

## CPSC Staff Statement on SEA, Ltd. Report "Rollover Tests of ATVs Outfitted with Occupant Protection Devices (OPDs)" January 2020

The report titled, "Rollover Tests of ATVs Outfitted with Occupant Protection Devices (OPDs)," presents the results of autonomous all-terrain vehicle (ATV) dynamic rollover tests and laboratory simulation of ATV rollover events conducted by SEA, Ltd. (SEA). SEA conducted the tests and simulation exercises on six adult, single-rider ATVs that had been equipped with two different aftermarket occupant protection devices. SEA used the results from rollovers of ATVs equipped with OPDs, with an anthropometric test device (ATD) as a surrogate rider, to study the feasibility and effectiveness of using OPDs on ATVs. SEA performed this work under Task Orders 1 and 2 of contract 61320618D0003. This contract covers general testing and evaluation of ATVs.

The development of an ATV-rollover simulator provides a new state-of-the-art tool that can be used to evaluate the performance of occupant-protection capabilities in an ATV rollover event. The results of this study are an exploratory look at how OPDs perform in low-energy and moderate-energy lateral rollovers.

The work represented by this report is part of a larger effort by CPSC staff to develop test methods, collect static and dynamic data, and identify opportunities for improving ATV performance characteristics related to vehicle stability and safety. The following reports have been published under this effort:

- Vehicle Characteristics Measurements of All-Terrain Vehicles<sup>2</sup>
- Effects on Vehicle Characteristics of Two Persons Riding ATVs<sup>3</sup>
- Effects on ATV Vehicle Characteristics of Rider Active Weight Shift<sup>4</sup>
- Vehicle Characteristics Measurements of ATVs Tested on Groomed Dirt<sup>5</sup>
- ATV Attribute Modification Study: Results of Baseline and Modified Vehicle Testing<sup>6</sup>
- ATV Rollover Tests and Verification of a Physical Rollover Simulator.

<sup>&</sup>lt;sup>1</sup> This statement was prepared by the CPSC staff, and the attached report was produced by SEA for CPSC staff. The statement and report have not been reviewed or approved by, and do not necessarily represent the views of, the Commission.

<sup>&</sup>lt;sup>2</sup> Available at: https://cpsc.gov/s3fs-

 $public/SEA\_Report\_to\_CPSC\_Vehicle\_Characteristics\_Measurements\_of\_All\_Terrain\_Vehicles.pdf. \\$ 

<sup>&</sup>lt;sup>3</sup> Available at: https://cpsc.gov/s3fs-public/SEA-Final-Report-to-CPSC-2-Rider-ATV-Study.pdf?V0ixJO3o\_kbtsmIBeKUInRAFx6hVocs5.

<sup>&</sup>lt;sup>4</sup> Available at: https://cpsc.gov/s3fs-public/SEA-Report-to-CPSC-Rider-Active-ATV-Study-December-2017.pdf?1nQBCXYgr.fkZoAR3axu7hkJ9l7mbSUl.

<sup>&</sup>lt;sup>5</sup> Available at: https://cpsc.gov/s3fs-public/SEA-Report-to-CPSC-Groomed-Dirt-ATV-Study.pdf?eK1E6h7IXBtznyCDatWHofAoHHmwD nr.

<sup>&</sup>lt;sup>6</sup> Available at: https://cpsc.gov/s3fs-public/ATV%20Attribute%20Modification%20Study%20-%20%20Results%20of%20Baseline%20and%20Modified%20Vehicle%20Testing\_0.pdf?ch3Lu\_.tpLpARkMCeX25aC0AlMNMzIHS.

Available at: https://cpsc.gov/s3fs-public/SEA%20Report%20to%20CPSC%20-%20ATV%20Rollover%20Simulator%20%286b%20cleared%29\_Redacted.pdf?mlCsq67xfdq8x94QejoFtK37zwXdLLJV

# Rollover Tests of ATVs Outfitted with Occupant Protection Devices (OPDs)

Results from Tests on Six 2014-2015 Model Year Vehicles

## for: U.S. Consumer Product Safety Commission

October 2019



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"These comments are those of SEA, Ltd. staff, and they have not been reviewed or approved by, and may not necessarily reflect the views of, the Commission."

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#### 1. OVERVIEW

This report contains results from measurements made by SEA, Ltd. (SEA) for the U.S. Consumer Product Safety Commission (CPSC) under CPSC contract 61320618D0003, a contract that covers general testing and evaluation of all-terrain vehicles (ATVs).

This report covers work completed under Task Orders 1 and 2 of contract 61320618D0003. Task Orders 1 and 2 involved:

- Conducting Autonomous Dynamic Rollovers (on a Groomed Dirt Surface) of All-Terrain
   Vehicles (ATVs) with an Anthropometric Test Device (ATD) used as a Surrogate Rider
   and Outfitted with aftermarket Occupant Protection Devices (OPDs): Testing OPDs on
   ATVs is required to determine the feasibility and effectiveness of using these devices on
   ATVs.
- Conducting Sled Rollovers (using a Physical Rollover Simulator) of ATVs with an ATD and Outfitted with aftermarket OPDs: Testing OPDs on ATVs is required to determine the feasibility and effectiveness of using these devices on ATVs.

SEA previously made measurements of ATV characteristics for the CPSC under U.S. Department of Health and Human Services (HHS) contract HHSP233201400030I. This contract was a five-year long, multi-task contract. Task Orders 1-4 and Task Order 6 of this contract involved conducting laboratory tests and dynamic field tests using twelve 2014-2015 model year ATVs, designated Vehicle A through Vehicle L.

The following five numbered sections provide brief descriptions and references of the previous work completed in Task Orders 1-4 and Task Order 6 to measure ATV characteristics.

- 1. Task Order 1 on contract HHSP233201400030I was to make characteristics measurements on 12 vehicles in the Driver Plus Instrumentation (DPI) loading condition (representing a nominal 215 lb driver) and in the Gross Vehicle Weight (GVW) loading condition. The SEA report to CPSC on these measurements is titled *Vehicle Characteristics Measurements of All-Terrain Vehicles Results from Tests on Twelve 2014-2015 Model Year Vehicles*<sup>8</sup>, and it contains results from laboratory and dynamic test track measurements made on all 12 vehicles. For the previous Task Order 1 testing, all 12 of the vehicles were tested in DPI loading condition and nine of them were also tested in the GVW loading condition. Vehicles B, H and I, were tested only in the DPI loading condition because the added weight of the test driver and instrumentation for these vehicles brought the total test weight up to near their manufacturer-specified maximum weight ratings. Vehicles B, H and I are the only three manual transmission vehicles and they are the three lightest vehicles. All the dynamic testing for the Task Order 1 measurements was conducted with a human test driver.
- 2. Task Order 2 was to make characteristics measurements on these same 12 vehicles in a two-person (driver and passenger) loading condition. For the two-person loading

<sup>8</sup> Vehicle Characteristics Measurements of All-Terrain Vehicles – Results from Tests on Twelve 2014-2015 Model Year Vehicles, HHS Contract HHSP233201400030I, SEA, Ltd. Report to CPSC, November 2016. <a href="https://www.cpsc.gov/s3fs-public/SEA">https://www.cpsc.gov/s3fs-public/SEA</a> Report to CPSC Vehicle Characteristics Measurements of All Terrain Vehicles.pdf

condition, the vehicles were each tested at a total test weight nominally 430 lb (representing two 215 riders) above the curb weight for each vehicle. All the testing was conducted using SEA's ATV Robotic Test Driver (ATV RTD). The ATV RTD is a system of automated steering, throttle, brake, and clutch controllers along with differential GPS that was used to conduct the tests in a fully autonomous mode, without a human test driver. Conducting the tests autonomously provided a means to use ballast fixed rigidly to the vehicle to represent the driver and passenger mass. The SEA report to CPSC on these measurements is titled *Effects on Vehicle Characteristics of Two Persons Riding ATVs – Results from Tests on Twelve 2014-2015 Model Year Vehicles*. 9

- 3. Task Order 3 on contract HHSP233201400030I was to make characteristics measurements on these same 12 vehicles to evaluate the effects on rollover resistance and vehicle handling characteristics when driver active weight shift is employed. For the Task Order 3 driver weight shift study, the vehicles were each tested at a total test weight nominally 215 lb (representing a 215 driver) above the curb weight for each vehicle. All the testing was conducted autonomously using SEA's ATV Robotic Test Driver (ATV RTD). Conducting the tests autonomously provided a means to use ballast fixed rigidly to the vehicle to represent the driver mass. The same ballast weight frame that was used to load the vehicles to the two-person loading condition in the Task Order 2 study was used in this study. Three different driver lateral lean angles were evaluated, one representing an upright driver (0° lateral lean angle), one representing a driver with a 20° lateral lean angle, and one representing a driver with a 40° lateral lean angle. The SEA report to CPSC on these measurements is titled *Effects on ATV Vehicle Characteristics of Driver Active Weight Shift Results from Tests on Twelve 2014-2015 Model Year Vehicles*. <sup>10</sup>
- 4. Task Order 4 was to make characteristic measurements on these same 12 vehicles when driven on a groomed dirt surface. Task Order 4 (as did Task Orders 2 and 3) involved doing only dynamic tests and doing the tests autonomously. Conducting the tests without a human driver mitigated the potential for having the test results influenced by human drivers shifting their weight to secure themselves to the vehicles during the tests and it eliminated the need to have the drivers attempt to lean to specific lateral lean angles. For the Task Order 4 groomed dirt study, the vehicles were each tested at a total test weight nominally 215 lb (representing a 215 driver) above the curb weight for each vehicle. The same ballast weight frame that was used in the Task Orders 2 and 3 studies was used in this study. The tests were conducted using the Task Order 3 loading condition that represents an upright driver, with 0° lateral lean angle. Replicating one of the same loading conditions that was used for tests on asphalt provided the opportunity for making direct comparisons of measured characteristics on groomed dirt and asphalt surfaces. Also, using the upright driver loading condition facilitated testing the vehicles in both the right and left turn The SEA report to CPSC on these measurements is titled Vehicle directions. Characteristics Measurements of ATVs Tested on Groomed Dirt – Results from Tests on

<sup>&</sup>lt;sup>9</sup> Effects on Vehicle Characteristics of Two Persons Riding ATVs – Results from Tests on Twelve 2014-2015 Model Year Vehicles, HHS Contract HHSP233201400030I, SEA, Ltd. Report to CPSC, September 2017. https://www.cpsc.gov/s3fs-public/SEA-Final-Report-to-CPSC-2-Rider-ATV-Study.pdf?V0ixJO3o\_kbtsmIBeKUInRAFx6hVocs5

<sup>&</sup>lt;sup>10</sup> Effects on ATV Vehicle Characteristics of Driver Active Weight Shift – Results from Tests on Twelve 2014-2015 Model Year Vehicles, HHS Contract HHSP233201400030I, SEA, Ltd. Report to CPSC, December 2017. <a href="https://www.cpsc.gov/s3fs-public/SEA-Report-to-CPSC-Rider-Active-ATV-Study-December-2017.pdf?1nQBCXYgr.fkZoAR3axu7hkJ917mbSU1">https://www.cpsc.gov/s3fs-public/SEA-Report-to-CPSC-Rider-Active-ATV-Study-December-2017.pdf?1nQBCXYgr.fkZoAR3axu7hkJ917mbSU1</a>

- 5. Task Order 6 on contract HHSP233201400030I had two objectives:
  - Conduct autonomous ATV dynamic rollovers (on a groomed dirt surface) with an ATD used as a surrogate rider: Results from intentional rollover events with an ATD onboard were required to verify and validate rollover simulator test results.
  - Conduct ATV sled rollovers (using a physical rollover simulator) with an ATD used as a surrogate rider: Controlled laboratory simulation of rollover events is required to facilitate the evaluation of aftermarket OPDs on ATVs.

For Task Order 6, rollover tests were conducted without OPDs using six of the twelve vehicles: Vehicles A, E, F, G, J and L. Vehicle L is a model year 2015 vehicle, and the other vehicles are model year 2014 vehicles. Four of these vehicles, Vehicles A, E, G and L, were used for the autonomous ATV dynamic rollover tests on a groomed dirt surface, and these tests are referred to as *dynamic* rollover tests. All six of the vehicles were used for the ATV rollover tests conducted on the rollover simulator, and these tests are referred to as *sled* rollover tests. During all the tests, sensor measurements were made of the motions of the ATV, and of the ATD head and chest accelerations and ATD head angular rates. Additionally, video sequences from five different camera angles were used to document the rollover events. The SEA report to CPSC containing the sensor and video measurements from these rollover tests without OPDs is titled *ATV Rollover Tests and Verification of a Physical Rollover Simulator – Results from Tests on Six 2014-2015 Model Year Vehicles*. <sup>12</sup>

For the testing covered in this report, Task Orders 1 and 2 of contract 61320618D0003, six vehicles were tested and two different aftermarket OPDs were evaluated. One of the OPDs, trade named is manufactured in New Zealand and the other OPD, trade named is manufactured in Australia. Three were procured by SEA for this study in the spring of 2019, and the main base and structural hoop of one of them was used for all the tests. Three were delivered to SEA from CPSC in the fall of 2018, and two of them were used for this study. The used were the original style with a rigid, hairpin shaped tubular hoop, not the more recent version with a flexible joint and single upright tube.

Five of the six vehicles (Vehicles A, E, F, G and J) used in this study were used in the previous rollover study that involved testing without OPDs. Vehicle L was not used for this study because portions of its rear rack is composed of plastic and the fitting instructions for one of the aftermarket OPDs recommended against using their OPD on a vehicle with a plastic carrier (because the OPD had not been tested or certified on plastic carriers). In addition, mounting the other OPD to Vehicle L would have required making modifications to the plastic carrier and rear rack. Therefore, Vehicle C was used instead of Vehicle L for rollover tests conducted with the aftermarket OPDs.

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Vehicle Characteristics Measurements of ATVs Tested on Groomed Dirt – Results from Tests on Twelve 2014-2015 Model Year Vehicles, HHS Contract HHSP233201400030I, SEA, Ltd. Report to CPSC, November 2017. <a href="https://www.cpsc.gov/s3fs-public/SEA-Report-to-CPSC-Groomed-Dirt-ATV-Study.pdf?eK1E6h7IXBtznvCDatWHofAoHHmwD\_nr">https://www.cpsc.gov/s3fs-public/SEA-Report-to-CPSC-Groomed-Dirt-ATV-Study.pdf?eK1E6h7IXBtznvCDatWHofAoHHmwD\_nr</a>

<sup>&</sup>lt;sup>12</sup> ATV Rollover Tests and Verification of a Physical Rollover Simulator – Results from Tests on Six 2014-2015 Model Year Vehicles, HHS Contract HHSP233201400030I, SEA, Ltd. Report to CPSC, In Review.

Website: www. com.au

Website: www.

All the vehicles have straddle seating and their intended use is for a single occupant, the driver. All the vehicles have clear warning labels stating, "Never Carry a Passenger" or "Never Carry Passengers." All the vehicles have handlebar (tiller) steering, thumb activated throttles, and hand and foot activated brakes.

Table 1 contains a list of assorted vehicle information for the six vehicles used in this study. The measured curb weights and maximum speeds are listed. Also listed in Table 1 is information on the transmission types (Automatic or Manual) and whether the vehicle has a Solid Rear Axle or Independent Rear Suspension. All the vehicles with solid rear axles are two-wheel drive (2WD) only vehicles. All the vehicles with independent rear suspensions are equipped with selectable four-wheel drive (4WD) or all-wheel drive (AWD). Table 1 contains the manufacturers' specified driveline setting options for each of the vehicles. All three vehicles used for the dynamic tests were tested in two-wheel drive mode, and in their most open driveline configurations.

The dynamic rollover tests were performed on SEA's groomed dirt test pad on numerous dates between June 3, 2019 and July 24, 2019. The sled rollover tests were performed on SEA's laboratory sled, configured for ATV rollover testing, on numerous dates between July 31, 2019 and August 27, 2019. While both OPDs evaluated potentially offer occupant protection features during forward pitch-over and rearward pitch-over events, these types of events were not evaluated in this study. Also, no evaluations of potential OPD obstructive hazards related to ATV operation or occupant egress were made as part of this study.

Two categories of dynamic rollover tests were performed using Vehicles A, E and G. The categories were specified by their intended level of rollover severity as: Minimum Energy Rollovers and Moderate Energy Rollovers. Four dynamic rollover tests were conducted using each of the three vehicles, two Minimum Energy Rollovers using both OPDS and two Moderate Energy Rollovers using both OPDs.

Two categories of sled rollover tests were performed using Vehicles A, C, E, F, G and J, specified as: Minimum Energy Rollovers and Moderate Energy Rollovers. Various sled configuration parameters were tuned to generate sled rollover events that were representative of the dynamic rollover events for these two categories of rollovers. Four sled rollover tests were conducted using each of the six vehicles, two Minimum Energy Rollovers using both OPDS and two Moderate Energy Rollovers using both OPDs.

During previous dynamic rollover tests without OPDs, the steering motor used to control steering inputs and its protective guard were mounted above the front racks on the test vehicles. During several of the previous dynamic rollover tests, the steering motor guard gouged the dirt surface during rollover events, and potentially altered the rollover dynamics of the vehicle. Therefore, for this current study, the steer motor was mounted beneath the front rack of each vehicle to mitigate the potential for this test equipment to interfere with the vehicle rollover dynamics and interactions between the ATV and ATD.

Also during previous dynamic and sled rollover tests without OPDs, four cameras (two high speed cameras with a frame rate of 25 fps and two real time cameras with a frame rate of 30 fps) with fixed views were used to record video that was used to generate image sequences of the rollover events. For this current study, these cameras were replaced with four cameras. The

cameras were operated at 60 fps, which provided better timing resolution for the video sequences used to document the rollover events. Furthermore, the cameras were manually panned during the dynamic rollover tests to improve the field of view captured in the video sequences.

This report has four main sections: Overview, Dynamic Testing and Discussion of Dynamic Rollover Results, Sled Testing and Discussion of Sled Rollover Results, and Comparison of Rollover Events of ATVs without an OPD, Outfitted with a and Outfitted with a This report also has six appendices. Appendices A and B contain test results from the dynamic and sled rollovers; Appendix C contains photographs of the on-vehicle test equipment; and Appendices D, E and F contain descriptions of the video equipment, ATD and ATD secure and release system, and ATV rollover sled, respectively, used for this study.

Table 1: Test Vehicle Information						
Vehicle A Curb Weight: 523.9 lb Maximum Speed: 47.0 mph	Automatic Transmission Solid Rear Axle 2WD					
Vehicle C	Automatic Transmission					
Curb Weight: 650.8 lb	Independent Rear Suspension					
Maximum Speed: 66.0 mph	2WD, 4WD, or 4WD Lock					
Vehicle E	Automatic Transmission					
Curb Weight: 734.1 lb	Independent Rear Suspension					
Maximum Speed: 45.7 mph	2WD, 4WD, or 4WD Lock					
Vehicle F Curb Weight: 526.2 lb Maximum Speed: 53.5 mph	Automatic Transmission Solid Rear Axle 2WD					
Vehicle G	Automatic Transmission					
Curb Weight: 694.0 lb	Independent Rear Suspension					
Maximum Speed: 69.0 mph	2WD or 4WD					
Vehicle J	Automatic Transmission					
Curb Weight: 649.8 lb	Independent Rear Suspension					
Maximum Speed: 60.5 mph	2WD or AWD					

#### 2. DYNAMIC TESTING AND DISCUSSION OF DYNAMIC ROLLOVER RESULTS

This section describes the dynamic rollover tests conducted on numerous dates between June 3, 2019 and July 24, 2019. All the vehicles were tested at SEA in Columbus, Ohio, on a groomed dirt test pad, approximately 300 ft by 300 ft square and with a grade of 0.33 percent. The test surface was maintained to be free of vegetation and rocks larger than about an inch in diameter. The test surface can be described as hard packed soil with a loose top layer, and is similar to dirt surfaces that might be found on some off-road trails.

The three vehicles used for the dynamic rollover tests (Vehicles A, E and G) have automatic transmissions and were tested in two-wheel drive mode, and in their most-open driveline configuration.

#### 2.1 Vehicle Loading Condition

The loading condition used for all of the dynamic rollover testing included an instrumented Hybrid III 50<sup>th</sup> percentile male anthropometric test device (ATD) with a standing pelvis, SEA's ATV Rollover Robotic Test Driver (RTD) needed to autonomously drive the ATV, an ATD secure and release system, vehicle data sensors and a data collection system. Pages 1 and 2 of Appendix C contain side and rear view photographs of an ATV prepared for dynamic rollover testing and with the ATD on the vehicle. Page 1 shows a vehicle outfitted with a OPD and Page 2 shows a vehicle outfitted with a OPD. For each ATV tested, the ATD was positioned to sit near the longitudinal center of the seat. The ATD's hands were affixed to the handgrips on the ATV handlebars and its feet were positioned on the footwells. The ATD was positioned to have no lateral lean at the start of each test. The seating and handhold positions of the ATD essentially dictated its forward lean angle, and Pages 1 and 2 of Appendix C show a forward lean typical of those used for all vehicles tested.

The ATV Rollover RTD consists of a computer-controlled 24V electric motor mounted beneath the front rack of the ATV for steering control, a pneumatic actuator to apply the throttle and a pneumatic actuator to apply the brake. Page 3 of Appendix C shows a steering controller configuration with the steering motor mounted beneath the front rack of the vehicle. The steer motor and gear box were uniquely mounted on each vehicle in an orientation that would allow for a coupler link mounted to the output of the gearbox to nominally rotate in a plane aligned with OEM steering tie rods. A custom connecting rod, attached to the coupler link, was connected to the base (bottom) of the steering column, so when the steer motor rotated the vehicle would steer. Steering ratio (steer motor angle to roadwheel steer angle) characteristics were measured for each vehicle so that steering inputs used for the current study could be related to steering inputs used in the previous rollover study.

Page 4 of Appendix C shows the brake and throttle pneumatic actuators, and Page 5 shows the pneumatic valves and pump used to control and pressurize the brake and throttle actuators (as well as for the ATD secure and release system). The ATV front hand-brake master cylinders were moved off the handlebars and mounted on the front racks of the vehicles. To activate the ATV brakes, the onboard controller commands the brake valve to open and extend the brake actuator rod, which then pushes on the master cylinder plunger. Braking levels were tuned by adjusting the flow control valve to the brake actuator. The ATV throttle cables were also moved off the handlebars and mounted on the front racks of the vehicles. To activate the ATV throttle, the onboard controller commands the throttle valve to open and retract the throttle actuator rod which

then extends the throttle cable. Throttle levels were tuned by mechanically limiting the stroke of the actuator rod (and throttle cable).

The ATV Rollover RTD also includes a GPS/IMU (OxTS RT4002), a National Instruments (NI) CompactRIO (the on-vehicle computer with the motor and valve controllers and data acquisition software), and antennas for wireless communication, an engine kill system, and batteries. Page 6 of Appendix C shows an antenna used for wireless communication, the NI CompactRIO, the GPS/IMU, the supplemental roll rate sensor, a manual kill switch and the wireless kill switch receiver on the vehicle. The wireless feature of the engine kill safety system was used on all the vehicles to provide remote disabling of the vehicle engine in the event of a test mishap. Page 7 of Appendix C shows the two 12V batteries (used to power the CompactRIO, the GPS/IMU and the pneumatic pump), the 9V battery used for the kill circuit, the 24V battery used to power the steering motor, and the antenna for the RT unit mounted flush with the fender of the ATV. The components shown on Pages 6 and 7 were mounted in such a way to avoid interference with the rollover dynamics of the vehicle.

The previously developed ATD "secure and release" system (consisting of a pneumatic actuator, cables extending to the ATD's hip and neck, and cable ties securing the ATD's hands to handlebars) was used for this rollover testing. The pneumatic actuator used for the ATD secure and release system is shown on Page 8 of Appendix C. The actuator rod holds the hip and neck cables until a signal from the on-vehicle controller, sent when the vehicle roll angle is 30°, opens the actuator thus releasing the hip and neck cable holds to the vehicle. Page 9 of Appendix C shows the cable tie arrangement used to secure the ATD's hands to the handlebar grips. The handhold (pull away) strength of the cable ties used withstands close to 80 pounds of pull away force before they break. Details of the ATD secure and release system are contained in Appendix E.

Table 2 lists the nominal weights of the components added to the curb weights of the ATVs in their dynamic rollover loading conditions when outfitted with a and a

#### 2.2 On-Vehicle Test Instrumentation

The instrumentation used during the dynamic rollover testing is listed in Table 3. The GPS/IMU (RT4002) was mounted at the rear of each vehicle, beneath the rear rack. For each vehicle, the longitudinal, lateral, and vertical offsets from the center of the RT4002 to the actual vehicle center-of-gravity (CG) location were measured and entered into the RT4002 system software. This information was used to translate the measured quantities to those at the CG of the vehicle.

The RT4002 has a rated range for rate measurements of  $\pm 300$  deg/s. During some of the dynamic (and sled) rollover events, the RT4002 roll rate signal gets "clipped" when vehicle roll rates exceeds 300 deg/s. When this happens, the RT4002 internal calculations used to compute roll angle gets corrupted because of the clipped roll rate. In order to get full range roll rate measurements and accurate roll angle measurements during all the rollover tests, a supplemental roll rate sensor was added to the vehicles for the dynamic (and sled) rollover tests. This rate sensor (Silicon Sensing CRH02-400) has a rated range of  $\pm 400$  deg/s, and it was evaluated and shown to provide good rate measurements of roll rate signals beyond  $\pm 400$  deg/s. Therefore, the roll rate signal from the supplemental roll rate sensor was used to measure roll rates during the rollover tests. Furthermore, the roll, pitch and yaw (heading change) angles from the dynamic (and sled) rollover tests were computed from the supplemental roll rate sensor and the RT4002's pitch rate

and yaw rate. The angle (orientation) calculations require integrating rates in the appropriate three-dimensional coordinate reference frame. The Euler angle method was used to compute the rates in the desired vehicle fixed coordinate system so they could be integrated to compute the roll, pitch and yaw angles about the vehicle-fixed coordinate system. <sup>15</sup>

Table 2: Dynamic Rollover Vehicle Loading					
Component	Nominal Weight (lb)				
ATD as Tested	174.0				
RT Unit and Roll Rate Sensor with Mounts	10.1				
Compact RIO	5.9				
Pneumatic Pump and Valves	5.1				
Pneumatic Cylinder and Mounts	8.0				
Cables	5.0				
2 12V Lithium Batteries (6.6 lb each)	13.2				
Steering Motor with Rods, Mount and Protective Frame	10.1				
24V Lithium Battery	7.5				
Kill Switch Circuit and Antennas	10.0				
Nominal Weight Added for Dynamic Tests Without OPD	248.9				
Additional Weight Added for Tests with	34.6				
Additional Weight Added for Tests with	16.3				
Total Nominal Weight Added for Tests with	283.5				
Total Nominal Weight Added for Tests with	265.2				

<sup>&</sup>lt;sup>15</sup> Doebelin, E.O. *System Modeling and Response, Theoretical and Experimental Approaches*, John Wiley & Sons, p484, 1980.

Table 3: Instrumentation Used During Dynamic Testing							
Transducer	Measurement	Range	Accuracy				
	Longitudinal, Lateral, and Vertical Accelerations	± 100 m/s <sup>2</sup> (± 10 g)	0.01 m/s <sup>2</sup> (0.001 g)				
Oxford Technical Solutions (OxTS)  RT4002 Inertial and GPS Navigation System	Roll, Pitch, and Yaw Rates	± 300 deg/s	0.01 deg/s				
	Speed	No Limit Specified	0.05 km/h (0.03 mph)				
	Roll and Pitch Angles	-180 to +180 deg	0.03 deg				
	Vehicle Heading	0 to 360 deg	0.1 deg				
Silicon Sensing CRH02-400	(Supplemental) Roll Rate	± 400 deg/s	0.5%				

#### 2.3 Dynamic Rollover Maneuvers

Two different categories of dynamic rollover tests were conducted, specified by their intended level of rollover severity as: Minimum Energy Rollovers and Moderate Energy Rollovers. All the rollover events involved autonomously driving the vehicles along a straight-line path and at some earth-fixed trigger position imparting a rapid left steer input, at a steering input rate at the handlebars of 40 deg/s. This steering rate is the same rate used in previous human driver and autonomous tests conducted on asphalt and groomed dirt. The left turns resulted in right side leading rollover events. Tests were only conducted in the left turn (right side leading rollover event) direction and at a fixed steering-trigger position to facilitate the placement of the multiple cameras needed to video record the rollover events. In addition, conducting the rollover events in the left turn direction only also facilitated the sled testing used to verify the quality of sled rollovers.

GPS coordinates of a straight-line, North to South path leading to the earth-fixed trigger position on the groomed dirt test pad was recorded. This path was used for the run up to the trigger position. For all the dynamic rollover tests, the steering motor was disabled 5.0 seconds after the left steering input was applied. The test conditions for the dynamic rollover categories are described below:

- Minimum Energy Dynamic Rollovers: The vehicle speeds and steering inputs used for the minimum energy rollovers were selected to produce rollover events resulting in at least 90 degrees but less than 180 degrees of maximum roll angle. Previous J-Turn tests of the same vehicles on groomed dirt that resulted in rollover events without OPDs<sup>16</sup> provided insight to the speeds and steering inputs needed to produce the minimum energy rollover events. Table 4 lists the vehicle speeds when the trigger position was reached, and the steering input applied at this instance. For the minimum energy, dropped throttle J-Turn tests, the same nominal speeds that were used during the previous rollover tests on these vehicles was used for this study: 20 mph for Vehicles A and G, and 23.5 mph for Vehicle E. The effective handlebar steering inputs used for these rollover tests with OPDS were similar, to within one degree, of those used during the previous minimum energy rollover tests without OPDs.
- Moderate Energy Dynamic Rollovers: The intent of the moderate energy rollovers was to produce rollover events resulting in at least 180 degrees of roll angle. Increasing the test speeds, beyond those used during the minimum energy rollovers, is one way to achieve moderate energy rollovers. Therefore, the same steering inputs that were used for the minimum energy rollovers were used for the moderate energy rollovers, but the throttle was not dropped during the approach to the trigger position. The resulting speeds at the trigger point used for the moderate energy rollovers are listed on Table 4. For the moderate energy rollover tests, the throttle was eventually dropped 0.6 seconds after the start of steering input.

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Table 4: Vehicle Speeds and Steering Magnitudes for Dynamic Rollover Tests							
Vehicle Letter	Maneuver Category	Speed at Trigger (mph)	Handlebar Steering Input (deg)				
	Minimum Energy Rollover –	20.0	28				
A	Minimum Energy Rollover –	20.1	28				
A	Moderate Energy Rollover –	23.5	28				
	Moderate Energy Rollover –	24.0	28				
	Minimum Energy Rollover –	23.3	39				
E	Minimum Energy Rollover –	23.4	39				
	Moderate Energy Rollover –	25.9	39				
	Moderate Energy Rollover –	25.7	39				
	Minimum Energy Rollover –	19.9	19				
G	Minimum Energy Rollover –	20.1	19				
	Moderate Energy Rollover –	24.2	19				
	Moderate Energy Rollover –	23.5	19				

#### 2.4 Discussion of Dynamic Rollover Results

Results from the dynamic rollover tests are contained in Appendix A. Appendix A is organized by vehicle: Vehicle A (Pages 1-71), Vehicle E (Pages 72-133) and Vehicle G (Pages 134-199); and further by rollover category (Minimum Energy Rollover – Minimum Energy Rollover – Moderate Energy Rollover – Moderate Energy Rollover – And Moderate Energy Rollover – The first 7 to 12 pages (depending on the amount of roll angle achieved during the test) of each vehicle section contain images taken from five different video cameras: the four cameras and the Drone Camera. The pages of camera images are followed by three pages of graphs containing data from the ATD: ATD Head Accelerations, ATD Head Angular Rates and ATD Chest Accelerations. These are followed by four pages of graphs containing data from the vehicle: Vehicle Body Fixed Accelerations, Vehicle Global (Earth Fixed) Accelerations, Vehicle Angular Rates and Vehicle Angles.

The vehicle body fixed coordinate system and global (earth fixed) coordinate system are both orthogonal coordinate systems and both have their origins at the center of gravity of the vehicle. For the vehicle body fixed coordinate system, the X-axis is in the longitudinal direction toward the front of the vehicle, the Y-axis is in the lateral direction with positive to the right, and the Z-axes is down. This coordinate system is fixed to the vehicle, and rotates with the vehicle as it pitches, rolls and yaws. For the vehicle global coordinate system, its Z-axis is always down, its X-axis is forward, and its Y-axis is to the right. This coordinate system rotates about its Z-axis, but it does not rotate about its X-axis or Y-axis, as the vehicle rolls and pitches. That is, Ax and Ay in the global coordinate system are in the ground plane, and Az is always down.

The ATD head and chest coordinate systems are orthogonal coordinate systems with their origins near the center of the head and chest, respectively. These are both ATD fixed coordinate systems, each with its X-axis directed toward the front of the ATD, its Y-axis directed to the right, and its Z-axis directed down.

#### 2.4.1 Video Image Results

A description of the video cameras and their relative locations during the rollover tests is contained in Appendix D.

The video images presented in Appendix A are digital JPEG format images of individual video frames from each camera. For example, the cameras were set to have a video frame rate of 60 frames per seconds, so 60 JPEG images were generated for each second of camera video. The number of video images presented in each section of Appendix A depends on the maximum roll angle during the rollover event. For all rollovers, images are shown for 30°, 45° and 90° of roll angle, the time when the ATD head first strikes the ground, the time of maximum roll angle, and the end of the run. Also, if the vehicle experienced 180°, 270°, 360° or 450° of roll angle, the images are included in the sections in Appendix A.

The four cameras were synchronized to each other and to the vehicle data using a camera flash attached to a pressure sensitive ribbon switch. The ribbon switch was positioned at the trigger point of the maneuver and aligned perpendicular to the path of the vehicle. Time zero for the cameras is when the front tires of the vehicle hit the ribbon switch, and this is time zero for the vehicle data, and the time when steering input is initiated. Therefore, the times listed on the titles of the camera images in Appendix A are the times from the start of the steering input. The

camera frame when the ATD head first strikes the ground was manually selected; and based on the number of frames between this frame and the frame of 90° roll angle, the time of ATD head strike was computed based on the frame rate. The time associated with each video image is included in the title above each image.

The drone camera was synchronized to the cameras (and therefore the vehicle time) using the time of ATD head strike with the ground. The and drone camera times for the image frame when the ATD head first strikes the ground were set equal to the time determined from the head strike image. All the other drone frames (to within one frame) were programmatically selected based on the differences between the time of the specific frame of interest and the time of the head strike frame. For example, if the time of head strike occurred 0.12 seconds after the time of 90° roll angle, the drone camera frame used for the 90° roll angle image would be three frames prior to the head strike frame (0.12 seconds multiplied by 24 frames per second – the frame rate for the drone camera – and rounded to the nearest integer number of frames is three).

#### 2.4.2 ATD Results

A description of the Anthropometric Test Device (ATD), the ATD sensors and data collection system, and the system used to secure and release the ATD during the rollover events is contained in Appendix E.

As mentioned earlier, each vehicle section in Appendix A contains the three pages of ATD results (that follow initial pages of video images of testing). The first page contains ATD Head Accelerations in the ATD head fixed X, Y and Z directions; the second page contains ATD Head Angular Rates about ATD head roll, pitch and yaw axes; and the third page contains ATD Chest Accelerations in the chest fixed X, Y and Z directions. All the ATD data was zeroed prior to the time the vehicle started moving, so the data presented shows the changes in accelerations and rates that occurred throughout the rollover event. All the ATD data shown has been filtered using a 1,000 Hz low pass, Butterworth filter.

All graphs containing ATD data include a vertical band (about 0.2 seconds wide) centered around the time when the ATD head first strikes the ground. This band provides a convenient reference for the head strike during the rollover event. The first peaks in the ATD accelerations and rates are all within this band.

#### 2.4.3 Vehicle Results

The pages of ATD results in each vehicle section in Appendix A are followed by four pages of vehicle results. The first page contains Vehicle Body Fixed Accelerations in the vehicle body fixed X, Y and Z directions; the second page contains Vehicle Global (Earth Fixed) Accelerations in the global X, Y and Z directions; the third page contains Vehicle Angular Rates about the vehicles roll, pitch and yaw axes; and the fourth page contains Vehicle Angles about the vehicles roll, pitch and yaw axes (the yaw angle is zeroed along the path of the vehicle thus providing the change in heading throughout the rollover event).

All the vehicle data is unfiltered, except for the acceleration data, which is filtered using a low pass filter with a cutoff frequency of 10 Hz. The acceleration data contains high frequency acceleration content, which if plotted unfiltered would obscure the underling acceleration trends of interest.

Prior to the start of steering (and up to time equals 0.0 seconds on the graphs), the vehicle body fixed longitudinal acceleration (Ax) and lateral acceleration (Ay) are very close to 0.0 g, while the vehicle body fixed vertical acceleration (Az) is close to -1.0 g. After the steering input starts at time equals zero seconds: the vehicle body fixed Ax drops below 0.0 g as the vehicle scrubs off speed during the J-Turn, the body fixed Ay also drops below 0.0 g as a result of the vehicle rolling to the right, and the body fixed Az increases from its initial -1.0 g level, also as a result of the vehicle rolling. When the vehicle roll angle approaches 90° during the minimum energy runs, the right side of the vehicle impacting the ground causes all the body fixed accelerations to peak. For the moderate energy runs, the first peaks in the acceleration traces occur at higher roll angles, between 125° and 150° of roll angle. The acceleration peaks in minimum and moderate energy test runs conducted with OPDs are similar to acceleration peaks measured in prior minimum and moderate energy test runs conducted without OPDs.<sup>17</sup>

Other peaks in the body fixed acceleration traces occur during rollover events that have other abrupt vehicle impacts with the ground. The body fixed accelerations at the end of the rollover events are a function of the final orientation of the vehicle at the end of the run. For example, the minimum energy runs of Vehicle G with both the and and had final roll angles near 90°. In these cases, the final body fixed Ay is near -1.0 g, and final body fixed Ax and Az are near 0.0 g.

The plots of the vehicle global accelerations in the earth fixed reference frame all start and end at the same levels: near 0.0 g for Ax and Ay and near -1.0 g for Az. The vehicle global Ay is the vehicle lateral acceleration that was plotted in previous reports from ATV testing, and this is the so called corrected or ground plane Ay. The absolute values of the peak Ay levels after the start of steering but before the vehicle roll angles reach about 30° are consistent with the levels of threshold lateral acceleration values measured during previous J-Turn tests that resulted in two-wheel lift outcomes and during previous rollover tests without OPDs. The vehicle global accelerations also exhibit their first and typically highest peaks when the vehicle body first impacts the ground, and for some of the rollover events, peaks occur at subsequent times when the vehicle body impacts the ground.

In all the dynamic rollovers conducted, the vehicle reached  $90^{\circ}$  of roll angle before the ATD first head strike with the ground occurred. Typically, the first ATD head strike with the ground occurs 0.1 seconds to 0.2 seconds after the vehicle reaches  $90^{\circ}$  of roll angle. As mentioned, the vehicle acceleration plots have their first spikes when the roll angle nears  $90^{\circ}$  for the minimum energy runs and between  $125^{\circ}$  to  $150^{\circ}$  for the moderate energy runs. The acceleration plots show that these acceleration spikes occur prior to or within the vertical band indicating the head strike. These results are the same as the dynamic rollover tests conducted without an OPD.

For the minimum energy rollovers, the vehicle roll rate plots have their peaks near 90° of vehicle roll angle. The roll rates exhibit a marked drop in magnitude in the range of 90° as the right side of the vehicle impacts the ground, which causes the decrease in roll rate. For the moderate energy

<sup>&</sup>lt;sup>17</sup> ATV Rollover Tests and Verification of a Physical Rollover Simulator – Results from Tests on Six 2014-2015 Model Year Vehicles, HHS Contract HHSP233201400030I, SEA, Ltd. Report to CPSC, In Review.

rollovers, the vehicle roll rate plots have their first peaks in the range of 125° to 150° of vehicle roll angle. These results are also similar to results of the rollover tests conducted without an OPD. With the exception of Vehicle G, the highest roll rate during the moderate energy runs for all vehicles was the first peak roll rate. During the moderate energy run of Vehicle G outfitted with a the peak roll rate occurred near 360° of roll angle, when the left rear tire of the vehicle impacted the ATD's helmet and caused a spike in roll rate.

The vehicle roll angle plots show the timing of the roll orientations listed on the titles used for the video camera images, as well as the timing and magnitude of the maximum roll angle and the final roll angle at the end of the run.

All the minimum energy dynamic rollovers conducted on vehicles without OPDs produced rollover events with maximum roll angles between 90° and 180°; and this is the case for the minimum energy rollover tests for Vehicles E and G outfitted with a and a However, the maximum roll angles during the minimum energy rollovers of Vehicle A were greater for both the test using a (298.2°) and the test using a (300.0°) than they were for the test with no OPD (177.9°).

Vehicle E had similar maximum and final roll angles in moderate energy dynamic rollover tests conducted without an OPD and in tests with both a and a However, moderate energy dynamic tests on Vehicles A and G conducted with a and a resulted in greater maximum and final roll angles than in the moderate energy dynamic tests conducted on these two vehicles without an OPD. Discussion of these differences is contained in Section 4 of this report.

#### 3. SLED TESTING AND DISCUSSION OF SLED ROLLOVER RESULTS

This section describes the sled rollover tests conducted on numerous dates between July 31, 2019 and August 27, 2019. All the vehicles were tested at SEA in Columbus, Ohio, on a laboratory sled that was configured for ATV rollover testing. Two categories of sled rollover tests were performed using Vehicles A, C, E, F, G, and J, specified as: Minimum Energy Rollovers and Moderate Energy Rollovers. Various sled configuration parameters were tuned to generate sled rollover events that were representative of the dynamic rollover events for these two categories of rollovers. Appendix F contains a description of the SEA laboratory sled configured for use as an ATV rollover simulator.

#### 3.1 Vehicle Loading Condition

The loading condition used for all the sled rollover testing included an instrumented Hybrid III 50<sup>th</sup> percentile male anthropometric test device (ATD) with a standing pelvis, the ATD secure and release system, vehicle data sensors and a data collection system. The ATV Rollover Robotic Test Driver (RTD) was not needed for the sled tests, so the electric steering motor and the pneumatic throttle and brake actuators were not used. Also, the engine kill system, the 24V battery and one of the two 12V batteries that were needed for the dynamic rollover tests were not used for the sled tests.

Table 5: Sled Rollover Vehicle Loading					
Component	Nominal Weight (lb)				
ATD as Tested	174.0				
RT Unit and Roll Rate Sensor with Mounts	10.1				
Compact RIO	5.9				
Pneumatic Pump and Valves	5.1				
Pneumatic Cylinder and Mounts	8.0				
Cables	5.0				
12V Lithium Battery	6.6				
Nominal Weight Added for Sled Tests Without OPD	214.7				
Additional Weight Added for Tests with	34.6				
Additional Weight Added for Tests with	16.3				
Total Nominal Weight Added for Tests with	249.3				
Total Nominal Weight Added for Tests with	231.0				

The same ATD with internal (head and chest) sensors and data acquisition system (DAQ), the same ATD positioning, and the same ATD secure and release system that were used during the dynamic rollover tests were used during the sled rollovers. The RT4002 and supplemental roll rate sensor, the pneumatic pump and actuator for the ATD secure and release system, the NI CompactRIO and remaining battery and cables were all positioned on the vehicles for the sled rollover tests in the same positions they were during the dynamic rollover tests.

Table 5 lists the nominal weights of the components added to the curb weights of the ATVs in their sled rollover loading conditions when outfitted with a and a

#### 3.2 On-Vehicle Test Instrumentation

The instrumentation used during the sled rollover testing is listed in Table 6. Since the sled track leading to the outdoor rollover pit is indoors, the RT4002 was not able to get GPS coordinate signals from satellites. Therefore, GPS position coordinates, as well as vehicle speed, roll angle, pitch angle and heading angle (which rely on sensor-merging technologies to merge signals from the RT4002 inertial and GPS sensors) were not available from the RT4002 for the sled rollover tests.

The RT4002 does provide accurate acceleration and rate measurements without GPS. However, during the sled moderate energy rollover runs, the RT4002 roll rate signal was clipped for rates above 300 deg/s. Therefore, as was the case for the dynamic rollovers, the roll rate signal from the supplemental roll rate sensor was used to measure roll rates during the sled rollover tests. Furthermore, the roll, pitch and yaw (heading change) angles from the sled rollover tests were computed from the supplemental roll rate sensor and the RT4002's pitch rate and yaw rate, using the same method/calculations that were used for the dynamic rollovers.

Table 6: Instrumentation Used During Sled Testing								
Transducer Measurement Range Accu								
OxTS RT4002	Longitudinal, Lateral, and Vertical Accelerations	± 100 m/s² (± 10 g)	0.01 m/s <sup>2</sup> (0.001 g)					
(without GPS)	Roll, Pitch, and Yaw Rates	± 300 deg/s	0.01 deg/s					
Silicon Sensing CRH02-400	(Supplemental) Roll Rate	± 400 deg/s	0.5%					

#### 3.3 Sled Rollover Maneuvers

Two categories of sled rollover tests were performed using Vehicles A, C, E, F, G, and J, specified as: Minimum Energy Rollovers and Moderate Energy Rollovers. Various sled configuration parameters were tuned to generate sled rollover events representative of the dynamic rollover events for these two categories of rollovers. Appendix F describes the ATV Rollover Simulator and provides discussion on how features and components on the sled facility were adjusted to generate sled rollovers to represent the minimum and moderate energy rollovers.

#### 3.4 Discussion of Sled Rollover Results

Results from the dynamic rollover tests are contained in Appendix B. Appendix B is organized by vehicle: Vehicle A (Pages 1-59), Vehicle C (Pages 60-117), Vehicle E (Pages 118-175), Vehicle F (Pages 176-234), Vehicle G (Pages 234-292), and Vehicle J (Pages 293-351); and further by rollover category (Minimum Energy Rollover – Minimum Energy Rollover -Moderate Energy Rollover – and Moderate Energy Rollover – The results presented for the sled tests are like the results presented for the dynamic rollover tests. The first 7 to 10 pages (depending on the amount of roll angle achieved during the test) of each section of results contain images taken from five different video cameras: the four and the Drone Camera. The pages of camera images are followed by three pages of graphs containing data from the ATD: ATD Head Accelerations, ATD Head Angular Rates and ATD Chest Accelerations. These are followed by three pages of graphs containing data from the vehicle: Vehicle Body Fixed Accelerations, Vehicle Angular Rates and Vehicle Angles. Note that there are no Vehicle Global (Earth Fixed) Acceleration graphs from the sled tests because GPS signals were not available for the predominately indoor portion of sled tests, and no earth fixed (i.e. ground plane) accelerations were available from the RT4002.

The same vehicle fixed and ATD fixed coordinate systems that were used for the dynamic rollover tests were used for the sled tests.

#### 3.4.1 Video Image Results

A description of the video cameras and their relative locations during the rollover tests is contained in Appendix D. The same selection of video image frames that was used to report the sequence of events during the dynamic rollovers was used for the sled rollovers.

The timing of the sled control system DAQ was synchronized to the timing of the vehicle DAQ system at the beginning of each sled run. The four cameras were synchronized to the sled DAQ (and therefore the vehicle DAQ) using a pressure sensitive ribbon switch that was triggered by one of pneumatic tires on the sled. The ribbon switch was positioned on the lab floor at the precise location when the sled electromagnetic particle brake was activated to generate the onset of sled deceleration. For the sled tests, time zero for the cameras and for the vehicle data is the time when sled deceleration input is initiated. The same method used for the dynamic rollover tests (using the frame of head strike with the ground as the sync point) was used to synchronize the sled drone camera with the cameras (and therefore the vehicle time).

The times listed on the titles of the camera images in Appendix B are the times from the start of the sled deceleration. Again, as was done with the dynamic rollover tests, the drone frames (to within one frame) were programmatically selected based on the differences between the time of the specific frame of interest and the time of the head strike frame.

#### 3.4.2 ATD Results

A description of the Anthropometric Test Device (ATD), the ATD sensors and data collection system, and the system used to secure and release the ATD during the rollover events is contained in Appendix E.

As mentioned earlier, each vehicle section in Appendix B contains three pages of ATD results

(that follow initial pages of video image results of dynamic sled testing). The first page contains ATD Head Accelerations in the ATD head fixed X, Y and Z directions; the second page contains ATD Head Angular Rates about ATD head roll, pitch and yaw axes; and the third page contains ATD Chest Accelerations in the chest fixed X, Y and Z directions. All the ATD data was zeroed prior to the time the vehicle started moving, so the data presented shows the changes in accelerations and rates that occurred throughout the rollover event. All the ATD data shown has been filtered using a 1,000 Hz low pass, Butterworth filter.

All the graphs containing ATD data include a vertical band (about 0.2 seconds wide) centered around the time when the ATD head first strikes the ground. This band provides a convenient reference for the head strike during the rollover event. The peaks in the ATD accelerations and rates are all within this band.

#### 3.4.3 Vehicle Results

The pages of ATD results in each vehicle section in Appendix B are followed by three pages of vehicle results. The first page contains Vehicle Body Fixed Accelerations in the vehicle body fixed X, Y and Z directions; the second page contains Vehicle Angular Rates about the vehicles roll, pitch and yaw axes; and the third page contains Vehicle Angles about the vehicles roll, pitch and yaw axes. For the sled tests, the heading change (the change in angle about the yaw axis) is the change from the initial angle of the vehicle as positioned on the sled. For the minimum energy sled rollovers, with the sled yaw platform edge rotated 20° from perpendicular to the direction of sled travel, the initial heading angle is -70°; and for the moderate energy sled rollovers, with the sled platform edge rotated only 10°, the initial heading angle is -80°. All the vehicle data from the sled tests is unfiltered.

Trends in the body fixed acceleration responses observed during the sled rollover tests were similar to those observed during the dynamic rollover tests. Immediately prior to the start of the sled braking (and up to time equals 0.0 seconds on the graphs), the vehicle body fixed longitudinal acceleration (Ax) and lateral acceleration (Ay) are very close to 0.0 g., while the vehicle body fixed vertical acceleration (Az) is close to -1.0 g. After time equals zero seconds (when the sled braking input starts) the vehicle body fixed Ax and Ay drop below 0.0 g as the sled and vehicle decelerate. The body fixed Ay also drop below 0.0 g as a result of the vehicle rolling to the right, and the body fixed Az increases from its initial -1.0 g level, also as a result of the vehicle rolling. When the vehicle roll angle approaches 90° during the minimum energy runs, the right side of the vehicle impacting the ground causes all the body fixed accelerations to peak. For the moderate energy runs, the first peaks in the acceleration traces occur at higher roll angles, between 100° and 150° of roll angle. These results regarding the roll angle ranges when the first peaks in vehicle accelerations occur are similar to the ranges during sled rollover tests conducted without an OPD. 18 Other peaks in the body fixed acceleration traces occur during rollover events that have other abrupt vehicle impacts with the ground. The body fixed accelerations at the end of the rollover events are a function of the final orientation of the vehicle at the end of the run.

In all the sled rollovers, the vehicle reached  $90^{\circ}$  of roll angle before the ATD first head strike with the ground occurred. Typically, the first ATD head strike with the ground occurs 0.1 seconds to 0.2 seconds after the vehicle reaches  $90^{\circ}$  of roll angle. As mentioned, the vehicle acceleration

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<sup>&</sup>lt;sup>18</sup> ATV Rollover Tests and Verification of a Physical Rollover Simulator – Results from Tests on Six 2014-2015 Model Year Vehicles, HHS Contract HHSP233201400030I, SEA, Ltd. Report to CPSC, In Review.

plots exhibit their first spikes when the roll angle nears  $90^{\circ}$  for the minimum energy runs and between  $100^{\circ}$  to  $150^{\circ}$  for the moderate energy runs. The acceleration plots show that these acceleration spikes occur prior to or within the vertical band indicating the head strike.

For the minimum energy rollovers, the vehicle roll rate plots peak near  $90^{\circ}$  of vehicle roll angle. The minimum energy run roll rates exhibit a marked drop in magnitude as the right side of the vehicle impacts the ground, which also causes the decrease in roll rate. For the moderate energy rollovers, the vehicle roll rate plots peak in the range of  $100^{\circ}$  to  $150^{\circ}$  of vehicle roll angle. These results are also similar to results from the sled rollover tests conducted without an OPD.

The vehicle roll angle plots show the timing of the roll orientations listed on the titles used for the video camera images, as well as the timing and magnitude of the maximum roll angle and the final roll angle at the end of the run.

All the minimum energy sled rollovers conducted on vehicles without OPDs produced rollovers events with maximum roll angles between 90° and 180°; similar results were found for the minimum energy sled tests for all vehicles outfitted with a minimum and with a
Vehicle F had similar maximum and final roll angles in moderate energy sled tests conducted
without an OPD and in tests with both a and a However, moderate energy
sled tests on Vehicles A and E conducted with both a and a resulted in greater
final roll angles than in the moderate energy sled tests conducted on these two vehicles without ar
OPD. The moderate energy sled test on Vehicle G outfitted with a resulted in markedly
greater final roll angle than the sled tests on Vehicle G with no OPD and outfitted with a
Conversely, the moderate energy sled test on Vehicle J outfitted with a resulted in
markedly greater final roll angle than the sled tests on Vehicle J with no OPD and outfitted with a
Discussion of these differences is contained in Section 4 of this report.

## 4. COMPARISON OF ROLLOVER EVENTS OF ATVs WITHOUT AN OPD, OUTFITTED WITH A AND OUTFITTED WITH A

This section contains results comparing ATV and ATD responses during dynamic and sled rollover events of ATVs without an Occupant Protection Device (OPD), outfitted with a and outfitted with a OPD. Vehicles A, C, E, F, G and J are used for the comparisons. Both dynamic rollover tests on groomed dirt and sled rollover tests were conducted using Vehicles A, E and G; and these tests included the three conditions: No OPD, and rollover tests only were conducted using Vehicles C, F and J. Vehicles F and J were tested in three while Vehicle C was only tested in two conditions: conditions: No OPD, and All results from dynamic and sled rollover tests conducted on ATVs and without an OPD are from the previous project conducted in 2018.<sup>19</sup> Vehicle C was not part of the 2018 study. After the dynamic rollover tests were completed, and before the sled rollover tests were conducted, each of the three vehicles was repaired to its original condition by replacing any components (e.g. fenders, racks and lights) that were damaged during the dynamic rollover tests. The same ATD, and the ATD secure and release system, was used for all the rollover tests. The ATD was inspected after each dynamic and sled rollover, and it was repaired to its original condition by replacing any damaged components. Also, the pants and shirt on the ATD were replaced when changing to a different vehicle, or as needed if they became moderately torn or dirty. Both the and retained their structural integrity during all the dynamic and sled rollover tests conducted. However, the following occurred: The shifted laterally on the rear rack (carrier) during some of the rollover events and in some cases the hooks used to retain the brackets to the rack bent. general physical location and orientation on the ATVs was Nevertheless, the not compromised during any of the rollover tests. The was examined after each rollover to confirm its overall integrity, and any bent retaining hooks were replaced prior to the next test. One main base and structural hoop was used for all the dynamic rollover tests, and there was no apparent damage to this main base and structural hoop after the dynamic rollover tests were completed. However, a second main base and structural hoop was used for all the sled rollover tests. During one of the moderate energy dynamic rollovers, the main structure of the experienced minor permanent deformation, and during one of the sled tests the bottom mount plate of the bent. Nevertheless, the general physical location and orientation on the ATVs was not compromised during any of the rollover tests. The was examined after each rollover to confirm its overall integrity, and the bent main structure and bottom mounting plate were replaced prior to the next test. Two were used for all tests. different

<sup>&</sup>lt;sup>19</sup> ATV Rollover Tests and Verification of a Physical Rollover Simulator – Results from Tests on Six 2014-2015 Model Year Vehicles, HHS Contract HHSP233201400030I, SEA, Ltd. Report to CPSC, In Review.

### 4.1 Discussion of Vehicle Responses During Rollover Tests on ATVs with No OPD, Outfitted with a and Outfitted with a

Table 8 contains values for maximum roll rate, maximum roll angle and final roll angle from all minimum energy dynamic and sled rollovers, while Table 9 contains values from the moderate energy tests. In total, results from 52 rollover tests are included in Table 8 (26 minimum energy rollovers) and Table 9 (26 moderate energy rollovers). The 52 tests include 16 rollovers with no OPD, 18 rollovers with a many and 18 rollovers with a

The information on these tables is easier to interpret by looking at graphs of maximum roll rates (Figure 1 for minimum energy and Figure 4 for moderate energy), maximum roll angles (Figure 2 for minimum energy and Figure 5 for moderate energy) and final roll angles (Figure 3 for minimum energy and Figure 6 for moderate energy). On Figures 1-6, values from sled tests are shown with square markers and values from dynamic tests are shown with triangle markers; and the tests with a have black markers.

For all vehicles and all test conditions, the maximum roll rates during the minimum energy rollovers (Figure 1) are less than the maximum roll rates during the moderate energy rollovers (Figure 4). For a given vehicle, the maximum roll rates during the minimum energy rollovers are relatively clustered together regardless of the test condition. For a given vehicle, the maximum roll rates during the moderate energy rollovers have a much wider range of values. The wider range of peak roll rates measured during the moderate energy rollovers is an artifact of how the side of the ATV and/or the OPD engage the test surface as the rollover sequence extends beyond 90° of roll angle.

The maximum roll angles during the minimum energy rollovers (Figure 2) are less than the maximum roll angles during the moderate energy rollovers (Figure 5), for all vehicles and all test conditions. Except for Vehicle A, the maximum roll angles during the minimum energy rollovers are relatively close regardless of the test condition, with all values between 121° and 165°. The maximum roll angle for the minimum energy dynamic test of Vehicle A with no OPD was near 180°, while it was close to 300° for the minimum energy dynamic rollovers with a and with a and and this is an artifact of how the OPDs engaged the test surface as the rollover sequence extended beyond 90° of roll angle. For a given vehicle, the maximum roll angles during the moderate energy rollovers have a much wider range of values. The wider range of peak roll angles measured during the moderate energy rollovers is again dependent on how the side of the ATV and/or the OPD engage the test surface as the rollover sequence extends beyond 90° of roll angle.

Likewise, for all vehicles and all test conditions, the final roll angles during the minimum energy rollovers (Figure 3) are less than the final roll angles during the moderate energy rollovers (Figure 6). Except for dynamic rollover tests on Vehicle A, the final roll angles during the minimum energy rollovers with a and with a are all close to 90°. In these tests with maximum roll angles less than 180°, both OPDs caused the ATV to roll back to a final rest position of close to 90°. For a given vehicle, the final roll angles during the moderate energy rollovers have a much wider range of values, and the trends in the final roll angles generally match the trends in the maximum roll angles; and they too are dependent on how the side of the ATV and/or the OPD engage the test surface as the rollover sequence extends beyond 90°. The final roll angles during the moderate energy tests with a and with a all end either close to 270°, 360°

or 450°. During several of the rollover tests without an OPD, the final roll angle ended near 180°, but the OPDs prevented 180° final roll angle outcomes for all minimum and moderate energy rollovers. The final roll angles for moderate energy rollovers were generally greater for the tests conducted with OPDs than for tests conducted with no OPD. In both dynamic and sled moderate energy rollover tests, some vehicles with OPDs had greater roll angles than the tests conducted without an OPD. Also, in some cases the tests with a produced nominally 90° more final roll angle than tests with a produced about 90° more final roll angle than tests with a

Figures 7-10 are plots from selected dynamic and sled rollover tests presented here to provide insight into the indeterminate nature of the maximum roll rates, maximum roll angles and final roll angles developed during some of the rollover tests with no OPD, with a rollower tests of Wehicle A. Figure 8 (moderate energy rollovers) are from dynamic rollover tests of Vehicle A. Figure 9 (Vehicle A) and Figure 10 (Vehicle E) are from moderate energy sled rollover tests.

rests are closely matched up to slightly above 90° of roll angle, at which point the side of the ATV and/or the OPD engage the test surface as the rollover sequence extends beyond 90°. In the case of Figure 7, in spite of the fact that the peak roll rates are similar in all three tests; the roll rate diminishes after about 2.25 seconds during the No OPD test and the vehicle settles to a final roll angle near 180°, while the tests with and develop enough sustained roll rate between about 2.25 and 4.0 seconds for the vehicle to roll to a final roll angle near 270°. There is enough roll energy in the tests for the ATV outfitted with an OPD to rotate up to 180° whereby it vaults to a final roll angle near 270°. In the No OPD test, energy is absorbed during the interaction of the ATV with the ATD, and the roll angle does not progress beyond 180°.

For the moderate energy dynamic rollovers of Vehicle A (Figure 8), the test resulted in a final roll angle near 450°, the test in a final roll angle of near 360°, and the NO OPD test near 180°. The roll rates and roll angles during these three tests were all similar up to about 180° of roll angle. However, during the tests with OPDs, the roll rates extended to higher levels and were sustained longer as the OPDs facilitated the ATV's roll motion near and beyond 180° of roll angle.

In the moderate energy sled tests of Vehicle A (Figure 9), the test resulted in greater final roll angle (near 360°) than the test (near 270°), and both of these tests had greater final roll angles than the No OPD test (near 180°). Figure 10 shows that in the moderate energy sled tests of Vehicle E, the test and test resulted in similar final roll angles (near 270°) and both tests had greater final roll angles than the No OPD test (near 140°). For the moderate energy sled rollovers of both vehicles, the No OPD rollovers had higher peak roll rates than the tests without an OPD, yet the final roll angles were greater during the tests with OPDs. As mentioned, differences in how the side of vehicle and/or the OPD structure engage the test surface during the rollover sequence is the cause for these variations in roll rate and roll angle outcomes.

### 4.2 Discussion of ATD Responses During Rollover Tests on ATVs with No OPD, Outfitted with a and Outfitted with a

For the dynamic and sled rollover events, the bulk of the ATD (its pelvis, abdomen, thorax and head) generally remained positioned between the seat and rear axle. The ATD essentially remained lateral to the ATV as the ATD released from the vehicle and as the vehicle rolled onto the ATD and, in some cases, over or above it.

The overall motion of the ATD as it detached from the ATV was consistent between the dynamic and sled tests. During all the dynamic and sled rollovers, the ATD detached with a head-leading posture, with the right shoulder and/or head making first contact with the ground. The general position and ground-plane orientation of the ATD relative to the ATV during the full rollover sequences were similar for the dynamic and sled rollover tests.

As described in Appendix E, the ATD used for the rollover tests was equipped with accelerometers in the head and chest to measure head and chest longitudinal acceleration (Ax), lateral acceleration (Ay) and vertical acceleration (Az); and with rate sensors in the head to measure roll rate, pitch rate and yaw rate. Graphical results of these measurements are provided in Appendix A for the dynamic rollover tests and in Appendix B for the sled rollover tests. For all the dynamic and sled rollover events, the maximum peaks in the head accelerations and rates occurred when the ATD head first impacted the ground.

The Head Injury Criterion (HIC) is a metric, based on the resultant magnitudes and durations of ATD head accelerations, developed for assessing potential injury levels in crash events. HIC is often used in studies to assess injury potential during automotive crashes, as well as other scenarios that involve potential head injury such as sports activities, and it is provided in this study of ATV rollovers to assess potential head injury levels.

For each rollover event, HIC values were computed as a measure of head impact severity using time duration ranges of 15 milliseconds and 36 milliseconds. These time duration ranges are commonly used, and they are denoted as HIC<sub>15</sub> and HIC<sub>36</sub>, respectively. The HIC value is the maximum of an integration involving the resultant head accelerations and time duration range, as the calculation is swept across the entire time span of the event (for this study, from five seconds before the trigger to fifteen seconds after the trigger). For all the dynamic and sled tests conducted, the peak HIC values occurred around the time when the ATD's head first struck the ground. The ATD's head in all tests was wearing a DOT approved large HJC model CL-33 open face helmet with a full-face shield.

Figures 11 and 12 are graphs of HIC<sub>15</sub> values and HIC<sub>36</sub> values, respectively, for all the sled and dynamic minimum energy rollover tests. Graphs of the HIC<sub>15</sub> and HIC<sub>36</sub> values for all the moderate energy rollover tests are provided in Figures 13 and 14.

During both the sled and dynamic tests, the HIC values are consistently greater during the moderate energy rollovers than during the minimum energy rollovers. In some instances, the HIC values are greater during dynamic rollovers and in some cases, they are greater during the sled rollovers. The HIC values computed in this study are all from tests conducted with the ATD wearing a helmet. The HIC values would likely be somewhat different if the tests were conducted with the ATD not wearing a helmet.

The HIC<sub>15</sub> values are consistently greater than the HIC<sub>36</sub> values. Having HIC<sub>15</sub> values greater than HIC<sub>36</sub> values means that the ATD head impacts that caused the peaks in the resultant head accelerations were relatively short lived. The National Highway Traffic Safety Administration (NHTSA) standard for performance requirements for the protection of vehicle occupants in frontal crashes (Federal Motor Vehicle Safety Standard 208<sup>20</sup>) specifies that maximum calculated HIC<sub>15</sub> values shall not exceed 700 and that the HIC<sub>36</sub> values shall not exceed 1,000. A review of technical literature indicates that HIC values of 1,000 have over a 50% probability of serious head injury and 90% probability of moderate head injury. In a study involving professional athletes, HIC values of 250 were found to result in concussions.<sup>21</sup>

The HIC<sub>15</sub> values averaged 154 for all the minimum energy rollovers and 231 for all the moderate energy rollovers, while the HIC<sub>36</sub> values averaged 87 for minimum energy rollovers and 144 moderate energy rollovers. The average HIC values are at levels that would suggest that moderate or severe head injuries are not likely to occur during rollover events like those conducted in the study. However, some of the No OPD, and moderate energy rollover tests had HIC<sub>15</sub> values near or above 250, suggesting that concussions could have occurred during these rollover events. As stated before, all tests were conducted with a helmet on the ATD.

As mentioned, the HIC values indicating the time when the resultant head accelerations were the largest all occurred when the ATD's head first struck the ground. Both OPDs evaluated in this study feature structures that extend upward from the vehicle to provide an occupant space when the vehicle overturns. For the lateral rollover tests used in this and previous study without OPDs, adding OPDs to the ATVs did not measurably influence how the ATD releases laterally from the vehicle. Accordingly, the ranges of HIC values measured during tests with a are generally in the range of HIC values measured with No OPD.

### 4.3 Discussion of ATV Interactions with ATD During Rollover Tests on ATVs with No OPD, Outfitted with a and Outfitted with a

Table 9 (for the minimum energy rollovers) and Table 10 (for the moderate energy rollovers) contain brief descriptive summaries of the significant contact events between the ATV and ATD during the dynamic and sled rollovers. Results from 52 rollovers are included in the two tables: 16 No OPD tests, 18 tests and 18 tests. The summary descriptions include comments on ATV to ATD interactions that occurred during the rollover events, as well as comments on the final rest position of the ATV relative to the ATD at the end of each run. In addition to the descriptive summaries, Tables 9 and 10 list the maximum and final roll angles during the rollover events, and show a photograph of the final rest position for each test.

Table 11 (minimum energy rollovers) and Table 12 (moderate energy rollovers) contain yes (X) or no (O) indicators of two items based on the summary descriptions in Tables 9 and 10:

- Item 1 whether or not there was significant ATV interaction with the ATD's pelvis, abdomen, thorax or head during any portion of the rollover event, and
- Item 2 whether or not the ATV came to rest on top of the ATD's pelvis, abdomen, thorax

<sup>21</sup> Viano, D.C., *Head Impact Biomechanics in Sport*, IUTAM Symposium on Impact Biomechanics: From Fundamental Insights to Applications, Solid Mechanics and Its Applications, Vol. 124, pp 121-130, Springer, 2005.

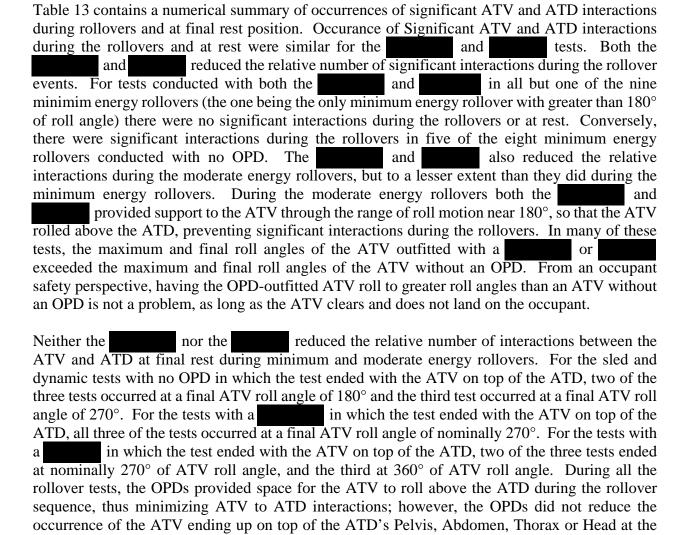
<sup>20</sup> FMVSS 208, Occupant Crash Protection, NHTSA, Federal Register 49 CFR 571.208, 2011. https://www.govinfo.gov/content/pkg/CFR-2011-title49-vol6/pdf/CFR-2011-title49-vol6-sec571-208.pdf

or head at the end of the run,

end of the rollover event.

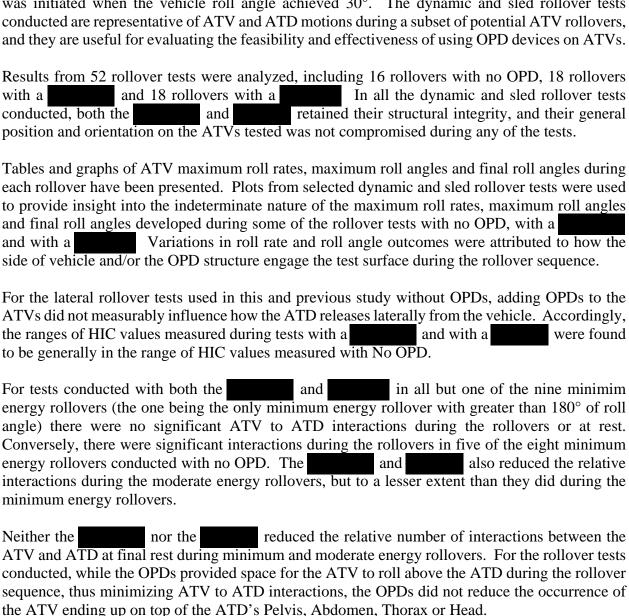
Significant interaction is defined here to be the occurrence of having a significant portion of the ATV – subjectively estimated to be a load of 50% or more of the total weight of the ATV – supported by the pelvis, abdomen, thorax or head at any time (regardless of duration) during the rollover event.

Certainly, ATV impacts to a rider's upper and/or lower limbs could result in severe injuries. However, potentially more serious injuries could occur to impacts with the pelvis, abdomen, thorax or head. Likewise, having an ATV come to rest on top of the pelvis, abdomen, thorax or head likely presents a greater potential for a rider to be pinned by the ATV and unable to free themselves, and in the case of the ATV resting on the thorax could potentially lead to suffocation.



#### 4.4 Summary

This current rollover study of ATV's outfitted with OPDs, and the previous rollover study of ATV's without OPDs, involved conducting actual (dynamic) and simulated (sled) steering-maneuver-induced lateral rollover events. Two levels of maneuver severity were studied: minimum energy and moderate energy. Except for the dynamic tests on Vehicle A, all the minimum energy rollovers conducted resulted in maximum roll angles less than 180° and all the moderate energy rollovers conducted resulted in more than 180° of roll angle. In both studies, the same ATD secure and release system was used, and the release of the ATD's body from the ATV was initiated when the vehicle roll angle achieved 30°. The dynamic and sled rollover tests conducted are representative of ATV and ATD motions during a subset of potential ATV rollovers, and they are useful for evaluating the feasibility and effectiveness of using OPD devices on ATVs.



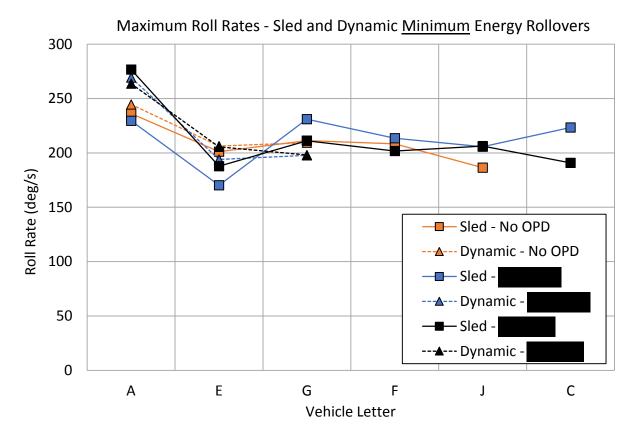
## Table 7: Maximum Roll Rate, Maximum Roll Angle and Final Roll Angle for all <u>Minimum Energy</u> Dynamic and Sled Rollovers

		Dyna	Dynamic Rollovers			Sled Rollovers		
Vehicle Letter	Condition	Max Roll Rate (deg/s)	Max Roll Angle (deg)	Final Roll Angle (deg)	Max Roll Rate (deg/s)	Max Roll Angle (deg)	Final Roll Angle (deg)	
	No OPD	244.6	177.9	174.1	236.2	154.8	144.4	
Α		269.3	298.2	280.9	229.5	137.7	93.2	
		263.7	300.0	277.3	276.6	136.6	92.4	
	No OPD	NA	NA	NA	NA	NA	NA	
С		NA	NA	NA	223.4	157.8	93.7	
		NA	NA	NA	190.9	147.2	94.3	
	No OPD	206.3	148.3	102.5	201.2	157.9	151.9	
Е		194.0	141.3	98.5	170.3	128.8	94.0	
		205.6	158.4	100.9	187.8	128.2	95.9	
	No OPD	NA	NA	NA	208.4	148.5	141.8	
F		NA	NA	NA	213.5	121.1	96.0	
		NA	NA	NA	201.7	123.2	96.8	
	No OPD	209.4	141.8	137.3	211.3	164.5	148.4	
G		197.7	136.6	93.2	231.0	150.9	92.8	
		198.1	140.3	94.1	211.2	161.6	90.6	
	No OPD	NA	NA	NA	186.4	131.9	94.6	
J		NA	NA	NA	205.7	137.8	99.5	
		NA	NA	NA	206.3	136.3	100.7	

## Table 8: Maximum Roll Rate, Maximum Roll Angle and Final Roll Angle for all <u>Moderate Energy</u> Dynamic and Sled Rollovers

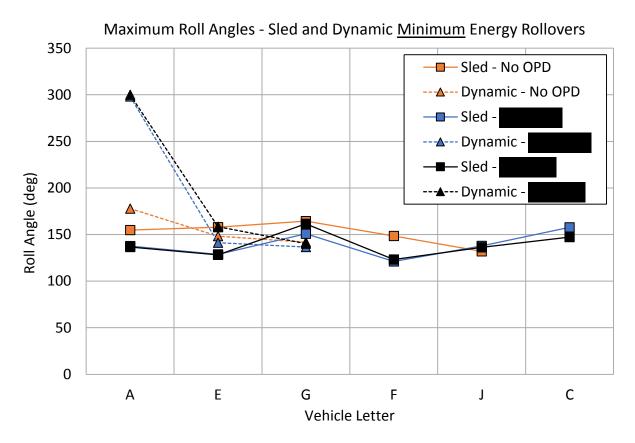
		Dyna	mic Rollo	overs	Sled Rollovers		
Vehicle Letter	Condition	Max Roll Rate (deg/s)	Max Roll Angle (deg)	Final Roll Angle (deg)	Max Roll Rate (deg/s)	Max Roll Angle (deg)	Final Roll Angle (deg)
	No OPD	311.0	217.5	184.9	386.3	283.5	168.2
Α		448.8	539.4	466.7	303.2	295.0	274.0
		368.3	369.9	358.8	356.5	369.4	355.5
	No OPD	NA	NA	NA	NA	NA	NA
С		NA	NA	NA	246.7	301.0	271.7
		NA	NA	NA	234.4	288.0	268.7
	No OPD	327.7	299.3	266.1	344.9	202.3	139.2
Е		349.1	279.3	261.1	268.7	294.8	286.1
		244.5	270.7	255.7	317.0	296.9	277.1
	No OPD	NA	NA	NA	393.9	281.6	253.1
F		NA	NA	NA	267.4	300.3	279.6
		NA	NA	NA	240.7	297.2	273.2
	No OPD	327.7	294.1	273.2	284.9	297.7	277.1
G		350.6	490.0	455.0	264.6	374.3	362.5
		432.4*	489.5	458.3	250.3	302.2	271.5
	No OPD	NA	NA	NA	306.4	274.8	241.0
J		NA	NA	NA	250.5	289.6	265.4
		NA	NA	NA	219.7	372.9	360.8

<sup>\*</sup> This peak occurred later in the rollover sequence than the other peak roll rates listed above, near 360° of roll angle when the ATV interacted with the ATD. The initial peak in roll rate near 150° of roll angle was 319.4 deg/s.



