TEST AND EVALUATION REPORT


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Active Safety Engineering, LLC

Pilot Study — Phase II
Of
Recreational Off-Highway Vehicles (ROV)

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ABSTRACT

This is the second pilot test program sponsored by the Consumer Product Safety Commission aimed at enhancing the rollover crash protection of recreational off-road vehicles (ROV). This pilot test program was conducted as an extension of the pilot program completed in May/June of 2010. The main purpose of this pilot extension was to explore the response differences between testing conducted on the HYGE accelerator sled at 2.5 g peak and testing performed with a deceleration sled platform at peak g's near the rollover threshold. To accomplish this, a contract was established with Autoliv, in Auburn Hills, MI. Testing was performed in Autoliv's crash test facility, using a movable platform that was slowly accelerated with the crash test propulsion system, then released and decelerated at a constant level by brake calipers attached to rails secured to the facility floor. Tests were conducted at near threshold g levels with two ROV's, two yaw angles, with and without seatbelts, and with two types of dummy occupant. The deceleration sled platform was found to produce repeatable test results, and testing was successfully performed at a small increment above the threshold deceleration required to initiate roll motion. Results, discussion and conclusions for the ten tests are contained herein.

Executive Summary

This pilot test program was conducted as a follow-on to a previous pilot test program conducted in May/June of this year. Whereas the previous program was conducted at the Transportation Research Center, Inc., using a HYGE accelerator sled, this program was conducted at Autoliv USA, using a decelerating rollover platform.

The main purpose of this test program was to conduct tests at a small increment of deceleration above the threshold required to initiate roll motion. From previous maneuver testing, a roll threshold just under 0.7 g's was observed for both the [redacted] and the [redacted] In trial tests with a decelerator platform, it was determined that lateral decelerations of 0.7 g's, at an initial velocity of 14 mph would be sufficient to produce desired roll motions. Testing was performed on the two ROV's at two angles, with and without seatbelts, and two types of dummy occupant. In all, ten tests were performed.

The decelerating rollover platform, with vehicles hinged to the platform, was found to produce repeatable rollover motions. This was determined by conducting three tests with the same input conditions and calculating the coefficient of variation of selected vehicle and occupant responses. The torso-bar type of passive restraint was again shown to be effective in keeping the occupant inside the vehicle at low deceleration environments. In unbelted tests, following the higher decelerations of tether jerk (to restrict the ROV rollover motion to 50-65 degrees) the dummy subsequently was either partially or fully ejected from the vehicle.

In all testing without a torso-bar type of passive restraint, the dummy head excursions were outside of the protective rollover cage (roll bars and support structure) of the ROV. This included testing with a 3-Pt. belt restraint, indicating that the belt system alone was not sufficient to keep the occupant inside the vehicle.

A test was performed with the EuroSID II side impact dummy. The purpose of this test was to observe response differences between the Hybrid 3 dummy used for most of the testing and the side impact dummy. The Hybrid 3 was selected because it has articulated arms and hands, allowing observation of arm and hand motion during the testing. It was noted that at low-g deceleration environments, the differences in shoulder, head and neck responses was small. At higher g environments, the differences became significant.

Descriptions of the test conditions, test variables, and test responses as well as discussion of results and conclusions are contained in the following sections.

Contents

1.0 Objectives

This test series was the second part of a pilot study performed to support increasing ROV safety by the Consumer Product Safety Commission. In the previous test series, two test devices, a HYGE sled and a FMVSS 301 roll platform, were explored as potential means to impart roll motions to the ROV. The HYGE accelerator sled was found to be a highly repeatable method of imparting rollover dynamic motions to the ROV's tested.

The current test series was conducted to explore an alternate, but similar method of imparting dynamic roll motions. For this method, the Autoliv crash barrier system was used as a propulsion device to gently accelerate a cart containing the ROV, and then the cart was decelerated at a controlled rate, causing the ROV to roll. This approach is very similar to the HYGE sled in ROV dynamics with the exception that the brake/deceleration system allows longer deceleration travel than is available with current HYGE accelerator systems.

The objective of the current test series was to conduct testing at deceleration levels closer to the threshold roll level obtained in test track testing, to compare the occupant dynamics to that obtained with the HYGE approach. A secondary objective was to observe the effectiveness of the torso bar (a passive restraint) concept of the [redacted] under belted and unbelted conditions and in a 60 degree deceleration environment. In addition, the dummy responses of the 50th percentile Hybrid 3 frontal dummy were compared with those of a EuroSID II, side impact dummy.

2.0 Test Conditions

2.1 Test Dummies

Most of the tests were performed with a 50th percentile Hybrid 3 male dummy. The dummy was instrumented with a triaxial accelerometer package in the head. One test was conducted with a 50th percentile male EuroSID dummy. The EuroSID was also instrumented with triaxial accelerometers in the head.

The left shoulder and elbow joints of the Hybrid 3 dummy were loosened to allow free motion of the left arm in the low deceleration and roll environment. Hand excursions were not measured or noted in this report, but the hand motion is captured in the movies, and is a significant outcome of the tests, due to the many corresponding hand and arm injuries in ROV accidents. The wrist tension was maintained at about a 1-g setting to allow the hands to rest on the steering wheel during the acceleration and coasting phase of testing. Since the EuroSID has stub arms, the shoulder settings were maintained at the normal "1-g" setting. The leg joints of both dummies were maintained at the usual 1-g setting.

The dummy was seated in the same manner as in the previous study. The pelvis was centered in the seat cushion, and forced back firmly against the seat back. The H-point was positioned in the same range of X-Y positions as in the previous study. The torso was positioned against the seat back, with the torso and head centered in the seat back and head restraint. The hands were positioned with the thumbs hooked over the steering wheel. The right foot was positioned on the accelerator pedal, and the left knee positioned the same distance from the right knee as in the previous study. Once the body was positioned within the target locations of the previous study, the vehicle and dummy references were documented using a 3-dimensional Faro Advantage Arm (Model C-12). This allowed subsequent positioning to be conducted much more quickly. Figure 2.1 shows the dummy positioning being done with the Faro-Arm. The Faro Arm seating procedure used 3 bolt locations on the ROV's as reference points from which the dummy targets were located. The origins of these reference points are shown in Figures 2.2 and 2.3 for the [redacted] and [redacted] respectively.

Since the vehicle was accelerated up to speed, then decelerated at a controlled rate, there was always some chance that the dummy might shift positions before initiation of the deceleration. One remedy would be to lightly tape the hand to the steering wheel. Observations from the trial tests did not show any significant dummy movement, so the hands were not taped to the steering wheel.

2.2 Vehicle Set-up

The two ROV's selected for this test program were the same models as used in the previous study conducted at the Transportation Research Center in Ohio. The first vehicle was a [redacted] [redacted] VIN [redacted]. It was documented in the previous program. The second vehicle was a [redacted] [redacted] [redacted] VIN [redacted]. Each vehicle was prepped by draining the fuel from the tank. No Stoddard fluid was added. Tubing was welded to the roll cage for mounting of the three on-board cameras. The on-board cameras were positioned to capture overhead, frontal and front-oblique views of dummy motion. The cameras mounted to the [redacted] and [redacted] are shown in Figures 2.4 and 2.5. The vehicle was also instrumented with accelerometers (X,Y,Z) and roll rate sensors (X,Y,Z) on the tunnel area of the occupant compartment.

All camera data and instrument signals were collected in an onboard data acquisition system, and relayed through a cable to the data processing system. All accelerometer and roll rate sensor data were processed according to SAE J211. Figure 2.6 contains a view of the data acquisition equipment in the cargo area of the vehicles.

The vehicle was mounted to a movable platform (cart) for the conduct of rollover simulations. This cart is routinely used by Autoliv to simulate rollover motions of vehicles. The tests were conducted in the crash barrier facility. Vehicle rollover motion was initiated by accelerating the cart up to the desired velocity, then braking the cart to a stop at a deceleration level sufficient to initiate roll motion of the vehicle. To prevent sliding motion of the vehicle on the cart, the leading (driver side) tires could be restrained either by a curb structure against the tires or by removing the tire/wheel assemblies and attaching the vehicle to the cart with a hinge structure. ASE chose to use a hinge assembly, in order to prevent any test variability due to tire/cart interactions. The hinge assembly used for the [redacted] is shown in Figure 2.7

In a driving maneuver, as the vehicle approaches tip-up, weight is transferred to the leading side of the vehicle, causing the leading tires and suspension to compress. In the cart test, the suspension is free to compress, but with the hinge attachment, dynamic tire compression is not possible. This effect was somewhat accounted for by adjusting the hub height at the hinge to the height measured with one occupant onboard, and the vehicle weight shifted to wheel lift on the opposite side. This resulted in the hub being lowered approximately 1 inch from the hub height with one occupant and no weight transfer. The tire compression is quite pronounced because of the low pressures ($\underset{\sim}{}$ 10 psi) recommended for ROV use. This pre-set of the driver side hub/hinge caused the vehicle to lean approximately 1.3 degrees. It is believed that accounting for this weight transfer resulted in a slightly lower rollover threshold acceleration.

The vehicle was also attached to the cart with a tether to prevent complete (1/4 turn) roll and subsequent damage to vehicle or cameras. The tethers were attached to the passenger side sill area by welding a plate to the sill and attaching nylon straps to the plate. The strap length was adjusted to allow approximately 55-60 degrees of roll motion before the tethers grabbed (i.e., tightened and restricted further roll motion). Figure 2.8 shows the tether attachment to the [redacted] and Figure 2.9 shows the [redacted] tilted to full motion, being held by the two tether straps. This differs from the tethering done in the previous pilot test program, in which the tethers were attached to the roll cage and the maximum roll closer to 45 degrees.

2.3 Cart Deceleration

The unique and defining feature of this facility is the brake/deceleration system. Figure 2.10 shows a perspective view of the brake rails. It can be seen that the cart is guided along a center rail that runs the length of the track. This guide rail is used for all types of tests, including frontal fixed-barrier tests and side, barrier-to-car crash tests and so forth. The guide rail is recessed into a channel in the concrete floor, with the top of the rail flush with the surface of the roadway. The tow cable that is used for propulsion is also in the channel. For this testing, the cart is attached to the tow cable with a breakaway mechanism. On either side of the cart is a protrusion which engages the brake mechanism. The brake mechanism is comprised of a rectangular box with calipers inside which grip the brake rails that are bolted to the floor. The gripping force, and hence the deceleration level is adjusted with pressure cylinders attached to the calipers. The caliper assemblies are positioned on the rails then the pressure is applied by the cylinders. Toward the end of the rails, are two more caliper assemblies on each side that serve as a back up to the primary system. They are intended to keep the cart from traveling to the end of the rail. Figure 2.11 is a view of the brake rails and calipers, looking straight down the guide-rail to the cart and ROV in the distance.

The calipers provide a fairly repeatable braking force. The operator makes adjustments based on the desired deceleration level, the travel speed and the total mass of the cart and vehicle. The cart is instrumented with accelerometers. A typical deceleration response of the cart consists of a hard spike corresponding to the inertial jolt of the metal shock absorbers hitting the metal caliper boxes. This spike is of a short duration ($\underset{\sim}{}$0.05 seconds), following which the remaining deceleration is fairly constant all the way until the cart is stopped. Figure 2.12 shows one of the Ace dampers on the cart that engages the brake calipers.

The advantage of this facility over a HYGE sled is the travel distance of the brake rails. If needed, the braking can occur over a distance of 15 feet. With the HYGE, the pulse is controlled by either a metering pin or by external actuators. Metering pins for the HYGE are typically less than 5 feet in length, which then is the distance over which acceleration can occur.

To visualize the need for distance, consider system where an ROV is hinged at a 90 degrees yaw orientation on a cart, and the deceleration is exactly the threshold (theoretically T/2h , half the track width divided by the c.g. height, for a rigid body without tire and suspension compliance). At this deceleration level, the forces and moments about the hinge point exactly balance each other, and the vehicle does not rotate. If the deceleration is increased by a very small increment, there is an imbalance in moments, and the vehicle begins to rotate. The rate of rotation is a function of the difference in moments and the rotational inertia of the vehicle. In this case, the rotation will be slow because of the incremental moment. Since rotation is occurring slowly, it must continue for a long time to achieve tip-up. Hence, it would require long travel distances. As the deceleration increases, the moment also increases, and less time (shorter distance) is required to achieve tip-up.

The required stopping distance is therefore linked to how close to the tip-up threshold the test is to be run. It was the desire of the CPSC to conduct these tests “near the threshold” required to tip the vehicles. Accordingly, the selected deceleration levels were estimated around 0.1 g greater than the threshold. It will be shown that brake travel distances of 90-110 inches resulted from most of the tests. With deceleration levels around 0.2 g’s above the threshold, it is estimated that the same tests could be performed with a typical accelerator (such as the HYGE) sled. Figure 2.13 shows the [redacted] fully prepped and ready for testing.

2.4 Camera Coverage

The ROV rollovers were documented with 7 high-speed cameras, and for most of the tests, one-digital real-time camera. Three cameras were mounted onboard the vehicle as previously described, to give an overhead, frontal and front-oblique view of the dummy motion. Two high speed cameras were placed on the track, positioned so as to show a frontal view of the leading edge of the ROV as it was nearing the end of deceleration and roll motion. One of these was a close-up view and the other further away. One camera was positioned on the ground from the rear of the vehicle and the last was over the guide rail, just beyond the brake rails. All of the cameras were triggered automatically by the test controller, except the real-time camera, which was hand operated from a station forward and off to the side of the brake rails.

For the first test, test 212, the cameras were set to run at 1000 frames per second. It was noted that some of the roll motion occurred after the cameras had reached the limit of data storage. The remaining tests were conducted with cameras running at either 500 or 250 frames per second. This enabled better lighting of the high-speed digital movies, and capture of the entire event. The slower frame rate was plenty fast enough to capture the motions of these relatively slow roll events. A schematic of camera placement is contained in Appendix A.

2.5 Test Parameters

The primary input parameters for the testing were the speed of the cart and the deceleration level set for the brakes. The travel speed of the cart primarily affects the time duration of the event i.e., the travel distance after brake engagement is directly proportional to the travel speed at which the cart engages the brakes. The deceleration level at which the brakes are set determines the rate at which roll motion is initiated. In theory, when the deceleration level reaches the required threshold (T/2h for rigid body estimation) roll motion will be initiated. As the deceleration increases above that value, roll motion occurs at a faster rate.

The severity level for most of these tests was to be a small increment above the threshold level that would cause the vehicle to roll, and maintain that level long enough to tip past 45 degrees. The threshold was explored in a brief trial test series for each ROV. It was estimated that in a 90 degree yaw orientation, each vehicle would begin to roll at just above 0.6 g's of deceleration. The target deceleration level was then chosen at 0.7 g's and a cart speed of 14 mph provided a pulse duration sufficient to achieve full tip-up. Both cart speed and deceleration levels were increased when testing was performed at 60 degrees yaw orientation of the ROV.

It is noted that the tip up threshold of these tests is likely below that of the driving maneuver tests due to the mass of the cameras and data acquisition equipment, and their location above the center of gravity of each ROV. No attempt was made to measure the effect of the test equipment on the tip threshold.

The parameters that were varied in the program were: 1) ROV model ([redacted] or [redacted] 2) yaw angle (90 degrees or 60 degrees), 3) belt condition (belted or unbelted), 4) dummy (Hybrid 3 frontal or EuroSID II) and 5) Passive torso restraint (this is standard for the [redacted] and was added to one of the [redacted] tests.

With five variables at two levels each, it is apparent that ten tests will not allow statistical analysis of the results for each variable. Since the primary objective of the program was to compare this method of decelerating the cart with the HYGE accelerator sled, the significance of each of the input variables was not considered important for this series. Table 2.1 shows the sequence of the tests conducted and the input conditions for each of the tests.

3.0 Test Results

All of the tests were conducted on September 14-16, 2010. The main objective of the test series was to obtain data from rollover events initiated near the threshold deceleration required. The occupant of the ROV is exposed to a low-g environment up until the time that the tethers arrest the roll motion of the vehicle. At that point, the vehicle stops suddenly, while the occupant is still moving, resulting in a higher-g environment as the occupant is stopped by the torso belt, torso bar or rapid ejection occurs. In the previous study, excursions and accelerations were separately reported prior to tether grab and after tether grab. In this report, the responses following tether grab are not considered. In the unbelted tests, the post-test position of the dummy is noted.

