HUMAN/DUMMY ROLLOVER FALLING (EXCURSION) SPEEDS

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Paper Number 07-0503

ABSTRACT

Measurements of human and dummy falling (often referred to as diving) speeds were made from four series of experiments. The first series consisted of a 5th and 50th percentile human and a 50th percentile dummy in a production vehicle with production belts, in a spit test at roll rates to 200 degrees per second. The second series was conducted with surrogates in dynamic repeatable rollover test roof impacts in the Jordan Rollover System (JRS) fixture. The third series photo analyzed dummy motion in the interior of dolly rollover tests with belted and unbelted hybrid III dummies to determine independently, the excursion and intrusion speeds of the dummy and roof. The fourth series analyzed Malibu rollcaged and production vehicle occupant belt loop load vs neck impact force similar to a previous analysis of Autoliv rollover tests.

The first series measured the near and far side lateral and vertical excursion, excursion speed, roll rate, and belt loads, as well as, documenting occupant kinematics by lateral and frontal view video cameras. The second series measured the near and far side excursion and excursion velocity of a belted surrogate in 15 mph, 350 degree per second JRS roof impact tests. The third series photo analyzed high resolution video of dolly rollover tests with 50% hybrid III dummies in addition to the parameters collected in the tests associated with roll rate, dummy head impact speed and belt loads. The fourth series analyzed Malibu roll caged and production belt loop load vs. neck impact force at roll rates up to 500 degrees per second.

The measurements are presented in a graphical format with discussion in the context of rollover injury potential. The conclusions are that belted humans and dummies with 3 to 5 inches of excursion, have excursion speeds of little more than 0.5 mph. The unbelted dummies with a similar amount of initial headroom have only slightly greater falling speed because of the short duration of the roof contact acceleration. Photo analysis of dolly rollover head impact speeds as measured by dummy neck loads, separated the excursion and roof intrusion speeds and indicated similar falling speeds. An inch or more of intrusion from a roll caged roof in combination with the close proximity of the head of a dummy result in composite head impact speeds of 3 mph or more.

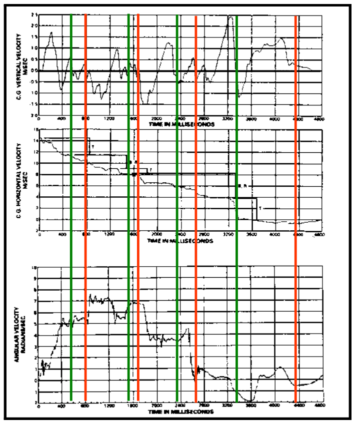
INTRODUCTION

Rollover accidents in the US result in 30,000 serious to fatal injuries and 10,000 fatalities annually. Occupant motion in rollover accidents is an important parameter in determining injury causation and crashworthiness improvements.

One theory of rollover head and neck injury propounded in 1975[1] is that the occupant dives into the roof which is stopped on the ground and that the injury occurs before the roof crushes. This might be correct if the diving height (or equivalent falling speed) of the vehicle and occupant were sufficient to produce a severe to fatal injury.

The Malibu experiments, were 16 rollovers with 8 production vehicles and 8 with roll cages, each with restrained and unrestrained occupants[2,3]. The production roofs typically struck the ground at 1 mph and rollcaged vehicles struck at 3 mph as shown in Figures 1 and 2. Roll caged roofs are not rigid: they typically intruded two inches at speeds of up to 5 mph. The roll caged vehicle and occupant falling speed in combination with the intrusion speed are insufficient to produce serious to fatal injury[4].

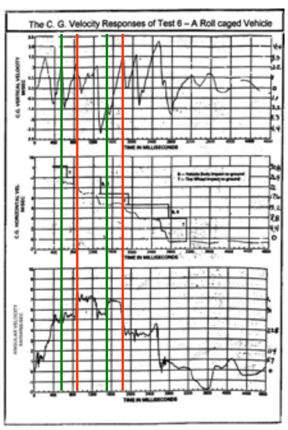
We analyzed the same Malibu and other experimental data to demonstrate that injuries are caused by a production vehicle's compartment crushing and impacting an occupant's head at increased speed. Measuring the crush speed of the roof and the excursion speed of the dummy during a rollover with different strength roofs determines how head and neck injuries are actually caused.



GM Malibu I
Test 5
(All data from GM)

Near Side Contacts:
(Green Lines)
550 ms = 0.6 mph
1500 ms = 0.3 mph
2350 ms = 1.2 mph
3350 ms = 1.2 mph
Far Side Contacts:
(Red Lines)
790 ms = 0.6 mph
1677 ms = 0.4 mph
2662 ms = 1.2 mph
4330 ms = 0.7 mph

Figure 1. Malibu production vehicle roof contact speed with the ground.



GM Malibu I
Test 6
(All data from GM)

Near Side Contacts:
(Green Lines)
575 ms = 2.2 mph
1500 ms = 2.5 mph
Far Side Contacts:
(Red Lines)
836 ms = 2.7 mph
1802 ms = 3.1 mph
Note: Similar data between vehicle types. The main difference is the rollcaged vehicle does not crush.

Figure 2. Malibu rollcaged vehicle roof contact speed with the ground.

Previous work on this topic has focused mostly on quasi-static testing with low rotation rates. Initial dynamic studies were conducted by Herbst, et. al. (1996)[5], Friedman, et al. (1996)[6], Friedman, et.al. (1998)[7] and Meyer et al. (2000)[8]. These studies found that safety belts in production vehicles from the 1990s allowed substantial excursion toward rigid roofs without injury, that cinching latch plate belts arrested human occupant falling velocity, and that people were not seriously injured with roof intrusion of less than about four inches and were serious to fatally injured with roof intrusion of more than 6 inches as shown in Figure 3.

Restrained Occupant Injuries	Average Roof Crush	
	cm	in
None	4.67	1.84
No Head, Face, or Neck	6.12	2.41
Head, Face and Neck @ AIS 1-2	9.80	3.86
Neck @ AIS 2-6	18.38	7.24
Head and Face @ AIS 3-6	26.69	10.51

Figure 3. Table 4 from [7]. Injury Severity vs. Roof Intrusion.

Dynamic rollover occupant kinematics were investigated further by Friedman et al. (2000)[9] in a roll fixture composed of a vehicle buck suspended between two large hoops. The system had an eccentricity of nine inches allowing the structure to be rotated subjecting the occupant to dynamic rollover motion with falling but without impacts.

A dynamic rollover occupant study was conducted by Moffatt et al. (2003)[10] using both humans and dummies. This study determined that there were minimal differences between the motion of anthropomorphic dummies and human volunteers. The excursion exhibited in this study did not increase with an increase in roll rate from 220 to 360 degrees per second as expected. This study determined by photo analysis that far side occupants had a larger excursion than near side occupants. This study did not investigate occupant motion due to the impact phase of a rollover accident and did not examine the occupants' falling velocities during the tests.

