CPSC Staff Statement on SEA, Ltd. Report "ATV Rollover Tests and Verification of a Physical Rollover Simulator"[1]
October 2019

The report titled, "ATV Rollover Tests and Verification of a Physical Rollover Simulator," presents the results of autonomous all-terrain (ATV) dynamic rollover tests and of laboratory simulation of ATV rollover events conducted by SEA, Ltd. (SEA), on six adult, single-rider ATVs. SEA used the results from the intentional autonomous ATV rollovers, with an anthropometric test device (ATD) as a surrogate rider, on a groomed dirt surface to verify and validate the laboratory ATV-rollover simulator. This work was conducted under Task Order 6 of contract HHSP233201400030I. This contract is funded by CPSC and is administered under an interagency agreement with the U.S. Department of Health and Human Services.

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. Staff previously identified a need for future testing, when resources are available, to include autonomous rollover testing and rollover-simulation testing, with a goal to discover opportunities to reduce the likelihood and severity of injury.

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 improvement regarding 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[2]
- Effects on Vehicle Characteristics of Two Persons Riding ATVs[3]
- Effects on ATV Vehicle Characteristics of Rider Active Weight Shift[4]
- Vehicle Characteristics Measurements of ATVs Tested on Groomed Dirt[5]
- ATV Attribute Modification Study: Results of Baseline and Modified Vehicle Testing[6]

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[1] 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.

[2] Available at: https://cpsc.gov/s3fs-public/SEA_Report_to_CPSC_Vehicle_Characteristics_Measurements_of_All_Terrain_Vehicles.pdf.

[3] Available at: https://cpsc.gov/s3fs-public/SEA-Final-Report-to-CPSC-2-Rider-ATV-Study.pdf?V0ixJO3o_kbtsmIBeKUInRAFx6hVocs5.

[4] Available at: https://cpsc.gov/s3fs-public/SEA-Report-to-CPSC-Rider-Active-ATV-Study-December-2017.pdf?1nQBCXYgr.fkZoAR3axu7hkJ9l7mbSUl.

[5] Available at: https://cpsc.gov/s3fs-public/SEA-Report-to-CPSC-Groomed-Dirt-ATV-Study.pdf?eK1E6h7IXBtznyCDatWHofAoHHmwD_nr.

[6] Available at: https://cpsc.gov/s3fs-public/ATV%20Attribute%20Modification%20Study%20-%20%20Results%20of%20Baseline%20and%20Modified%20Vehicle%20Testing_0.pdf?ch3Lu_.tpLpARkMCeX25aC0AlMNMzIHS.

ATV Rollover Tests and Verification of a Physical Rollover Simulator

Results from Tests on Six 2014-2015 Model Year Vehicles

for:
U.S. Consumer Product Safety Commission

April 2019

Vehicle Dynamics Division
7001 Buffalo Parkway
Columbus, Ohio 43229

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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 U.S. Department of Health and Human Services (HHS) contract HHSP233201400030I.

This report covers work completed on Task Order 6 of the multi-task contract for testing and evaluating all-terrain vehicles (ATVs):

- Conduct Autonomous ATV Dynamic Rollovers (on a Groomed Dirt Surface) with an Anthropometric Test Device (ATD) used as a Surrogate Rider: Results from intentional rollover events with an ATD onboard are required to verify and validate rollover simulator test results.

- Conduct ATV Sled Rollovers (using a Physical Rollover Simulator) with an Anthropometric Test Device (ATD) used as a Surrogate Rider: Controlled laboratory simulation of rollover events is required to facilitate the evaluation of aftermarket Occupant Protective Devices (OPDs) on ATVs. Testing of these OPDs is required to determine the feasibility and effectiveness of using these devices on ATVs.

Previous task orders on this contract (Task Orders 1-4) involved conducting laboratory tests and dynamic field tests using twelve 2014-2015 model year ATVs, designated Vehicle A through Vehicle L. This report contains test results for measurements made on six of these 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 rollover tests on a groomed dirt surface. In this report, 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. In this report, these tests are referred to as *sled* rollover tests.

The following four paragraphs provide brief descriptions and references of the previous work completed in Task Orders 1-4 to measure ATV characteristics.

