NHTSA RESEARCH ON IMPROVED RESTRAINTS IN ROLLOVERS

Allison E. Louden
National Highway Traffic Safety Administration
United States

Doug Weston
Transportation Research Center, Inc.
United States

Paper Number 11-0213

ABSTRACT

As part of a comprehensive plan to reduce the risk of death and serious injury in rollover crashes, the National Highway Traffic Safety Administration (NHTSA) has a program to characterize restraint system response in rollovers. A rollover restraint tester (RRT) was developed and utilized to produce a 180 degree roll followed by a simulated roof-to-ground impact. This device was modified to incorporate a reaction surface to analyze how advanced restraints would perform in a more realistic environment. The device was renamed as a rollover reaction surface tester (RRST). The original device (RRT) was discussed in previous ESV papers.(1,2) Recognizing the unpredictability of the real world rollover phenomenon, this test device provides a repeatable and consistent dynamic environment for suitable lab evaluation. Technologies that were evaluated for this study included integrated seat systems, pyrotechnic and electric resettable pretensioners, and four-point belt systems. High speed video data were collected and analyzed to examine occupant head excursion throughout the tests and are presented for discussion. The RRST has demonstrated to be repeatable; however, there are some concerns about the real world relevancy of the RRST dynamics in the absence of a lateral component. The RRST does not have a mechanical component for lateral motion that is typical in some real world rollover events.

Results presented in paper 09-0483 demonstrated that excursion characteristics can be affected with the implementation of advanced restraints in tests using the Hybrid III50th and 95th percentile male and 5th percentile female dummies [Sword, 2009]. This paper presents expanded research with the 50th percentile male and 5th percentile female dummies using the RRST and compares the results back to the RRT results. In addition to the RRST testing, a series of full scale dynamic tests was also conducted using a full vehicle in various dynamic rollover scenarios. The advanced restraints were chosen based on the test results of the RRST and availability of the devices. The following tests were conducted and will be discussed in this paper: Federal Motor Vehicle Safety Standard (FMVSS) No. 208 dolly test, curb trip, soil trip, and corkscrew ramp. The goals of the testing were to understand how the improved restraints perform in various conditions and to assess the occupant's kinematics in the various conditions.

INTRODUCTION

In previous ESV papers,(1,2) the rollover restraint tester (RRT) was discussed in detail, as were the advanced restraints. It was a device that provided a repeatable dynamic environment suitable for comparing various restraint configurations. No single device can replicate the dynamics of all rollovers because every rollover crash is very different and unique. This device allowed for consistent repeatability of a specific dynamic environment.

Advanced restraints were tested with the 50th and 95th percentile male and the 5th percentile female dummies. The observations from the previous testing included:

1. Pretensioners and integrated seats reduced lateral and vertical excursions in both pre- and post-impacts.
2. The motorized retractor pretensioners reduced pre-impact lateral excursions
3. The inflatable belts with the pretensioners produced the largest reductions in vertical and outboard lateral excursions.
4. The 4-point belts reduced vertical and inboard lateral excursions.

5. The results varied with the dummy size, but general trends held between the restraints.

Based on the observations and repeatability of the RRT, further research was conducted to look at the performance of the improved restraints when used in conjunction with inflatable curtains.

ROLLOVER REACTION SURFACE TESTER TESTS

Test Device

The original RRT was modified to include a roof and door structure along with an inflatable curtain and was renamed the rollover reaction surface tester (RRST). The cab structure (the roof and door structure) was taken from a 2006 Honda Ridgeline truck cab, and the inflatable curtain was from a 2007 Chevrolet Silverado 1500. This structure was enhanced by various support beams to ensure multiple testing could be conducted. Although a headliner was not used, a deflection pan was fabricated to ensure a repeatable inflation into the cab structure. Figure 1 shows the curtain inflated in the cab structure. The original characteristics and framework[1,2] of the device remained the same.

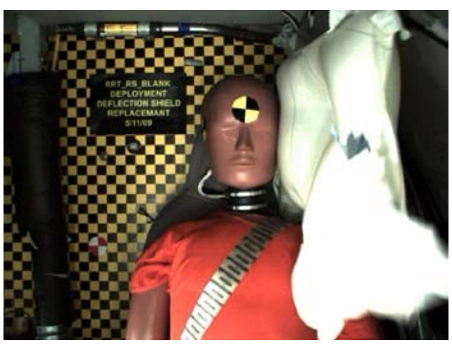


Figure 1: Deployed Airbag

Figure 2 is a schematic of the device, and Figure 3 shows the actual test device. The coordinate system is set to the dummy for excursion analysis. The device has four (4) main features consisting of the following:

1) A support framework,
2) A counter-balanced test platform with rotating axle,
3) A free weight drop tower assembly, and
4) A shock tower.

Instrumentation

The RRST was instrumented to help characterize the dynamics of the testing. An angular rate sensor (ARS-1500, DTS, Inc.) was used to monitor the roll rate. Two (2) 50,000 lb. load cells were mounted to the roll table at the point of impact to record the impact force. A string potentiometer was utilized to measure the shock absorber deflection. A 2,000 g rated accelerometer, mounted to the platform directly underneath the center line of the seat was used to collect the acceleration at impact.

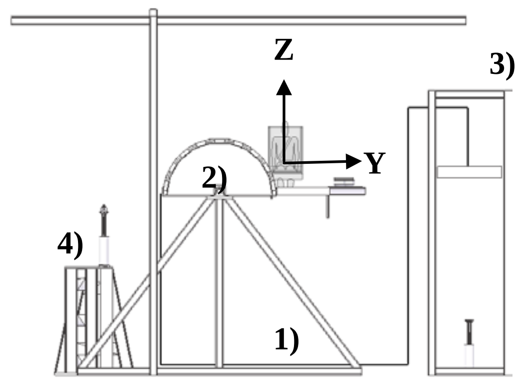


Figure 2: Rollover Restraint Tester (RRT)

Figure 3: Rollover Reaction Surface Tester (RRST)

The Hybrid III dummies used for testing contained head, neck, chest, and pelvis instrumentation. Seat belt load cells were used for both the lap and shoulder portions of the belts. The event was filmed with high speed digital (1000 frames per second) cameras that were used to obtain excursion measurements using TEMA film analysis software.

The inflatable curtain and pretensioners (if applicable) were deployed when the device platform reached 45 degrees of rotation (based on previous testing[2]). The RRST had a roll rate velocity on average of 310±5 degs/sec (compared to the RRT device with an average of 320±10 degs/sec).**Test Matrix**

The test matrix for the restraint evaluation is included in Table 1. It includes the configuration description, code, and the test series for the 50th percentile male and 5th percentile female adult dummies. Each configuration was repeated three times with each dummy. Configuration C was the baseline treatment for test comparison. It was a standard 3-pt. non-integrated seat belt without pretensioning. The seat belts chosen for this series of testing were the available, better performing devices based on the RRT testing.