In the current study, we examined occupant motion in dynamic spit tests and utilized a Hybrid III dummy in a dynamic rollover experiment. Further analyses of existing dolly rollover test results enabled us to verify our results.

DYNAMIC SPIT TESTING

Spit testing is important to determine how an occupant can move during a rollover. It can be determined whether an occupant can strike the roof or pass through a window opening under specific rollover conditions. Dynamic testing is the most realistic method of examining these issues without actually conducting a rollover test. In this study, instrumented vehicles were rotated about the longitudinal axis of rotation. Both human and dummy surrogates were placed into the vehicles to determine their excursion and excursion velocities through the use of string potentiometers. The rotation was accomplished by spinning the vehicle by hand. This allowed for quick start up and stopping of the vehicle after the test phase of three to four rotations was completed. In general, the vehicles were up to speed within one rotation and could be stopped within one rotation while achieving peak rotation rates of 208 to 237°/second.

We used the Jordan Rollover System (JRS) fixture for this study. The vehicle was suspended between the two drop towers which allowed the vehicle to be freely rotated about its longitudinal roll axis as shown in Figure 4.

All the vehicles used in this study are production models. The majority are late model mid-sized SUV's, but the study also incorporates one sedan.

The occupants for this study were volunteers and ranged in size from a 5'2", 109 lb female to a 5'11", 165 lbs male. In addition a Hybrid II dummy with seated pelvis was also used to determine how this compared to the human surrogates.

The first part of this analysis examined the motion of a restrained occupant relative to the interior of a vehicle in a dynamic spit test. In this test, the occupant was in a vehicle that is free to rotate about its longitudinal axis.

The occupants were all volunteers. Prior to each test the occupant witnessed the rotation of the vehicle and was rotated slowly in the vehicle at least once to become accustom to the motion of the vehicle and their motion in the interior of the vehicle.

The occupant was instrumented with various devices including a string potentiometer positioned underneath the seat and attached to the occupant. This device allowed the direct measurement of the motion of the occupant during the test and calculation of the excursion velocity. In addition, the vehicle was instrumented to allow monitoring of the roll rate throughout the test sequence. Other instrumentation varied, but typically included a string potentiometer to measure lateral motion, a set of belt load cells, a string potentiometer to monitor retractor motion and video cameras. Occupant data was collected by an onboard data acquisition system and transmitted to a stationary system.

In the first test series, three occupants were used; a 5'2", 109 lbs female, a 5'11", 155 lbs male and a 50th percentile Hybrid II male dummy. The occupants were placed in the driver's seat of a midsized SUV, which was then rotated both passenger and driver side leading monitoring the motion of the occupant and the vehicle. In general, the vehicle was rotated four or more times in each direction. The peak roll rates are shown in Table 1. The occupant positioned the seat in a comfortable location prior to the test and donned the seat belt in a comfortable position. This resulted in unlocked restraints on properly seated occupants. This study did not look at out-of-position occupants.

Figure 4. Spit Test Setup.

Table 1.
Peak Roll Rates

Subject	Peak Roll Rate
Human Female	237 deg/sec
Human Male	223 deg/sec
Hybrid II Dummy	208 deg/sec

The production, mid-sized SUV used in this study was mounted in the test fixture as a buck with the front of the vehicle and running gear removed. It was ballasted at the rear and front to rebalance the vehicle around its longitudinal roll axis. The nature of this test did not require the vehicle to have mass properties equivalent to the production condition except for the location of the roll axis.

This vehicle had ample headroom, see Table 2. During these tests, none of the occupants struck the upper roof panel. There was light contact in one of the tests with the grab handle at the driver's seating location on the roof rail. This contact did not affect additional excursion. In addition, none of the occupants' heads went outside of the vehicle through the side window opening.

Data from two of the tests with the same occupant on both the near and far side of the vehicle are shown in Figures 5 and 6. The near side excursion was lower than the far side excursion. In addition, the near side excursion is fairly consistent from roll to roll, while the far side excursion increases modestly with increasing numbers of rolls.

Table 2.
Normally Seated Occupant Headroom

Subject	Headroom
Human Female	9.25”
Human Male	5.25”
Hybrid II Dummy	7.5”

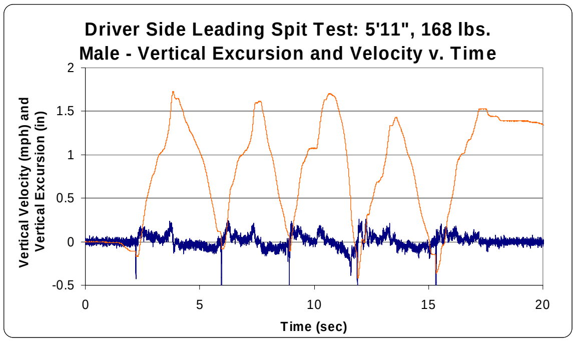


Figure 5. Spit Test Results – Near Side Occupant. Excursion (inches) in orange and velocity (mph) in blue.

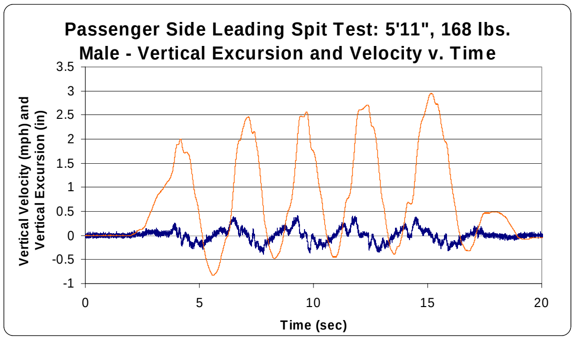


Figure 6. Spit Test Results – Far Side Occupant. Excursion (inches) in orange and velocity (mph) in blue.

Table 3 lists the peak excursion and excursion velocities for the various occupants. The data traces for these tests are similar to Figure 5 and 6. In general, the far side excursion was higher than the near side excursion. The excursion velocities were low with a peak velocity of ~.52 mph.

The prior study focused on a range of occupants in one vehicle moving as both near and far side occupants. Additional testing was conducted in other production vehicles with a range of occupant sizes. This testing was both near and far side leading, with and without pretensioners. The instrumentation was similar and this study focuses on the vertical excursion and vertical excursion velocity measured during the tests.