> Task Order 1 on this contract 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*[7], 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 of the dynamic testing for the Task Order 1 measurements was conducted with a human test driver.

[7] *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. **https://www.cpsc.gov/s3fs-public/SEA_Report_to_CPSC_Vehicle_Characteristics_Measurements_of_All_Terrain_Vehicles.pdf**

Task Order 2 on this contract was to make characteristics measurements on these same 12 vehicles in a two-person (driver and passenger) loading condition. For the two-person loading condition, the vehicles were each tested at a total test weight nominally 430 lb (representing two 215 lb 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*.[8]

Task Order 3 on this contract 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 lb 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*.[9]

Task Order 4 on this contract 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 of nominally 215 lb (representing a 215 lb 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 directions. The SEA report to CPSC on these measurements is titled *Vehicle Characteristics Measurements of*

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8 *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**

9 *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. **https://www.cpsc.gov/s3fs-public/SEA-Report-to-CPSC-Rider-Active-ATV-Study-December-2017.pdf?1nQBCXYgr.fkZoAR3axu7hkJ9l7mbSUl**

ATVs Tested on Groomed Dirt – Results from Tests on Twelve 2014-2015 Model Year Vehicles.[10]

All of the vehicles used for Task Order 6 testing were selected by CPSC. All of the vehicles have straddle seating and their intended use is for a single occupant, the driver. All of the vehicles have clear warning labels stating "Never Carry a Passenger" or "Never Carry Passengers." All of the vehicles have handlebar (tiller) steering, thumb activated throttles, and hand and foot activated brakes.

Table 1 contains a list of assorted vehicle information and tire specifications 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 of the vehicles with solid rear axles are two-wheel drive (2WD) only vehicles. All of 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. For the dynamic tests, all four vehicles were tested in two-wheel drive mode, and in their most open driveline configurations. Table 1 also lists the front and rear tire make, tire size, and tire pressure for each vehicle.

The dynamic rollover tests were performed on SEA's groomed dirt test pad on numerous dates between May 8, 2018 and August 14, 2018. The sled rollover tests were performed on SEA's laboratory sled, configured for ATV rollover testing, on numerous dates between October 17, 2018 and December 12, 2018.

Three categories of dynamic rollover tests were performed using Vehicles A, E, G and L. The categories were specified by their intended level of rollover severity as: Minimum Energy Rollovers, Moderate Energy Rollovers, and Moderate Energy Rollovers with a Trip Feature.

Two categories of sled rollover tests were performed using Vehicles A, E, F, G, J and L, 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.

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 Sled and Dynamic Rollovers. This report also has five 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.

[10] *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. **https://www.cpsc.gov/s3fs-public/SEA-Report-to-CPSC-Groomed-Dirt-ATV-Study.pdf?eK1E6h7IXBtznyCDatWHofAoHHmwD_nr**

Table 1: Test Vehicle Information and Tire Specifications		
Vehicle A **Curb Weight: 523.9 lb** **Maximum Speed: 47.0 mph**	**Automatic Transmission** **Solid Rear Axle** **2WD**	
	Front Tires	Rear Tires
Tire Size	AT25X8-12 4 Ply	AT25X10-12 4 Ply
Tire Pressure (psi)	3.6	3.6
Vehicle E **Curb Weight: 734.1 lb** **Maximum Speed: 45.7 mph**	**Automatic Transmission** **Independent Rear Suspension** **2WD, 4WD, or 4WD Lock**	
	Front Tires	Rear Tires
Tire Size	AT25X8-12 6 Ply	AT25X10-12 6 Ply
Tire Pressure (psi)	5	5
Vehicle F **Curb Weight: 526.2 lb** **Maximum Speed: 53.5 mph**	**Automatic Transmission** **Solid Rear Axle** **2WD**	
	Front Tires	Rear Tires
Tire Size	AT22X7-10 4 Ply	AT22X10-10 4 Ply
Tire Pressure (psi)	4	3.5
Vehicle G **Curb Weight: 694.0 lb** **Maximum Speed: 69.0 mph**	**Automatic Transmission** **Independent Rear Suspension** **2WD or 4WD**	
	Front Tires	Rear Tires
Tire Size	AT25X8-12 4 Ply	AT25X10-12 4 Ply
Tire Pressure (psi)	5	5
Vehicle J **Curb Weight: 649.8 lb** **Maximum Speed: 60.5 mph**	**Automatic Transmission** **Independent Rear Suspension** **2WD or AWD**	
	Front Tires	Rear Tires
Tire Size	AT25X8 R12	AT25X10 R12
Tire Pressure (psi)	4.4	3.6
Vehicle L **Curb Weight: 716.4 lb** **Maximum Speed: 52.7 mph**	**Automatic Transmission** **Independent Rear Suspension** **2x4 or AWD**	
	Front Tires	Rear Tires
Tire Size	AT24X8-12 6 Ply	AT24X10-12 6 Ply
Tire Pressure (psi)	5	5