Table 1:
Test Matrix for 50th & 5th Hybrid III Dummies

Configuration Description	*Code[2]*	*50th*	*5th*
Integrated Seat	A	X	X
* 3-pt. Non-Integrated (3PN)	C	X	X
(3PN) Retractor w/Buckle Pretensioner	G	X	X
(3PN) Motorized Retractor w/Buckle Pretensioner	I	X	X
4-pt system w/Pretensioner	M	X	X

**Baseline Configuration for comparison*

Evaluated Restraint Technology

A variety of seat belt configurations were selected for testing. They ranged from current consumer-available technologies to prototype devices. The details of the restraints were discussed in the previous ESV paper [Sword, 2009]. The restraints used for this research testing are described below.

- **Configuration C:** 3-point non-integrated seat belt without pretensioners.
- **Configuration G:** 3-point non-integrated seat belt with pretensioners in both the retractor and buckle.
- **Configuration I:** 3-point non-integrated seat belt with a motorized retractor and a buckle pretensioner.
- **Configuration A:** 3-point integrated seat belt without pretensioners.
- **Configuration M:** 4-point non-integrated seat belt with pretensioners in both the retractor and buckle.

The inflatable belts (Configuration K) were not tested in this series due to unavailability.

RESULTS

Dummy Kinematics

As discussed before in the previously mentioned ESV papers, dummy kinematics were influenced by a combination of platform rotational and gravitational forces. At the onset of the test, the dummy was seated in an upright position. Gravity was the primary initial force acting on the dummy during the slow starting action of the rotating platform. As the platform began to rotate, the dummy's course was changed, and gravitational forces tended to move the dummy inboard (negative Y-direction).

The angular velocity of the platform increased with the centripetal or normal acceleration, creating the appearance of an outward or centrifugal force on the dummy. This outward force pushed the dummy outboard and up (toward the roof of the vehicle) (positive Y-direction, positive Z) during the pre-impact roll event. The dummy tended to start moving in the positive Y-direction at about 90 degrees of platform rotation. Gravitational forces continued to play a role for Z-direction motion (out of the seat toward the roof) past 90 degrees of rotation, until impact.

After impact, the dummy immediately changed from an outboard and up (i.e. off the seat) motion to a dramatic inboard and amplified up motion. The centripetal accelerations were eliminated when the table stopped, leaving momentum and gravity to act on the dummy.

Dummy Head Excursion

Video data of the dummy's head were collected for excursion analysis. X-direction (fore and aft) data have been omitted. The kinematics of the RRST do not have an X-direction motion component, and the analysis for the RRST shows less significance X-direction motion compared to the Y and Z directions. The presented data will focus only on Y and Z-direction motions.

Figures 4 and 5 plot the average Y-direction and Z-direction head excursion for the tested configurations for both the 50th percentile male and 5th percentile female dummies. The figures contain both the non-reaction (RRT) and reaction surface (RRST) tests. The non-reaction (RRT) tests data was discussed in previous ESV papers[1,2].

The blue bars represent the 5th percentile female dummy, and the red bars represent the 50th percentile male dummy. The solid colored bars represent the non-reaction tests, and the hatched bars represent the reaction surface for the lateral excursions plot (Figure 4). The lighter shades of the red and blue bars represent the non-reaction surface, and the darker shades represent the reaction surface testing on the vertical excursion plots (Figure 5). The hatched versus non-hatched bars represent the pre- and post- impact results.

Y-Direction Excursion

Compared to the non-reaction surface testing, the lateral outboard excursions were reduced for the reaction surface testing for both sized occupants for all of the configurations. This was primarily because of the curtain deploying into the occupant compartment along with the dummy contacting the door which did not allow the occupant to move outboard. The inboard movement was reduced for Configuration C for both occupants and increased for Configuration M. (Note: The Configuration M seat in the original testing had a more defined seat bolster than that used originally in the non-reaction surface testing, causing slightly different occupant kinematics.) Overall, the lateral inboard and outboard excursions for the reaction surface testing were all less than 120 mm, while some exceeded 200 mm in the non-reaction surface testing.

For the reaction surface testing, Configuration I produced the least inboard excursion for both dummies, followed by Configuration A. For the 5th percentile female, Configurations C and G produced very similar inboard excursions, while it was somewhat higher for Configuration M. For the 50th percentile male, Configurations C and M resulted in similar inboard excursions, while it was reduced in Configuration G.

Z-Direction Excursion

The Z-direction or vertical excursions for the reaction surface testing are plotted in Figure 5. The reaction surface reduced these excursions for all configurations for both sized occupants, compared to the tests without the reaction surface. The air curtain allowed for minimal movement outboard, which slowed the occupant kinematics and kept the occupant in the seat as the platform rotated. This allowed for the seat belt to maintain better engagement with the occupant, thus allowing less vertical movement.

For the reaction surface testing, Configuration I produced the least vertical excursion for the 5th percentile female and only slightly more than Configuration G for the 50th percentile male. Configuration I had a motorized retractor and a buckle pretensioner and also allowed the lowest lateral excursions. For the 5th percentile female, Configurations G and M also produced lower excursions than the baseline configuration (C), while Configuration A results were similar to baseline. For the 50th percentile male, Configurations A and M allowed for similar excursions as baseline. The pre-impact vertical excursions were all under 60 mm, and total vertical excursions were all less than 150 mm.

Summary of RRST Testing

Testing with the reaction surfaces (roof, door, and air curtain) produced less lateral outboard and vertical excursion than the non-reaction surface testing, for both dummies and all of the belt configurations. This was not necessarily the case for inboard lateral motion. Configuration I generally had the lowest, or nearly the lowest, excursions for both dummies.