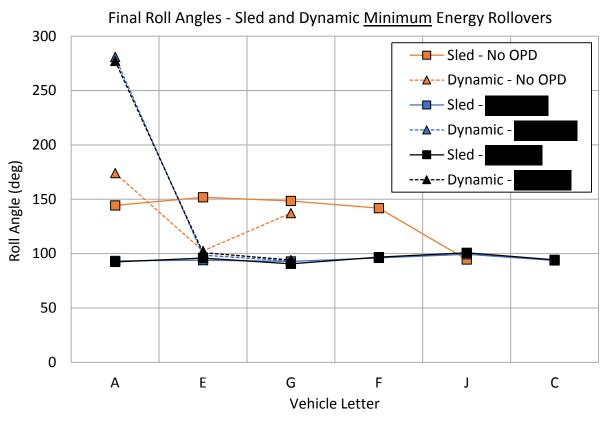
	Maximum Roll Rates (deg/s)							
Vehicle Letter	Dynamic - No OPD	Dynamic -	Dynamic -	Sled - No OPD	Sled -	Sled -		
Α	245	269	264	236	230	277		
E	206	194	206	201	170	188		
G	209	198	198	211	231	211		
F				208	214	202		
J				186	206	206		
С					223	191		

Figure 1: Maximum Roll Rates from Sled and Dynamic Minimum Energy Rollovers



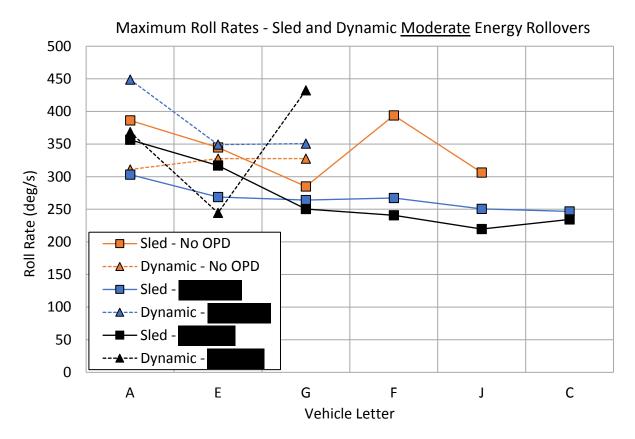
	Maximum Roll Angles (deg)						
Vehicle Letter	Dynamic - No OPD	Dynamic -	Dynamic -	Sled - No OPD	Sled -	Sled -	
Α	178	298	300	155	138	137	
E	148	141	158	158	129	128	
G	142	137	140	165	151	162	
F				149	121	123	
J				132	138	136	
С					158	147	

Figure 2: Maximum Roll Angles from Sled and Dynamic <u>Minimum</u> Energy Rollovers



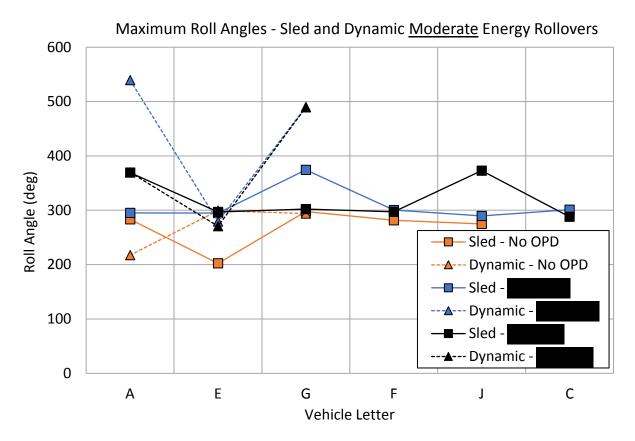
Final Roll Angles (deg)						
Vehicle Letter	Dynamic - No OPD	Dynamic -	Dynamic -	Sled - No OPD	Sled -	Sled -
Α	174	281	277	144	93	92
E	103	99	101	152	94	96
G	137	93	94	148	93	91
F				142	96	97
J				95	100	101
С					94	94

Figure 3: Final Roll Angles from Sled and Dynamic Minimum Energy Rollovers



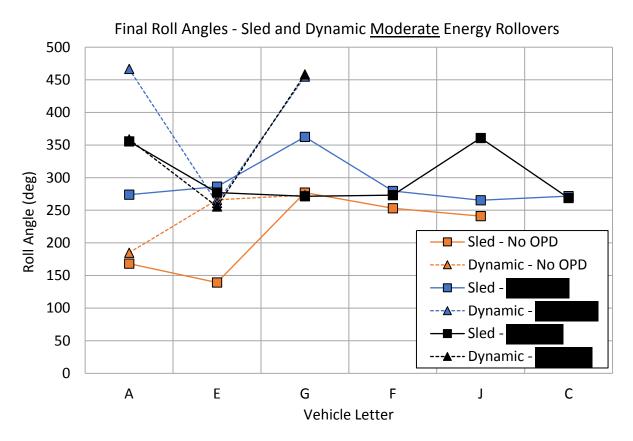
	Maximum Roll Rates (deg/s)						
Vehicle Letter	Dynamic - No OPD	Dynamic -	Dynamic -	Sled - No OPD	Sled -	Sled -	
Α	311	449	368	386	303	357	
E	328	349	245	345	269	317	
G	328	351	432	285	264	250	
F				394	267	241	
J				306	251	220	
С					247	234	

Figure 4: Maximum Roll Rates from Sled and Dynamic <u>Moderate</u> Energy Rollovers



	Maximum Roll Angles (deg)						
Vehicle Letter	Dynamic - No OPD	Dynamic -	Dynamic -	Sled - No OPD	Sled -	Sled -	
Α	218	539	370	284	295	369	
E	299	279	271	202	295	297	
G	294	490	490	298	374	302	
F				282	300	297	
J				275	290	373	
С					301	288	

Figure 5: Maximum Roll Angles from Sled and Dynamic Moderate Energy Rollovers



	Final Roll Angles (deg)						
Vehicle Letter	Dynamic - No OPD	Dynamic -	Dynamic -	Sled - No OPD	Sled -	Sled -	
Α	185	467	359	168	274	356	
E	266	261	256	139	286	277	
G	273	455	458	277	363	272	
F				253	280	273	
J				241	265	361	
С					272	269	

Figure 6: Final Roll Angles from Sled and Dynamic <u>Moderate</u> Energy Rollovers

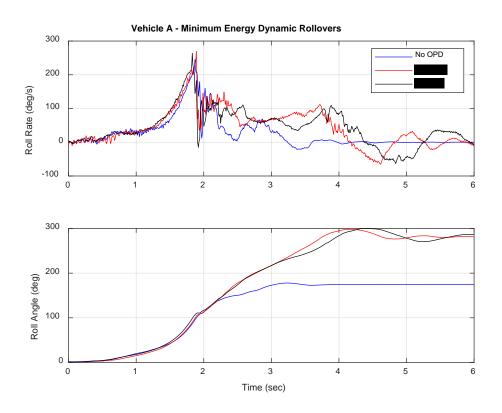


Figure 7: Roll Rate and Roll Angle Minimum Energy Dynamic Rollovers – Vehicle A

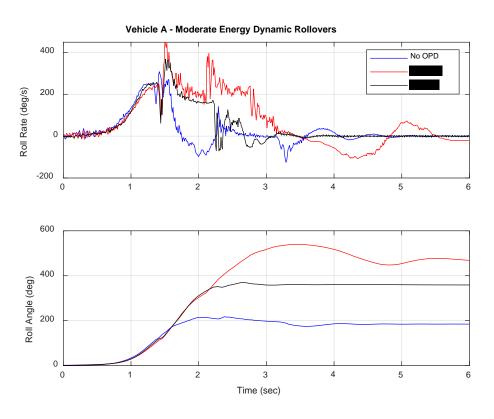


Figure 8: Roll Rate and Roll Angle Moderate Energy Dynamic Rollovers – Vehicle A

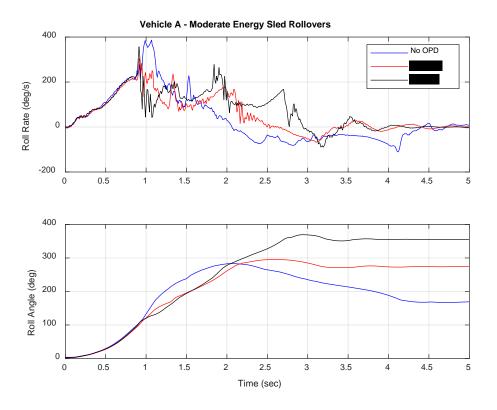


Figure 9: Roll Rate and Roll Angle Moderate Energy Sled Rollovers – Vehicle A

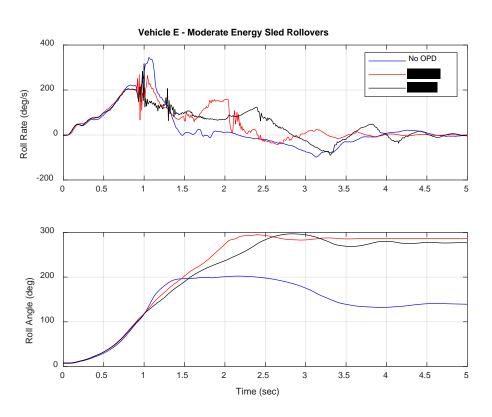


Figure 10: Roll Rate and Roll Angle Moderate Energy Sled Rollovers – Vehicle E

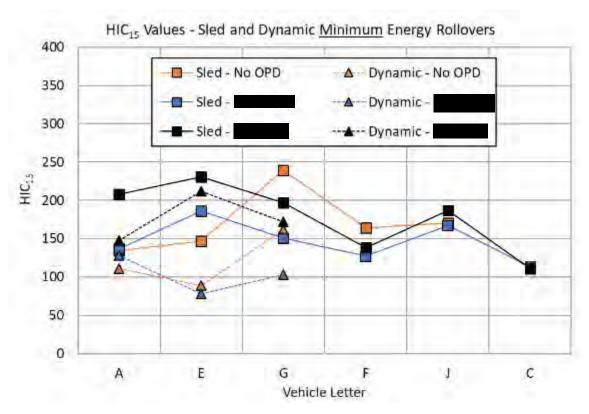


Figure 11: HIC<sub>15</sub> Values from Sled and Dynamic Minimum Energy Rollovers

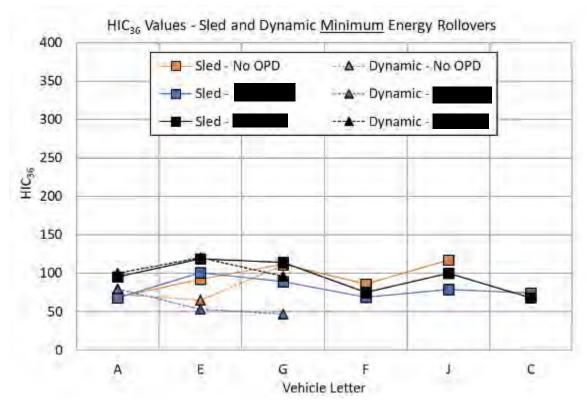


Figure 12: HIC<sub>36</sub> Values from Sled and Dynamic Minimum Energy Rollovers

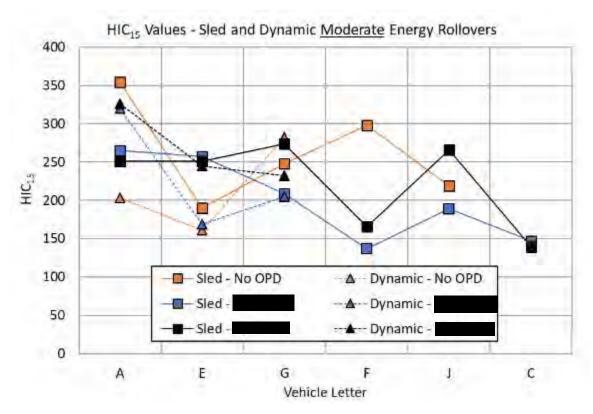


Figure 13: HIC<sub>15</sub> Values from Sled and Dynamic Moderate Energy Rollovers

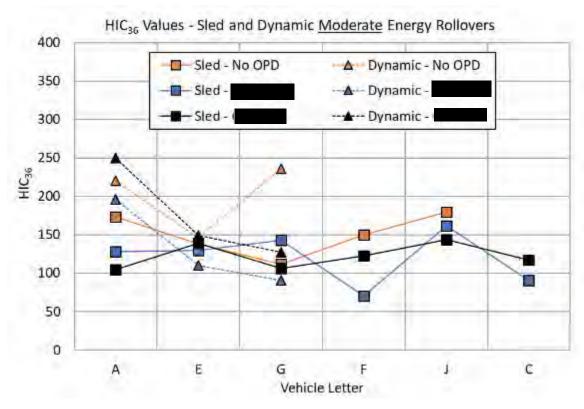


Figure 14: HIC<sub>36</sub> Values from Sled and Dynamic Moderate Energy Rollovers

### Table 9: Vehicle A Dynamic and Sled <u>Minimum</u> Energy Rollovers – Description of Significant ATV and ATD Interactions and Rest Position Photographs

Vehicle A	Dyr	namic Rollovers	Sled Rollovers		
No OPD	Max Roll 178° – Final Roll 174°  The ATV rolled onto the ATD near its maximum roll angle and came to rest on the ATD's back and head (helmet).		Max Roll 155° – Final Roll 144°  The ATV's seat rolled up onto the ATD's pelvis near its maximum roll angle, and the ATV's seat came to rest on top of the ATD's right knee.		
	Max Roll 298° – Final Roll 281°  The ATV's left rear fender and rack landed on the ATD's head near 225° of roll angle and came to rest on the ATD's head.		Max Roll 138° – Final Roll 93°  The prevented the ATV from having any significant contact with the ATD.		
	Max Roll 300° – Final Roll 277°  The ATV's left rear fender and rack landed on the ATD's head near 225° of roll angle and came to rest on the ATD's head.		Max Roll 137° – Final Roll 92°  The prevented the ATV from having any significant contact with the ATD.		

### Table 9 (Continued): Vehicle E Dynamic and Sled <u>Minimum</u> Energy Rollovers – Description of Significant ATV and ATD Interactions and Rest Position Photographs

Vehicle						
E	Dyı	namic Rollovers	S	Sled Rollovers		
No OPD	Max Roll 148° – Final Roll 103°  The ATV's seat rolled up onto the ATD's pelvis near its maximum roll angle, and then rolled off the ATD at its final rest position.		Max Roll 158° – Final Roll 152°  The ATV's seat rolled up onto the ATD's pelvis near its maximum roll angle, and the ATD's right lower leg remained pinned under the seat in its final rest position.			
	Max Roll 141° – Final Roll 99°  The prevented the ATV from having any significant contact with the ATD.		Max Roll 129° – Final Roll 94°  The prevented the ATV from having any significant contact with the ATD.			
	Max Roll 158° – Final Roll 101°  The prevented the ATV from having any significant contact with the ATD.		Max Roll 128° – Final Roll 96°  The prevented the ATV from having any significant contact with the ATD.			

	Table 9 (Continued): Vehicle G Dynamic and Sled Minimum Energy Rollovers – Description of Significant ATV and ATD Interactions and Rest Position Photographs						
Vehicle <b>G</b>	Dynami	ic Rollovers	S	led Rollovers			
No OPD	Max Roll 142° – Final Roll 137°  The ATV rolled onto only the ATD's right lower leg and came to rest on the right lower leg.		Max Roll 165° – Final Roll 148°  The ATV rolled completely onto the ATD near its maximum roll angle. The ATV rolled off the ATD and came to rest on the ATD's right leg.				
	Max Roll 137° – Final Roll 93°  The prevented the ATV from having any significant contact with the ATD.		Max Roll 151° – Final Roll 93°  The prevented the ATV from having any significant contact with the ATD.				
	Max Roll 140° – Final Roll 94°  The prevented the ATV from having any significant contact with the ATD.		Max Roll 162° – Final Roll 91°  The prevented the ATV from having any significant contact with the ATD.				

### Table 9 (Continued): Vehicle F Sled <u>Minimum</u> Energy Rollovers – Description of Significant ATV and ATD Interactions and Rest Position Photographs

	Description of Significant ATV and ATD interactions and Rest Position Photographs					
Vehicle F	Dyn	amic Rollovers	Sled	d Rollovers		
No OPD	NA	NA	Max Roll 149° – Final Roll 142°  The ATV seat rolled up against the ATD's buttocks near its maximum roll angle. The ATD's right lower leg was pinned beneath the ATV seat at rest.			
	NA	NA	Max Roll 121° – Final Roll 96°  The prevented the ATV from having any significant contact with the ATD.			
	NA	NA	Max Roll 123° – Final Roll 97°  The prevented the ATV from having any significant contact with the ATD.			

### Table 9 (Continued): Vehicle J Sled <u>Minimum</u> Energy Rollovers – Description of Significant ATV and ATD Interactions and Rest Position Photographs

	2000p	1 of organicant ATV and ATD line	idoliono ana reocti ocilioi	. i notograpno	
Vehicle J	Dyr	amic Rollovers	Sled Rollovers		
No OPD	NA	NA	Max Roll 132° – Final Roll 95°  The ATV seat rolled up close to ATD's buttocks near its maximum roll angle. There was minimum contact between the ATV and ATD once the ATD released from the ATV. No part of the ATD was pinned beneath the ATV at rest.		
	NA	NA	Max Roll 138° – Final Roll 100°  The prevented the ATV from having any significant contact with the ATD.		
	NA	NA	Max Roll 136° – Final Roll 101°  The prevented the ATV from having any significant contact with the ATD.		

#### Table 9 (Continued): Vehicle C Sled Minimum Energy Rollovers -Description of Significant ATV and ATD Interactions and Rest Position Photographs Vehicle **Sled Rollovers Dynamic Rollovers** C No OPD NA NA NA NA Max Roll 158° – Final Roll 94° prevented the NA NA ATV from having any significant contact with the ATD. Max Roll 147° – Final Roll 94° NA NA prevented the ATV from having any significant contact with the ATD.

### Table 10: Vehicle A Dynamic and Sled <u>Moderate</u> Energy Rollovers – Description of Significant ATV and ATD Interactions and Rest Position Photographs

Vehicle A	Dyr	namic Rollovers	Sled Rollovers	
No OPD	Max Roll 218° – Final Roll 185°  Near 180°, the steering motor guard gouged into the dirt causing the rear of the ATV to pitch up. The ATV landed on the ATD near the end of the run, and at the end of the run the ATD's pelvis was pinned under the ATV.		Max Roll 284° – Final Roll 168°  The left side of the ATV rolled completely onto ATD as it went from 180° to 284°, and then rolled off the ATD at its final rest position.	
	Max Roll 539° – Final Roll 467°  The ATV landed on the ATD's pelvis, abdomen, thorax and head near 360° and then rolled off the ATD at its final rest position.		Max Roll 295° – Final Roll 274°  The caused the ATV to roll above the ATD until the left side of the ATV landed on the ATD's left leg near 270°. At the final position, the was resting on the ATD's left arm.	
	Max Roll 370° – Final Roll 359°  The ATV landed on the ATD's pelvis, abdomen and thorax near 360° and came to rest on the ATD.		Max Roll 369° – Final Roll 356°  The caused the ATV to roll above the ATD until the left side of the ATV landed on the ATD's left arm near 270°. The ATV continued to roll completely off the ATD to its rest position.	

#### Table 10 (Continued): Vehicle E Dynamic and Sled <u>Moderate</u> Energy Rollovers – Description of Significant ATV and ATD Interactions and Rest Position Photographs

Vehicle E	Dynamic Rollovers	3	Sled Rollovers	
No OPD	Max Roll 299° – Final Roll 266°  The ATV landed on the ATD's lower legs and left hand near 270° of roll angle. The ATV came to rest on the ATD's left hand and right foot.		Max Roll 202° – Final Roll 139°  The ATV rolled completely onto ATD near its maximum roll angle. The ATV's rear rack came to rest on the ATD's right foot.	
	Max Roll 279° – Final Roll 261°  The ATV's left rear wheel landed on the ATD's abdomen, thorax and head near 270° and came to rest with its left front wheel on the ATD's pelvis.		Max Roll 295° – Final Roll 286°  The caused the ATV to roll above the ATD until the left side base of the and left side of the rear rack of the ATV landed on the ATD's head near 270° and came to rest on the ATD's head at final rest position.	
	Max Roll 271° – Final Roll 256°  The left side of the ATV landed on the ATD's pelvis, abdomen, thorax and head near 270° and came to rest on the on the ATD's pelvis and abdomen.		Max Roll 297° – Final Roll 277°  The caused the ATV to roll above the ATD until the left side of the ATV landed on the ATD's left leg near 270° and came to rest on ATD's left leg.	

### Table 10 (Continued): Vehicle G Dynamic and Sled <u>Moderate</u> Energy Rollovers – Description of Significant ATV and ATD Interactions and Rest Position Photographs

Vehicle G	Dyr	namic Rollovers	S	led Rollovers
No OPD	Max Roll 294° – Final Roll 273°  Near 180°, the steering motor guard gouged into the dirt causing the rear of the ATV to pitch up. Between 270° and maximum roll angle, the ATV landed on the ATD's right leg. The ATV came to rest on the ATD's right arm.		Max Roll 298° – Final Roll 277°  The ATV rolled completely onto ATD's body and head at a little past 180° of roll angle. The ATV then rolled mostly off, and back onto, the ATD before coming to rest with its left side resting on the ATD's left leg and left arm.	
	Max Roll 490° – Final Roll 455°  Contact between the and ground during the rollover sequence caused the ATV to vault over the ATD and there were no significant interactions between the ATV and ATD.		Max Roll 374° – Final Roll 363°  The caused the ATV to roll above the ATD until the left side base of the and left side of the rear rack of the ATV landed on the ATD's head near 270°. After this contact, the ATV rolled clear of the ATD.	
	Max Roll 490° – Final Roll 458°  The ATV's left rear tire landed on the ATD's thorax and head near 360° and then continued to roll off the ATD at its rest position.		Max Roll 302° – Final Roll 272°  The caused the ATV to roll above the ATD throughout the entire rollover sequence and the ATV landed clear of the ATD at its rest position	

### Table 10 (Continued): Vehicle F Sled <u>Moderate</u> Energy Rollovers – Description of Significant ATV and ATD Interactions and Rest Position Photographs

	Description of Significant ATV and ATD interactions and Rest Position Photographs						
Vehicle F	Dyr	namic Rollovers	Sled Rollovers				
No OPD	NA	NA	Max Roll 282° – Final Roll 253°  The ATV landed on the ATD's right leg near 180° and continued to roll onto the ATD's pelvis and chest near its maximum roll angle. The rear of the ATV came to rest on top of the ATD's pelvis and chest.				
	NA	NA	Max Roll 300° – Final Roll 280°  The left side of the landed on the ATD's left arm and the left side of the ATV landed on the ATD's left leg near 270°. The ATV come to rest clear of the ATD.	1			
	NA	NA	Max Roll 297° – Final Roll 273°  The caused the ATV to roll above the ATD throughout the entire rollover sequence. The engaged the ATD's leg arm near 180°. At rest, the ATV landed clear of the ATD.				

### Table 10 (Continued): Vehicle J Sled <u>Moderate</u> Energy Rollovers – Description of Significant ATV and ATD Interactions and Rest Position Photographs

	Description of Significant ATV and ATD interactions and Rest Position Photographs						
Vehicle J	Dyr	namic Rollovers	Sled Rollovers				
No OPD	NA	NA	Max Roll 275° – Final Roll 241°  The ATV landed on the ATD's pelvis and chest near 270° of roll angle. The rear of the ATV came to rest leaning on ATD's pelvis.	*			
	NA	NA	Max Roll 290° – Final Roll 265°  The caused the ATV to roll above the ATD throughout the entire rollover sequence. The engaged the ATD's helmet near 225°. At rest, the ATV landed clear of the ATD.				
	NA	NA	Max Roll 373° – Final Roll 361°  The caused the ATV to roll above the ATD throughout the entire rollover sequence and the ATV landed clear of the ATD at its rest position				

#### Table 10 (Continued): Vehicle C Sled Moderate Energy Rollovers -Description of Significant ATV and ATD Interactions and Rest Position Photographs Vehicle **Dynamic Rollovers Sled Rollovers** C No OPD NA NA NA NA Max Roll 301° - Final Roll 272° caused the ATV to roll above the ATD until the left side of the ATV landed on NA NA the ATD's left arm near 270°. brushed the ATD's helmet as the ATV rolled back to its final rest position, off the ATD. Max Roll 288° - Final Roll 269° caused the ATV to NA NA roll above the ATD throughout the entire rollover sequence and the ATV landed clear of the ATD at its rest position

# Table 11: Summary of Significant ATV and ATD Interactions During Minimum Energy Rollovers and at Final Rest Position

Vehicle Letter	Rollover Type		No OPD		
A	Dynamic -	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	х	х	Х
		ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	х	х	х
	Sled	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	х	0	0
		ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	0	0	0
	Dynamic	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	х	0	0
_		ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	0	0	0
E	Sled -	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	х	0	0
		ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	0	0	0
G	Dynamic -	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	О	0	0
		ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	0	0	0
	Sled	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	х	0	0
		ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	0	0	0
_	Sled	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	0	0	0
F		ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	0	0	0
	Sled	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	0	0	0
J		ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	0	0	0
	Sled	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	NA	0	0
С		ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	NA	0	0

# Table 12: Significant ATV and ATD Interactions During Moderate Energy Rollovers and at Final Rest Position

Vehicle Letter	Rollover Type		No OPD		
A	Dynamic -	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	х	х	х
		ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	х	0	х
	Sled	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	х	0	0
		ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	0	0	0
E	Dynamic	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	0	х	х
		ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	0	х	х
	Sled	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	х	х	0
		ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	0	х	0
G	Dynamic -	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	0	0	х
		ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	0	0	0
	Sled	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	х	х	0
		ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	0	0	0
_	Sled	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	х	0	0
F		ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	х	0	О
J	Sled	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	Х	0	0
		ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	0	0	0
С	Sled	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	NA	0	0
		ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	NA	0	О

# Table 13: Summary of Significant ATV and ATD Interactions During Rollovers and at Final Rest Position

		No OPD		
Minimum Energy Dynamic and Sled	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	5/8	1/9	1/9
Rollovers	ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	1/8	1/9	1/9
Moderate Energy	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	6/8	4/9	3/9
Dynamic and Sled Rollovers	ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	2/8	2/9	2/9
All	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	11/16	5/18	4/18
Dynamic and Sled Rollovers	ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	3/16	3/18	3/18

#### Roll Angle = $30^{\circ}$ - Time = 1.35 sec



Vehicle A - Dynamic Minimum Energy Rollover -

#### Roll Angle = $45^{\circ}$ - Time = 1.54 sec



Vehicle A - Dynamic Minimum Energy Rollover -

#### Roll Angle = $90^{\circ}$ - Time = 1.83 sec



Vehicle A - Dynamic Minimum Energy Rollover -

#### ATD Head Strike - Time = 1.91 sec



Vehicle A - Dynamic Minimum Energy Rollover -

#### Roll Angle = $180^{\circ}$ - Time = 2.53 sec



Vehicle A - Dynamic Minimum Energy Rollover -

#### Roll Angle = $270^{\circ}$ - Time = 3.65 sec



Vehicle A - Dynamic Minimum Energy Rollover -

#### Max Roll Angle = $298.2^{\circ}$ - Time = 4.17 sec



Vehicle A - Dynamic Minimum Energy Rollover -

#### End of Run - Roll Angle = 280.9°



Vehicle A - Dynamic Minimum Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 1.35 sec

Drone Camera - Roll Angle = 45° - Time = 1.54 sec



Drone Camera - Roll Angle = 90° - Time = 1.83 sec



Drone Camera - ATD Head Strike - Time = 1.91 sec



Drone Camera - Roll Angle = 180° - Time = 2.53 sec



Drone Camera - Roll Angle =  $270^{\circ}$  - Time = 3.65 sec



Vehicle A - Dynamic Minimum Energy Rollover -

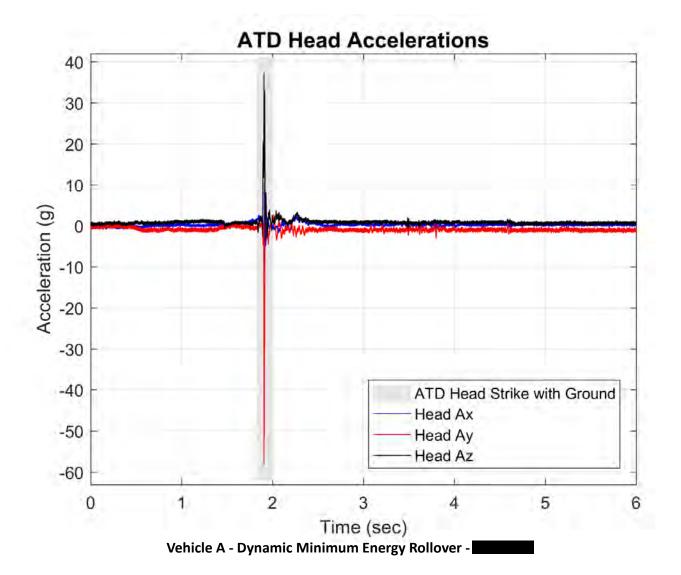
Drone Camera - Max Angle = 298.2° - Time = 4.17 sec

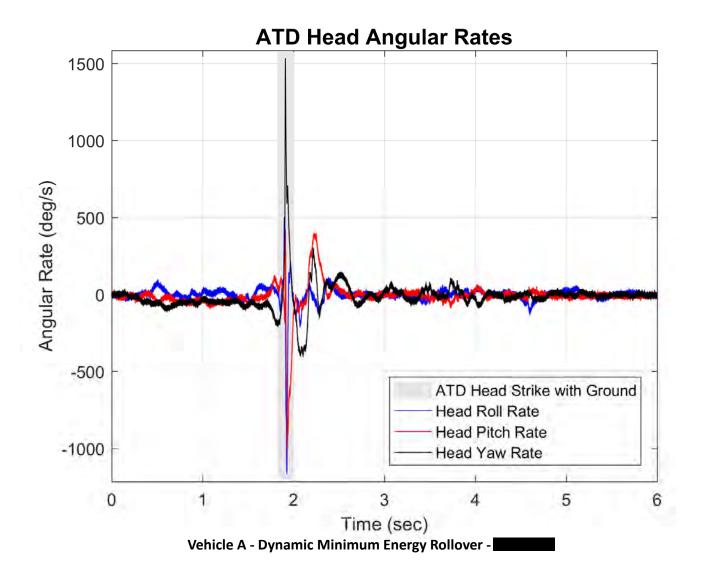


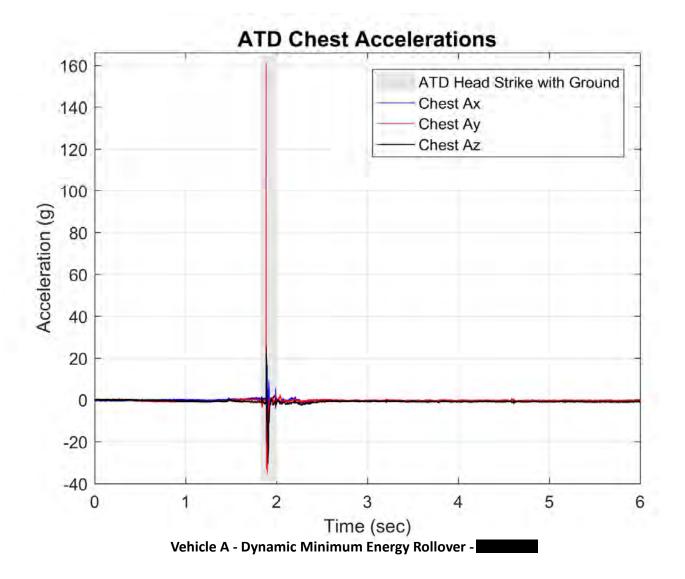
Drone Camera - End of Run - Roll Angle = 280.9°

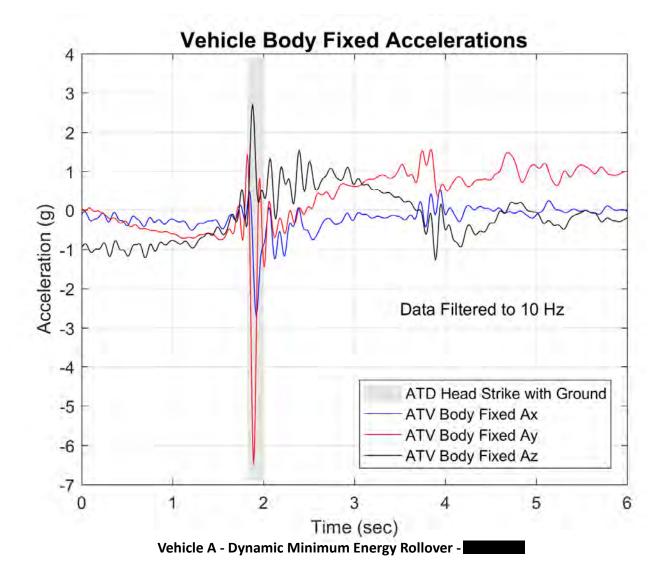


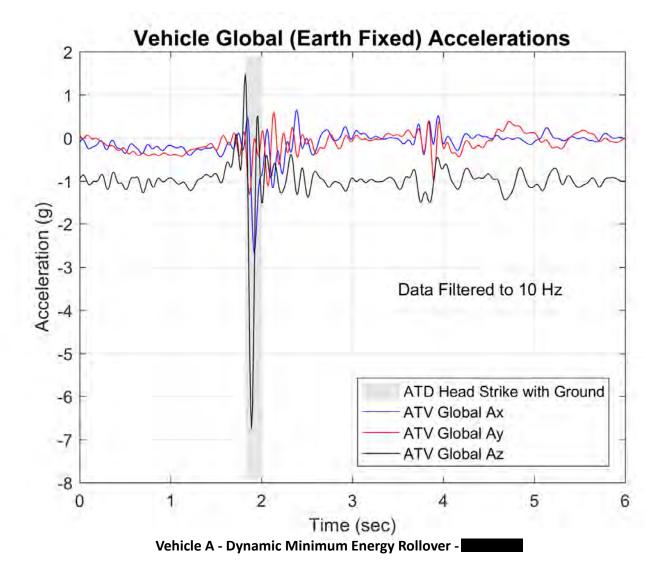
Vehicle A - Dynamic Minimum Energy Rollover -

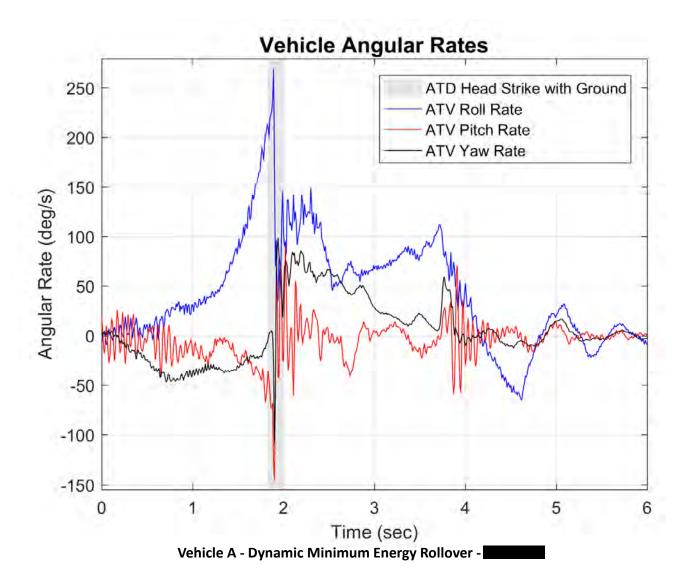


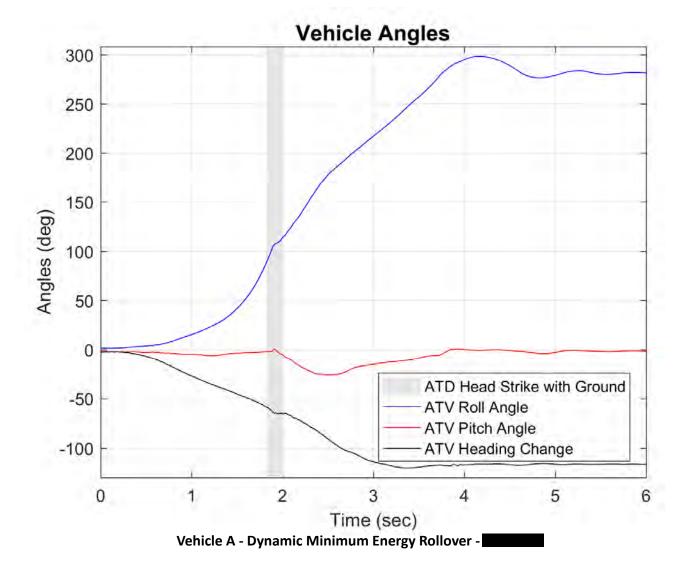












### Roll Angle = $30^{\circ}$ - Time = 1.29 sec



Vehicle A - Dynamic Minimum Energy Rollover -

## Roll Angle = $45^{\circ}$ - Time = 1.49 sec



Vehicle A - Dynamic Minimum Energy Rollover -

### Roll Angle = $90^{\circ}$ - Time = 1.8 sec



Vehicle A - Dynamic Minimum Energy Rollover -

#### ATD Head Strike - Time = 1.93 sec



Vehicle A - Dynamic Minimum Energy Rollover -

# Roll Angle = $180^{\circ}$ - Time = 2.55 sec



Vehicle A - Dynamic Minimum Energy Rollover -

### Roll Angle = $270^{\circ}$ - Time = 3.86 sec



Vehicle A - Dynamic Minimum Energy Rollover -

### Max Roll Angle = $300.0^{\circ}$ - Time = 4.37 sec



Vehicle A - Dynamic Minimum Energy Rollover -

### End of Run - Roll Angle = 277.3°



Vehicle A - Dynamic Minimum Energy Rollover -



CPSC ATV Rollovers - Results from Dynamic Rollovers with OPDs

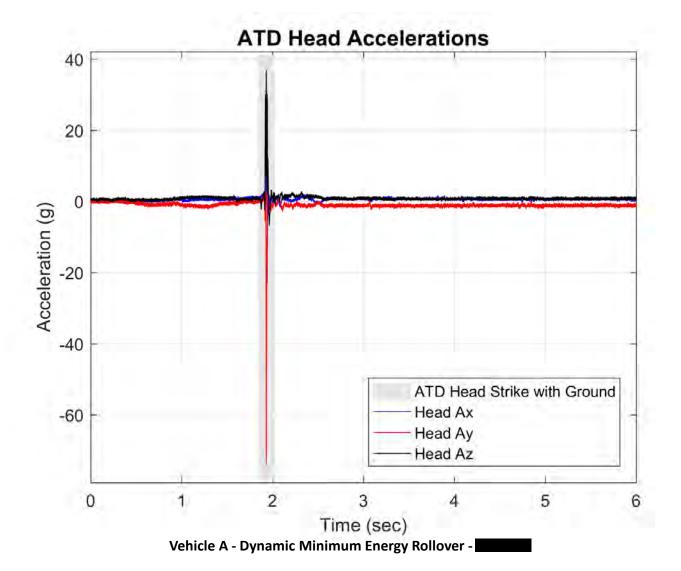
Drone Camera - Max Angle = 300.0° - Time = 4.37 sec

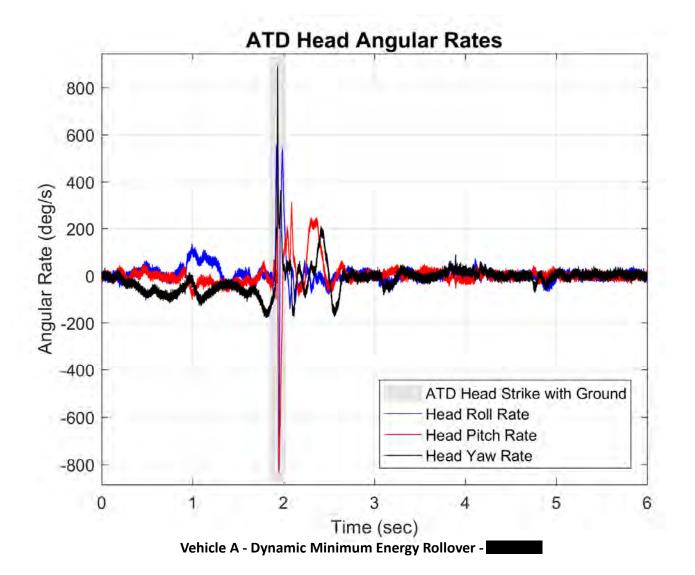
Drone Camera - End of Run - Roll Angle = 277.3°

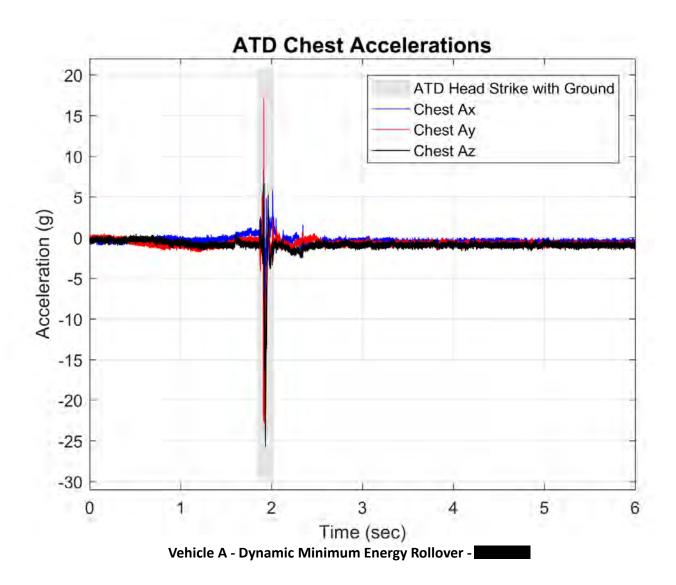


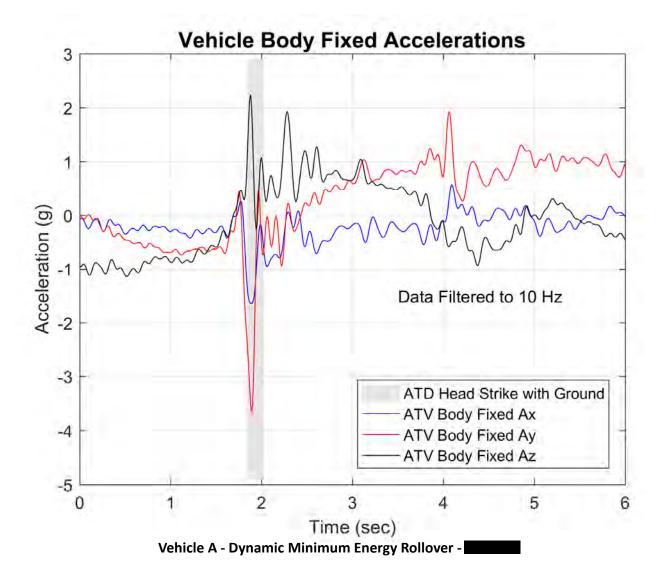


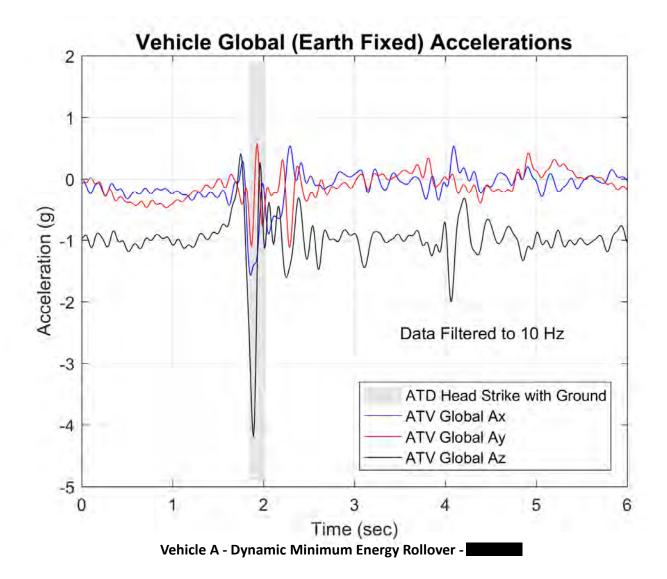
Vehicle A - Dynamic Minimum Energy Rollover -

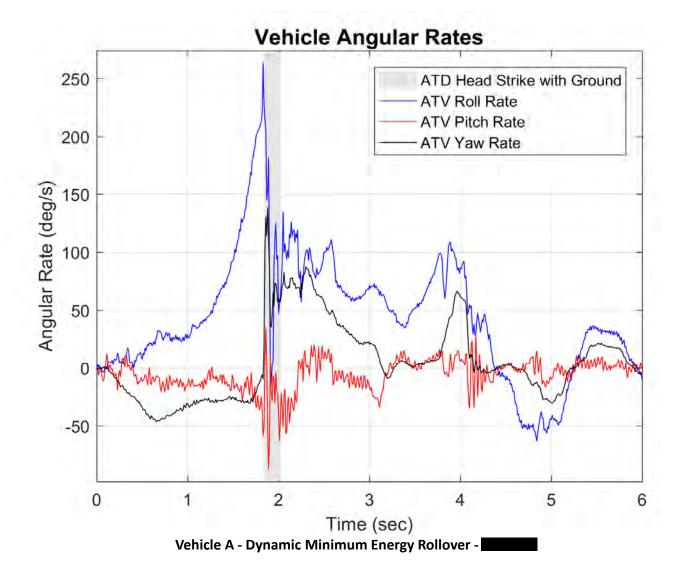


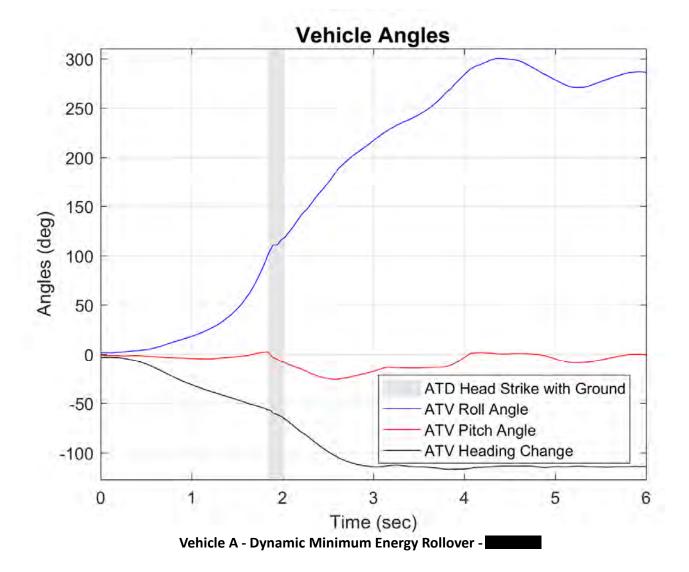












### Roll Angle = $30^{\circ}$ - Time = 1.1 sec



Vehicle A - Dynamic Moderate Energy Rollover -

### Roll Angle = $45^{\circ}$ - Time = 1.2 sec



Vehicle A - Dynamic Moderate Energy Rollover -

## Roll Angle = $90^{\circ}$ - Time = 1.41 sec



Vehicle A - Dynamic Moderate Energy Rollover -

#### ATD Head Strike - Time = 1.56 sec



Vehicle A - Dynamic Moderate Energy Rollover -

### Roll Angle = $180^{\circ}$ - Time = 1.72 sec



Vehicle A - Dynamic Moderate Energy Rollover -

### Roll Angle = $270^{\circ}$ - Time = 1.96 sec



Vehicle A - Dynamic Moderate Energy Rollover -

### Roll Angle = $360^{\circ}$ - Time = 2.31 sec



Vehicle A - Dynamic Moderate Energy Rollover -

# Roll Angle = $450^{\circ}$ - Time = 2.66 sec



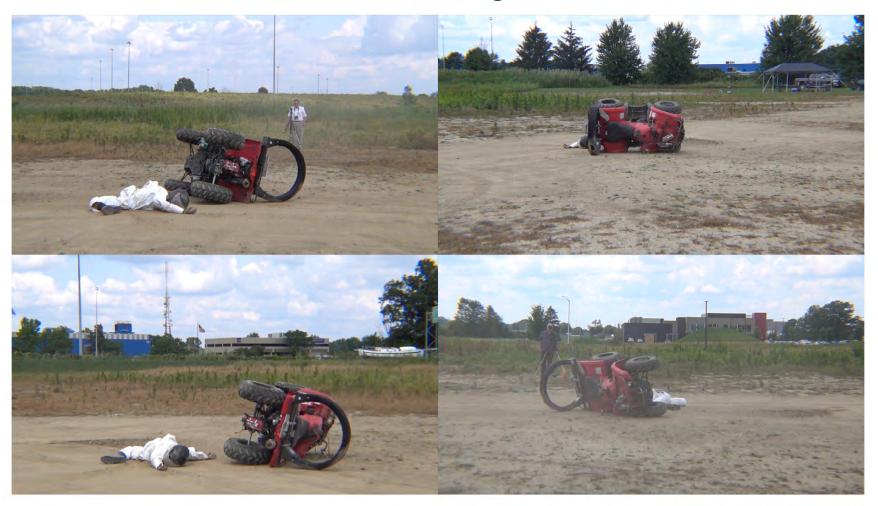
Vehicle A - Dynamic Moderate Energy Rollover -

### Max Roll Angle = $539.4^{\circ}$ - Time = 3.54 sec



Vehicle A - Dynamic Moderate Energy Rollover -

### End of Run - Roll Angle = 466.7°



Vehicle A - Dynamic Moderate Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 1.1 sec



Drone Camera - Roll Angle = 45° - Time = 1.2 sec



Drone Camera - Roll Angle = 90° - Time = 1.41 sec



Drone Camera - ATD Head Strike - Time = 1.56 sec



Drone Camera - Roll Angle = 180° - Time = 1.72 sec



Drone Camera - Roll Angle = 270° - Time = 1.96 sec



Vehicle A - Dynamic Moderate Energy Rollover -

Drone Camera - Roll Angle = 360° - Time = 2.31 sec



Drone Camera - Roll Angle = 450° - Time = 2.66 sec



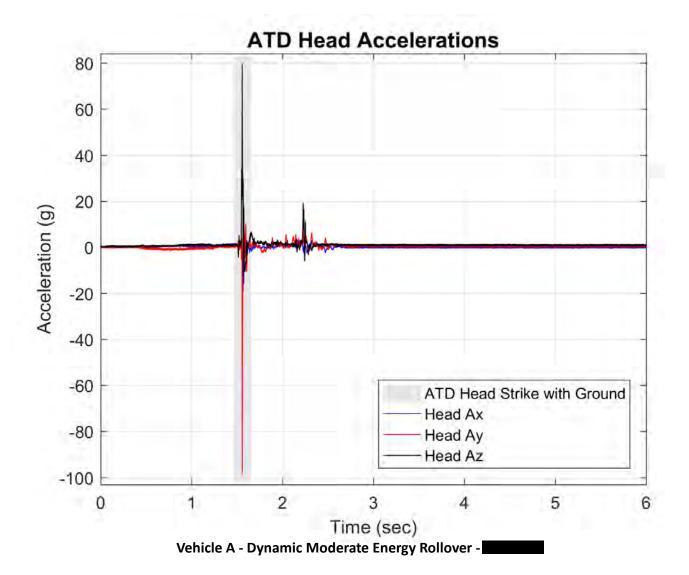
Drone Camera - Max Angle = 539.4° - Time = 3.54 sec

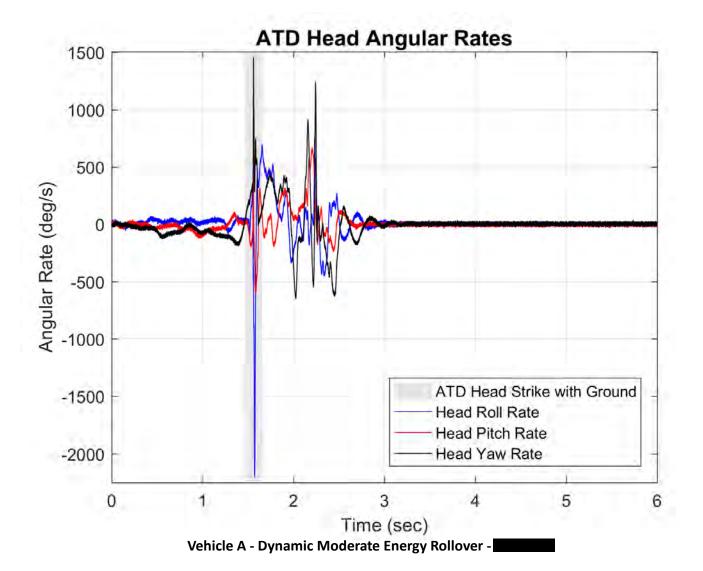


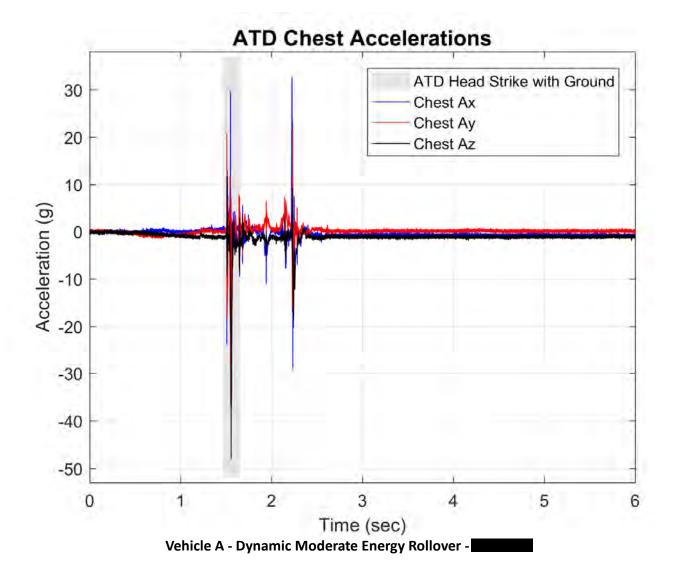
Drone Camera - End of Run - Roll Angle = 466.7°

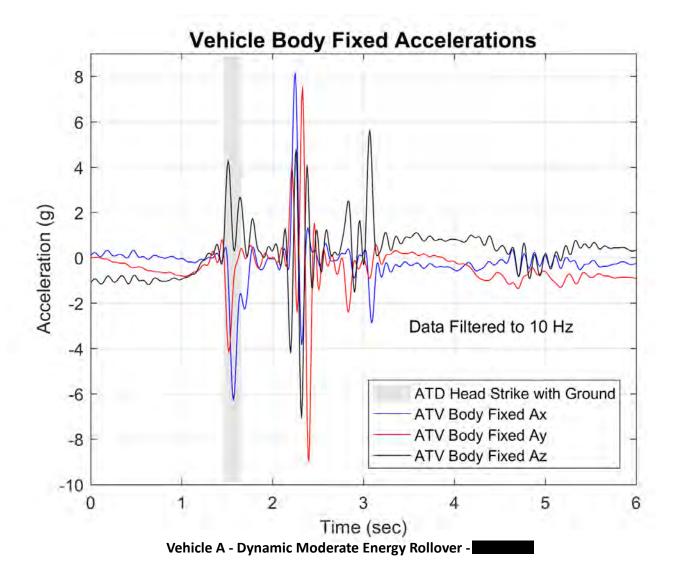


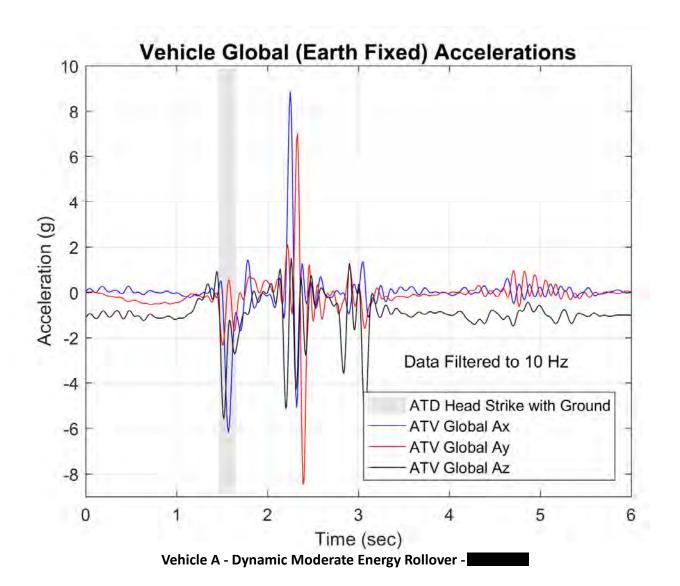
Vehicle A - Dynamic Moderate Energy Rollover -

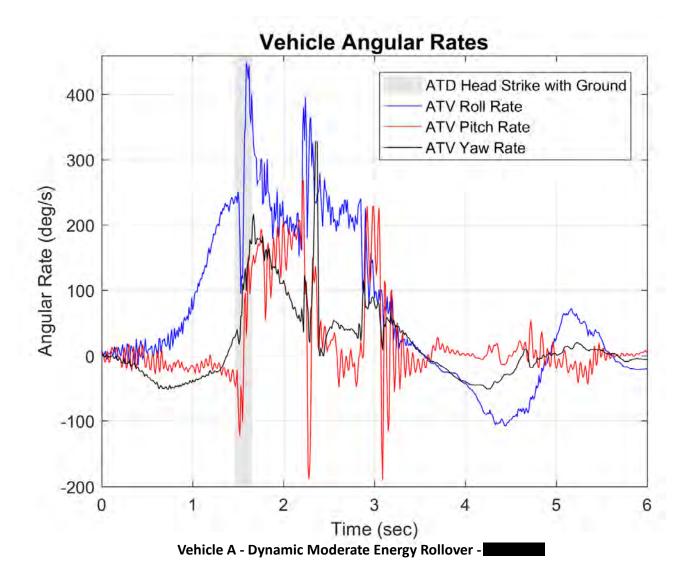


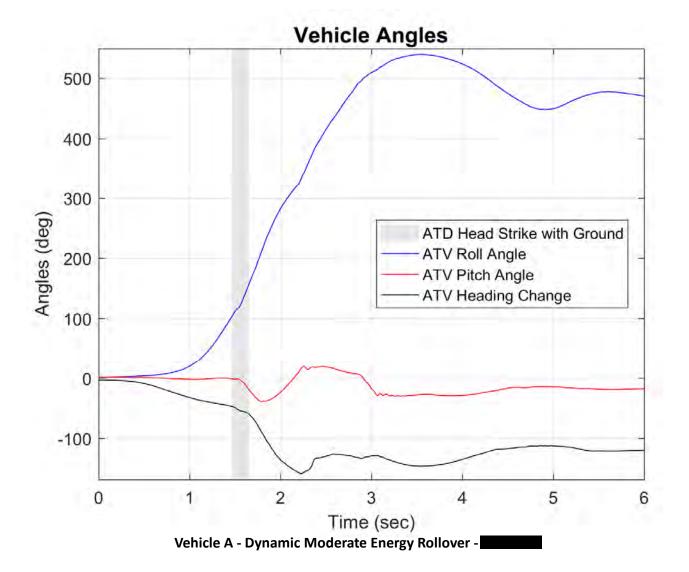












# Roll Angle = $30^{\circ}$ - Time = 1.01 sec



Vehicle A - Dynamic Moderate Energy Rollover -

#### Roll Angle = $45^{\circ}$ - Time = 1.1 sec



Vehicle A - Dynamic Moderate Energy Rollover -

## Roll Angle = $90^{\circ}$ - Time = 1.3 sec



Vehicle A - Dynamic Moderate Energy Rollover -

#### ATD Head Strike - Time = 1.48 sec



Vehicle A - Dynamic Moderate Energy Rollover -

## Roll Angle = $180^{\circ}$ - Time = 1.63 sec



Vehicle A - Dynamic Moderate Energy Rollover -

## Roll Angle = $270^{\circ}$ - Time = 1.86 sec



Vehicle A - Dynamic Moderate Energy Rollover -

## Roll Angle = $360^{\circ}$ - Time = 2.49 sec



Vehicle A - Dynamic Moderate Energy Rollover -

## Max Roll Angle = $369.9^{\circ}$ - Time = 2.66 sec



Vehicle A - Dynamic Moderate Energy Rollover -

## End of Run - Roll Angle = 358.8°



Vehicle A - Dynamic Moderate Energy Rollover -



Vehicle A - Dynamic Moderate Energy Rollover -

Drone Camera - Roll Angle = 360° - Time = 2.49 sec

Drone Camera - Max Angle = 369.9° - Time = 2.66 sec

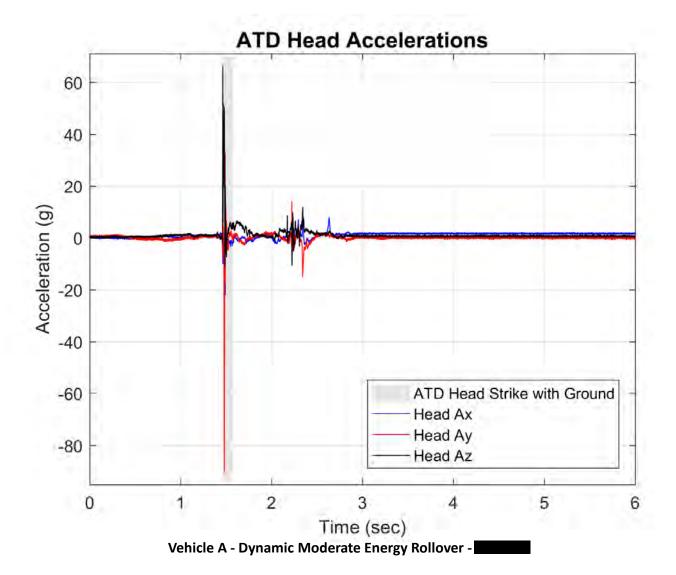
Drone Camera - End of Run - Roll Angle = 358.8°

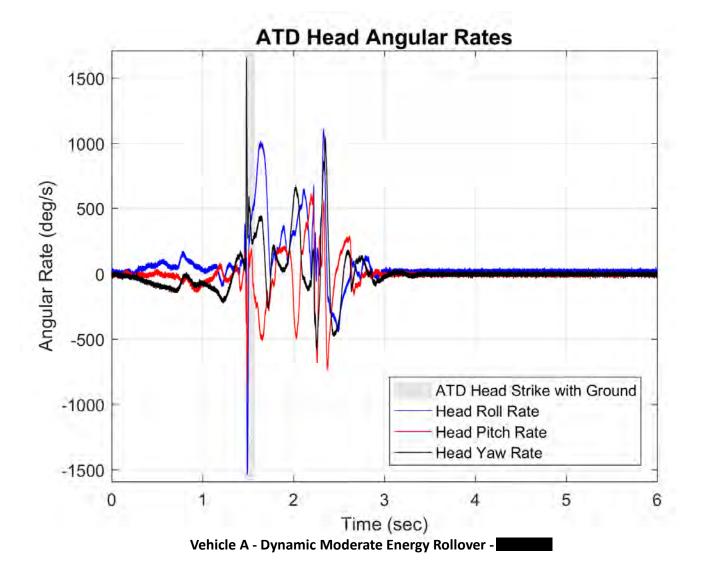


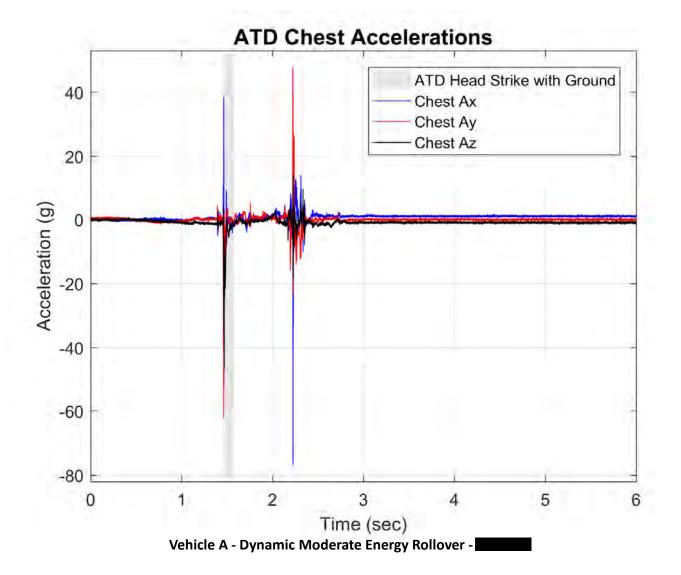


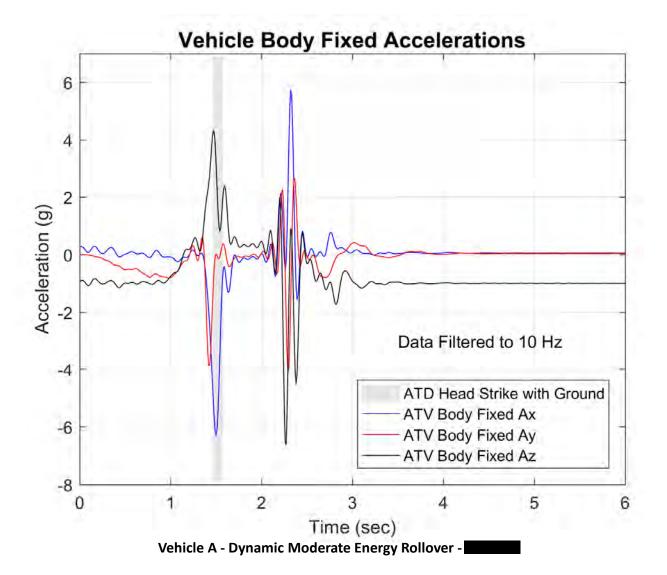


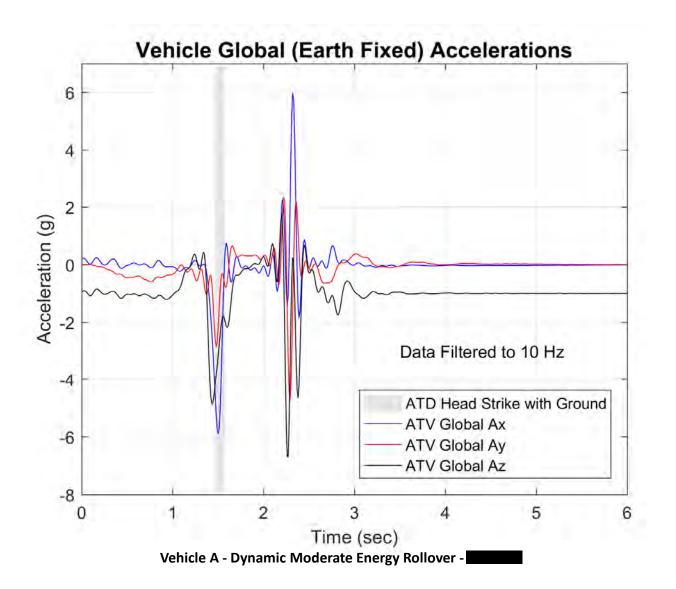
Vehicle A - Dynamic Moderate Energy Rollover -

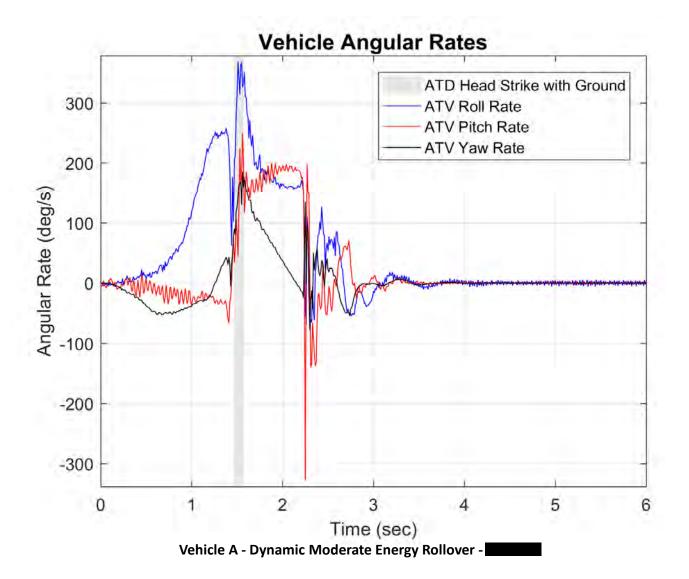


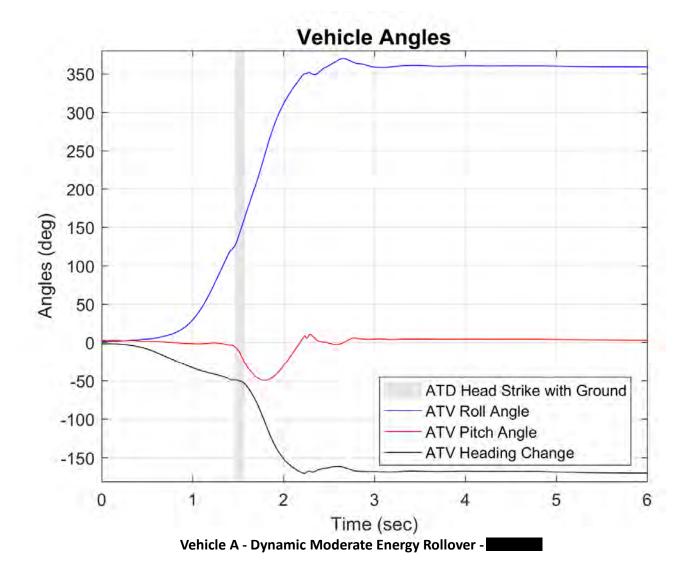












## Roll Angle = $30^{\circ}$ - Time = 2.13 sec



Vehicle E - Dynamic Minimum Energy Rollover -

## Roll Angle = $45^{\circ}$ - Time = 2.31 sec



Vehicle E - Dynamic Minimum Energy Rollover -

# Roll Angle = $90^{\circ}$ - Time = 2.62 sec



Vehicle E - Dynamic Minimum Energy Rollover -

#### ATD Head Strike - Time = 2.74 sec



Vehicle E - Dynamic Minimum Energy Rollover -

# Max Roll Angle = $141.3^{\circ}$ - Time = 3.43 sec



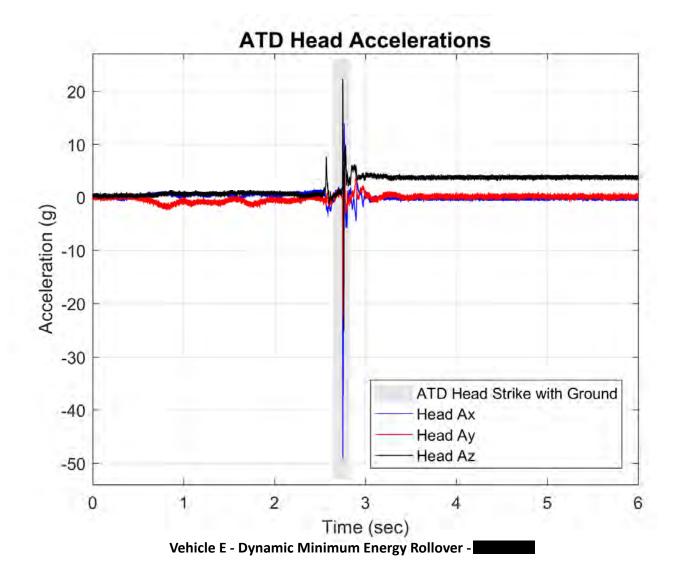
Vehicle E - Dynamic Minimum Energy Rollover -

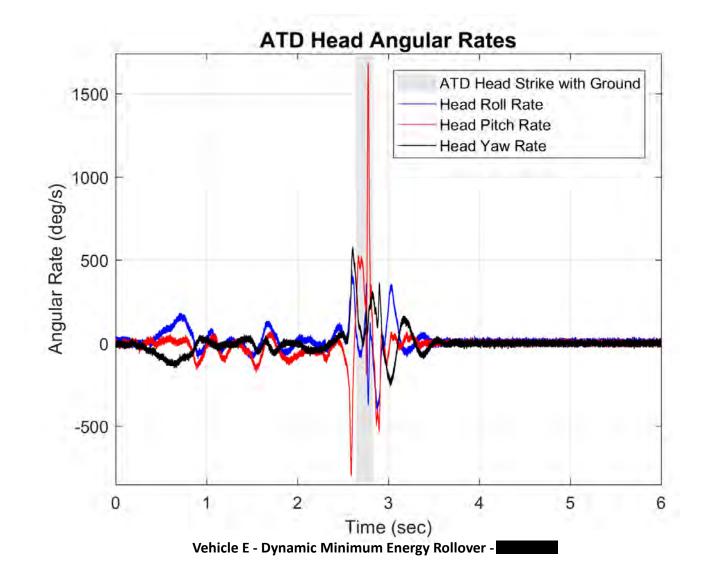
# End of Run - Roll Angle = $98.5^{\circ}$