Table 3.
Test Results

	Near Side Excursion		Far Side Excursion	
Subject	Peak	Peak Velocity	Peak	Peak Velocity
Human Female	3.8”	.32 mph	5.2”	.36 mph
Human Male	1.7”	.26 mph	2.9”	.41 mph
Hybrid II Dummy	2.5”	.47 mph	3.3”	.51 mph

The results of these tests are similar to those of the prior study. Dynamic excursion ranged from 1.35 inches (with a pretensioner) to 2.6 inches at peak excursion velocities of 0.69 mph with a range of occupant sizes.

The tests were conducted in the same way as the prior study. Table 4 illustrates the results of these additional tests. The results of these tests were very similar to the first test series.

Table 4.
Results from Additional Tests.

	Near Side		Far Side	
Subject	Peak Excur-sion	Peak Excursion Velocity	Peak Excur-sion	Peak Excursion Velocity
5’8” 165 lbs Male	2.2”	.36 mph	2.6”	.33 mph
5’5”, 144 lbs. Female			2.2”	.69 mph
5’7”, 145 lbs. Female	Without pretensioner		2.6”	.68 mph
5’7”, 145 lbs. Female	With Pretensioner		1.4”	.33 mph

In order to further examine the question of occupant motion and roof crush in rollover accidents, experimental data must be examined in which there are impacts to the roof allowing impact effects and roof crush as mentioned in Moffat (2003)[10].

DYNAMIC ROLLOVER TESTING

While spit testing can be used to examine occupant motion during a rollover, it is limited in that it does not examine the effects of roof impacts and crush on the occupant. This is important in both determining the occupant excursion velocity, the roof intrusion rate, the motion of the vehicle and how this relates to occupant injury.

The spit testing in this study was conducted in the Jordan Rollover System (JRS). This system can be used to conduct repeatable, rollover testing. This testing allows for the positioning of anthropomorphic dummies in the vehicle and a direct examination of the excursion velocity, roof crush and neck load due to a rollover impact to the roof.

In the first phase of the study, it was seen that the Hybrid II dummy is an effective surrogate for human occupants in vertical occupant motion with fairly similar excursion and excursion velocity. This is also noted in other studies [10] with a Hybrid III (HIII) dummy. This allows an examination of excursion and excursion velocity under impact conditions.

This test is similar to the spit testing portion of the study where an instrumented HIII dummy was placed in the near side of a midsize SUV, which underwent a dynamic impact, see Figure 7. The test vehicle, which had a strong roof, had previously undergone two dynamic rollover tests with only slight damage to the near side. The impact was from a drop height of 4 inches, at 214 degrees per second of roll and a roadway velocity of 15.7 mph. The vehicle struck the ground at a roll angle of 153 degrees, a yaw angle of 10 degrees and a pitch angle of 10 degrees.

The impact resulted in roadway loads of approximately 8,500 lbs. After this impact, the vehicle continued to rotate striking the ground on the far side of the roof before the test was completed. The only significant neck load to the HIII dummy was measured in the impact directly at the dummy’s seating location.

The Hybrid III dummy was instrumented with a head accelerometer, neck load cells and string potentiometers measuring the lateral and vertical motion of the dummy. The vertical string potentiometer was positioned underneath the dummy through a hole in the seat. The lateral string potentiometer was placed on the center console adjacent to the dummy.

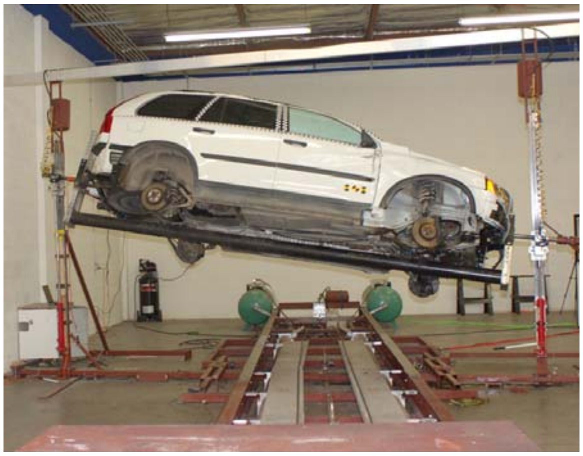


Figure 7. JRS Test Setup.

In addition to the dummy instrumentation, the roof of the vehicle was instrumented with string potentiometers placed approximately at the roll axis of the vehicle. The near side string potentiometer was attached to the top of the A-pillar. This allowed for monitoring the motion of the roof towards the roll axis of the vehicle. This data gives timing information on the roof crush and the relative motion of the roof structure. The head contact point of the dummy is rearward of this position, but the roof crush timing should be equivalent.

The data traces of interest in this study are presented as a function of time in Figure 8. The vehicle roll angle is 158 degrees at the 1.725 seconds and 163.4 degrees at 1.75 seconds.

Figure 8 illustrates the motion of the roof at the A-pillar, the hybrid III dummy and the resulting neck load during the near side impact. In this case with a near side occupant, a peak neck load of 2,670 N was recorded at which time the A-pillar was intruding into the occupant compartment at ~.5 ft/sec while the dummy was moving towards the roof at less than 1 ft/sec due to the impact and excursion. At the time of this impact, the dummy had moved outward and upward and was positioned under the roof rail near the intersection with the door window frame. At this point, the excursion of the dummy was limited by the roof. The neck load was due to a combination of the motion of the dummy and the roof.