KEY
RED- 50th Male
BLUE-5th Female

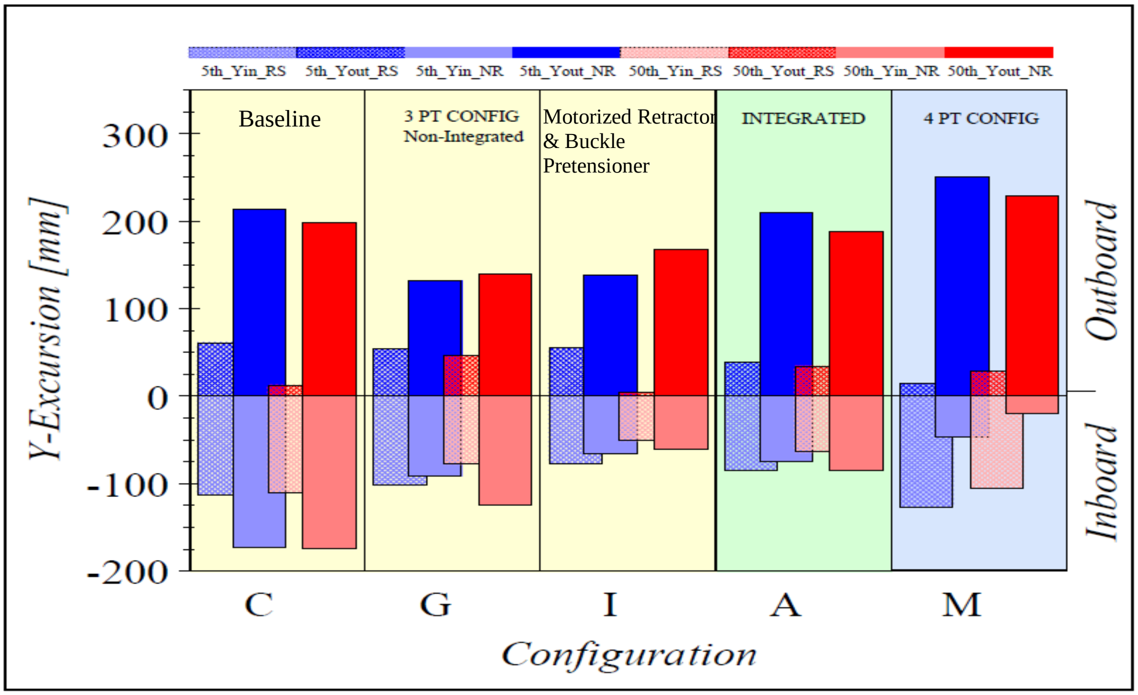


Figure 4: Reaction vs Non-Reaction Lateral Excursions

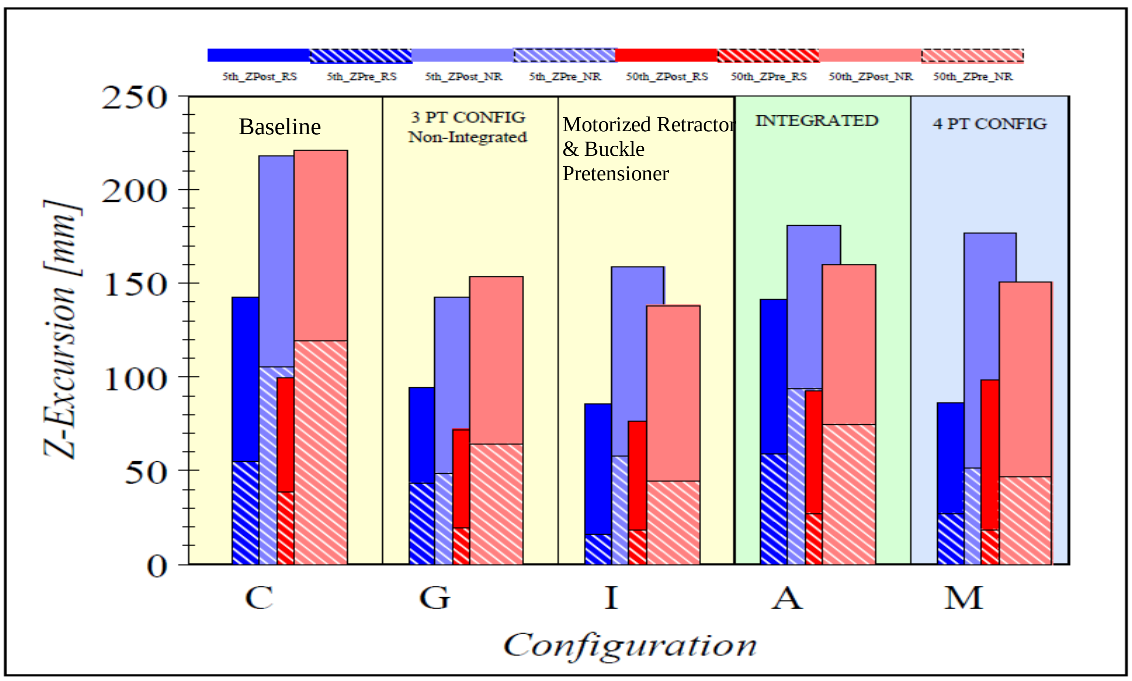


Figure 5: Reaction vs Non-Reaction Vertical Excursions

FULL-SCALE DYNAMIC ROLLOVER TESTS

A series of full-scale dynamic rollover tests were conducted with a modified 2007 Ford Expedition. Various restraint configurations were chosen based on their performance in the RRT/RRST tests. The full-scale tests were conducted in order to help identify the dynamics and occupant kinematics in various rollover scenarios; assess what dynamics and occupant kinematics should be considered when evaluating restraint performance; and compare the performance of the restraints to that in the RRT/RRST tests.

Setup/Test Matrix

A 2007 Ford Expedition was modified by replacing the 2nd row bench seat of the vehicle with a front seat. Replicating the front seat/belt configuration in the 2nd row was done to allow a more direct comparison between the front and 2nd row test results. The factory installed restraints were removed and replaced with the different configurations listed in Table 2.

The following test scenarios were tested using the Hybrid III 50th percentile male dummies.

- FMVSS No. 208 Dolly
- Soil Trip
- Curb Trip
- Corkscrew Ramp

Table 2 shows the test matrix and what restraints were used for all occupants. The front-to-rear comparisons were set-up on the trailing side of the vehicle, which differed depending on the test mode. For each test, the trailing edge dummies were seated similarly using a FARO Arm (FARO Technologies, Inc.). Figure 6 shows the two dummies placed in the vehicle.

Except for the FMVSS No. 208 dolly tests, two tests were conducted in each of the test modes. For the first test of each mode, the trailing side front and rear occupants and the leading side front occupant were restrained using the baseline configuration (C). For the second test of each mode, the trailing side front and rear occupants were restrained using Configuration I, and the leading side front passenger was restrained using Configuration G. These same configurations, and others, were also tested in the four FMVSS No. 208 dolly tests, but not necessarily in the same order. See Table 2 for details. This paper focuses on the results from the trailing side occupants.