A typical roll velocity curve is shown in Figure 3.1 (Appendix B contains all roll velocity plots). The roll velocity increases steadily until approximately 0.8 seconds, then decreases until about 1 second. This is likely due to the effect of the occupant mass being picked up and accelerated. The roll rate then increases again until about 1.25 seconds, then drops off sharply to zero. This sharp drop occurs when the tethers grab the vehicle. The time of tether grab can be determined from either the roll velocity trace or from the off-board movie views

3.1 Overall Results

The results of the Autoliv, deceleration test series are summarized in Table 3.1. The source of the data in Table 3.1 is as follows:

Cart Velocity	Off-board speed trap
Time of Tether Grab	Roll rate sensor or film analysis
Peak Roll Velocity	Roll rate sensor
Average Platform Deceleration	Platform accelerometers
Peak Head Resultant Acceleration	Head X-Y-Z accelerometers
Peak Head Excursion	On-board forward camera
Seat Belt Pay-out	Post-test measurement of marker on belt

It is noted that the target lateral deceleration for the first 9 tests was 0.7 g's. The target deceleration for the last test (223) was 1.6 g's, which was an attempt to duplicate the overall severity of a previous HYGE accelerator-sled test which had a triangular shape pulse with a 2.5 g peak value. Following Test 214, it was suspected that inconsistencies in the [redacted] responses might be due to inconsistencies in seat belt locking, so markers were placed on the belt near the D-ring and the amount of belt travel recorded, starting with test 215.

The peak head excursions were determined using software analysis package, tracking the marker on top of the dummy head, relative to markers on the vertical roll cage and the sill area. It is noted that such analysis is subject to distortion, due to the differences in distance from the camera focal point to the head marker and the vehicle reference points.

3.1 Test Repeatability

As in the previous pilot study, repeatability testing was performed with the Autoliv deceleration sled. Tests 214, 215 and 216 were conducted with the same input parameters ([redacted] 60 degree, belted, Hybrid 3 dummy). The cart deceleration was set for about 0.81 g's, which should result in a lateral deceleration of the ROV of 0.7g's. Table 3.2 contains the peak roll velocity, the peak head resultant acceleration (Appendix C contains all head resultant acceleration data plots) and the peak head excursion values of the 3 tests, along with the coefficient of variation (standard deviation divided by the mean) for each value.

As can be seen, the test repeatability for the 3 tests is excellent for all values except peak head excursion. The peak roll velocity, average cart deceleration and peak resultant head acceleration all have CV's less than 5%, which is excellent for any type of impact testing. The head excursion value of test 216 was quite different from that of 214 and 215, even though the estimated belt spool-out is fairly close between the tests. In examining possible reasons for the variation, it was noted that in tests 214 and 215, the belt remains in contact with the upper flesh of the torso jacket, whereas in test 216, it appears that the torso belt slips over the torso flesh and into the neck. Since the Hybrid 3 dummy was designed primarily for frontal crash environments, this type of loading might not have been anticipated. It is possible that this could easily be resolved with a jacket with a higher neck or by adding something to provide a more realistic transition from torso to neck. Differences were also noted in the arm motion between the two tests, which could influence lateral movement of the dummy as well.

The CV's of this series were generally on the same order as those from the accelerator sled test series (See previous Pilot Study report dated June, 2010). The accelerator test series was conducted at 90 degrees and at a higher severity than the decelerator test series, so it is not possible to directly compare the two, but both are excellent overall. Also, roll velocity was not measured in the accelerator sled series.

The time history of the roll velocities is shown in Figure 3.2. The time history of the head resultant accelerations is shown in Figure 3.3. These figures also illustrate the high degree of repeatability of the decelerator sled approach. A visual look at the repeatability is shown in Figure 3.4, with the dummy position at max excursion in each of the 3 repeatability tests.

3.2 Comparison of HYGE and Deceleration Head Excursion Values

The previous test series (HYGE sled tests) was conducted with a triangular shaped pulse, with a peak acceleration value of 2.5 g's, and this current series was conducted at a constant deceleration of 0.7g's. In theory, the vehicle and occupant responses would be the same in an acceleration environment as in a deceleration environment, provided the same pulses were used. Since the pulse shapes were different, as was the overall severity of the accelerator and decelerator series', the comparison is skewed. Table 3.3 contains the head excursion values for the tests in which all conditions were the same except the pulse. It is seen that the HYGE tests resulted in higher excursion levels, although in some conditions, the differences were small.

3.3 Comparison of Hybrid 3 and EuroSID Responses

The Hybrid 3 frontal dummy was selected for the previous and current test series primarily because the dummy has articulated arms and hands. The Hybrid 3 dummy was designed to exhibit acceptable biofidelity in a frontal crash environment. The chest (sternum area) of the dummy is instrumented to measure deflections caused by crash-induced forces. The neck is also designed to respond properly to frontal crash forces. In a lateral impact environment, the shoulder of the Hybrid 3 is essentially a rigid beam with only the arm flesh able to deflect.

The EuroSID dummy was designed with improved chest, head/neck and shoulder biofidelity (biofidelity is a measure of how humanlike the dummy responds…for example, the HYBRID 3 neck has been shown to be much stiffer than a human neck in side collisions) in lateral crash environments. The shoulder complex is attached to a shoulder rib, which is compliant in lateral impacts. The arm of the EuroSID represents only the upper arm, and is primarily to add to the biofidelity of the chest in the lateral direction.

In the current test series, the primary outcome of each test is the maximum lateral head excursion, with particular interest in whether or not the head travels outside the periphery of roll cage of the ROV. In order to get some idea of the importance of which dummy is being used, the last test of the series was an attempt to replicate a test from the HYGE series, only substituting a EuroSID dummy for the Hybrid 3 used in the previous test. The test vehicle was the [redacted] and the test conditions: 90 degree, belted. The pulse for the HYGE test had a 2.5 g peak and a pulse-width of about .45 seconds. It was estimated that the average acceleration over the period was about 1.6 g's. The deceleration sled test was set up with those parameters, a deceleration level of 1.6 g's and a pulse width around 0.45 seconds.

The estimated peak dummy head excursion for the Hybrid 3 test (max prior to tether jerk) was 1 inch and 3 inches for the EuroSID. Figure 3.5 shows the Hybrid 3 at peak excursion prior to tether grab, and Figure 3.6 shows the same thing for the EuroSID. It is noted that the EuroSID is leaning slightly further out of the vehicle than the Hybrid 3. The position of the 2 dummies after tether jerk is shown in Figures 3.7 and 3.8. It is noted that in this higher deceleration environment, the EuroSID has significantly more lateral head/neck rotation than the Hybrid 3 dummy.

There is clearly a response difference between the two dummies late in the event. The amount of difference is greater in higher loading environments such as after the tether jerk in the ROV testing. The response difference was moderate in the 1.6 g, 0.45 seconds, square-wave pulse of this testing, prior to tether jerk. It is estimated from these tests that in a threshold acceleration/deceleration environment (~ 0.7 g's), prior to tether jerk, the response difference would not be significant. Therefore, either dummy could be used at threshold g's. If arm/hand motion is of interest, the Hybrid 3 dummy is a better choice.

3.4 Effectiveness of the [redacted] Passive Torso Restraint

As discussed in the previous pilot study, the [redacted] was equipped with a passive torso and hip restraint. The [redacted] was modified in the previous study in order to bolt the [redacted] torso restraint directly onto the roll bar of the [redacted] Figure 3.9 shows the torso restraint of the [redacted] and Figure 3.10 shows the restraint mounted to the roll bar of the [redacted]

To assess the effectiveness of the torso passive restraint, testing is performed with and without the restraint, and the results compared. In the previous Pilot Study, such testing was performed. Unbelted testing was conducted on the [redacted] at 90 degrees, with the 50th male Hybrid 3 dummy, with a peak acceleration level of about 1 g. In the test without the torso restraint, the dummy was partially ejected, with only the legs remaining inside the vehicle. In the test performed with the torso restraint, the dummy remained inside the vehicle, with no head excursion outside the periphery of the roll cage. It is noted that this pair of tests only tipped partially up, and tether jerk did not occur.

In the current test series, three tests were performed that are relevant to this issue. The first test (Test 213) was similar to the unbelted test without the torso restraint with the [redacted] vehicle performed in the previous series. The vehicle was decelerated near the threshold g level (0.7 g's) for sufficient time to cause full tip up to tether jerk. The dummy response was similar to the previous test up until about 700 msec., but following tether jerk, the dummy was ejected onto the roadway. Figure 3.11 shows the dummy position at 756 msec., and Figure 3.12 shows the dummy at 1.2 seconds into the event. This indicates the importance of using belt restraints. This test also illustrates one advantage of this type of sled, in that the threshold g level can be sustained long enough to achieve full tip-up. The stopping distance for the deceleration sled was 92.5 inches. With an accelerator sled such as the HYGE, a metering pin could hypothetically be machined with a length of 60 inches and a near-square-wave pulse. Under these conditions, it would require somewhat higher acceleration (due to the shorter travel length) to achieve the same degree of tip-up.

Test 217 was conducted with the [redacted] at 60 degrees, unbelted, with a torso bar installed. This test was the first test to explore the effectiveness of the torso restraint with a forward component of deceleration. Figure 3.13 shows the position of the dummy at the time of tether jerk. Up to this time, the torso restraint provides enough restraining force to keep the dummy inside the roll cage. Following the tether jerk, the dummy was ejected. Figure 3.14 shows the position of the dummy at 2.2 seconds, in the process of exiting the ROV. It is postulated that in a threshold roll on a hard, smooth surface, the dummy would remain in the vehicle through a full ¼ turn. This is significant because many injuries are caused by crushing of the body between the vehicle and the ground. As long as the occupant remains inside the roll cage, these crushing injuries could be prevented. Tether jerk could represent the vehicle being stopped at a quarter turn, or being stopped by an outside object. The importance of considering the response following tether jerk depends on the distribution of accidents in which the vehicle encounters an outside object during the roll event. Again, for purposes of this study, the responses following tether jerk are considered out of scope.

The final test of the torso restraint effectiveness was Test 221. This test was conducted with the same conditions as Test 217, except with the [redacted] The torso restraint is standard equipment with the [redacted] The occupant kinematics in this test was very much like that of the corresponding [redacted] test, in that at the time of tether jerk, the occupant is still upright and within the periphery of the roll cage, and following tether jerk, the occupant slides off the torso restraint and is ejected. Figure 3.15 shows the position of the occupant at the moment of tether jerk, and 3.16 the final resting position of the occupant following the completion of the test.

4.0 Discussion of Test Method

The main purpose of conducting these tests at the Autoliv facility, was to determine the differences in occupant kinematics at rollover conditions close to the rollover threshold observed in steer maneuvers on a smooth asphalt roadway. One type of maneuver is a constant radius turn, with slowly increasing speed. In such a maneuver, the lateral acceleration slowly builds up as the speed increases. The lateral deceleration profile is not constant due to such factors as static and sliding friction, and the heating of the tire rubber as lateral slip increases. But for laboratory purposes, the event can be simulated with a near constant level of deceleration.

The primary advantage of a facility such as the one used for this testing is the travel distance available during vehicle deceleration. With an accelerator device such as a HYGE sled (either 12” or 24” diameter propulsion device) the acceleration distance is determined by the length of the metering pin. This distance is typically limited to around 5 feet. Comparatively, the usable brake distance at the Autoliv facility is on the order of 15 feet.

To visualize the importance of this distance, consider a test where the deceleration level is a fraction below the tip threshold (theoretically T/2H for a rigid body without tire and suspension compliance). No matter how long or how far the ROV travels, no tip-up occurs. As the deceleration level increases to a small fraction above the threshold, roll motion is initiated. The closer the deceleration is to the threshold, the longer the time and distance required to achieve a desired degree of roll.

Maneuver results were available for both of the ROV models used in this test series. From these maneuver results, it was estimated that tip was initiated at about 0.69 g’s for each of the two vehicles. It is certain that the cameras, camera mounts and data acquisition equipment added above the vehicle center of gravity decreased the tip threshold, but the change was not measured or calculated. It was noted that with the [redacted] two trial tests were conducted at a lateral deceleration of about 0.6 g, and roll motion was initiated, but full tip-up was not achieved in the available distance. Based on the trial tests, most of the testing of this series was conducted with a lateral deceleration of about 0.7 g.

The travel distance for the brake calipers ranged from 63 inches to 145 inches. For testing near the threshold tip level (.7 g), the brake caliper travel ranged from 92 inches to 145 inches.

The [redacted] was selected as the first test vehicle. The velocity was estimated from the end velocity of the previous HYGE testing, and was set at 14 mph. Following the two tests at 90 degrees, three repeatability (identical input conditions) tests were conducted at 60 degrees. The speed and target deceleration was estimated by dividing the 90 degree values by the sine 60 degrees (.866). This resulted in a target speed around 16 mph and a deceleration level of about 0.8 g.

4.1 HYGE Accelerator Test Method

The previous pilot program demonstrated that smooth, repeatable roll events can be conducted with the HYGE accelerator sled. The pin used in the previous program produced the pulse shape shown in Figure 4.1. It is noted that tailoring pulse shapes with HYGE metering pins is not an exact science, and metering pins must be individually machined. A metering pin that produces a fairly constant acceleration could be machined. This would result in a test wherein a constant acceleration could be applied for a distance around 60 inches of travel. An acceleration level of about 0.9-1.0 g’s would probably be required to achieve full tip up. Advantages of the HYGE accelerator test method are:

- Less expensive cost per test
- Abundance of test facilities with HYGE accelerator sleds
- Highly repeatable test input

Disadvantages of the HYGE accelerator sled:

- Stroke limited to around 60 inches, hence full tip-up could not be achieved at 0.7 g’s
- Specific pulse shapes are more difficult to achieve

It is noted that some facilities, including Autoliv, have created a hybrid variety of the accelerator sled, wherein the propulsion system provides the energy, and the pulse is controlled by fast-acting, servo-hydraulic actuators attached to brake calipers. Using this method, nearly any pulse shape can be achieved with a single metering pin, and the acceleration levels are highly controlled. Only a small number of facilities have converted their HYGE sleds to hybrid sleds.

4.2 Brake Caliper Deceleration Sled

The Autoliv sled controls the deceleration levels by adjusting the pressure to brake calipers which grip steel rails. In theory, the rails could be any length, and could accommodate a broad range of velocity-deceleration combinations. The advantages of the brake-caliper deceleration sled are:

- Capable of rollover testing close to the tip threshold deceleration
- Repeatable deceleration levels
- More realistic in appearance (accidents involve deceleration-initiated rolls)

The disadvantages are:

- Cost is generally higher due to greater expense of crash test facilities
- Very limited number of facilities available
- Only constant deceleration levels can be simulated

4.3 Additional Considerations of Test Approach

In the two phases of the pilot study of ROV rollover occupant protection, a variety of test conditions were utilized. The primary outcome of the testing was whether or not the occupant (especially occupant's head) was contained within the protective roll cage of the ROV. It was observed in testing with the driver restrained with only a lap/shoulder belt, the head went outside the roll cage. It was further observed in testing with a torso-bar type passive restraint, the occupant was kept within the roll cage until the roll motion was arrested by tethers attached to the ROV. The indication was that such a passive restraint, in addition to the belts, could successfully contain the occupant through a full ¼ turn of an ROV.

In further examining the tests with a torso bar type passive restraint, it was observed that the peak head excursion of the dummy occurred early, in about 0.250 seconds, and the amount of roll motion of the vehicle that occurred in that time was close to 5 degrees (see Table 4.1).