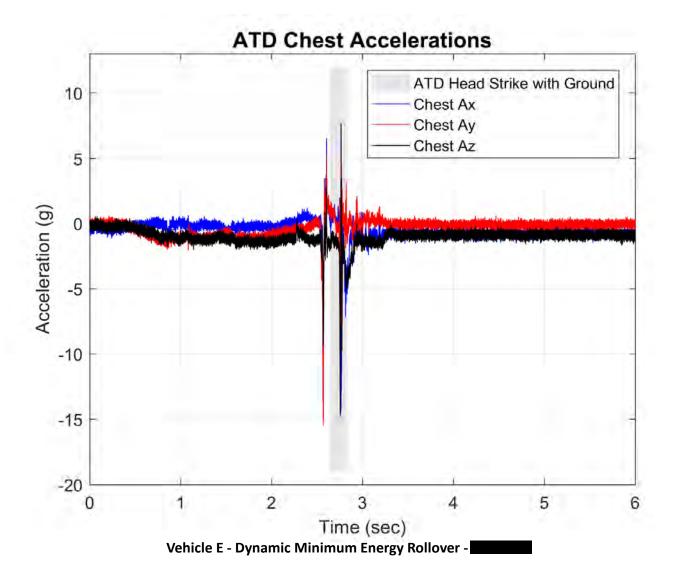


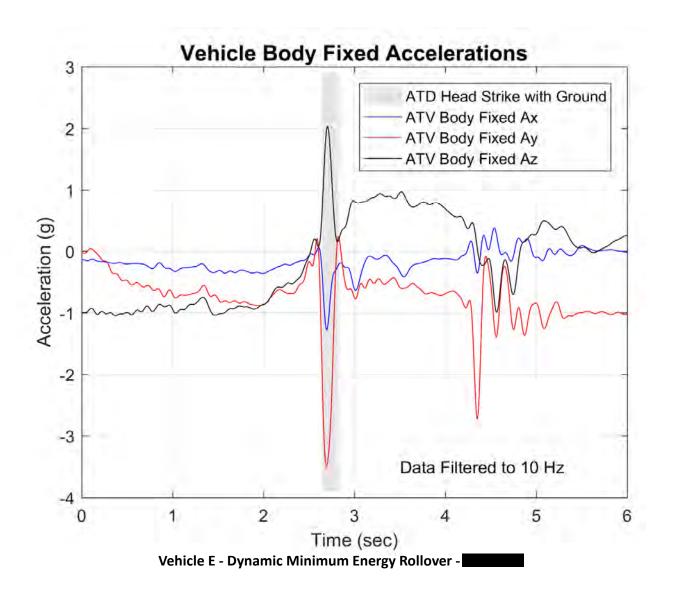
Vehicle E - Dynamic Minimum Energy Rollover -

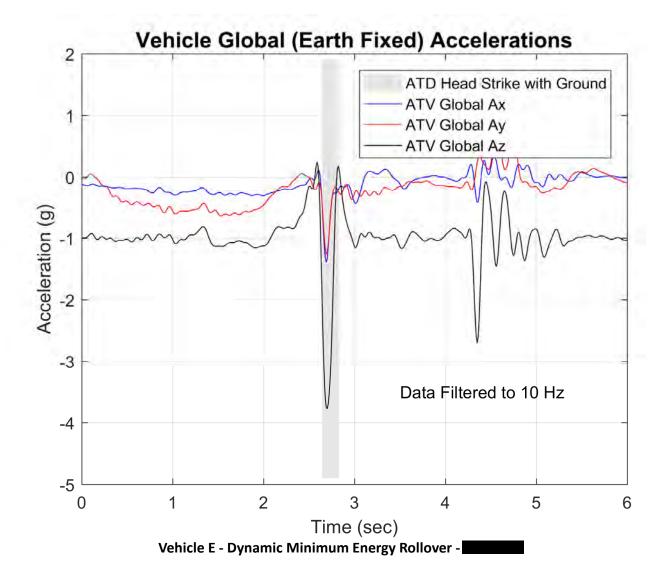


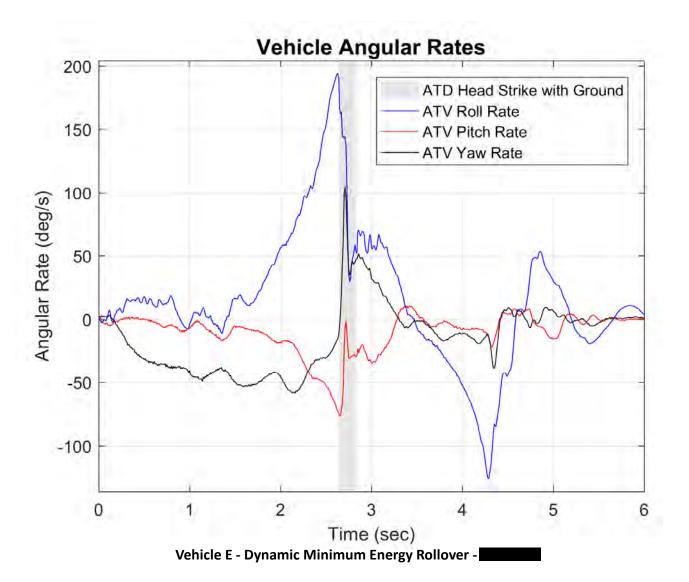


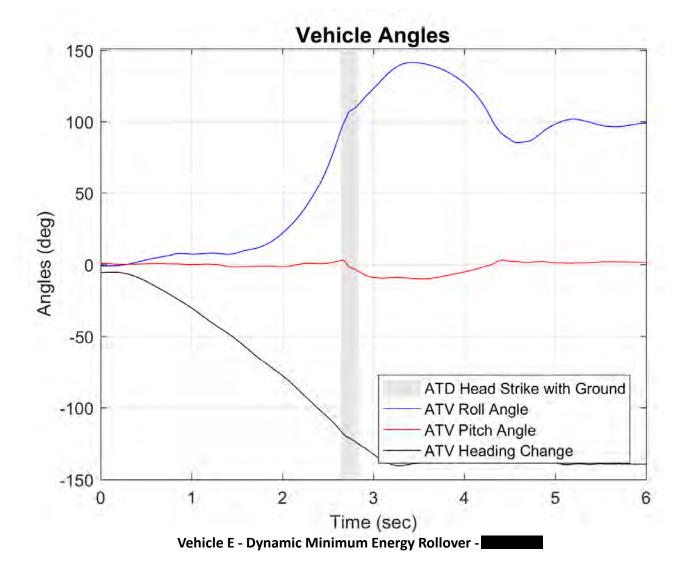












## Roll Angle = $30^{\circ}$ - Time = 2.12 sec



Vehicle E - Dynamic Minimum Energy Rollover -

# Roll Angle = $45^{\circ}$ - Time = 2.28 sec



Vehicle E - Dynamic Minimum Energy Rollover -

# Roll Angle = $90^{\circ}$ - Time = 2.58 sec



Vehicle E - Dynamic Minimum Energy Rollover -

### ATD Head Strike - Time = 2.71 sec



Vehicle E - Dynamic Minimum Energy Rollover -

# Max Roll Angle = $158.4^{\circ}$ - Time = 3.49 sec



Vehicle E - Dynamic Minimum Energy Rollover -

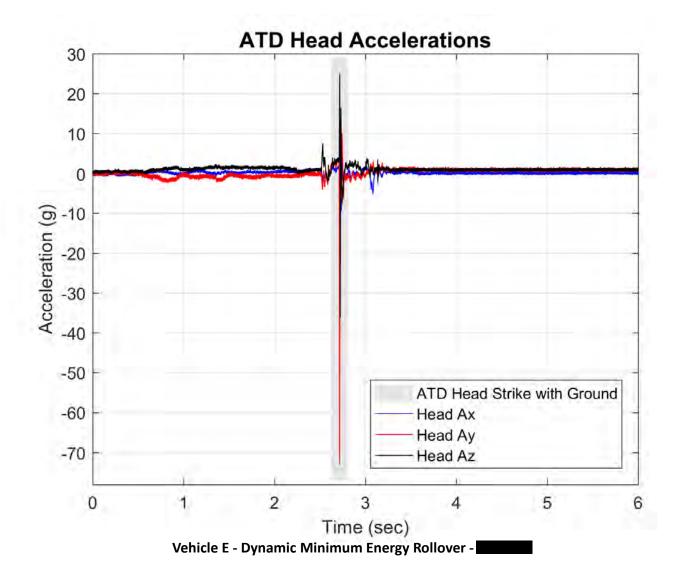
# End of Run - Roll Angle = $100.9^{\circ}$

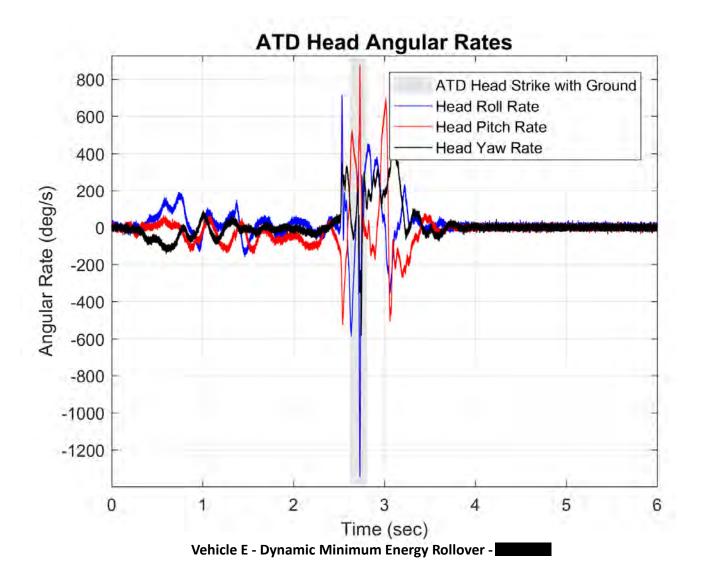


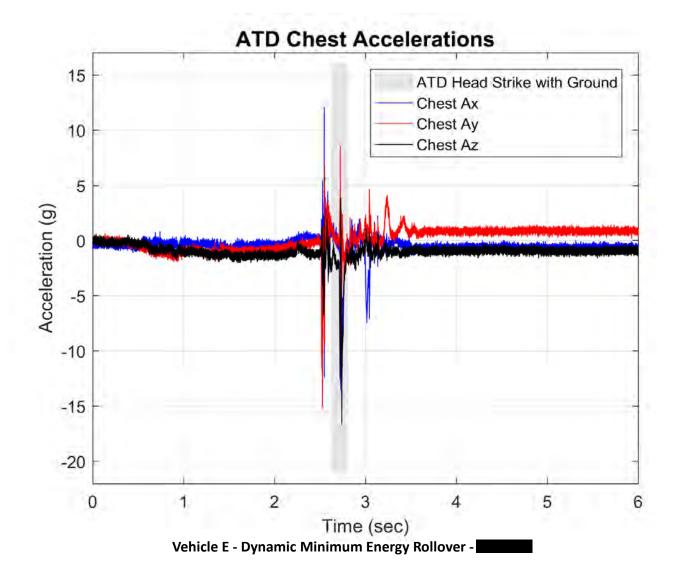
Vehicle E - Dynamic Minimum Energy Rollover -

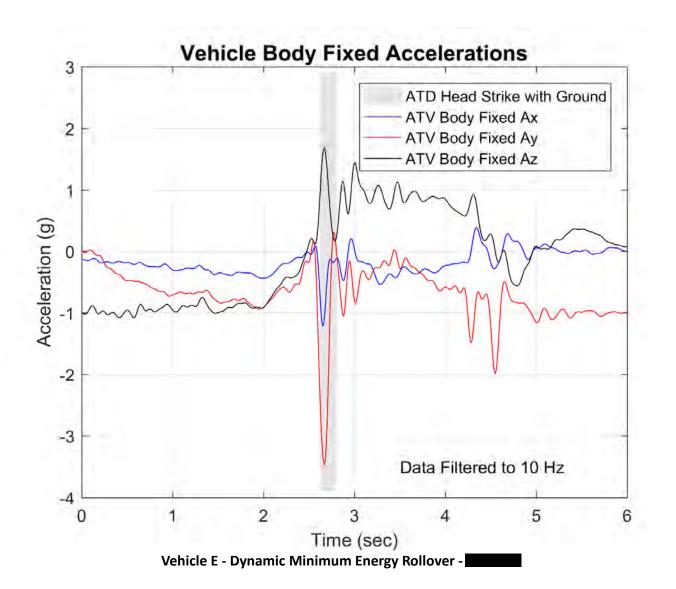
Drone Camera - Roll Angle = 30° - Time = 2.12 sec Drone Camera - Roll Angle = 45° - Time = 2.28 sec Drone Camera - Roll Angle = 90° - Time = 2.58 sec Drone Camera - ATD Head Strike - Time = 2.71 sec Drone Camera - Max Angle = 158.4° - Time = 3.49 sec Drone Camera - End of Run - Roll Angle = 100.9°

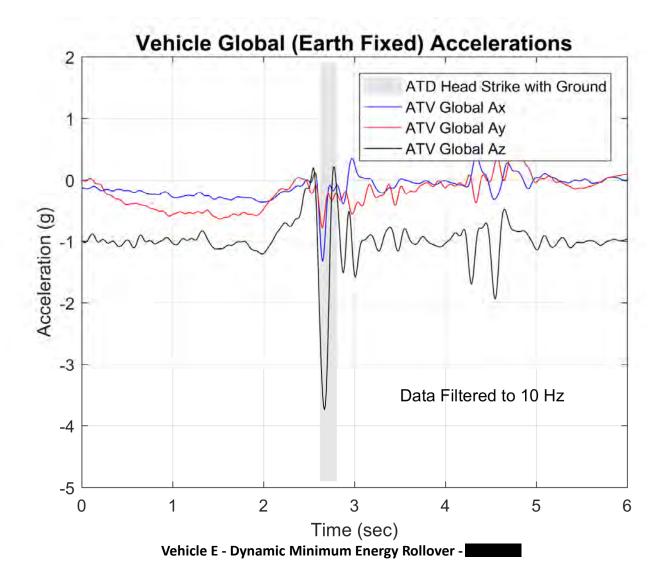
Vehicle E - Dynamic Minimum Energy Rollover -

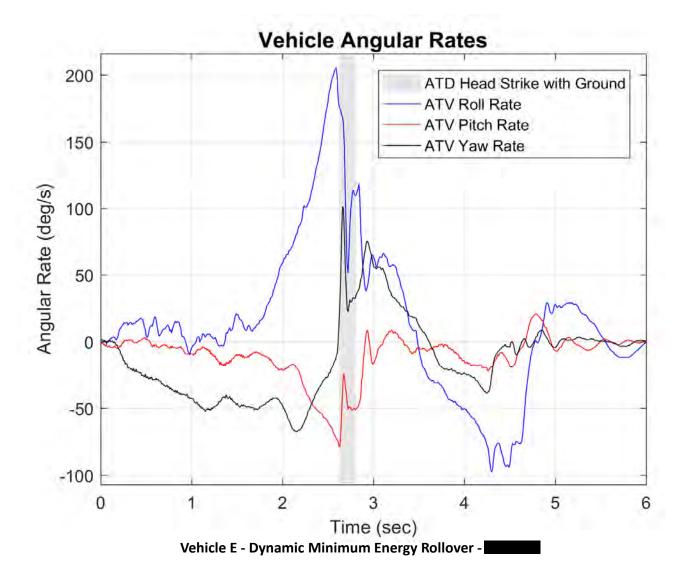


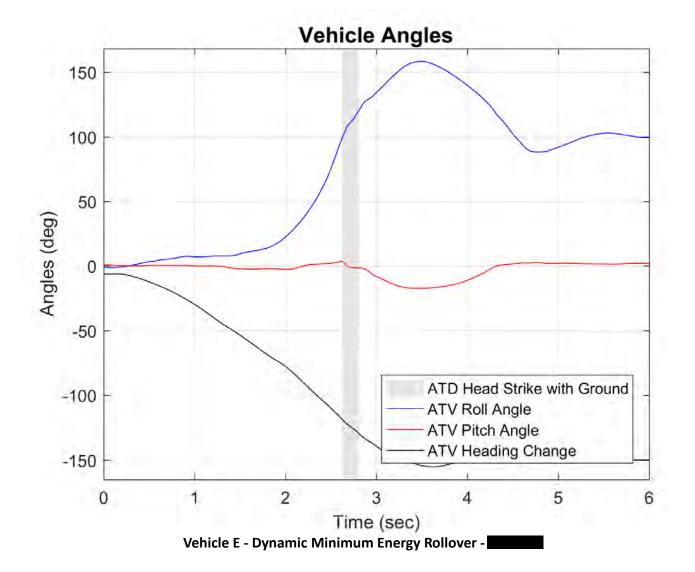












# Roll Angle = $30^{\circ}$ - Time = 2.06 sec



Vehicle E - Dynamic Moderate Energy Rollover -

# Roll Angle = $45^{\circ}$ - Time = 2.16 sec



Vehicle E - Dynamic Moderate Energy Rollover -

# Roll Angle = $90^{\circ}$ - Time = 2.37 sec



Vehicle E - Dynamic Moderate Energy Rollover -

### ATD Head Strike - Time = 2.52 sec



Vehicle E - Dynamic Moderate Energy Rollover -

# Roll Angle = $180^{\circ}$ - Time = 2.75 sec



Vehicle E - Dynamic Moderate Energy Rollover -

# Roll Angle = $270^{\circ}$ - Time = 3.12 sec



Vehicle E - Dynamic Moderate Energy Rollover -

# Max Roll Angle = $279.3^{\circ}$ - Time = 3.19 sec

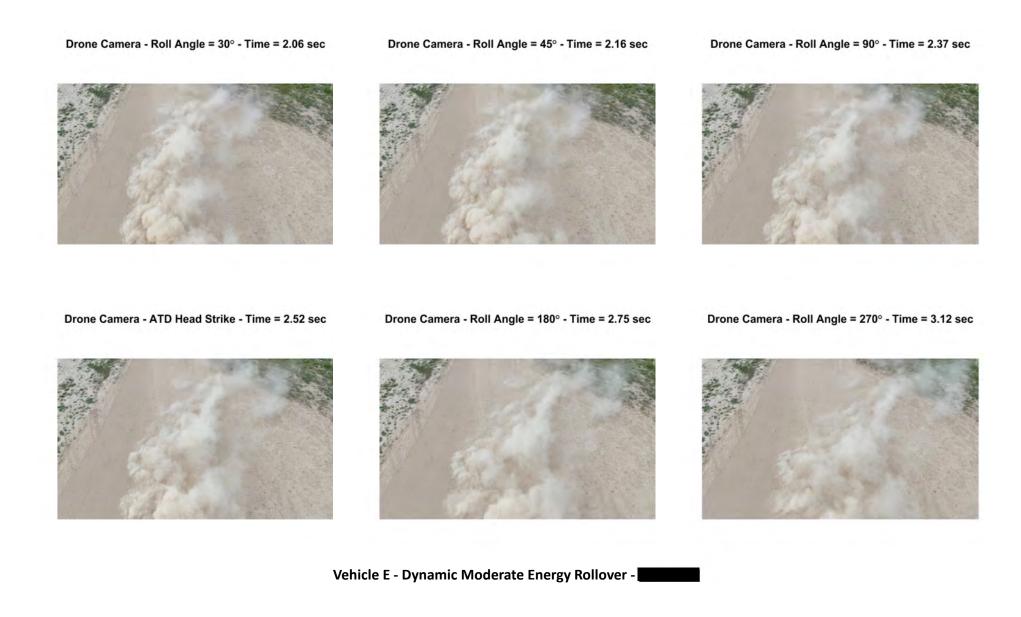


Vehicle E - Dynamic Moderate Energy Rollover -

# End of Run - Roll Angle = 261.1°



Vehicle E - Dynamic Moderate Energy Rollover -



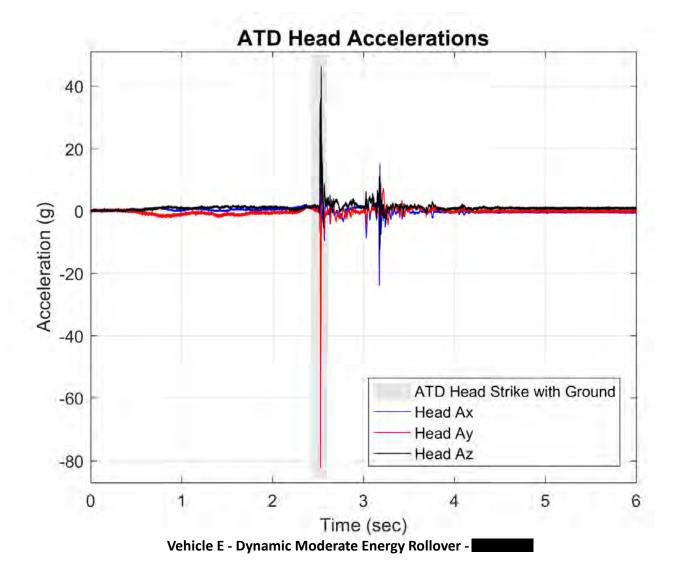
Drone Camera - Max Angle = 279.3° - Time = 3.19 sec

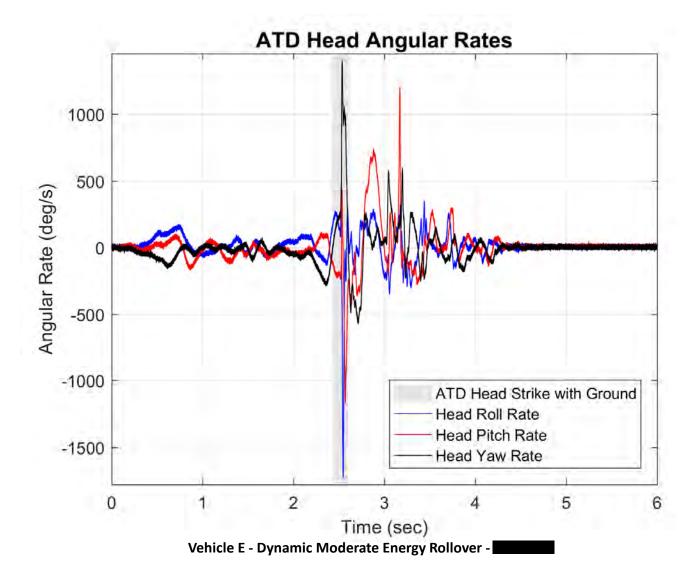
Drone Camera - End of Run - Roll Angle = 261.1°

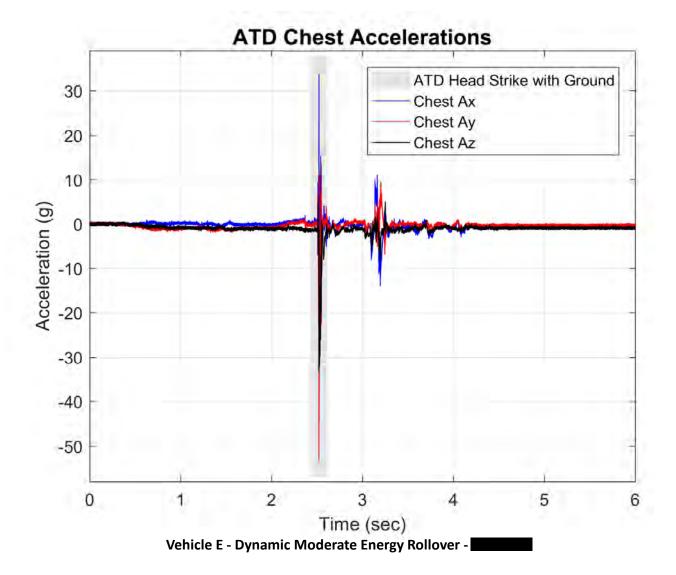


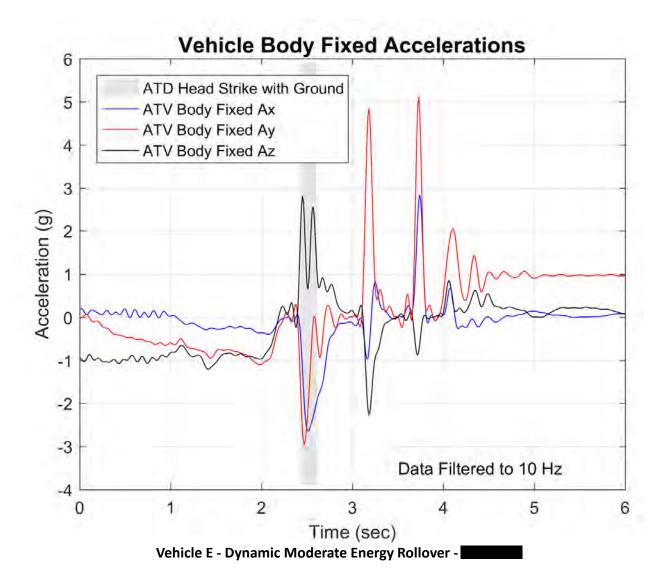


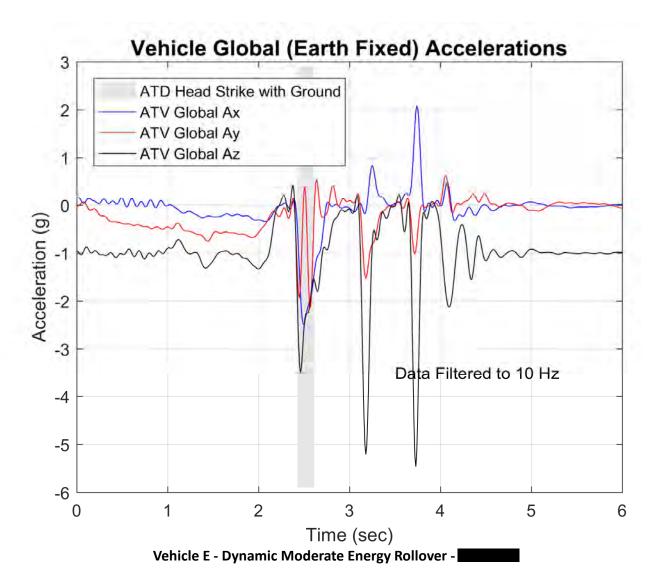
Vehicle E - Dynamic Moderate Energy Rollover -

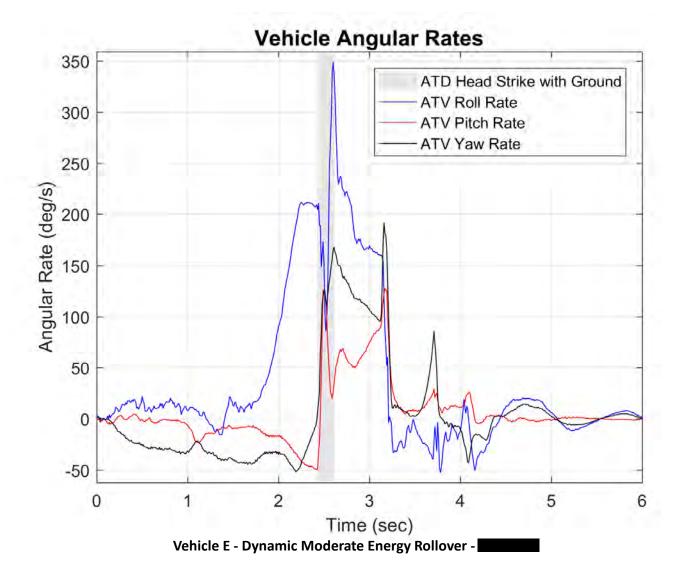


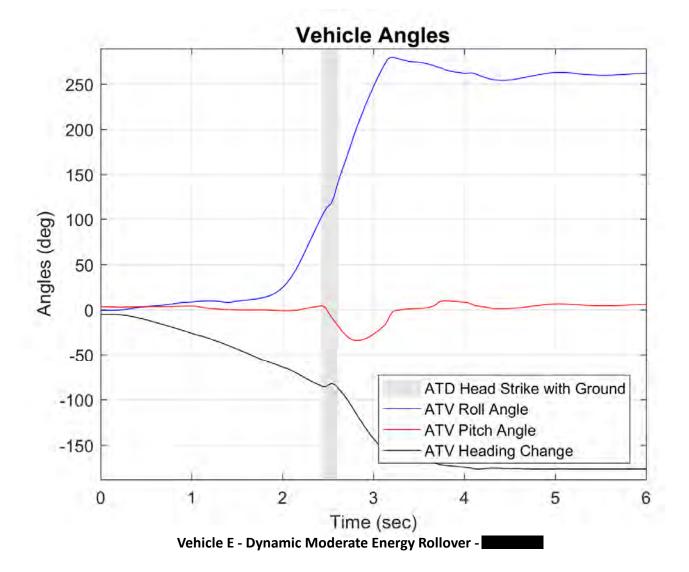












# Roll Angle = $30^{\circ}$ - Time = 2.89 sec



Vehicle E - Dynamic Moderate Energy Rollover -

# Roll Angle = $45^{\circ}$ - Time = 3.02 sec



Vehicle E - Dynamic Moderate Energy Rollover -

# Roll Angle = $90^{\circ}$ - Time = 3.28 sec



Vehicle E - Dynamic Moderate Energy Rollover -

### ATD Head Strike - Time = 3.43 sec



Vehicle E - Dynamic Moderate Energy Rollover -

# Roll Angle = $180^{\circ}$ - Time = 3.72 sec



Vehicle E - Dynamic Moderate Energy Rollover -

# Roll Angle = $270^{\circ}$ - Time = 4.65 sec



Vehicle E - Dynamic Moderate Energy Rollover -

## Max Roll Angle = $270.7^{\circ}$ - Time = 4.7 sec

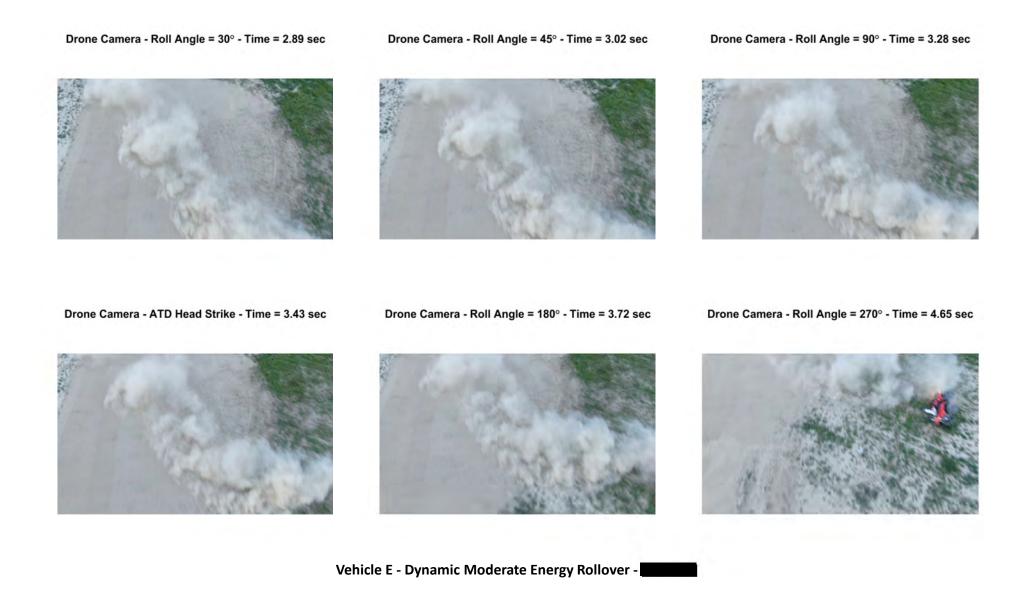


Vehicle E - Dynamic Moderate Energy Rollover -

# End of Run - Roll Angle = $255.7^{\circ}$



Vehicle E - Dynamic Moderate Energy Rollover -



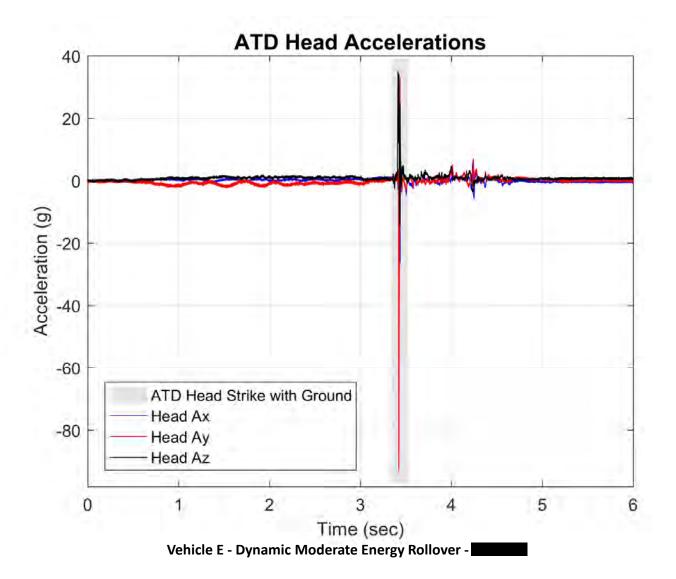
Drone Camera - Max Angle = 270.7° - Time = 4.7 sec

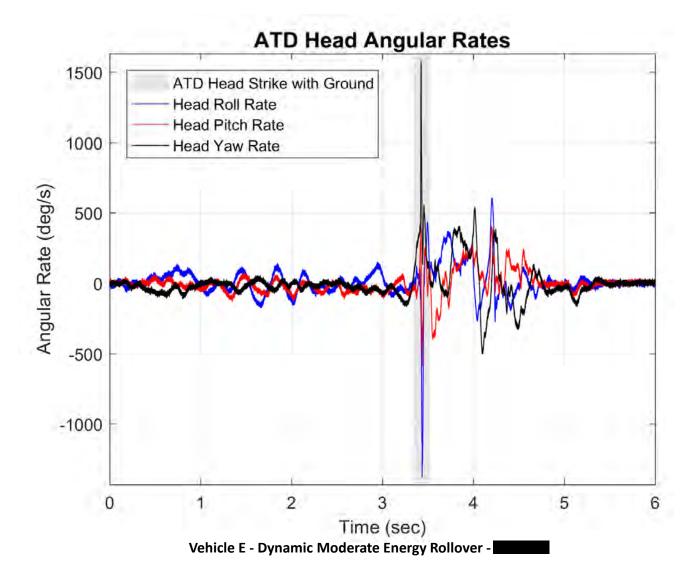
Drone Camera - End of Run - Roll Angle = 255.7°

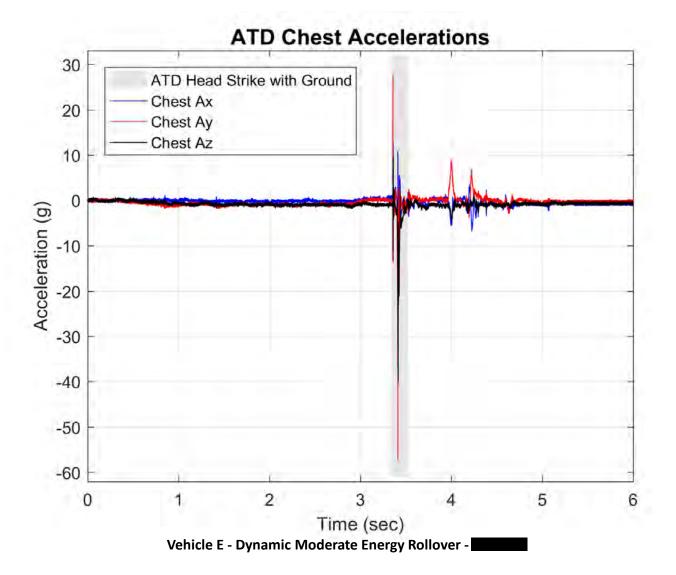


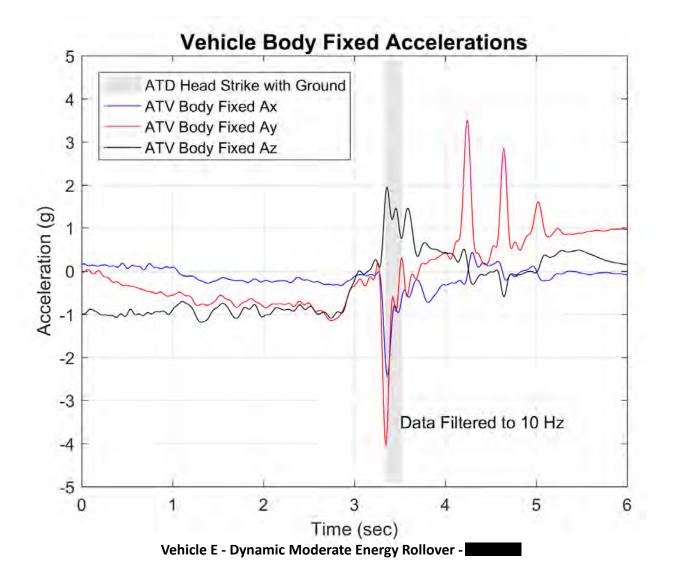


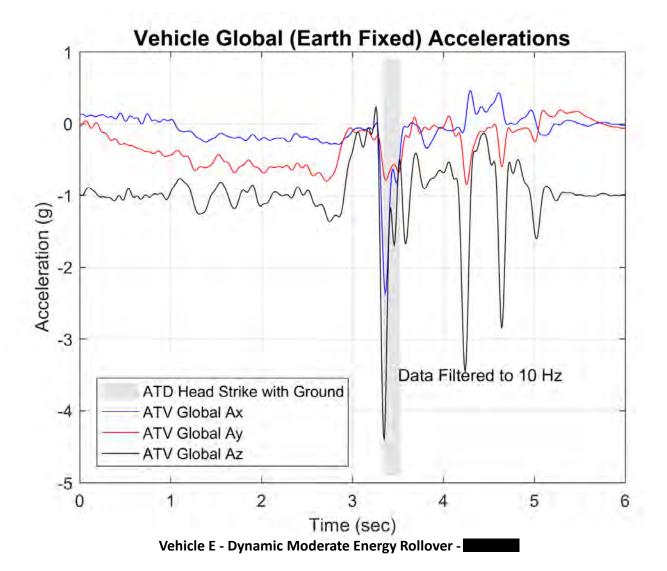
Vehicle E - Dynamic Moderate Energy Rollover -

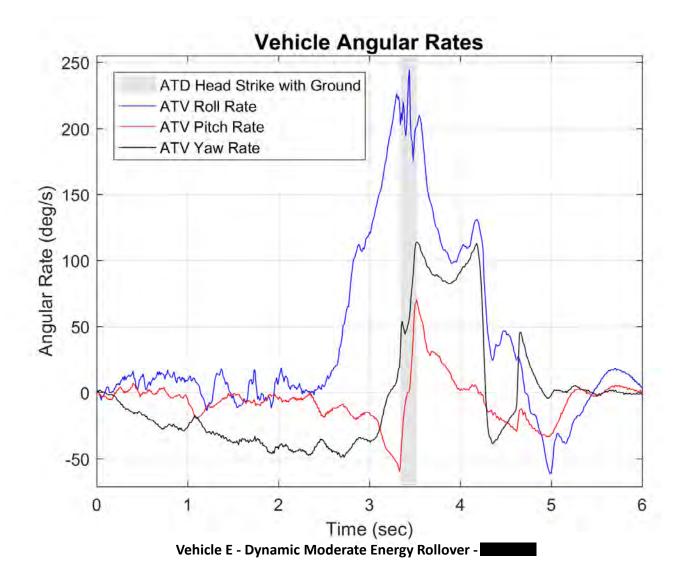


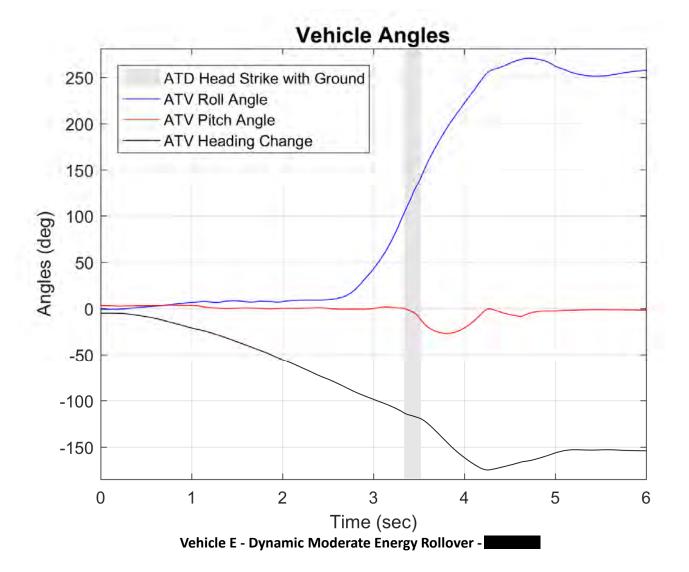












# Roll Angle = $30^{\circ}$ - Time = 1.54 sec



Vehicle G - Dynamic Minimum Energy Rollover -

## Roll Angle = $45^{\circ}$ - Time = 1.75 sec



Vehicle G - Dynamic Minimum Energy Rollover -

## Roll Angle = $90^{\circ}$ - Time = 2.1 sec



Vehicle G - Dynamic Minimum Energy Rollover -

#### ATD Head Strike - Time = 2.2 sec



Vehicle G - Dynamic Minimum Energy Rollover -

## Max Roll Angle = $136.6^{\circ}$ - Time = 2.83 sec



Vehicle G - Dynamic Minimum Energy Rollover -

## End of Run - Roll Angle = 93.2°



Vehicle G - Dynamic Minimum Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 1.54 sec



Drone Camera - Roll Angle = 90° - Time = 2.1 sec







Drone Camera - ATD Head Strike - Time = 2.2 sec

Drone Camera - Max Angle = 136.6° - Time = 2.83 sec

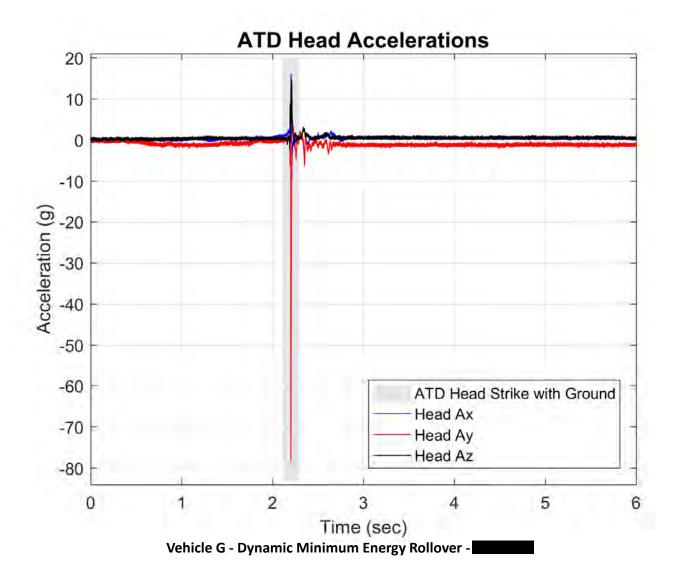
Drone Camera - End of Run - Roll Angle = 93.2°

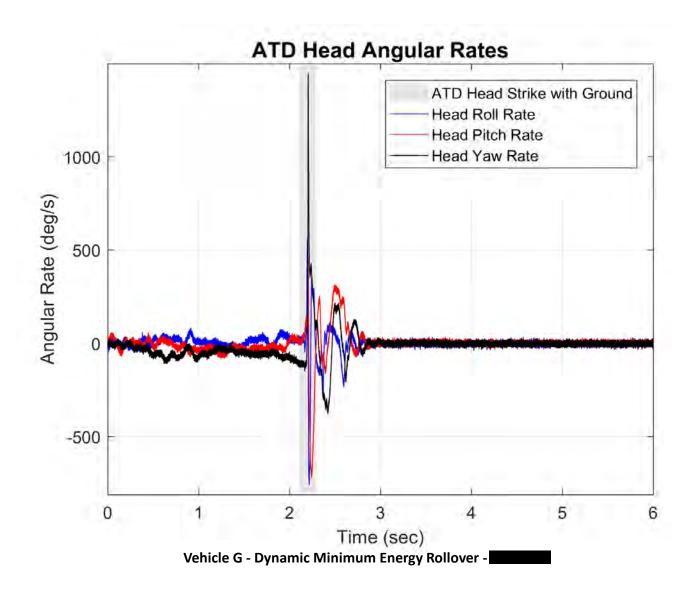


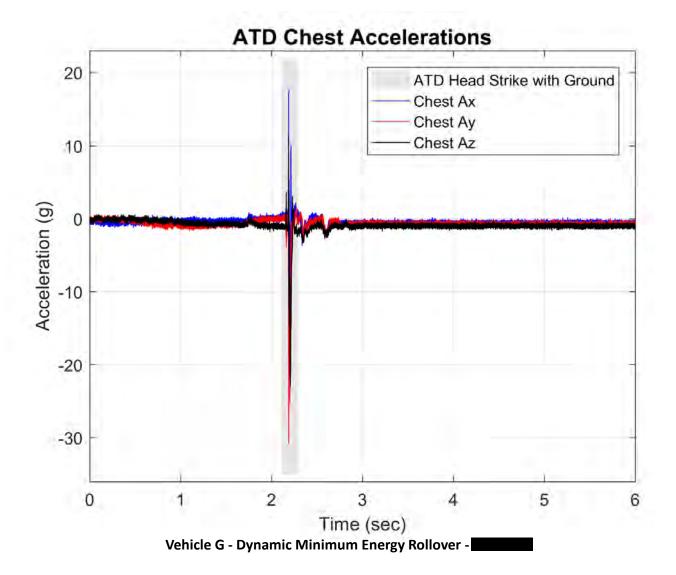


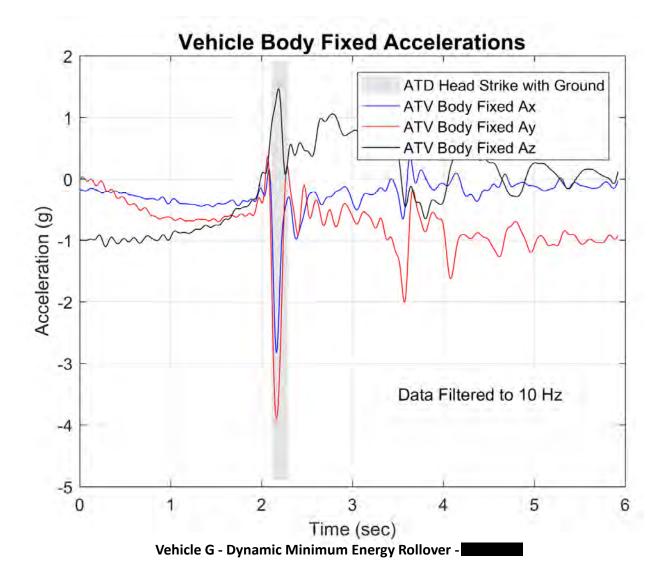


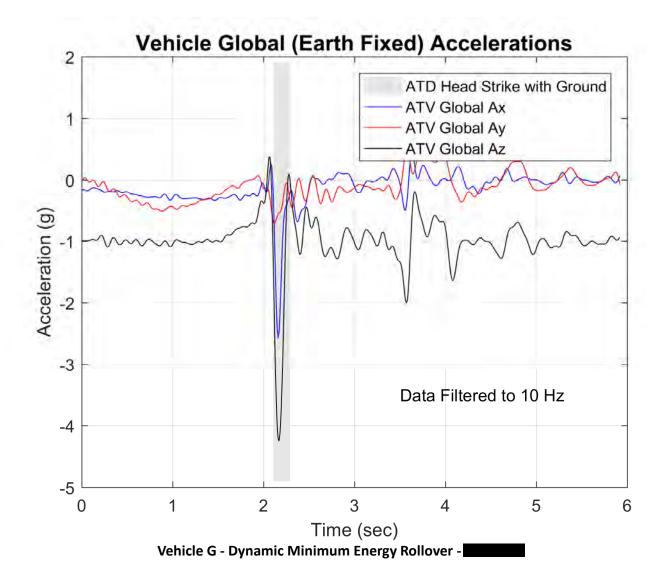
Vehicle G - Dynamic Minimum Energy Rollover -

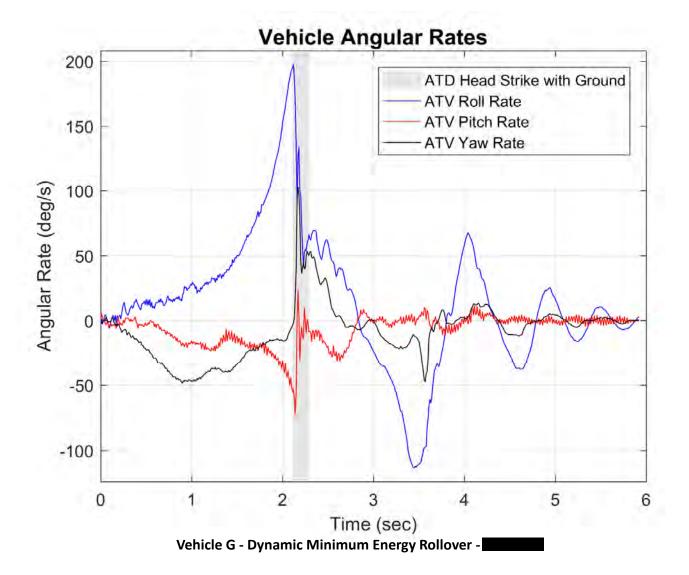


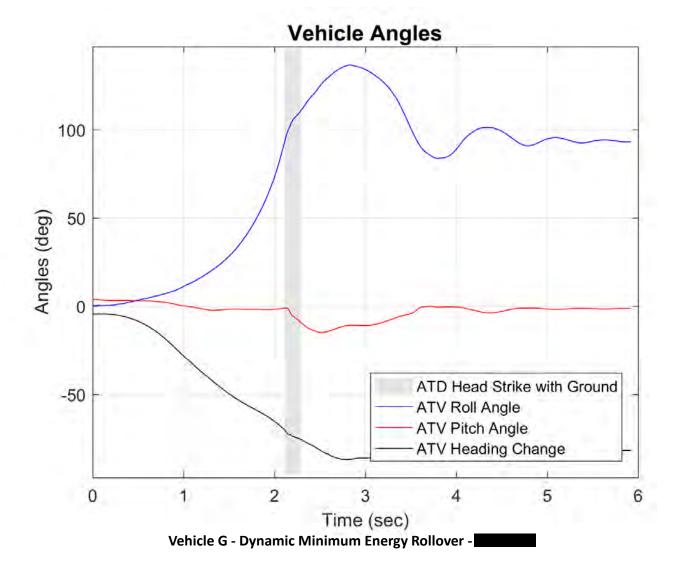












# Roll Angle = $30^{\circ}$ - Time = 1.65 sec



Vehicle G - Dynamic Minimum Energy Rollover -

## Roll Angle = $45^{\circ}$ - Time = 1.85 sec



Vehicle G - Dynamic Minimum Energy Rollover -

## Roll Angle = $90^{\circ}$ - Time = 2.18 sec



Vehicle G - Dynamic Minimum Energy Rollover -

#### ATD Head Strike - Time = 2.28 sec



Vehicle G - Dynamic Minimum Energy Rollover -

## Max Roll Angle = $140.3^{\circ}$ - Time = 2.94 sec



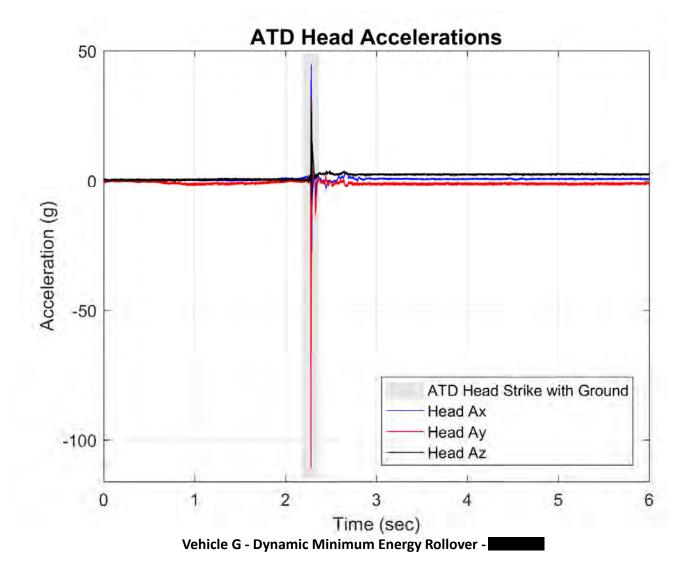
Vehicle G - Dynamic Minimum Energy Rollover -

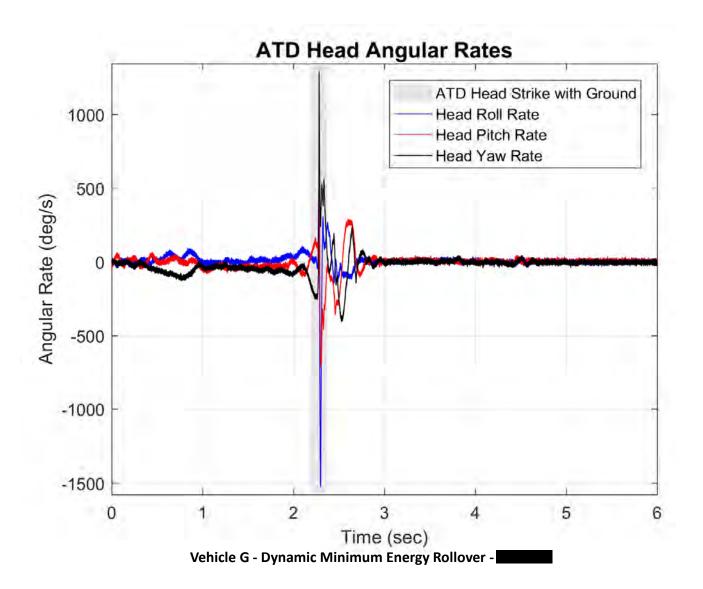
## End of Run - Roll Angle = 94.1°

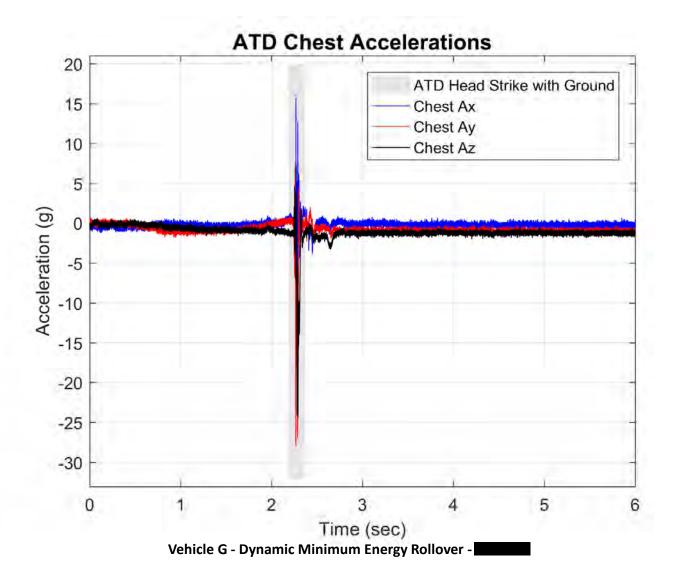


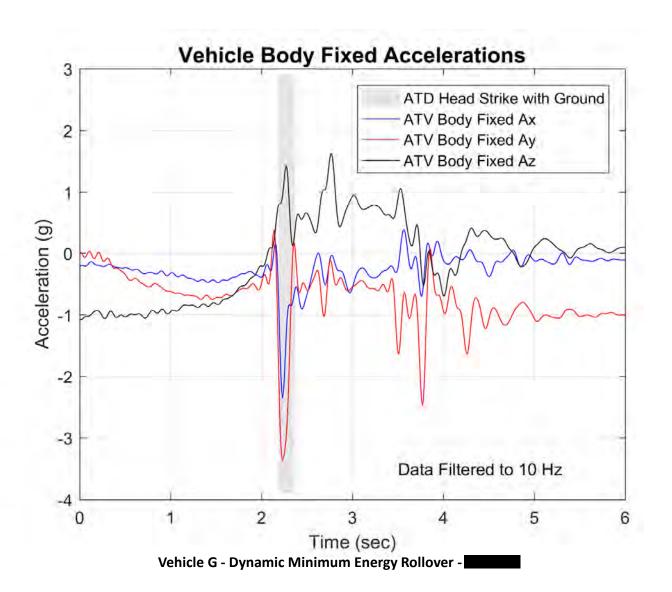
Vehicle G - Dynamic Minimum Energy Rollover -

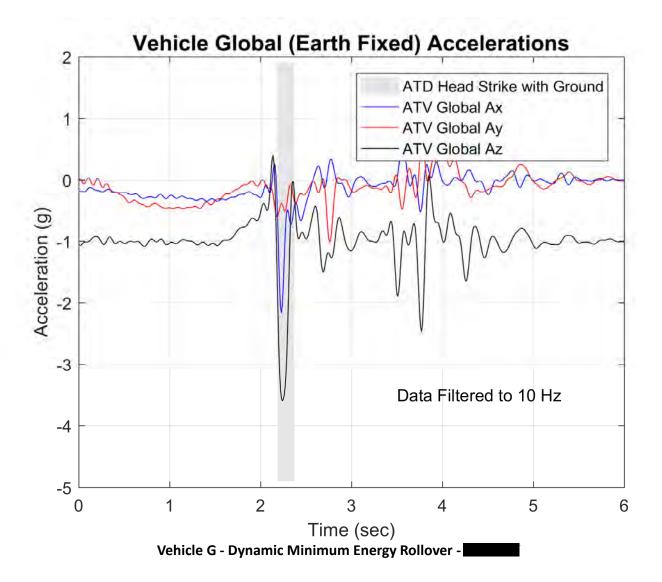


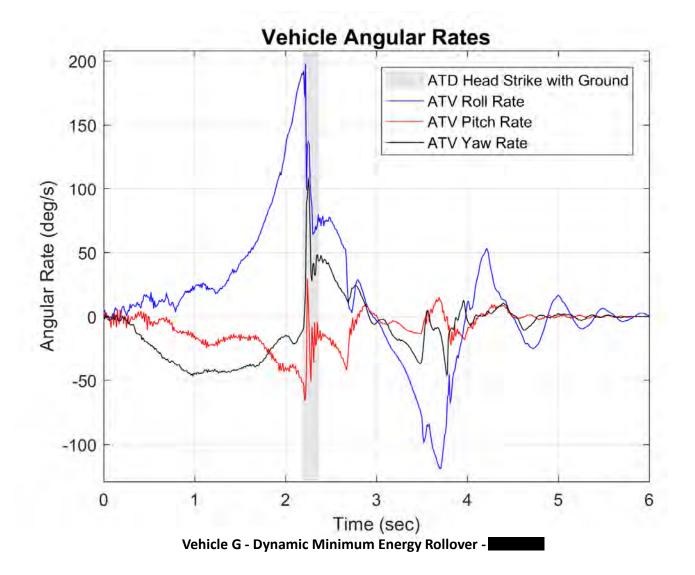


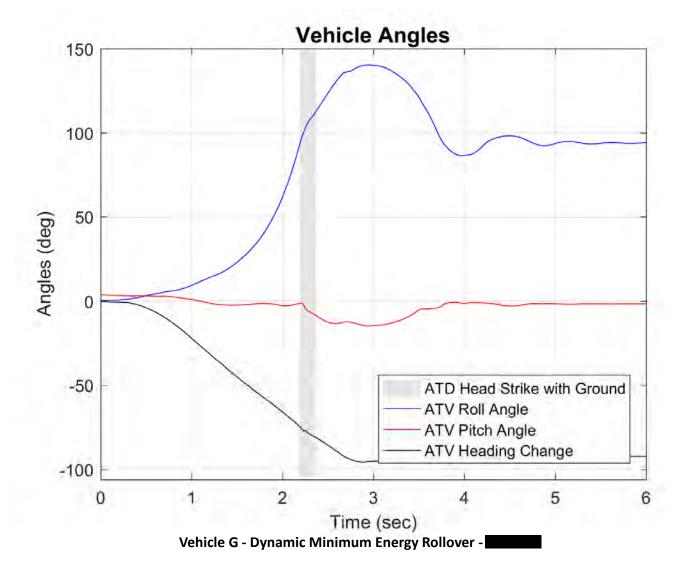












# Roll Angle = $30^{\circ}$ - Time = 1.27 sec



Vehicle G - Dynamic Moderate Energy Rollover -

# Roll Angle = $45^{\circ}$ - Time = 1.39 sec



Vehicle G - Dynamic Moderate Energy Rollover -

# Roll Angle = $90^{\circ}$ - Time = 1.63 sec



Vehicle G - Dynamic Moderate Energy Rollover -

### ATD Head Strike - Time = 1.78 sec



Vehicle G - Dynamic Moderate Energy Rollover -

# Roll Angle = $180^{\circ}$ - Time = 1.94 sec



Vehicle G - Dynamic Moderate Energy Rollover -

# Roll Angle = $270^{\circ}$ - Time = 2.17 sec



Vehicle G - Dynamic Moderate Energy Rollover -

# Roll Angle = $360^{\circ}$ - Time = 2.47 sec



Vehicle G - Dynamic Moderate Energy Rollover -

# Roll Angle = $450^{\circ}$ - Time = 2.89 sec



Vehicle G - Dynamic Moderate Energy Rollover -

# Max Roll Angle = $\sim$ 490.0° - Time = 3.27 sec



Vehicle G - Dynamic Moderate Energy Rollover -

# End of Run - Roll Angle = $\sim$ 455.0°



Vehicle G - Dynamic Moderate Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 1.27 sec

Drone Camera - Roll Angle = 45° - Time = 1.39 sec

Drone Camera - Roll Angle = 90° - Time = 1.63 sec







Drone Camera - ATD Head Strike - Time = 1.78 sec

Drone Camera - Roll Angle = 180° - Time = 1.94 sec

Drone Camera - Roll Angle = 270° - Time = 2.17 sec

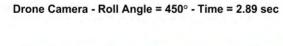






Vehicle G - Dynamic Moderate Energy Rollover -

Drone Camera - Roll Angle = 360° - Time = 2.47 sec



Drone Camera - Max Angle = 490.0° - Time = 3.27 sec



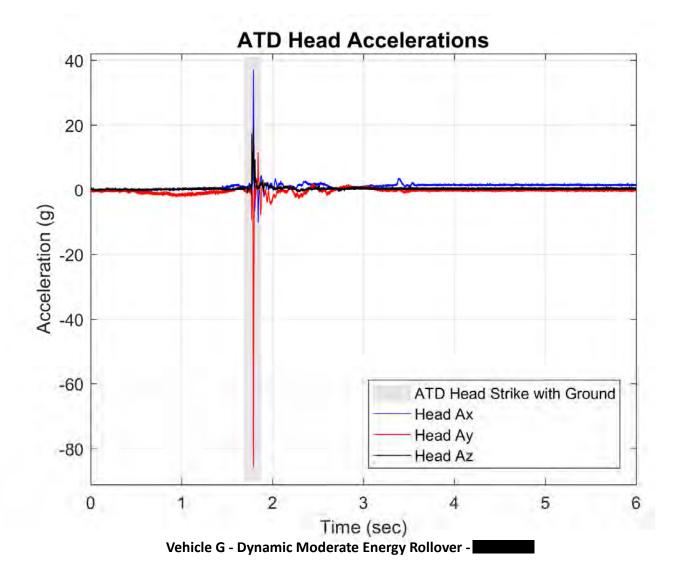


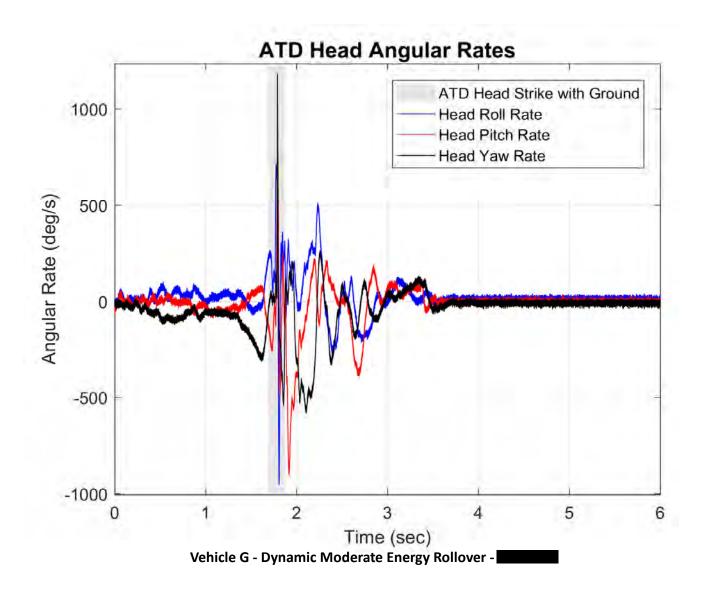


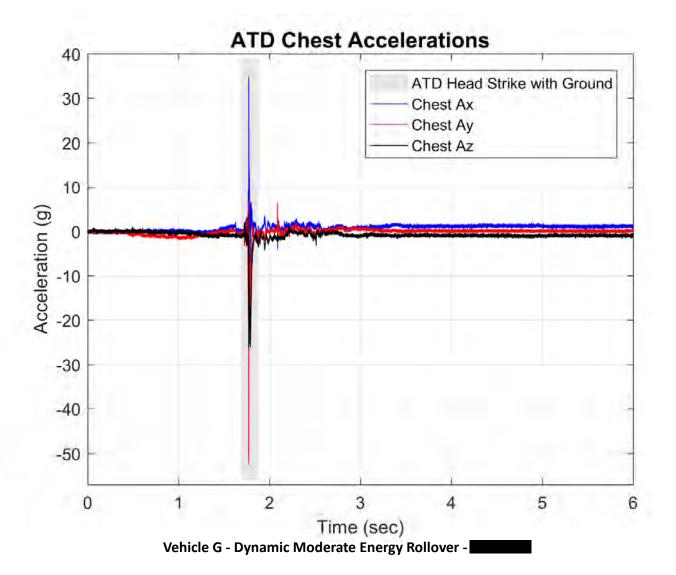
Drone Camera - End of Run - Roll Angle = 455.0°

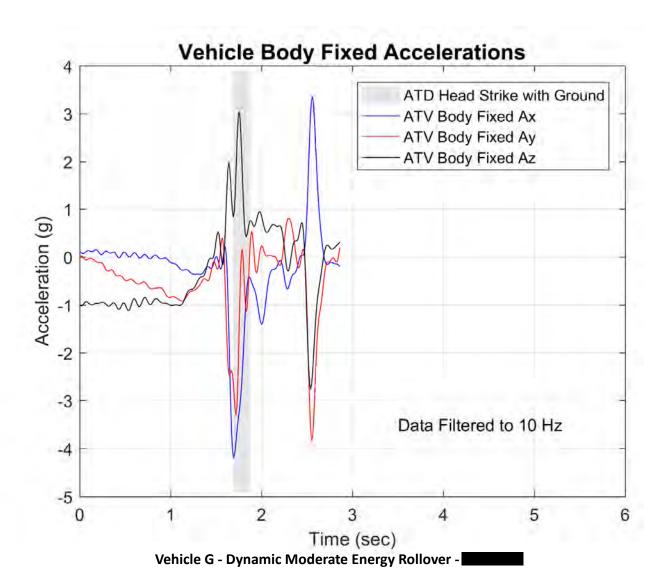


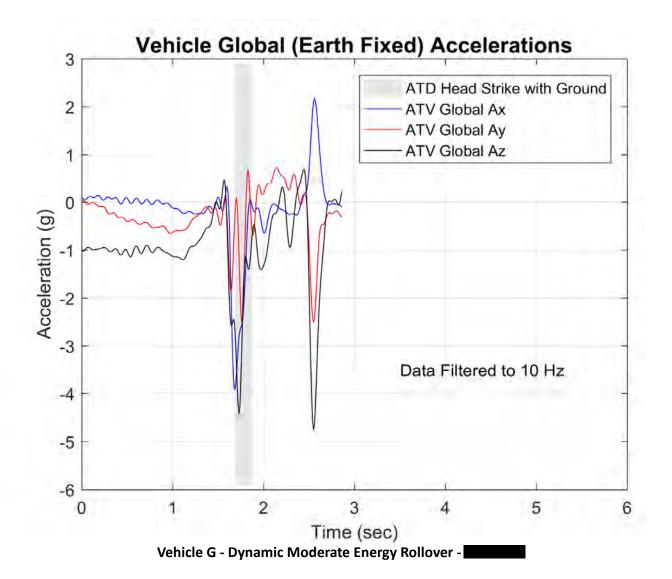
Vehicle G - Dynamic Moderate Energy Rollover -

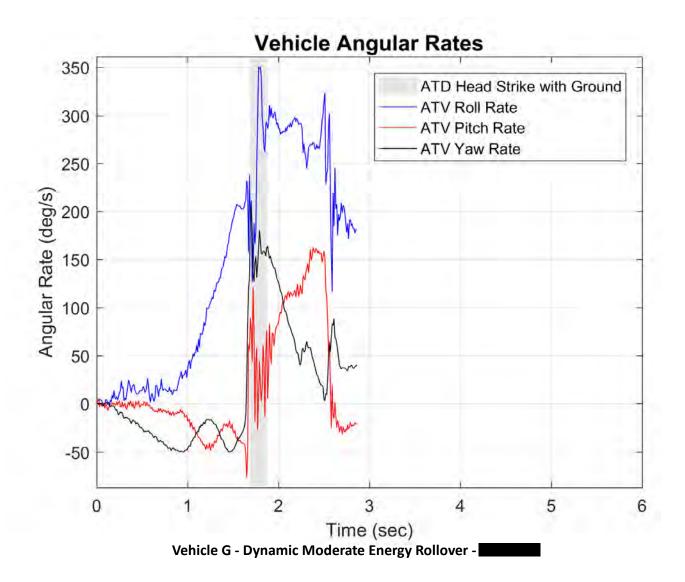


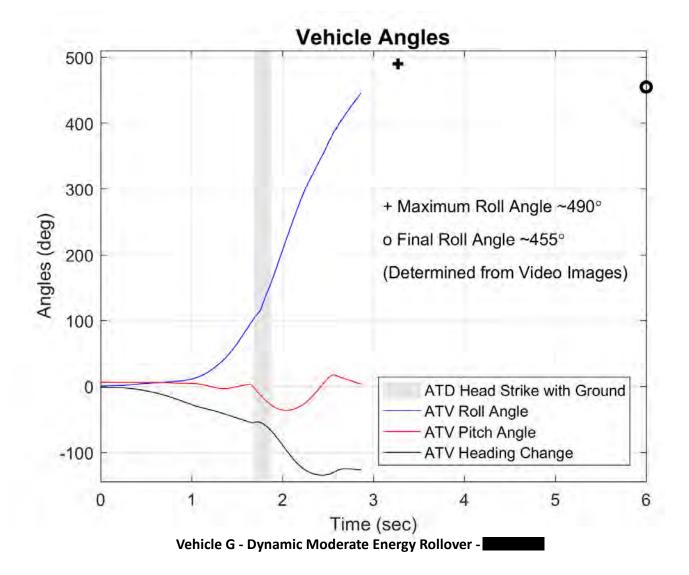












# Roll Angle = $30^{\circ}$ - Time = 1.39 sec



Vehicle G - Dynamic Moderate Energy Rollover -

# Roll Angle = $45^{\circ}$ - Time = 1.5 sec



Vehicle G - Dynamic Moderate Energy Rollover -

# Roll Angle = $90^{\circ}$ - Time = 1.71 sec



Vehicle G - Dynamic Moderate Energy Rollover -

### ATD Head Strike - Time = 1.86 sec



Vehicle G - Dynamic Moderate Energy Rollover -

# Roll Angle = $180^{\circ}$ - Time = 2.04 sec



Vehicle G - Dynamic Moderate Energy Rollover -

# Roll Angle = $270^{\circ}$ - Time = 2.35 sec



Vehicle G - Dynamic Moderate Energy Rollover -

# Roll Angle = $360^{\circ}$ - Time = 2.76 sec



Vehicle G - Dynamic Moderate Energy Rollover -

# Roll Angle = $450^{\circ}$ - Time = 3.28 sec



Vehicle G - Dynamic Moderate Energy Rollover -

# Max Roll Angle = $489.5^{\circ}$ - Time = 3.87 sec



Vehicle G - Dynamic Moderate Energy Rollover -

# End of Run - Roll Angle = 458.3°



Vehicle G - Dynamic Moderate Energy Rollover -



Vehicle G - Dynamic Moderate Energy Rollover -

Drone Camera - Roll Angle = 360° - Time = 2.76 sec

Drone Camera - Roll Angle = 450° - Time = 3.28 sec

Drone Camera - Max Angle = 489.5° - Time = 3.87 sec



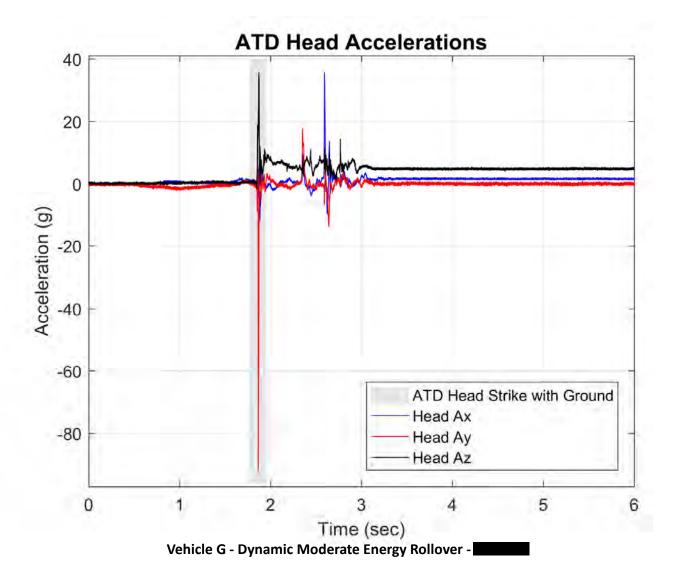


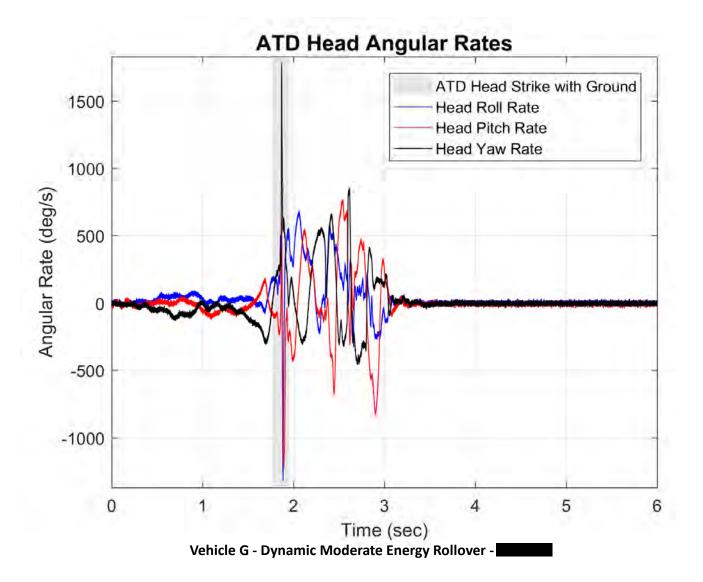


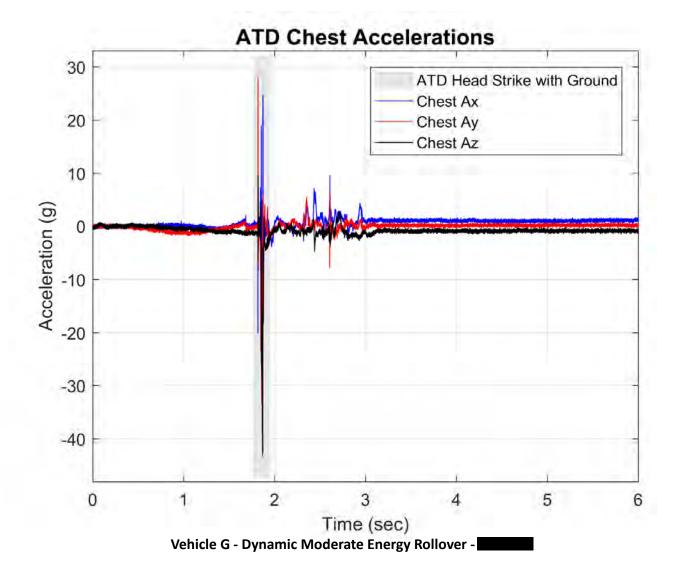
Drone Camera - End of Run - Roll Angle = 458.3°