2. DYNAMIC TESTING AND DISCUSSION OF DYNAMIC ROLLOVER RESULTS

This section describes the dynamic rollover tests conducted on numerous dates between May 8, 2018 and August 14, 2018. All of the vehicles were tested at SEA in Columbus, Ohio, on a groomed dirt vehicle dynamics test pad. The groomed dirt test pad is approximately 300 ft by 300 ft square, and has 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 it is similar to a dirt surface that might be found on some off-road trails.

All of the vehicles used for the dynamic rollover tests (Vehicles A, E, G and L) had automatic transmissions and they 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 50th 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. Page 1 of Appendix C contains a photograph showing an ATV prepared for dynamic rollover testing, and Page 2 shows the same vehicle with the ATD on the vehicle. 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 to 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 Page 2 of Appendix C shows a forward lean typical of those used for all vehicles tested.

The ATV Rollover RTD consists of a computer-controlled 24V electric motor that mounts to the front rack of an 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 the steering controller configuration that includes a tubular steel protective guard used to prevent the steering motor from being damaged in the rollovers. The configuration uses a four-bar linkage arrangement, consisting of two rods connecting the steering motor drive gear to a cross brace mounted to the ATV handlebars. This configuration differs from the configuration used in previous non-rollover testing in that the connecting rods are moved inboard and the heights of the handlebars are maintained at their original height. These two features were intended to mitigate having the steering controller influence the rollover dynamics of the vehicles.

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 of the handlebars and mounted to a plate 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 of the handlebars and mounted to a plate 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). These brake and throttle actuators differ from the brake and throttle controllers used in the previous non-rollover testing. For the previous non-rollover testing, two electric motors were mounted to the handlebars. One motor was mounted with its output shaft connected to the hand-brake actuator through a lever-arm mechanism, and the other motor's output shaft was wired to the throttle thumb-actuator. The electric motors mounted to the handlebars were vulnerable to being damaged during rollovers, and their positions on the handlebars could have influenced the rollover dynamics of the vehicles. Therefore, the less intrusive pneumatic system for braking and throttle activation was developed and used for the rollover testing.

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), antennas for wireless communication, an engine kill system, and batteries. Page 4 of Appendix C shows the manual kill switch for use when a test driver is doing preparation runs, the on/off switch for the pneumatic pump, and one of the antennas used for wireless communication. Page 6 of Appendix C shows another antenna, the NI CompactRio, the GPS/IMU, the supplemental roll rate sensor, another 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 of 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 not interfere with the rollover dynamics of the vehicle.

An 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 developed and 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 provides 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 condition.

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	25.4
24V Lithium Battery	7.5
Kill Switch Circuit and Antennas	10.0
Total Nominal Weight Added During Dynamic Rollover Tests	**264.2**

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 ±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 of the rollover tests, a supplemental roll rate sensor was added to the vehicles for the dynamic (and sled) rollover tests. While this rate sensor (Spectrum 11206AC) also has a rated range of ±300 deg/s, it has been evaluated and shown to provide good rate measurements of roll rate signals beyond ±400 deg/s. Therefore, the roll rate signal from the supplemental roll rate sensor was used to measure roll rates during the rollover tests. Further, the roll, pitch and yaw (heading change) angles from the dynamic (and sled) rollover tests were computed from the supplemental roll rate sensor roll rate 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[11].