Possible Alternative Test – As a result of the observations from the two ROV pilot studies, an alternative, simpler test is possible. If a restraint is to successfully keep the head within the roll cage, it appears that it must catch the occupant very early in the event. If the first 0.25 seconds of the rollover simulation is isolated, the occupant is seated in an ROV and exposed to a lateral deceleration slightly above the tip threshold. The occupant slides toward the door opening, the torso bar stops shoulder displacement, and the inertia of the head causes the head to rotate outward. The peak head excursion occurs in about 0.25 seconds. The **average** vehicle roll angle over the 0.25 seconds would be around 2.5 degrees. This is believed to be negligible, indicating that a horizontal platform/vehicle orientation might work just as well. The alternative test procedure would then be as follows:

- Position the ROV on a horizontal sled platform at the desired yaw angle (i.e., 90 or 60 degrees)
- Attach the vehicle securely to the platform, restraining the vehicle from translational or roll motion
- Accelerate or decelerate the vehicle at 0.7-0.9 g's for a period of about 0.5 seconds
- Measure and document the dummy head excursion relative to the outer periphery of the roll cage

Advantages – The advantages of this alternative test are:

- Faster, less costly set up
  - Vehicle could be driven directly onto test platform
  - No hinge fabrication and installation
  - No tether attachment
  - Not necessary to drain any fluids or expensive vehicle prep
  - Less instrumentation required on vehicle…one accelerometer
  - Less likely to cause vehicle damage due to tether jerk
- Can be performed with either an accelerator (HYGE) or decelerator (Autoliv type brake platform)
- Occupant head excursion could be documented with a vehicle mounted or sled-platform mounted camera
- Following test, vehicle could be detached and driven off the platform

5.0 Summary and Conclusions

This is the second pilot study performed prior to a more extensive test program aimed at enhancing the rollover protection of recreational off-road vehicles (ROV). The main purpose of this test program was to explore the vehicle performance and occupant responses in a rollover environment that is close to the threshold acceleration required to initiate rollover. Since rollover motion near the threshold g level requires longer travel distances to achieve full tip-up, the rollover platform facility at Autoliv in Auburn Hills, MI, was contracted to conduct these tests. The following conclusions are offered for this program:

- The deceleration-sled rollover platform at Autoliv (with ROV hinged to the platform) produced repeatable test results.
  - The coefficient of variation (CV) of peak roll velocity for three repeat tests was 2.1%
  - The CV of average cart deceleration was 3.1%
  - The CV of peak head resultant acceleration was 1.4%
  - The CV of maximum head excursion was 21% (see discussion in text)
- Dummy head excursions were outside of the protective roll cage in all tests without a torso-bar type of passive restraint
- In tests with a torso-bar type of passive restraint, the maximum head excursion did not go outside the roll cage, and occurred early in the roll event (around ¼ second) with ROV roll angles less than 5 degrees
  - This suggests that the complication of reproducing roll motion may not be significant to peak head excursion
  - A much simpler horizontal test for maximum head excursion may be sufficient

- Hybrid 3 and EuroSid II dummies were tested at higher severities, and based on this, it is believed that either dummy is sufficient for testing near threshold g levels
    - The response differences became significant at higher g levels (after tether jerk)
- The torso bar provided with the [redacted] kept an unbelted dummy in place up until tether jerk in tests conducted at 60 degrees (i.e., with a forward component of deceleration)
    - Following tether jerk, the unbelted dummy slid off the torso bar and partial or full ejection occurred.
    - This suggests that this type of restraint, in addition to the belt system, may be sufficient to prevent occupant ejection through a ¼ turn rollover event, which could prevent crushing injuries caused by the ROV rolling onto the occupant.

6.0 TABLES

Test No.	Vehicle	Dummy	Angle	Belt Use	Torso Bar Added	Target Lateral Decel
B1100212	[redacted]	Hybrid 3	90	Y	N	0.7
B1100213	[redacted]	Hybrid 3	90	N	N	0.7
B1100214	[redacted]	Hybrid 3	60	Y	N	0.7
B1100215	[redacted]	Hybrid 3	60	Y	N	0.7
B1100216	[redacted]	Hybrid 3	60	Y	N	0.7
B1100217	[redacted]	Hybrid 3	60	N	Y	0.7
B1100220	[redacted]	Hybrid 3	60	Y	N/A	0.7
B1100221	[redacted]	Hybrid 3	60	N	N/A	0.7
B1100222	[redacted]	Hybrid 3	90	Y	N/A	0.7
B1100223	[redacted]	EuroSID II	90	Y	N/A	1.6

Table 2.1 Deceleration Induced Rollover Test Conditions

Test No.	Vehicle	Dummy	Angle	Belt Use	Torso Bar Added	Velocity	Time of Tether Grab	Peak Roll Vel.	Avg Platform Decel.	Peak Head Result.	Peak Head Excursion	Seat Belt Pay-out
B1100212	[redacted]	Hybrid 3	90	Y	N	13.5	1.852	61.24	0.683	1.91	6.7	*
B1100213	[redacted]	Hybrid 3	90	N	N	13.6	1.5	68.31	0.675	2.9	>12	unbelted
B1100214	[redacted]	Hybrid 3	60	Y	N	15.7	1.232	96.1	0.853	2.41	4.9	3
B1100215	[redacted]	Hybrid 3	60	Y	N	15.8	1.346	94.65	0.85	2.45	4.8	10.5
B1100216	[redacted]	Hybrid 3	60	Y	N	15.7	1.272	92.15	0.806	2.48	6.7	10
B1100217	[redacted]	Hybrid 3	60	N	Y	15.7	1.25	97.97	0.807	3.93	0	unbelted
B1100220	[redacted]	Hybrid 3	60	Y	N/A	17.8	1.45	69.38	0.832	4.74	0	3
B1100221	[redacted]	Hybrid 3	60	N	N/A	17.9	1.019	134.46	0.852	3.94	0	unbelted
B1100222	[redacted]	Hybrid 3	90	Y	N/A	15.8	0.87	161.34	0.927	3.92	0	2.25
B1100223	[redacted]	EuroSID II	90	Y	N/A	16.6	0.473	246.56	1.59	5.98	3	3

* not monitored

Table 3.1 Results of Deceleration Induced Rollover Testing

Test Number	Peak Roll Velocity	Avg. Cart Deceleration	Peak Head Resultant	Peak Head Excursion
B1100214	96.1	0.853	2.41	4.6
		.		
B1100215	94.65	0.85	2.45	4.9
B1100216	92.15	0.806	2.48	6.7
Mean Value	94.3	0.836	2.45	5.4
CV	2.10%	3.10%	1.40%	21%

Table 3.2 Repeatability of Deceleration Test Results

Vehicle	Angle	Belt Use	HYGE Excursion 2.5 g's	Decel Excursion .7 g's
[redacted]	90	Y	6.7	6.3
[redacted]	60	Y	7	5.4
[redacted]	90	Y	1	0
[redacted]	60	Y	4	0

Table 3.3 Comparison of HYGE Acceleration –Deceleration Test Results

Angle	Restraint	Peak Head Excursion Time	Approx. ROV Roll Angle
90 deg	belt	.756 sec	15 deg
60 deg	belt	.578 sec	< 15 deg
60 deg	torso bar	0.256	< 5 deg

Table 4.1 ROV Roll Angle at Time of Peak Head Excursion

7.0 Figures

Figure 2.1 Faro Arm Seating Procedure

Figure 2.2 Reference 0,0,0 for [redacted]

Figure 2.3 [redacted] Seating Reference 0,0,0

Figure 2.4Camera Mounts on [redacted]

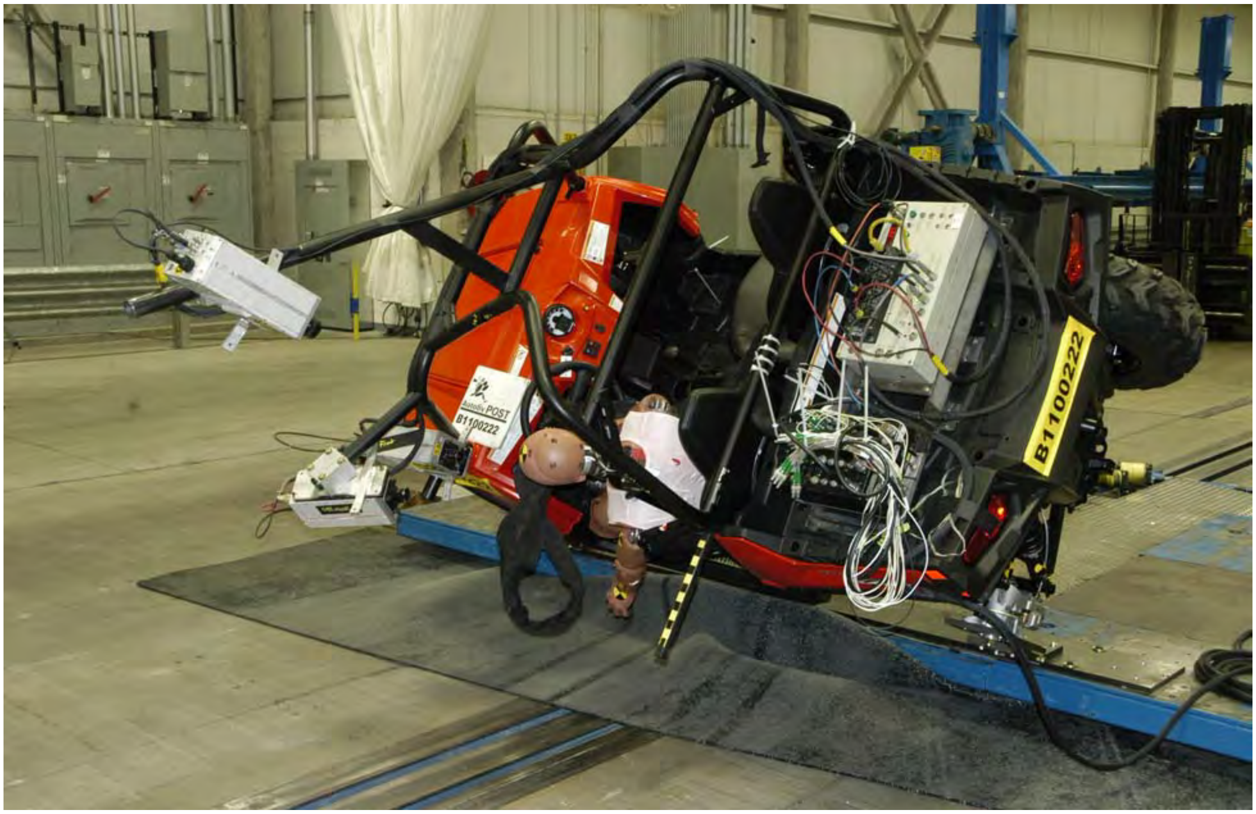


Figure 2.5 Camera Mounts on [redacted]

Figure 2.6 Signal Conditioning System on [redacted]

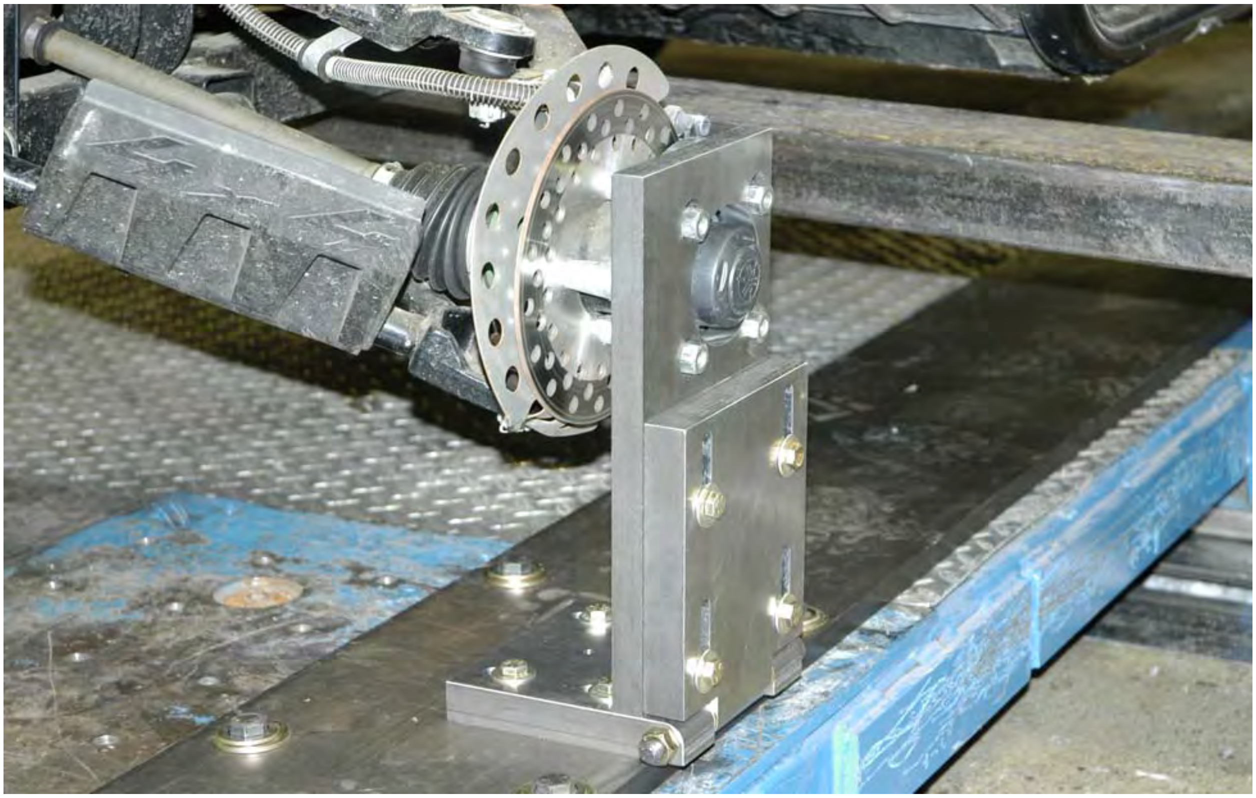


Figure 2.7 Close up of Hinge Assembly on [redacted]

Figure 2.8 [redacted] Tethered to Cart

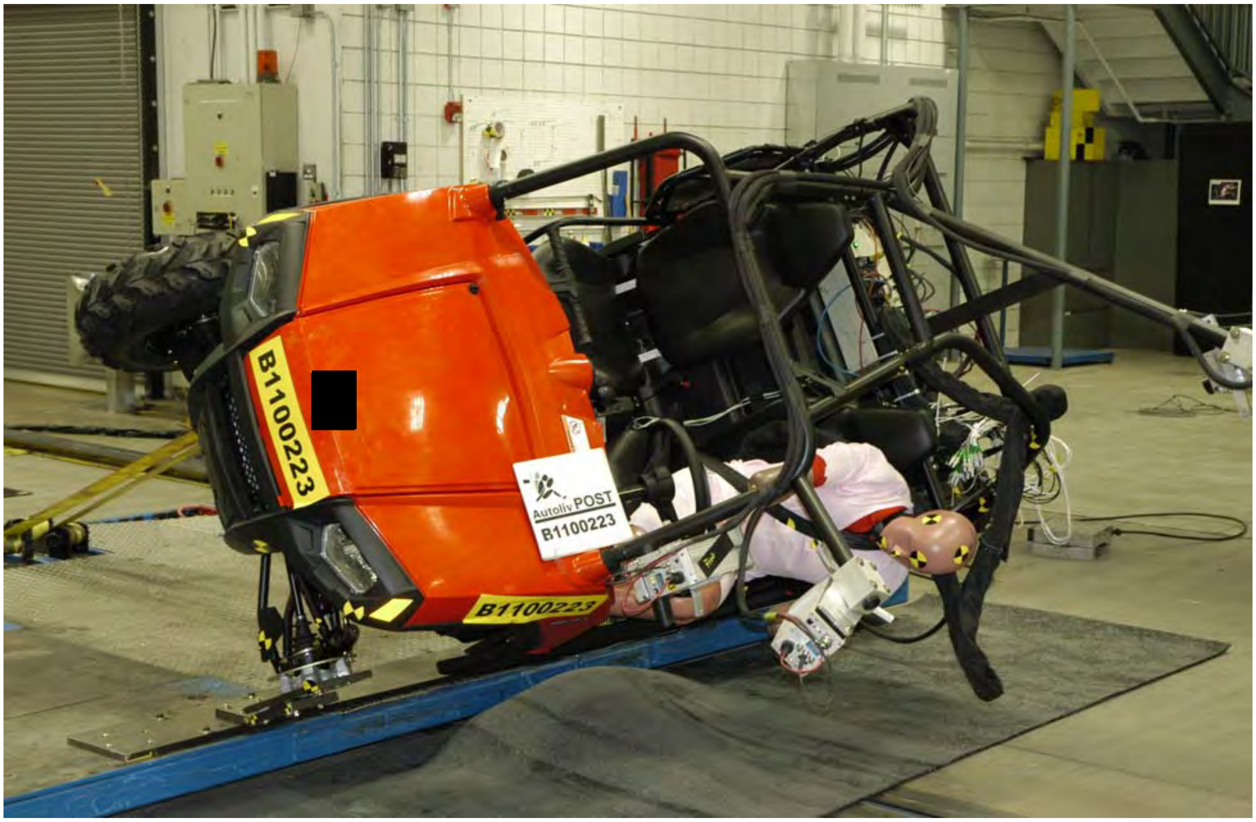


Figure 2.9 [redacted] Secured by Hinges and Tether

Figure 2.10 Brake Rails and Caliper System


[redacted]