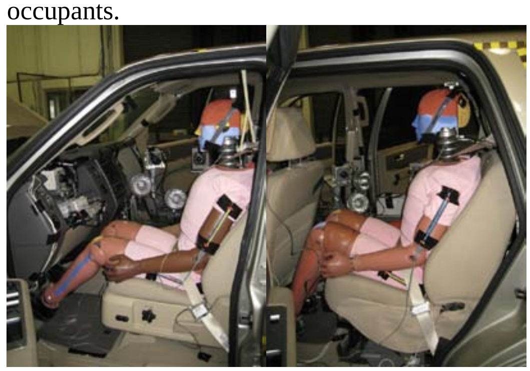


Figure 6: Trailing Front and Rear Occupants

Instrumentation

The Hybrid III dummies used for testing contained head, neck, chest, and pelvis instrumentation. The vehicle was instrumented with accelerometers in the engine, rear deck, roof rail, center of gravity, multiple seat locations, and all A-D Pillar locations. Roll rate sensors were located at the center of gravity and rear deck locations. Seat belt load cells were used for both the lap and shoulder portions of the belts.

The event was filmed with high speed digital cameras that were used to obtain excursion measurements. The inflatable curtain and pretensioners (if applicable) were deployed manually at a pre-determined time, depending on the test mode. The motorized retractors (Configuration I) were activated prior to the launch of the vehicle.

Test Modes

FMVSS No. 208 Dolly: The vehicle was mounted on the dolly platform, which was rotated 23 degrees from horizontal, with the left side of the vehicle being the trailing side (Figure 7). The dolly was propelled at 30 mph and then abruptly decelerated, allowing the vehicle to fly off the dolly and freely roll about its longitudinal axis into the desired area.

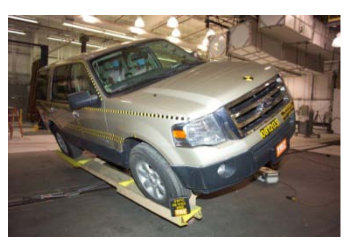


Figure 7: Dolly Cart with Vehicle

Table 2 TEST MATRIX

Test Type	Config C	Config I	Config G	Config A	Air Curtain/Fire Time
FMVSS 208 Dolly #1	1, 2				NO/
FMVSS 208 Dolly #2	3	1, 2			NO
FMVSS 208 Dolly #3			3	1, 2	NO
FMVSS 208 Dolly #4		1, 2	3		YES/100 ms
Corkscrew Ramp	1, 2, 3				YES/300ms
Corkscrew Ramp		1, 2	3		YES/300 ms
Soil Trip	1, 2, 3				YES/100 ms
Soil Trip		1, 2	3		YES/100 ms
Curb Trip	1, 2, 3				YES/100 ms
Curb Trip		1, 2	3		YES/100 ms

KEY: 1 – Front Occupant, Trailing Side 2 – Rear Occupant, Trailing Side 3 – Front Occupant, Leading Side
**Firing times were based on discussions with Ford safety engineers.

Corkscrew Ramp Trip: The vehicle was propelled at 30 mph and released prior to the ramp, allowing it to freely roll up a corkscrew ramp (height of 6' and maximum twist angle of about 50°). The right side of the vehicle was the trailing side (Figure 8).

Figure 8: Corkscrew Ramp

Soil Trip: The vehicle was pulled laterally at 30 mph and then released prior to the soil so that it could rotate freely into the soil. The soil consisted of #9 crushed limestone aggregate in a 300 square foot area (see Figure 9). The left side of the vehicle was the trailing side.

Figure 9: Soil Pit and Aggregate.

Curb Trip: The vehicle was pulled laterally at 20 mph into a curb structure (Figure 10) and then released. The wheels interacted with stops that decelerated the vehicle, allowing the vehicle to freely roll about its longitudinal axis. The left side of the vehicle was the trailing side.

Figure 10: Curb Trip

RESULTS

A comparison of Configuration I and Configuration C is included for each test mode. The overall occupant kinematics is discussed along with vehicle kinematics. Each section contains a summary table identifying lateral and vertical excursions, roll angle and restraint status for the front and rear trailing occupants. The lateral excursions recorded are peak inboard and peak outboard measurements. The vertical excursions recorded, are initial movement up (usually around 180°) and secondary movement up (usually at the end of the event). Plots of peak excursion and neck compression values are located in Appendix A. The tests were conducted at TRC, Inc. and are located in the NHTSA database.[3]

FMVSS No. 208 Dolly Test Results

In a typical dolly test, the vehicle comes off the platform with some rotational velocity. Then the leading side tires (right side for these tests) interact with the ground, tripping the vehicle and causing it to rotate one or more quarter turns (Figure 11).

Figure 11: FMVSS No. 208 Dolly Test

Four FMVSS No. 208 dolly tests were conducted using several different restraint configurations (see Table 2). In two of the four tests, the vehicles completed eight quarter turns (tests 1 and 2), while the vehicle in test 3 completed only one quarter turn, and the vehicle in test 4 did not roll. As shown in Figure 12, the roll velocities were not repeatable. Even for the two vehicles that completed eight quarter turns (red and green curves), the angular velocities were different, particularly after the vehicles impacted the pavement (at about 0.4 sec.).

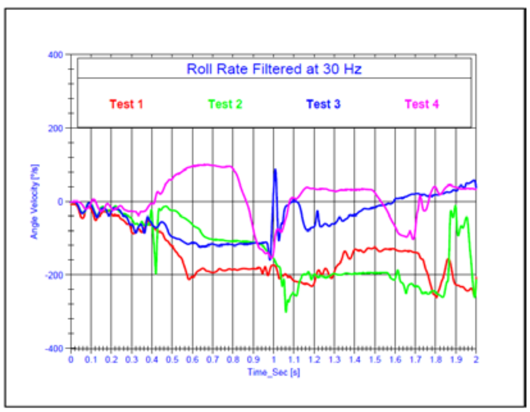


Figure 12: FMVSS No. 208 Dolly Roll Velocities.

The roll velocities were slower than in the RRT/RRST tests, but the initial vehicle roll (up to 180 degrees) provided occupant kinematics responses similar to those in the RRT/RRST testing. The occupants showed little longitudinal movement in the dolly tests.

Table 3 provides the summary of the data for all four of the dolly tests conducted, although this paper focuses on tests 1 and 2.