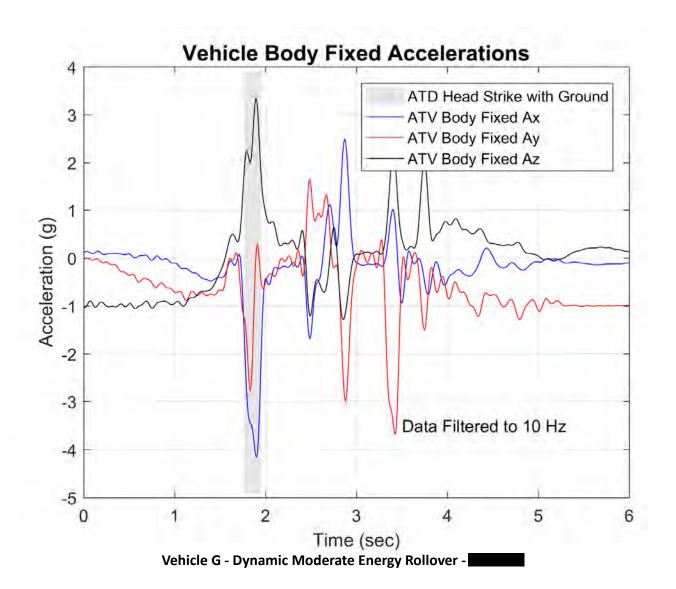


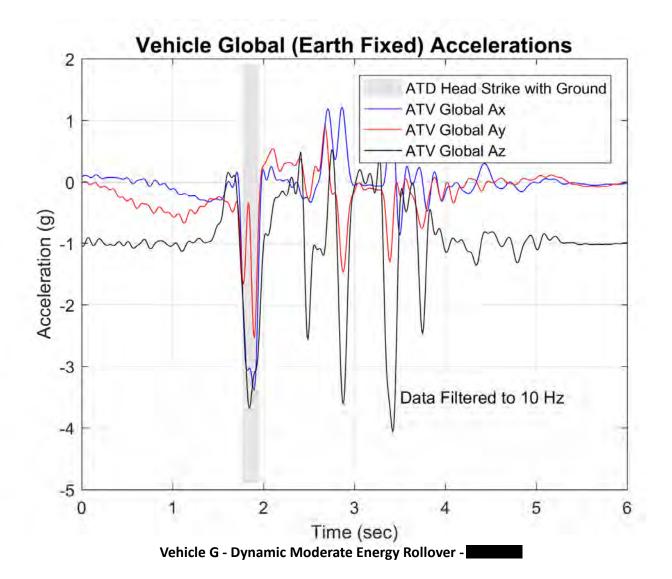
Vehicle G - Dynamic Moderate Energy Rollover -

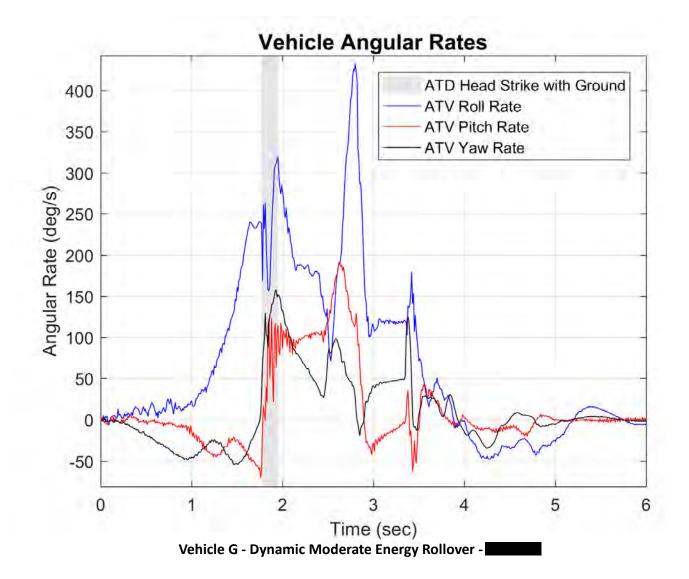


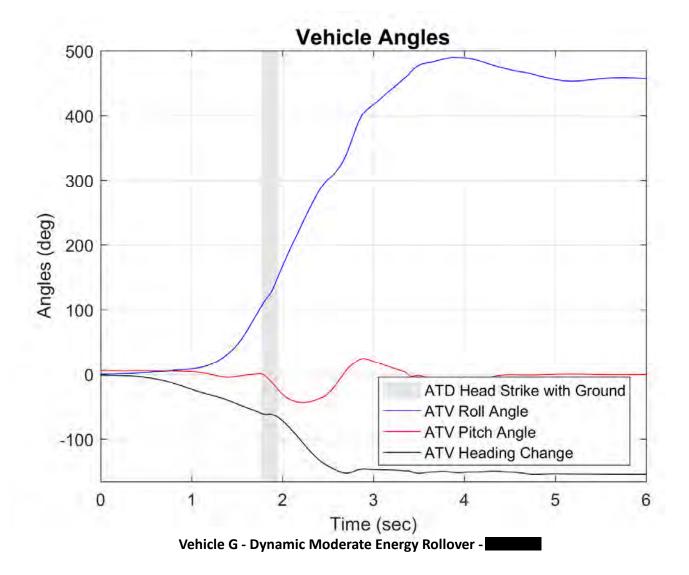












# Roll Angle = $30^{\circ}$ - Time = 0.65 sec



Vehicle A - Sled Minimum Energy Rollover -

## Roll Angle = $45^{\circ}$ - Time = 0.75 sec



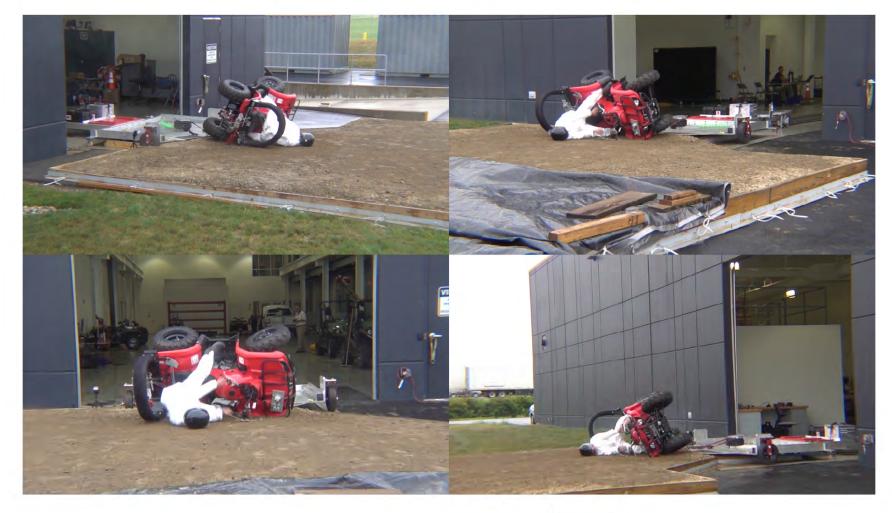
Vehicle A - Sled Minimum Energy Rollover -

# Roll Angle = $90^{\circ}$ - Time = 0.97 sec



Vehicle A - Sled Minimum Energy Rollover -

### ATD Head Strike - Time = 1.10 sec



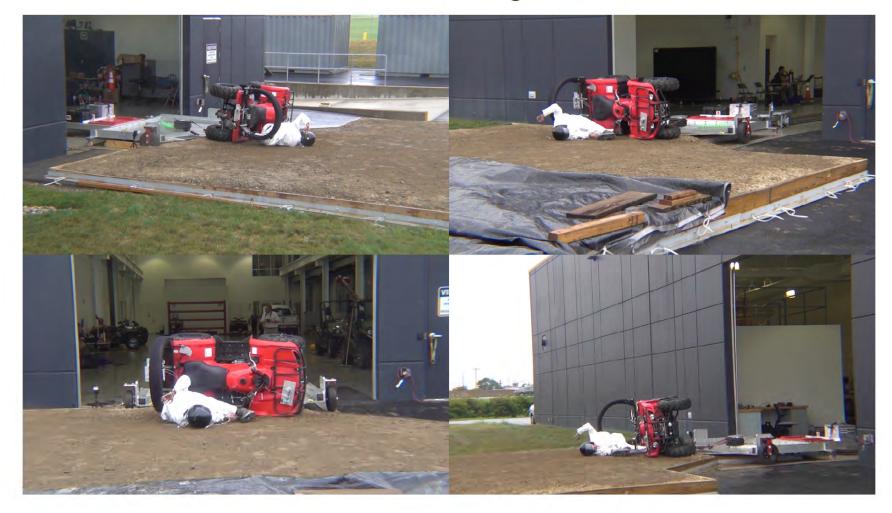
Vehicle A - Sled Minimum Energy Rollover -

## Max Roll Angle = $137.7^{\circ}$ - Time = 1.62 sec



Vehicle A - Sled Minimum Energy Rollover -

## End of Run - Roll Angle = 93.2°



Vehicle A - Sled Minimum Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.65 sec



Drone Camera - Roll Angle =  $45^{\circ}$  - Time = 0.75 sec



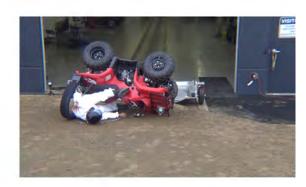
Drone Camera - Roll Angle = 90° - Time = 0.97 sec



Drone Camera - ATD Head Strike - Time = 1.10 sec



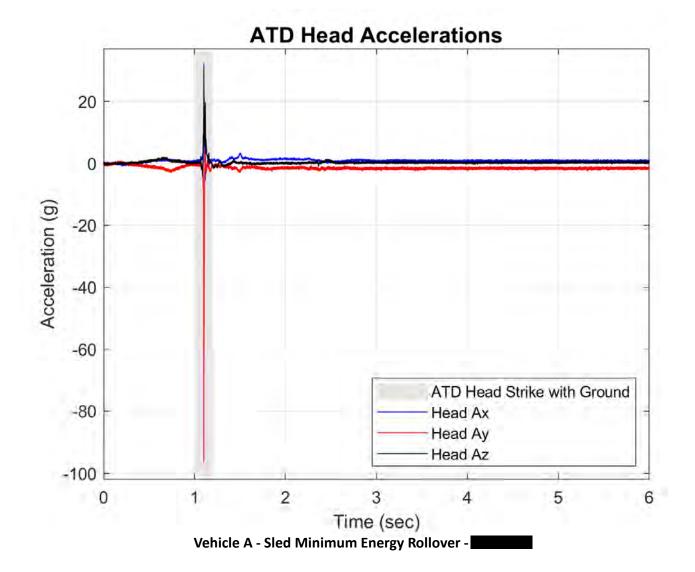
Drone Camera - Max Angle = 137.7° - Time = 1.62 sec

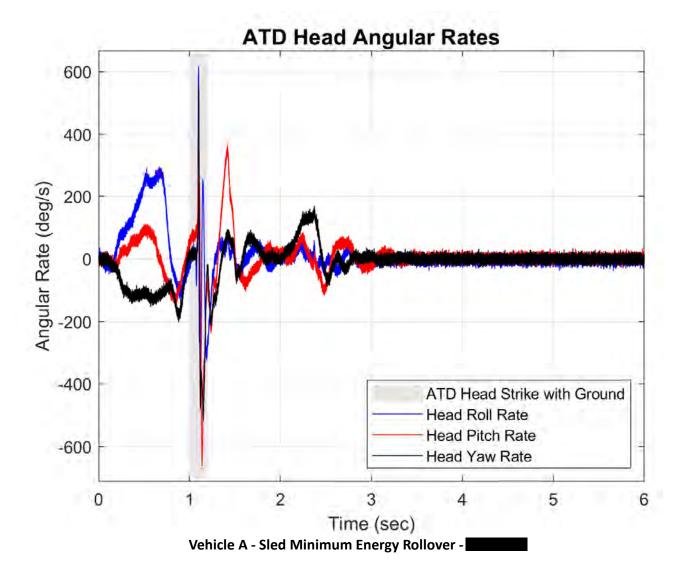


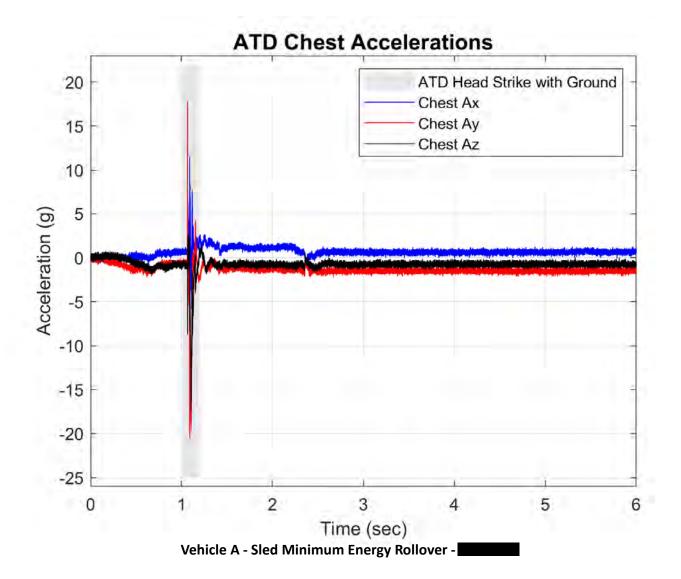
Drone Camera - End of Run - Roll Angle = 93.2°

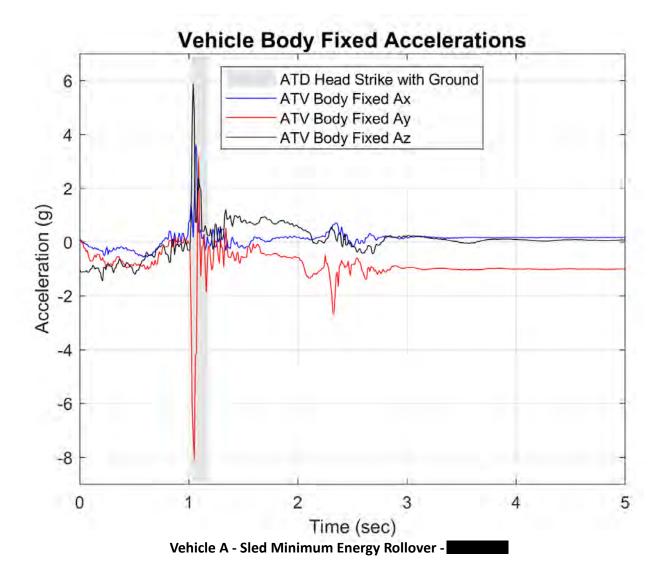


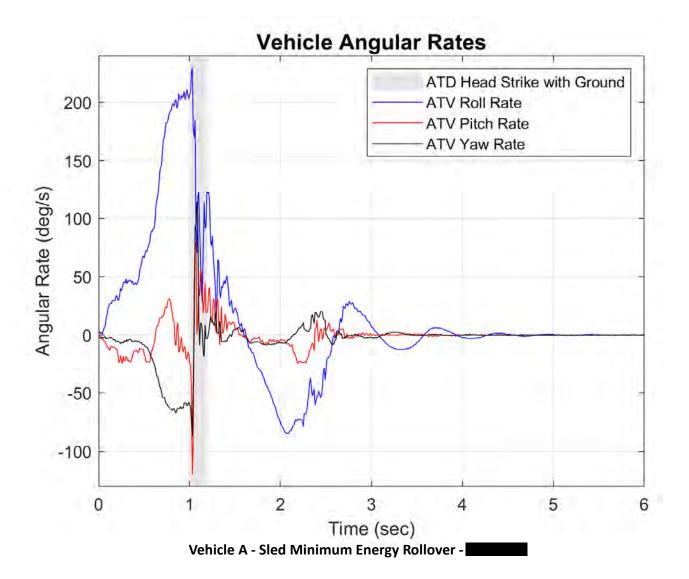
Vehicle A - Sled Minimum Energy Rollover -

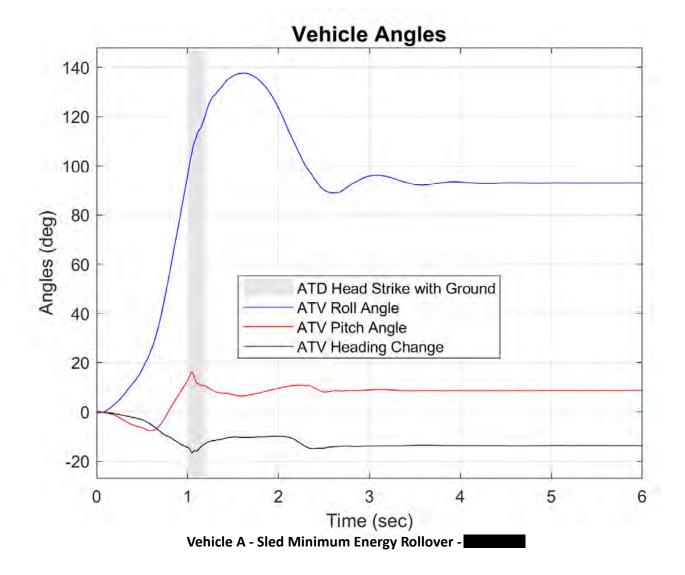




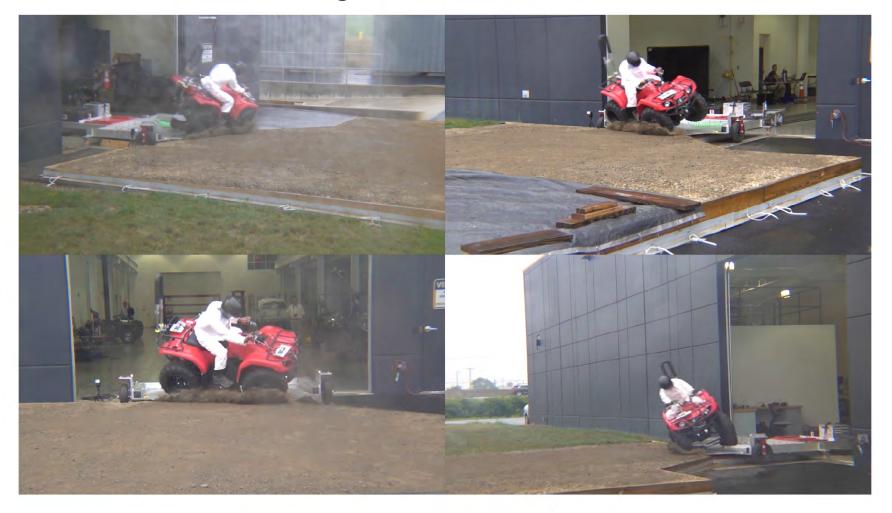






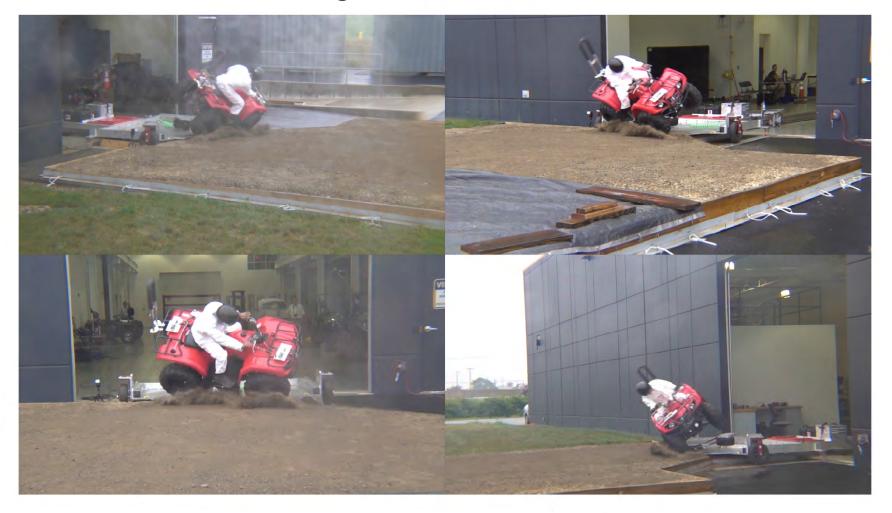


## Roll Angle = $30^{\circ}$ - Time = 0.67 sec



Vehicle A - Sled Minimum Energy Rollover -

## Roll Angle = $45^{\circ}$ - Time = 0.77 sec



Vehicle A - Sled Minimum Energy Rollover -

# Roll Angle = $90^{\circ}$ - Time = 1.03 sec



Vehicle A - Sled Minimum Energy Rollover -

### ATD Head Strike - Time = 1.18 sec



Vehicle A - Sled Minimum Energy Rollover -

## Max Roll Angle = $136.6^{\circ}$ - Time = 1.67 sec



Vehicle A - Sled Minimum Energy Rollover -

## End of Run - Roll Angle = 92.4°



Vehicle A - Sled Minimum Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.67 sec



Drone Camera - Roll Angle = 45° - Time = 0.77 sec



Drone Camera - Roll Angle = 90° - Time = 1.03 sec



Drone Camera - ATD Head Strike - Time = 1.18 sec



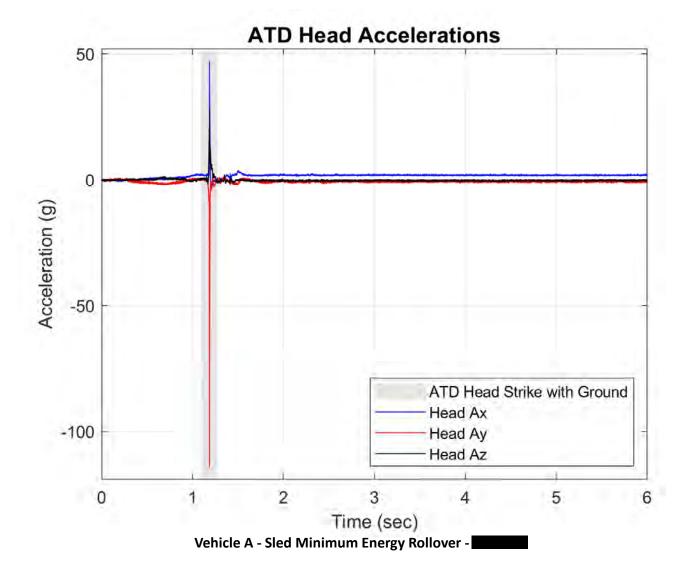
Drone Camera - Max Angle = 136.6° - Time = 1.67 sec

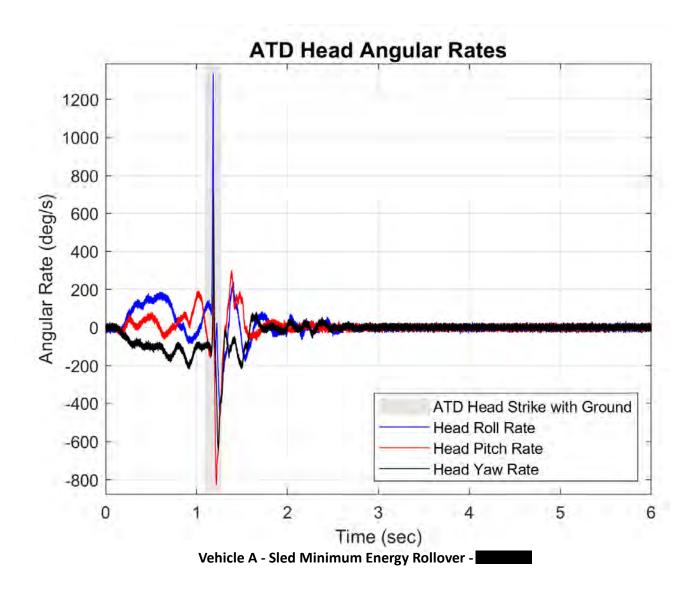


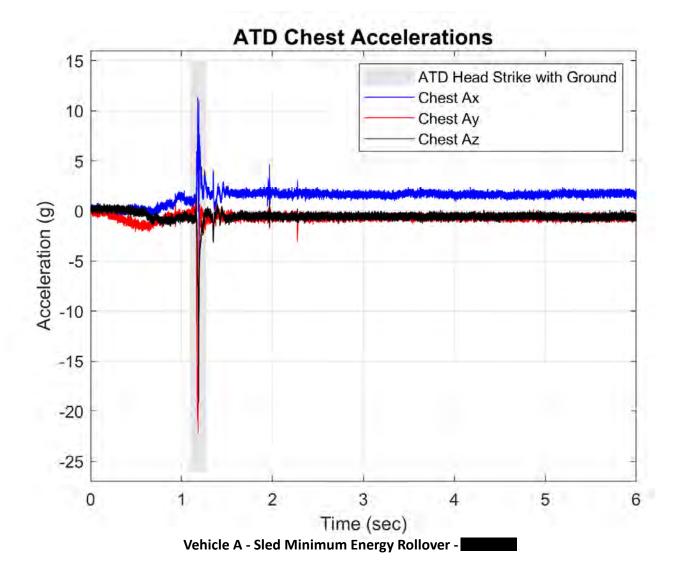
Drone Camera - End of Run - Roll Angle = 92.4°

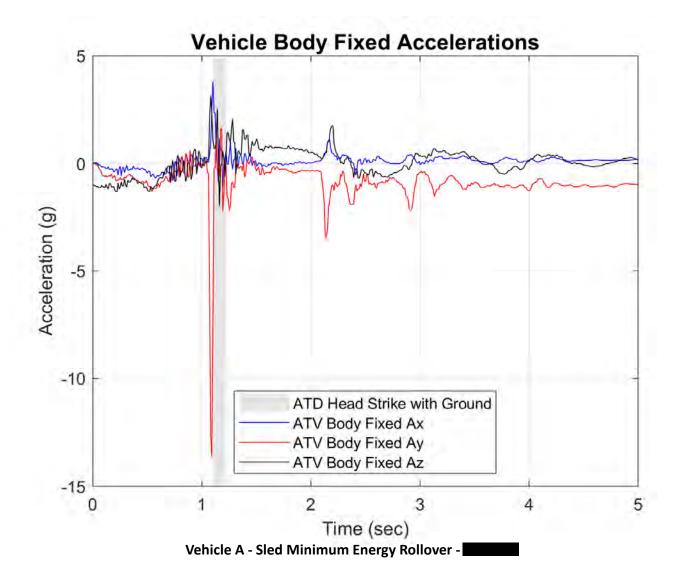


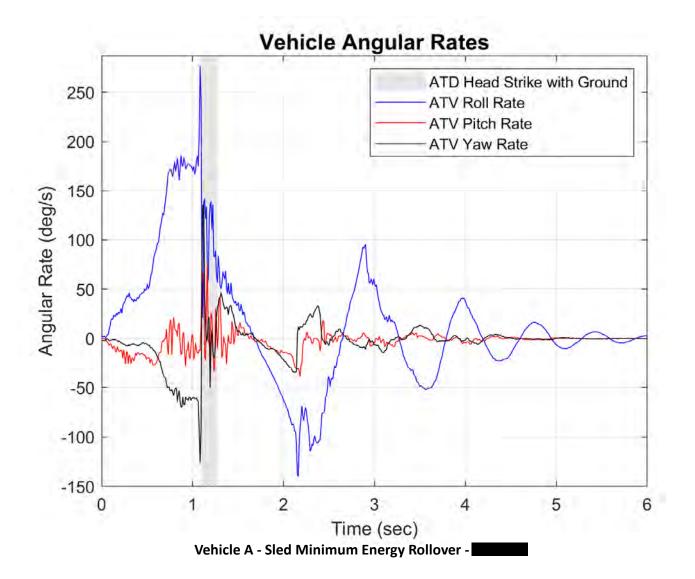
Vehicle A - Sled Minimum Energy Rollover -

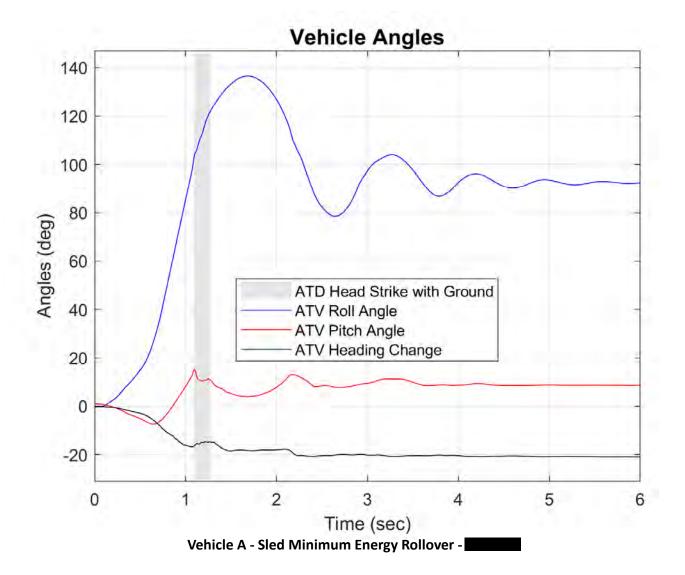










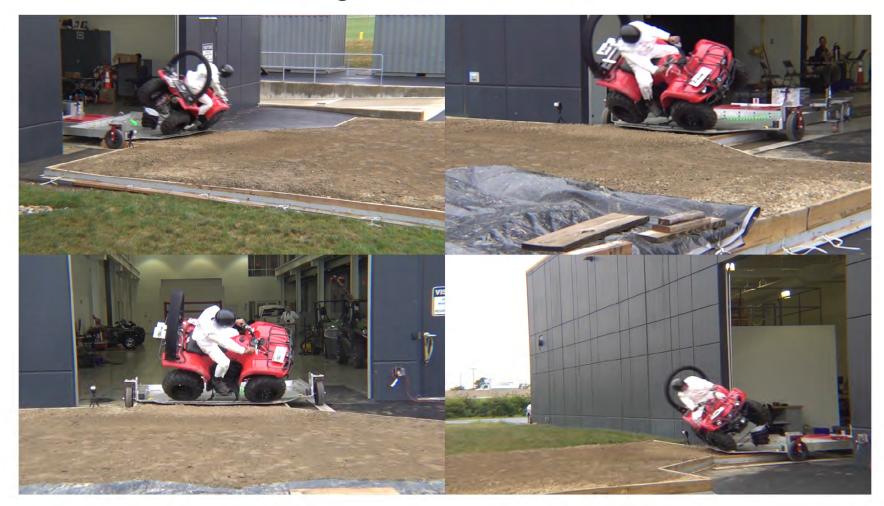


## Roll Angle = $30^{\circ}$ - Time = 0.52 sec



Vehicle A - Sled Moderate Energy Rollover -

## Roll Angle = $45^{\circ}$ - Time = 0.64 sec



Vehicle A - Sled Moderate Energy Rollover -

# Roll Angle = $90^{\circ}$ - Time = 0.87 sec



Vehicle A - Sled Moderate Energy Rollover -

### ATD Head Strike - Time = 0.99 sec



Vehicle A - Sled Moderate Energy Rollover -

## Roll Angle = $180^{\circ}$ - Time = 1.36 sec



Vehicle A - Sled Moderate Energy Rollover -

### Roll Angle = $270^{\circ}$ - Time = 2.06 sec



Vehicle A - Sled Moderate Energy Rollover -

# Max Roll Angle = $295.0^{\circ}$ - Time = 2.59 sec



Vehicle A - Sled Moderate Energy Rollover -

### End of Run - Roll Angle = 274.0°

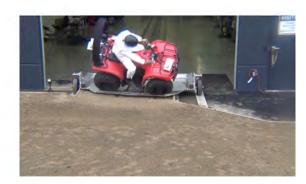


Vehicle A - Sled Moderate Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.52 sec



Drone Camera - Roll Angle =  $45^{\circ}$  - Time = 0.64 sec



Drone Camera - Roll Angle = 90° - Time = 0.87 sec



Drone Camera - ATD Head Strike - Time = 0.99 sec



Drone Camera - Roll Angle = 180° - Time = 1.36 sec



Drone Camera - Roll Angle = 270° - Time = 2.06 sec



Vehicle A - Sled Moderate Energy Rollover -

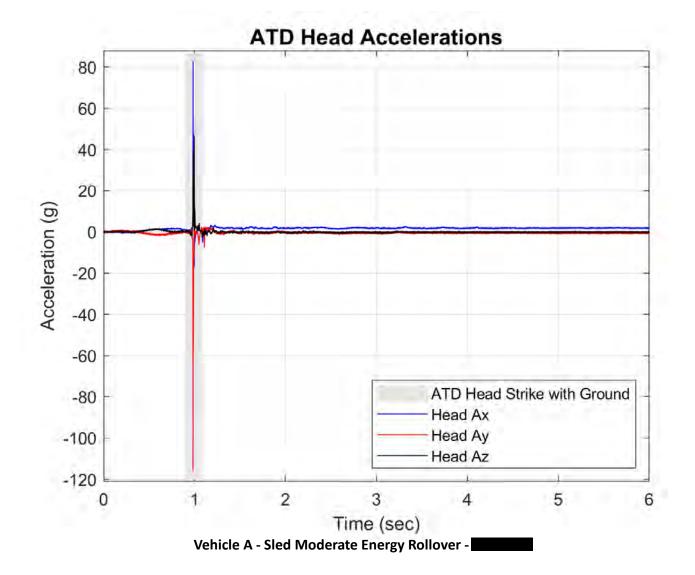
Drone Camera - Max Angle = 295.0° - Time = 2.59 sec

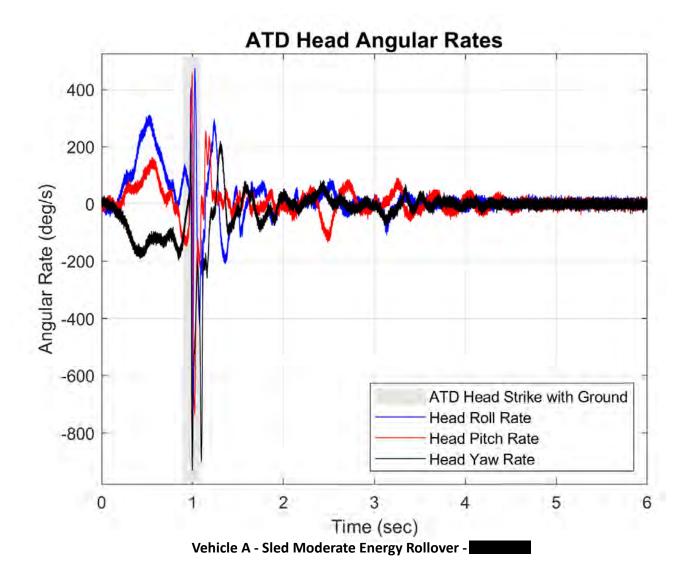
Drone Camera - End of Run - Roll Angle = 274.0°

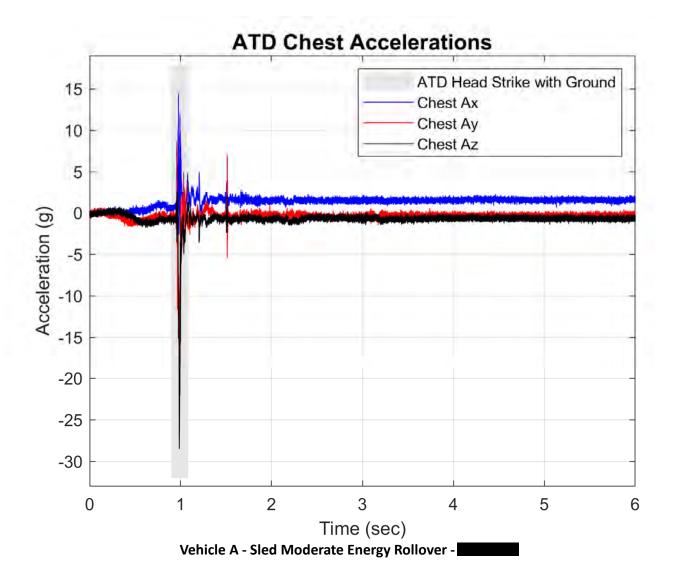


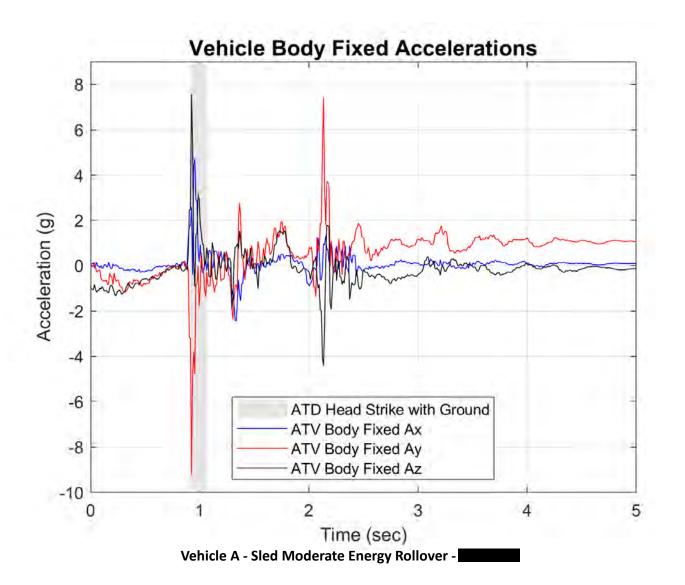


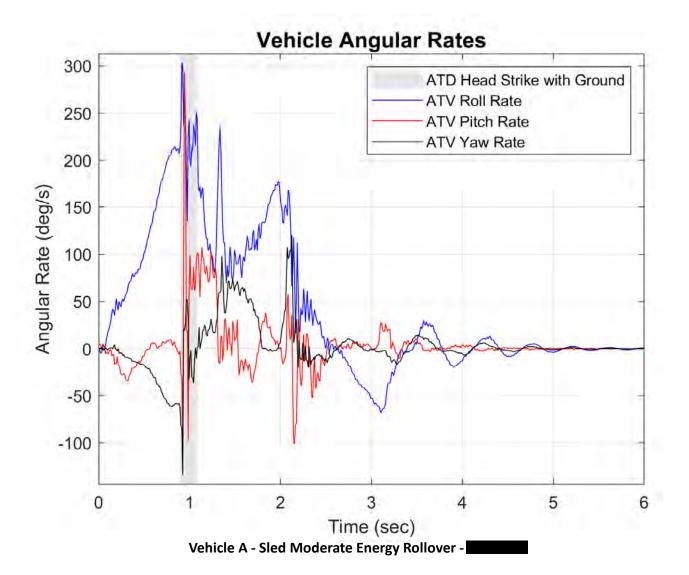
Vehicle A - Sled Moderate Energy Rollover -

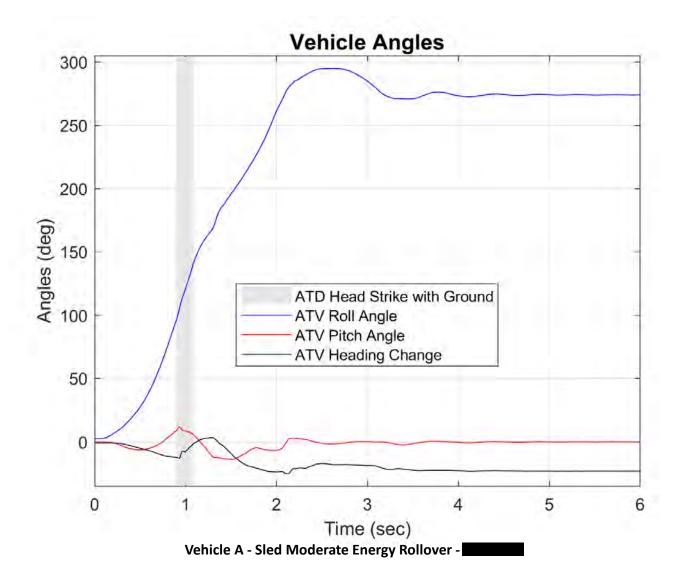










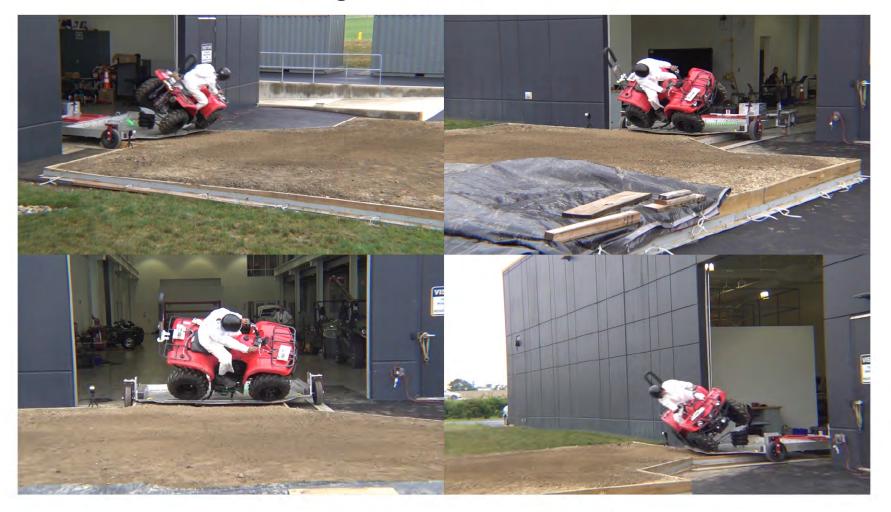


### Roll Angle = $30^{\circ}$ - Time = 0.51 sec



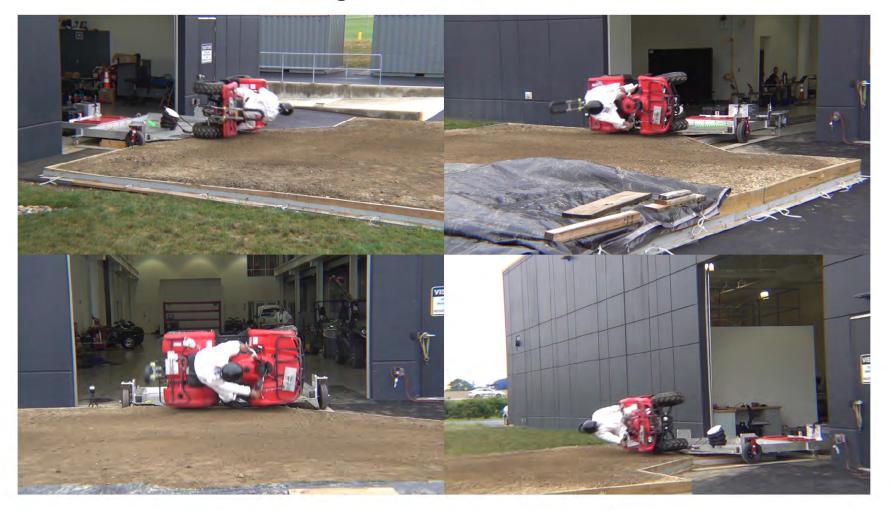
Vehicle A - Sled Moderate Energy Rollover -

### Roll Angle = $45^{\circ}$ - Time = 0.63 sec



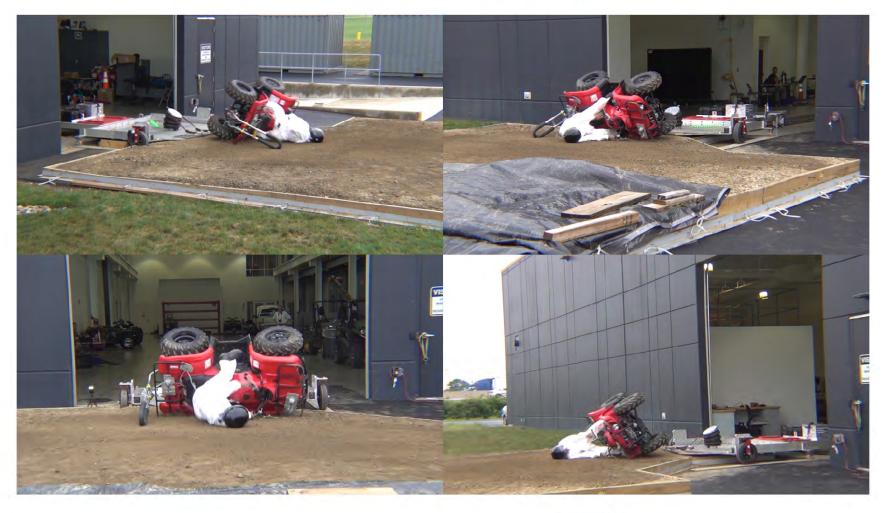
Vehicle A - Sled Moderate Energy Rollover -

# Roll Angle = $90^{\circ}$ - Time = 0.86 sec



Vehicle A - Sled Moderate Energy Rollover -

#### ATD Head Strike - Time = 0.98 sec



Vehicle A - Sled Moderate Energy Rollover -

### Roll Angle = $180^{\circ}$ - Time = 1.41 sec



Vehicle A - Sled Moderate Energy Rollover -

### Roll Angle = $270^{\circ}$ - Time = 1.95 sec



Vehicle A - Sled Moderate Energy Rollover -

### Roll Angle = $360^{\circ}$ - Time = 2.75 sec



Vehicle A - Sled Moderate Energy Rollover -

### Max Roll Angle = $369.4^{\circ}$ - Time = 2.94 sec



Vehicle A - Sled Moderate Energy Rollover -

### End of Run - Roll Angle = 355.5°

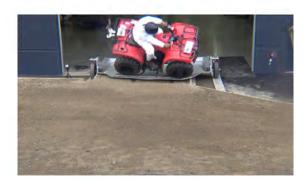


Vehicle A - Sled Moderate Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.51 sec



Drone Camera - Roll Angle = 45° - Time = 0.63 sec



Drone Camera - Roll Angle = 90° - Time = 0.86 sec



Drone Camera - ATD Head Strike - Time = 0.98 sec



Drone Camera - Roll Angle = 180° - Time = 1.41 sec



Drone Camera - Roll Angle = 270° - Time = 1.95 sec



Vehicle A - Sled Moderate Energy Rollover -

Drone Camera - Roll Angle = 360° - Time = 2.75 sec

Drone Camera - Max Angle = 369.4° - Time = 2.94 sec

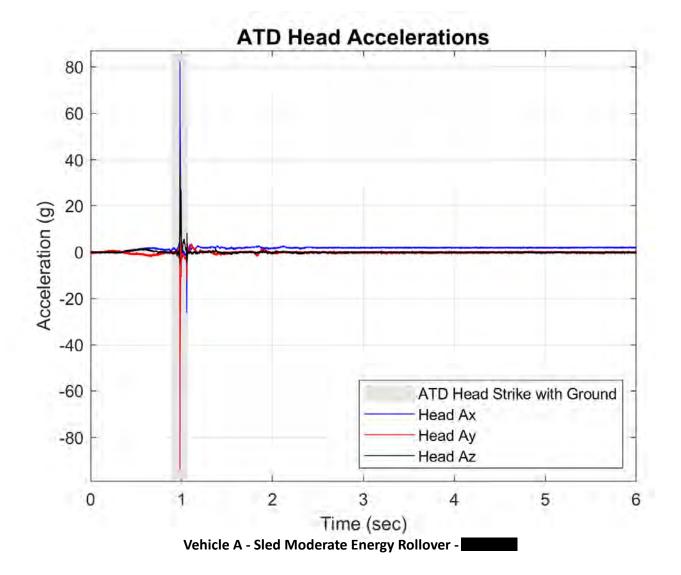
Drone Camera - End of Run - Roll Angle = 355.5°

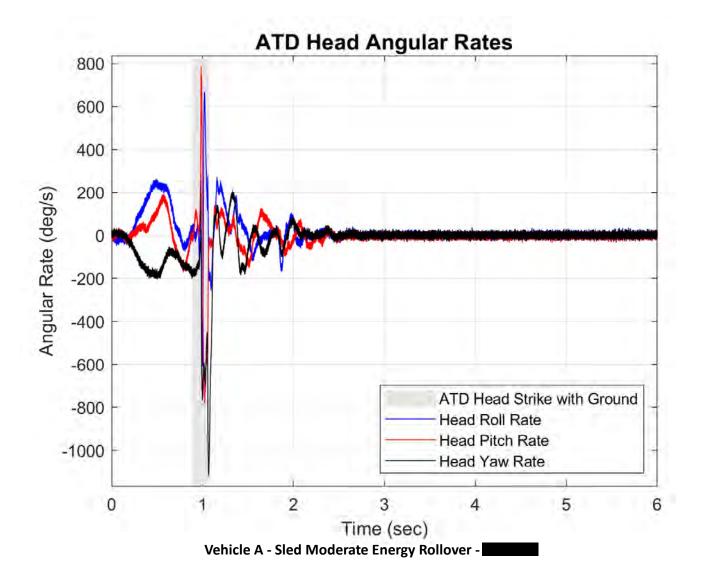


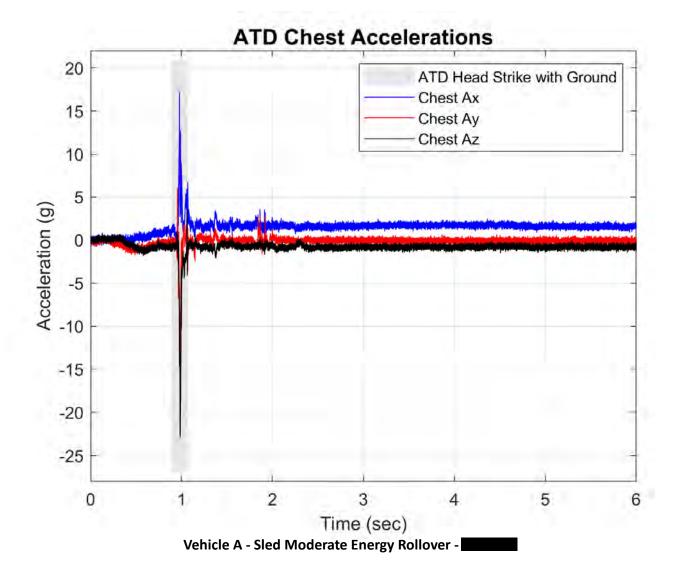


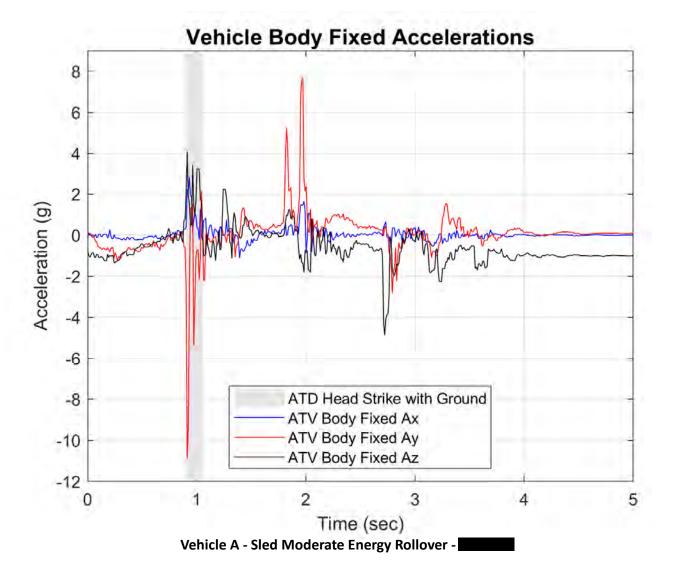


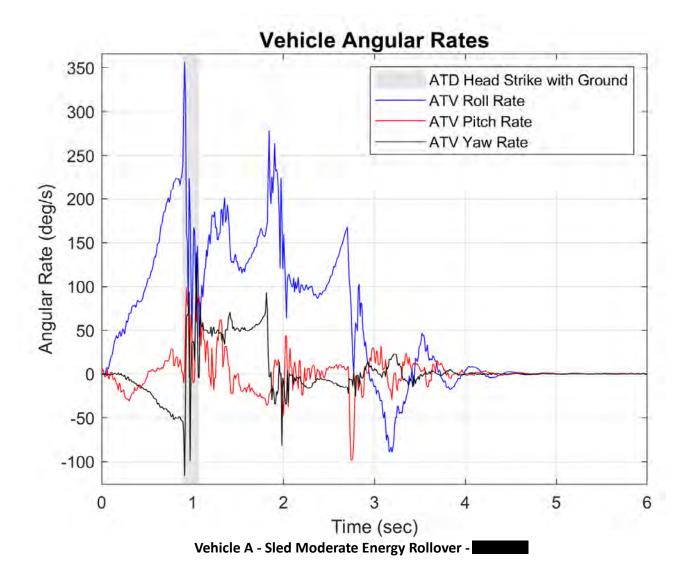
Vehicle A - Sled Moderate Energy Rollover -

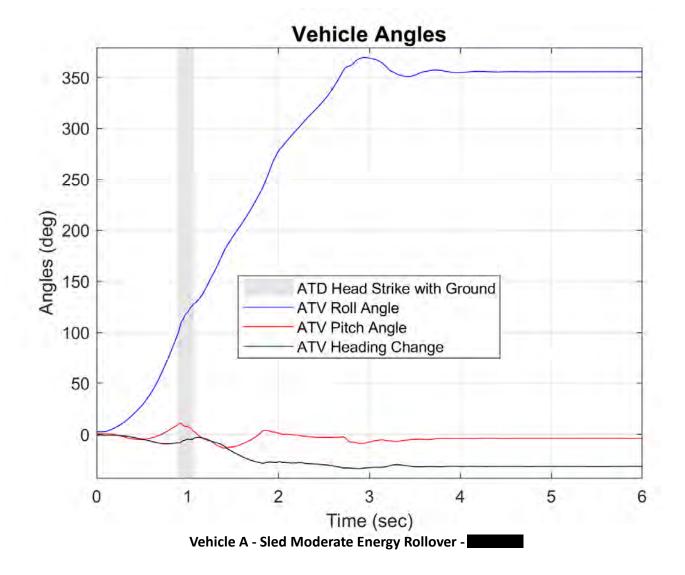












### Roll Angle = $30^{\circ}$ - Time = 0.55 sec



Vehicle C - Sled Minimum Energy Rollover -

### Roll Angle = $45^{\circ}$ - Time = 0.65 sec



Vehicle C - Sled Minimum Energy Rollover -

# Roll Angle = $90^{\circ}$ - Time = 0.88 sec



Vehicle C - Sled Minimum Energy Rollover -

#### ATD Head Strike - Time = 1.05 sec



Vehicle C - Sled Minimum Energy Rollover -

### Max Roll Angle = $157.8^{\circ}$ - Time = 1.92 sec



Vehicle C - Sled Minimum Energy Rollover -

### End of Run - Roll Angle = $93.7^{\circ}$



Vehicle C - Sled Minimum Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.55 sec



Drone Camera - Roll Angle = 45° - Time = 0.65 sec



Drone Camera - Roll Angle = 90° - Time = 0.88 sec



Drone Camera - ATD Head Strike - Time = 1.05 sec



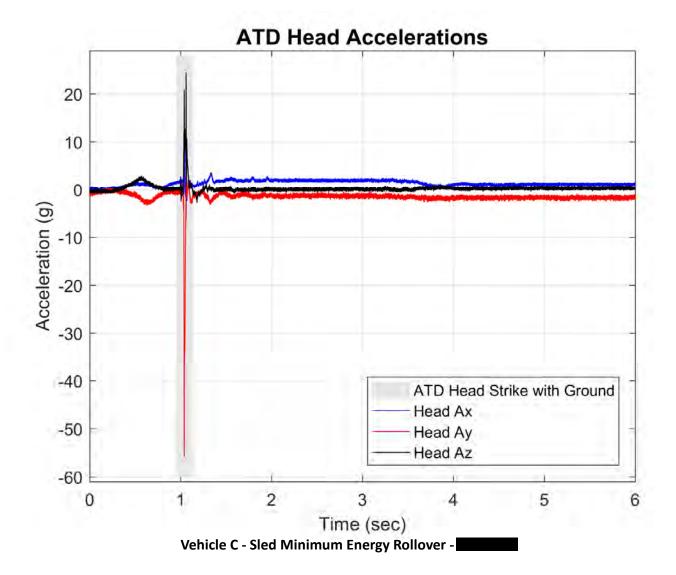
Drone Camera - Max Angle = 157.3° - Time = 1.92 sec

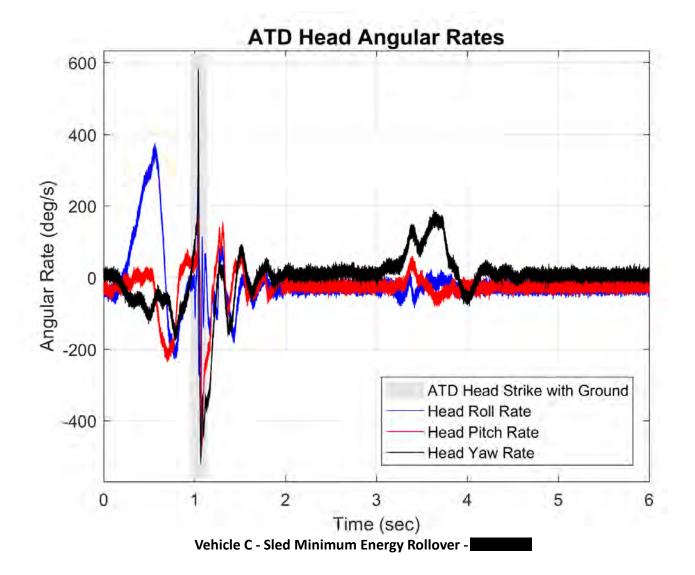


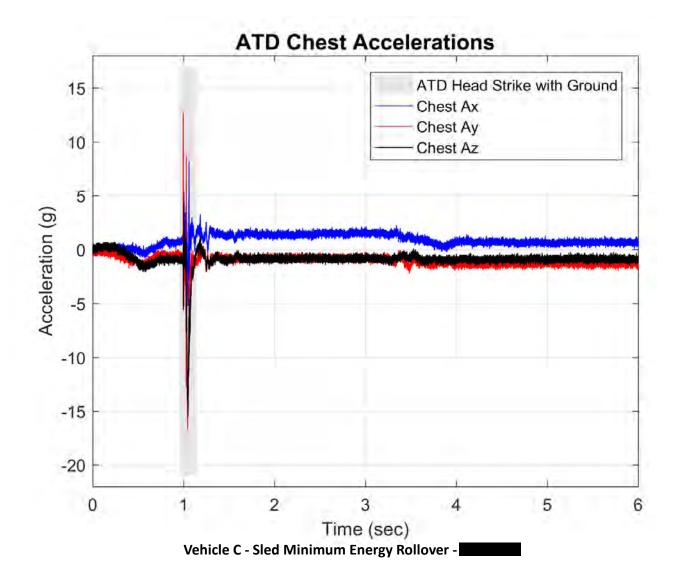
Drone Camera - End of Run - Roll Angle = 93.7°

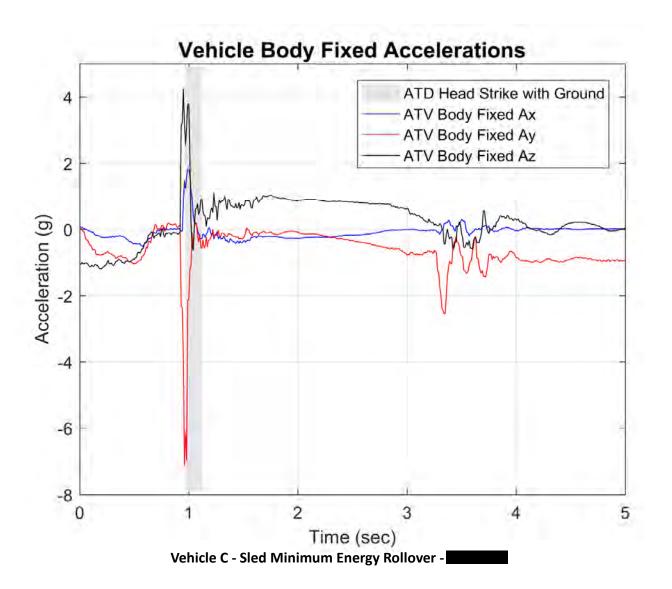


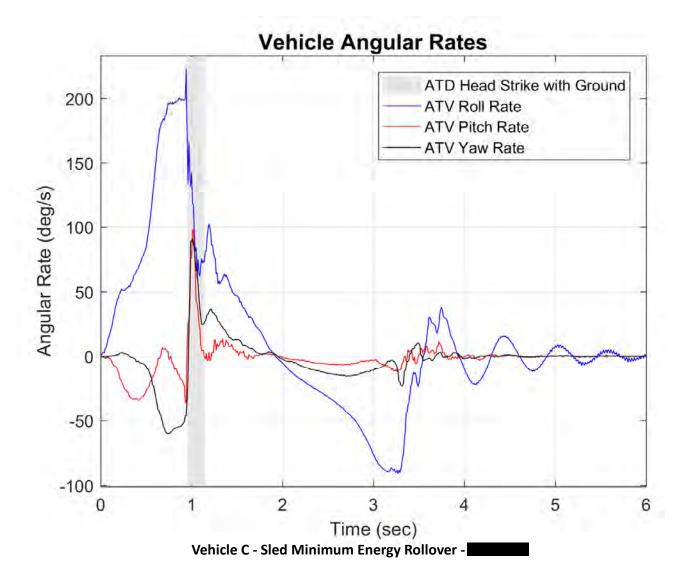
Vehicle C - Sled Minimum Energy Rollover -

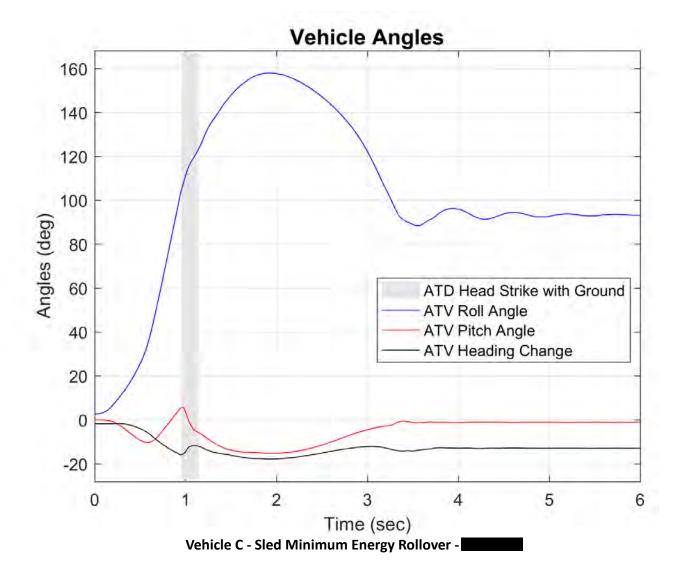












## Roll Angle = $30^{\circ}$ - Time = 0.54 sec



Vehicle C - Sled Minimum Energy Rollover -

### Roll Angle = $45^{\circ}$ - Time = 0.65 sec



Vehicle C - Sled Minimum Energy Rollover -

## Roll Angle = $90^{\circ}$ - Time = 0.89 sec



Vehicle C - Sled Minimum Energy Rollover -

### ATD Head Strike - Time = 1.06 sec



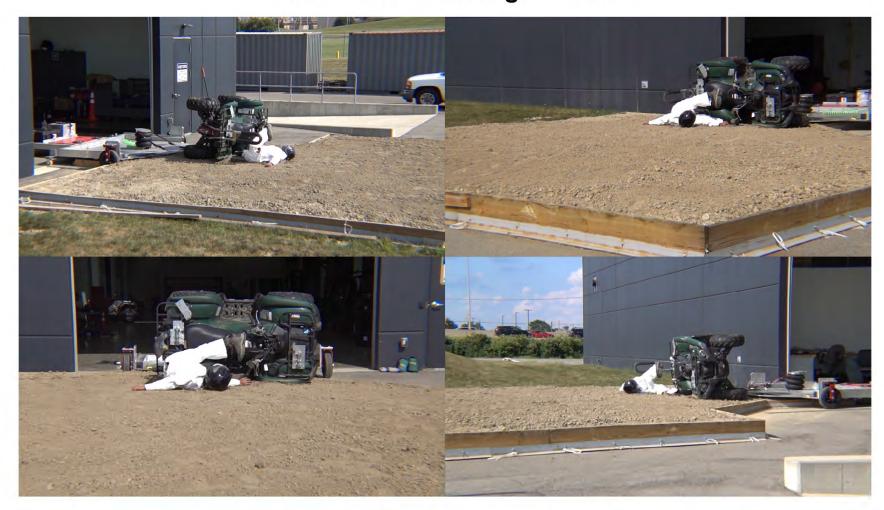
Vehicle C - Sled Minimum Energy Rollover -

## Max Roll Angle = $147.2^{\circ}$ - Time = 1.68 sec



Vehicle C - Sled Minimum Energy Rollover -

## End of Run - Roll Angle = 94.3°



Vehicle C - Sled Minimum Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.54 sec



Drone Camera - Roll Angle = 45° - Time = 0.65 sec



Drone Camera - Roll Angle = 90° - Time = 0.89 sec



Drone Camera - ATD Head Strike - Time = 1.06 sec



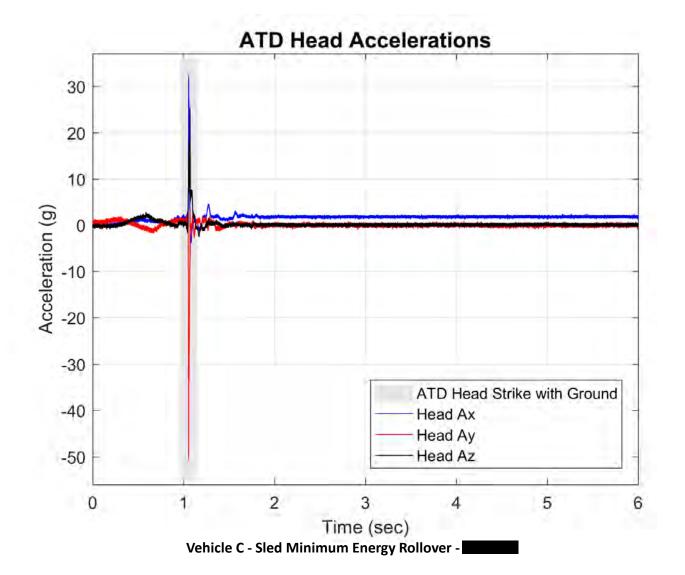
Drone Camera - Max Angle = 147.2° - Time = 1.68 sec

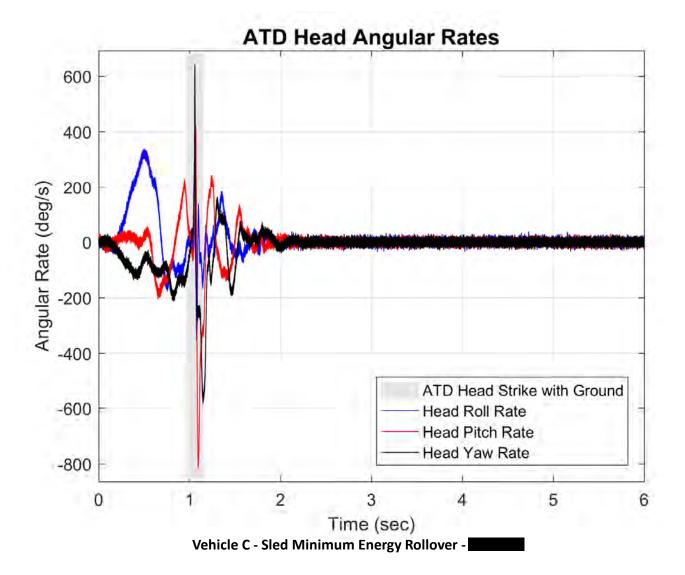


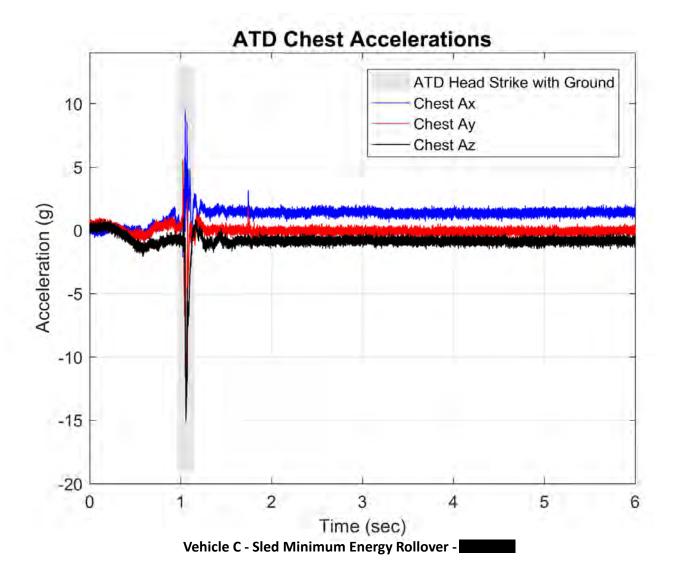
Drone Camera - End of Run - Roll Angle = 94.3°

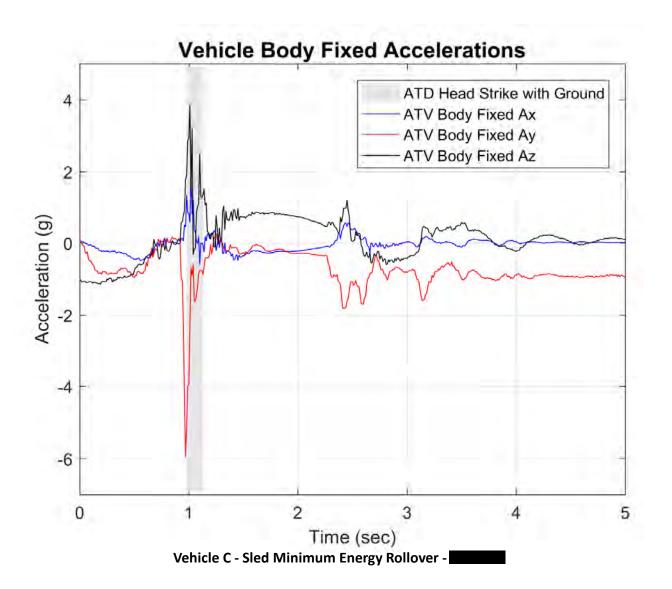


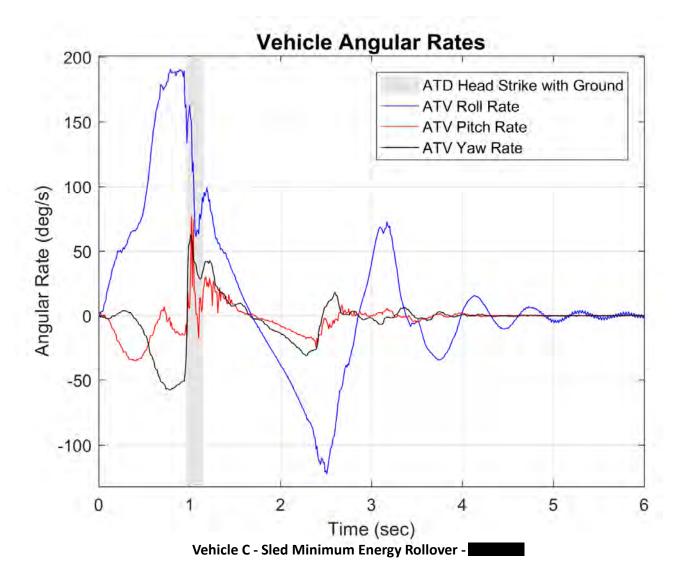
Vehicle C - Sled Minimum Energy Rollover -

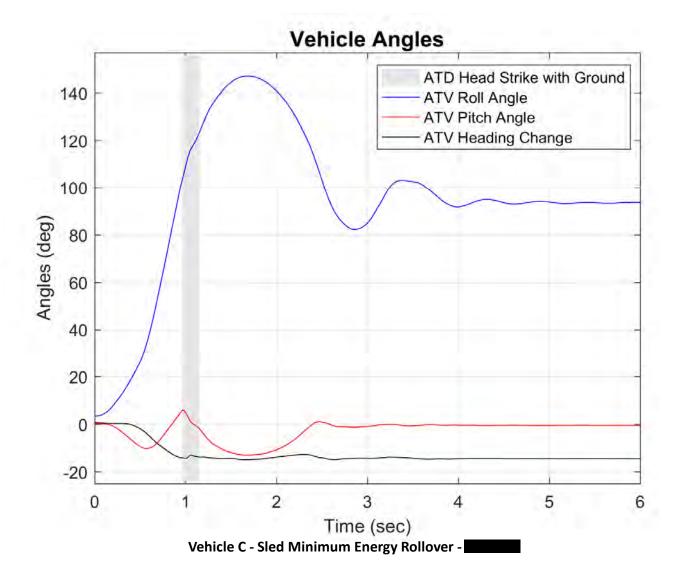












## Roll Angle = $30^{\circ}$ - Time = 0.42 sec



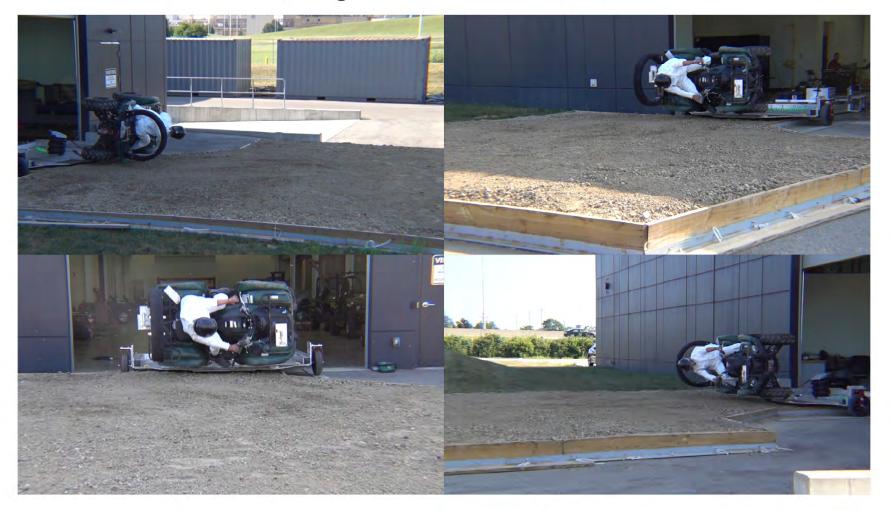
Vehicle C - Sled Moderate Energy Rollover -