Figure 2.11 Brake Rails and Guide Rail

Figure 2.12 Ace Damper for Engaging Brake Caliper

Figure 2.13 [redacted] Ready for Testing

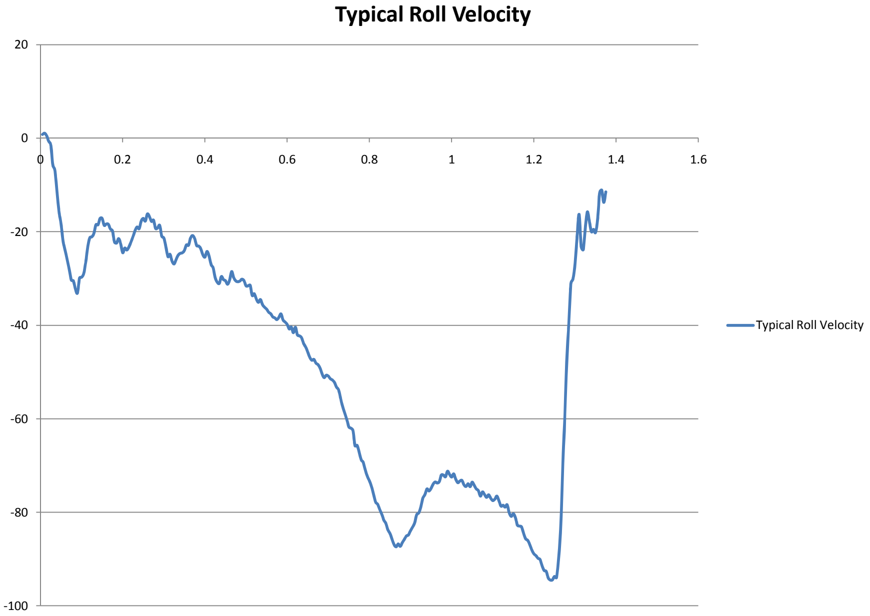


Figure 3.1 Typical Roll Velocity Time History

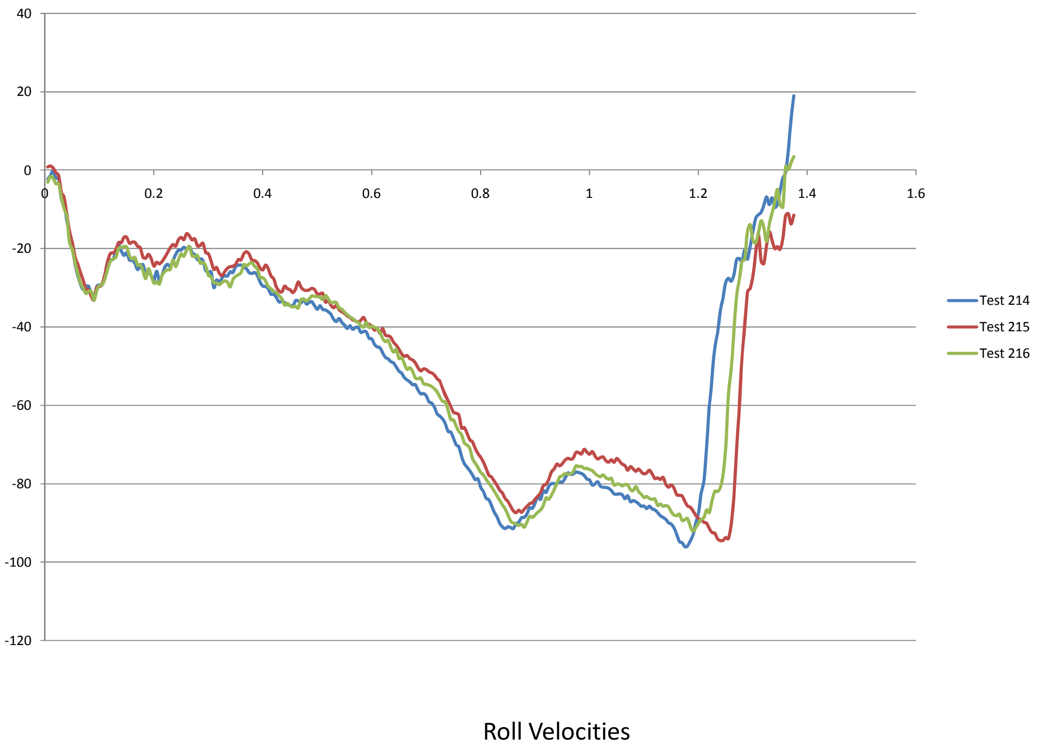


Figure 3.2 Overlay of Roll Velocities of Repeat Tests

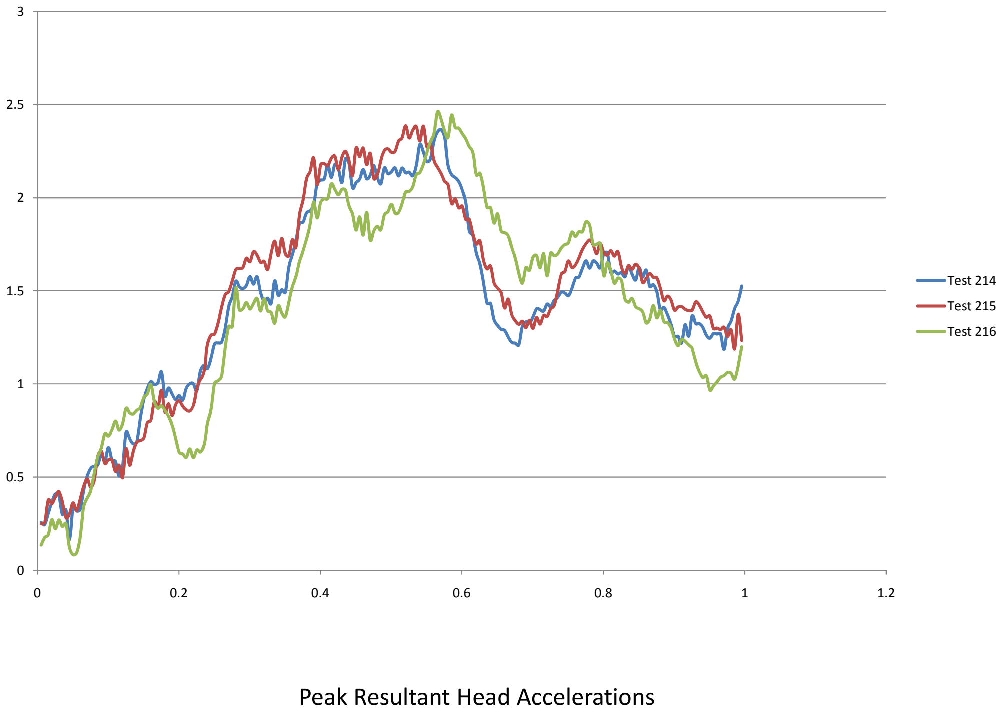


Figure 3.3 Overlay of Resultant Head Accelerations of Repeat Tests

Test 214 @ 578 msec

Test 215 @ 578 msec

Test 216 @ 630 msec

Figure 3.4

Max Dummy Excursions for Repeat Tests

Figure 3.5 Hybrid 3 Before Tether Jerk

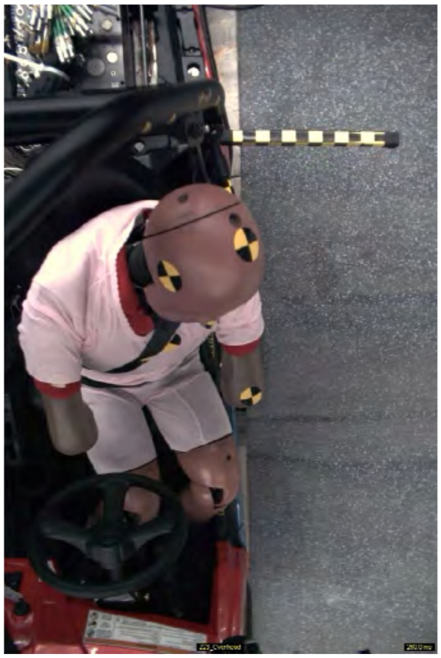


Figure 3.6 EuroSID Before Tether Jerk

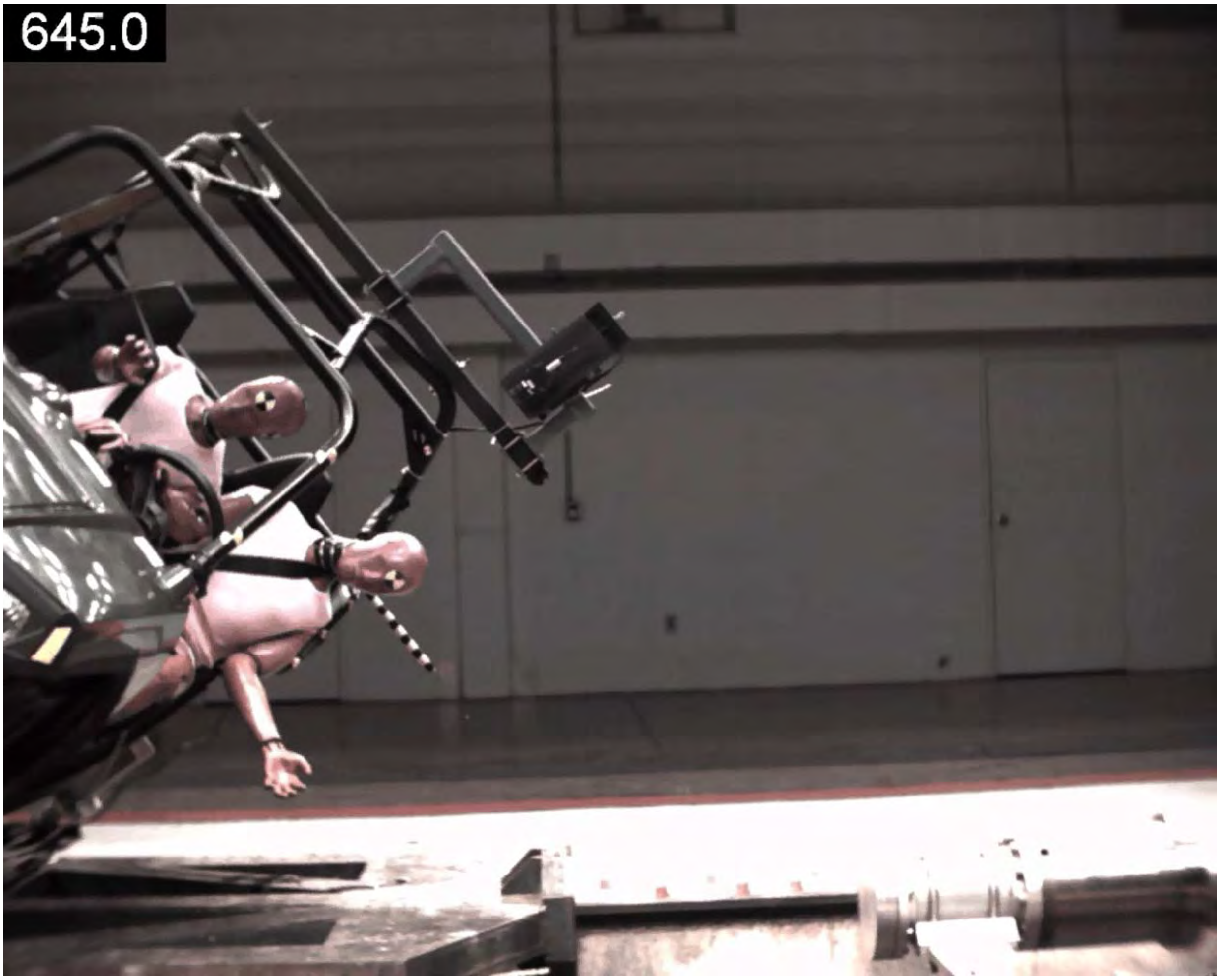


Figure 3.7 Hybrid 3 After Tether Jerk

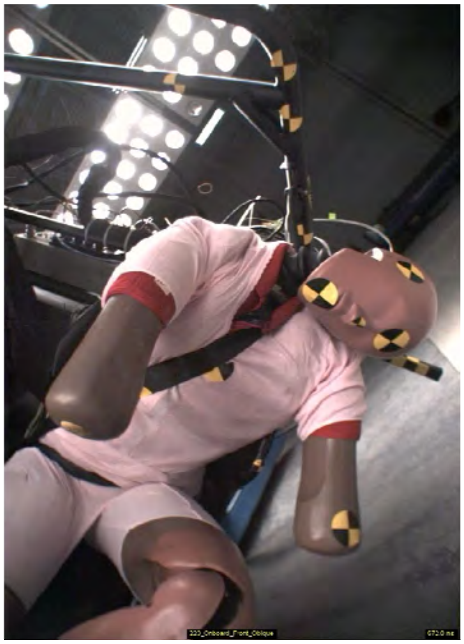


Figure 3.8 EuroSID After Tether Jerk

Figure 3.9 [redacted] Torso and Hip Restraint

Figure 3.10 Torso Restraint Added to [redacted]

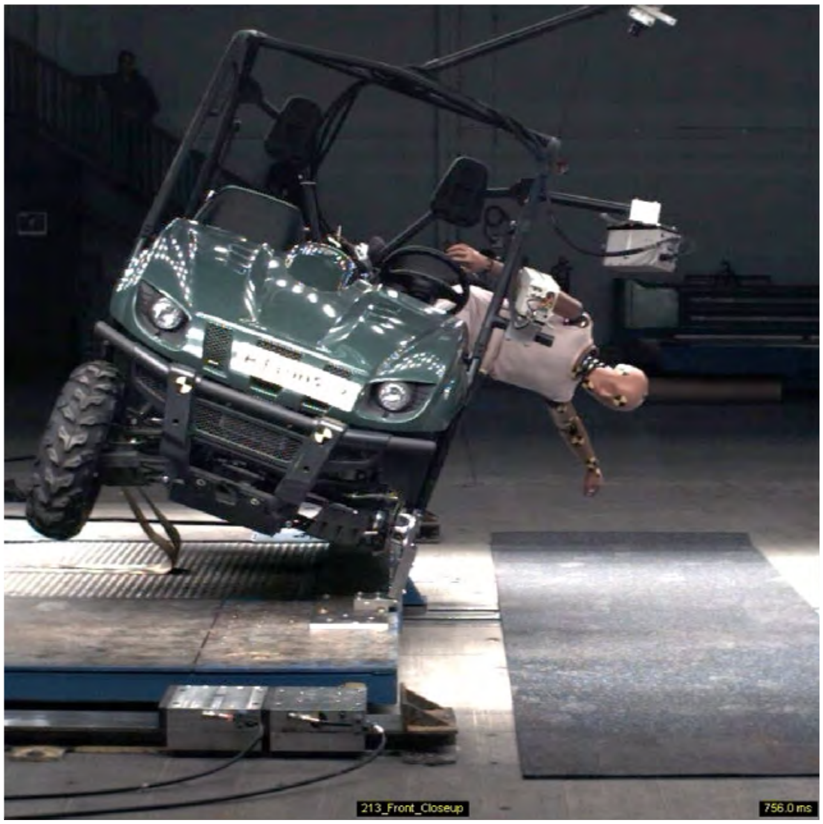


Figure 3.11 Unbelted [redacted] Test without Torso Restraint (756 msec)

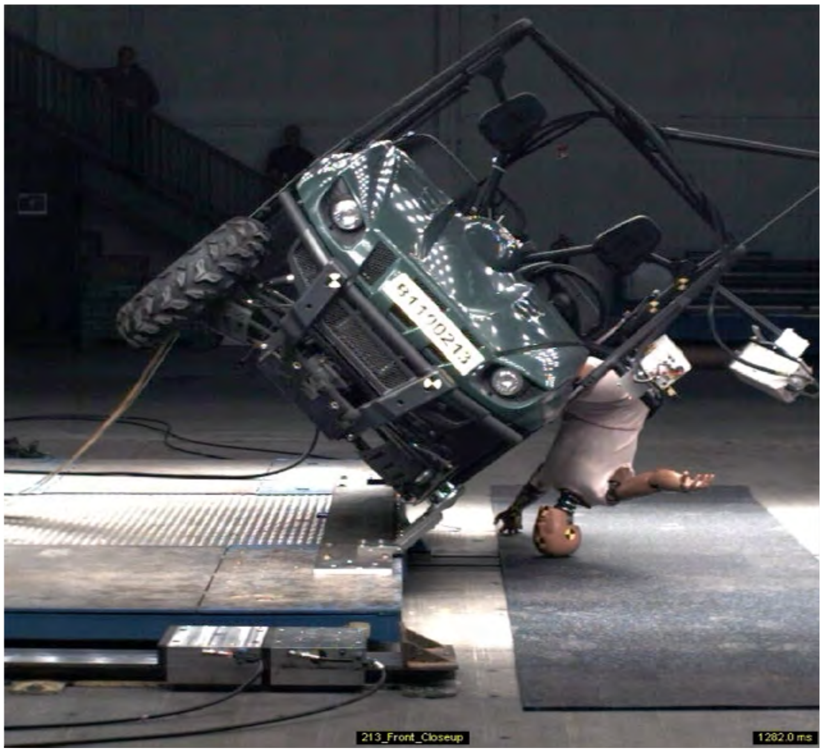


Figure 3.12 Unbelted [redacted] Test WithoutTorso Restraint (1.2 sec)