Table 3
FMVSS No. 208 Dolly Summary

	Dolly						
	Test 1		Test 2		Test 3		Test 4
NHTSA #	6957		6956		6955		6954
Belt Configuration	C		I		A		I
Speed (mph)	30		30		30		30
Roll	720°		720°		120°		No Roll
Time to 180°	1.2 sec		1.47 sec		120° at 1.5s		N/A
Restraints							
Front Trailing Occupant	slid off .42 sec 17°		slid off .59 sec 15°		slid off .44 sec 43°		slid off 1.79 sec N/A
Rear Trailing Occupant	Stayed ON		Stayed ON		slid off .39 sec 34°		slid off .32 sec N/A
Video Analysis							
Front Trailing Excursion Lateral In/Out (mm)	389	242	Lost Camera view		479	115	Did not Roll
Front Trailing Excursion Vertical Up1/Up2 (mm)	30	130			29	115	
Rear Trailing Excursion Lateral In/Out (mm)	341	199	160	178	378	102	
Rear Trailing Excursion Vertical Up1/Up2 (mm)	30	62	38	80	29	123	

In test 1, the trailing side front occupant's belt slipped off the shoulder soon after the vehicle was separated from the dolly (17°). The rear occupant's belt remained on during the entire rollover event. The vehicle completed 2 full rolls (720°).

In test 2, the trailing side front and rear occupant kinematics were similar to test 1 occupant kinematics. The test vehicle also completed 2 full rolls (720°). The trailing side front occupant slid out of the shoulder belt early in the event (15°). The rear occupant on the trailing side remained in the shoulder belt and slid out slightly in the second roll.

The excursions were measured from the head of the dummies using video analysis. The high speed camera data for the trailing side front occupant was lost in test 2, so this analysis could not be done for that dummy. For the rear seat occupant, lateral inboard and outboard movements were less in test 2 (Configuration I) than in test 1 (Configuration C). See Appendix A, Plot 2.

Appendix A, Plot 4, shows the neck compression results of the comparable tests. The blue bars represent Configuration C and the orange bars represent Configuration I. The black lines in the bars represent the peak neck compression when the vehicle was at 180 degrees.

In tests 1 and 2, curtain airbags were not present. Both trailing side front occupants exceeded the injury assessment reference value (IARV) for upper neck compression (4000N). In test 1, the peak neck response of 4037 N occurred during the first roll (188°) slightly after the vehicle was at 180°, whereas in test 2, the neck compression was 505 N in the initial roll.. Neck compression exceeded the IARVof 4000 N in the second roll with a value of 6605 N.

The trailing side rear occupant in test 1 had a neck compression of 890 N. In test 2, the trailing side rear occupant neck compression exceeded 80% of the IARV with a value of 3623 N, but it only reached 396 N during the first 180°.

The high neck responses in both the trailing side front and the rear occupant locations can be attributed to a combination of pillar and roof crush and the dummies slipping out of the shoulder belts. Other injury criteria including Head Injury Criterion (HIC) and the Neck Injury Criterion (N_{ij}) were low for all occupants. See Figure 13 and Appendix A, Plot 4, for additional details.

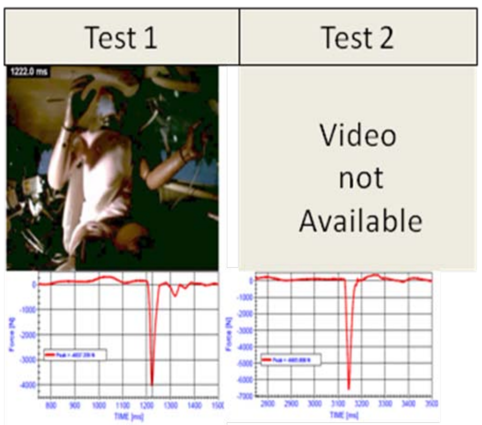


Figure 13: Front Trailing Occupant Neck Compression Response

There was extensive roof and A-pillar lateral and vertical crush on the trailing side front rows in both tests, as shown in Figure 14. Refer to the report for actual crush measurements[3]. Video motion analysis of test 1 indicated a vertical head excursion for the front occupant of 130 mm. The video of the front occupant in test 2 was lost during the test therefore no excursion measurements could be obtained.

Figure 14: Dolly Test Vehicles

The trailing side rear occupants were subjected to lower vertical excursions, as shown in Table 3. Roof crush was less behind the B-pillar on both sides of the vehicles.

Corkscrew Ramp Results

These tests were conducted such that the trailing side was the right side of the vehicle. The vehicles were released at the base of the ramp at 30 mph. As the vehicles rolled up the ramp, the right front corner rose rapidly, and the vehicles rolled counter clockwise (Figure 15).

Figure 15: Corkscrew Ramp

The kinematics of the vehicles in the two corkscrew ramp tests were similar through the first 90°. In test 1, the vehicle rolled 180° and landed on its roof. In test 2, the vehicle rotated about 114°, but came back to about 90°, ending up on its left side.

The roll velocities of the two tests are shown in Figure 16, and they are somewhat similar, peaking at about 120 degs/sec. This was a slower roll rate than in the other test modes. Table 4 provides the corkscrew ramp summaries for both tests. The curtains and other pyrotechnics were fired manually 300 ms into the event.

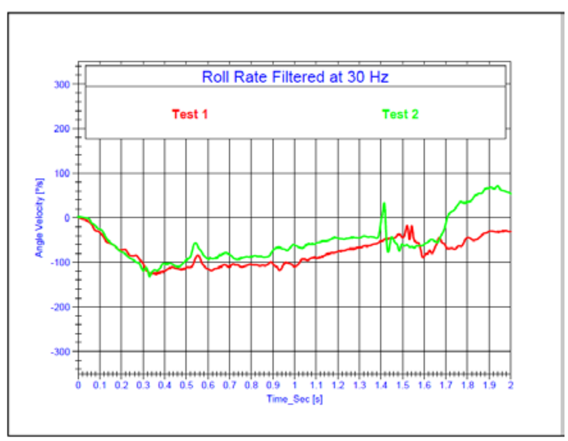


Figure 16: Corkscrew Ramp Roll Velocities

Table 4:
Corkscrew Ramp Summary

	Corkscrew			
	Test 1		Test 2	
NHTSA #	6961		6962	
Belt Configuration	C		I	
Speed (mph)	29.9		30.1	
Roll	180°		114°	
Time to 180°	2.59 sec		1.71 sec	
Restraints				
Front Trailing Occupant	slid off 1.01 sec 72°		slid off 1.45 sec 100°	
Rear Trailing Occupant	Stayed ON		Stayed ON	
Video Analysis				
Front Trailing Excursion Lateral In/Out (mm)	480	159	157	138
Front Trailing Excursion Vertical Up1/Up2 (mm)	24	0	0	0
Rear Trailing Excursion Lateral In/Out (mm)	141	116	154	208
Rear Trailing Excursion Vertical Up1/Up2 (mm)	47	47	0	0

In test 1, the trailing side front occupant's belt slipped off the shoulder early in the event (72°). The rear occupant's belt remained on the entire rollover event. In test 2, the front occupant's kinematics were similar to those in test 1, with the occupant slipping out of the restraint after completing ¼ roll (about 100°). The trailing side rear occupant's shoulder belt remained on throughout the event.