## Roll Angle = $45^{\circ}$ - Time = 0.55 sec



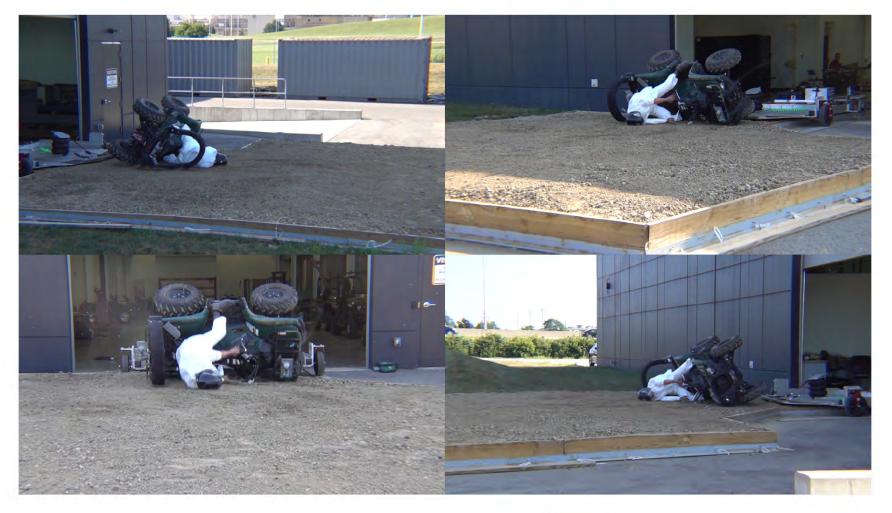
Vehicle C - Sled Moderate Energy Rollover -

# Roll Angle = $90^{\circ}$ - Time = 0.79 sec



Vehicle C - Sled Moderate Energy Rollover -

### ATD Head Strike - Time = 0.94 sec



Vehicle C - Sled Moderate Energy Rollover -

## Roll Angle = $180^{\circ}$ - Time = 1.26 sec



Vehicle C - Sled Moderate Energy Rollover -

## Roll Angle = $270^{\circ}$ - Time = 1.94 sec



Vehicle C - Sled Moderate Energy Rollover -

## Max Roll Angle = $301.0^{\circ}$ - Time = 2.55 sec



Vehicle C - Sled Moderate Energy Rollover -

## End of Run - Roll Angle = 271.7°



Vehicle C - Sled Moderate Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.42 sec



Drone Camera - Roll Angle = 45° - Time = 0.55 sec



Drone Camera - Roll Angle = 90° - Time = 0.79 sec



Drone Camera - ATD Head Strike - Time = 0.94 sec



Drone Camera - Roll Angle = 180° - Time = 1.26 sec



Drone Camera - Roll Angle = 270° - Time = 1.94 sec



Vehicle C - Sled Moderate Energy Rollover -

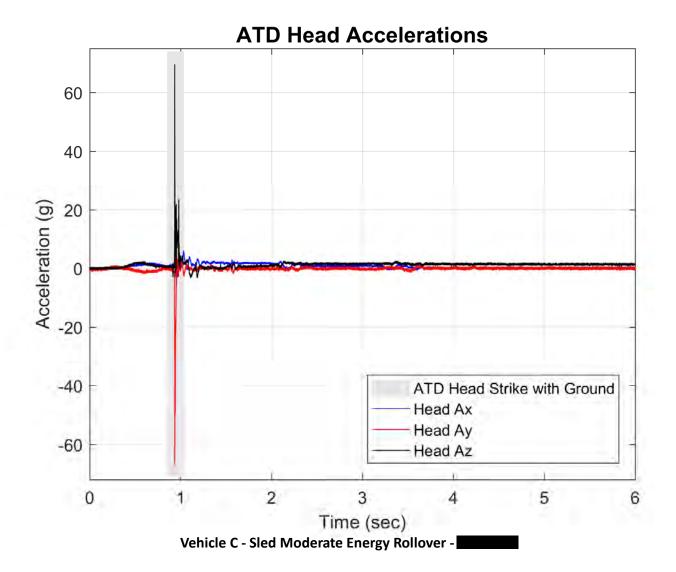
Drone Camera - Max Angle = 301.0° - Time = 2.55 sec

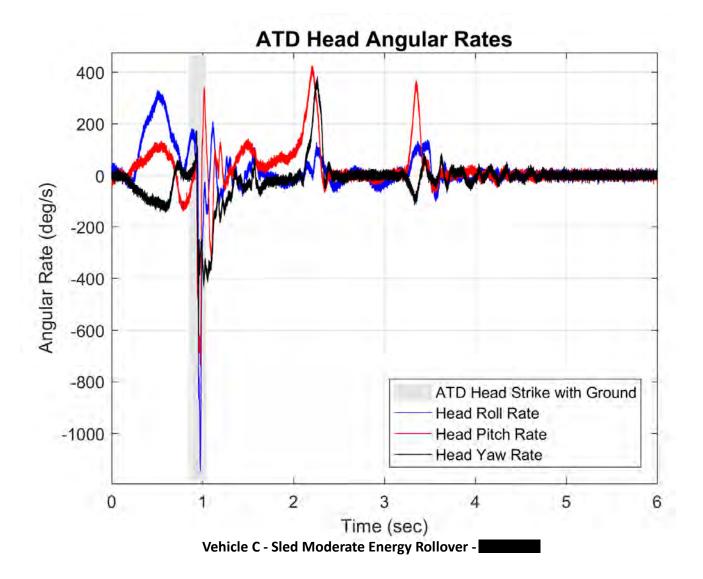
Drone Camera - End of Run - Roll Angle = 271.7°

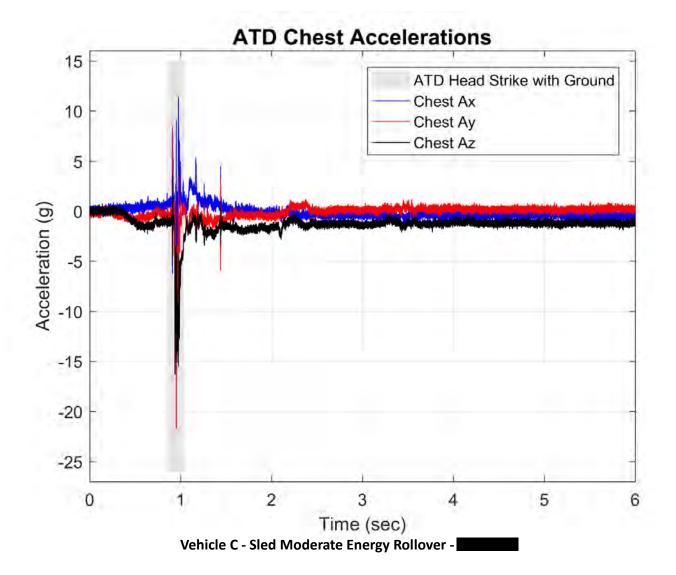


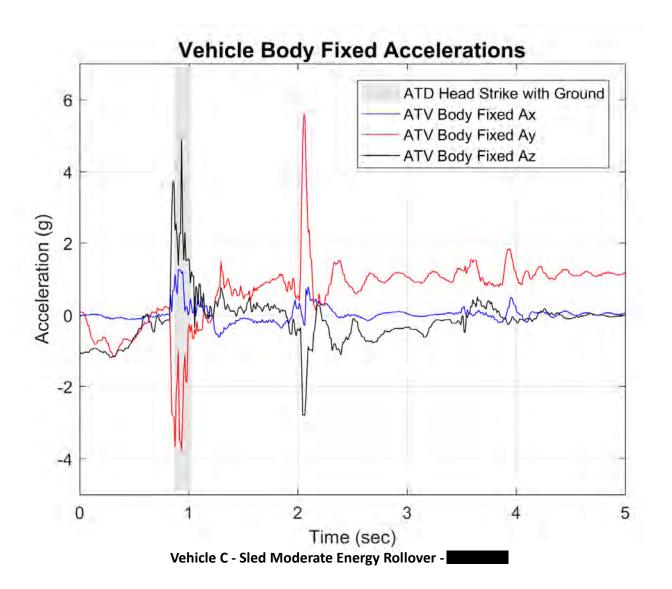


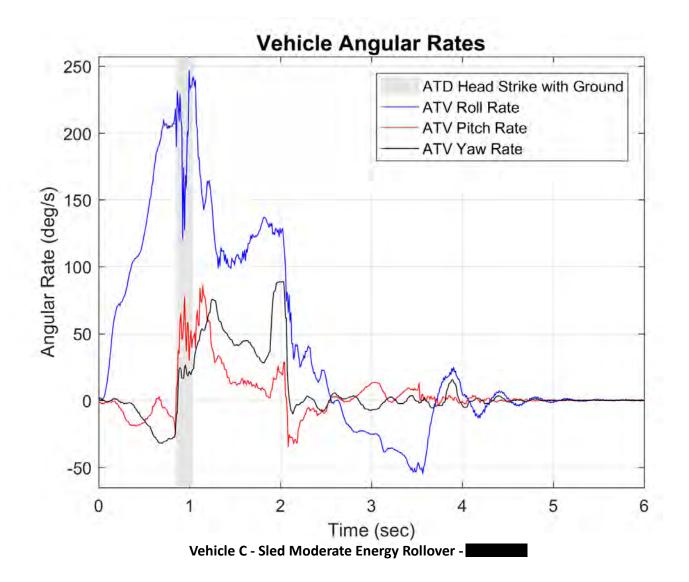
Vehicle C - Sled Moderate Energy Rollover -

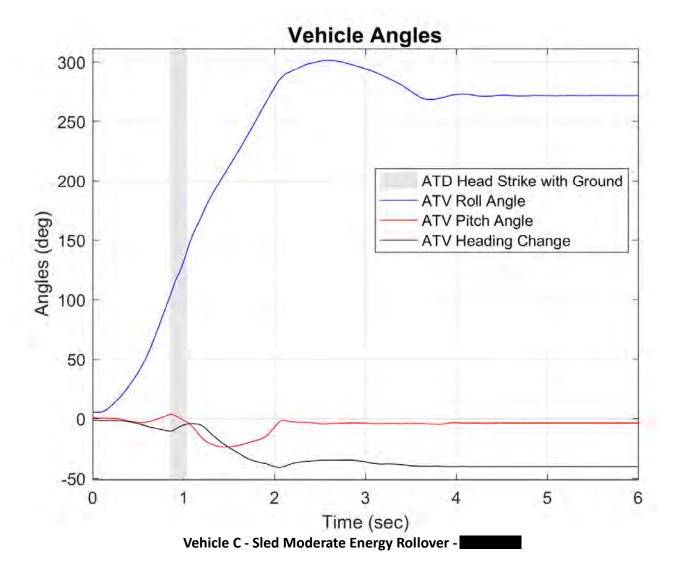




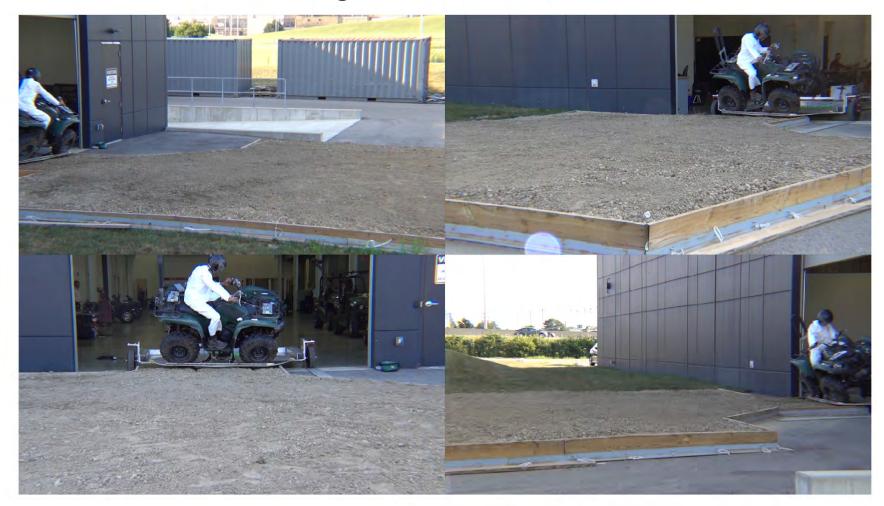








## Roll Angle = $30^{\circ}$ - Time = 0.43 sec



Vehicle C - Sled Moderate Energy Rollover -

## Roll Angle = $45^{\circ}$ - Time = 0.55 sec



Vehicle C - Sled Moderate Energy Rollover -

## Roll Angle = $90^{\circ}$ - Time = 0.80 sec



Vehicle C - Sled Moderate Energy Rollover -

### ATD Head Strike - Time = 0.95 sec



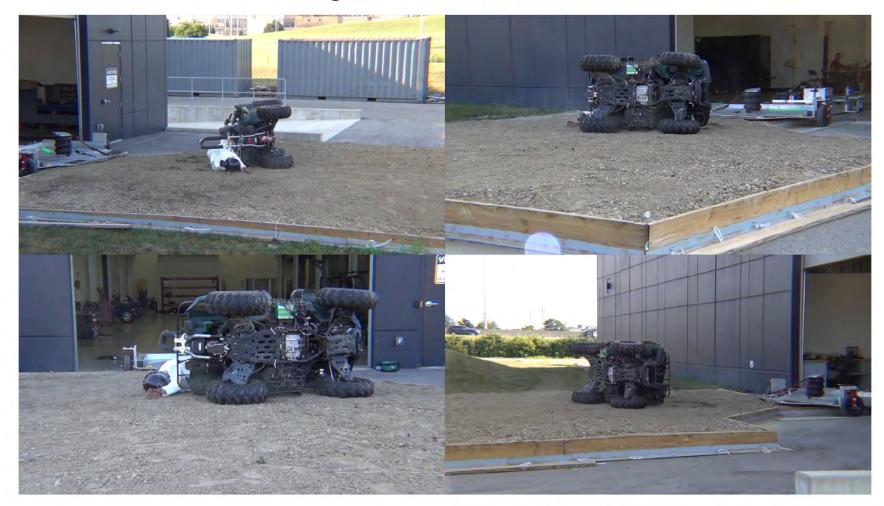
Vehicle C - Sled Moderate Energy Rollover -

## Roll Angle = $180^{\circ}$ - Time = 1.34 sec



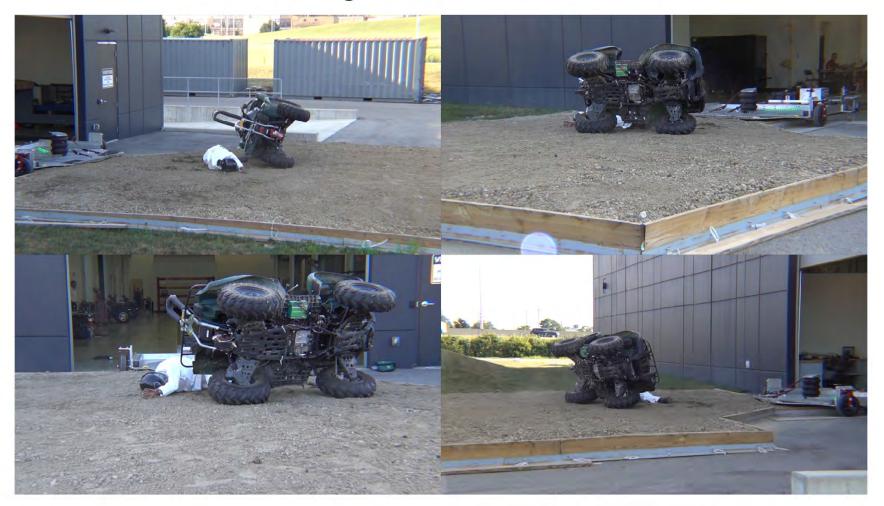
Vehicle C - Sled Moderate Energy Rollover -

## Roll Angle = $270^{\circ}$ - Time = 2.02 sec



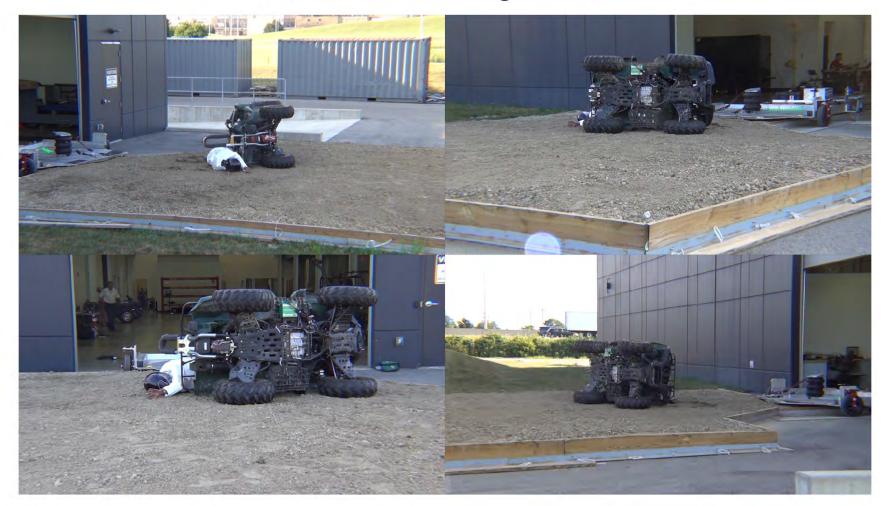
Vehicle C - Sled Moderate Energy Rollover -

## Max Roll Angle = $288.0^{\circ}$ - Time = 2.43 sec



Vehicle C - Sled Moderate Energy Rollover -

# End of Run - Roll Angle = 268.7 $^{\circ}$

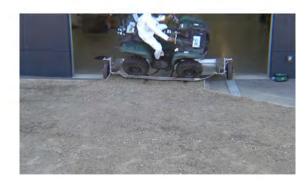


Vehicle C - Sled Moderate Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.43 sec



Drone Camera - Roll Angle = 45° - Time = 0.55 sec



Drone Camera - Roll Angle = 90° - Time = 0.8 sec



Drone Camera - ATD Head Strike - Time = 0.95 sec



Drone Camera - Roll Angle = 180° - Time = 1.34 sec



Drone Camera - Roll Angle = 270° - Time = 2.02 sec



Vehicle C - Sled Moderate Energy Rollover -

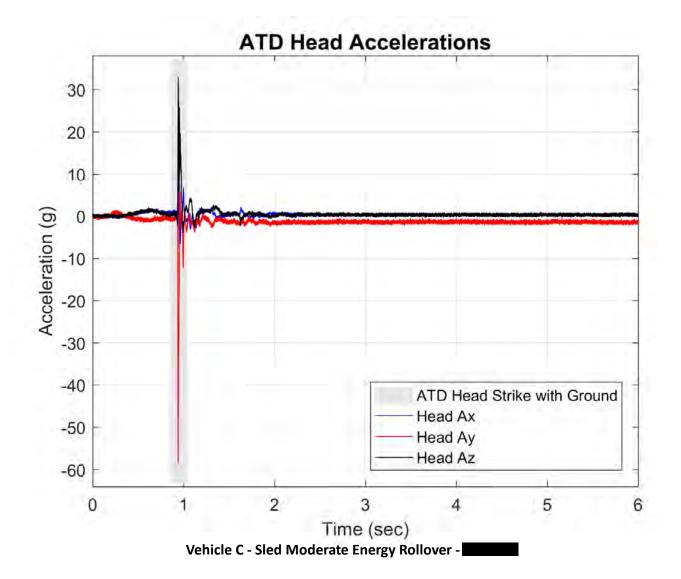
Drone Camera - Max Angle = 288.0° - Time = 2.43 sec

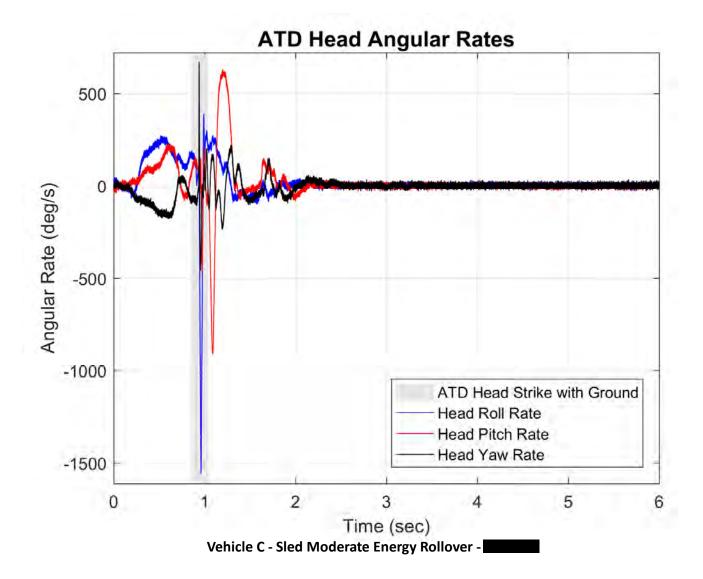
Drone Camera - End of Run - Roll Angle = 268.7°

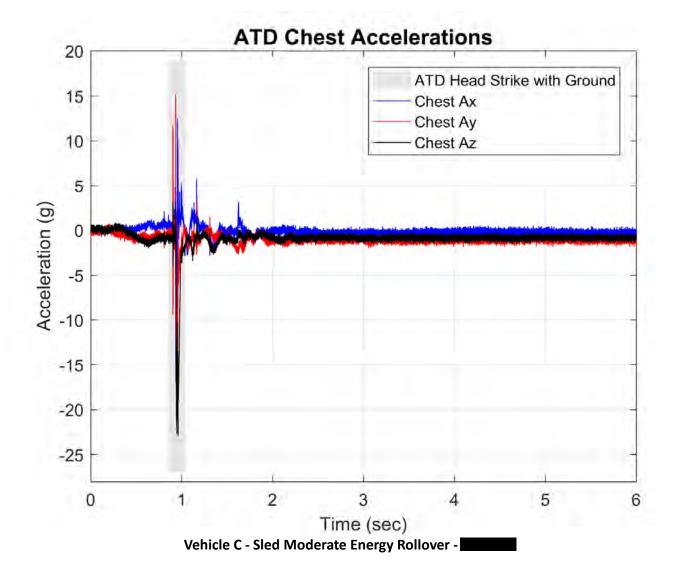


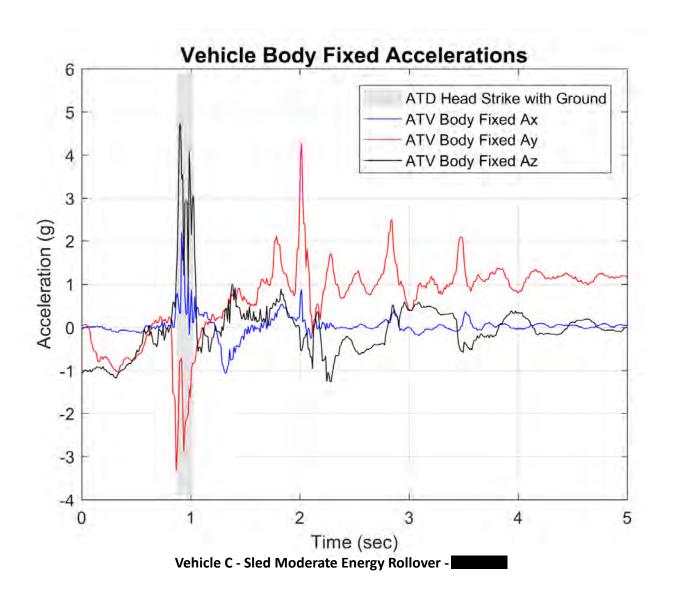


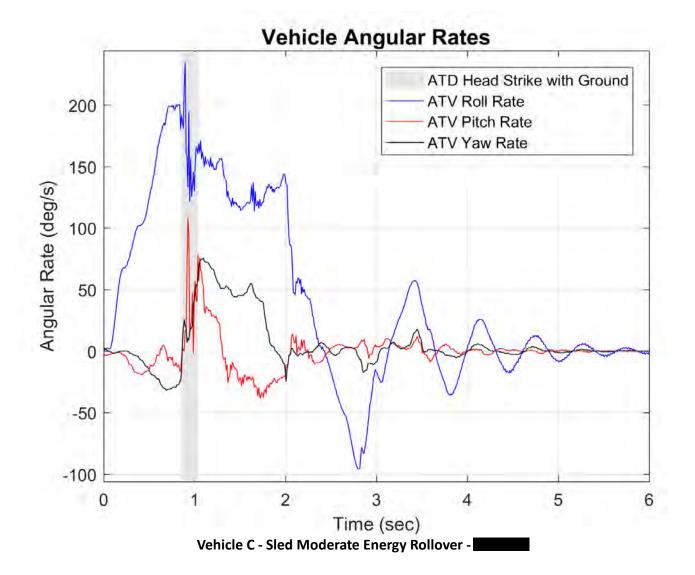
Vehicle C - Sled Moderate Energy Rollover -

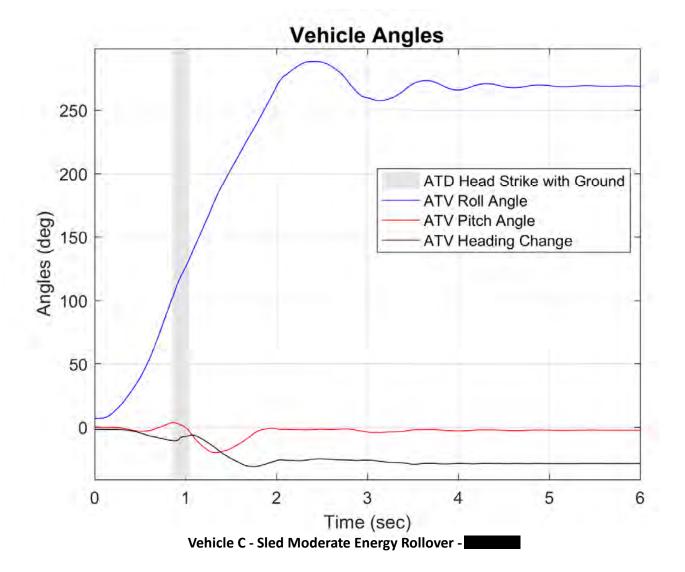












## Roll Angle = $30^{\circ}$ - Time = 0.63 sec



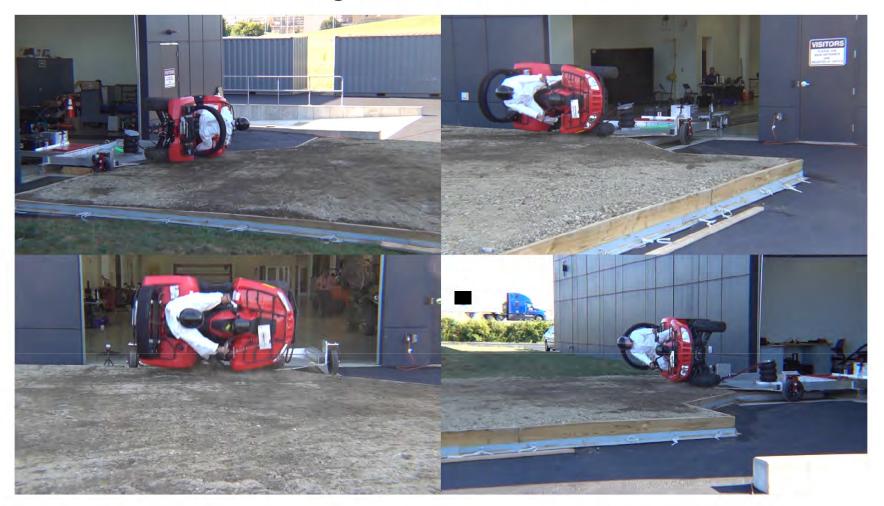
Vehicle E - Sled Minimum Energy Rollover -

## Roll Angle = $45^{\circ}$ - Time = 0.75 sec



Vehicle E - Sled Minimum Energy Rollover -

## Roll Angle = $90^{\circ}$ - Time = 1.02 sec



Vehicle E - Sled Minimum Energy Rollover -

#### ATD Head Strike - Time = 1.19 sec



Vehicle E - Sled Minimum Energy Rollover -

## Max Roll Angle = $128.8^{\circ}$ - Time = 1.70 sec



Vehicle E - Sled Minimum Energy Rollover -

## End of Run - Roll Angle = 94.0°

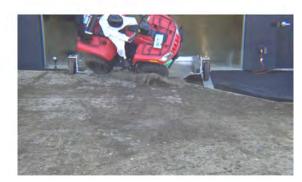


Vehicle E - Sled Minimum Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.63 sec



Drone Camera - Roll Angle = 45° - Time = 0.75 sec



Drone Camera - Roll Angle = 90° - Time = 1.02 sec



Drone Camera - ATD Head Strike - Time = 1.19 sec



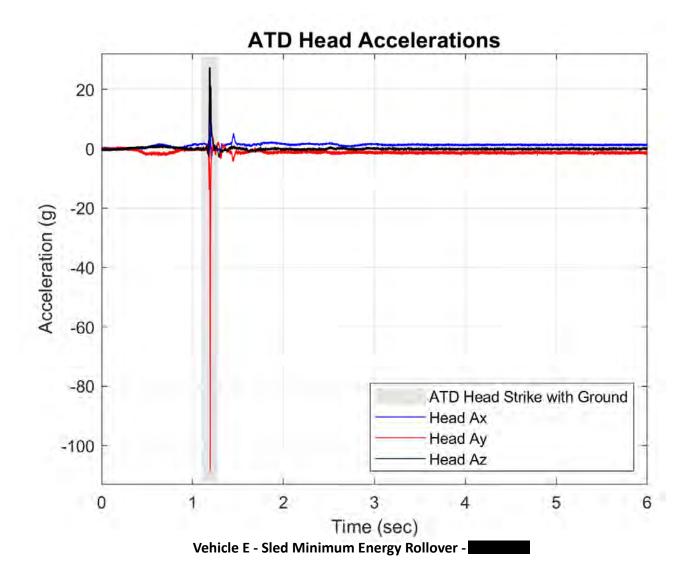
Drone Camera - Max Angle = 128.8° - Time = 1.70 sec

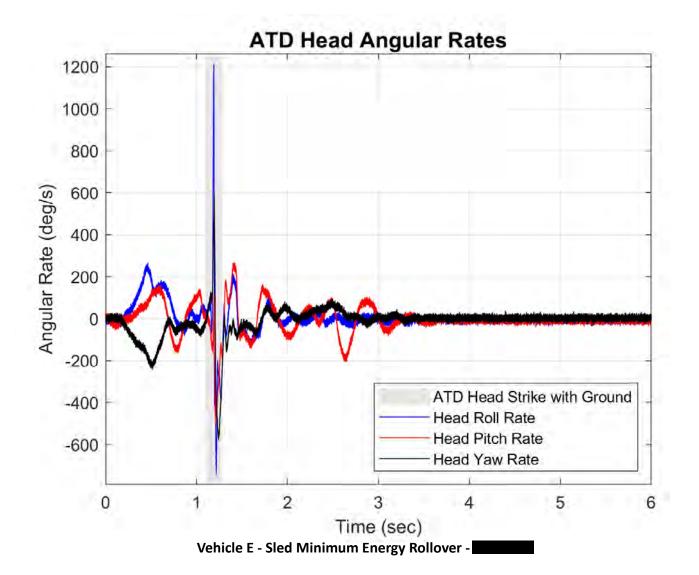


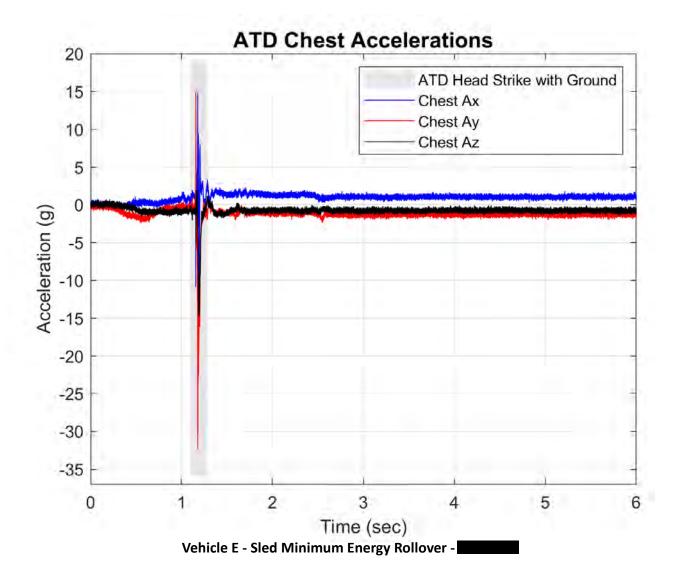
Drone Camera - End of Run - Roll Angle = 94.0°

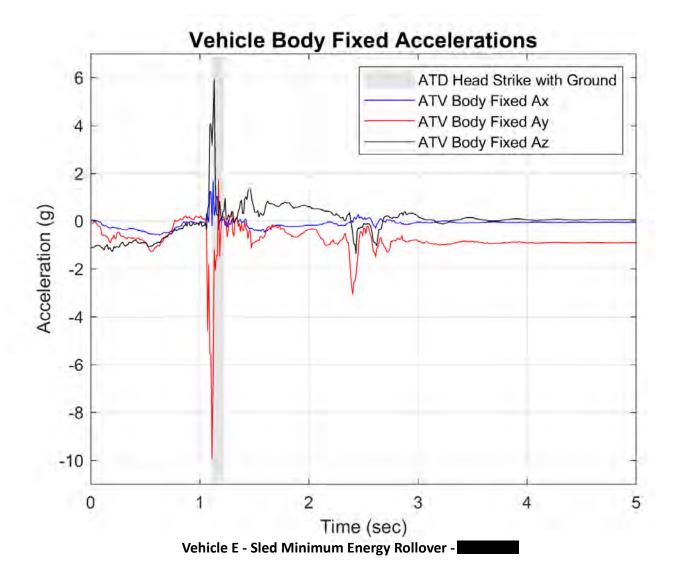


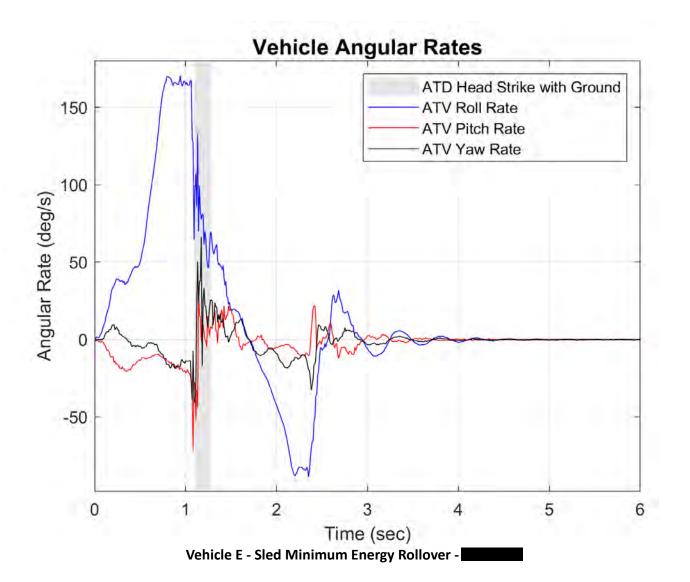
Vehicle E - Sled Minimum Energy Rollover -

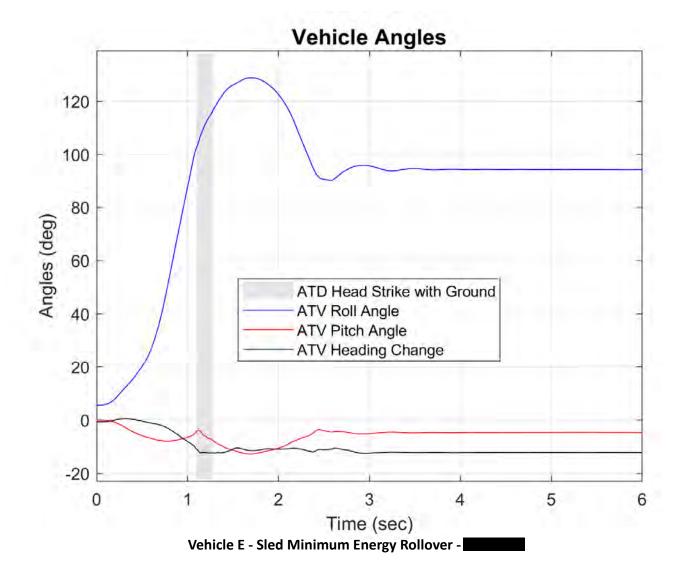












## Roll Angle = $30^{\circ}$ - Time = 0.60 sec



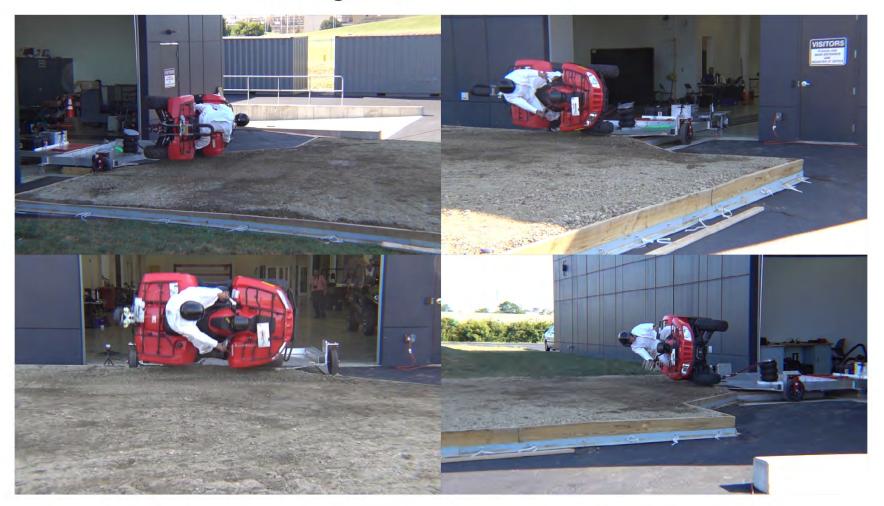
Vehicle E - Sled Minimum Energy Rollover -

## Roll Angle = $45^{\circ}$ - Time = 0.72 sec



Vehicle E - Sled Minimum Energy Rollover -

## Roll Angle = $90^{\circ}$ - Time = 0.96 sec



Vehicle E - Sled Minimum Energy Rollover -

#### ATD Head Strike - Time = 1.16 sec



Vehicle E - Sled Minimum Energy Rollover -

## Max Roll Angle = $128.2^{\circ}$ - Time = 1.60 sec



Vehicle E - Sled Minimum Energy Rollover -

## End of Run - Roll Angle = 95.9°



Vehicle E - Sled Minimum Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.60 sec



Drone Camera - Roll Angle = 45° - Time = 0.72 sec



Drone Camera - Roll Angle = 90° - Time = 0.96 sec



Drone Camera - ATD Head Strike - Time = 1.16 sec



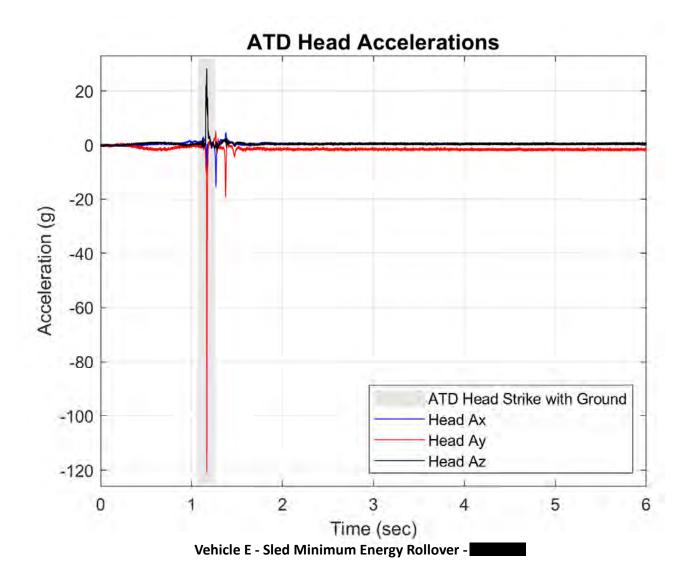
Drone Camera - Max Angle = 128.2° - Time = 1.60 sec

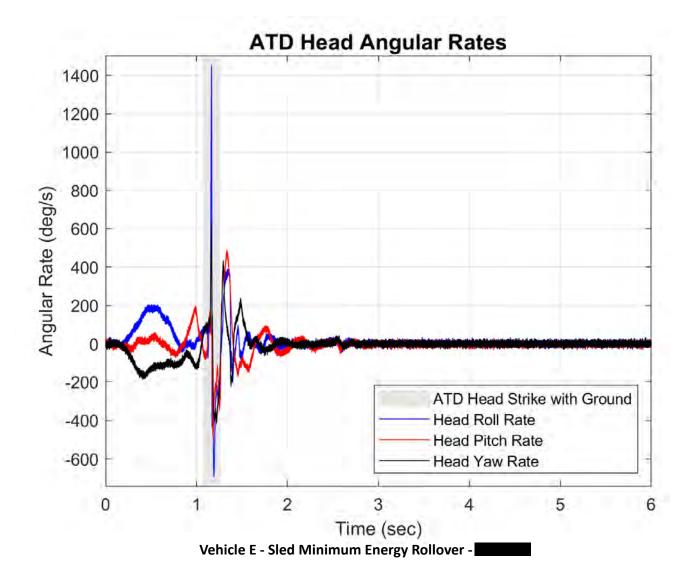


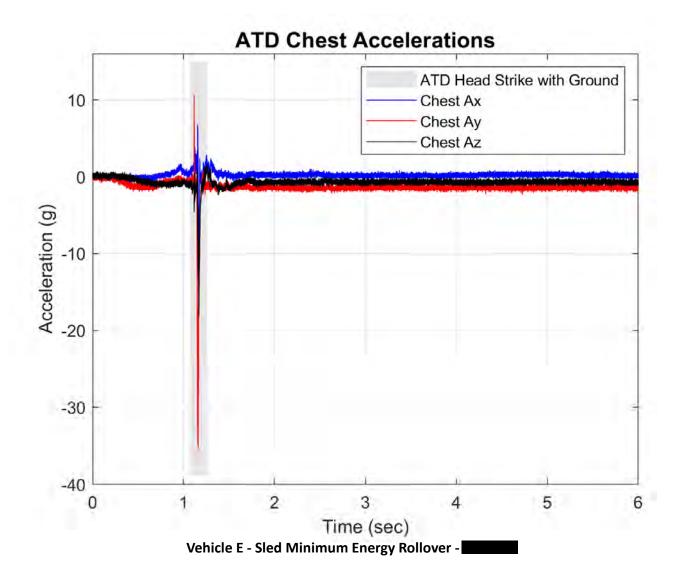
Drone Camera - End of Run - Roll Angle = 95.9°

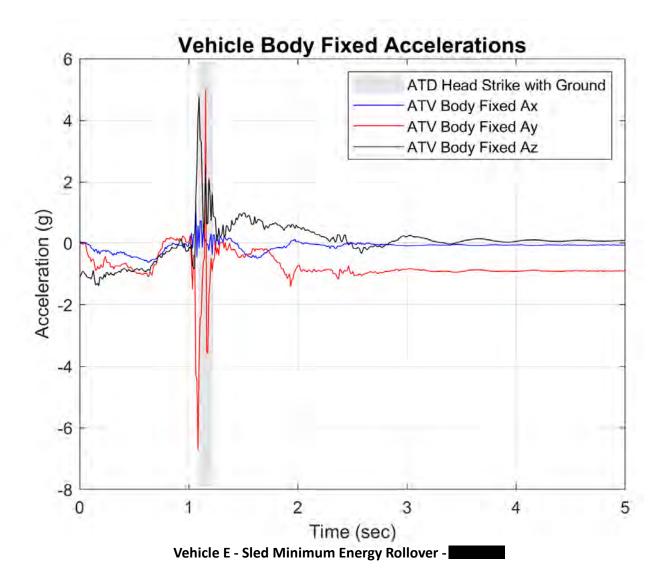


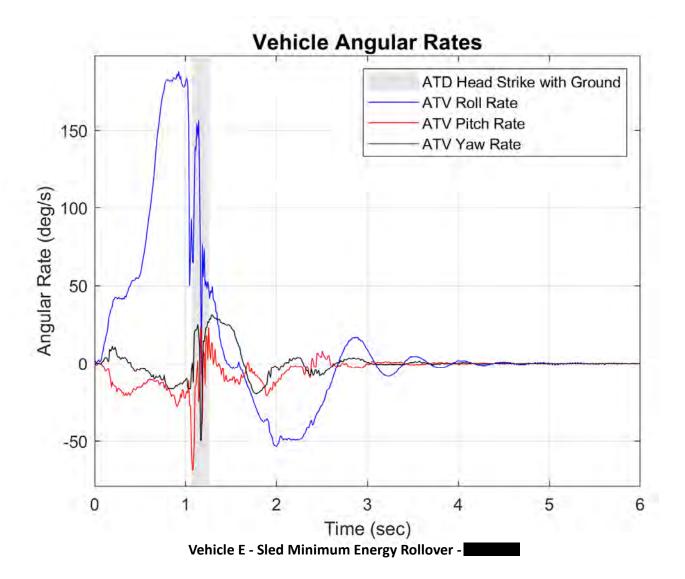
Vehicle E - Sled Minimum Energy Rollover -

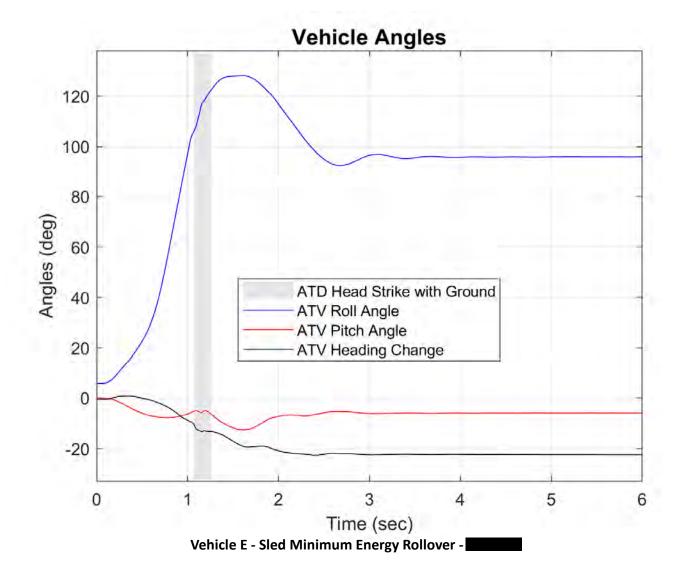




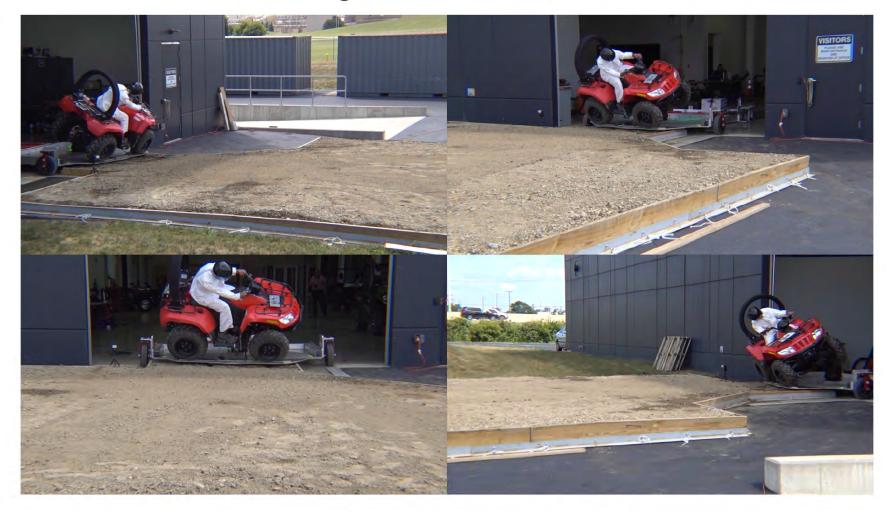








## Roll Angle = $30^{\circ}$ - Time = 0.48 sec



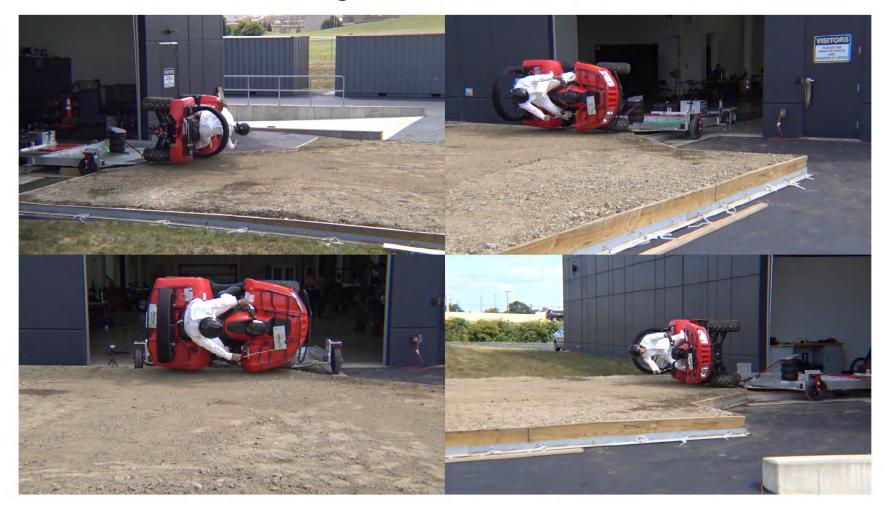
Vehicle E - Sled Moderate Energy Rollover -

## Roll Angle = $45^{\circ}$ - Time = 0.61 sec



Vehicle E - Sled Moderate Energy Rollover -

# Roll Angle = $90^{\circ}$ - Time = 0.86 sec



Vehicle E - Sled Moderate Energy Rollover -

### ATD Head Strike - Time = 1.01 sec



Vehicle E - Sled Moderate Energy Rollover -

# Roll Angle = $180^{\circ}$ - Time = 1.34 sec



Vehicle E - Sled Moderate Energy Rollover -

# Roll Angle = $270^{\circ}$ - Time = 1.98 sec



Vehicle E - Sled Moderate Energy Rollover -

## Max Roll Angle = $294.8^{\circ}$ - Time = 2.41 sec



Vehicle E - Sled Moderate Energy Rollover -

# End of Run - Roll Angle = 286.1°



Vehicle E - Sled Moderate Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.48 sec



Drone Camera - Roll Angle = 45° - Time = 0.61 sec



Drone Camera - Roll Angle = 90° - Time = 0.86 sec



Drone Camera - ATD Head Strike - Time = 1.01 sec



Drone Camera - Roll Angle = 180° - Time = 1.34 sec



Drone Camera - Roll Angle = 270° - Time = 1.98 sec



Vehicle E - Sled Moderate Energy Rollover -

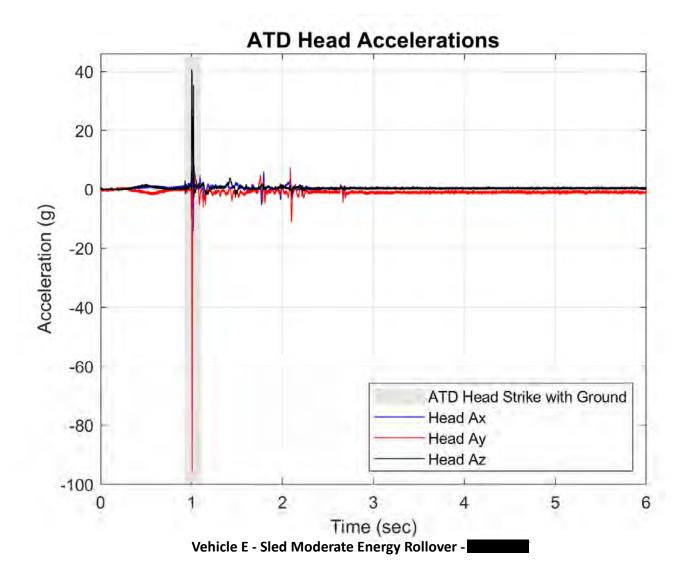
Drone Camera - Max Angle = 294.8° - Time = 2.41 sec

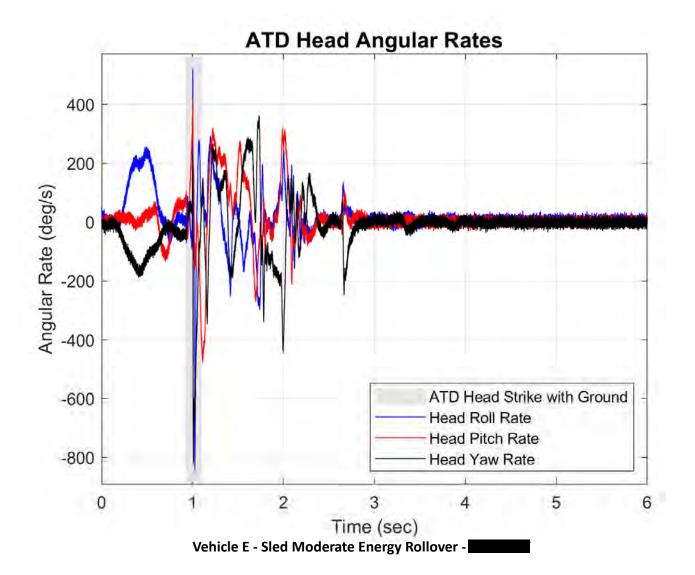
Drone Camera - End of Run - Roll Angle = 286.1°

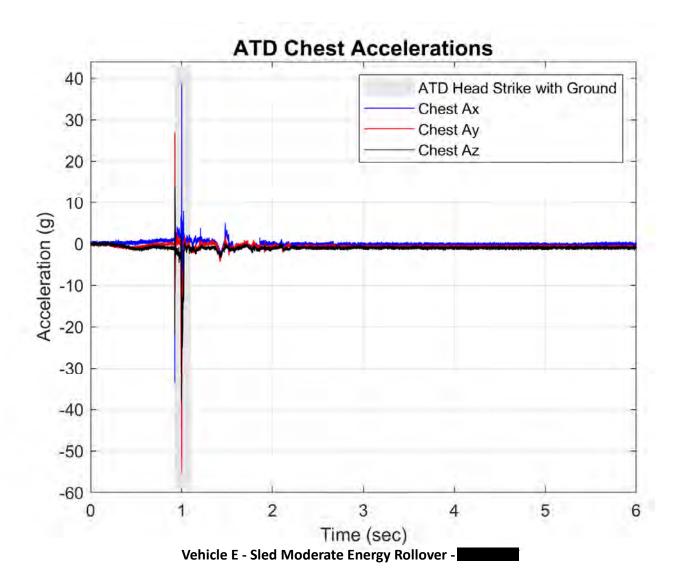


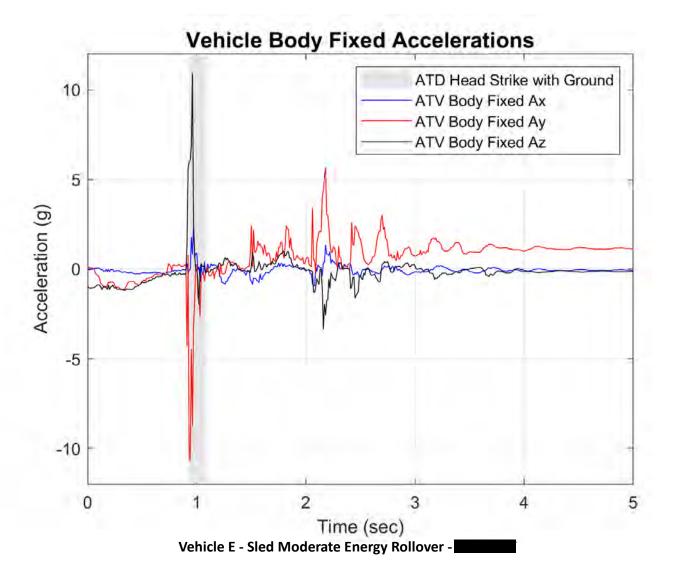


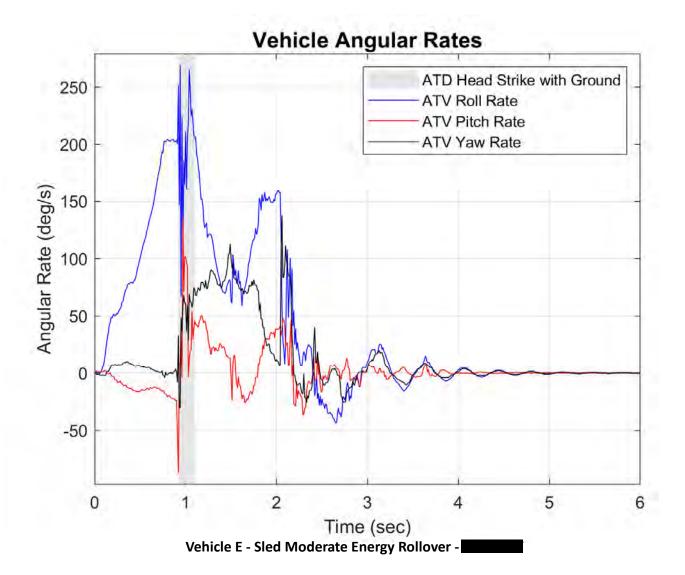
Vehicle E - Sled Moderate Energy Rollover -

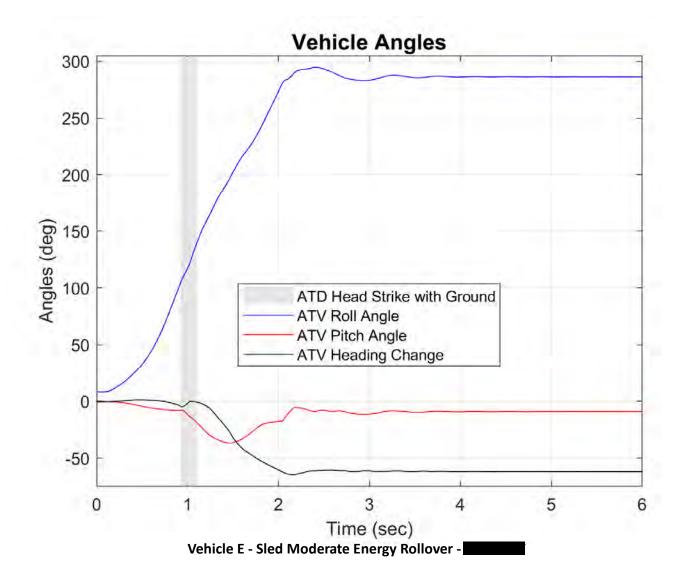












## Roll Angle = $30^{\circ}$ - Time = 0.48 sec



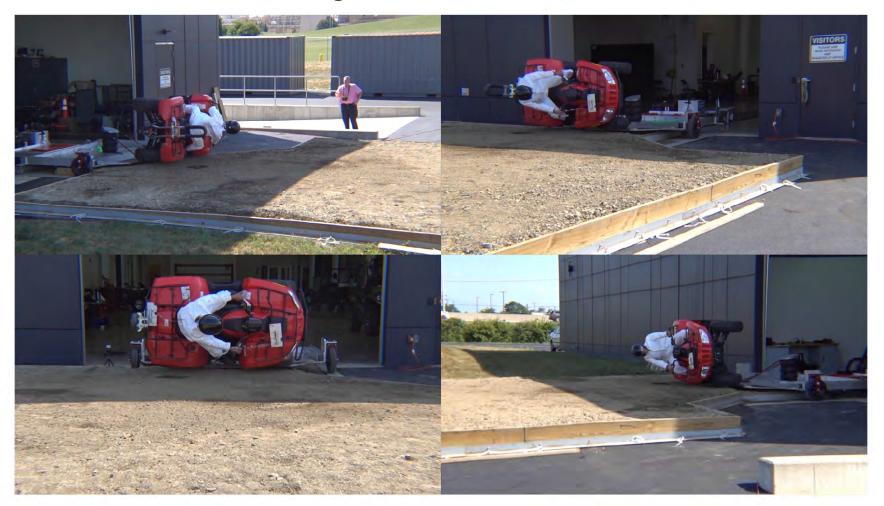
Vehicle E - Sled Moderate Energy Rollover -

# Roll Angle = $45^{\circ}$ - Time = 0.62 sec



Vehicle E - Sled Moderate Energy Rollover -

# Roll Angle = $90^{\circ}$ - Time = 0.87 sec



Vehicle E - Sled Moderate Energy Rollover -

### ATD Head Strike - Time = 1.02 sec



Vehicle E - Sled Moderate Energy Rollover -

# Roll Angle = $180^{\circ}$ - Time = 1.43 sec



Vehicle E - Sled Moderate Energy Rollover -

# Roll Angle = $270^{\circ}$ - Time = 2.37 sec



Vehicle E - Sled Moderate Energy Rollover -

## Max Roll Angle = $296.9^{\circ}$ - Time = 2.83 sec



Vehicle E - Sled Moderate Energy Rollover -

# End of Run - Roll Angle = 277.1°



Vehicle E - Sled Moderate Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.48 sec



Drone Camera - Roll Angle = 45° - Time = 0.62 sec



Drone Camera - Roll Angle = 90° - Time = 0.87 sec



Drone Camera - ATD Head Strike - Time = 1.02 sec



Drone Camera - Roll Angle = 180° - Time = 1.43 sec



Drone Camera - Roll Angle = 270° - Time = 2.37 sec



Vehicle E - Sled Moderate Energy Rollover -

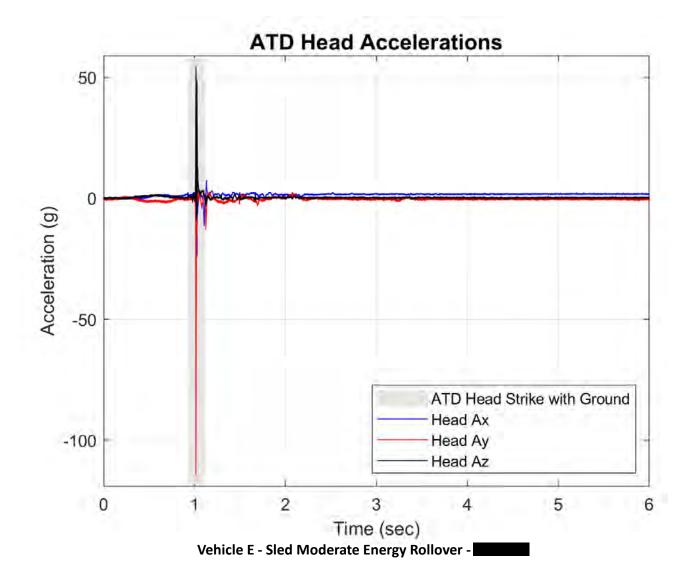
Drone Camera - Max Angle = 296.9° - Time = 2.83 sec

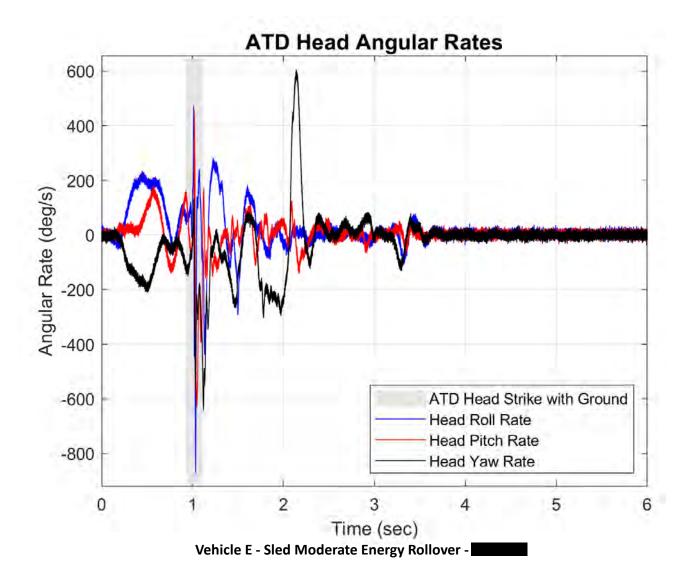
Drone Camera - End of Run - Roll Angle = 277.1°

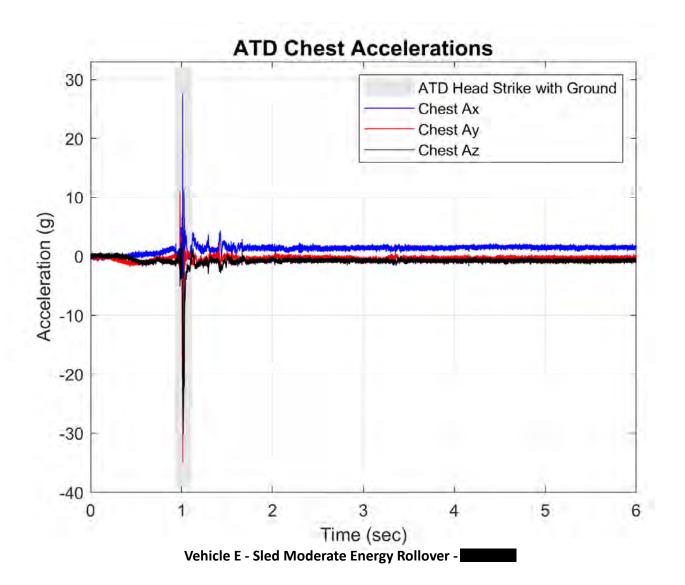


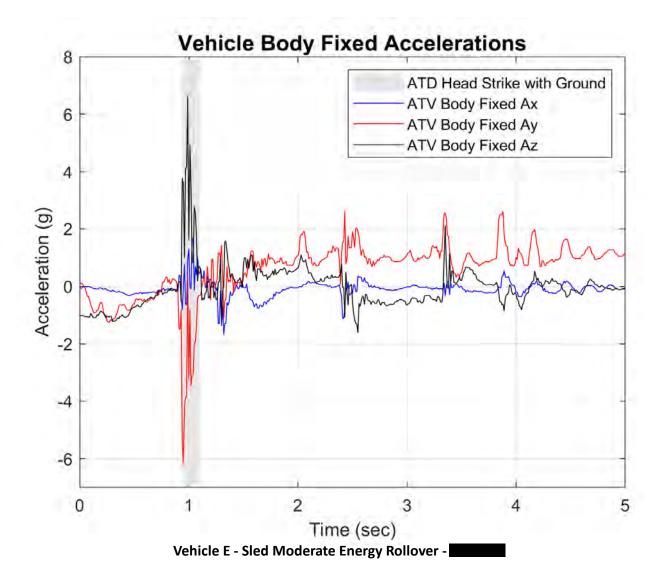


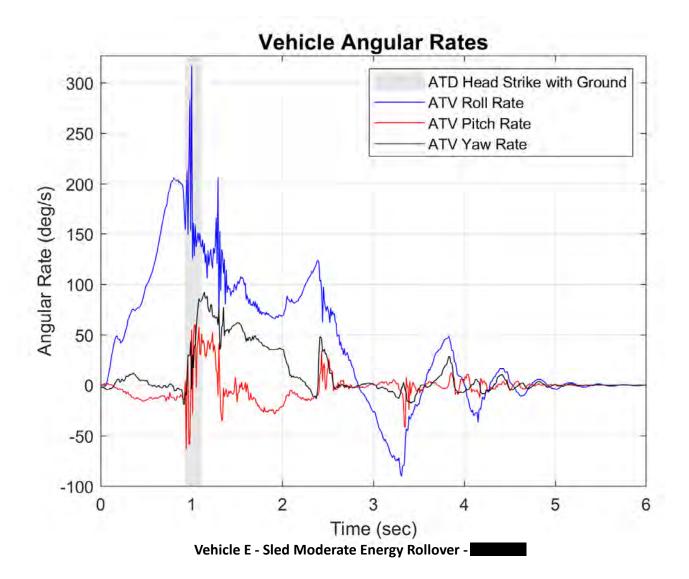
Vehicle E - Sled Moderate Energy Rollover -

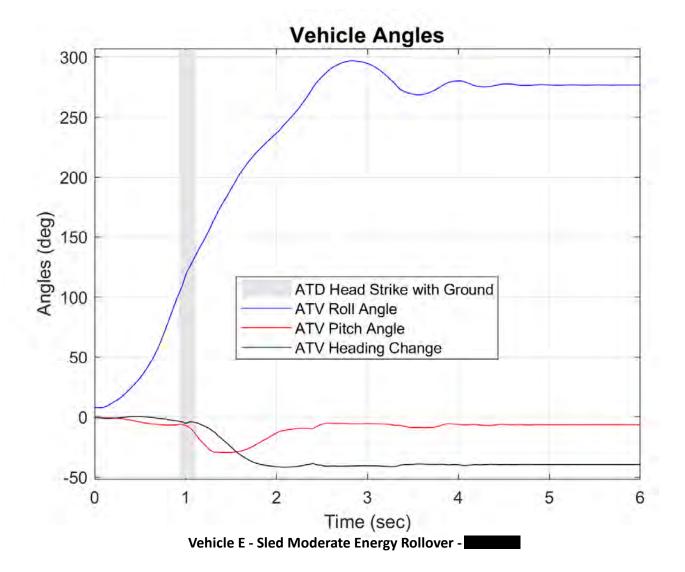










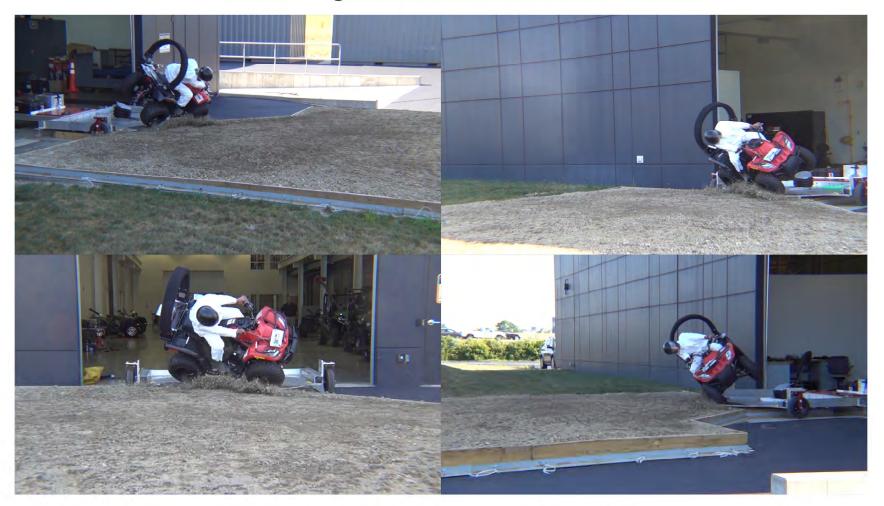


## Roll Angle = $30^{\circ}$ - Time = 0.66 sec



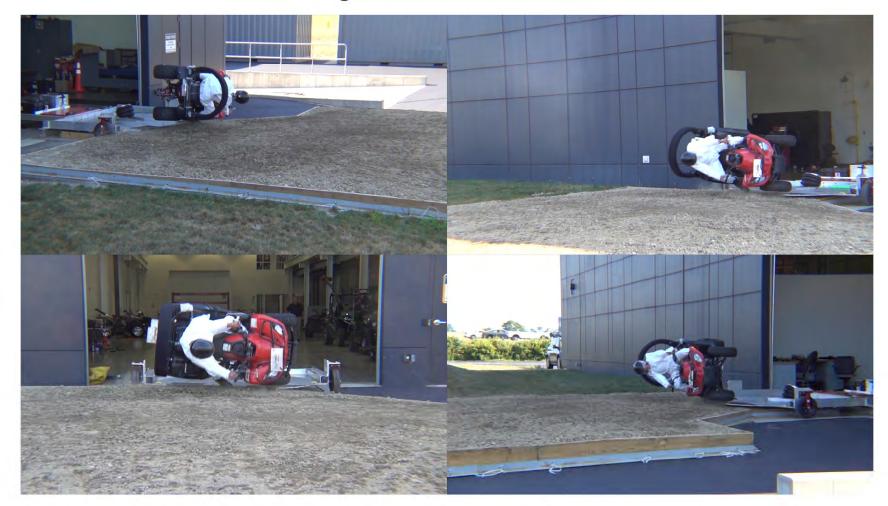
Vehicle F - Sled Minimum Energy Rollover -

## Roll Angle = $45^{\circ}$ - Time = 0.75 sec



Vehicle F - Sled Minimum Energy Rollover -

## Roll Angle = $90^{\circ}$ - Time = 0.97 sec



Vehicle F - Sled Minimum Energy Rollover -

### ATD Head Strike - Time = 1.12 sec



Vehicle F - Sled Minimum Energy Rollover -

## Max Roll Angle = $121.4^{\circ}$ - Time = 1.35 sec



Vehicle F - Sled Minimum Energy Rollover -

## End of Run - Roll Angle = 96.0°



Vehicle F - Sled Minimum Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.66 sec



Drone Camera - Roll Angle = 45° - Time = 0.75 sec



Drone Camera - Roll Angle = 90° - Time = 0.97 sec



Drone Camera - ATD Head Strike - Time = 1.12 sec



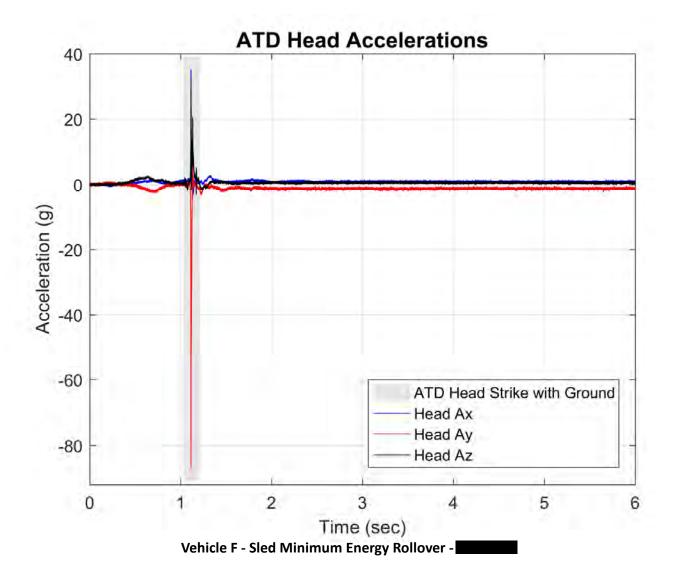
Drone Camera - Max Angle = 121.1° - Time = 1.35 sec