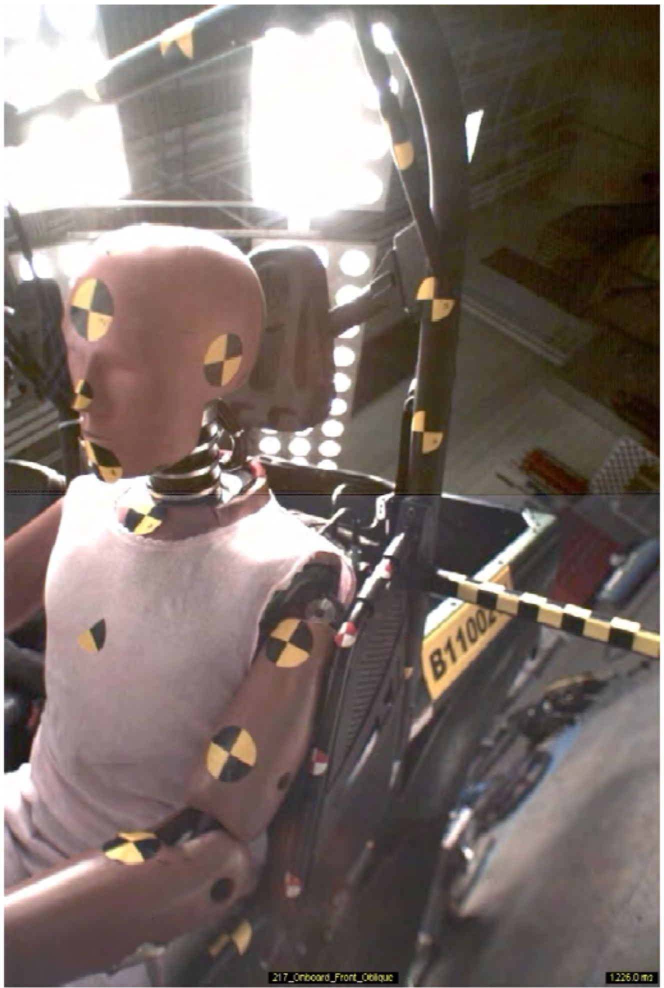


Figure 3.13 Unbelted [redacted] at 60 deg. With Torso Restraint
(at time of tether jerk)

Figure 3.14 Unbelted [redacted] at 60 deg, With Torso Restraint
(at 2.2 sec.)

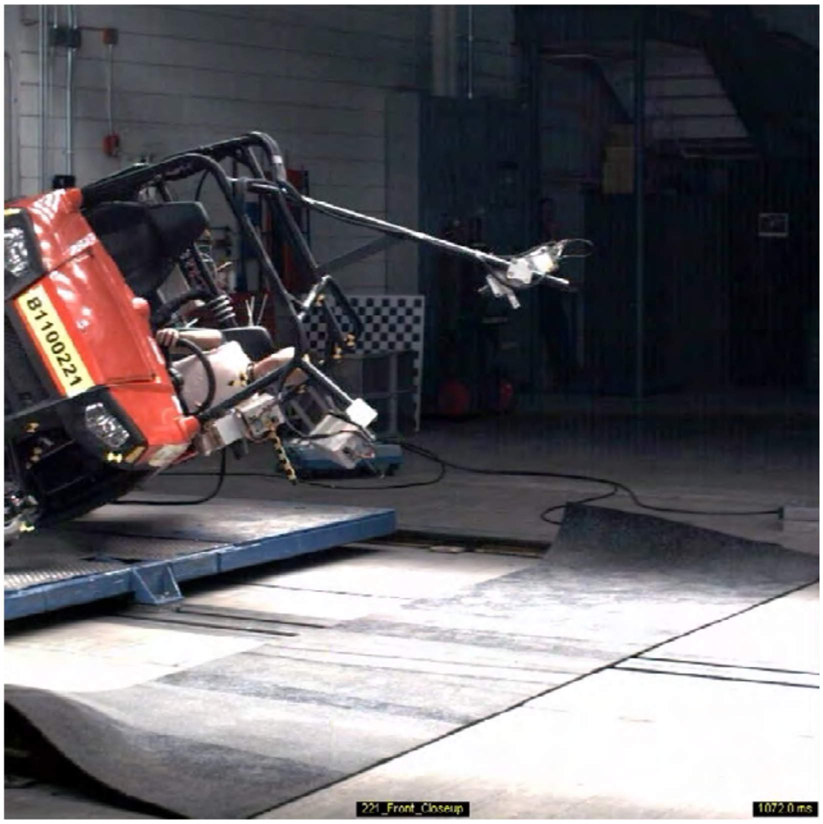


Figure 3.15 Unbelted [redacted] at 60 deg
(at time of Tether Jerk)

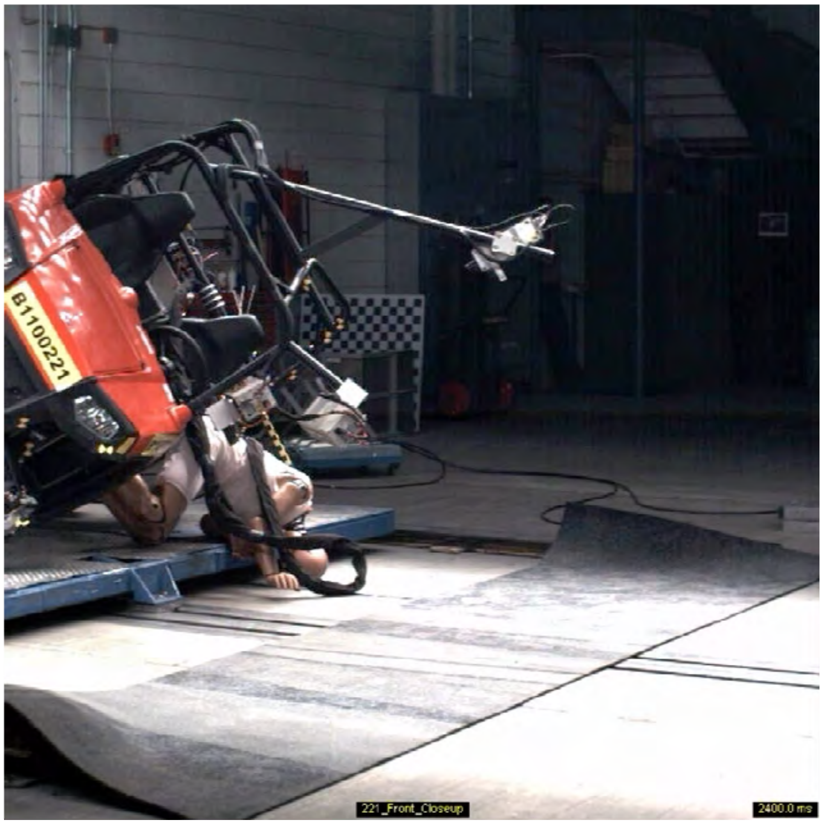
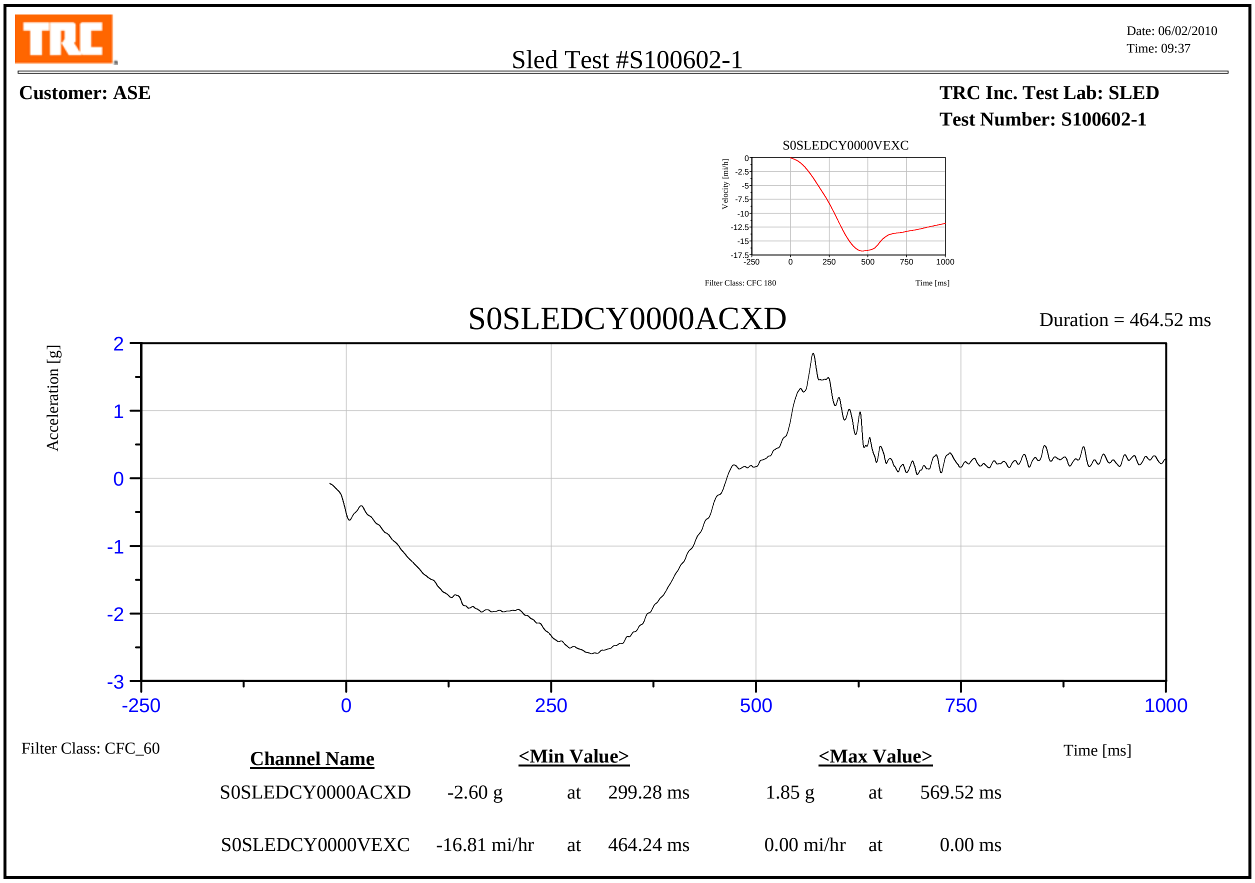


Figure 3.16 Unbelted [redacted] at 60 deg
(at final rest)



Date: 06/02/2010
Time: 09:37

Sled Test #S100602-1

Customer: ASE

TRC Inc. Test Lab: SLED
Test Number: S100602-1

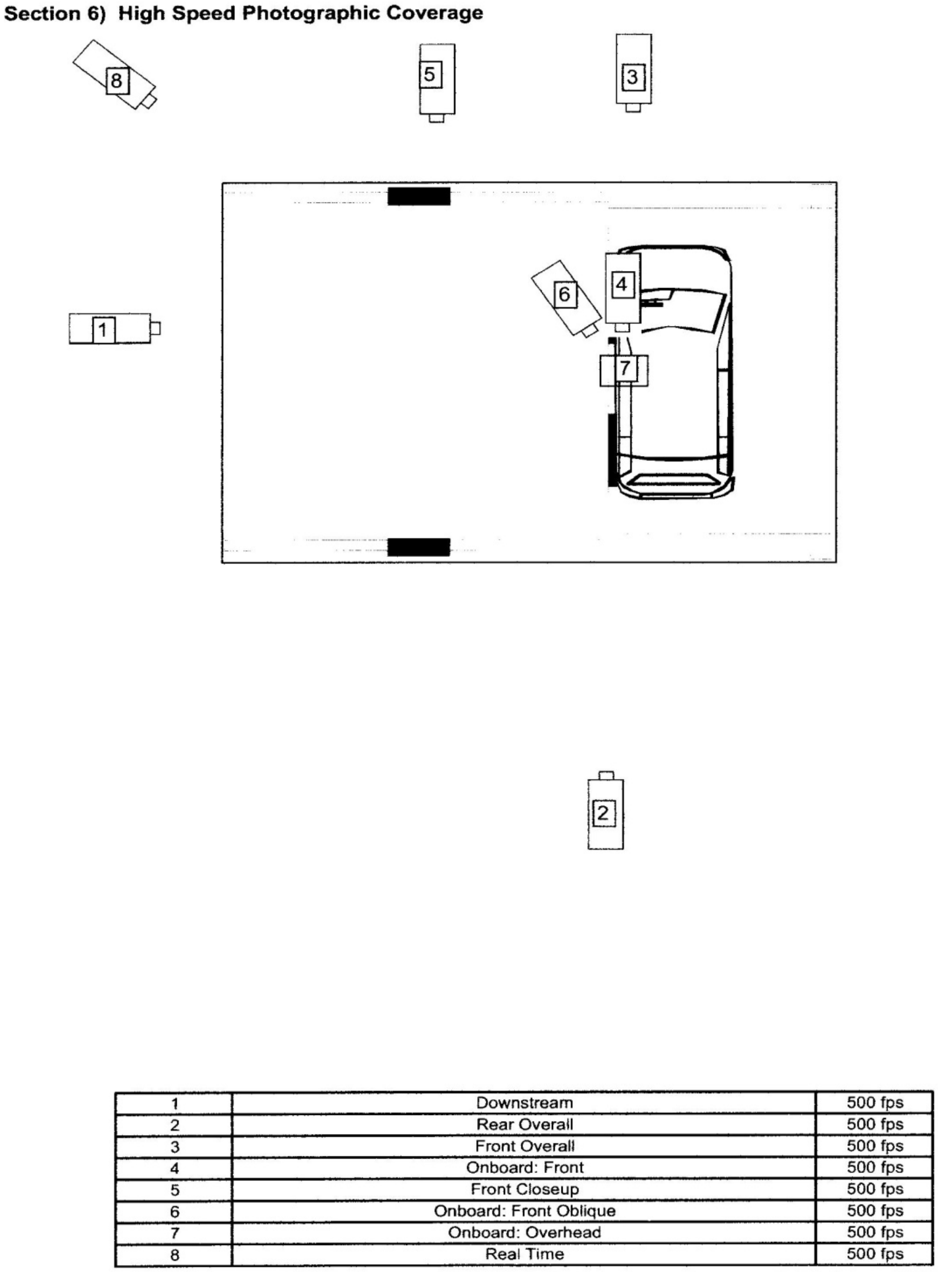
Duration = 464.52 ms

Filter Class: CFC_60

Channel Name	**<Min Value>**			**<Max Value>**		
S0SLEDCY0000ACXD	-2.60 g	at	299.28 ms	1.85 g	at	569.52 ms
S0SLEDCY0000VEXC	-16.81 mi/hr	at	464.24 ms	0.00 mi/hr	at	0.00 ms

Figure 4.1 Typical Acceleration Pulse from HYGE Sled Test Series

8.0 Appendix A Camera Placement Schematics

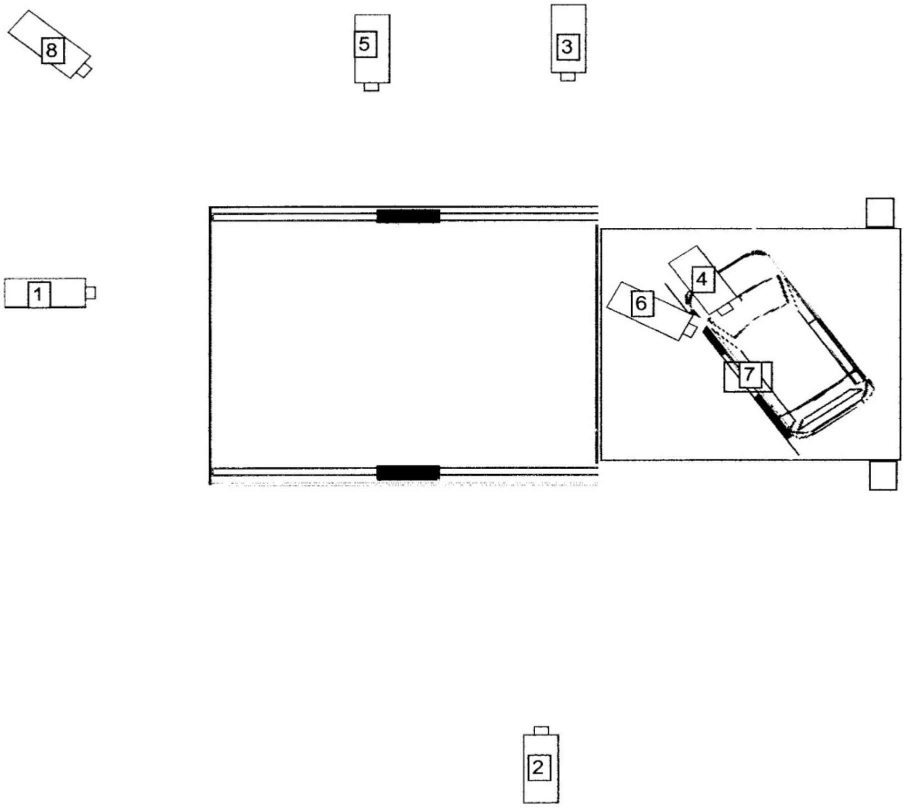


Section 6) High Speed Photographic Coverage

1	Downstream	500 fps
2	Rear Overall	500 fps
3	Front Overall	500 fps
4	Onboard: Front	500 fps
5	Front Closeup	500 fps
6	Onboard: Front Oblique	500 fps
7	Onboard: Overhead	500 fps
8	Real Time	500 fps