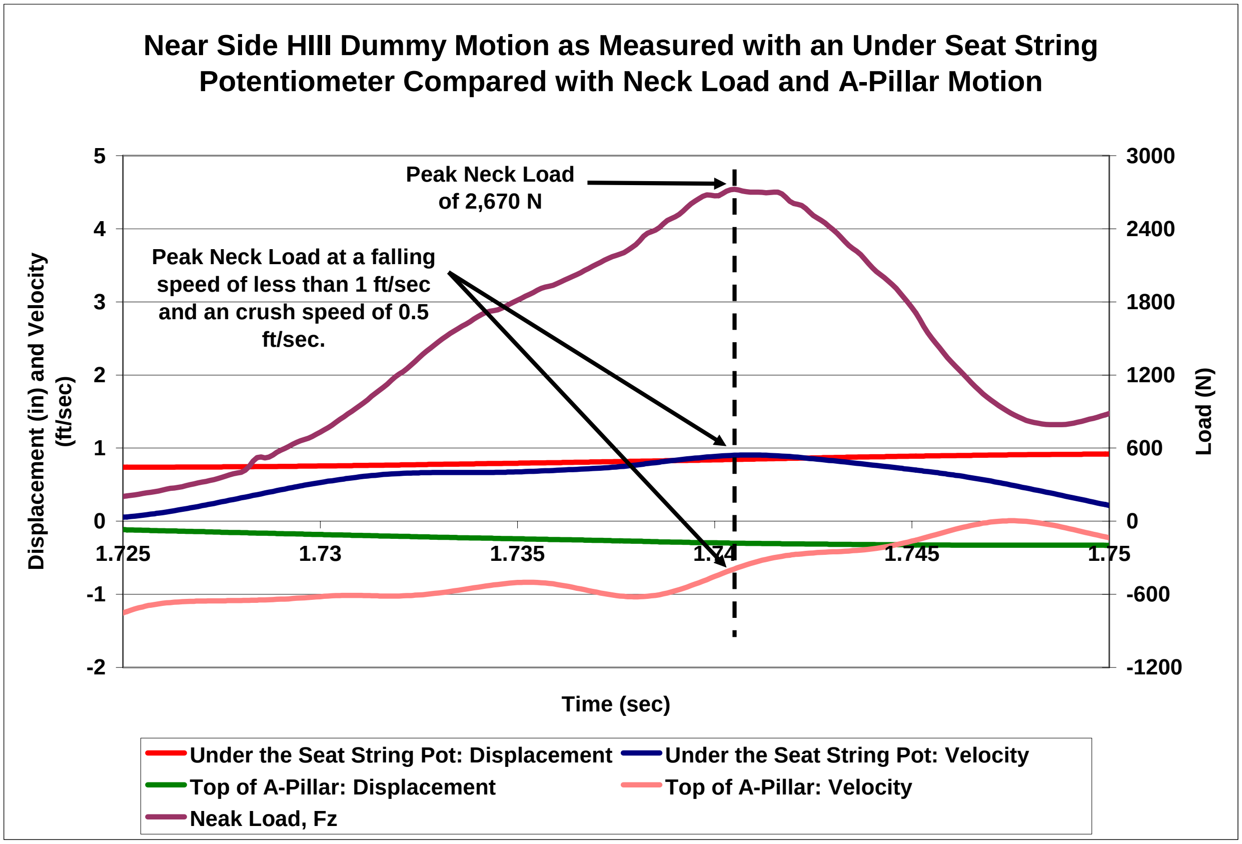


Figure 8. JRS test results focusing on the near side impact.

Figure 9 illustrates the same test sequence over a longer time period illustrating the effects of the far side impact. Figure 9 represents the vehicle traveling from 142 degrees of roll to 230 degrees. In the far side impact, the roof was moved upward and outward away from the near side occupant. This allowed the dummy to move further upward at higher velocities with the deforming roof. This resulted in the highest recorded excursion velocity of ~3 feet per second. However, due to the motion of the roof/vehicle and the dummy there is only a small increase in neck load at this time.

This test clearly illustrates the motion of the dummy, roof and resultant neck load during a near side impact. The excursion velocity is only above 1 ft/sec when the matchboxing roof allows a higher velocity. The peak neck load is due to a combination of roof intrusion and dummy excursion.

The near side impact during this test was significant with a vertical load of 8,500 lbs measured by the instrumented roadbed. This device allows for direct measurement of the load applied to the structure. This load was approximately 1.8 times the weight of the vehicle and is illustrated in Figure 10. After the near side impact, the vehicle continued to roll striking the far side of the roof prior to the end of the test. In this case, the load was much higher on the far side of the roof with a peak load of ~19,300 lbs (or 4 times the weight of the vehicle). It should be noted that the near and far side loads do not always follow this pattern. Larger near side than far side loads have been seen in several tests.

In this dynamic rollover test, the circumstances around a near side impact are investigated examining the excursion velocity of the near side occupant and the timing of the peak neck load as compared to the roof and dummy motion. The peak neck load occurs due to motion of both the dummy and the roof structure. This light, non-injurious impact occurred at a head impact speed of approximately 1.5 ft/sec. At this point, the roof has crushed only a minor amount, ~0.3 inches, with the peak crush speed, ~2.0 ft/sec, prior to the peak neck load. The occupant has moved upward ~0.8 inches and the peak neck load does correspond to a local peak excursion velocity at ~0.9 ft/sec. A clearer picture of occupant injury will be seen in a far side impact where larger neck loads are typically seen

This test was done at rotation rates of less than 240 deg/sec, although the dynamic rollover test achieved higher rotation rates after the near side contact.