This test mode resulted in forward longitudinal movement as the vehicle rolled up the ramp, and there was more belt spool out in Configuration C (no pretensioning) than in Configuration I. This was more dominant with the trailing side front occupant than for the rear occupant. Figure 17 shows the trailing side front occupant and the corresponding vehicle position at several times during the event.

The longitudinal excursions were not measured for the front occupants. This forward motion was not observed in the other test modes or the RRT/RRST testing.

The trailing side front occupant had less lateral inboard and outboard excursion with Configuration I than with Configuration C, while the opposite occurred for the rear occupant. Vertical excursions were less for both the trailing side front and rear occupants with Configuration I than with Configuration C. Note that these results can at least partially be explained by the difference in the amount of rollover between the two tests.

Figure 17: Trailing Side Front Occupant and Vehicle Positions

Roof crush was focused on the leading side A-pillar in test 1. Test 2 had minimal roof crush damage.

Soil Trip Results

The vehicles were pulled laterally into a crushed limestone aggregate soil pit, which represented soft soil. As the vehicles were released, the tires dug into the stone, decelerating the vehicles and causing them to roll laterally (Figure 18).

Figure 18: Soil Trip

In the first test, the vehicle rolled 720° (two complete rolls), and in the second test, it rolled 630° (1 ¾ rolls). The vehicle's maximum roll rate velocity was about 300 deg/sec for test 1 and about 340 deg/sec for test 2 (Figure 19). These roll rates were the most comparable to the RRT (about 320 deg/sec).

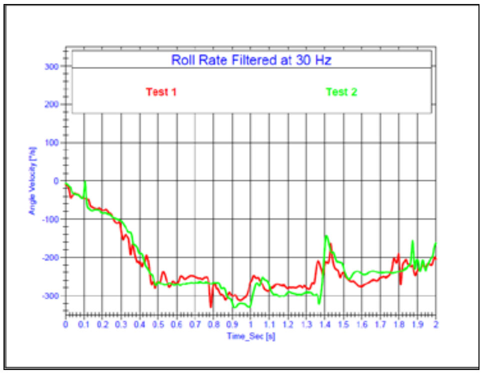


Figure 19: Soil Trip Roll Velocities

A summary of the soil trip tests is provided in Table 5. In both tests, the front occupant kinematics were similar during the initial 180°, but as the vehicles continued to roll, the occupant in test 1, Configuration C, began slipping out of the shoulder belt resulting in higher excursions. Then as the vehicles began into the second roll, occupant kinematic differences appeared. The front occupant slipped out of the restraint for both configurations. The rear occupant's shoulder belt stayed on during test 2, Configuration I, resulting in lower vertical excursions.

In test 1, the trailing side front occupant's belt slipped off the shoulder late in the first roll of the event (vehicle at 294°). The dummy's peak upper neck compression was recorded as 2853 N, which is 71% of the IARV. In association with high neck compression, the roof and A-pillar were crushing into the vehicle (Figure 20). In the comparative test with Configuration I, the neck response was 791 N. The dummy remained in itsshoulder belt during the first roll and did not contact the roof. See Appendix A, Plot 4 for additional information.

In test 1, the rear occupant's belt came off the shoulder early in the event (5°), thus allowing for more vertical and lateral movement. In test 2, the shoulder belt remained on the rear occupant throughout camera coverage (494°).

Table 5:
Soil Trip Summary

	Soil Trip			
	Test 1		Test 2	
NHTSA #	6960		6959	
Belt Configuration	C		I	
Speed (mph)	30.3		30.5	
Roll	720°		630°	
Time to 180°	.94 sec		.95 sec	
Restraints				
Front Trailing Occupant	slid off 1.76 sec 294°		slid off 1.93 sec 433°	
Rear Trailing Occupant	slid off .20 sec 5°		Stayed ON	
Video Analysis				
Front Trailing Excursion Lateral In/Out (mm)	116	143	98	100
Front Trailing Excursion Vertical Up1/Up2 (mm)	71	107	45	72
Rear Trailing Excursion Lateral In/Out (mm)	86	204	124	113
Rear Trailing Excursion Vertical Up1/Up2 (mm)	72	109	26	26

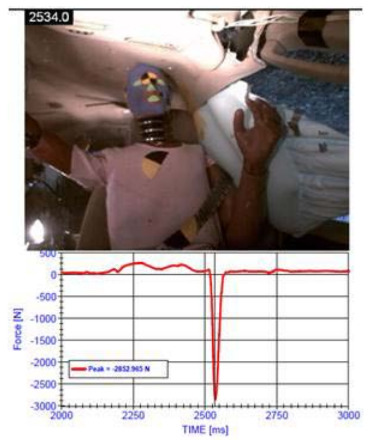


Figure 20: Trailing Side Front Occupant-Peak Neck Compression

Compared to Configuration C, the test with Configuration I showed reduced vertical and lateral outboard excursions for the trailing side front and rear occupants. The lateral inboard excursions were also slightly reduced for the trailing side front occupant with Configuration I. This is shown in Appendix A, Plots 1-3.

The two vehicles obtained similar damage to the roof and the A through D-pillars. In test 1, the front occupant slipped out of the belt and contacted the roof, and this was not seen in test 2 or with the rear occupant. Figure 21 shows the roof crush damage from the two tests.

Figure 21: Soil Trip Vehicles

Curb Trip Results

The vehicles were pulled laterally into a deformable curb, which used flat plates mounted onto honeycomb to interact with the wheels and decelerate the vehicles, forcing a trip over event (Figures 10 and 22).

Figure 22: Curb Trip Test

This test mode had a very abrupt impact, which causes the trailing side occupants to move forcefully inboard, allowing them to slip out of the shoulder belts. This happened with both belt configurations, although the vertical excursions were less for both the front and rear occupants with Configuration I than with Configuration C (Table 6).

Table 6:
Curb Trip Summary

	Curb Trip			
	Test 1		Test 2	
NHTSA #	6958		6963	
Belt Configuration	C		I	
Speed (mph)	20.7		20.6	
Roll	180°		270°	
Time to 180°	1.37 sec		1.03 sec	
Restraints				
Front Trailing Occupant	slid off .11 sec 15°		slid off .13 sec 19°	
Rear Trailing Occupant	slid off .25 sec 44°		slid off .11 sec 15°	
Video Analysis				
Front Trailing Excursion Lateral In/Out (mm)	615	0	427	63
Front Trailing Excursion Vertical Up1/Up2 (mm)	126	155	79	82
Rear Trailing Excursion Lateral In/Out (mm)	473	0	230	0
Rear Trailing Excursion Vertical Up1/Up2 (mm)	84	103	53	53

In test 1, the vehicle completed 1/2 roll (180 degrees). The trailing side front and rear occupants slid out of their shoulder belts early in the event (15° and 44°, respectively). In test 2, similar kinematics were observed, with the front occupant slipping out at about 19° and the rear occupant at about 15°.