Figure 8.1 Camera Placement for 90 degree tests

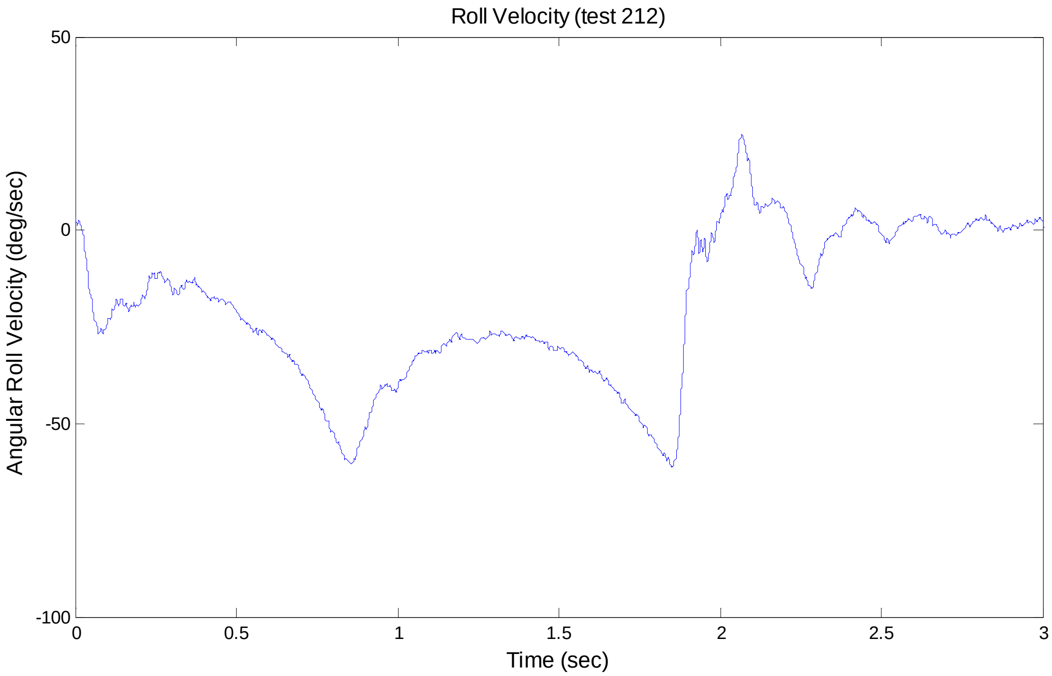
Section 6) High Speed Photographic Coverage

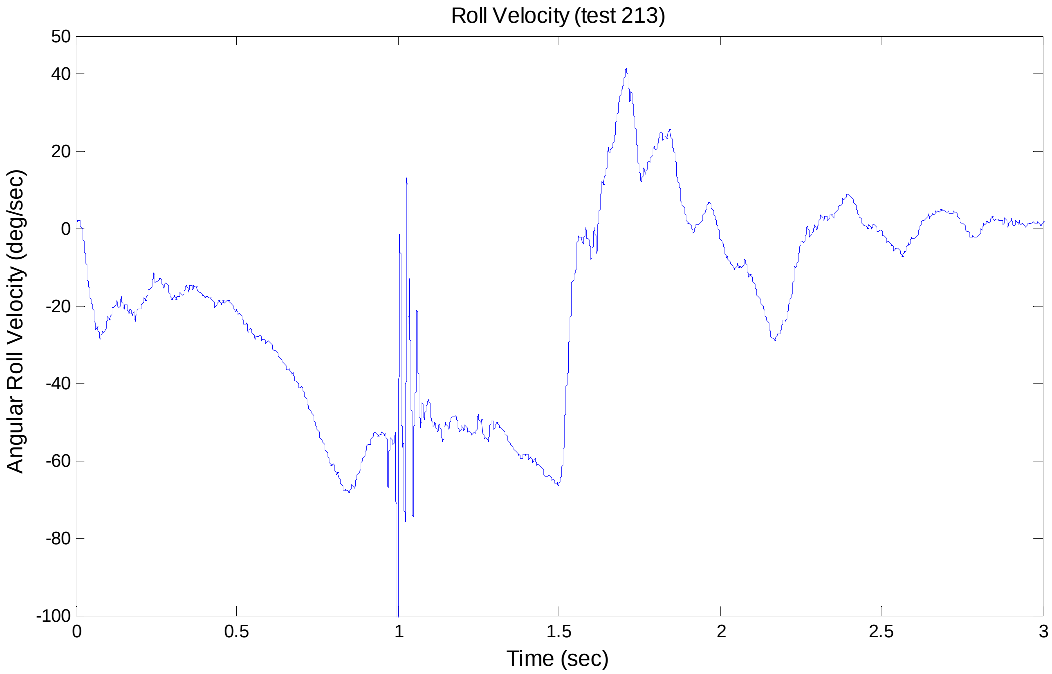


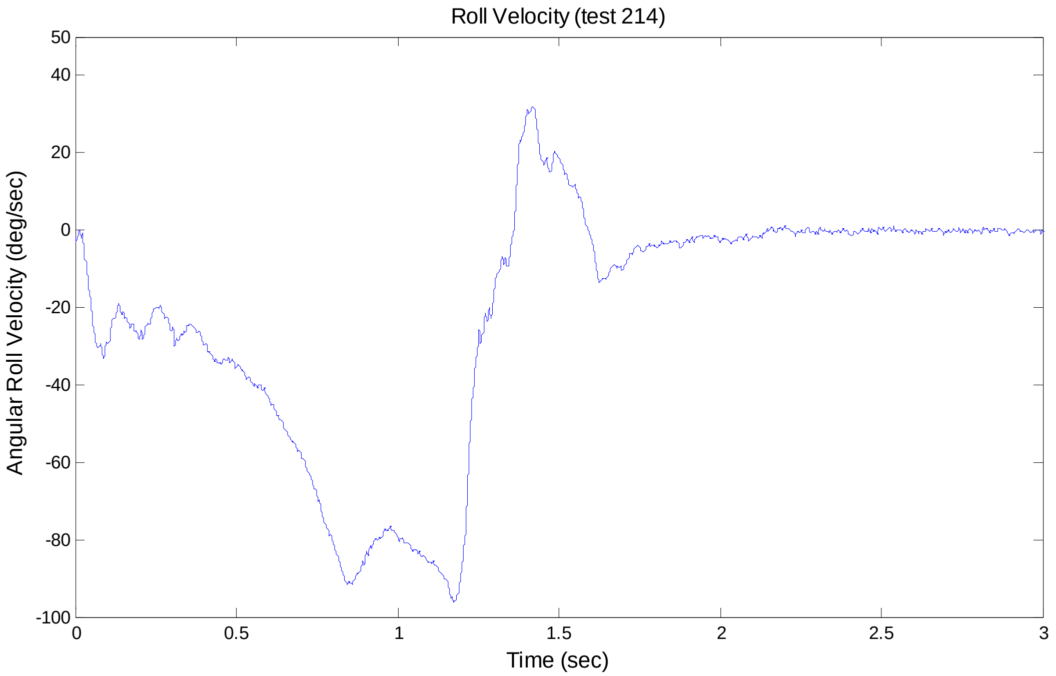
1	Downstream	500 fps
2	Rear Overall	500 fps
3	Front Overall	500 fps
4	Onboard: Front	500 fps
5	Front Closeup	500 fps
6	Onboard: Front Oblique	500 fps
7	Onboard: Overhead	500 fps
8	Real Time	500 fps

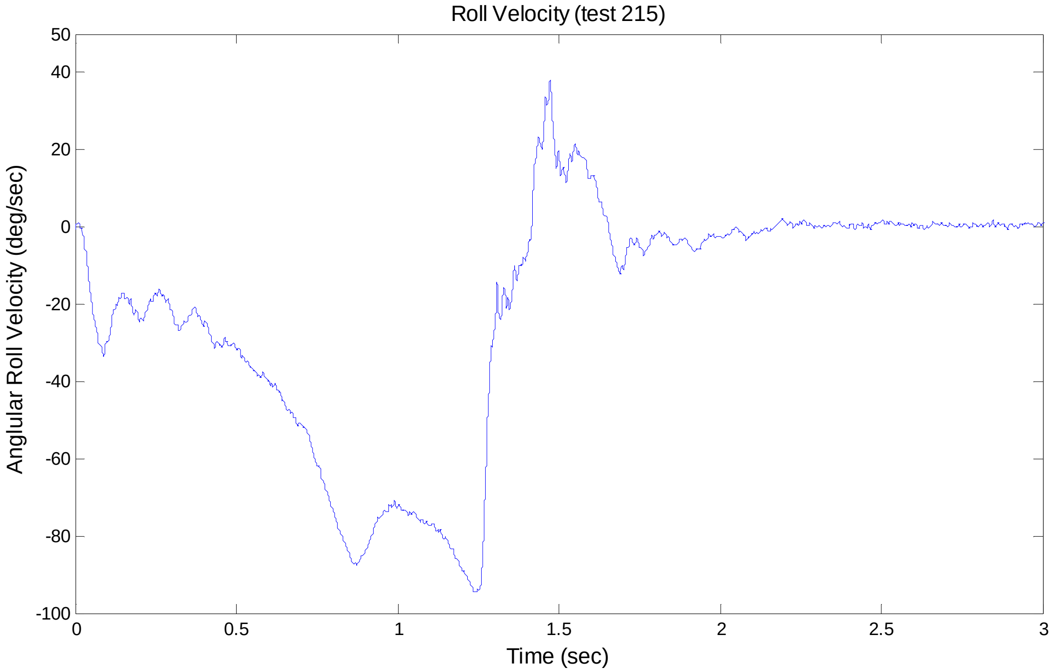
Figure 8.2 Camera Placement for 60 degree Tests

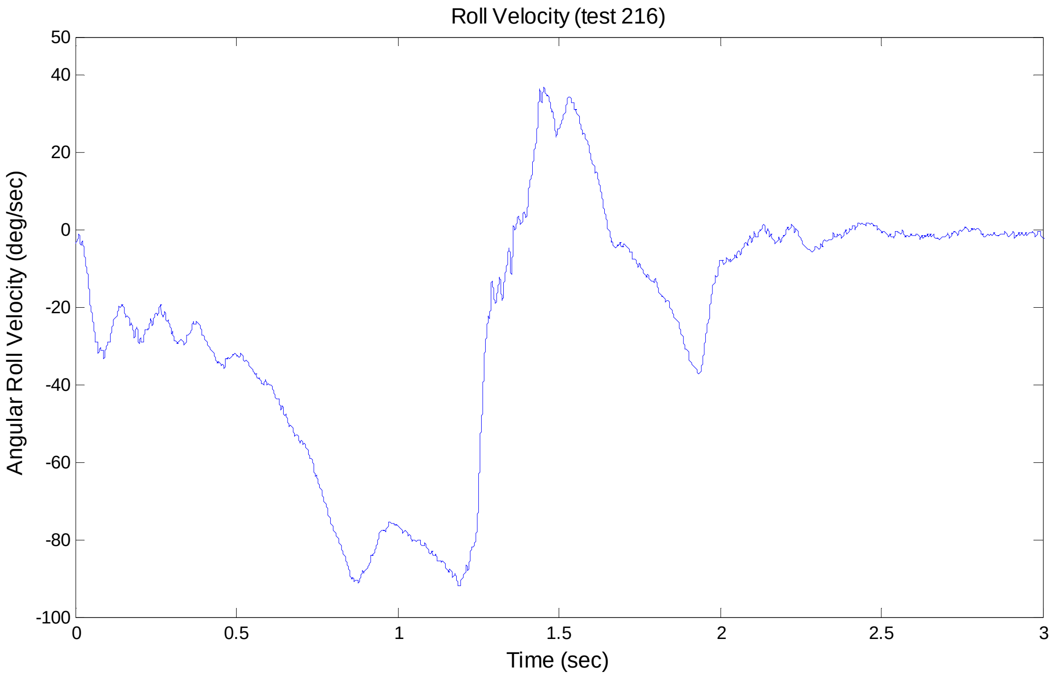
9.0 Appendix B Roll Velocity Data Plots

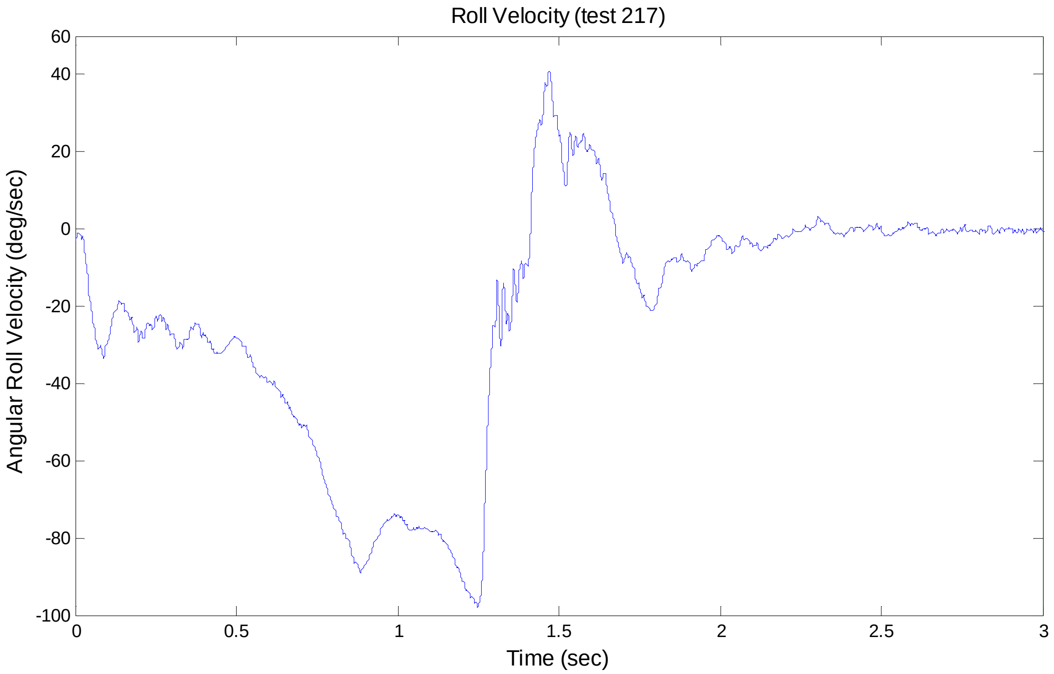

Roll Velocity (test 212)
Angular Roll Velocity (deg/sec)
50
0
-50
-100
0
0.5
1
1.5
2
2.5
3
Time (sec)