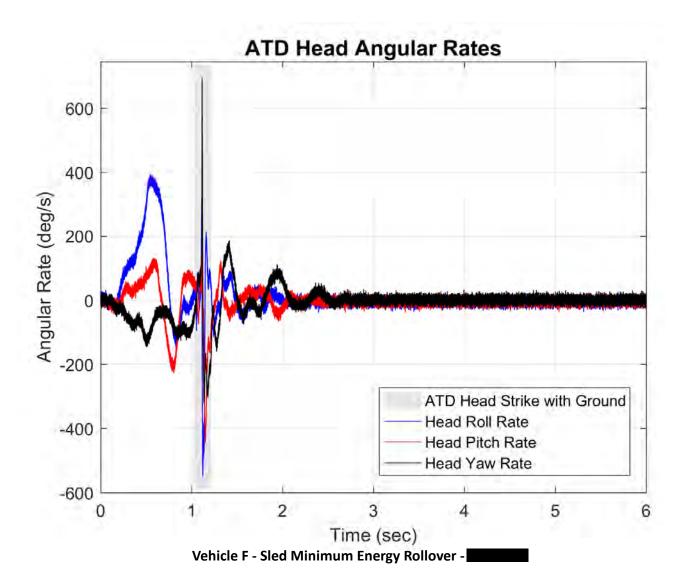


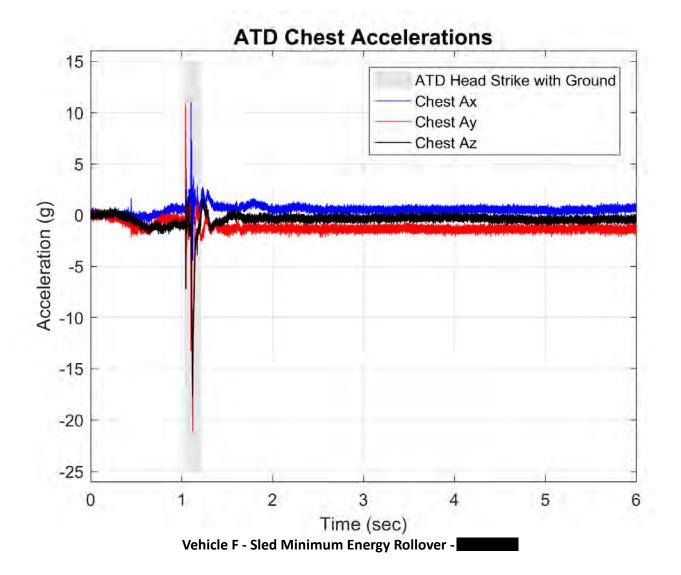
Drone Camera - End of Run - Roll Angle = 96.0°

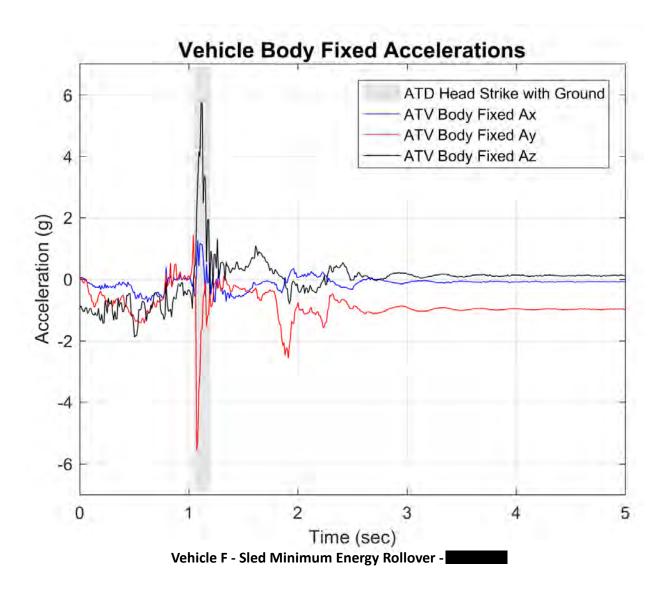


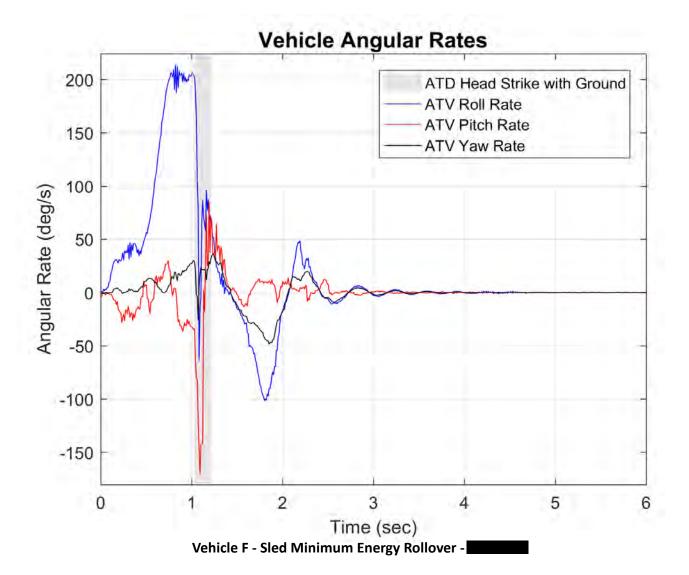
Vehicle F - Sled Minimum Energy Rollover -

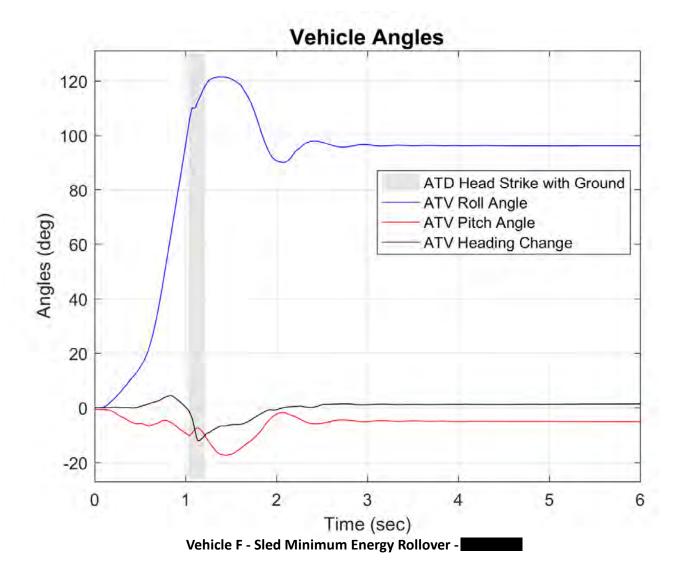




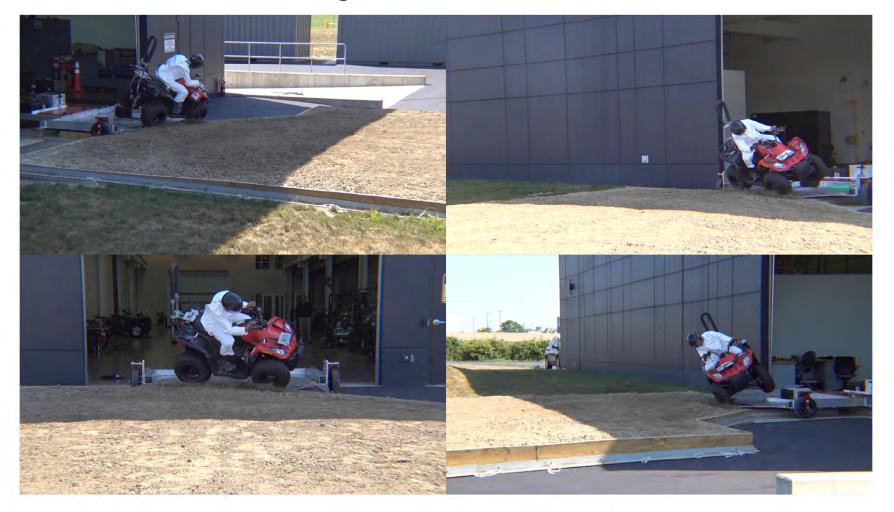






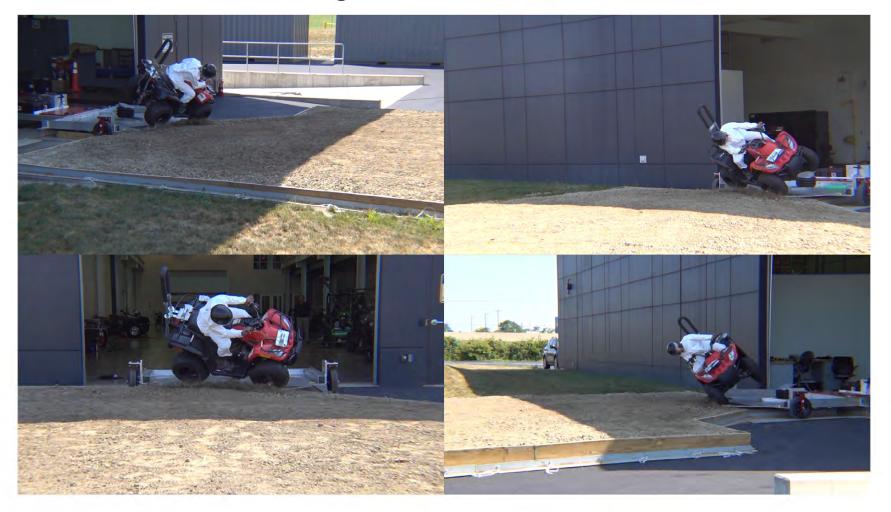


## Roll Angle = $30^{\circ}$ - Time = 0.67 sec



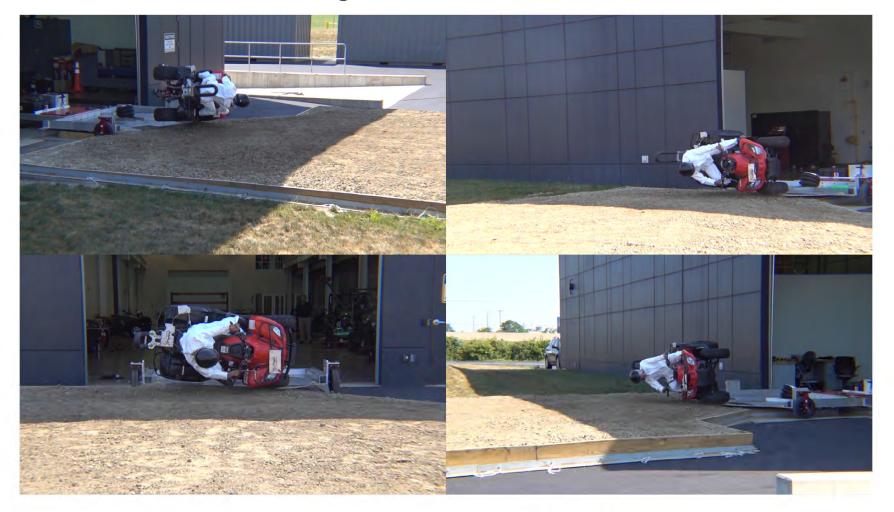
Vehicle F - Sled Minimum Energy Rollover -

## Roll Angle = $45^{\circ}$ - Time = 0.76 sec



Vehicle F - Sled Minimum Energy Rollover -

# Roll Angle = $90^{\circ}$ - Time = 1.00 sec



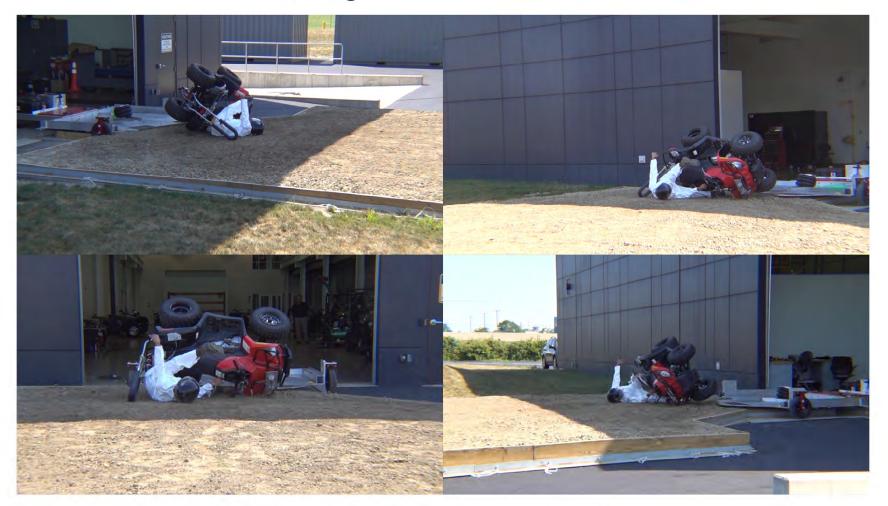
Vehicle F - Sled Minimum Energy Rollover -

### ATD Head Strike - Time = 1.12 sec



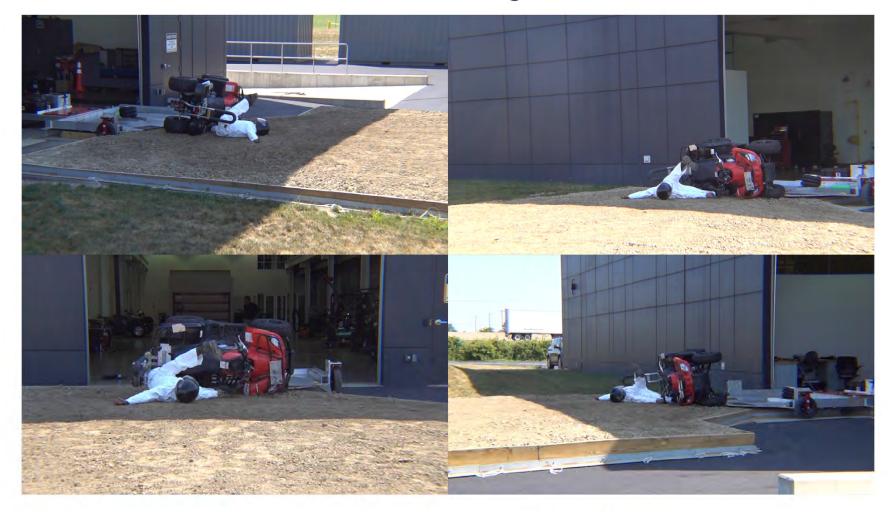
Vehicle F - Sled Minimum Energy Rollover -

## Max Roll Angle = $123.2^{\circ}$ - Time = 1.37 sec



Vehicle F - Sled Minimum Energy Rollover -

## End of Run - Roll Angle = 96.8°



Vehicle F - Sled Minimum Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.67 sec



Drone Camera - Roll Angle = 45° - Time = 0.76 sec



Drone Camera - Roll Angle = 90° - Time = 1.00 sec



Drone Camera - ATD Head Strike - Time = 1.12 sec



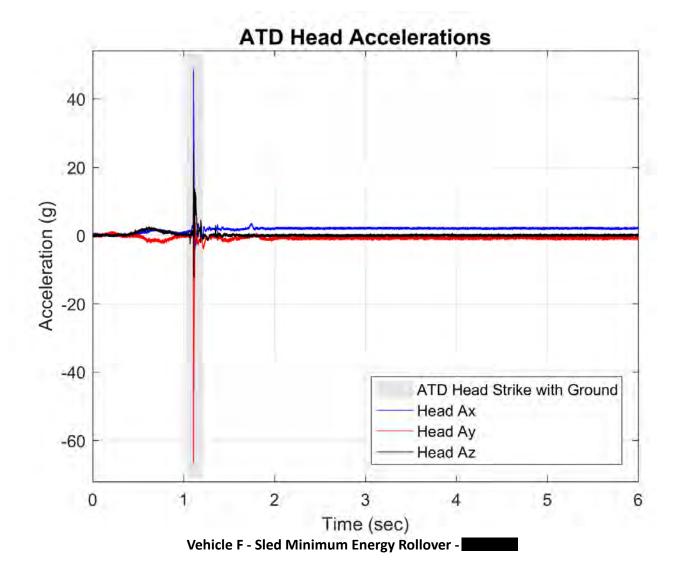
Drone Camera - Max Angle = 123.2° - Time = 1.37 sec

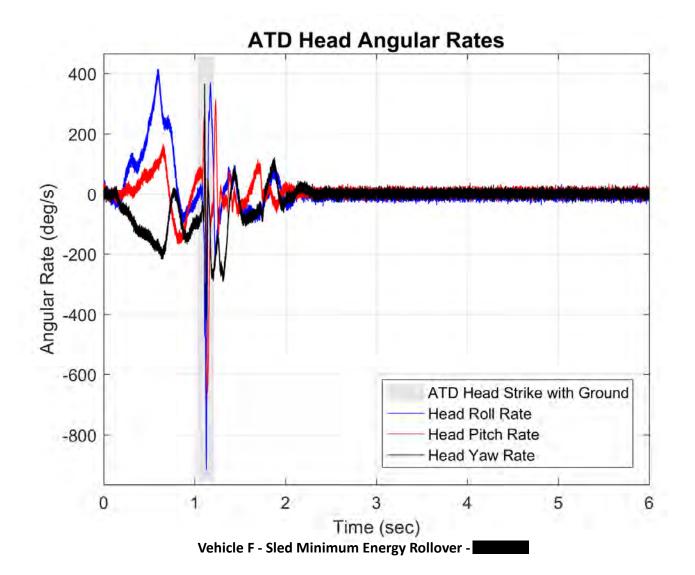


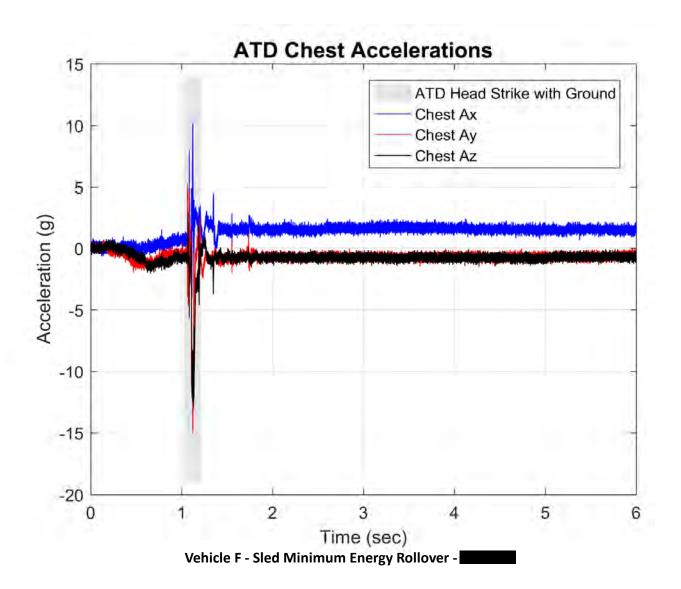
Drone Camera - End of Run - Roll Angle = 96.8°

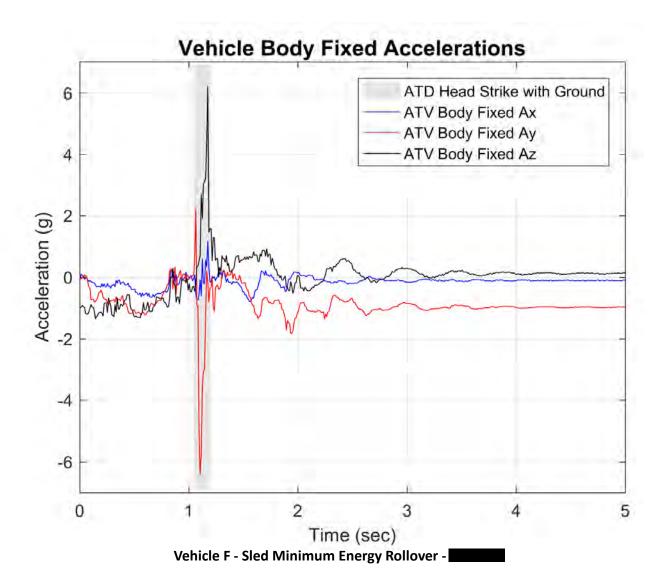


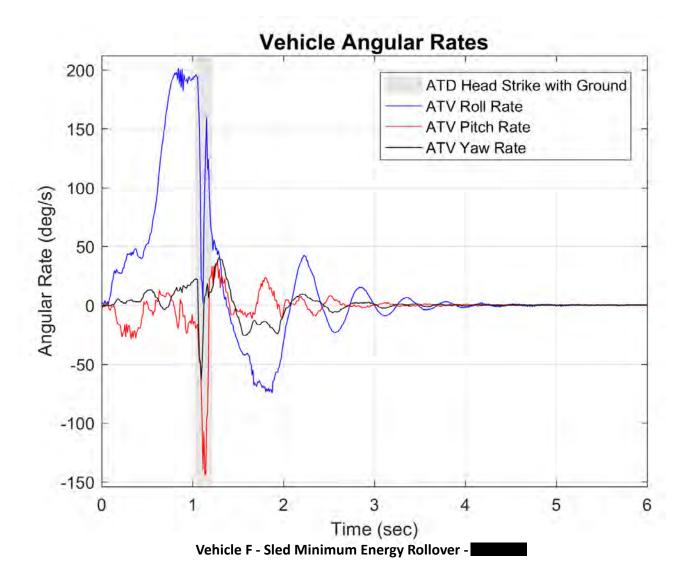
Vehicle F - Sled Minimum Energy Rollover -

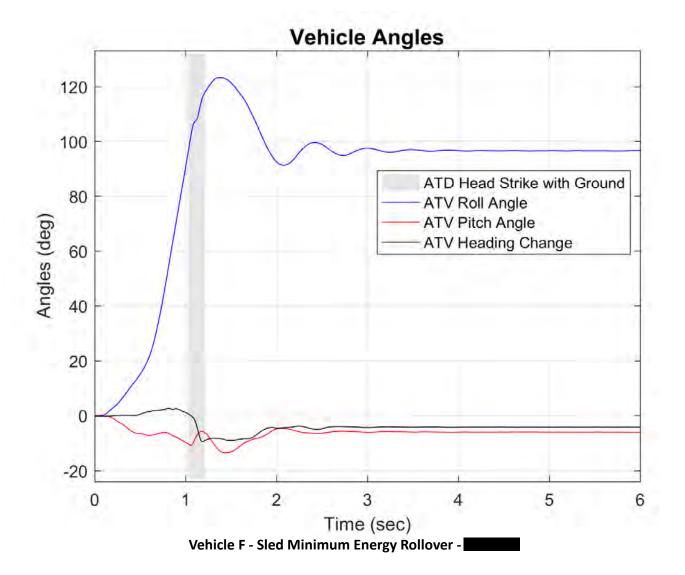




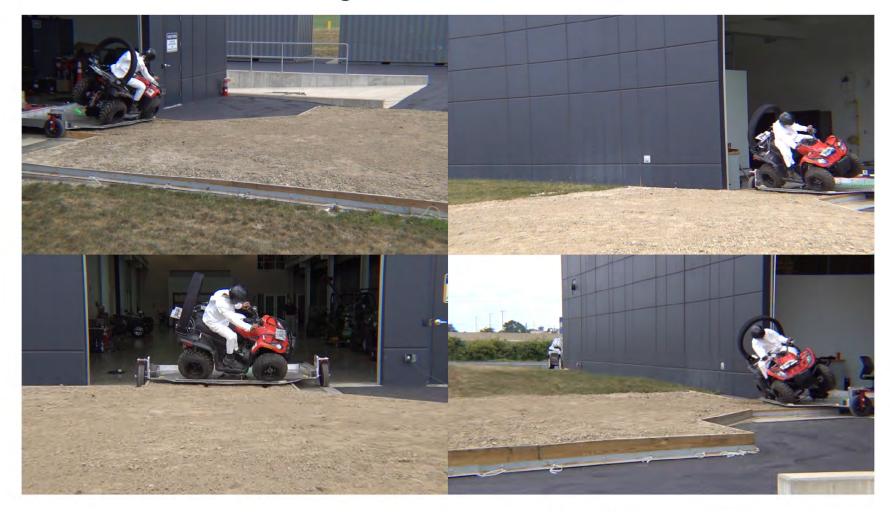






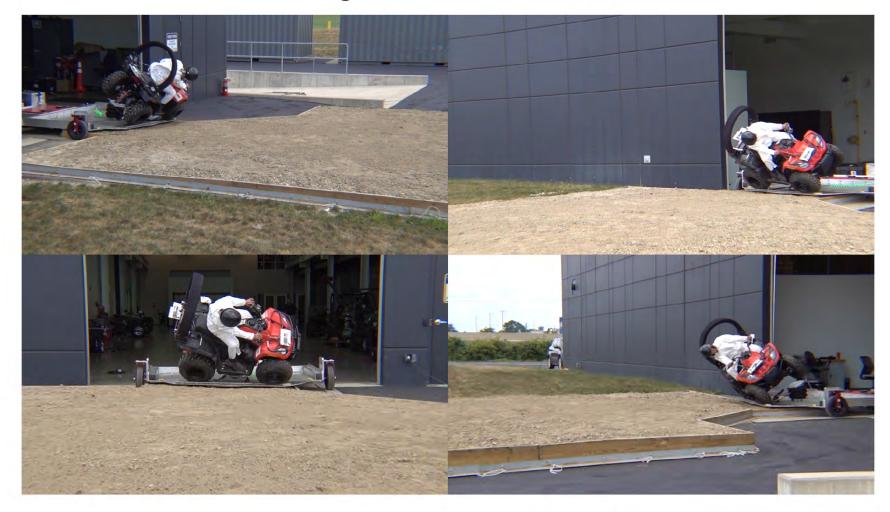


## Roll Angle = $30^{\circ}$ - Time = 0.52 sec



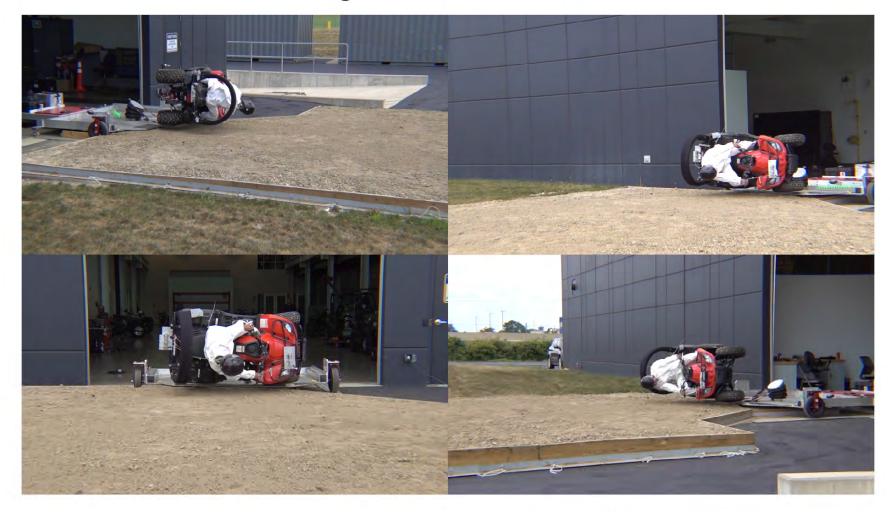
Vehicle F - Sled Moderate Energy Rollover -

## Roll Angle = $45^{\circ}$ - Time = 0.64 sec



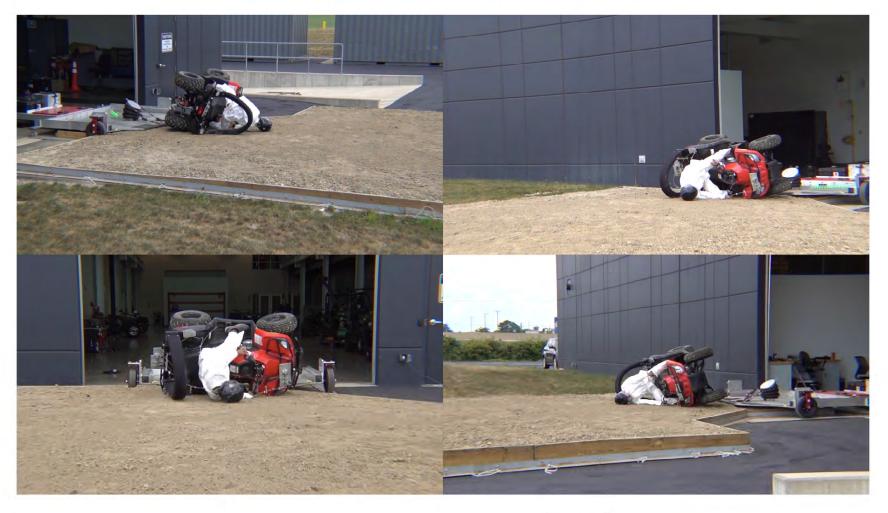
Vehicle F - Sled Moderate Energy Rollover -

# Roll Angle = $90^{\circ}$ - Time = 0.86 sec



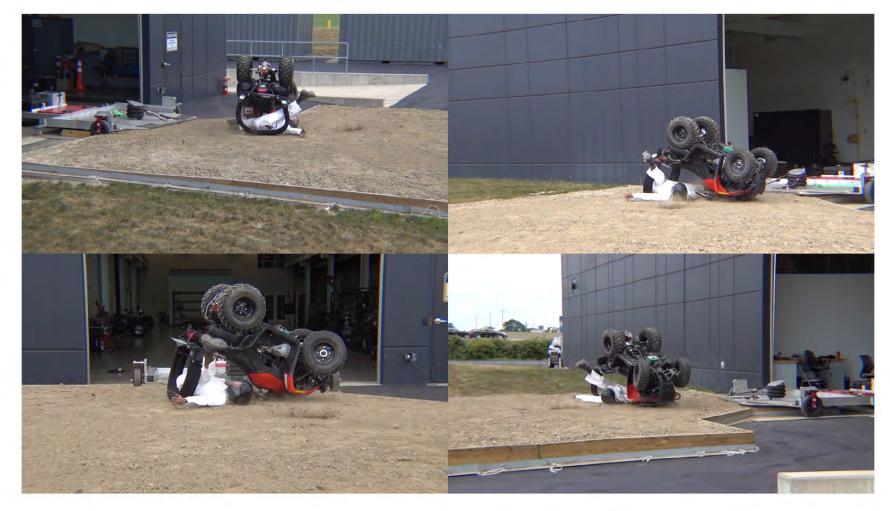
Vehicle F - Sled Moderate Energy Rollover -

### ATD Head Strike - Time = 0.95 sec



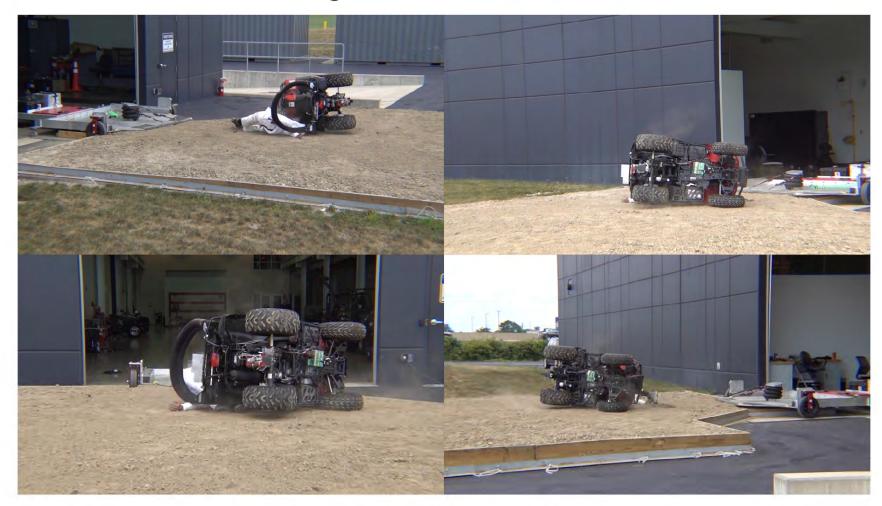
Vehicle F - Sled Moderate Energy Rollover -

## Roll Angle = $180^{\circ}$ - Time = 1.34 sec



Vehicle F - Sled Moderate Energy Rollover -

## Roll Angle = $270^{\circ}$ - Time = 1.93 sec



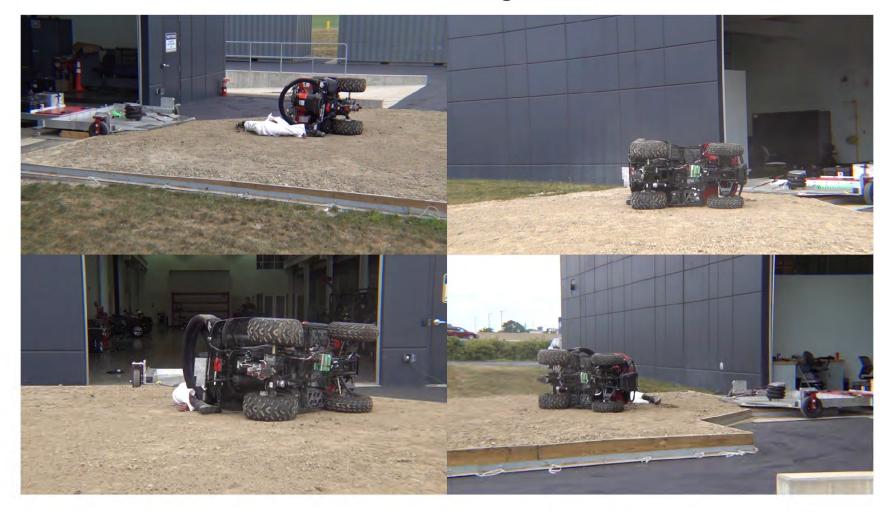
Vehicle F - Sled Moderate Energy Rollover -

## Max Roll Angle = $300.3^{\circ}$ - Time = 2.51 sec



Vehicle F - Sled Moderate Energy Rollover -

## End of Run - Roll Angle = 279.6°



Vehicle F - Sled Moderate Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.52 sec



Drone Camera - Roll Angle = 45° - Time = 0.64 sec



Drone Camera - Roll Angle = 90° - Time = 0.86 sec



Drone Camera - ATD Head Strike - Time = 0.95 sec



Drone Camera - Roll Angle = 180° - Time = 1.34 sec



Drone Camera - Roll Angle = 270° - Time = 1.93 sec



Vehicle F - Sled Moderate Energy Rollover -

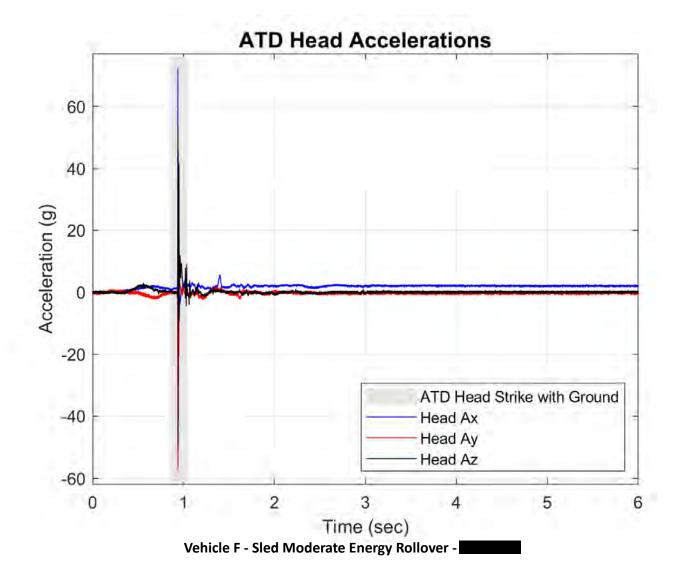
Drone Camera - Max Angle = 300.3° - Time = 2.51 sec

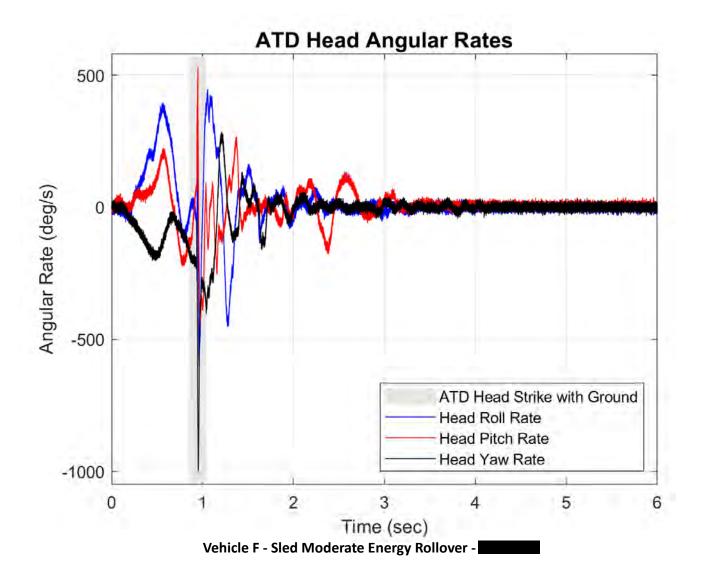
Drone Camera - End of Run - Roll Angle = 279.6°

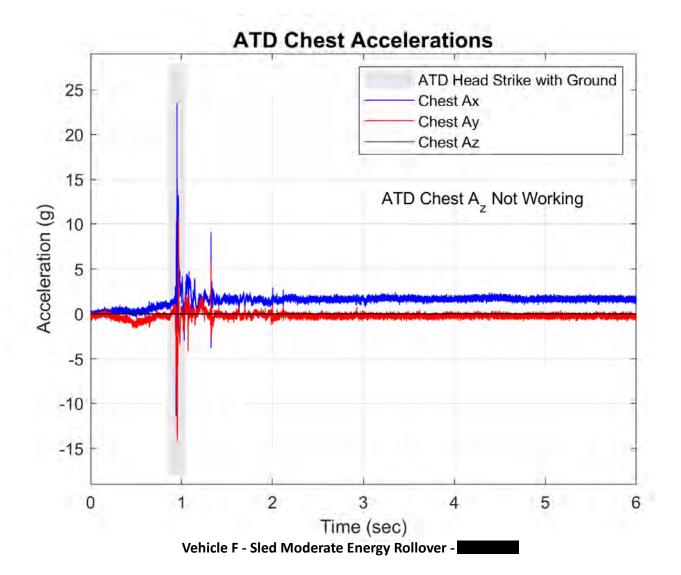


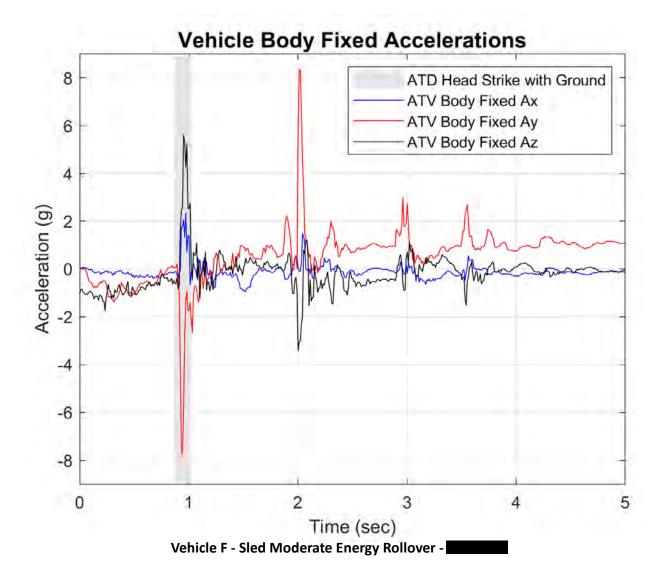


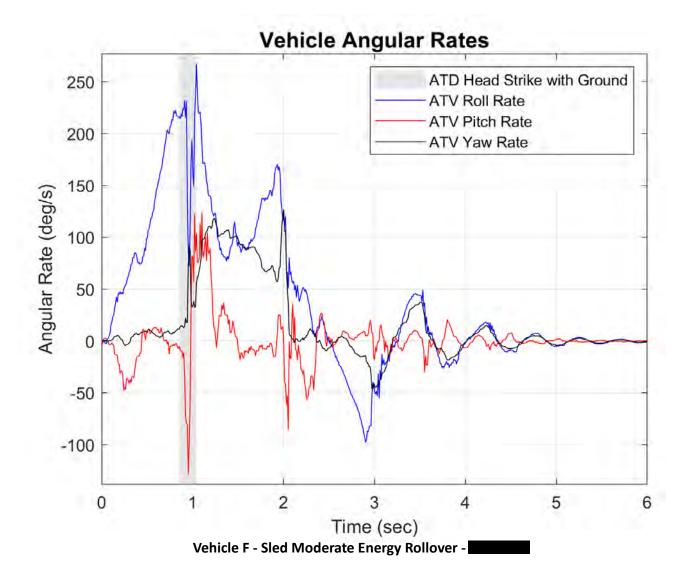
Vehicle F - Sled Moderate Energy Rollover -

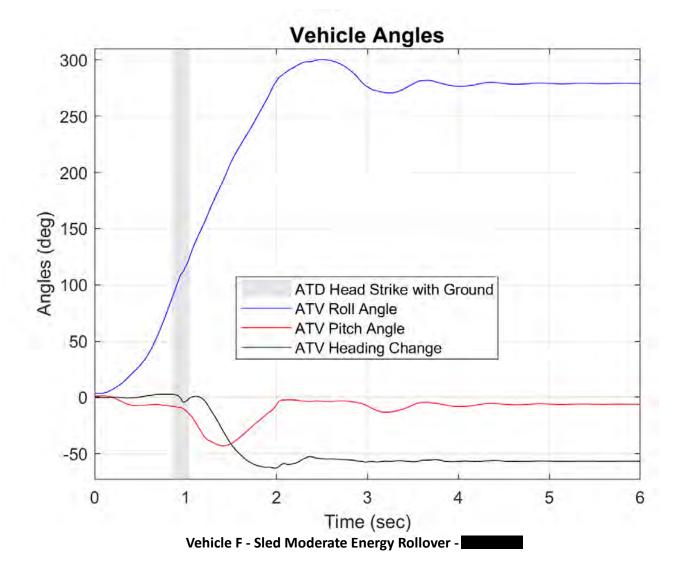




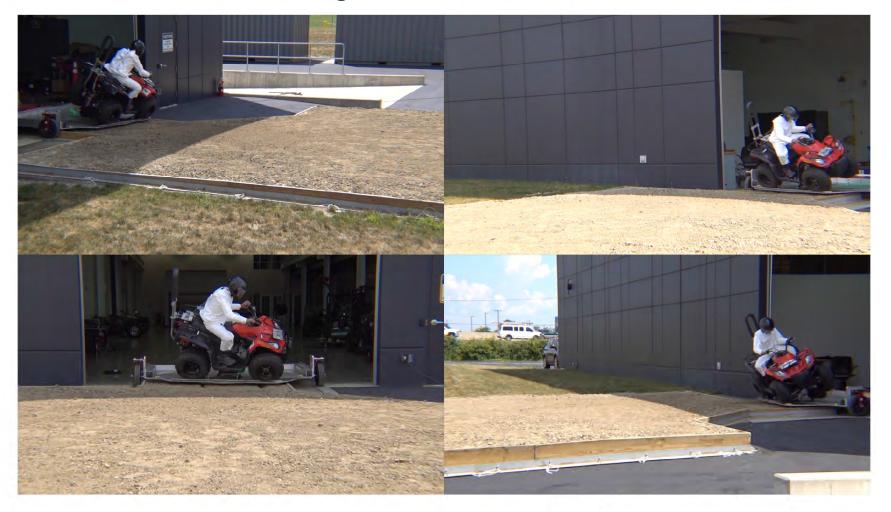






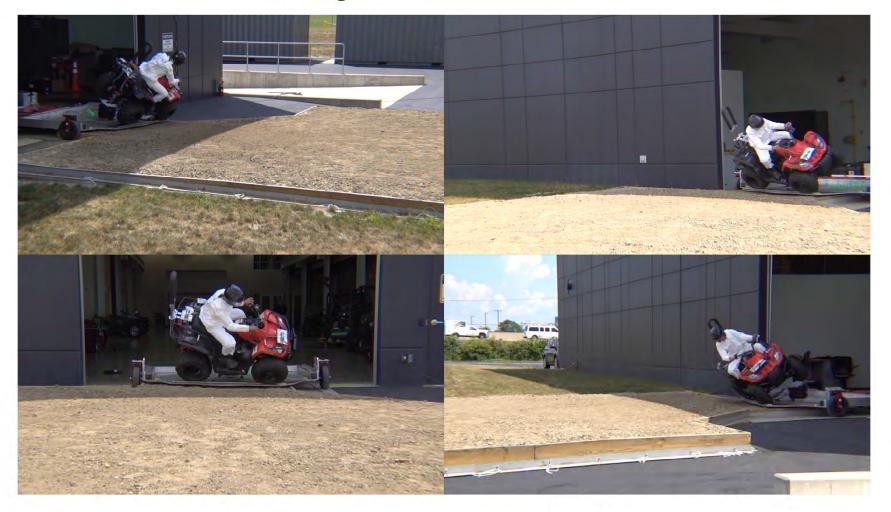


### Roll Angle = $30^{\circ}$ - Time = 0.55 sec



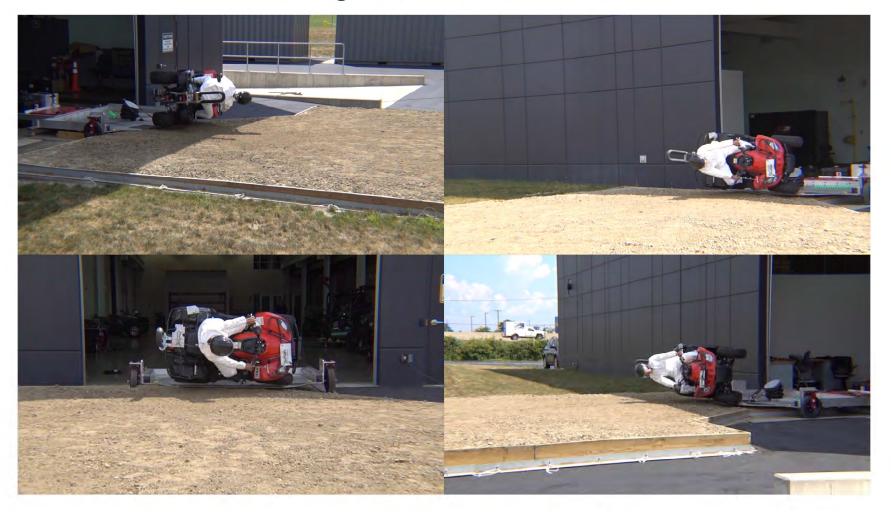
Vehicle F - Sled Moderate Energy Rollover -

### Roll Angle = $45^{\circ}$ - Time = 0.67 sec



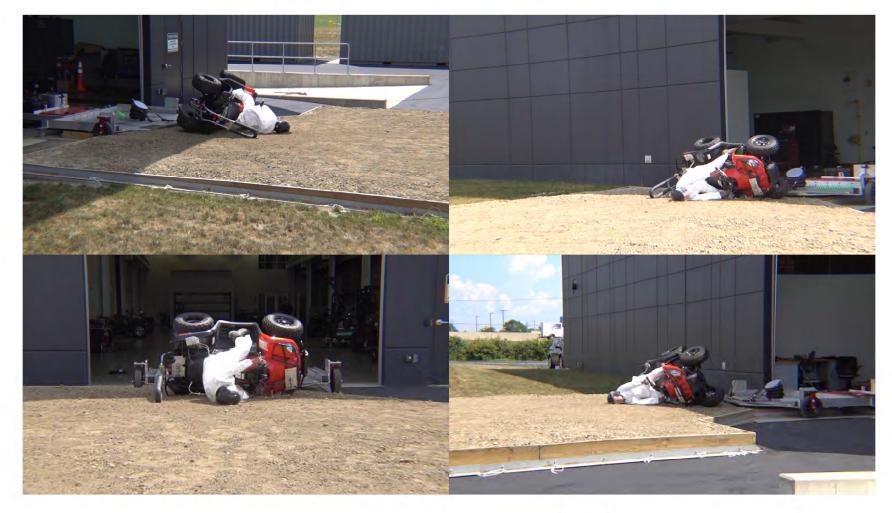
Vehicle F - Sled Moderate Energy Rollover -

## Roll Angle = $90^{\circ}$ - Time = 0.89 sec



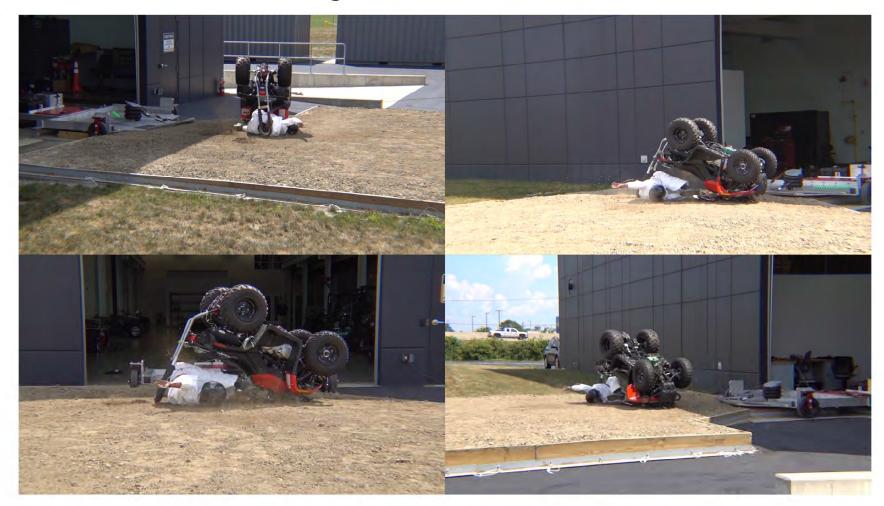
Vehicle F - Sled Moderate Energy Rollover -

#### ATD Head Strike - Time = 1.02 sec



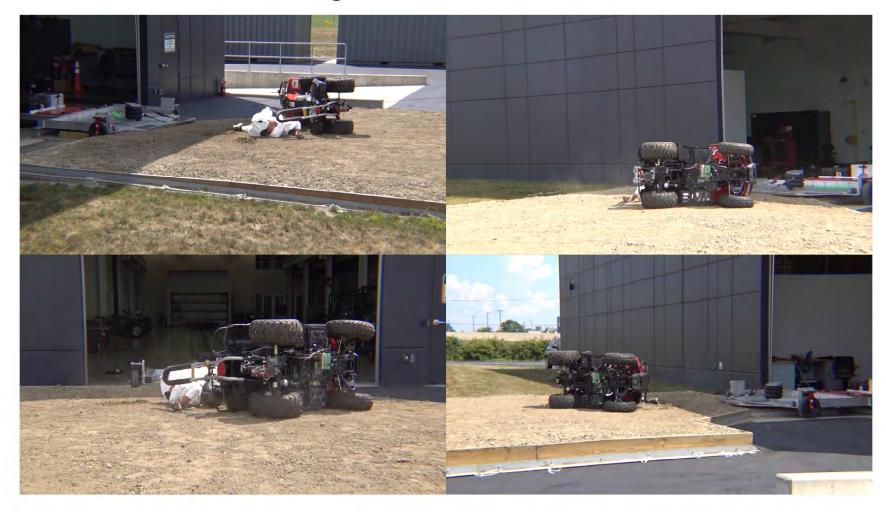
Vehicle F - Sled Moderate Energy Rollover -

### Roll Angle = $180^{\circ}$ - Time = 1.47 sec



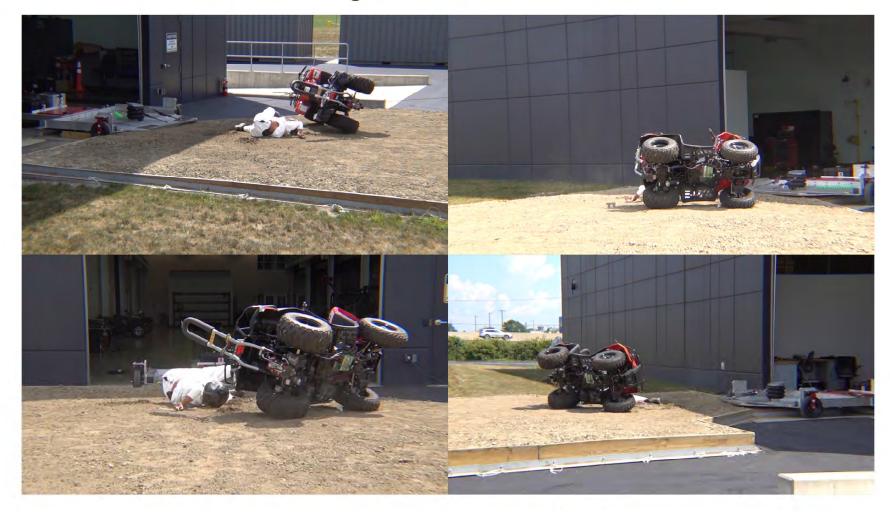
Vehicle F - Sled Moderate Energy Rollover -

# Roll Angle = $270^{\circ}$ - Time = 2.15 sec



Vehicle F - Sled Moderate Energy Rollover -

# Max Roll Angle = $297.2^{\circ}$ - Time = 2.63 sec



Vehicle F - Sled Moderate Energy Rollover -

### End of Run - Roll Angle = 273.2°



Vehicle F - Sled Moderate Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.55 sec



Drone Camera - Roll Angle = 45° - Time = 0.67 sec



Drone Camera - Roll Angle = 90° - Time = 0.89 sec



Drone Camera - ATD Head Strike - Time = 1.02 sec



Drone Camera - Roll Angle = 180° - Time = 1.47 sec



Drone Camera - Roll Angle = 270° - Time = 2.15 sec



Vehicle F - Sled Moderate Energy Rollover -

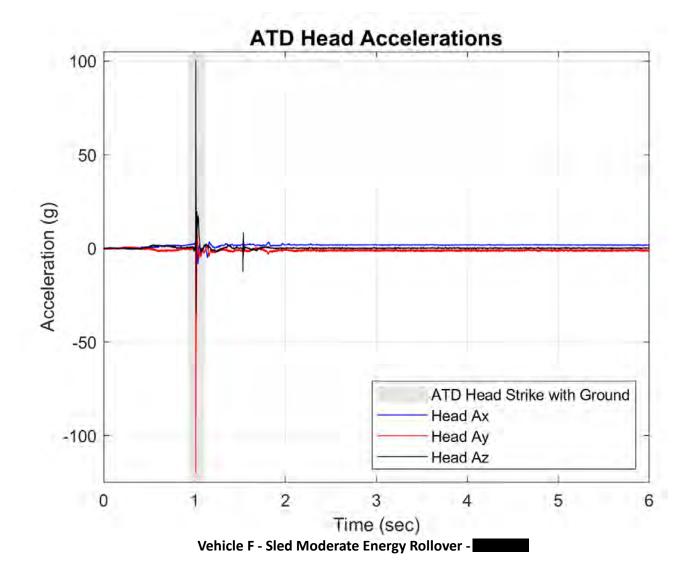
Drone Camera - Max Angle = 297.2° - Time = 2.63 sec

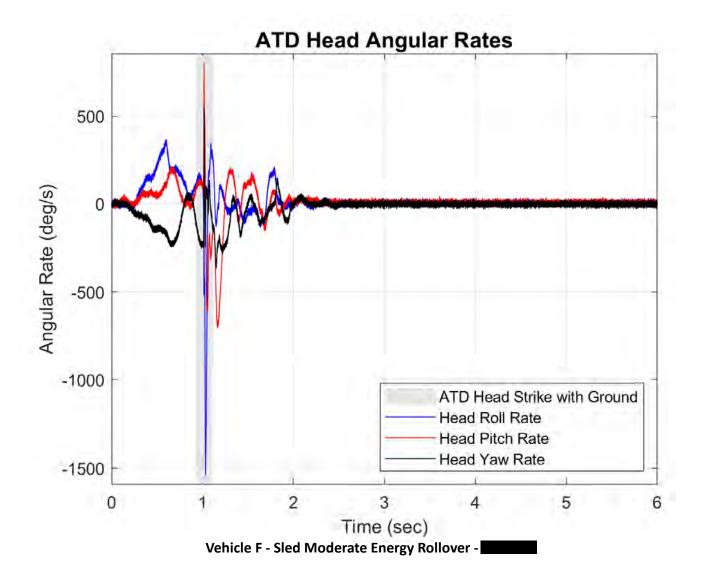
Drone Camera - End of Run - Roll Angle = 273.2°

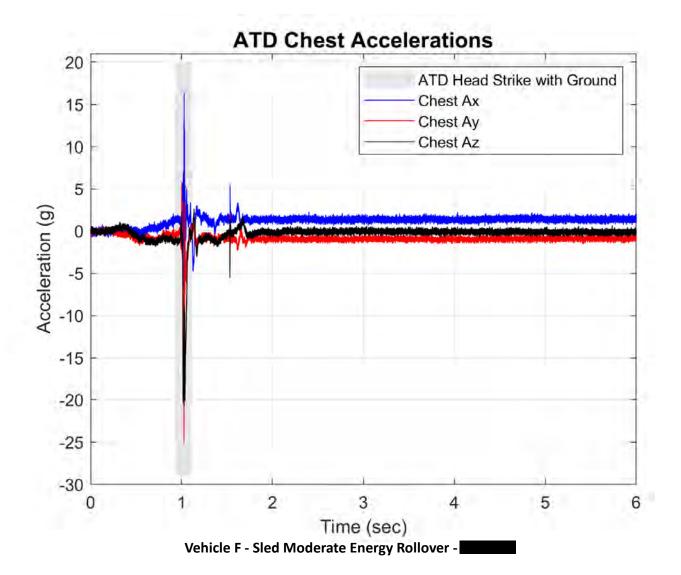


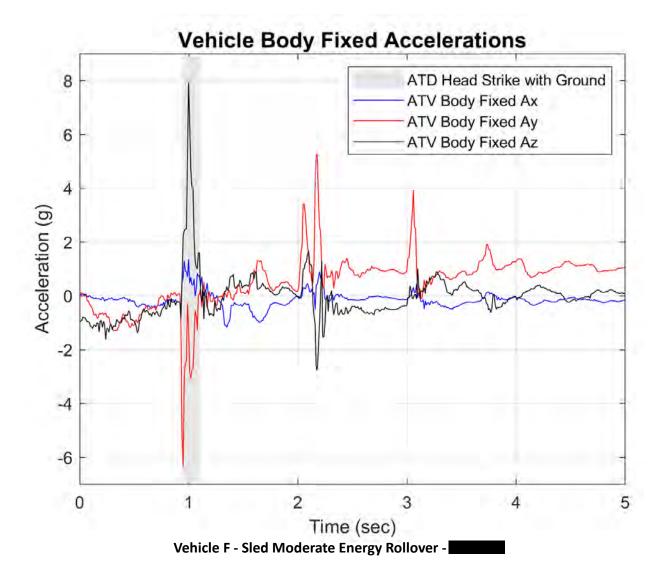


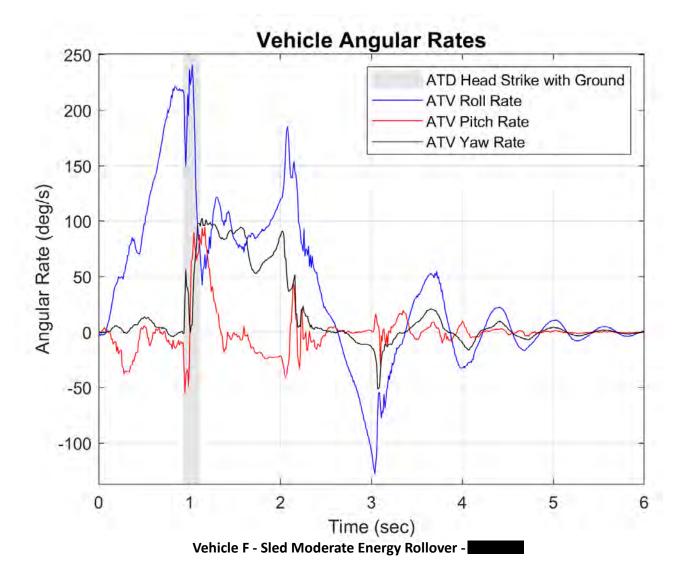
Vehicle F - Sled Moderate Energy Rollover -





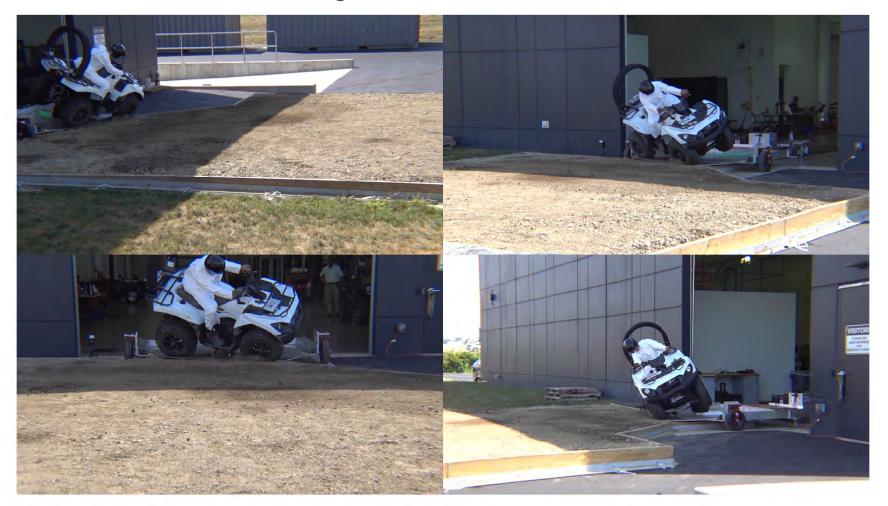






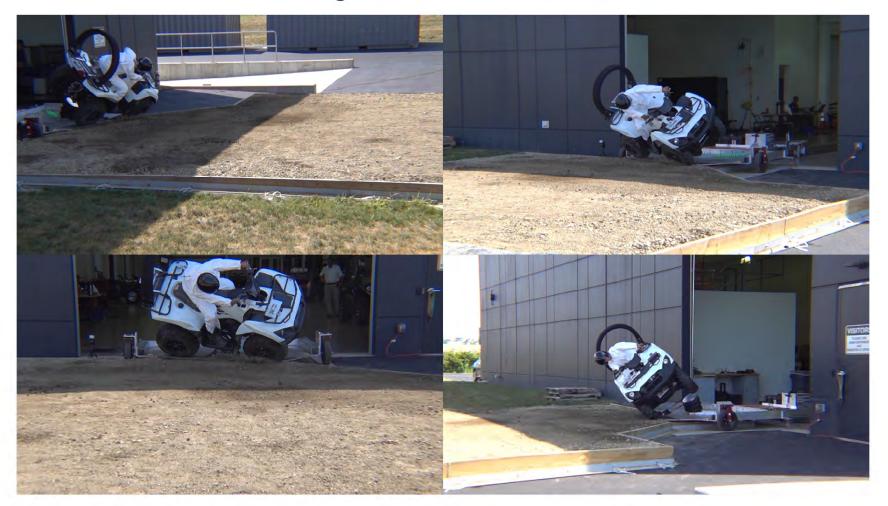


### Roll Angle = $30^{\circ}$ - Time = 0.57 sec



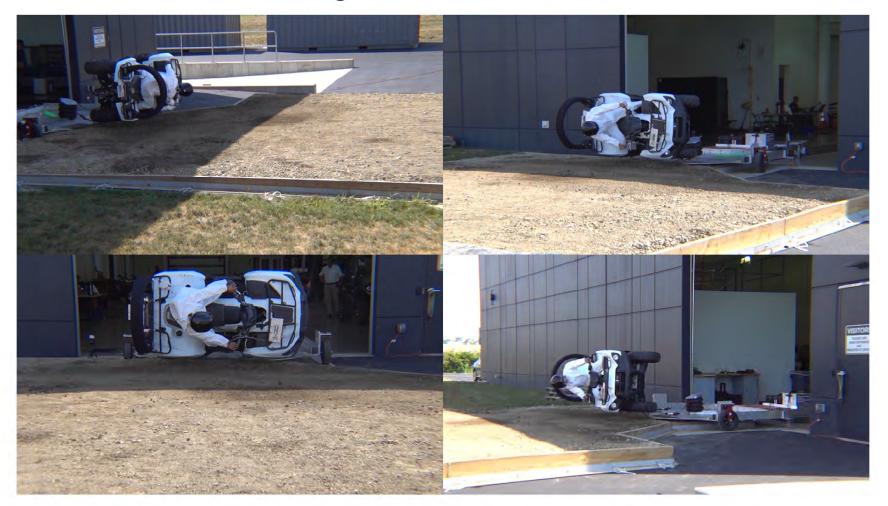
Vehicle G - Sled Minimum Energy Rollover -

### Roll Angle = $45^{\circ}$ - Time = 0.68 sec



Vehicle G - Sled Minimum Energy Rollover -

### Roll Angle = $90^{\circ}$ - Time = 0.90 sec



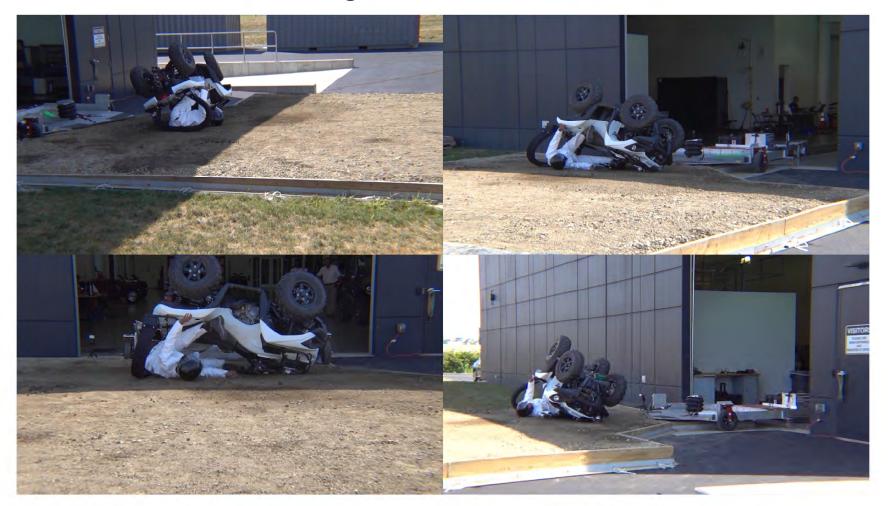
Vehicle G - Sled Minimum Energy Rollover -

#### ATD Head Strike - Time = 1.05 sec



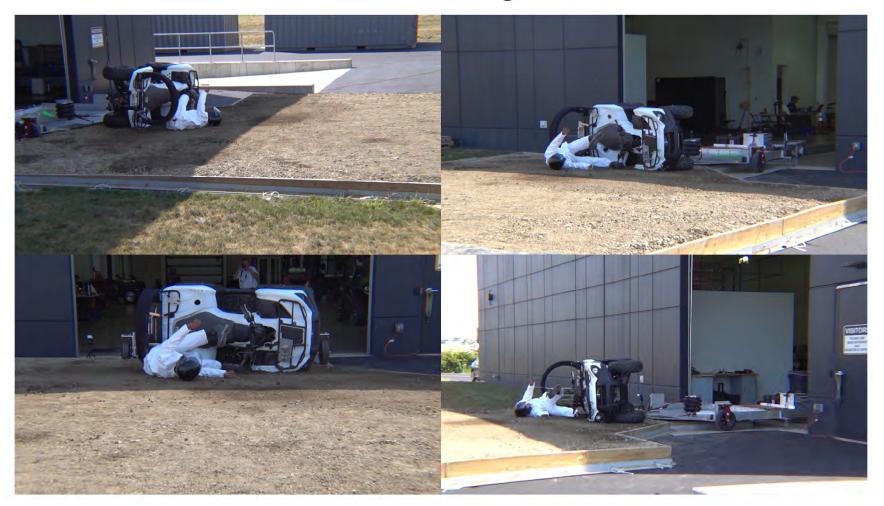
Vehicle G - Sled Minimum Energy Rollover -

### Max Roll Angle = $150.9^{\circ}$ - Time = 1.73 sec



Vehicle G - Sled Minimum Energy Rollover -

### End of Run - Roll Angle = 92.8°



Vehicle G - Sled Minimum Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.57 sec



Drone Camera - Roll Angle = 45° - Time = 0.68 sec



Drone Camera - Roll Angle = 90° - Time = 0.90 sec



Drone Camera - ATD Head Strike - Time = 1.05 sec



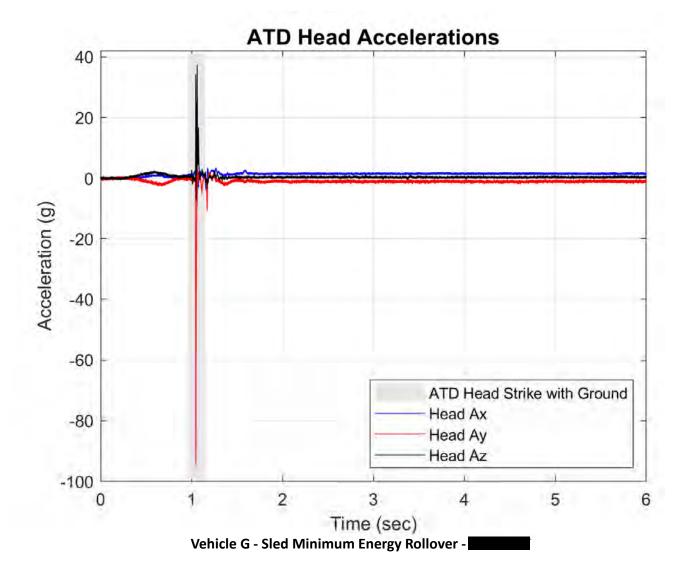
Drone Camera - Max Angle = 150.9° - Time = 1.73 sec

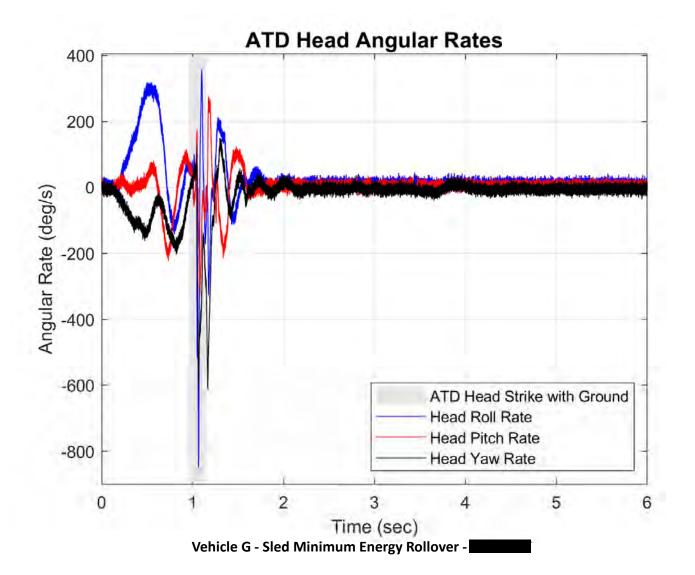


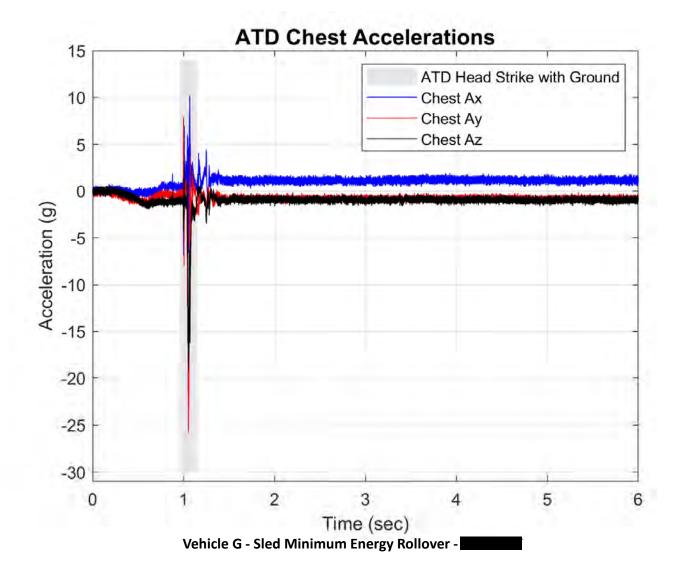
Drone Camera - End of Run - Roll Angle = 92.8°

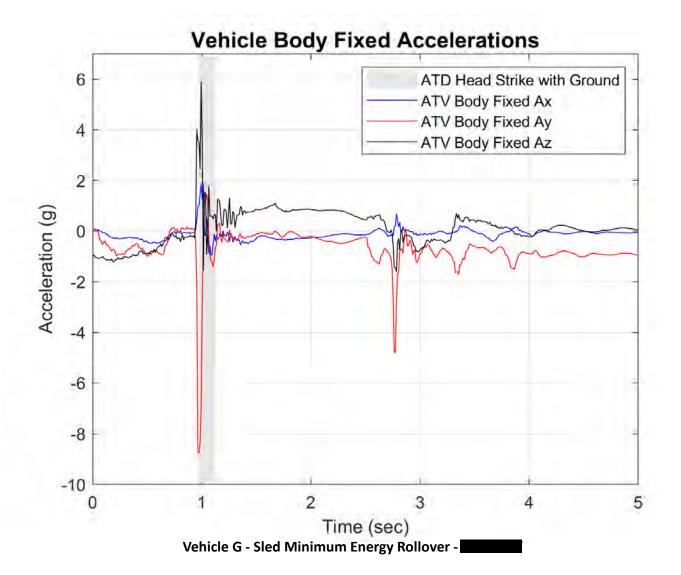


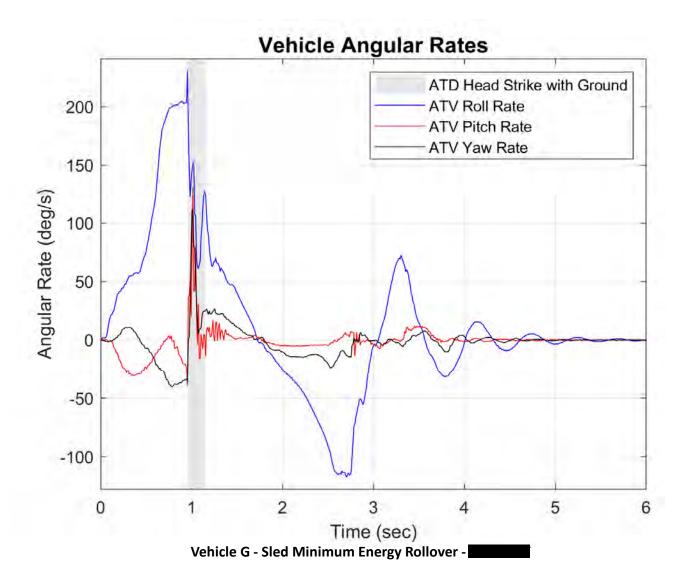
Vehicle G - Sled Minimum Energy Rollover -