Table 3: Instrumentation Used During Dynamic Testing			
Transducer	**Measurement**	**Range**	**Accuracy**
Oxford Technical Solutions (OxTS) RT4002 Inertial and GPS Navigation System	Longitudinal, Lateral, and Vertical Accelerations	± 100 m/s^2 (± 10 g)	0.01 m/s^2 (0.001 g)
	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
Spectrum 11206AC R300-B100-T15.D-L001	(Supplemental) Roll Rate	± 300 deg/s	0.5%

2.3 Dynamic Rollover Maneuvers

Three different categories of dynamic rollover tests were conducted, specified by their intended level of rollover severity as: Minimum Energy Rollovers, Moderate Energy Rollovers, and Moderate Energy Rollovers with a Trip Feature. All of 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 of the dynamic rollovers tests, the steering motor was disabled 5.0 seconds after the left steering input was applied. The test conditions for the three dynamic rollover categories are described below:

[11] Doebelin, E.O. *System Modeling and Response, Theoretical and Experimental Approaches*, John Wiley & Sons, p484, 1980.

- **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 two-wheel lift outcomes[12] provided insight to the speeds and steering inputs needed to produce the minimum energy rollover events. For all three rollover categories, Table 4 lists the vehicle speeds when the trigger position was reached and the steering input applied at this instance. The previous J-Turn tests conducted on groomed dirt were dropped throttle events where the steering input was applied when the vehicle speed dropped to 20.0 mph. The plan was to conduct all of the minimum energy rollovers using steering inputs at a dropped-throttle speed of 20.0 mph. This was done for Vehicles A, G and L, but a higher speed was needed for Vehicle E to achieve the representative minimum rollover event. The commanded handlebar steering input magnitudes used were initially set to the handlebar steering inputs needed to generate two-lift outcomes in the previous tests. Tests using these steering inputs did not result in minimum energy rollovers because the loading condition used for the dynamic rollover testing differed from the loading condition used during the previous testing. For Vehicles A, G and L (at nominally 20.0 mph), the commanded handlebar steering inputs were subsequently increased to the values shown on Table 4 until a representative minimum energy rollover outcome was achieved. For Vehicle E at 20.0 mph the steering magnitude was increased to its maximum of 39 degrees, and no rollover occurred. So for Vehicle E the steering input of 39 degrees was used and the dropped-throttle test speed increased (to 23.5 mph) until a representative minimum energy rollover outcome occurred.

- **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.

- **Moderate Energy Dynamic Rollovers with a Trip Feature**: The intent of the moderate energy rollovers with a trip feature was to study how a trip feature – in this case a nominally 6-10 inch deep, 16-24 inch wide, and at least 22 foot long trench dug into the groomed dirt surface and traversing the path of the vehicle when it was in its rollover phase – would influence the rollover dynamics of the vehicle. The location of the trench and the angle at which it traversed the path of the vehicle were determined from the moderate energy rollover runs. The trench was dug at a location when the roll angle of the vehicle would be close to 10° and thus into its rollover phase. The location of the vehicle and its heading angle when the roll angle was 10° were known from the moderate energy rollovers. The goal was to orient the trench so the right front tire of the vehicle would be aligned with the trench when the vehicle passed through the trench. Therefore, for each vehicle the orientation of the

[12] *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.
https://www.cpsc.gov/s3fs-public/SEA-Report-to-CPSC-Groomed-Dirt-ATV-Study.pdf?eK1E6h7IXBtznyCDatWHofAoHHmwD_nr

trench was set to the heading angle plus the steer angle of the vehicle when the vehicle experienced 10° of roll angle during its moderate energy rollover run. The location of the trench was also unique for each vehicle, having the centerline of the trench coincide with the location where the vehicle experienced 10° of roll angle during its moderate energy rollover run.

The same steering inputs used during the moderate energy rollovers were used for the tests with the trip feature. Likewise the same throttle commands that were used for moderate energy rollovers were used for the tests with the trip feature, but the actual test speeds varied somewhat (within 1.1 mph) from the test speeds used during the moderate energy rollovers, as shown in Table 4. Like for the moderate energy rollover tests, the throttle was dropped 0.6 seconds after the start of steering input for the tests with the trip feature.

