehicle orientation, location of the head contact, or dynamic deformation of the vehicle's structure, as shown in Figures 6 through 11.

Table 8. Restraint condition and ATD location in tests with upper neck compression IARV exceeded by vehicle orientation

	Restraint usage - Contacts by vehicle orientation			
	Neck compression IARV exceeded			
	On wheels	On leading side	On roof	On trailing side
Unbelted Leading Side	1	9	1	1
Belted Leading Side	0	9	2	0
Unbelted Trailing Side	2	12	2	0
Belted Trailing Side	0	3	18	0
Sum:	3	33	23	1

Lower Neck Compression Peak

For the leading side ATDs with lower neck load cells installed, there were two tests in which the upper neck compression and lower neck compression IARVs were not both exceeded during the same impact. This was likely due to the ATD orientation during loading. In one of these tests, the upper neck aft shear IARVs were exceeded and in the other, the Ncf (Neck compression-flexion) IARV was exceeded, demonstrating the off-axis nature of the neck loading in these impacts. When the loading of the neck was primarily axial, the magnitudes of the upper and lower neck compressions were similar.

For the trailing side ATDs with lower neck load cells installed, lower neck compression peaks did show an associated IARV exceeded for the upper neck compression, due to the more axial nature of loading.

Nij

The Nij IARV was exceeded in 9 impacts for the leading side ATD and a single impact for the trailing side. There were no cases in which the Nij was the only IARV exceeded.

CONCLUSIONS

General Motors has conducted 176 laboratory-based rollover sensor signature tests for developing test methods as well as for development of rollover sensor calibrations for 2005 and 2006 model year vehicles. These tests have a distribution of rollover initiation type that is similar to field frequencies.

The tests were conducted with a combination of restraint characteristics – unbelted, belted with and without retractor and buckle pretensioners, with belts mounted to pillars and with all-belts-to-seat configurations. For this dataset, the likelihood of an ATD exceeding an IARV decreases with the use of belts.

General Motors has developed a method for evaluating ATDs in a rollover test in which an IARV was exceeded. This method distills a complex crash test into a one page summary chart. This summary chart shows the times of peak injury assessment values, the vehicle roll angle, vehicle and ATD contacts, ATD orientation relative to the vehicle and ground, and vehicle orientation relative to ground.

An analysis of ATD contact locations in the vehicle during which an IARV was exceeded demonstrates the complex nature of ATD motion during rollover crashes. IARVs can be exceeded through contact to:

1. The vehicle structure on the leading side of the vehicle (roof, pillars, roof rail, etc)
2. The vehicle overhead structure on the trailing side of the vehicle (roof, pillars, roof rail, etc)
3. The vehicle door at the belt-line
4. The other ATD
5. The nylon-fabric membrane covering the window
6. The ground through an open convertible roof
7. The ground through the window membrane

ATD motion and location of contact during which an IARV was exceeded can be affected by ATD location, test type, and restraint usage.

For leading side ATDs, tests with lower angular rates led to ATD motion that was influenced primarily by gravity, leading to head contact to the window membrane and the ground. For tests with higher angular rates, the ATD motion was primarily upward and outward, leading to contacts with the vehicle structure on the leading side. Restraint usage did not show a significant effect on ATD motion for the leading side ATDs.

On the trailing side, however, the trends differed. The motion of the ATD was influenced primarily by the restraint condition and did not appear to be significantly affected by test type. Belted trailing side ATDs primarily contacted the trailing side structure when an IARV was exceeded. Unbelted trailing side ATDs primarily made contacts on the leading side of the vehicle. Contact locations included impacts to the leading side structure, ATD, window membrane, and the ground through the leading side window membrane.

An evaluation of vehicle kinematics, quarter turn, and orientation during ATD contacts with an associated IARV exceeded showed that an IARV can be exceeded with the vehicle at any orientation and at any number of quarter turns.

An analysis of this dataset showed that it is possible that the HIC IARV could be exceeded without exceeding any additional IARVs. The only ATD contacts during which HIC IARV was exceeded were head to ground contacts through the window membrane.

In addition, the analysis showed that neck compression IARVs could be exceeded with the vehicle at any orientation, independent of belt usage, and through any contact during which the head of the ATD stopped moving prior to the rest of its body. These ATD contacts occurred with the ground, door, roof rail, roof, window membrane or the other ATD.

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