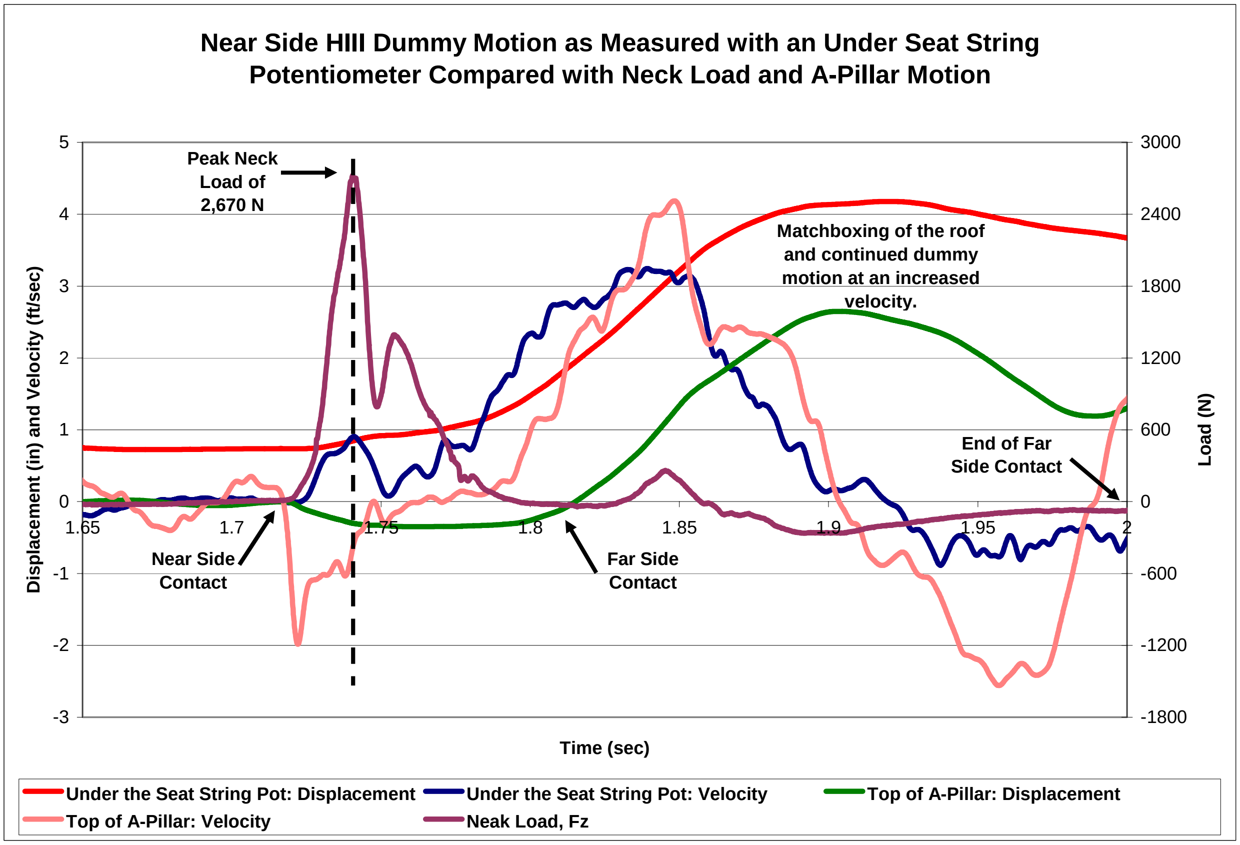


Figure 9. JRS test results focusing on the near side impact.

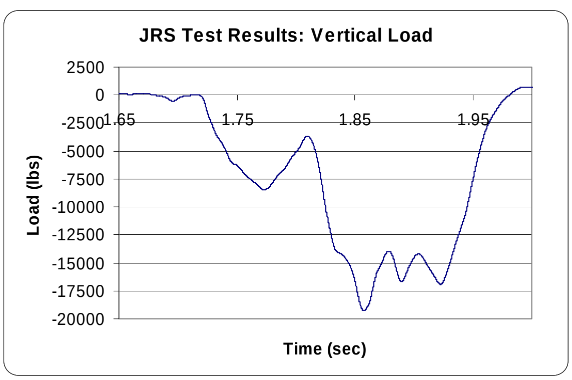


Figure 10. Vertical load during impact.

OTHER EXPERIMENTAL PROOFS

At higher rotation rates, the occupant becomes pinned to the vehicle at the upper corner. In those cases, the only component of occupant “diving” velocity has to come from the bulk motion of the vehicle. This can be examined from dolly rollover tests in which data is publicly available. The Malibu II study [3] can be used for this purpose.

The Malibu II study is an examination of eight dolly rollover tests with two restrained front seat occupants. Half of the vehicles were reinforced while the remaining were in the production state. The vehicles and occupants were instrumented and filmed both internally and externally.

For this study, it is also of interest to look at the Malibu II neck loads, belt loads and vehicle roll rates. This allows an examination of the occupant motion through the belt loads, impact with the roof through neck load and vehicle dynamics through the roll rate. If the occupant was undergoing a “diving” type loading the belt load would need to increase with increasing neck load. A graphical examination of this data is illustrated in the following figures.

These figures from Malibu II were created by digitizing the graphical data provided with the study. The electronic data has never been released to the public for independent analysis. They provide another method for examining the cause of the high neck loads seen during several of the tests in this series. Figure 11 is a graph of Malibu II Test 2, a reinforced vehicle. A peak neck load is at the end of the sequence where the roll rate has decreased to less than 200 degrees per second from an earlier peak of more than 500 degrees per second. In effect this relieves the lap belt loop load as the dummy reacts to lower centrifugal force.

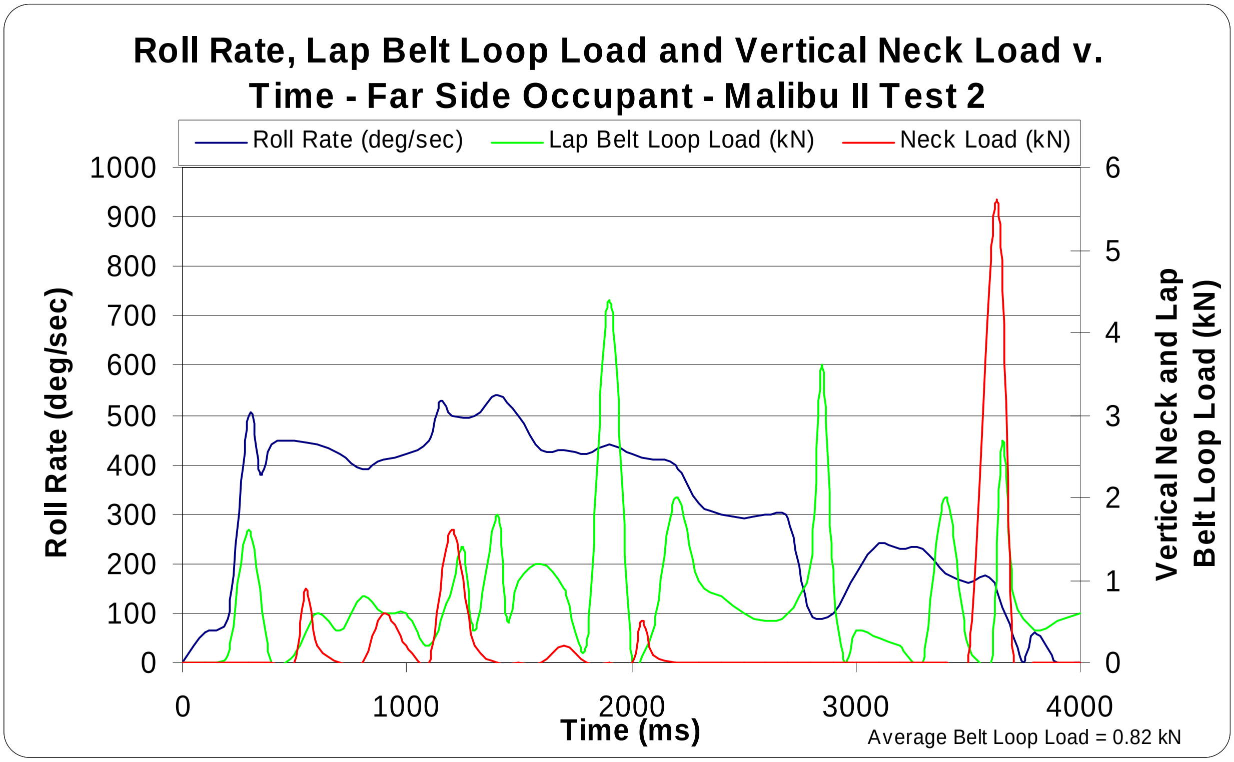


Figure 11. Malibu II Test 2 – Rollcaged Vehicle Data.

The occupant excursion and excursion velocity during this impact can be analyzed by examining the high speed video of the test and utilizing the timing data determined during the original analysis of the tests. In this impact, dubbed Potentially Injurious Impact (Pii) 2L1 (Test 2, left dummy, first impact over 2000 N) the interior photoanalysis of 2L1 roof and occupant motion is shown in Figure 12 just as roof/head contact starts. The intrusion velocity of the rollcaged roof after 0.97 inches of intrusion is 4.7 mph while the occupant is moving towards the roof at 0.9 mph as identified by the by the dummy buttocks motion.