Table 4: Vehicle Speeds and Steering Magnitudes for Dynamic Rollover Tests

Vehicle Letter	Maneuver Category	Speed at Trigger (mph)	Handlebar Steering Input (deg)
A	Minimum Energy Rollover	20.1	28
	Moderate Energy Rollover	23.2	28
	Moderate Energy Rollover with Trip Feature	23.5	28
E	Minimum Energy Rollover	23.5	39
	Moderate Energy Rollover	25.1	39
	Moderate Energy Rollover with Trip Feature	24.0	39
G	Minimum Energy Rollover	19.8	20
	Moderate Energy Rollover	23.8	20
	Moderate Energy Rollover with Trip Feature	24.3	20
L	Minimum Energy Rollover	19.5	36
	Moderate Energy Rollover	22.4	36
	Moderate Energy Rollover with Trip Feature	22.0	36

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 1-42), Vehicle E (Pages 43-83), Vehicle G (Pages 84-125) and Vehicle L (Pages 126-167); and further by rollover category (Minimum Energy Rollover – Moderate Energy Rollover – Moderate Energy Rollover with Trip Feature). The first several pages of each section of results contain images taken from five different cameras: AOS Camera 1, AOS Camera 2, RT Camera 1, RT Camera 2 and Drone Camera. Following the pages containing camera images are 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 JPEG images of individual video frames from each camera. For example, the AOS cameras were set to have a video frame rate of 25 frames per seconds, so 25 JPEG images were generated for each second of AOS 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° or 360° of roll angle, the images are included in the sections in Appendix A.

The AOS cameras were synchronized to the vehicle data using 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 AOS cameras (and other 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 AOS camera images in Appendix A are the times from the start of the steering input. The AOS 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 AOS frame rate. The time associated with each video image is included in the title above each image.

The real-time (RT) and drone cameras were synchronized to the AOS cameras (and therefore the vehicle time) using the time of ATD head strike with the ground. The RT 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 AOS head strike image. All of the other RT and 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 RT camera frame used for the 90° roll angle image would be four frames prior to the head strike frame (because 0.12 seconds multiplied by 30 frames per second – the frame rate for the RT cameras – and rounded to the nearest integer number of frames is four).

There is no Drone Camera video available for the minimum energy dynamic rollover of Vehicle E and no RT Camera 2 video available for the moderate energy dynamic rollover of Vehicle G.

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.

Following the video image results in each section are the three pages of ATD results. 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 of the ATD data were 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 of the ATD data shown have been filtered using a 1,000 Hz low pass, Butterworth filter.

All of 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.

2.4.3 Vehicle Results

Following the ATD results in each section are the 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 (which is zeroed along the path of the vehicle thus providing the change in heading throughout the rollover event).

All of the vehicle data are unfiltered, except for the acceleration data for Vehicles A and G, which are filtered using a low pass filter with a cutoff frequency of 10 Hz. The acceleration data for these two vehicles contained significant high frequency acceleration content, which if plotted unfiltered would have obscured the underling acceleration trends of interest. Vehicle A has a solid rear axle, and the mounting location of the RT4002 at the rear of the rear axle caused the high frequency vibrations. For Vehicle G, the high frequency vibrations were likely caused by engine vibrations or a less than desirable rigid attachment of the RT4002 at the rear of the vehicle.

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 time equals zero seconds (when the steering input starts) 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 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, all of the body fixed accelerations have peaks caused by the right side of the vehicle impacting the ground. For the moderate energy runs, the first peaks in the acceleration traces are at higher roll angles, between 125° and 150° of roll angle. 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, take the case of the minimum energy run of Vehicle L which has a final roll angle of 92°. In this case 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. 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 of the dynamic rollovers conducted, except for the minimum energy run of Vehicle L, the vehicle reached 90° of roll angle before the first ATD 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° of roll angle. As mentioned, the vehicle acceleration plots have their first spikes when the roll angle nears 90° for the minimum energy runs and between 125° to 150° 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 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 rollovers, the vehicle roll rate plots have their peaks in the range of 125° to 150° of vehicle roll angle. 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 of the minimum energy runs produced rollover events with maximum roll angles between 90° and 180°; and all of the moderate energy runs and moderate energy runs with a trip feature produced rollover events with maximum roll angles greater than 180°.