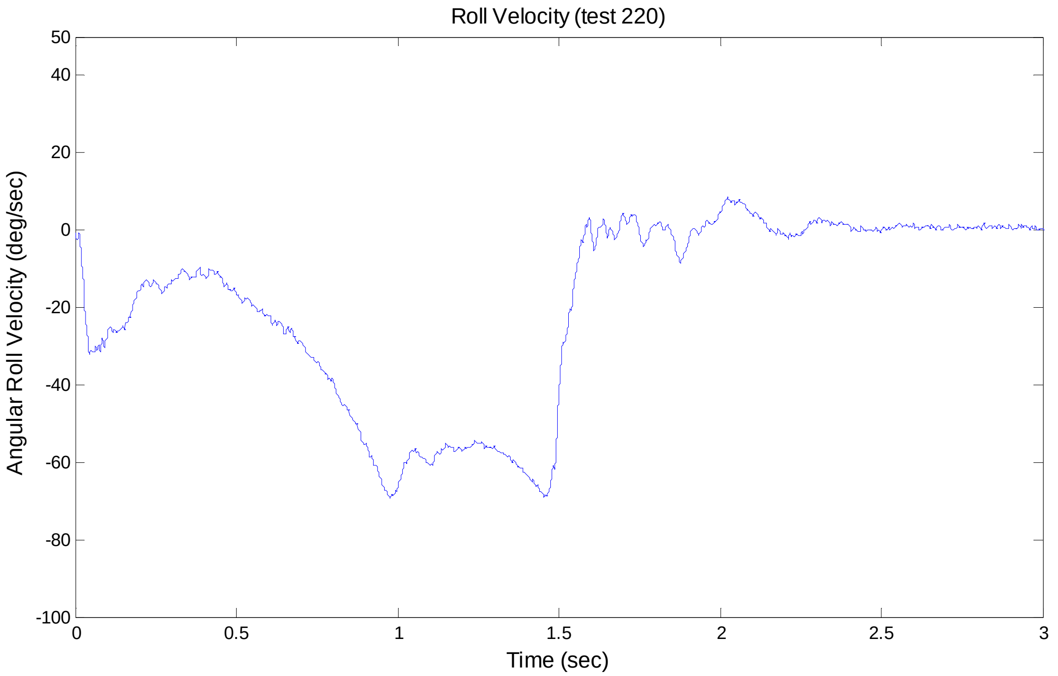

Roll Velocity (test 213)
Angular Roll Velocity (deg/sec)
50
40
20
0
-20
-40
-60
-80
-100
0
0.5
1
1.5
2
2.5
3
Time (sec)

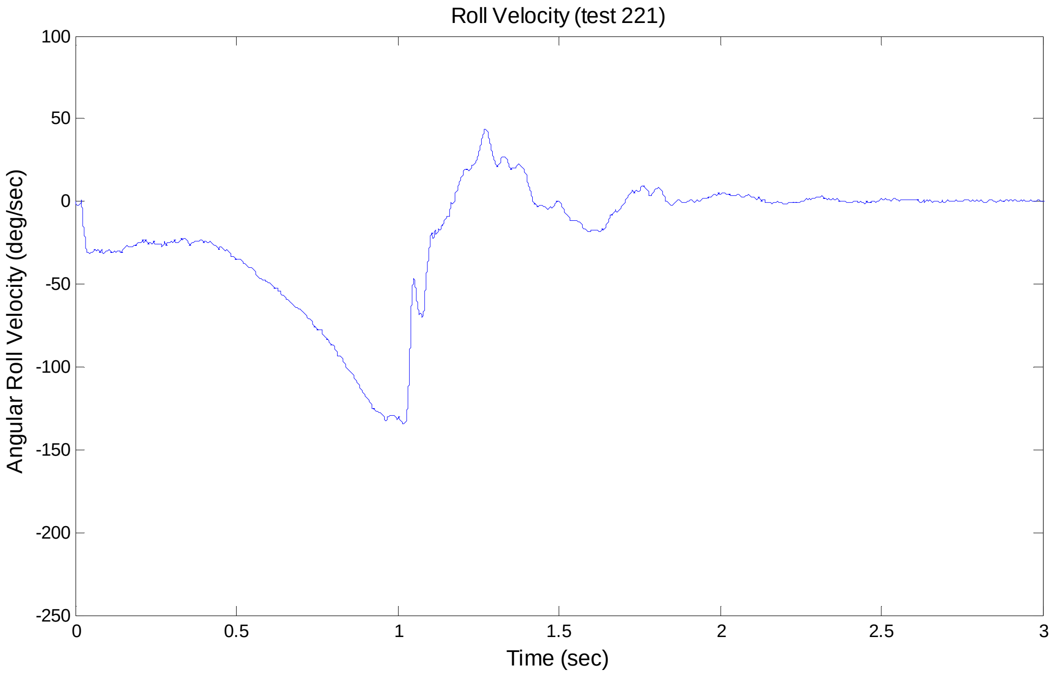

Roll Velocity (test 214)
Angular Roll Velocity (deg/sec)
50
40
20
0
-20
-40
-60
-80
-100
0
0.5
1
1.5
2
2.5
3
Time (sec)

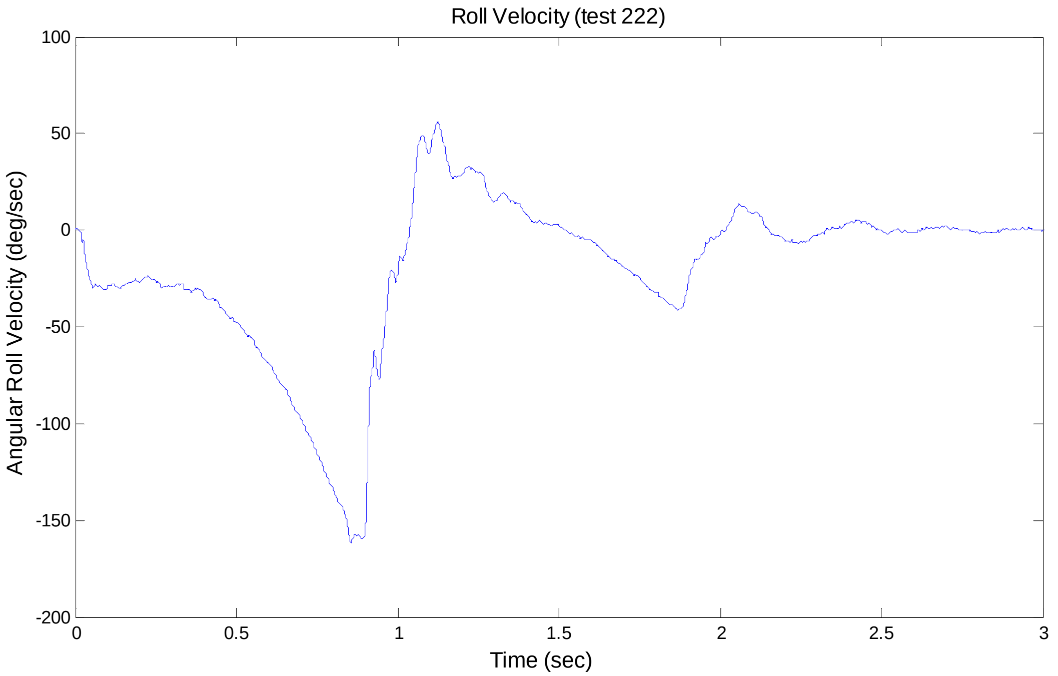

Roll Velocity (test 215)
Anglular Roll Velocity (deg/sec)
50
40
20
0
-20
-40
-60
-80
-100
0
0.5
1
1.5
2
2.5
3
Time (sec)

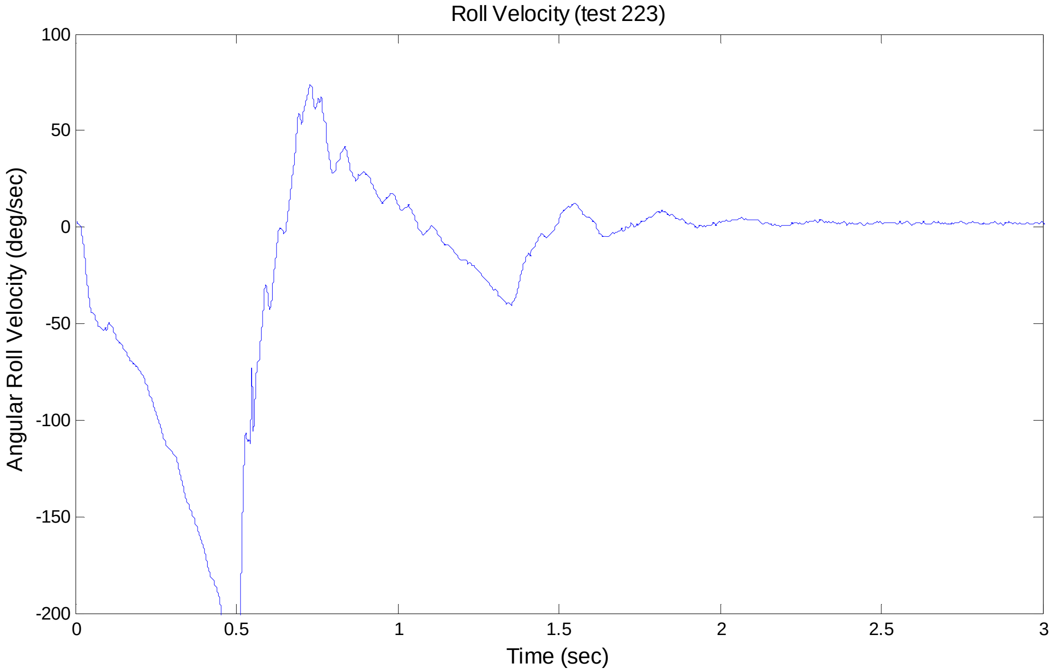

Roll Velocity (test 216)
Angular Roll Velocity (deg/sec)
Time (sec)
50
40
20
0
-20
-40
-60
-80
-100
0
0.5
1
1.5
2
2.5
3


Roll Velocity (test 217)
Angular Roll Velocity (deg/sec)
Time (sec)
60
40
20
0
-20
-40
-60
-80
-100
0
0.5
1
1.5
2
2.5
3

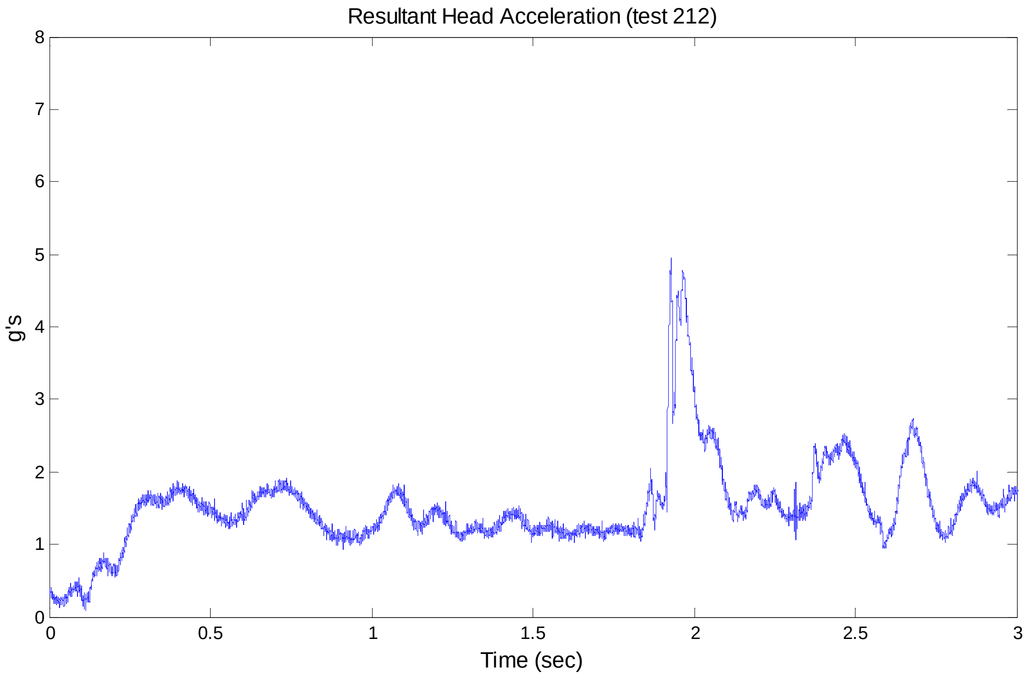

Roll Velocity (test 220)
Angular Roll Velocity (deg/sec)
50
40
20
0
-20
-40
-60
-80
-100
0
0.5
1
1.5
2
2.5
3
Time (sec)

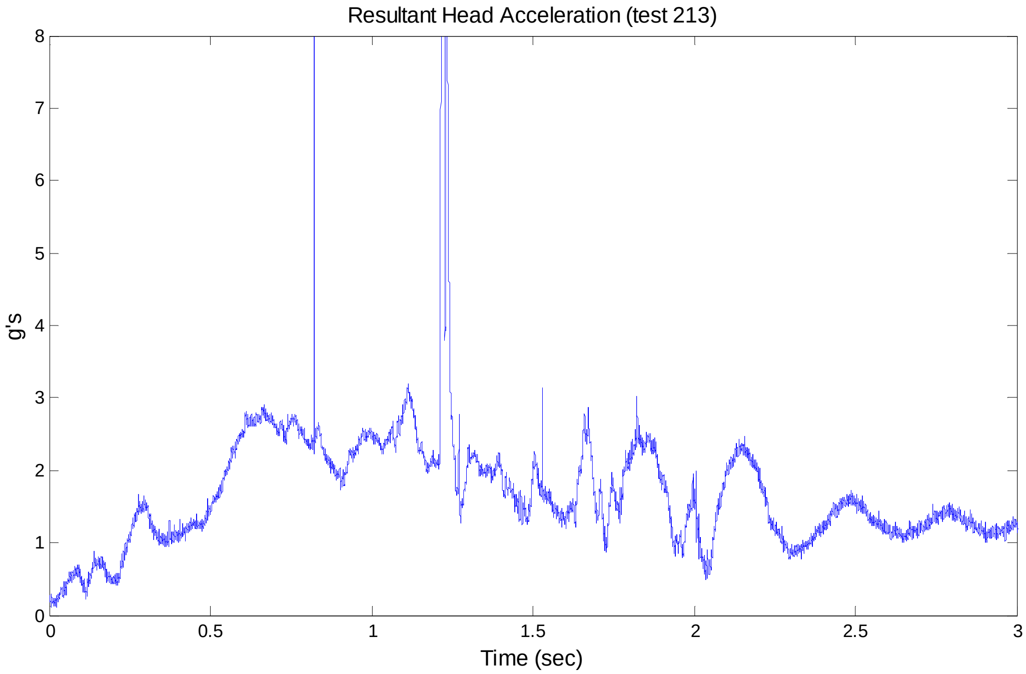

Roll Velocity (test 221)
Angular Roll Velocity (deg/sec)
100
50
0
-50
-100
-150
-200
-250
0
0.5
1
1.5
2
2.5
3
Time (sec)

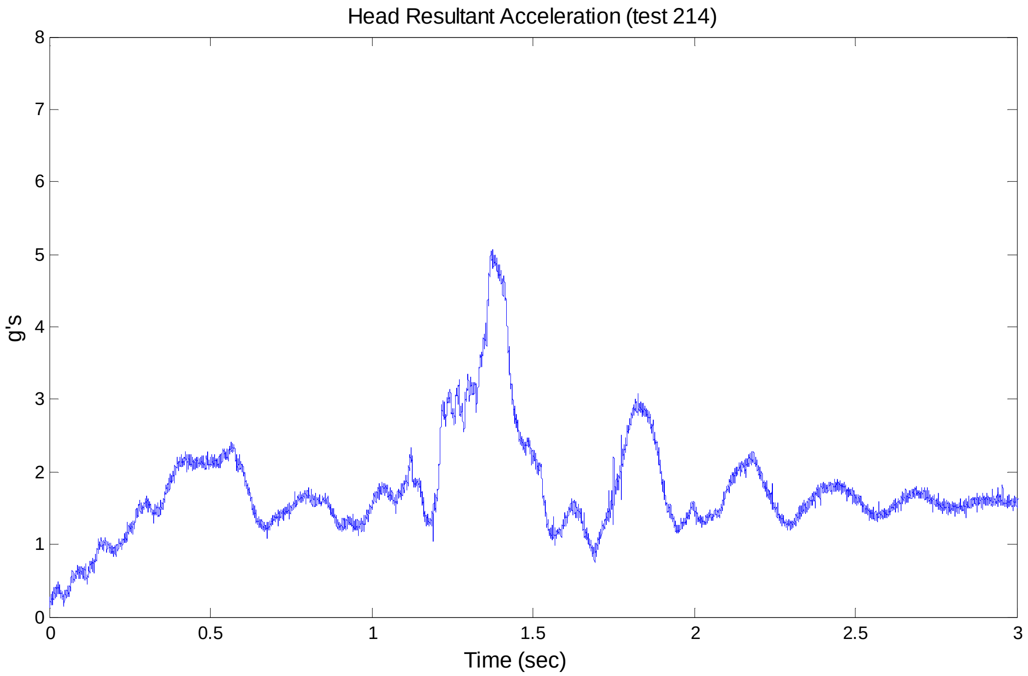

Roll Velocity (test 222)
Angular Roll Velocity (deg/sec)
100
50
0
-50
-100
-150
-200
0
0.5
1
1.5
2
2.5
3
Time (sec)