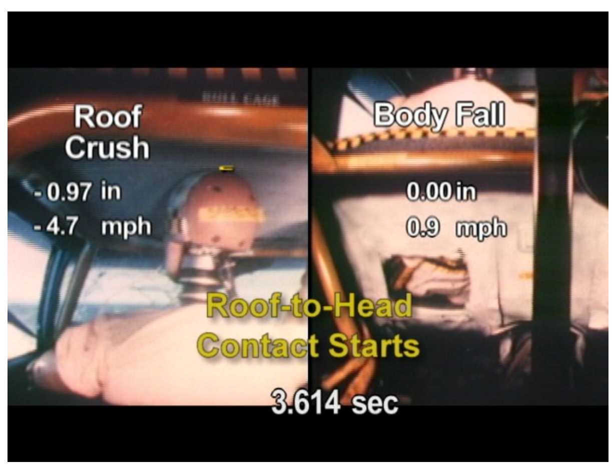


Figure 12. Split screen of Malibu II 2L1 roof and dummy motion.

Figure 13 examines Malibu II Test 3 of a production vehicle. In this test, there are two spikes in the neck load early in the test at approximately 700 and 1300 ms. An examination of these neck load spikes illustrates a corresponding decrease in the lap belt load. The decrease in belt load is caused by the roof deformation pushing the dummy towards the seat and unloading the belt. Any lessening of belt load due to moving of belt anchor points, typically the D-ring on the B-pillar, would occur with the roof crush after the diving theory would predict an injury – prior to roof crush.

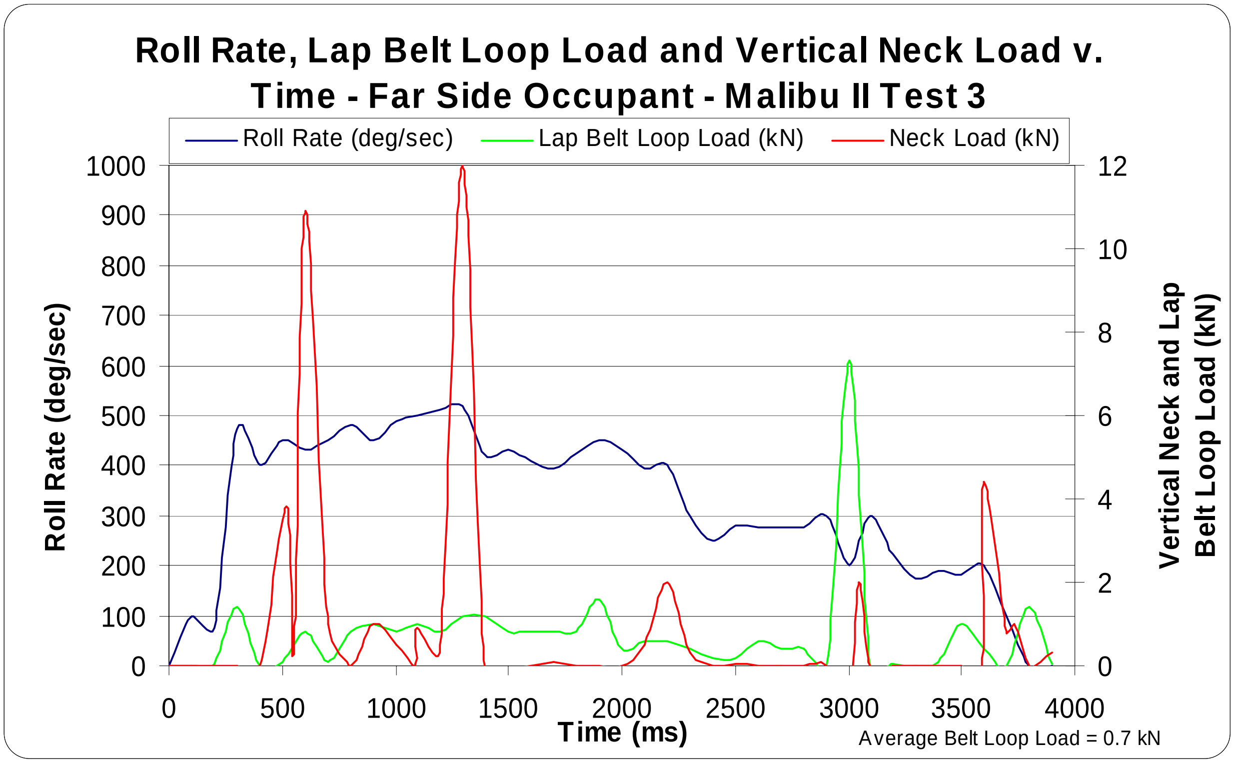


Figure 13. Malibu II Test 3 – Production Vehicle Data.

Figure 14 examines Malibu II Test 7 of a production vehicle. This is similar to the graphs from Test 3. In this case, the peak neck load is near the end of the sequence where the roll rate has decreased to approximately 200 degrees per second. The belt load is relatively low as compared to the peak belt load in the test at which point there was no neck load of note. If a diving type mechanism was the prime force in this event, then you would need to see an increase in belt load, but this is not present. The data clearly indicates something else is driving the neck load. Examination of the test video illustrates a moving buckle, as described in Malibu I [2], striking the dummy's head and reported in a 2005 ESV paper [11].

A similar study was conducted on a series of Ford Explorer rollover tests and presented to NHTSA [12]. This study also looked at a comparison between neck and belt loads realizing that diving could only occur with an increase in belt load as the torso loads the neck of an occupant. In a similar fashion to this study, the article concluded that diving type injuries can occur at low impact speeds in the absence of roof crush with the neck load increasing with increasing neck load. However, in the presence of roof crush and higher neck loads, the belt load decreased with increasing neck loads illustrating the crushing roof forcing the dummy towards the seat and possibly the loosening of the belt due to the deforming roof and moving seat belt anchor locations. Either of these motions preclude the diving theory as both necessitate the presence of roof crush and the diving theory states that the injury occurs prior to roof crush.