Two of the moderate energy runs with a trip feature (Vehicles A and G) resulted in final roll angle that were almost 90° more than the runs without the trip feature. The other two moderate energy runs with a trip feature (Vehicles E and L) had similar final roll angles as the runs without the trip feature. Vehicles A and E had lower peak roll rates during their moderate energy runs with the trip feature than without the trip feature, while Vehicles G and L had greater peak roll rates during the runs with the trip feature. The vehicle acceleration and rate plots for the runs with the trip feature exhibit spikes when the vehicle roll angles are near 10° of roll angle, caused by the vehicle crossing the trench. These trench-caused spikes, in the range of 0.5 second duration, settle down prior to the time when the vehicles reach 45° of roll angle. As a result of this settling, the outcomes of tests conducted with the particular trip feature used in this study are not significantly different than the test outcomes without the trip feature. Also, the video images do not show any clear differences in the visual trends of the rollover events with or without the particular trip feature used in this study. The vehicle speeds were still above 20 mph when the vehicles crossed the trench. In spite of the fact that the trench size, location and orientation were designed to trip the vehicles, the right side tires of the vehicles generally simply dropped into the trench, bounced or slid through it, returned to ground level and continued to roll like they did in the runs without the trench. The vehicle suspensions absorbed the energy from the trench, and striking the trench had very little influence on the vehicle roll angles as the vehicles passed over the trench.

Different types and locations of trip features could be designed to have a greater impact on the rollover outcomes; however, given the similarities in the test outcomes of the runs with and without trench trip feature conducted in this study, either category of run could be used to represent moderate energy runs. The moderate energy rollover runs (without the trip feature) are used in Section 4 of this report to verify the moderate energy rollover runs conducted on the rollover sled.

3. SLED TESTING AND DISCUSSION OF SLED ROLLOVER RESULTS

This section describes the sled rollover tests conducted on numerous dates between October 17, 2018 and December 12, 2018. All of 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, E, F, G, J and L, 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 of the sled rollover testing included an instrumented Hybrid III 50th 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
Total Nominal Weight Added During Sled Rollover Tests	**214.7**

The same ATD with internal (head and chest) sensors and 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 condition.

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. Further, the roll, pitch and yaw (heading change) angles from the sled rollover tests were computed from the supplemental roll rate sensor roll rate 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	Accuracy
OxTS RT4002 (without GPS)	Longitudinal, Lateral, and Vertical Accelerations	± 100 m/s^2 (± 10 g)	0.01 m/s^2 (0.001 g)
	Roll, Pitch, and Yaw Rates	± 300 deg/s	0.01 deg/s
Spectrum 11206AC R300-B100-T15.D-L001	(Supplemental) Roll Rate	± 300 deg/s	0.5%

3.3 Sled Rollover Maneuvers

Two categories of sled rollover tests were performed using Vehicles A, E, F, G, J and L, 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 1-25), Vehicle E (Pages 26-50) , Vehicle F (Pages 51-75), Vehicle G (Pages 76-100), Vehicle J (Pages 101-125) and Vehicle L (Pages 126-150); and further by rollover category (Minimum Energy Rollover – Moderate Energy Rollover). The results presented for the sled tests are similar to the results presented for the dynamic rollover tests. The first several pages of each section of results contain images taken from five different cameras: AOS Camera 1, AOS Camera 2, RT Camera 1, RT Camera 2 and Drone Camera. Following the pages containing camera images are 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. This is 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 AOS 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 AOS cameras (and other 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 real-time (RT) and drone cameras with the AOS 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 in the same way as was for the dynamic rollover tests, the RT and 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.

Following the video image results in each section for the sled tests are the same three pages of ATD results provided for the dynamic tests. 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 of 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 of the ATD data shown has been filtered using a 1,000 Hz low pass, Butterworth filter.