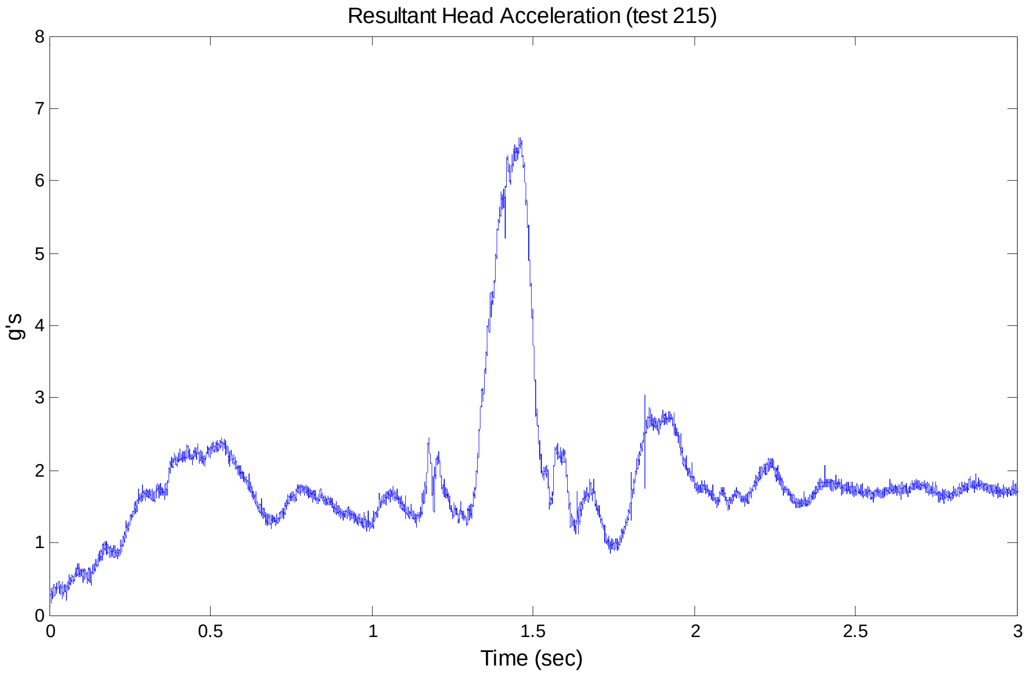

Roll Velocity (test 223)
Angular Roll Velocity (deg/sec)
100
50
0
-50
-100
-150
-200
0
0.5
1
1.5
2
2.5
3
Time (sec)

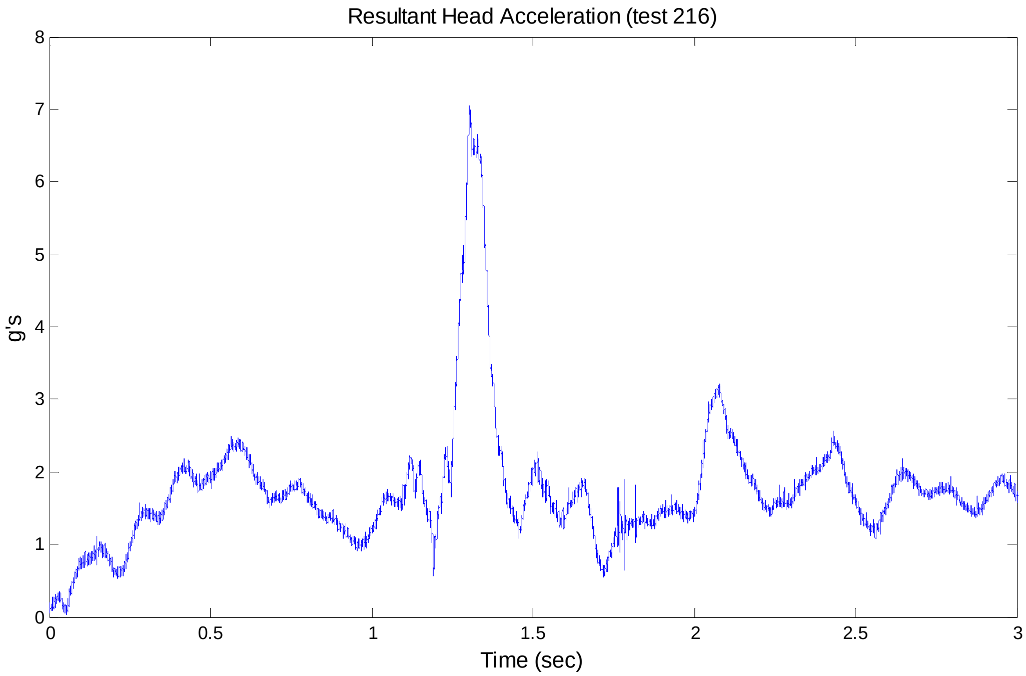
10.0 Appendix C Head Resultant Acceleration Data Plots

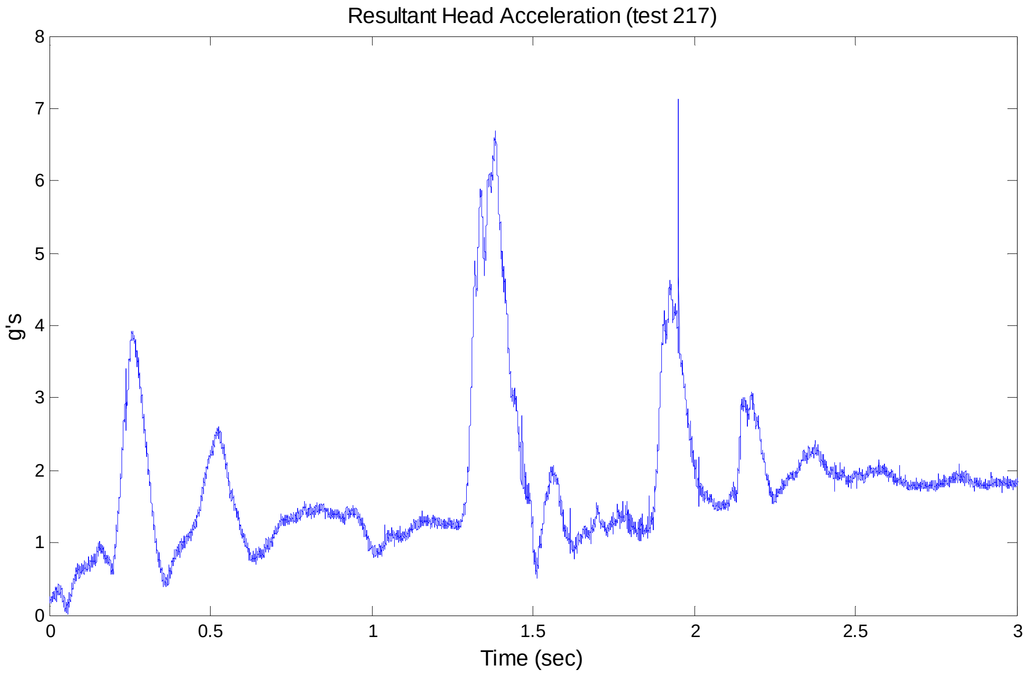

Resultant Head Acceleration (test 212)

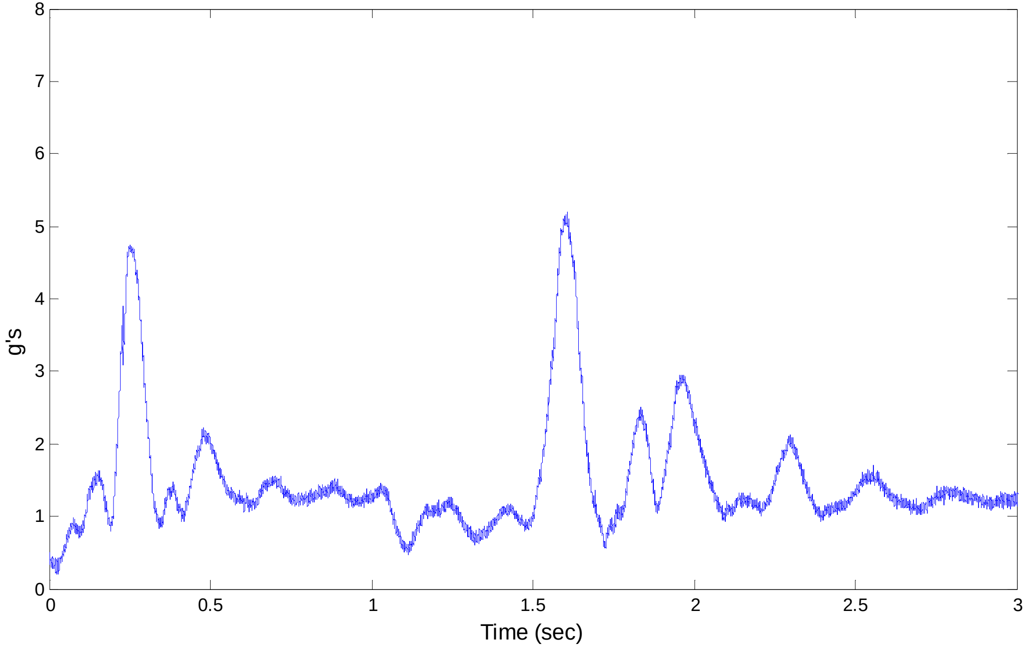

Resultant Head Acceleration (test 213)


Head Resultant Acceleration (test 214)

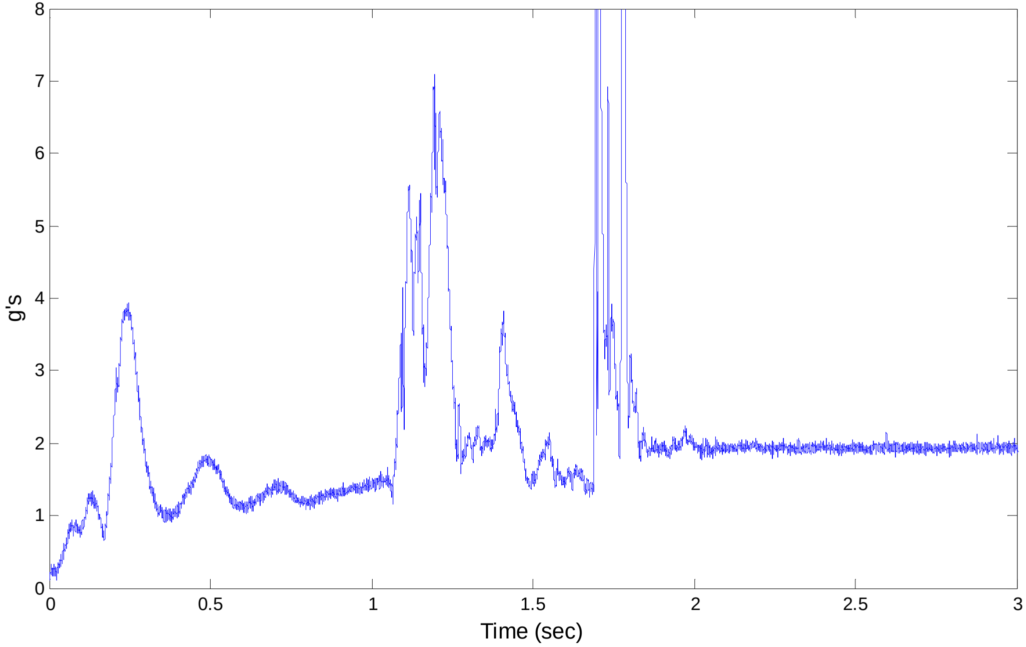

Resultant Head Acceleration (test 215)


Resultant Head Acceleration (test 216)
g's
8
7
6
5
4
3
2
1
0
0
0.5
1
1.5
2
2.5
3
Time (sec)

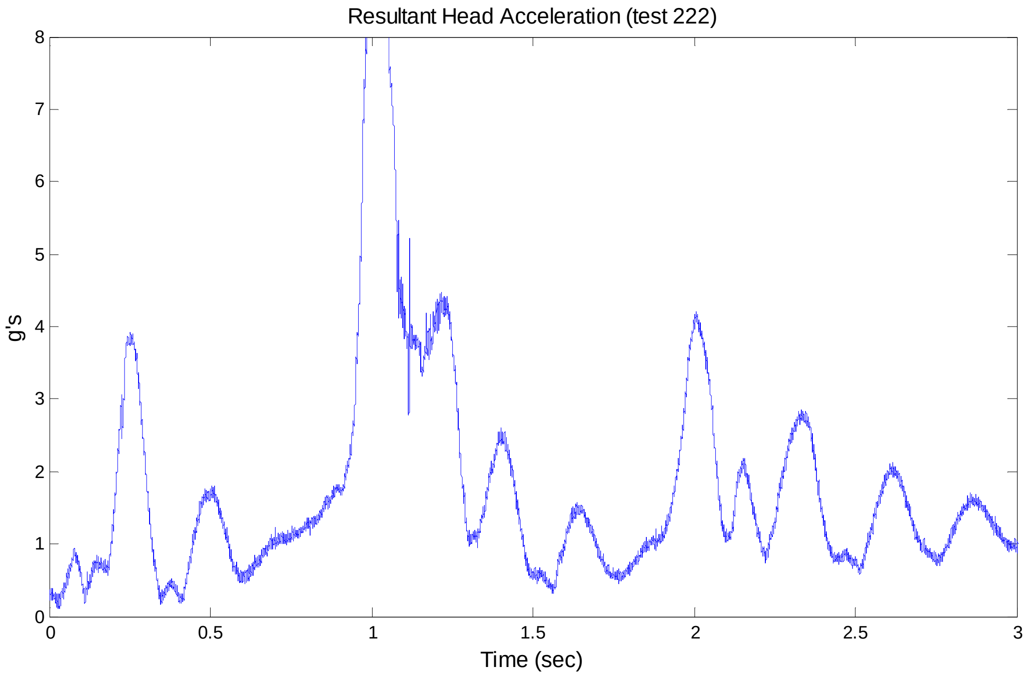

Resultant Head Acceleration (test 217)
g's
8
7
6
5
4
3
2
1
0
0
0.5
1
1.5
2
2.5
3
Time (sec)

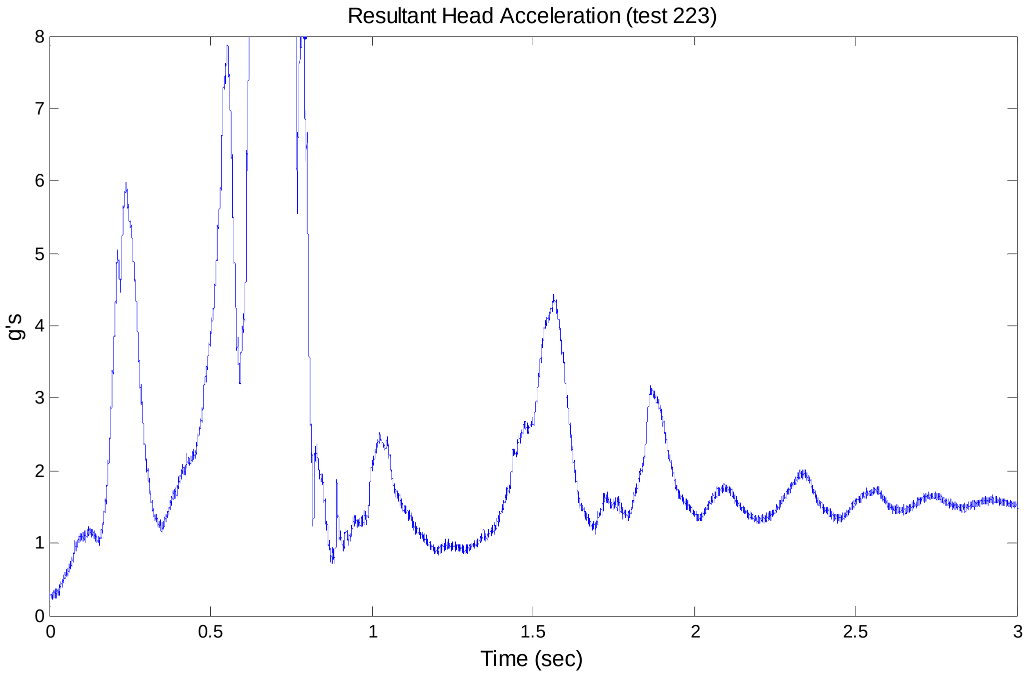


Restultant Head Acceleration (test 220)



Resultant Head Acceleration (test 221)


Resultant Head Acceleration (test 222)
g's
0
1
2
3
4
5
6
7
8
0
0.5
1
1.5
2
2.5
3
Time (sec)


Resultant Head Acceleration (test 223)
g's
0
1
2
3
4
5
6
7
8
0
0.5
1
1.5
2
2.5
3
Time (sec)