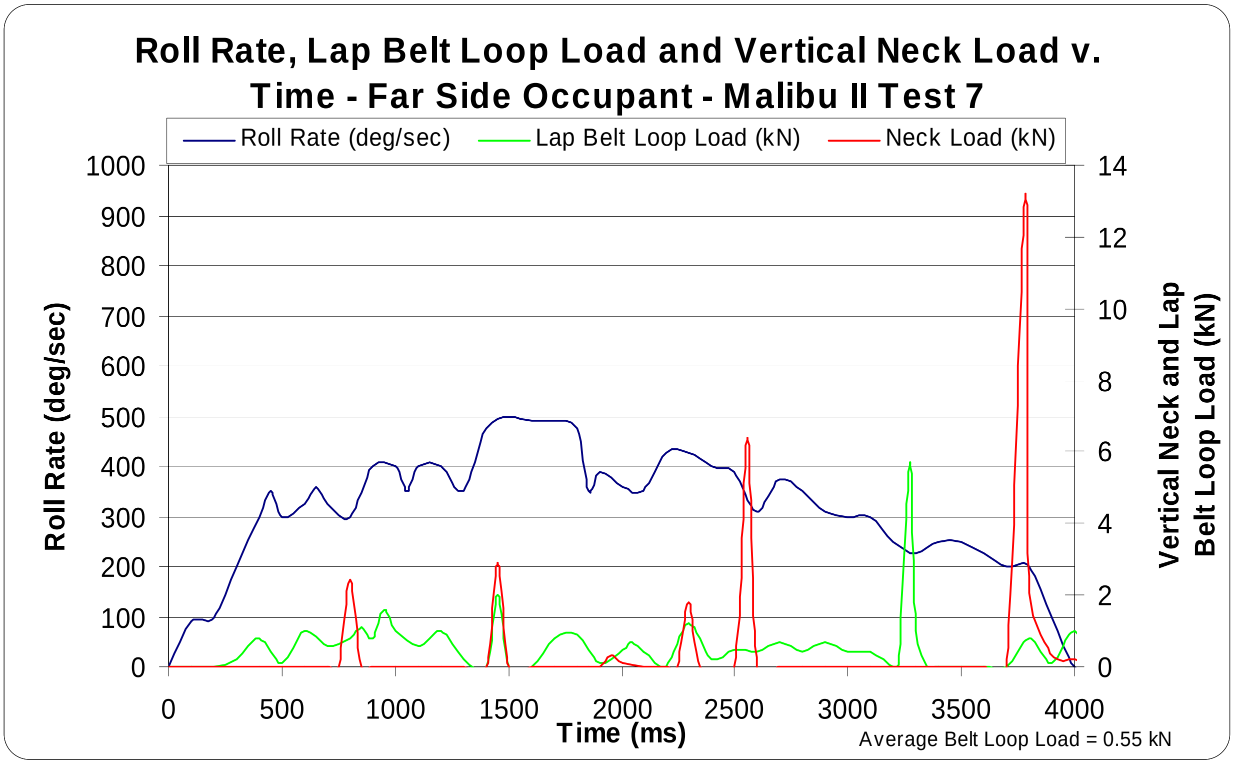


Figure 14. Malibu II – Production Vehicle Test 7 Data.

A comparison of neck load, belt load and roof crush was also made experimentally in a dynamic rollover test utilizing the JRS. In this test, a mid-sized SUV was tested with a restrained, instrumented Hybrid III 5th percentile occupant in the far side rear seat. The vehicle was instrumented with string potentiometers on the near and far side with an interior high speed camera. The test was an examination of small occupant motion in rollover accidents as no roof contact was expected during the test. However, a large buckle was formed due to the design of the roof and the occupant was contacted. This impact can clearly be seen on the high speed interior camera, see Figure 15.

The data from this test clearly demonstrates the peak neck load occurring as the belt load is decreasing with little or no motion of the restraint system anchor points, see Figure 16.

While there were no string potentiometers immediately above the rear seat dummy, a string potentiometer was located above the driver's seat and recorded the motion of the buckle that struck the occupant. The timing and motion of this buckling structure is very similar to the effects above the dummy. Figure 17 illustrates the motion of the roof and comparison to the neck load in the dummy.

While this test did not include a under the seat string potentiometer to examine excursion velocity, it clearly illustrates the non-injurious motion of the occupant in the absence of roof crush. With this small occupant, the roof crush is the reason the dummy was struck and had a peak neck load of 2,622 N.

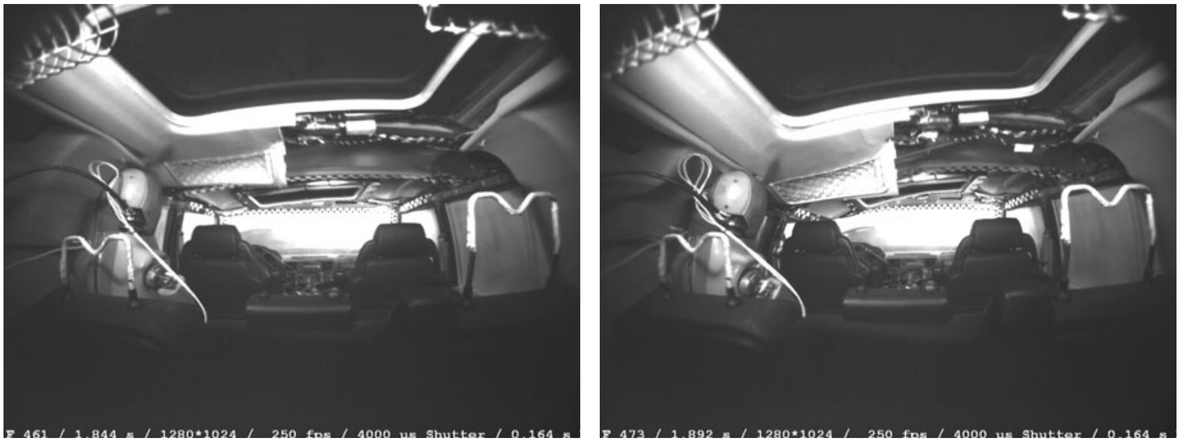


Figure 15 A and B. Video excerpts from test. In the first picture, the dummy has moved upwards toward the roof and the roof is beginning to crush. In the second picture, the roof is loading the dummy.