All of 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

Following the ATD results in each section are the 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 of 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, all of the body fixed accelerations have peaks caused by the right side of the vehicle impacting the ground. For the moderate energy runs, the first peaks in the acceleration traces are at higher roll angles, between 125° and 150° of roll angle. 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 of the sled rollovers the vehicle reached 90° 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° of roll angle. As mentioned, the vehicle acceleration plots have their first spikes when the roll angle nears 90° for the minimum energy runs and between 125° to 150° 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 have their peaks near 90° of vehicle roll angle. The minimum energy run 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 rollovers, the vehicle roll rate plots have their peaks in the range of 125° to 150° of vehicle roll angle. 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.

4. COMPARISON OF SLED AND DYNAMIC ROLLOVERS

This section contains comparisons between ATV responses and ATD responses during dynamic rollovers conducted on a groomed dirt surface and sled rollovers conducted using a laboratory sled configured for use as an ATV rollover simulator. Vehicles A, E, G and L were used for the comparisons. After the dynamic rollover tests were completed, and before the sled rollover tests were conducted, each of the four 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 of 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 (e.g. a part in the right shoulder assembly of the ATD was damaged during a dynamic rollover event, but replaced prior to the next test). 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.

Two additional ATVs, Vehicles F and J, were tested only on the sled. These tests were performed to evaluate how ATV and ATD responses during sled tests conducted on these two vehicles, for which no prior dynamic rollover responses were available, would compare to the responses from the sled tests conducted using the other four vehicles.

4.1 Discussion of Vehicle Response During Sled and Dynamic Rollover Tests

Known differences exist between some vehicle motion states for tests conducted on the sled compared to the dynamic tests they are intended to replicate. For instance, the yaw rate of the vehicle leading up to the rollover events on the sled is zero but during the dynamic rollover events the yaw rate leading up to the rollover events is not zero. Also, prior to and during the rollover events, the forward speed of the vehicle on the sled is less than the forward speeds during the dynamic tests. However, these differences in some vehicle motion states are not relevant to the sled's ability to simulate the roll mode motions of the vehicle during a rollover. Comparing the acceleration and roll rate profiles measured during the sled rollover tests to those measured during the dynamic rollover tests is fundamental to verifying that the sled rollover events are representative of the dynamic rollover events they are intended to replicate.

To verify that the roll mode vehicle responses from the sled runs are representative of those from the dynamic runs, time domain plots of the body fixed longitudinal acceleration, lateral acceleration and roll rate can be compared. It is important that these variables correlate during the period of time when the vehicle is in the process of rolling up to 90º. To do this comparison, data from the sled tests and dynamic tests were time synchronized to have time equal to zero occur at 45º degrees of roll angle. Figures 1, 2 and 3 show these comparisons for the minimum energy runs, for the moderate energy runs, and all of the runs (minimum and moderate energy runs), respectively. These figures contain results for the four vehicles (Vehicles A, E, G and L) that were rollover tested both dynamically and on the sled.

Time ranges from about -0.4 seconds to 0.2 seconds are indicated by the ovals on the graphs. During this period of time, for both the dynamic and sled tests, the roll angle is beyond the angle needed for two-wheel lift but not yet to 90º (when the acceleration and roll rate traces get disturbed by the vehicle impacting the dirt surface). The acceleration graphs on Figures 1, 2 and 3 contain data that has been low-pass filtered to 10 Hz. The acceleration data from the dynamic rollover tests conducted on Vehicles A and G contained significant high frequency content (due to vibration from Vehicle A's solid rear axle and from engine vibrations or possible loose attachment of the RT4002 unit on Vehicle G) and required 10 Hz filtering to extract meaningful underlying data traces. Therefore, all of the acceleration data were filtered to 10 Hz for the sake of providing more direct comparisons.

Prior to the time range represented by the oval on the graph, the longitudinal accelerations (Ax) and lateral accelerations (Ay) do not match between the dynamic and sled runs. For all of the sled tests (shown with solid lines), Ax and Ay remain near zero until sled braking begins. The start of sled brake is clearly indicated on the Ay plots, when Ay drops from near zero to less than -0.5 g. For all of the dynamic tests (shown with dashed lines), Ay becomes progressively more negative as the vehicle progresses through its left turn J-Turn maneuver. For the minimum energy dynamic tests, Ax is negative leading into the time of the oval because the vehicles are decelerating as a result of the dropped-throttle J-Turns conducted for the dynamic minimum energy rollovers. Ax is positive prior to the time of the oval for the dynamic moderate energy runs because the vehicles are accelerating as a result of the throttle-on J-Turns conducted for the dynamic moderate energy rollovers.