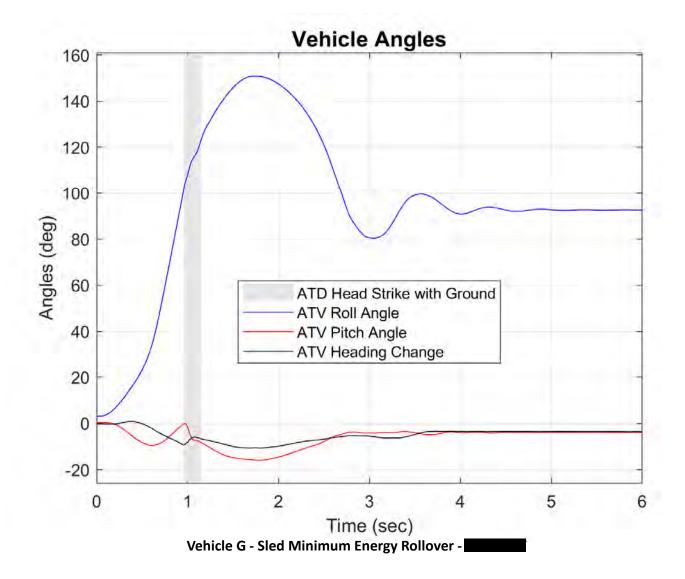




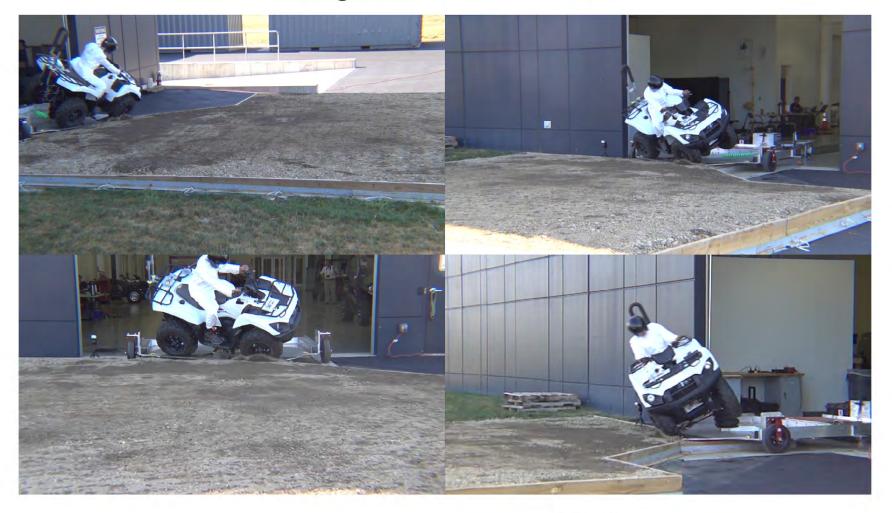






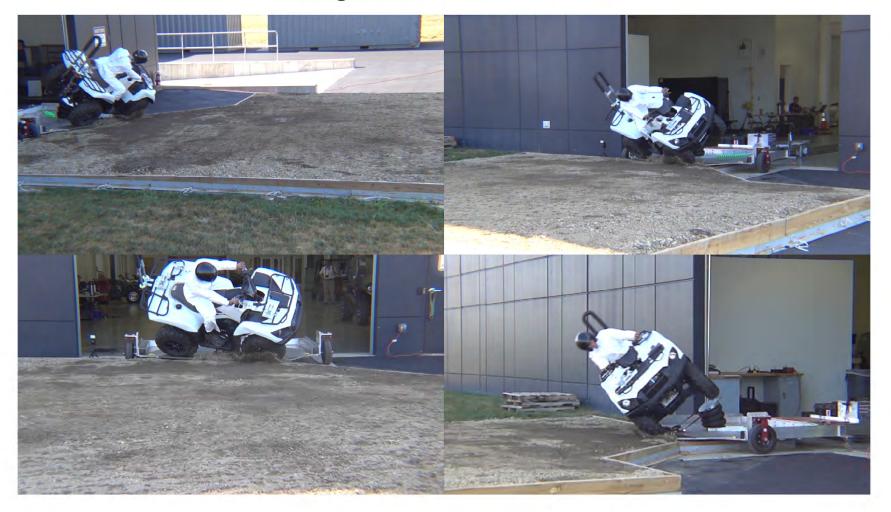


### Roll Angle = $30^{\circ}$ - Time = 0.52 sec



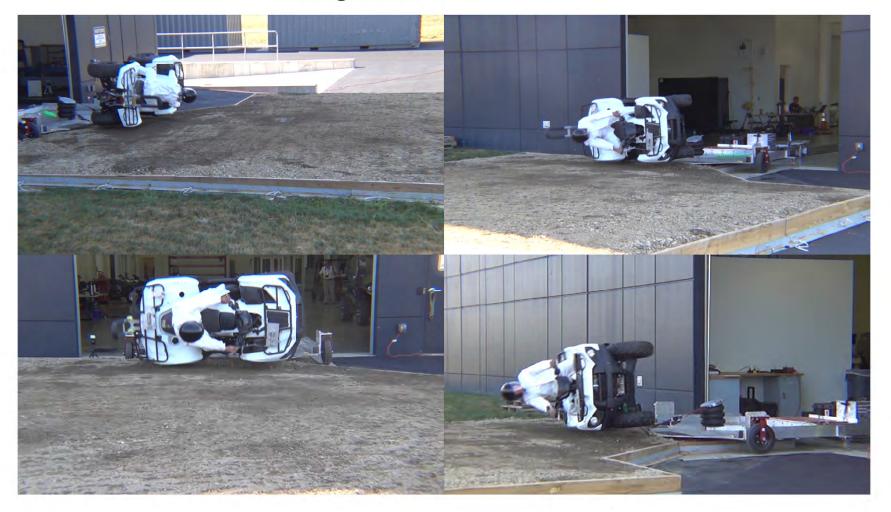
Vehicle G - Sled Minimum Energy Rollover -

### Roll Angle = $45^{\circ}$ - Time = 0.63 sec



Vehicle G - Sled Minimum Energy Rollover -

### Roll Angle = $90^{\circ}$ - Time = 0.86 sec



Vehicle G - Sled Minimum Energy Rollover -

#### ATD Head Strike - Time = 0.98 sec



Vehicle G - Sled Minimum Energy Rollover -

### Max Roll Angle = $161.6^{\circ}$ - Time = 2.17 sec



Vehicle G - Sled Minimum Energy Rollover -

### End of Run - Roll Angle = 90.6°



Vehicle G - Sled Minimum Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.52 sec



Drone Camera - Roll Angle = 45° - Time = 0.63 sec



Drone Camera - Roll Angle = 90° - Time = 0.86 sec



Drone Camera - ATD Head Strike - Time = 0.98 sec



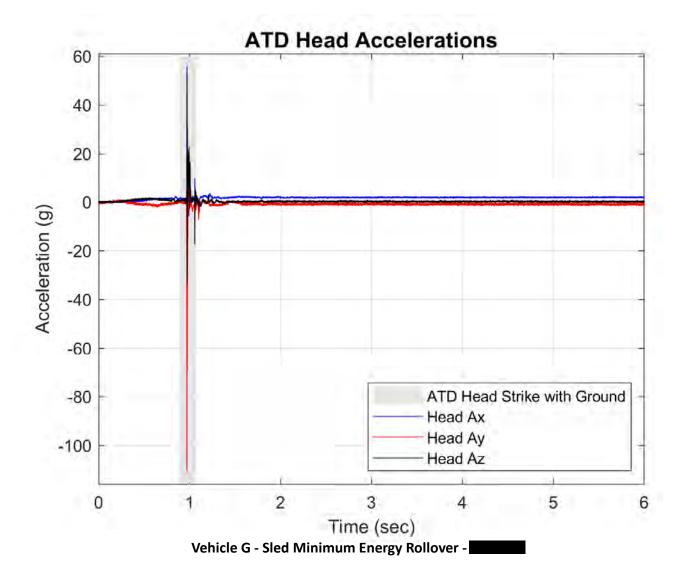
Drone Camera - Max Angle = 161.6° - Time = 2.17 sec

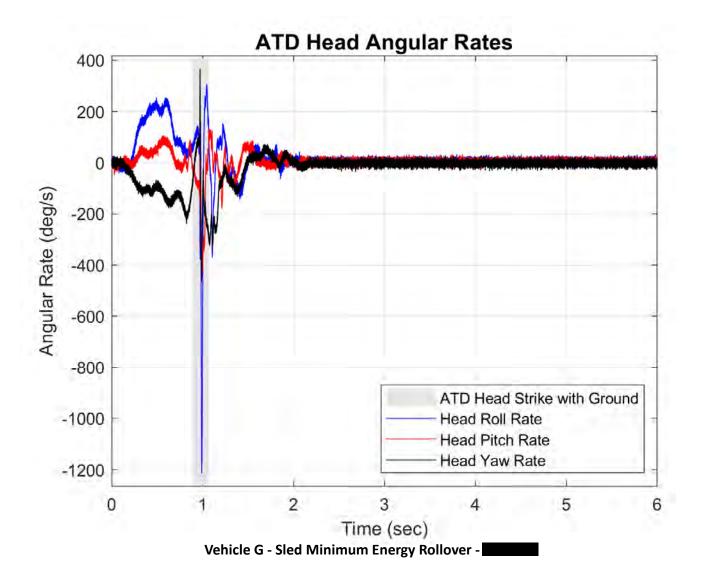


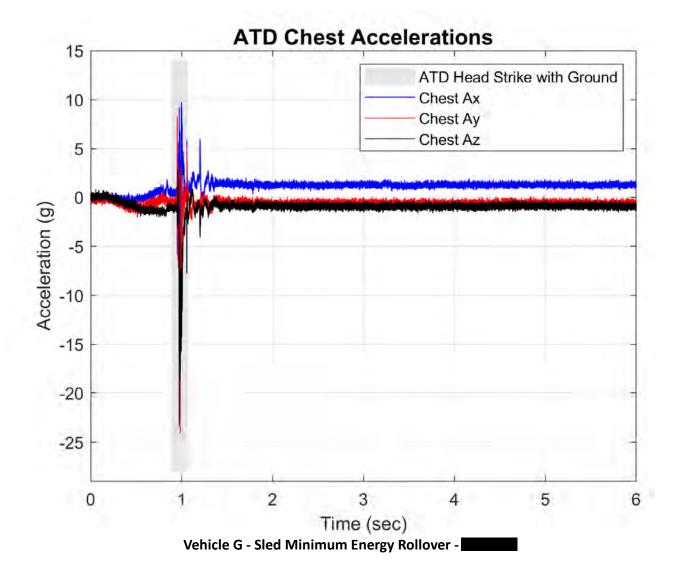
Drone Camera - End of Run - Roll Angle = 90.6°

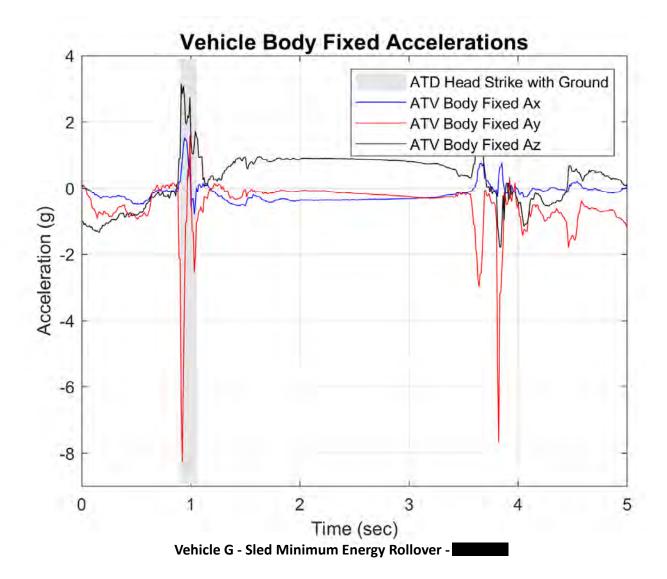


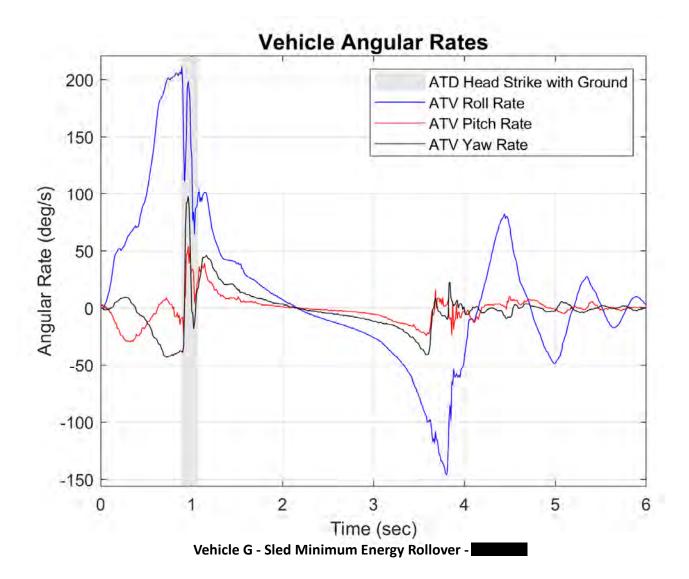
Vehicle G - Sled Minimum Energy Rollover -

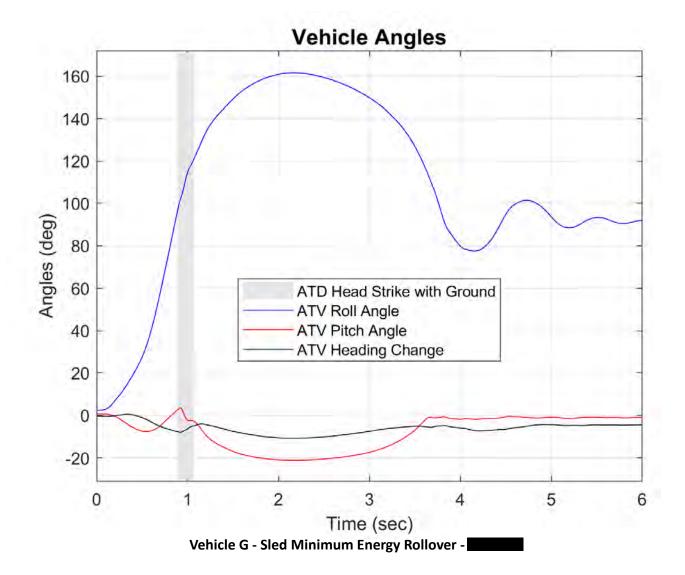










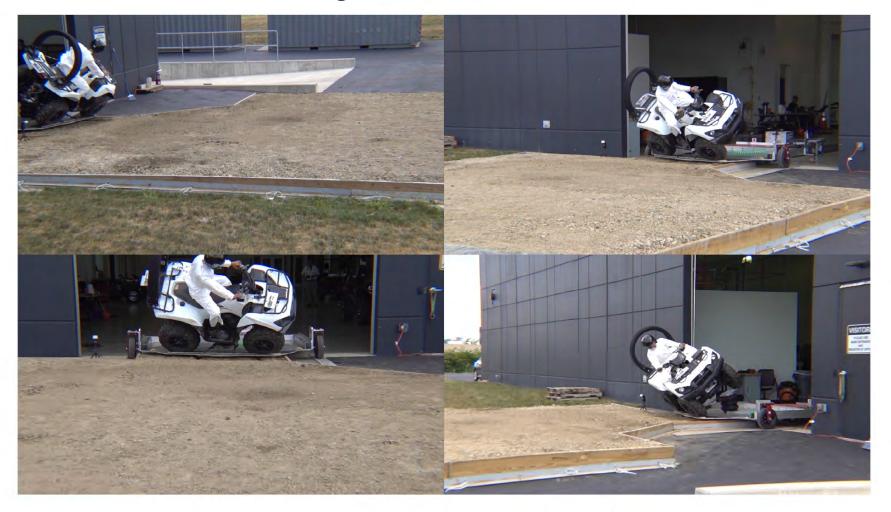


### Roll Angle = $30^{\circ}$ - Time = 0.46 sec



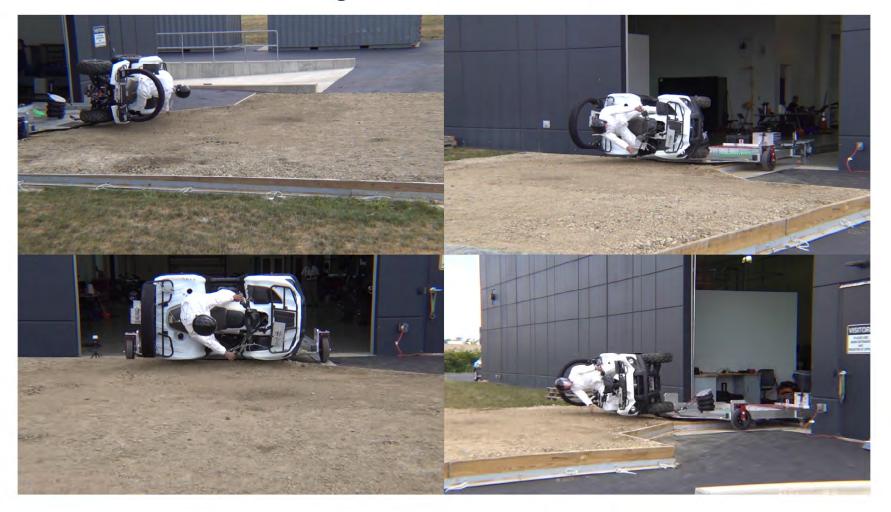
Vehicle G - Sled Moderate Energy Rollover -

### Roll Angle = $45^{\circ}$ - Time = 0.58 sec



Vehicle G - Sled Moderate Energy Rollover -

### Roll Angle = $90^{\circ}$ - Time = 0.82 sec



Vehicle G - Sled Moderate Energy Rollover -

#### ATD Head Strike - Time = 0.95 sec



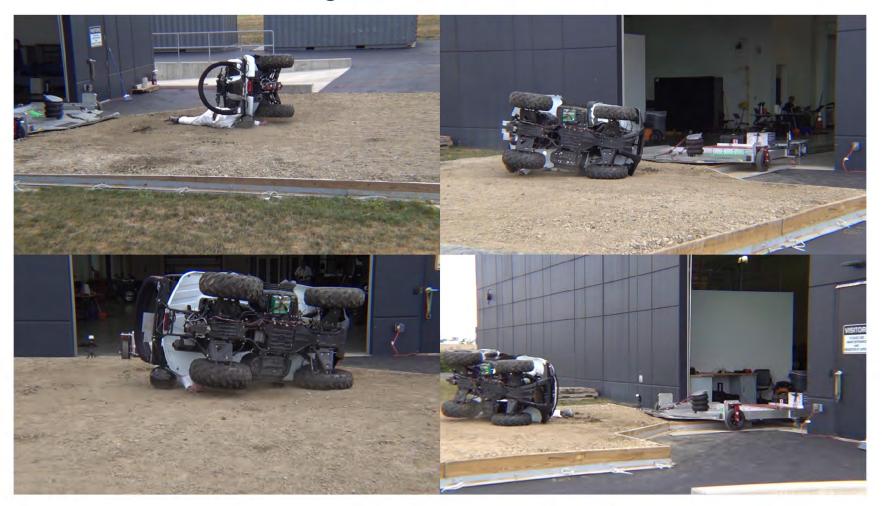
Vehicle G - Sled Moderate Energy Rollover -

### Roll Angle = $180^{\circ}$ - Time = 1.28 sec



Vehicle G - Sled Moderate Energy Rollover -

### Roll Angle = $270^{\circ}$ - Time = 1.93 sec



Vehicle G - Sled Moderate Energy Rollover -

### Roll Angle = $360^{\circ}$ - Time = 3.05 sec



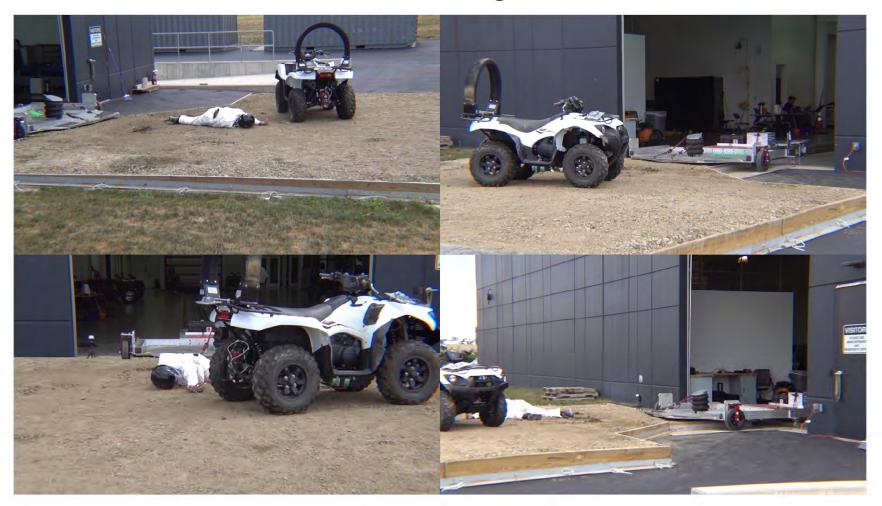
Vehicle G - Sled Moderate Energy Rollover -

### Max Roll Angle = $374.3^{\circ}$ - Time = 3.30 sec



Vehicle G - Sled Moderate Energy Rollover -

#### End of Run - Roll Angle = 362.5°



Vehicle G - Sled Moderate Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.46 sec



Drone Camera - Roll Angle = 45° - Time = 0.58 sec



Drone Camera - Roll Angle = 90° - Time = 0.82 sec



Drone Camera - ATD Head Strike - Time = 0.95 sec



Drone Camera - Roll Angle = 180° - Time = 1.28 sec



Drone Camera - Roll Angle = 270° - Time = 1.93 sec



Vehicle G - Sled Moderate Energy Rollover -

Drone Camera - Roll Angle = 360° - Time = 3.05 sec

Drone Camera - Max Angle = 374.3° - Time = 3.30 sec

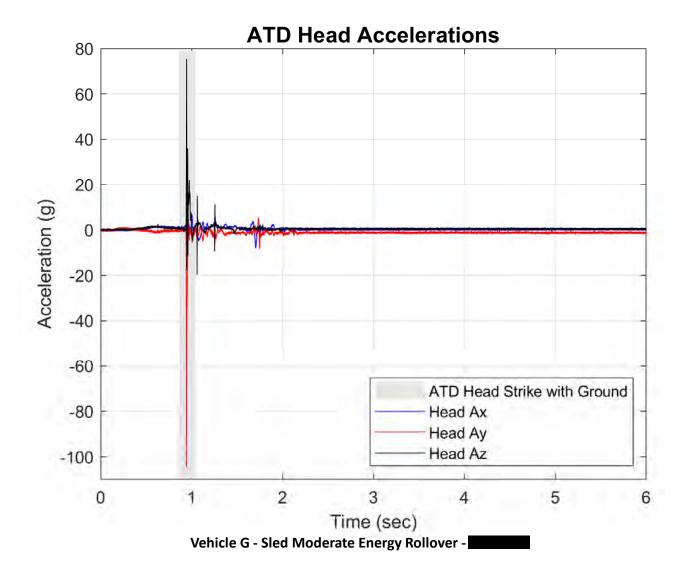
Drone Camera - End of Run - Roll Angle = 362.5°

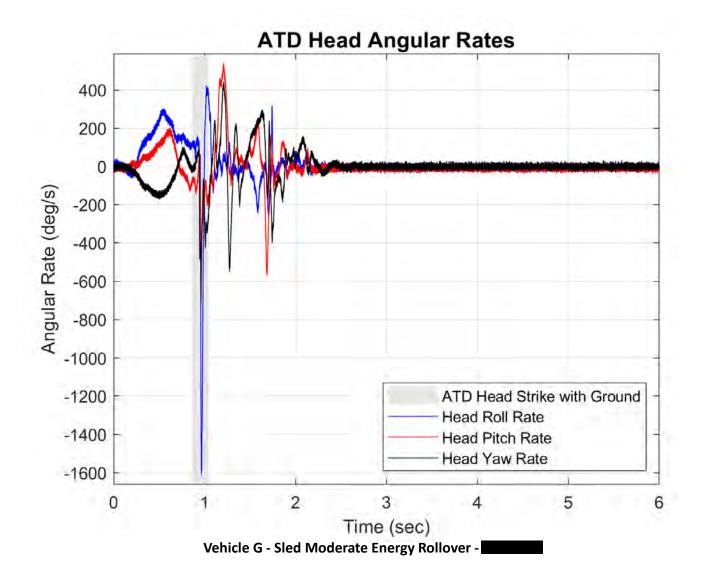


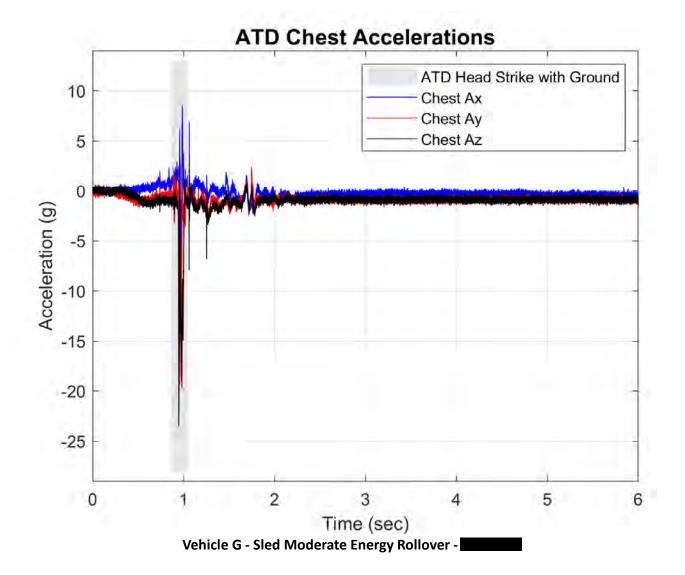


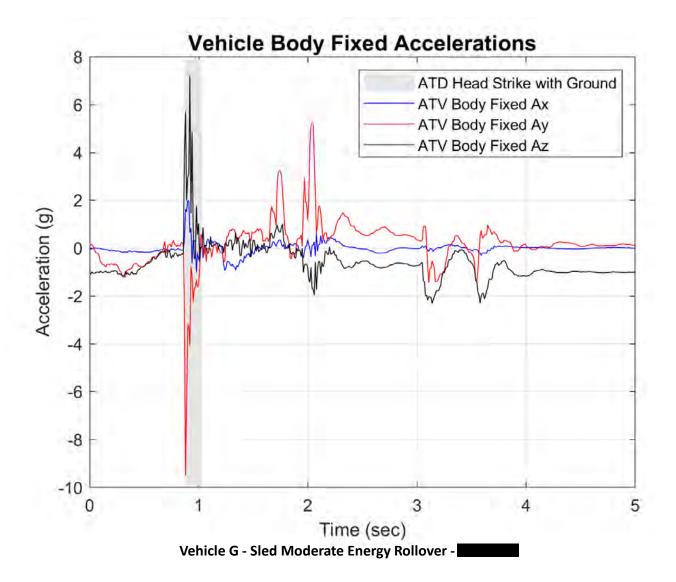


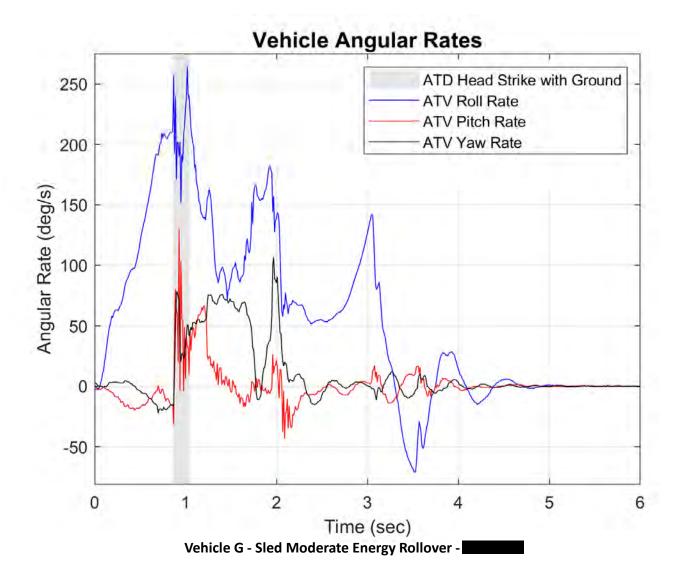
Vehicle G - Sled Moderate Energy Rollover -

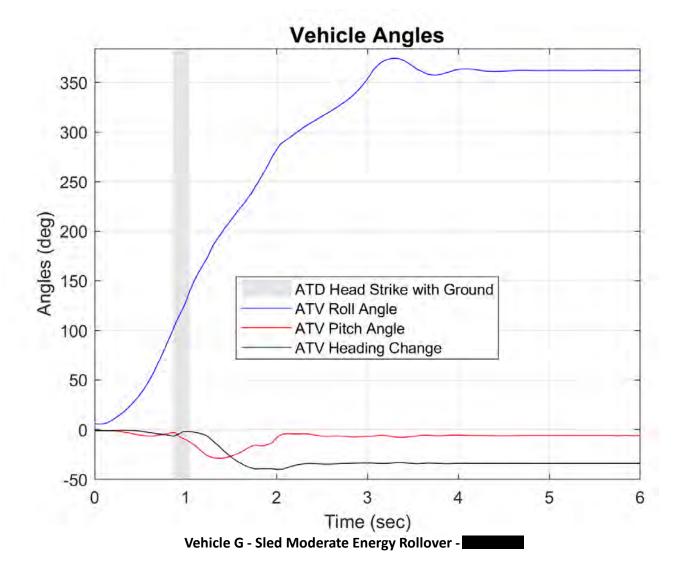




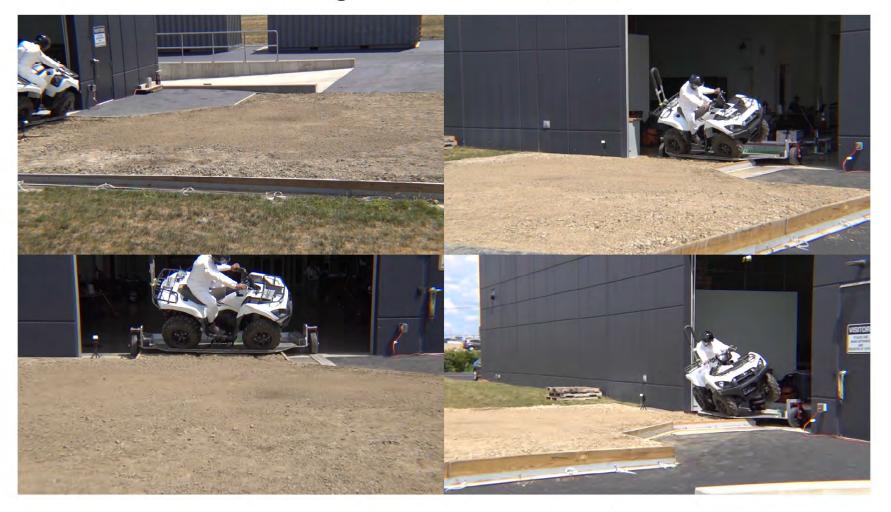








# Roll Angle = $30^{\circ}$ - Time = 0.41 sec



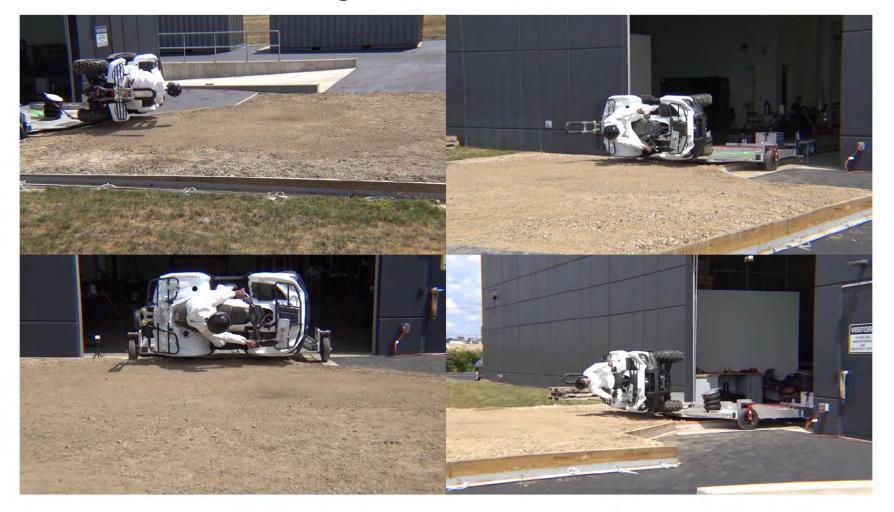
Vehicle G - Sled Moderate Energy Rollover -

# Roll Angle = $45^{\circ}$ - Time = 0.53 sec



Vehicle G - Sled Moderate Energy Rollover -

# Roll Angle = $90^{\circ}$ - Time = 0.77 sec



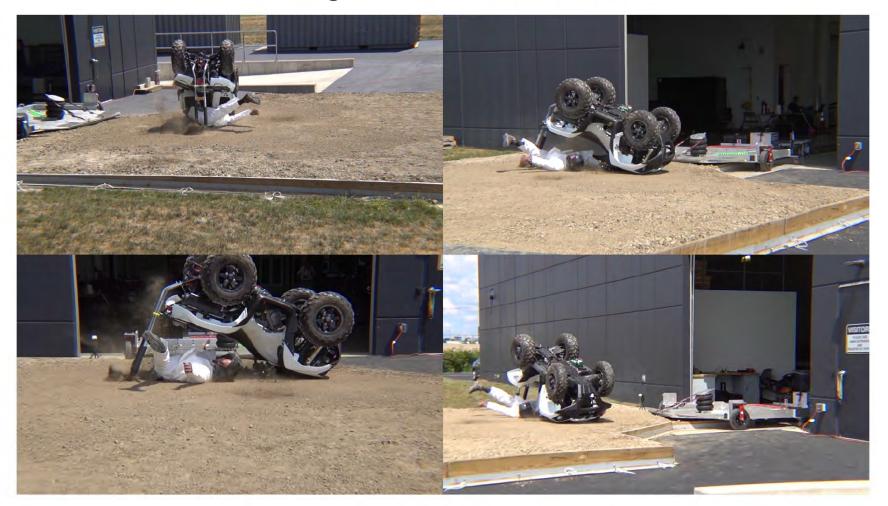
Vehicle G - Sled Moderate Energy Rollover -

#### ATD Head Strike - Time = 0.88 sec



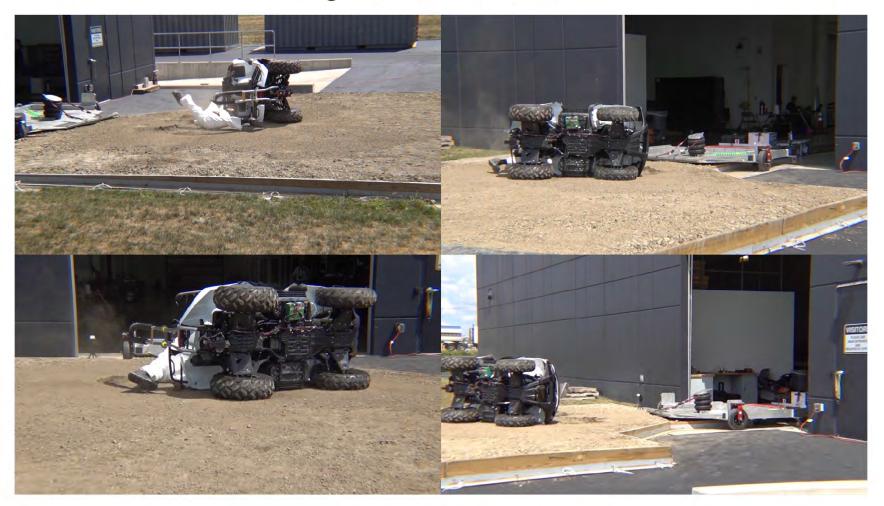
Vehicle G - Sled Moderate Energy Rollover -

# Roll Angle = $180^{\circ}$ - Time = 1.32 sec



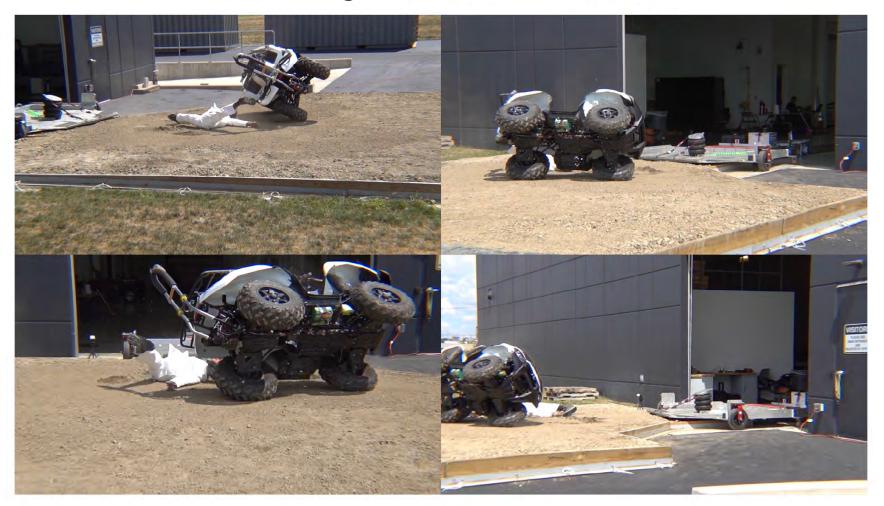
Vehicle G - Sled Moderate Energy Rollover -

# Roll Angle = $270^{\circ}$ - Time = 1.92 sec



Vehicle G - Sled Moderate Energy Rollover -

#### Max Roll Angle = $302.2^{\circ}$ - Time = 2.58 sec



Vehicle G - Sled Moderate Energy Rollover -

# End of Run - Roll Angle = $271.5^{\circ}$



Vehicle G - Sled Moderate Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.41 sec



Drone Camera - Roll Angle = 45° - Time = 0.53 sec



Drone Camera - Roll Angle = 90° - Time = 0.77 sec



Drone Camera - ATD Head Strike - Time = 0.88 sec



Drone Camera - Roll Angle = 180° - Time = 1.32 sec



Drone Camera - Roll Angle = 270° - Time = 1.92 sec



Vehicle G - Sled Moderate Energy Rollover -

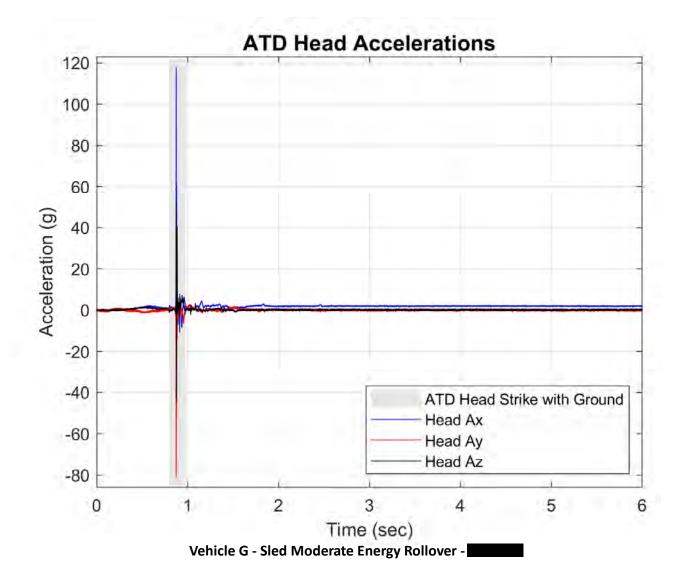
Drone Camera - Max Angle = 302.2° - Time = 2.58 sec

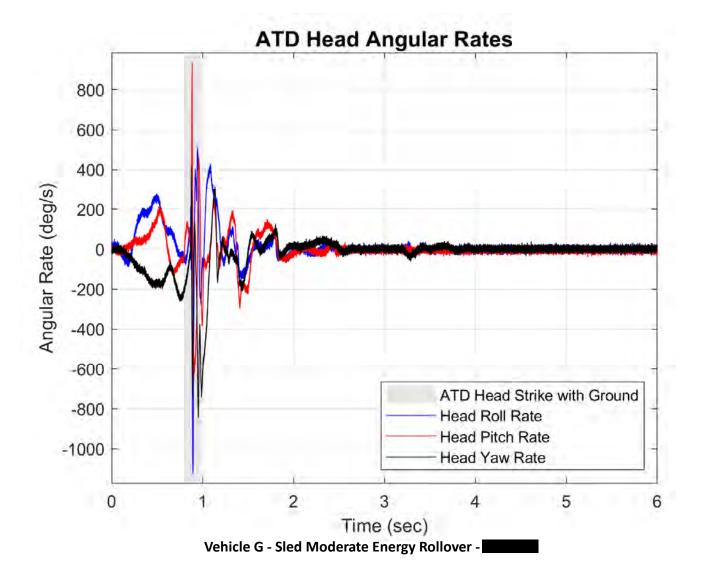
Drone Camera - End of Run - Roll Angle = 271.5°

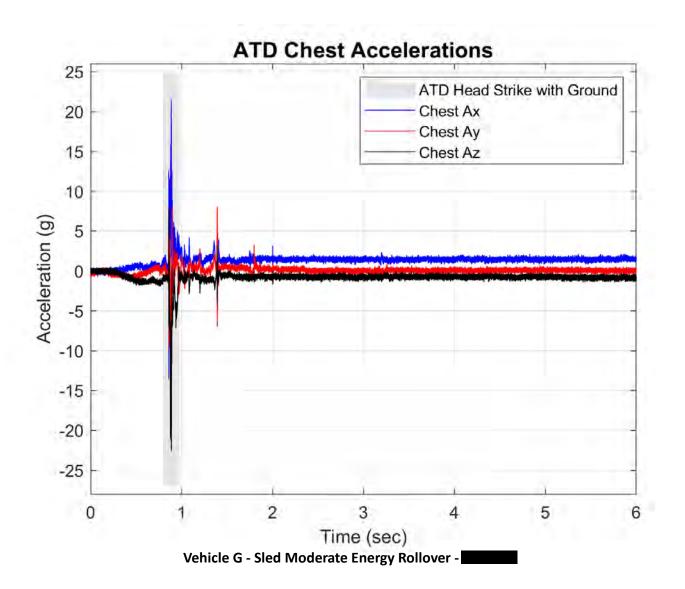


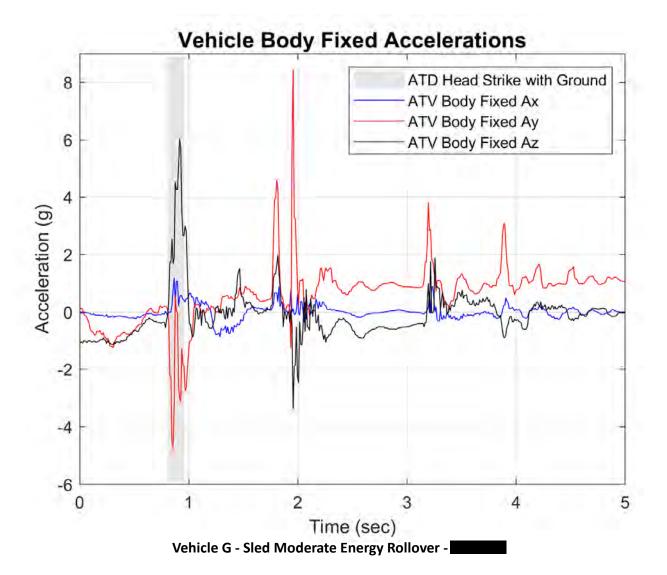


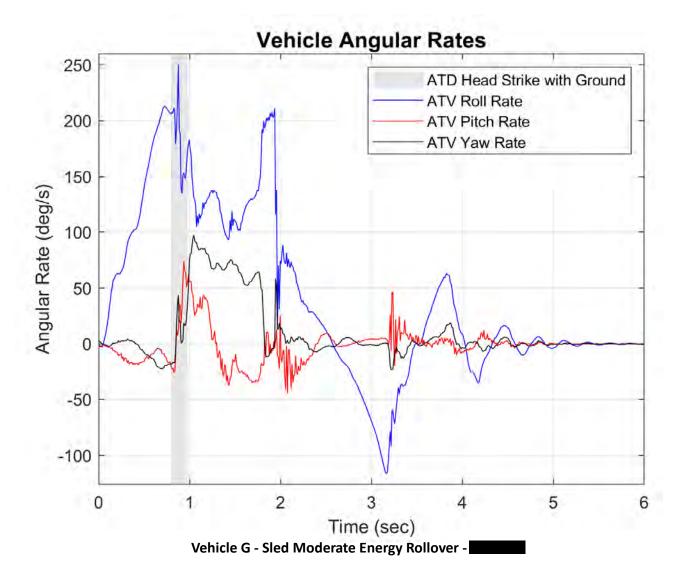
Vehicle G - Sled Moderate Energy Rollover -

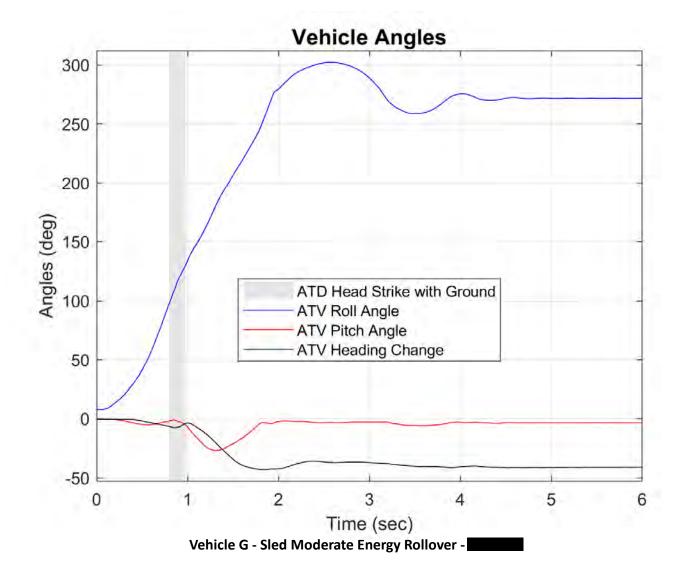












### Roll Angle = $30^{\circ}$ - Time = 0.65 sec



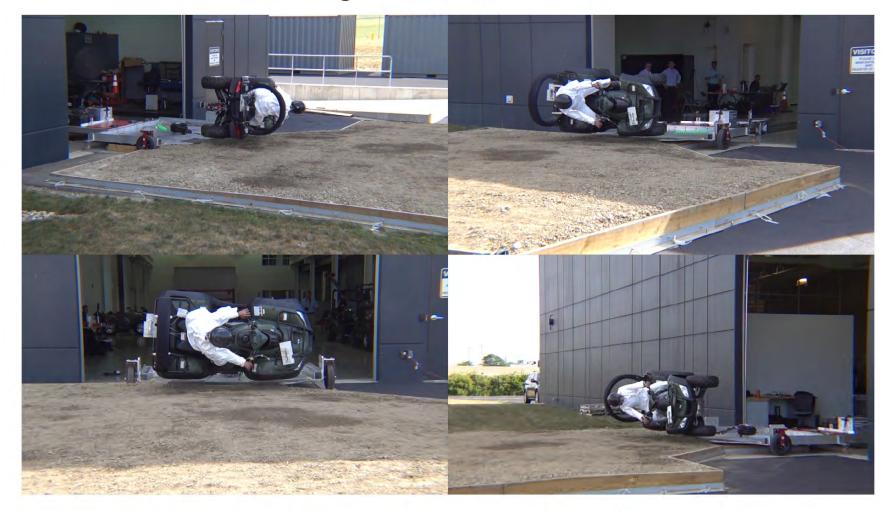
Vehicle J - Sled Minimum Energy Rollover -

### Roll Angle = $45^{\circ}$ - Time = 0.74 sec



Vehicle J - Sled Minimum Energy Rollover -

## Roll Angle = $90^{\circ}$ - Time = 0.97 sec



Vehicle J - Sled Minimum Energy Rollover -

#### ATD Head Strike - Time = 1.14 sec



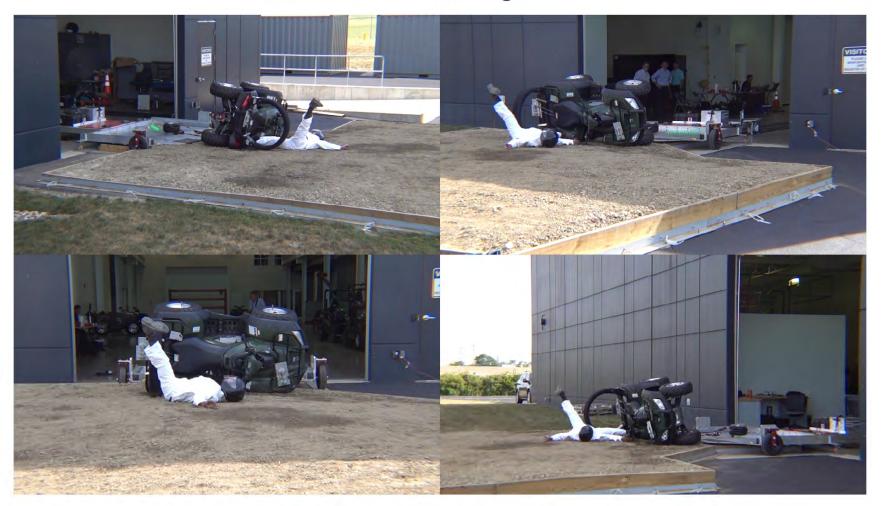
Vehicle J - Sled Minimum Energy Rollover -

### Max Roll Angle = $137.8^{\circ}$ - Time = 1.60 sec



Vehicle J - Sled Minimum Energy Rollover -

# End of Run - Roll Angle = $99.5^{\circ}$



Vehicle J - Sled Minimum Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.65 sec



Drone Camera - Roll Angle = 45° - Time = 0.74 sec



Drone Camera - Roll Angle = 90° - Time = 0.97 sec



Drone Camera - ATD Head Strike - Time = 1.14 sec



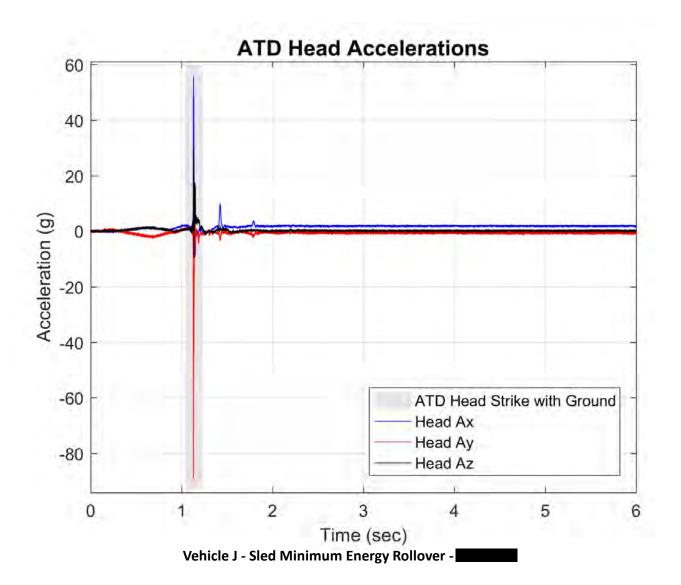
Drone Camera - Max Angle = 137.8° - Time = 1.60 sec

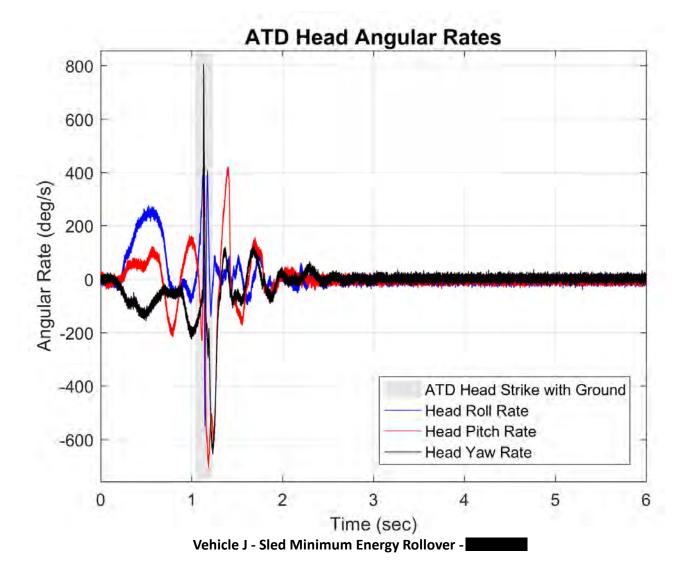


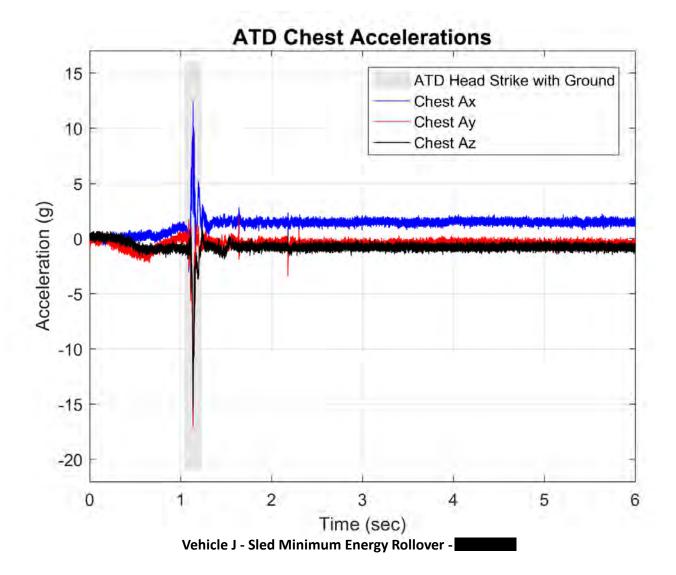
Drone Camera - End of Run - Roll Angle = 99.5°

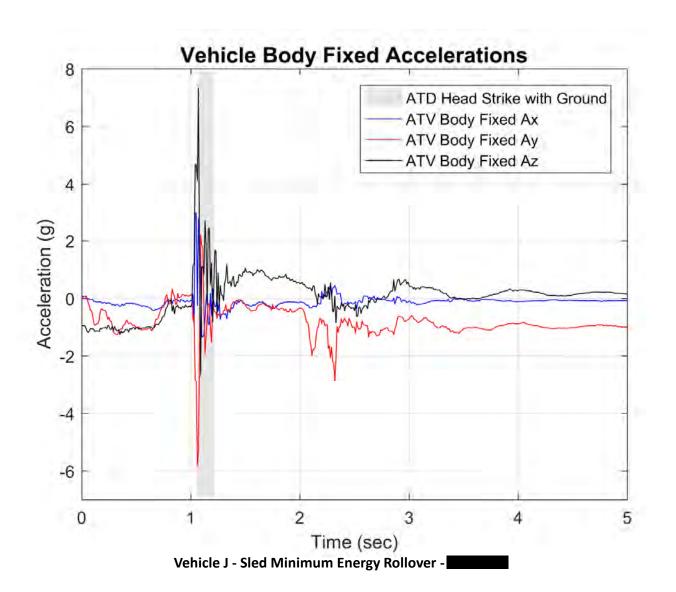


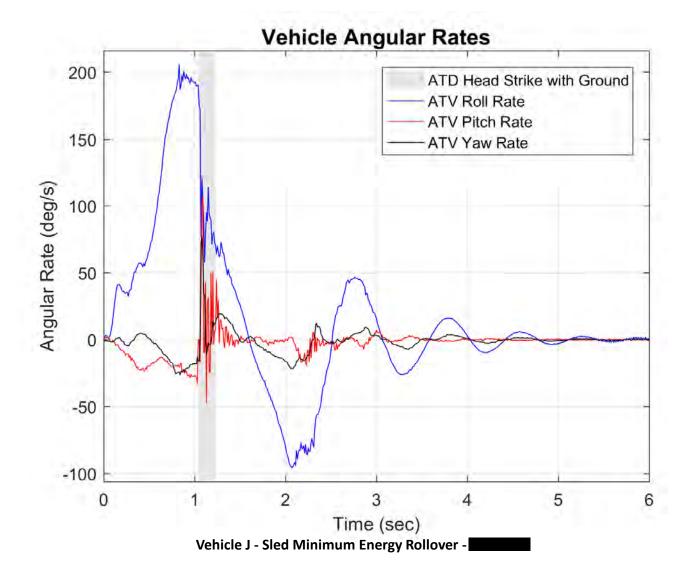
Vehicle J - Sled Minimum Energy Rollover -

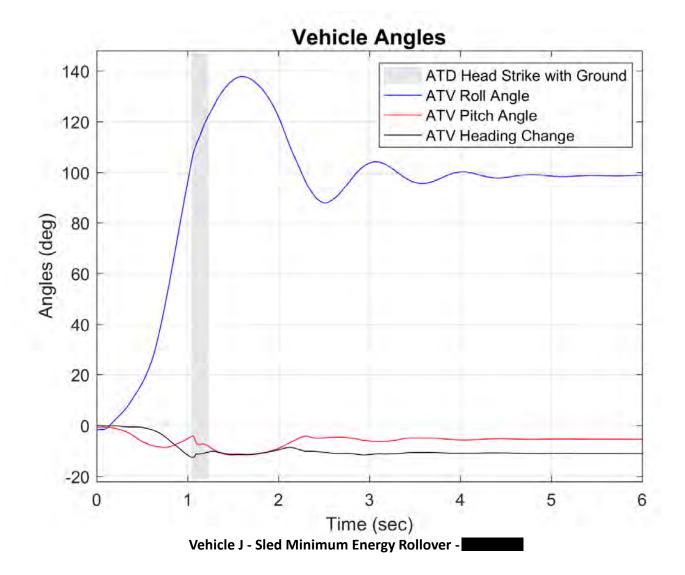




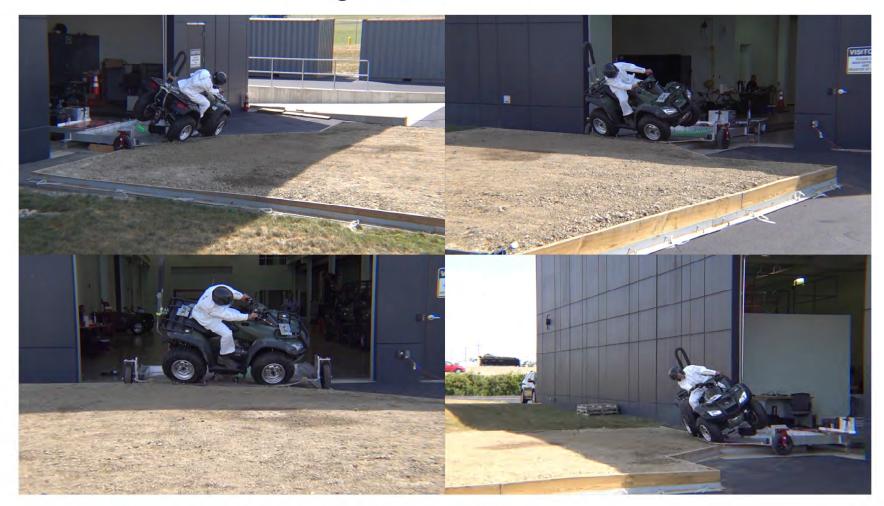








### Roll Angle = $30^{\circ}$ - Time = 0.65 sec



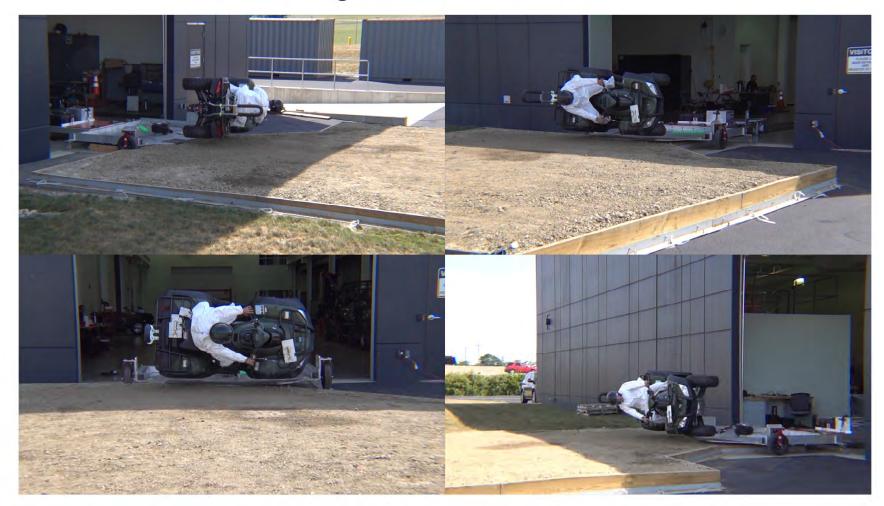
Vehicle J - Sled Minimum Energy Rollover -

### Roll Angle = $45^{\circ}$ - Time = 0.75 sec



Vehicle J - Sled Minimum Energy Rollover -

## Roll Angle = $90^{\circ}$ - Time = 0.97 sec



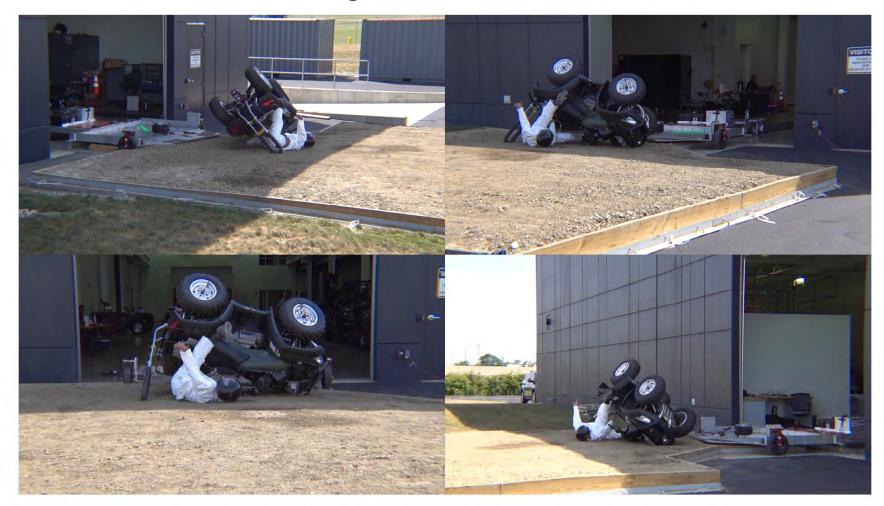
Vehicle J - Sled Minimum Energy Rollover -

#### ATD Head Strike - Time = 1.13 sec



Vehicle J - Sled Minimum Energy Rollover -

### Max Roll Angle = $136.2^{\circ}$ - Time = 1.54 sec



Vehicle J - Sled Minimum Energy Rollover -

### End of Run - Roll Angle = 100.7°



Vehicle J - Sled Minimum Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.65 sec



Drone Camera - Roll Angle = 45° - Time = 0.75 sec



Drone Camera - Roll Angle = 90° - Time = 0.97 sec



Drone Camera - ATD Head Strike - Time = 1.13 sec



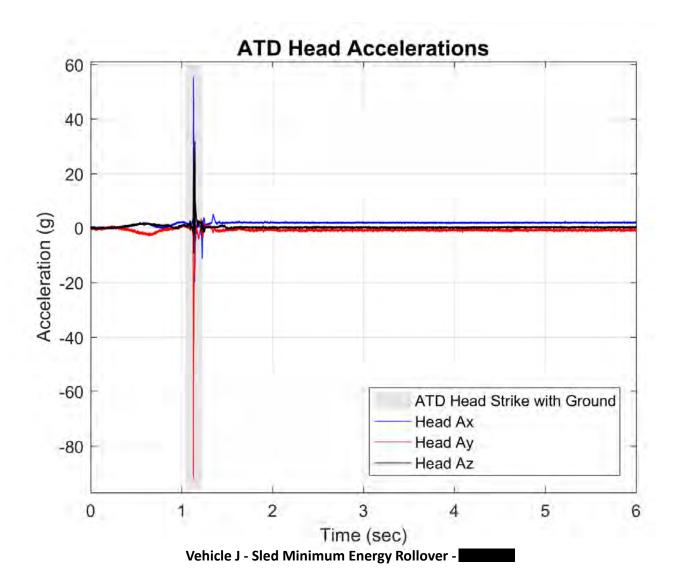
Drone Camera - Max Angle = 136.2° - Time = 1.54 sec

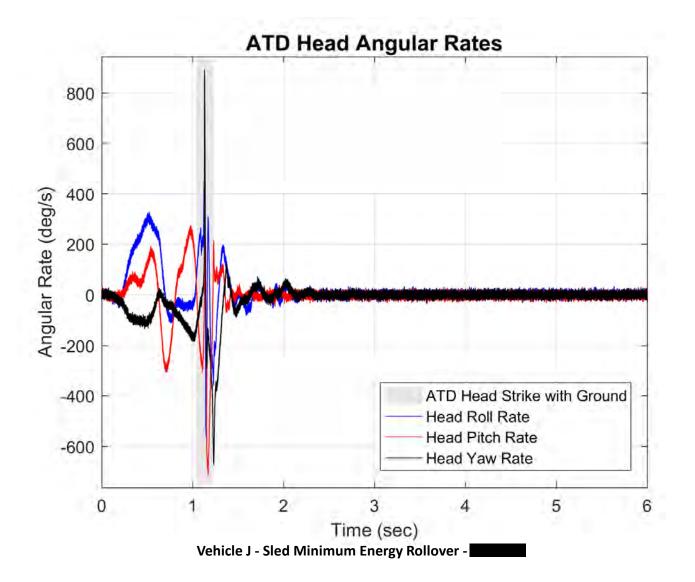


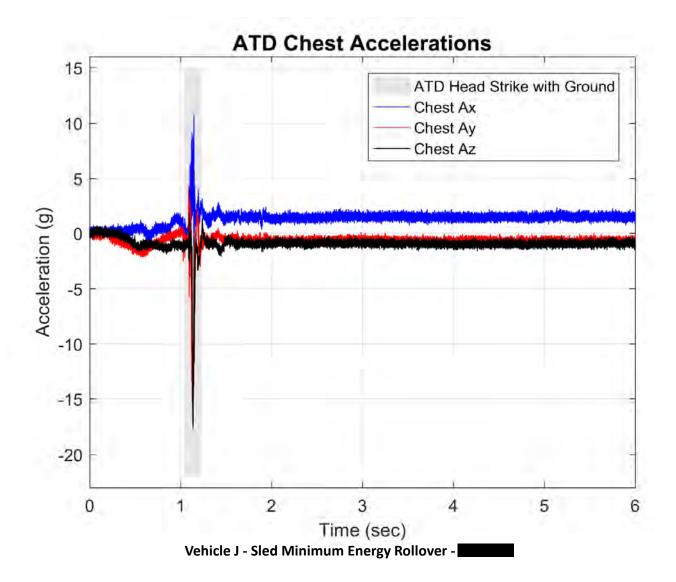
Drone Camera - End of Run - Roll Angle = 100.7°

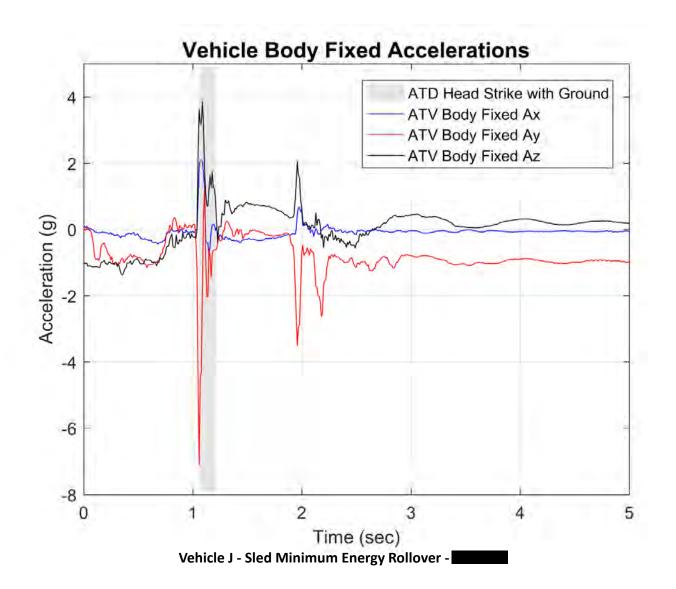


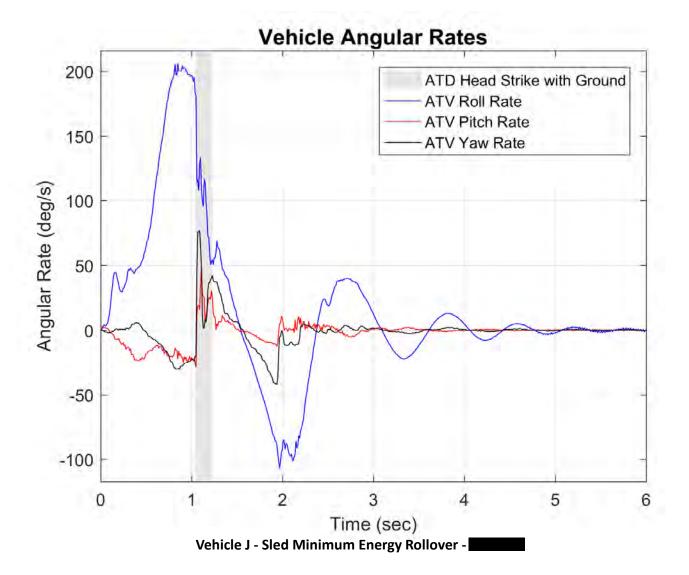
Vehicle J - Sled Minimum Energy Rollover -

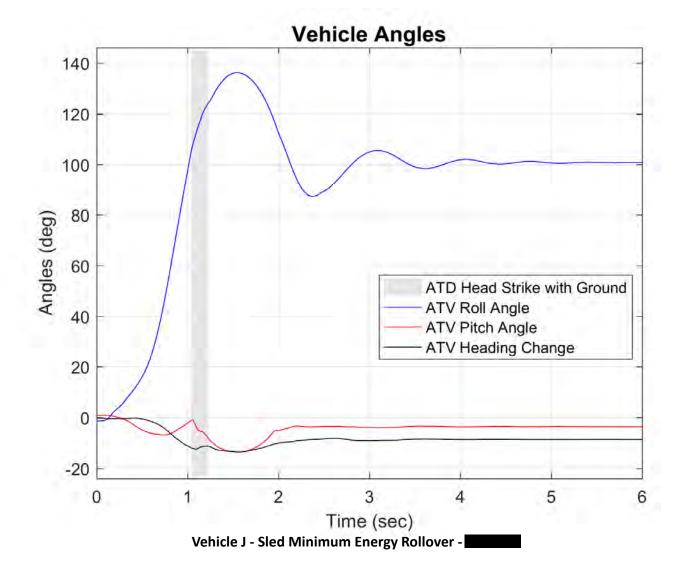




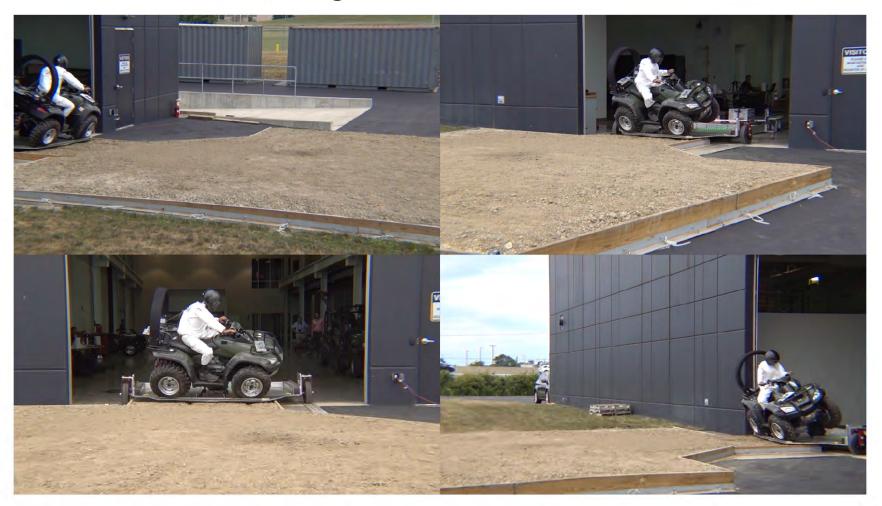






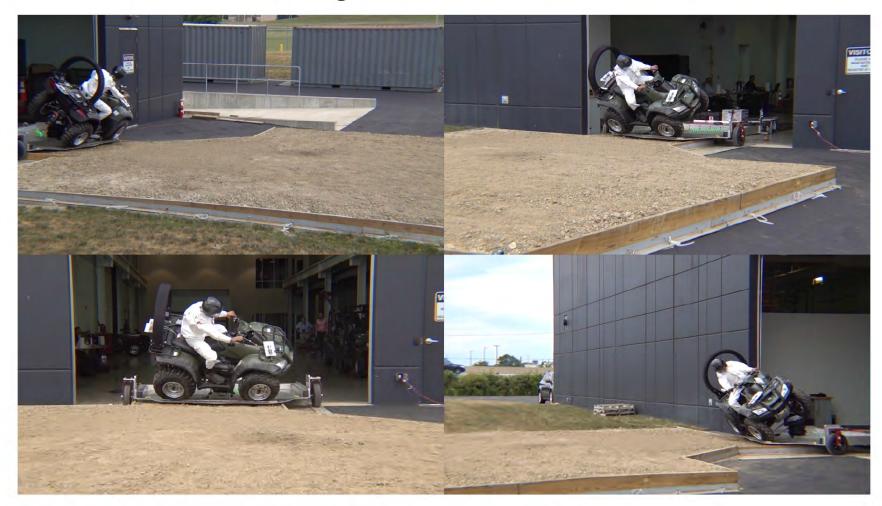


### Roll Angle = $30^{\circ}$ - Time = 0.47 sec



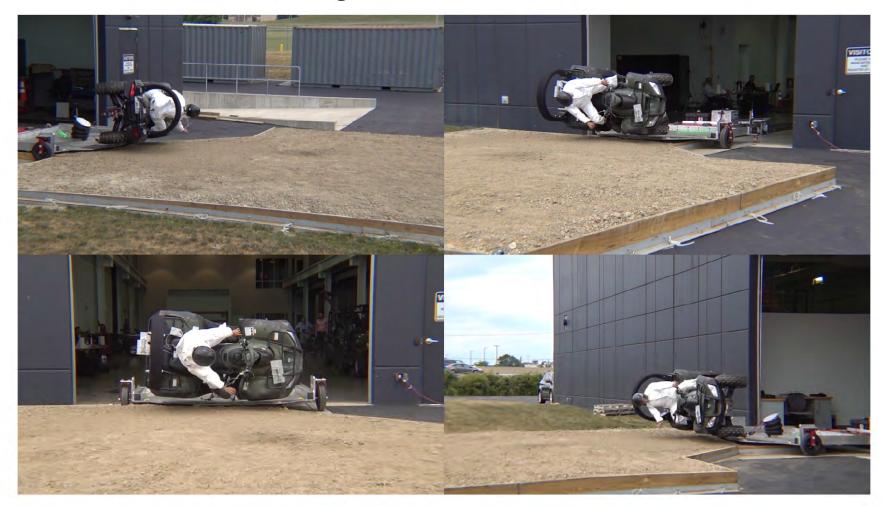
Vehicle J - Sled Moderate Energy Rollover -