Configuration I reduced the inboard lateral and vertical excursions for both trailing side occupants, compared to Configuration C. This is shown in Appendix A, Plots 1-3. The outboard lateral excursions were very low in all cases. The trailing side front occupant had the greatest vertical excursion measurement in any of the full-scale rollover tests during the first 180 degrees of roll (126 mm).

The roll velocities in the two tests were very similar, about 269-276 deg/sec (Figure 23). The vehicle in test 1 rolled about 180°, and the vehicle in test 2 rolled about 270°.

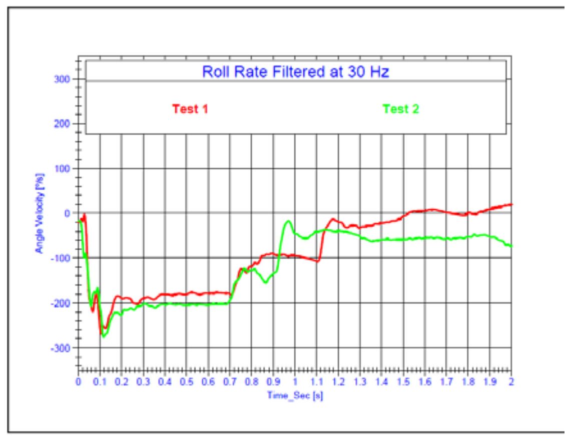


Figure 23: Curb Trip Roll Velocities

In test 1, the maximum roof crush was on the trailing side A-pillar. In test 2, the leading A-pillar area struck the back side of the curb approximately 170° into the event (Figure 24) causing more damage.

Figure 24: Post Test Curb Trip Vehicles

FULL-SCALE DYNAMIC ROLLOVER TEST SUMMARY

Improved Restraints

Front and rear occupant kinematics were similar to one another during the first 180 degrees of the event for the majority of the test modes. As each of the events continued beyond 180 degrees of rotation, the occupant interaction became more erratic and different kinematics were observed.

The belt slid off the trailing side front occupants' shoulders before the vehicles came to rest in all test modes. The belt slid off of the trailing side rear occupants' shoulders in both curb trip tests and in the soil trip test with Configuration C.

Occupant Excursions

In general, excursions with Configuration I (motorized retractors and buckle pretensioners) were reduced when compared to Configuration C (non-pretensioning). This was a consistent trend that was also seen in RRT/RRST tests.

Injury Criteria

Injury measures were generally low. No clear injury trend was observed for Configuration C vs. I. Upper neck compression exceeded 70 percent of IARV in three tests (excluding dolly test #4). Two of the high neck compressions occurred in Configuration C test modes, and one occurred in a Configuration I test mode. This could be attributed to a combination of roof/pillar crush and restraint performance.

Test Mode Repeatability

The four full-scale FMVSS No. 208 dolly rollover tests were not repeatable. The roll rates varied, as did the roll angles.

The roll rates were similar in the corkscrew ramp tests, although the roll angle was not repeated. The ramp test mode added longitudinal movement that produced differences in the restraint performance.

The soil trip test was the most repeatable. The roll rates were similar, and the vehicles rolled 1¾ and 2 complete turns.

The curb trip tests had similar roll rates, and both vehicles rolled at least 180 degrees of rotation, although one vehicle rotated 270 degrees.

OBSERVATIONS

Different test methods resulted in various roll speeds and various vehicle kinematics. The motorized retractors and buckle pretensioners generally reduced occupant excursions, as compared to the standard 3-point belts with no pretensioning for both RRST and full-scale dynamic rollovers. The shoulder belts slipped off the shoulders of both front and rear occupants in the full-scale tests, but more frequently for the front occupants. Since the higher excursions tended to result when this slippage occurred, restraint designs that reduce or eliminate this slippage may provide for improved performance. Additional research would be needed to confirm this.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Transportation Research Center, Inc., Autoliv Test Center, Inc., Honda of America R&D, and Ford Motor Company for providing details about test procedures, test setup, and sensor development.

REFERENCES

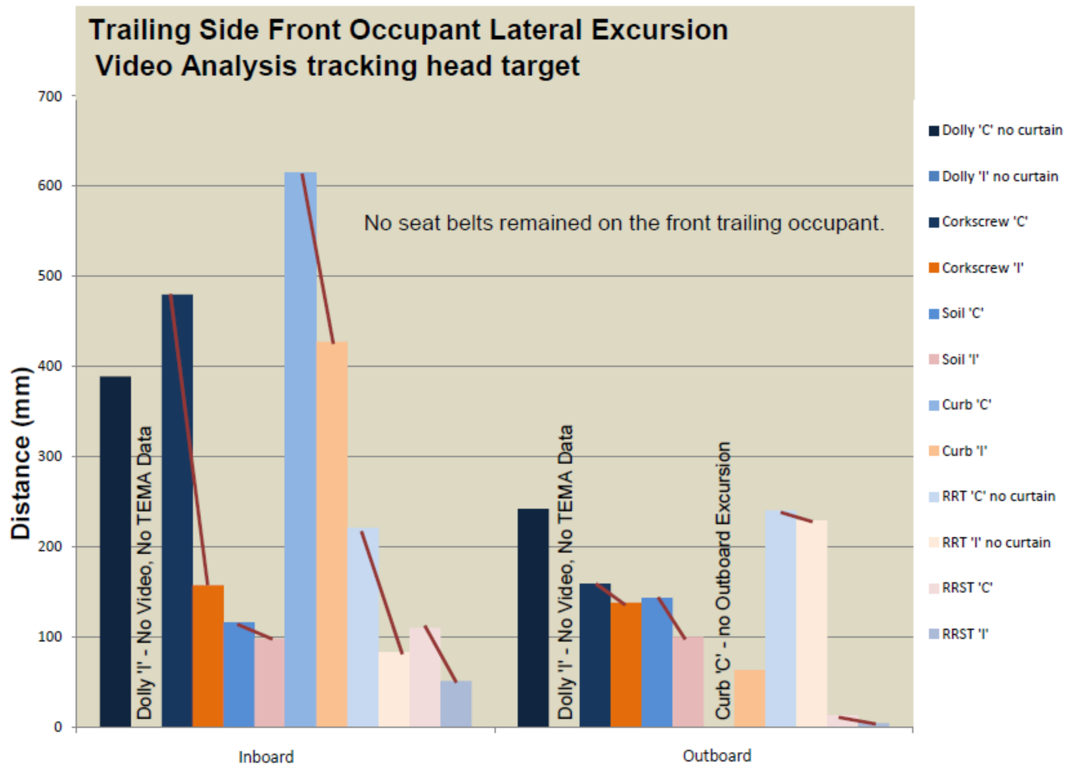
1. Sword, Michael L., and Sullivan, Lisa, K. "NTHSA Research on Improved Restraints in Rollovers" 20th International ESV Conference Proceedings, 07-0279, 2007, Lyon France.