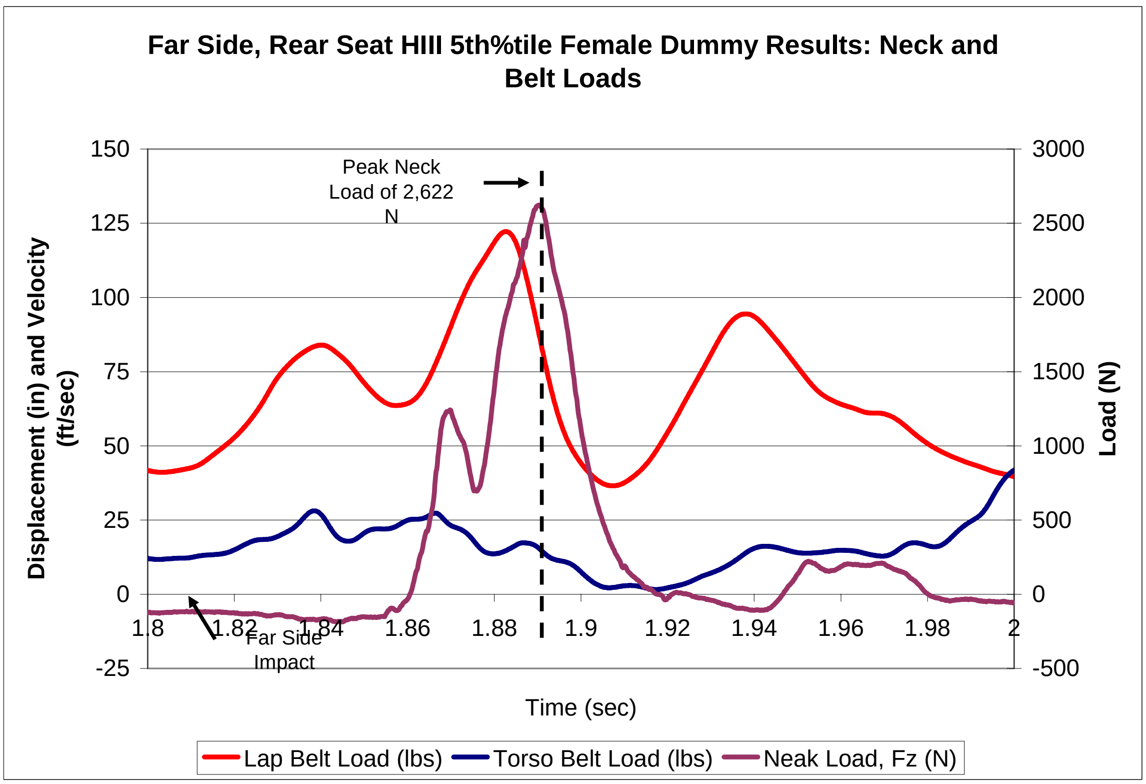


Figure 16. JRS test results focusing on belt and neck loads during a far side impact.

DISCUSSION

This study is an initial look at occupant motion in rolling vehicles with a focus on excursion velocity and effects on occupant injury. It was found that occupant excursion inside the vehicle is not at injurious speeds. Further examination of additional studies illustrate that the diving mechanism is not the main factor in rollover injuries. While torso augmentation may contribute to neck loading, it is not enough to cause injury in the absence of roof crush and additional occupant loading due to intrusion into the occupant survival space as is found in all other accident modes – front, side and rear.

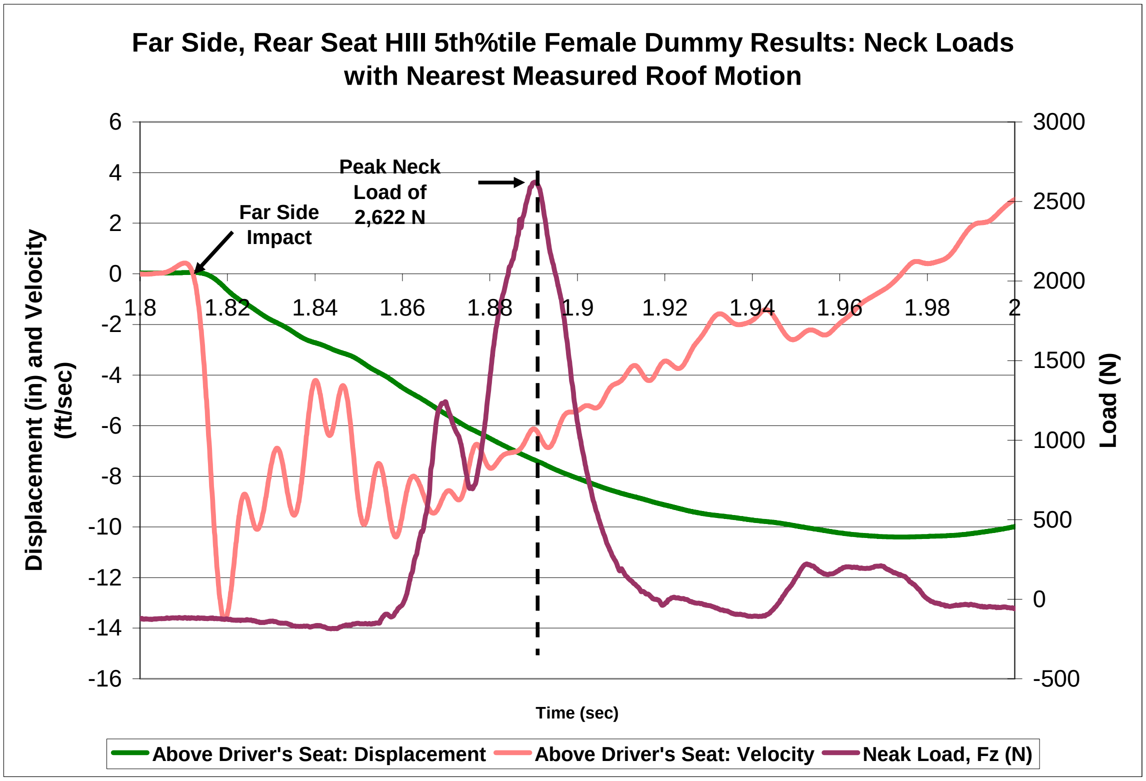


Figure 17. JRS test results focusing on roof motion and neck loads during a far side impact.

CONCLUSIONS

The Jordan Rollover System allows for dynamic spit testing and dynamic repeatable rollover testing.

In dynamic spit testing, it was seen that:

- Occupants do not necessarily contact the roof structure when rotated at rates up to above 200 degrees per second.
- Occupant excursion velocities are in the range of 0.5 mph. The occupant does not move faster than this relative to the seat in a non-deforming structure.
- Human and Dummy surrogates are both effective in this type of testing. However, the human occupants move differently in the motion of there arms, legs and especially the flexing of the neck.

In the dynamic rollover testing, it was seen that:

- Peak neck loads are caused by a combination of roof crush and occupant motion.
- Even with an impact, peak excursion velocities are limited to less than 1 mph. However, a higher speed was observed when the roof moved away from the occupant at a higher rate.
- In the test of the near side occupant, the dummy occupant moved upward a small amount and then was retained by the roof.
- In the test of a far side, rear seat occupant, the dummy moved upward without contacting the roof. Roof contact and neck loads were made when the crushing roof structure contacted the dummy due to a large buckle formed by the design of the roof and roof rack assembly.

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