### Roll Angle = $45^{\circ}$ - Time = 0.60 sec



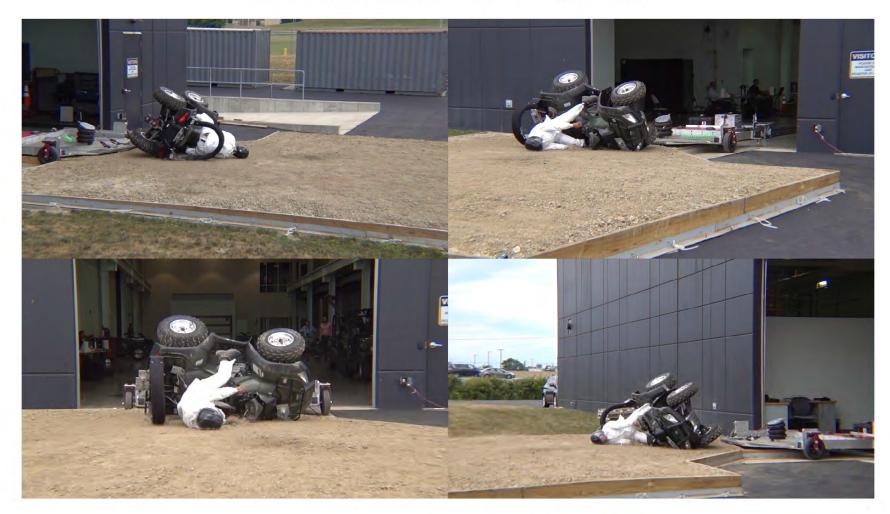
Vehicle J - Sled Moderate Energy Rollover -

## Roll Angle = $90^{\circ}$ - Time = 0.84 sec



Vehicle J - Sled Moderate Energy Rollover -

### ATD Head Strike - Time = 1.01 sec



Vehicle J - Sled Moderate Energy Rollover -

### Roll Angle = $180^{\circ}$ - Time = 1.38 sec



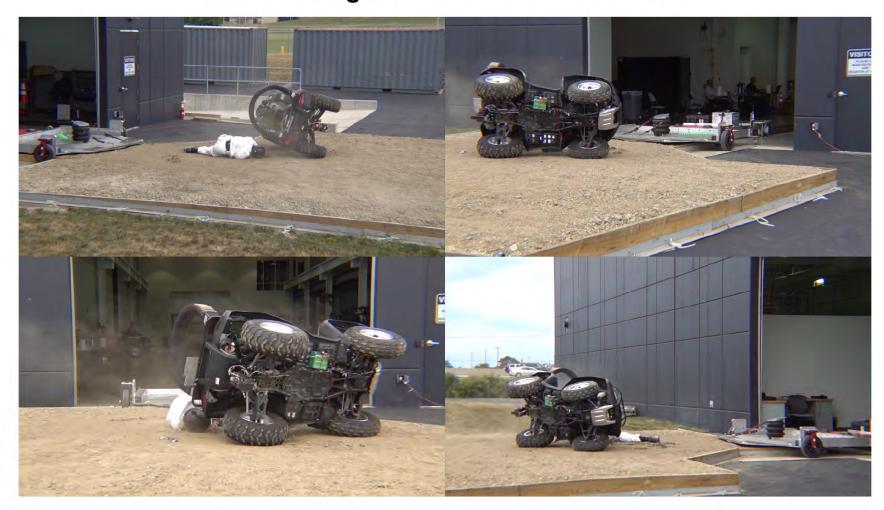
Vehicle J - Sled Moderate Energy Rollover -

### Roll Angle = $270^{\circ}$ - Time = 2.16 sec



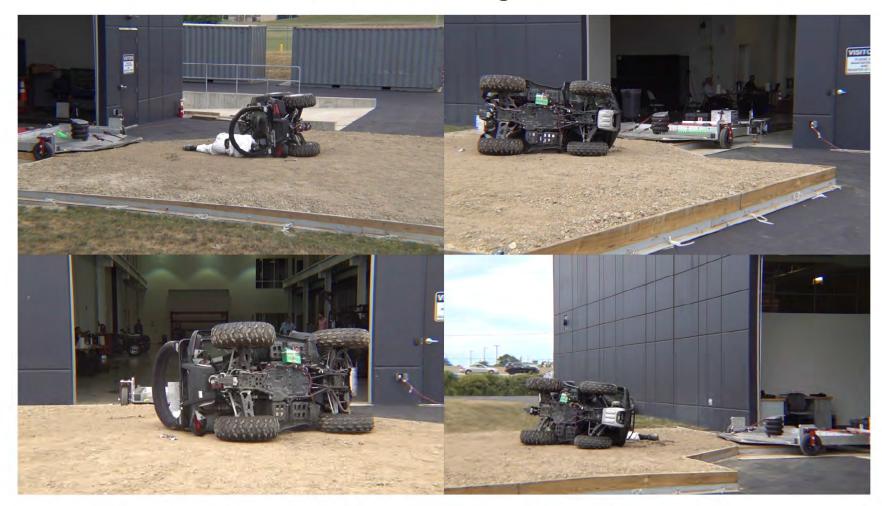
Vehicle J - Sled Moderate Energy Rollover -

# Max Roll Angle = $289.6^{\circ}$ - Time = 2.58 sec



Vehicle J - Sled Moderate Energy Rollover -

### End of Run - Roll Angle = 265.4°



Vehicle J - Sled Moderate Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.47 sec



Drone Camera - Roll Angle = 45° - Time = 0.60 sec



Drone Camera - Roll Angle = 90° - Time = 0.84 sec



Drone Camera - ATD Head Strike - Time = 1.01 sec



Drone Camera - Roll Angle = 180° - Time = 1.38 sec



Drone Camera - Roll Angle = 270° - Time = 2.16 sec



Vehicle J - Sled Moderate Energy Rollover -

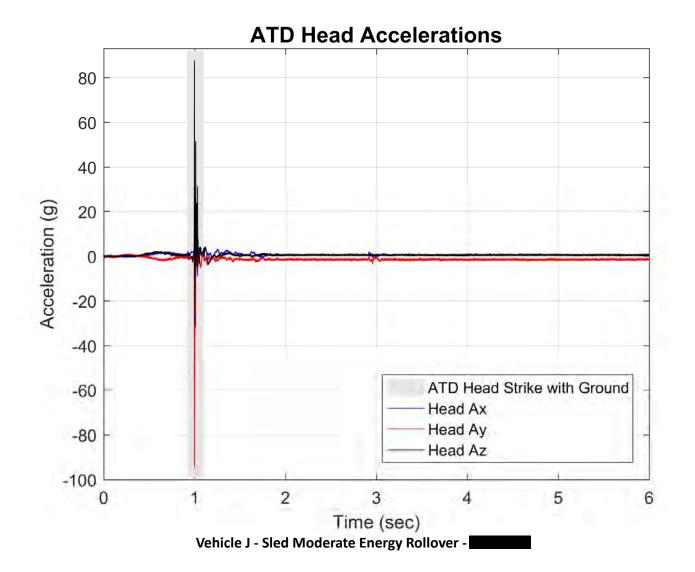
Drone Camera - Max Angle = 289.6° - Time = 2.58 sec

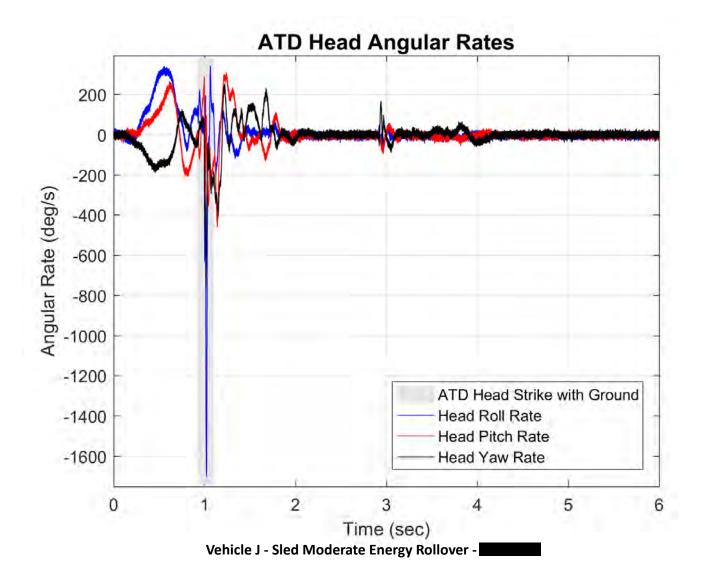
Drone Camera - End of Run - Roll Angle = 265.4°

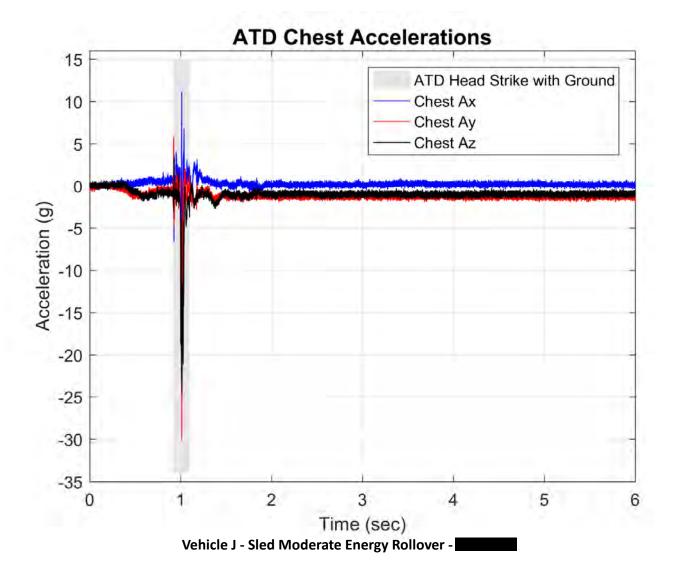


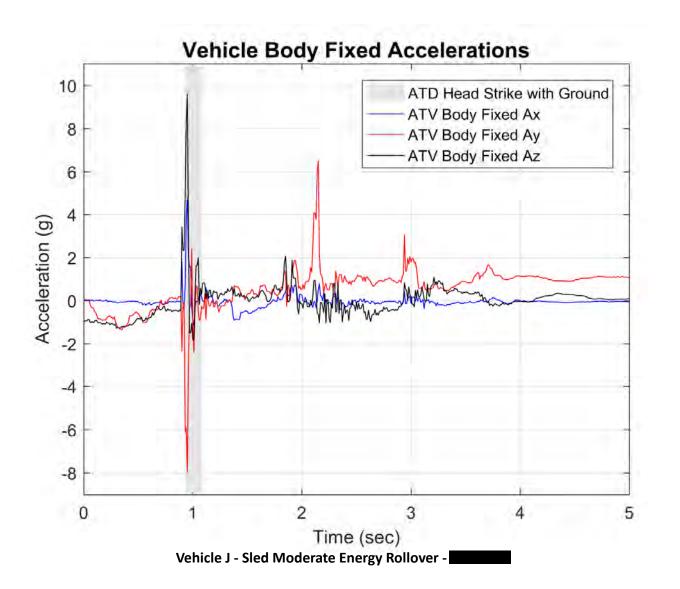


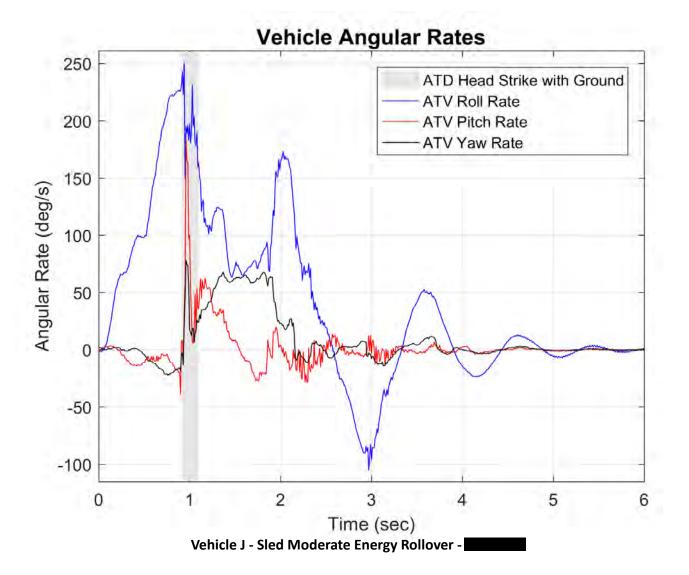
Vehicle J - Sled Moderate Energy Rollover -

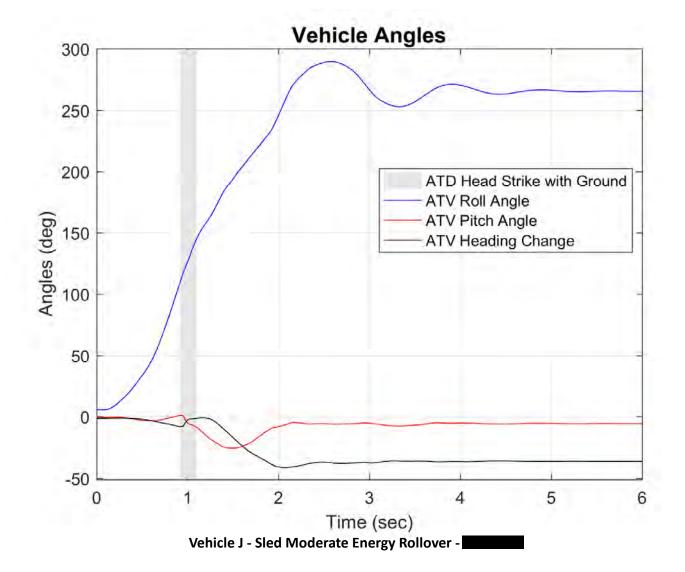




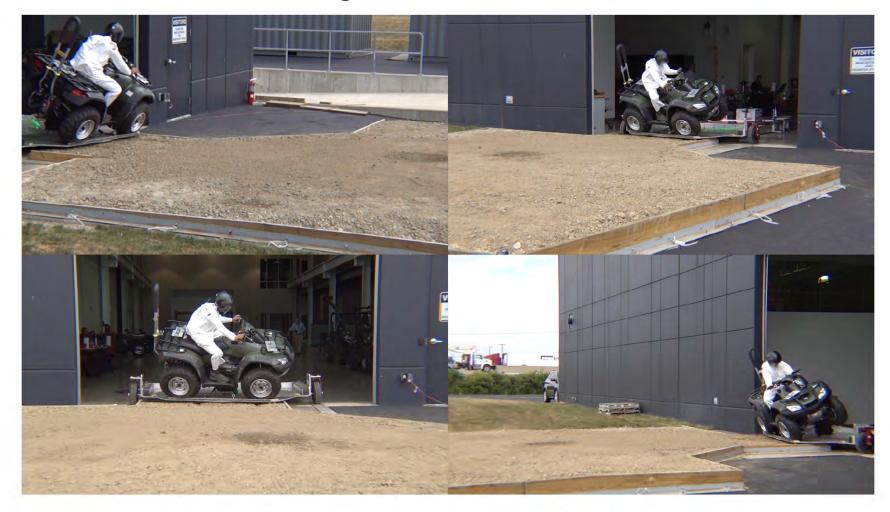








### Roll Angle = $30^{\circ}$ - Time = 0.48 sec



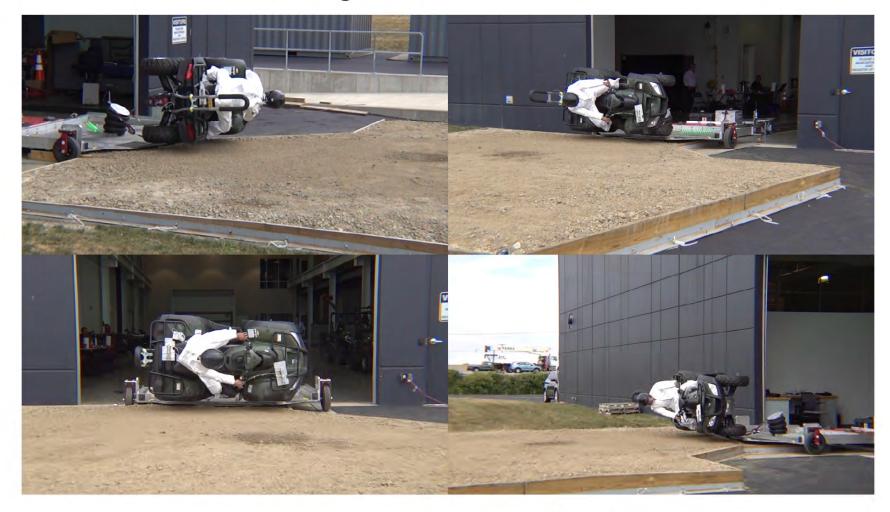
Vehicle J - Sled Moderate Energy Rollover -

### Roll Angle = $45^{\circ}$ - Time = 0.61 sec



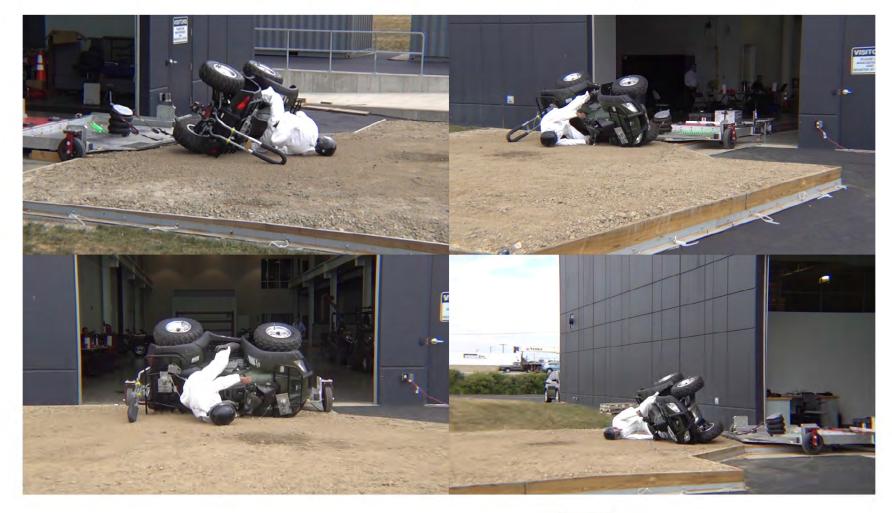
Vehicle J - Sled Moderate Energy Rollover -

## Roll Angle = $90^{\circ}$ - Time = 0.84 sec



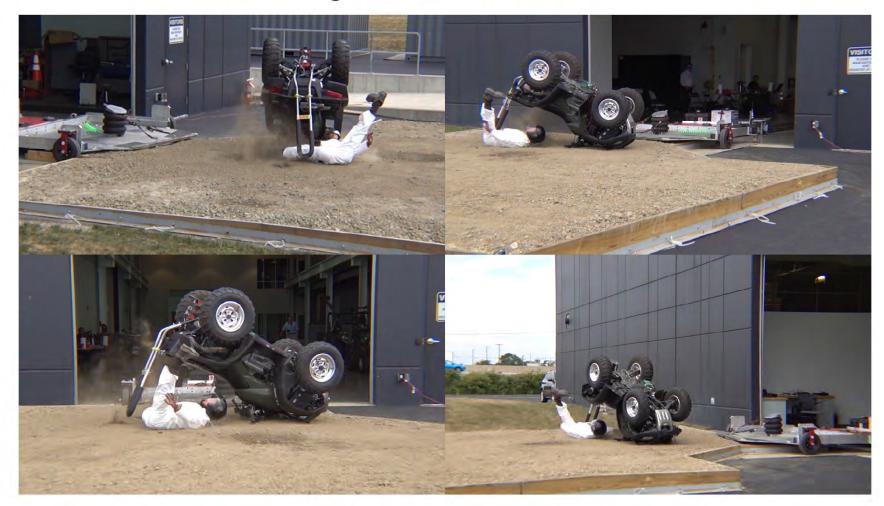
Vehicle J - Sled Moderate Energy Rollover -

### ATD Head Strike - Time = 0.97 sec



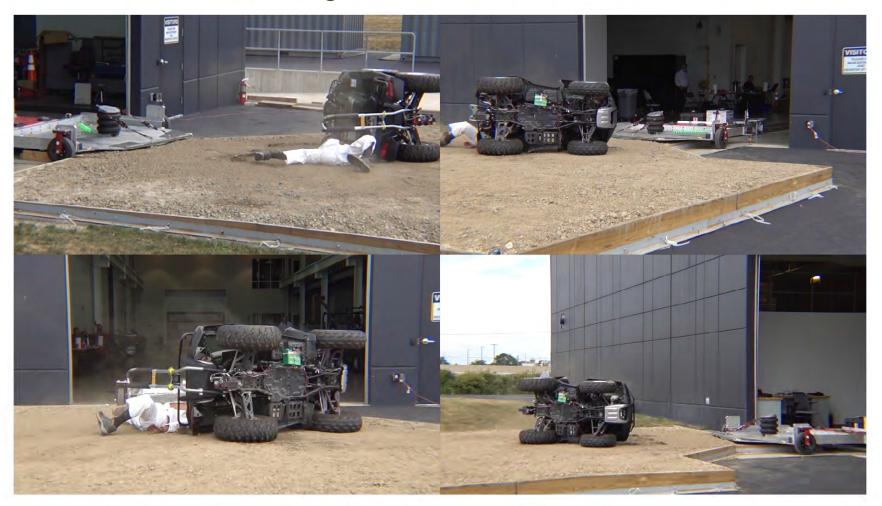
Vehicle J - Sled Moderate Energy Rollover -

### Roll Angle = $180^{\circ}$ - Time = 1.37 sec



Vehicle J - Sled Moderate Energy Rollover -

## Roll Angle = $270^{\circ}$ - Time = 1.98 sec



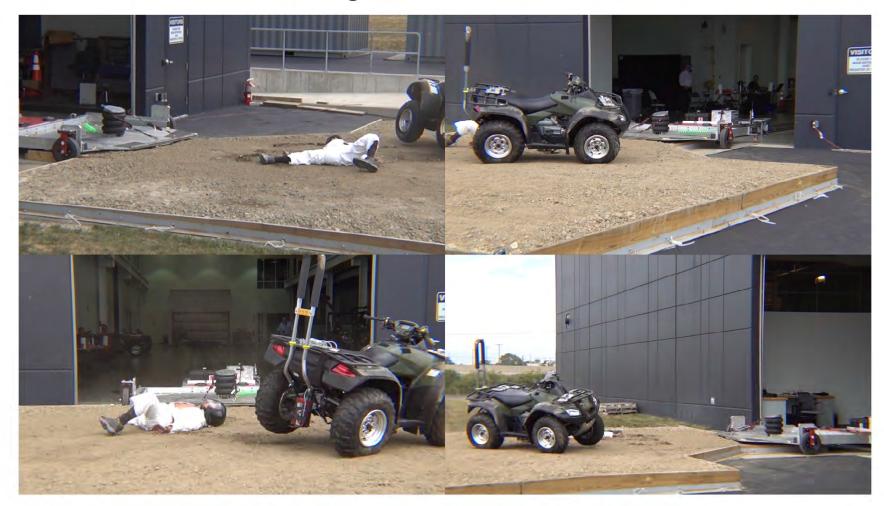
Vehicle J - Sled Moderate Energy Rollover -

### Roll Angle = $360^{\circ}$ - Time = 3.09 sec



Vehicle J - Sled Moderate Energy Rollover -

### Max Roll Angle = $372.9^{\circ}$ - Time = 3.31 sec



Vehicle J - Sled Moderate Energy Rollover -

### End of Run - Roll Angle = 360.8°



Vehicle J - Sled Moderate Energy Rollover -

Drone Camera - Roll Angle = 30° - Time = 0.48 sec



Drone Camera - Roll Angle = 45° - Time = 0.61 sec



Drone Camera - Roll Angle = 90° - Time = 0.84 sec



Drone Camera - ATD Head Strike - Time = 0.97 sec



Drone Camera - Roll Angle = 180° - Time = 1.37 sec



Drone Camera - Roll Angle = 270° - Time = 1.98 sec



Vehicle J - Sled Moderate Energy Rollover -

Drone Camera - Roll Angle = 360° - Time = 3.09 sec

Drone Camera - Max Angle = 372.9° - Time = 3.31 sec

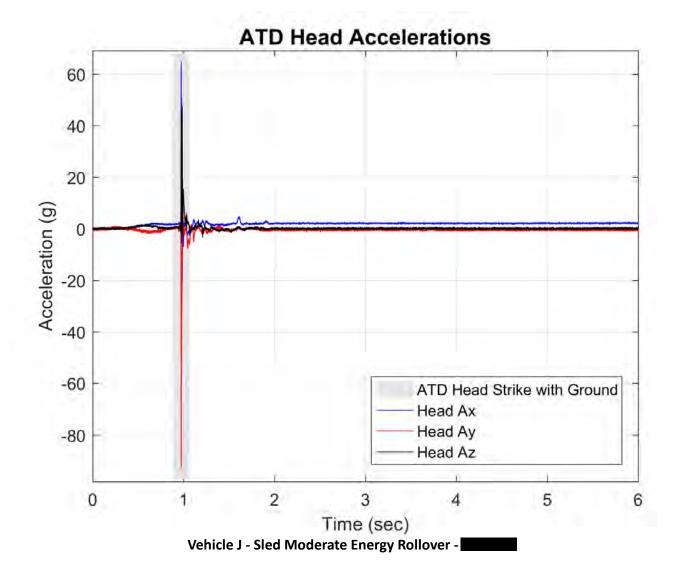
Drone Camera - End of Run - Roll Angle = 360.8°

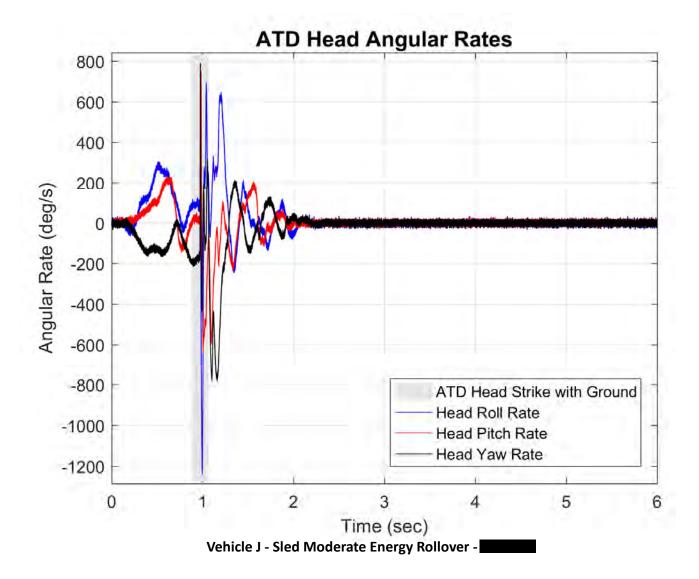


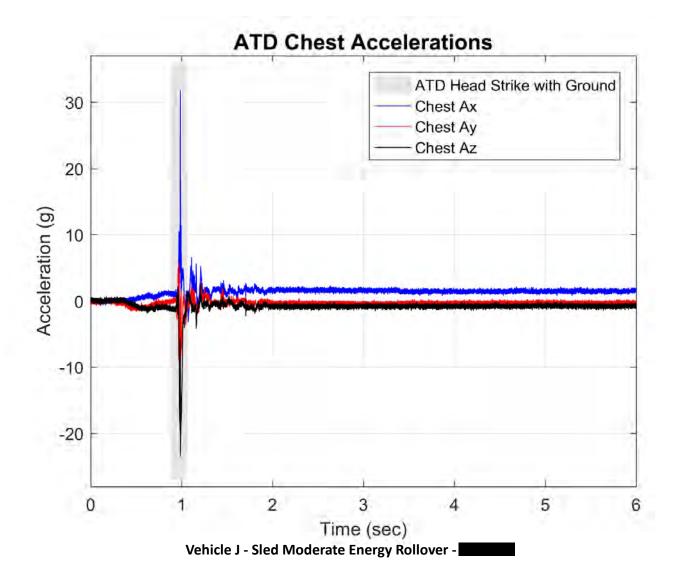


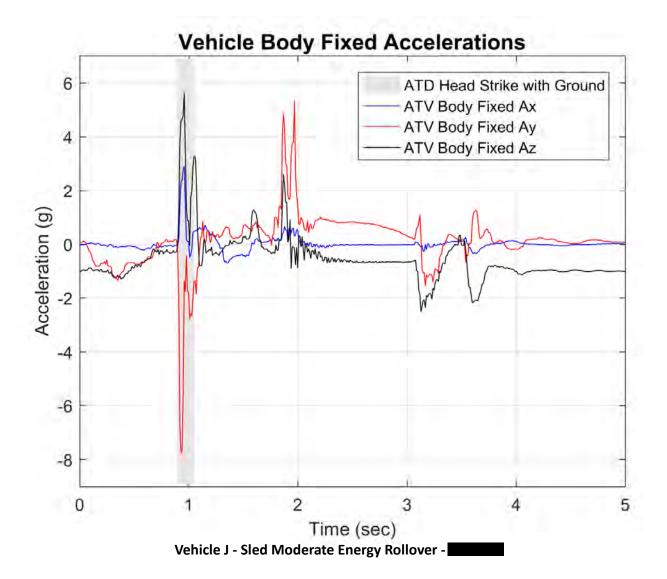


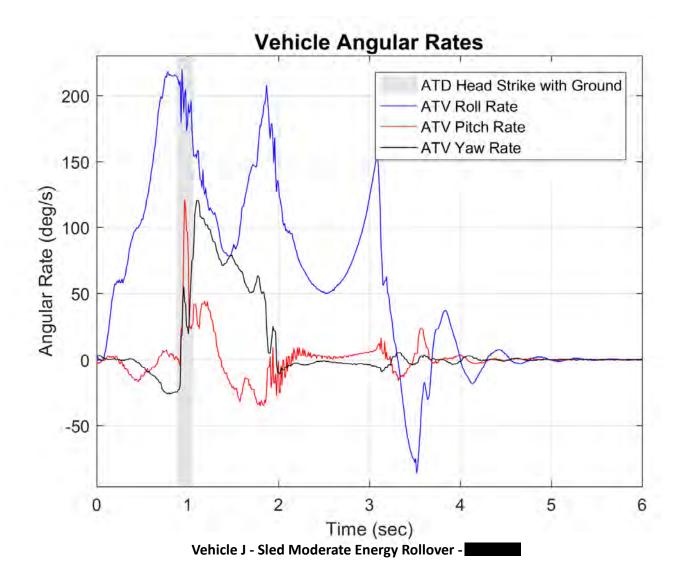
Vehicle J - Sled Moderate Energy Rollover -

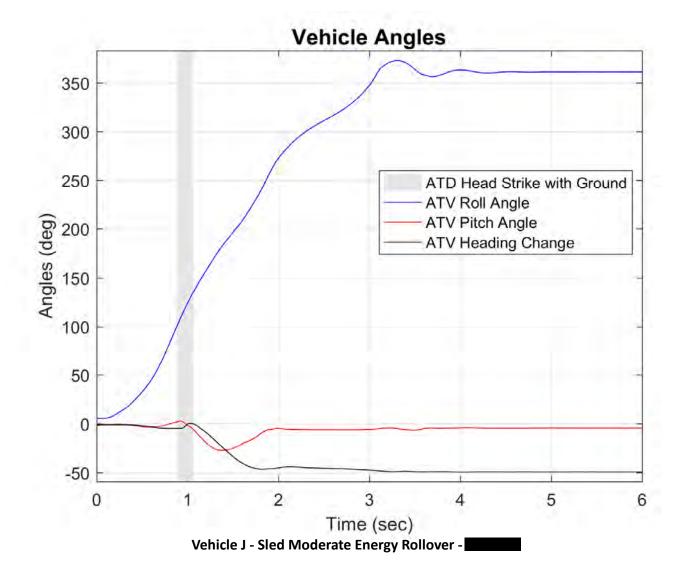












### Side and Rear Views of Test Vehicle Outfitted with



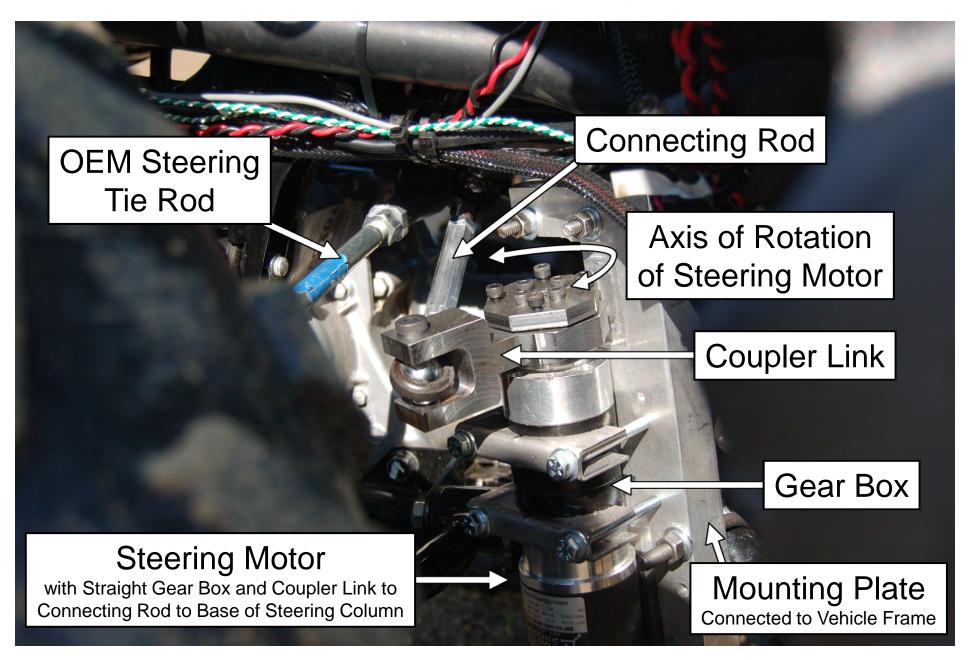


### Side and Rear Views of Test Vehicle Outfitted with

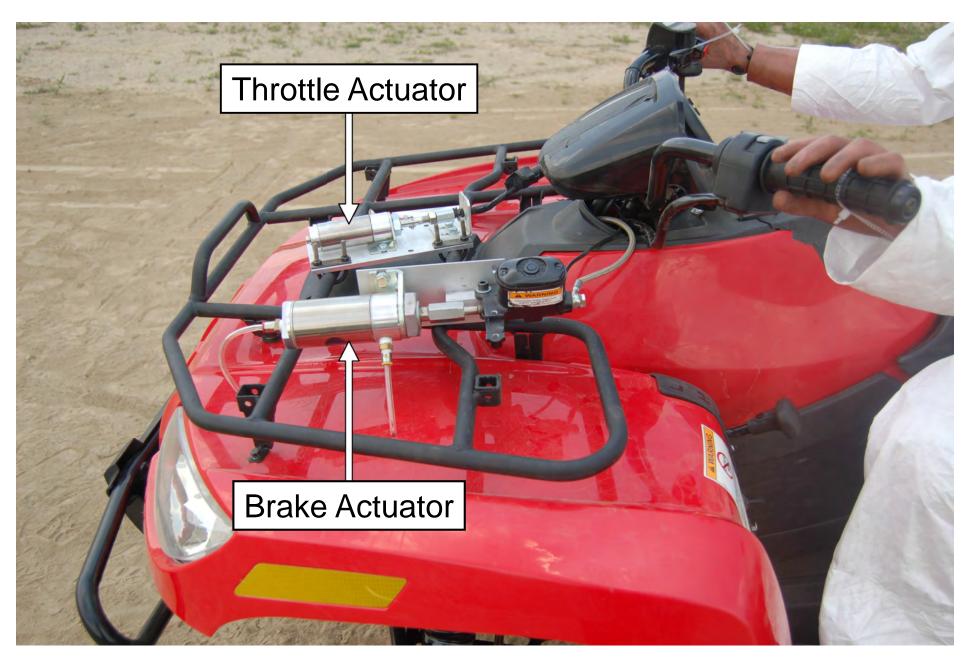




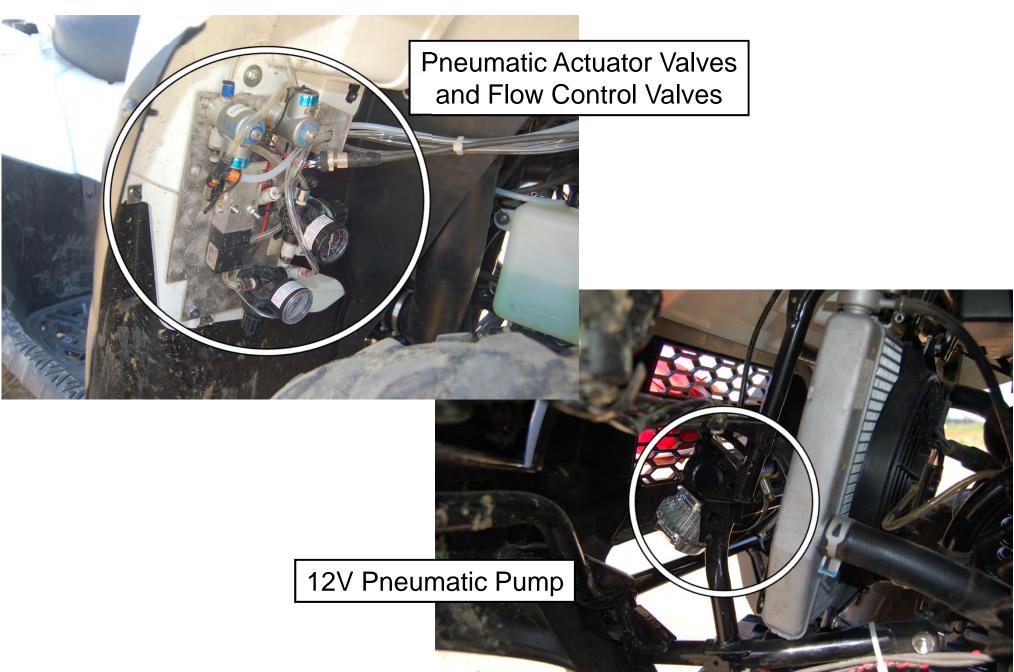
### **ATV Under-Rack Dynamic Rollover Steering Controller**



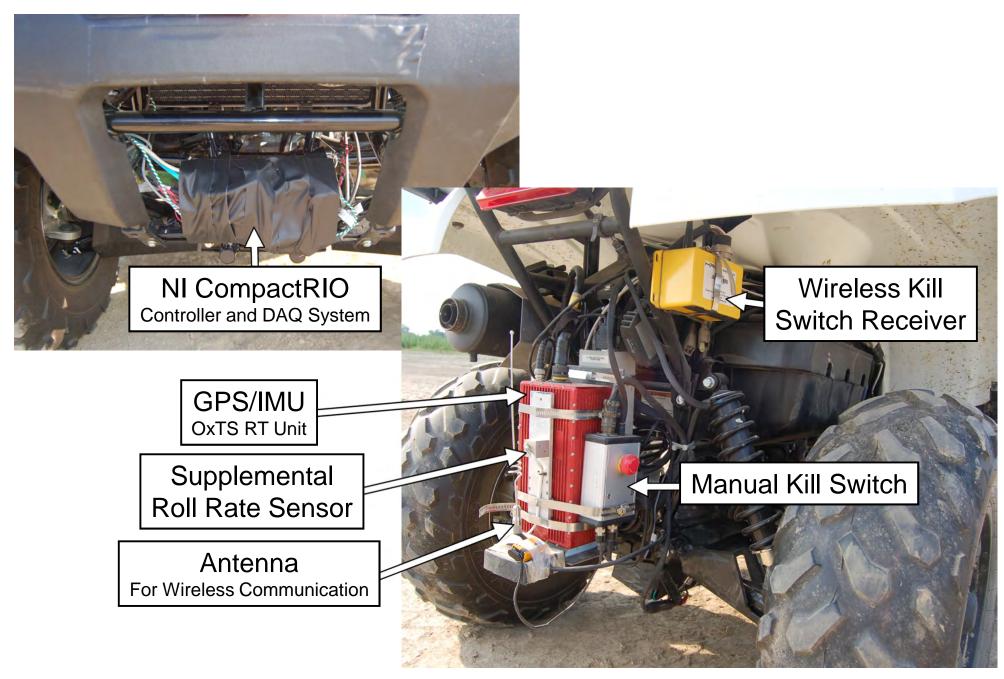
### **ATV Dynamic Rollover Brake and Throttle Pneumatic Actuators**



# **ATV Dynamic and Sled Rollover Pneumatic Valves and Pump**



## ATV Dynamic Rollover Controller/DAQ, Sensors and Kill Circuit Switches

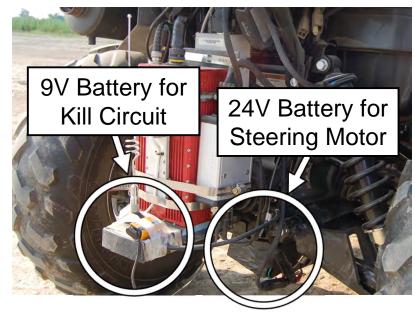


# **Batteries and RT Antenna Mounting used for ATV Dynamic Rollover**



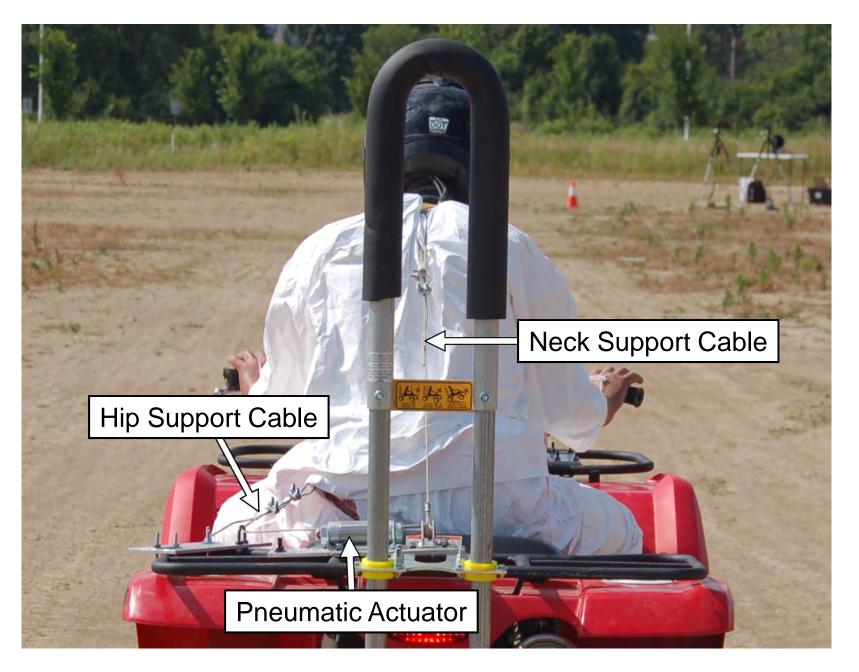
Two 12V Batteries Under Footwells



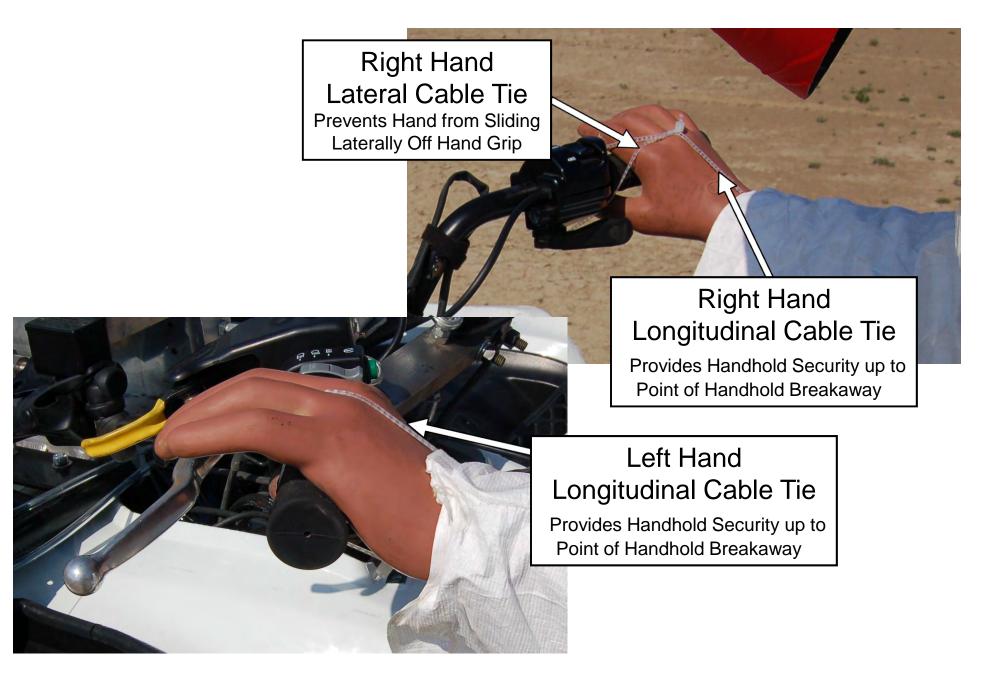




# ATV Dynamic and Sled Rollover ATD Pneumatic Portion Secure and Release System



## ATV Dynamic Rollover ATD Mechanical Portion Secure and Release System



### Appendix D: Description of Video Equipment

Seven video cameras were used during the dynamic and sled tests. The cameras used included:

- Four cameras manufactured by The four cameras were synchronized to each other and to the vehicle data using a camera flash attached to a pressure sensitive ribbon switch. The ribbon switch was positioned at the trigger point of the maneuver and aligned perpendicular to the path of the vehicle or sled. For the dynamic tests, time zero for the cameras is when the front tires of the vehicle hit the ribbon switch; and for the sled tests, time zero is when the right tire on the sled platform hit the ribbon switch. To improve the field of view during the dynamic tests, the cameras were manually panned.
- Two high-speed (HS) cameras were used to capture high-speed video of the rollover events at 600 fps. While these cameras provided video that provides good slow-motion replays of the rollover events, their image resolution is not as good as the other cameras. Therefore, none of the images from the HS cameras set to record high-speed video are used in this report.
- One camera was used to record overhead videos, and images from this camera are referred to as Drone Camera images. For the dynamic rollover tests conducted on the groomed dirt surface, an actual drone (unmanned aerial vehicle) with camera was used. The drone was flown about 10 feet above the groomed dirt surface, and its camera was aimed looking in a direction along the straight-line approach path of travel of the test vehicle. The overall area of the sled rollover events is much smaller than the area of the dynamic rollover events, and the position of the start of sled rollover phase is known. Therefore, for the sled rollover tests the overhead (Drone Camera) video was taken using a fixed camera mounted about 10 feet above the dirt landing area.

Table D.1 lists the cameras used during the dynamic and sled rollover tests and their frame rates.

Figure D.1 is a schematic representation of the orientations of the video cameras as arranged during the dynamic and sled rollover tests. Cameras 2 and 4 were set up to be roughly orthogonal to one another. Camera 1 and HS Camera 1 were set up very close to one another, as were Camera 3 and HS Camera 2. These pairs of cameras were also set up to be roughly orthogonal to one another. Since the potential area of the rollover events was much larger during the dynamic rollover events than during the sled rollover events, the cameras were positioned further away for the dynamic rollover tests than for the sled rollover tests.

Table D.1: Video Cameras used During Dynamic and Sled Rollover Tests				
Camera	Manufacturer	Model	Frame Rate (fps)	
Cameras 1-4			60	
High Speed 1-2			600	
Drone Camera (All Dynamic Rollovers)			24	
Drone Camera (All Sled Rollovers)			60	

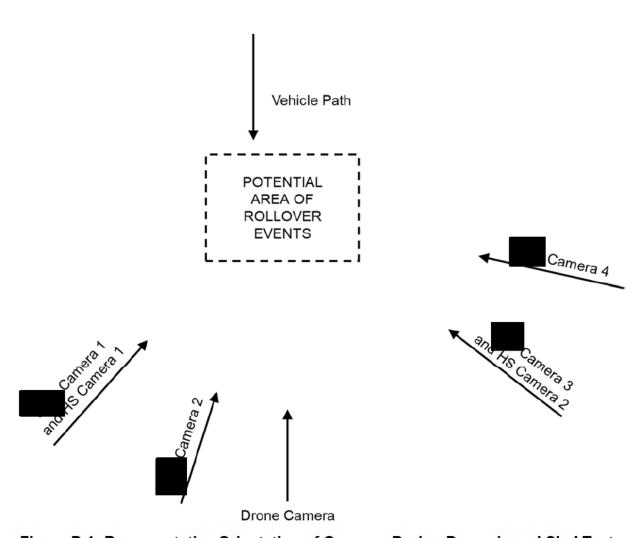


Figure D.1: Representative Orientation of Cameras During Dynamic and Sled Tests

### Appendix E: Description of ATD and ATD Secure and Release System

For all the dynamic and sled rollover tests, an instrumented Hybrid III 50<sup>th</sup> percentile male Anthropometric Test Device (ATD) with a standing pelvis was used as the surrogate driver. A full-face helmet was used on the ATD and its clothing included disposable pants, disposable long-sleeved shirt, socks, and boots.

#### **ATD Instrumentation**

The ATD was instrumented with a so-called six degree-of-freedom sensor (three linear accelerometers and three angular rate sensors) in its head and with a triaxial acceleration sensor (three linear accelerometers) in its chest. Table E.1 lists the sensors used in the ATD. A DTS Nano Slice data acquisition system (Nano Base 3000-20100 microprocessor) was used to acquire all ATD data at a sampling rate of 10 kHz. Figure E.1 shows the DTS Nano Slice package (which includes the Nana Base slice as well as ancillary bridge and battery slices) and the DTS 6DX Pro sensor mounted inside the head of the ATD. The main battery for the DTS system was mounted inside the chest cavity of the ATD, as shown in Figure E.2. Figure E.2 also indicates the general location of the triaxial chest acceleration sensor, which is mounted on the ATD's spine.

Table E.1: ATD Instrumentation					
Transducer	Measurement	Range	Linearity		
DTS 6DX Pro Sensor 2K-1500	Head X, Y and Z Accelerations	± 2,000 g	1% of Reading		
	Head Roll, Pitch, and Yaw Rates	± 1,500 deg/s	1% of Reading		
Endevco 7264-2KTZ-2-360	Chest X, Y and Z Accelerations	± 2,000 g	1% of Reading		

The ATD instrumentation package is self-contained inside the ATD. Prior to each use, the ATD instrumentation package was armed, readying it to start data collection as soon as one of two trigger levels was reached. For all the dynamic and sled tests, the ATD data system would trigger if any of the accelerometers in the head exceeded ±30 g or if any of the head angular rates exceeded ±200 deg/sec. The DAQ was configured to save data five seconds before the trigger to 15 seconds after the trigger. The data was downloaded from the ATD after each run.

The Head Injury Criterion (HIC) is a metric, based on the resultant magnitudes and durations of ATD head accelerations, developed for assessing potential injury levels in crash events. HIC is often used in studies to access injury potential during automotive crashes, it is also used by

researchers conducting studies not involving automotive crashes<sup>1,2</sup>, and it is used in this study of ATV rollovers to assess potential head injury levels, as well as to verify that the ADT head impacts with the ground were comparable in the dynamic and sled rollover tests conducted.

HIC was computed using the following equation:

$$HIC(\Delta t_{max}) = \left[ \left( \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) \right)^{2.5} (t_2 - t_1) \right]_{max_{t_1, t_2}}$$
 Equ. E.1

Where, a(t) is the resultant acceleration of the  $A_x$ ,  $A_y$  and  $A_z$  acceleration measurements computed using the following equation:

$$a(t) = \sqrt{A_x^2 + A_y^2 + A_z^2}$$
 Equ. E.2

Prior to computing the HIC values, the accelerations were filtered using a 1,000 Hz Butterworth low-pass filter. For each data run, HIC values were computed for time durations  $(t_2 - t_1)$  of 15 milliseconds and 36 milliseconds. The HIC value is the maximum value of the calculation shown on the right side of Equation E.1, as the time range (with a duration of either 15 or 36 milliseconds) is swept across the entire time span of the event, from five seconds before the trigger to fifteen seconds after the trigger. These time range duration limits are commonly used, and they are denoted as HIC<sub>15</sub> and HIC<sub>36</sub>, respectively. For all of the dynamic and sled rollover tests conducted, all of the final HIC values occurred at the time when the ATD's head first struck the ground.

#### **ATD Secure and Release System**

It was necessary to design a system to secure the ATD to the ATV during the runups leading to the dynamic and sled rollovers, and to design a system that allowed the ATD to disengage or release from the ATV at an appropriate time during the rollover event. A single system was designed which would both secure the ATD during the runup phase and release it at the appropriate time during the rollover event.

Grip strength, the amount of force someone can apply while gripping an object, is different from handhold strength, the amount of force required to breakaway someone's grip while holding an object. Research shows that healthy, college-aged, males and females have quasi-static handhold strengths (holding forces) of approximately one times their body weight when holding onto a steel, 1" diameter, horizontal, overhead bar. Research also shows that size, shape and orientation of the object being held can significant affect handhold strength. Tests were conducted at SEA to evaluate handhold strength while holding onto a horizontal ATV handlebar grip. These tests also confirmed that handhold strengths on the order of one times the weight of the test subject are

<sup>&</sup>lt;sup>1</sup> Viano, D.C., *Head Impact Biomechanics in Sport*, IUTAM Symposium on Impact Biomechanics: From Fundamental Insights to Applications, Solid Mechanics and Its Applications, Vol. 124, pp 121-130, Springer, 2005.

<sup>&</sup>lt;sup>2</sup> Gao, D. and Wampler, C.W., *Head Injury Criterion, Assessing the Danger of Robot Impact*, IEEE Robotics and Automation Magazine 1070-9932/09, December 2009.

<sup>&</sup>lt;sup>3</sup> Young, J.G., *Biomechanics of Hand/Handhold Coupling and Factors Affecting the Capacity to Hang On*, PhD Dissertation, University of Michigan, 2011.

representative of typical, quasi-static handhold strengths when pulling perpendicular to the hand grip.

However, during a dynamic event like an ATV rollover event, it is believed that handhold strength will be significantly lower than the levels measured during quasi-static tests in laboratories. For example, the dynamic vibrations of the vehicle, the change in handhold orientation as the handlebars move, and the surprise of needing to hang on all reduce handhold capacity during an ATV rollover event. Zellner and Kebschull conducted ATV rollover tests with a Motorcycle Anthropometric Test Device (MATD), and to secure the MATD hands to the handlebar grips they used a single wrap of cloth tape that provided a tear away force (perpendicular to the hand grip) of 80 lb.<sup>4</sup> They reported that 80 lb is comparable to the tear away force of the gripping MATD hands. A tear away force of 80 lb is a little less than one-half times the weight of a 50<sup>th</sup> percentile male ATD (which has a nominal weight of 165 lb). For this study, a force of 80 lb was also selected as the nominal desired handhold tear away force.

Several methods for securing the hands of the ATD to the ATV hand grips were studied, including using tape, magnets and cable ties. Tests were conducted to evaluate the breaking strength and the repeatability of these various connection methods. While appropriate sizes and types of tape, and magnets could have been used, ultimately the decision was made to use cable ties. Using cable ties is believed to be a more repeatable and less problematic attachment method than using the other attachment methods considered. Tests on several different sizes of cable ties were conducted, and 11 inch long ladder cable ties (methods to provide a consistent loop breaking force very close to 80 lb, within 3 lb for all samples tested.

The cable ties selected fit conveniently in the open wrist area of the ATD. A single cable tie was looped through each wrist, looped through the second and third fingers of the ATD's hands, and secured snuggly to the ATV hand grips. These longitudinally directed cable ties provide for a handhold strength of close to 80 lb for each hand. In some of the early dynamic rollover tests conducted on ATVs without OPDs, during the left-turn turning portion of the maneuver, the ATD's right hand slide to the right and off the hand grip too soon and without breaking the cable tie. Therefore, a second cable tie was added to the righthand side attachment. This cable tie was looped through the longitudinal cable tie and around an inboard portion of the hand grip to prevent the right hand from sliding sideways off the hand grip. This second laterally directed wire tie was attached so as to not interfere with the handhold strength provided by the longitudinal cable tie. Figure E.3 shows the cable tie arrangement used to secure the ATD's hands to the hand grips.

No information from actual ATV rollover events with human drivers is available to indicate when a human driver might actually disengage or be thrown from the vehicle. Therefore, a system was designed to secure the ATD to the ATV at its left hip and neck, and to release it depending on the roll angle of the vehicle. This system allows for releasing the ATD at any specified roll angle. Figure E.4 shows an overall view of this system. Figure E.5 shows the waist harness belted on the ATD and used to secure the hip cable (wire rope) to the ATD. A strap, placed loosely

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<sup>&</sup>lt;sup>4</sup> Zellner, J.W. and Kebschull, S.A., Full-Scale Dynamic Overturn Tests of an ATV With and Without a "Quadbar" CPD Using an Injury-Monitoring Dummy, DRI Report DRI-TR-15-04, March 2015.

around the ATD's neck so as to not crimp the ATD instrumentation wires, was used to secure the neck cable to the ATD, as shown on Figure E.6.

The hip support cable and neck support cable are both securely attached to the ATV via loops held by the rod in the pneumatic actuator. At the specified roll angle, the valve controlling the pneumatic actuator is opened to retract the rod and release both cables. The bulk of the ATD weight is then released from the ATV. For all the dynamic and sled tests conducted, a specified roll angle of 30° was used as the initiation point for releasing the hip and neck cables. Latency in the pneumatic system is small, and full release of the ATV from the ATD happens at close to 45° of roll angle.

During a couple of sled tests conducted during the previous study of ATV rollovers without OPDs, the right hand longitudinal cable tie broke during the acceleration phase of the runup to the rollover pit. The sled helper spring was being used during these tests. The ATD's right hand pulled with enough force, as the sled accelerated and the helper spring deflected somewhat, to break the cable tie. To prevent this from happening during any subsequent tests, a pneumatic actuator system like the one used to secure and release the hip and neck cables used, as shown in Figure E.7. The wire rope cable is attached to the ATD in the open wrist area and positioned through the second and third fingers of the right hand, similar to how the cable tie was positioned. The pneumatic actuator releases the cable at 30° of roll angle, the same time the hip and neck cables are released.

The ATD secure and release system works as intended; it provides a reliable and repeatable system for securing and releasing the ATD. The cable ties and wire ropes both secure the ATD to the ATV during the runup phases leading to dynamic and sled rollover events. The neck cable prevents the ATD from leaning forward and the left hip cable prevents the ATD from leaning to the right during deceleration phases leading to tip ups. The pneumatic release system used for the hip and neck cables provide secure ATD attachment to the ATV up to 30° of roll angle with full release occurring around 45° of roll angle. After about 45° of roll angle the bulk of ATD is freed from the ATV and allowed to move as the dynamics of the maneuver dictate. In general, there is some small gap between the ATD's buttocks and seat at 90° of roll angle and a sizeable gap by the time the ATD head first strikes the ground. While there is no baseline reference from rollover tests conducted with a human driver, the overall motion of the ATD during the dynamic and sled rollover tests is thought to be representative of how a human driver would respond in this type of ATV rollover event.

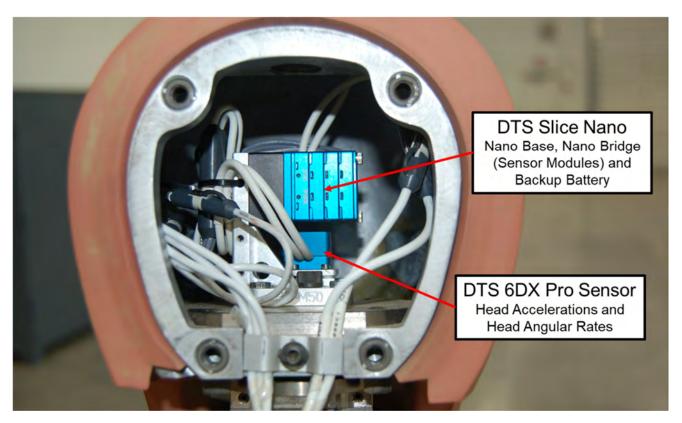


Figure E.1: Instrumentation in ATD Head

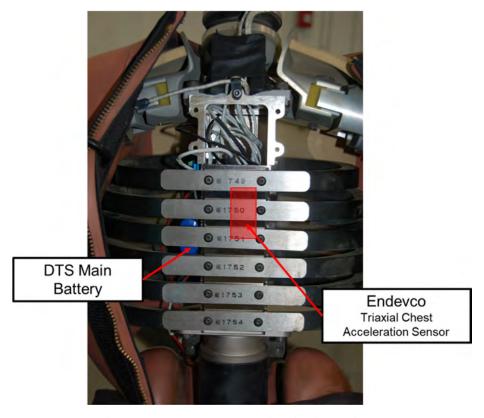


Figure E.2: Instrumentation in ATD Chest

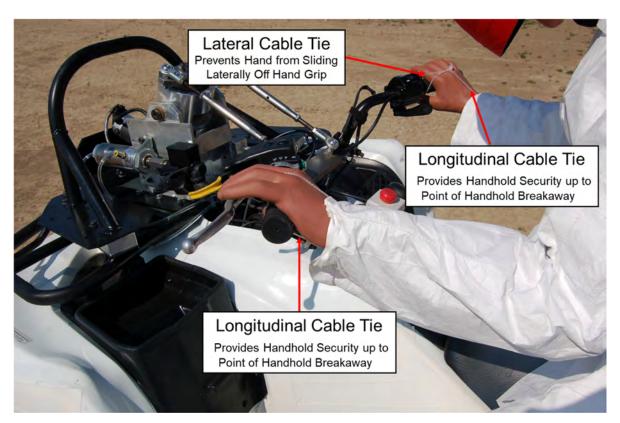


Figure E.3: Cable Tie Arrangement used to Secure the ATD's Hands to the Hand Grips

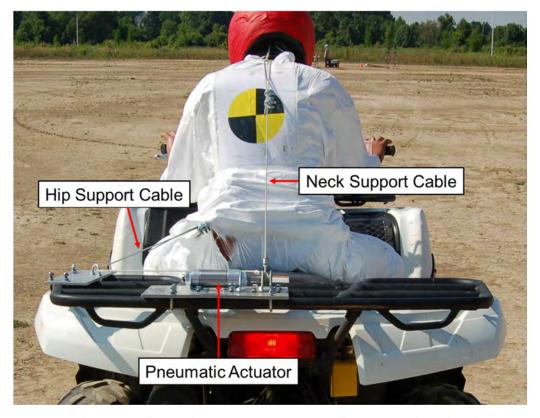


Figure E.4: Wire Rope Cable Arrangement used to Secure the ATD's Hip and Neck



Figure E.5: Harness used for Attaching the Hip Cable to the ATD



Figure E.6: Strap used for Attaching the Neck Cable to the ATD



Figure E.7: Pneumatically Released Handhold used on Right Hand During Sled Tests

#### **Appendix F: Description of ATV Rollover Simulator**

SEA's laboratory sled, configured for ATV rollover testing, was used to simulate the dynamic test rollovers performed on the groomed dirt surface. Many of the major components, instrumentation and control algorithms for ATV sled rollover testing are similar to those used for the previous sled roll testing on Recreational Off-Highway Vehicles (ROVs). A single wire rope cable connects to a sled base unit, that is accelerated using a hydraulic motor (the prime mover) and decelerated using an electromagnetic particle brake. With the sled in the ROV configuration, the vehicle is secured and remains fixed to a rolling platform; and the vehicle is free to roll up to 90° degrees before engaging a foam cushion. However, for the ATV rollover configuration, the vehicle is simply placed on the edge of a non-rolling sled platform. The sled platform is accelerated up to the desired test speed and then decelerated so that it stops precisely as the vehicle rolls off the edge of the platform, and onto a dirt rollover landing pit. The ATV is free to roll beyond 90°.

Figure F.1 shows two views of the ATV Rollover Simulator along the direction of travel of the sled. The hydraulic motor, particle brake, cable system and guide rails are inside of the laboratory.

Figure F.2 shows a view of the sled rollover landing pit, which is outside of the laboratory. Only the end of the sled, the portion with the sled platform on top of it, extends outdoors at the end of the run when the sled is being decelerated to a stop. At the point when the vehicle rolls off the platform, the platform is situated directly on top of the dirt landing area. The rollover landing pit is approximately 35 feet long by 35 ft wide, and it is filled with 8-12 inches of dirt. The dirt used to fill the pit was taken from the SEA's groomed dirt test pad. The tops of the sides of the pit are level, so the dirt-filled pit provides a level surface for the rollover events. In general, the sled rollover landing pit surface is similar to the groomed dirt surface where the dynamic rollover tests were conducted.

Various components of the ATV Rollover Sled are shown on Figure F.3. The ATV sits on the yaw platform, which can be rotated to achieve the desired balance of lateral acceleration (Ay) and longitudinal acceleration (Ax). To facilitate controlling the sled speed and deceleration, the sled is ballasted (using steel weights as shown on Figure F.3) so that the moving mass (entire mass of the sled and ATV with ATD) is the same for all vehicles tested. The sled battery and data acquisition boxes, wireless network antenna, and on-sled speed transducer are indicated on the top photo of Figure F.3. The so-called helper spring, used to impart initial roll angles during some of the moderate energy sled rollover tests, is shown on the bottom photo of Figure F.3.

<sup>&</sup>lt;sup>1</sup> Zagorski, S.B., *Modeling, Control and State Estimation of a Roll Simulator*, PhD Dissertation, The Ohio State University, 2012.

<sup>&</sup>lt;sup>2</sup> Zagorski, S.B., Guenther, D.A., Heydinger, G.J. and Sidhu, A.S., *Validation of a Roll Simulator for Recreational Off-Highway Vehicles*, SAE 2012-01-0241, 2012

<sup>&</sup>lt;sup>3</sup> Zagorski, S.B., Guenther, D.A., Heydinger, G.J. and Sidhu, A.S., and Andreatta, D.A., *Modeling and Validation of a Roll Simulator for Recreational Off-Highway Vehicles*, ASME IMECE 2011-62603, 2011.

<sup>&</sup>lt;sup>4</sup> Zagorski, S.B., Guenther, D.A., Heydinger, G.J., and Sidhu, A.S. and Bixel, R.A., *Control Strategies for a Roll Simulator for Recreational Off-Highway Vehicles*, ASME IMECE 2011-62601, 2011.

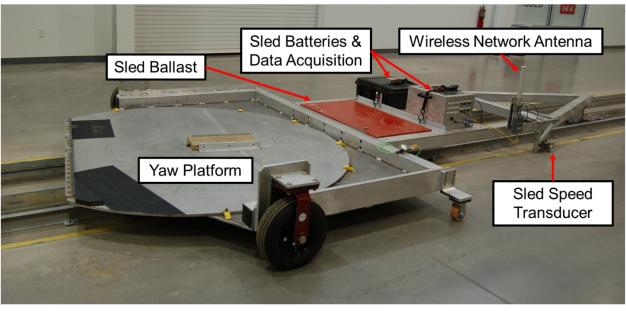




Figure F.1: Views of ATV Rollover Simulator Along the Direction of Sled Translation



Figure F.2: View of ATV Rollover Simulator Landing Pit



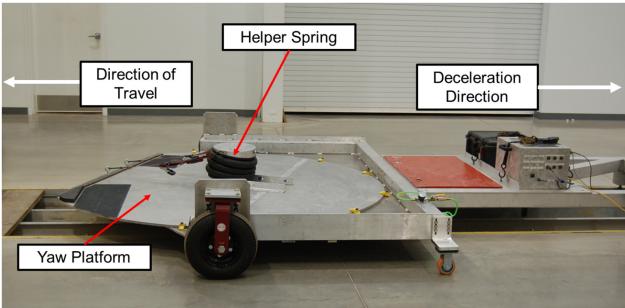


Figure F.3: ATV Rollover Sled Components

Top: Without Helper Spring – Bottom: With Helper Spring

The ATV Rollover Simulator was designed with the following list of variables or parameters that could be adjusted to achieve simulated rollover events which matched the dynamic minimum energy and moderate energy rollover events.

#### 1. Sled Entry Speed

Sled entry speed is the peak speed used for each sled run, and it is achieved prior to the time when the sled is decelerated to cause the ATV rollover event. Based on the previous sled tests conducted using ATV without OPDs, a sled entry speed of 21 ft/sec was used for the minimum energy rollovers and a sled entry speed of 27 ft/sec was used for the moderate energy rollovers.

#### 2. Sled Acceleration and Deceleration

The sled is accelerated at about 0.2 g during the run-up phase to achieve the sled entry speed. After the sled achieves the desired entry speed, the sled acceleration phase is discontinued so the sled, ATV and ADT can settle into a brief period (about 0.5 sec) of constant speed. This settling phase with no acceleration allows the ATV and ATD to return to their static load conditions prior to the application of the final deceleration that leads to rollover. As the sled approaches the dirt landing pit, it hits a floor switch which initiates closing of the hydraulic valve and energizes the electromagnetic particle brake to impart deceleration to the sled. The sled assembly stops as it reaches the dirt rollover pit at which point the ATV rolls off the yaw platform and onto the rollover pit. The deceleration force provided by the particle brake generates a sled deceleration greater than the lateral acceleration needed to cause the vehicle to rollover. The particle brake force is somewhat tunable by varying the tension in the sled cable, and a cable tension of 1,800 lb was used for all the sled rollover tests.

With the entry speed and acceleration/deceleration profiles specified, the approximate overall required distance of sled travel can be computed. However, the vehicles tested have different levels of rollover resistance (i.e. different track widths, masses, center-of-gravity locations, and roll inertias); so for each vehicle, trial runs were conducted to pinpoint the required overall sled travel distance leading to the point of rollover. For the trial runs, the vehicles and ATD where secured to the sled platform to stop them from rolling more than 45° (to avoid damaging the vehicle or rolling it over at the wrong location along the sled track). Conducting the trial runs provided the sled starting points needed for each vehicle and maneuver severity. All the sled rollovers occurred with the sled stopping within a few inches of the nominal desired location, with the leading edge of the sled platform over the dirt landing pit.

### 3. Platform Yaw Angle

As mentioned, the yaw platform can be oriented such that the sled deceleration translates the desired lateral acceleration (Ay) and longitudinal acceleration (Ax) to the vehicle. Leading up to the rollovers, the longitudinal decelerations of the ATVs were greater during the dynamic minimum energy runs (which were dropped-throttle J-Turn maneuvers) than for the dynamic moderate energy runs (which were throttle-on J-Turn maneuvers), while similar levels of lateral acceleration were observed during both minimum and moderate energy dynamic runs. To achieve the appropriate ratio of ATV longitudinal to lateral acceleration at the onset of the

sled rollovers, the platform edge was rotated 20° (relative to the sled direction of travel) for the minimum energy runs and 10° for the moderate energy runs, as shown in Figure F.4. Also, a trip rail and sandpaper surface beneath the leading tires of the ATV were used to assure that the ATV did not slide off the platform prior to reaching the desired location of the stopping point of the sled (with the platform edge over the rollover pit). A 0.5 in high trip rail was used for the minimum energy runs and 1.0 in high trip rail was used for the moderate energy runs. The friction provided by the sandpaper surface is likely adequate for preventing the ATV from sliding off the platform prematurely, the trip rails were used to make sure this did not happen. The trip rails do not have a significant influence in the rollover dynamics of the ATV, as the tires basically simply roll over the trip rail.

### 4. Vehicle Steer Angle

Constant magnitude left steering was used leading up to the rollovers during the dynamic rollover tests. The steering input of an ATV largely dictates the position of the upper body and arms of the driver (ATD surrogate driver in this case). To replicate the left steering and the position of upper body and arms of the ATD during the dynamic rollovers, a steer angle block was inserted between the right front tire of the ATV and the trip rail, as shown on Figure F.5. The block angle used for all tests was 10°, and 0.5 in and 1.0 in high blocks were used with the 0.5 in and 1.0 in high trip rails, respectively.

#### 5. Vehicle Initial Roll Angle

To achieve the desired levels of maximum roll rate and roll angle, the ATV was rolled to an initial roll angle prior to test initiation during some of the sled rollover tests. Starting with the ATV initially rolled in the direction of the rollover helps generate greater roll energy in the test, and results in greater maximum roll rates and angles during the rollover. The helper spring, an air bladder similar to ones used on suspensions of commercial vehicles, was used to set the initial roll angle. Figure F.6 shows the helper spring situated beneath an ATD. The helper spring is inflated to the pressure needed to produce the desired initial roll angle. A pressure of 6.0 psi caused a 7.0° initial roll angle in the case shown on Figure F.6. In addition to contributing to greater roll rates and angles by setting the initial roll angle, the helper spring also provides gains in the maximum roll rates and angles because it does exert some upward force on the left side of the ATV during the first 20-30 degrees of the rollover event. Knowledge gained from the previous sled tests conducted on ATVs without OPDs was used to set the initial roll angles for this study with OPDs. For vehicles that were used in the previous study, the same initial roll angles were used for this study.

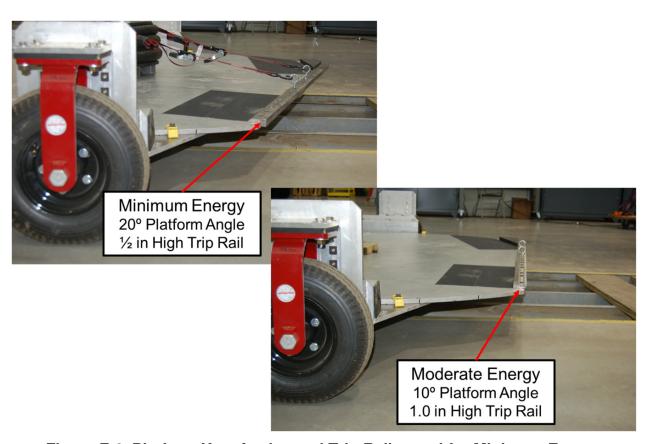


Figure F.4: Platform Yaw Angles and Trip Rails used for Minimum Energy and Moderate Energy ATV Sled Rollovers



Figure F.5: Photo Showing Steer Angle Block



Figure F.5: Photo Showing Helper Spring used to Set ATV Initial Roll Angle