2. Sword, Michael L., and Louden, Allison E. "NTHSA Research on Improved Restraints in Rollovers" 21st International ESV Conference Proceedings, 09-0483, 2009, Stuttgart, Germany.

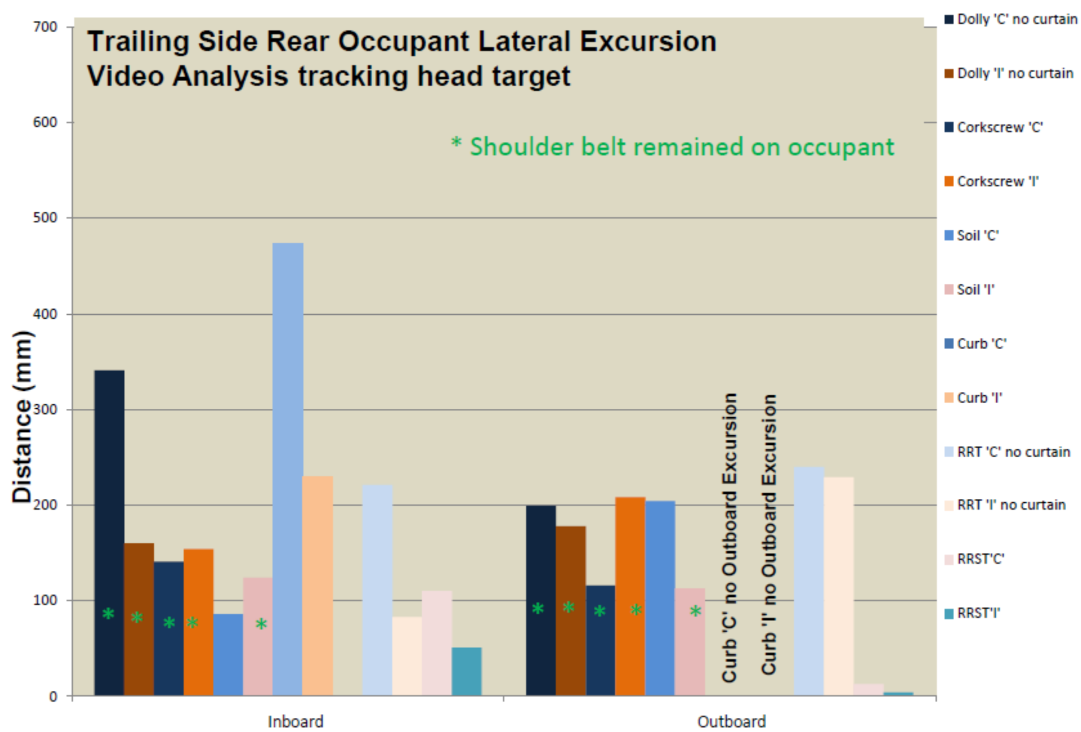
3. http://www.nhtsa.gov/Research/Databases+and+Software

Appendix A

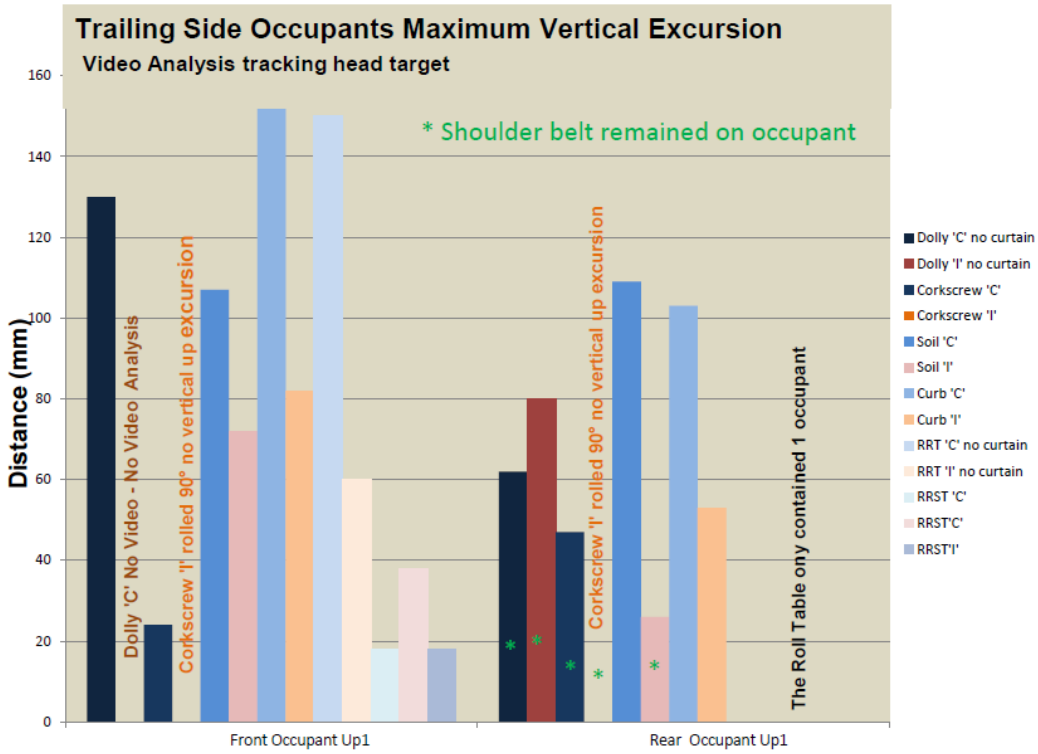
PLOT 1: Trailing Side Front Occupant Lateral Excursion



PLOT 2: Trailing Side Rear Occupant Lateral Excursion



PLOT 3: Trailing Side Front and Rear Occupant Vertical Excursion



PLOT 4: Trailing Side Front and Rear Occupant Upper Neck Compression Configuration C vs I