However, in the important portion of the comparison in the range of 45º roll angle, the longitudinal accelerations (Ax) and lateral accelerations (Ay) correlate well between the dynamic and sled runs, for both the minimum and moderate energy rollover events. The top graph on Figure 3 shows that both the dynamic and sled longitudinal deceleration (Ax) levels are greater in magnitude during minimum energy runs than during moderate energy runs. The sled platform yaw angle was set to achieve the appropriate split between Ax and Ay during the sled tests; to achieve greater magnitude Ax during the simulated minimum energy rollovers than during the simulated moderate energy rollovers. The middle graph on Figure 3 indicates that the Ay levels near 45º of roll angle are mostly similar for both dynamic and sled tests and for both the minimum and moderate energy rollovers. The Ay levels are related to the rollover resistance of the vehicle, and once the Ay level reaches a magnitude that overcomes the rollover resistance of the vehicle, the vehicle will roll over, regardless of whether the maneuver is minimum or moderate energy.

The peak roll rates from the sled and dynamic tests compare fairly well for both the minimum energy and moderate energy runs. However, near 45º of roll angle, the sled roll rates are greater than the dynamic roll rates for the minimum energy rollovers, while the sled roll rates are lower than the dynamic roll rates for the moderate energy rollovers. Without adding a roll rate control feature to the sled, it is difficult to tune the roll rate responses to make them match much better than this in the range of 45º roll angle. However, as shown on Figure 3, all of the sled roll rates generally fall between the dynamic roll rates near 45º of roll angle so they are within the plausible range of dynamic roll rates. Furthermore, the peak roll rates during the sled and dynamic minimum energy runs are distinct from the peak roll rates during the sled and dynamic moderate energy runs. If they had overlapped, the roll simulator would not be valid.

Table 7 contains values for maximum roll rate, maximum roll angle and final roll angle for all dynamic and sled rollovers, including the sled rollovers conducted on Vehicles F and J. The information on this table is easier to interpret by looking at graphs of the maximum roll rates (Figure 4), maximum roll angles (Figure 5) and final roll angles (Figure 6). As mentioned in Section 2, only the moderate energy rollover runs (without the trip feature) are being used to verify the moderate energy rollover runs conducted on the rollover simulator, so the values for the dynamic moderate energy runs with the trip feature are not included on Figures 4-6. On Figures

4-6 values from sled tests are shown with square markers and values from dynamic tests are shown with triangle markers; and the minimum energy markers are orange and the moderate energy markers are blue.

Figure 4 shows that the ranges of maximum roll rates during the sled and dynamic minimum energy rollover tests are distinct from the ranges of maximum roll rates during the moderate energy rollover tests. For the minimum energy tests the roll rates are between 180 deg/s and 250 deg/s, and for the moderate energy tests they are greater than 250 deg/s. There is very close agreement between the sled and dynamic maximum roll rates for the minimum energy rollovers. For the moderate energy rollovers, Vehicle G had a greater maximum roll rate during its dynamic rollover test while the other three vehicles (A, E and L) had greater maximum roll rates during their sled rollover tests. Vehicles F and J were tested only on the sled. Vehicle F had the highest maximum roll rate in the moderate energy rollover tests, but it was only slightly greater than the maximum roll rates for Vehicles A and L. The maximum roll rate for Vehicle F during its minimum energy rollover test, and the maximum roll rates for Vehicle J in both of its tests, were in the range of the maximum roll rates for the other four vehicles tested.

The maximum roll angles during the sled and dynamic rollover tests also show distinct ranges between the minimum and moderate energy rollover tests (Figure 5). The maximum roll angles ranged from 90°-180° for all of minimum energy rollovers and they are over 180° for all of the moderate energy rollovers The maximum roll angles are relatively close between the sled and dynamic tests for the minimum energy rollovers, and for the moderate energy rollover tests conducted on Vehicles G and L. For the moderate energy rollover tests, Vehicle A had a greater maximum roll angle during its sled test while Vehicle E had a greater angle during its dynamic test. The moderate energy rollover events are significantly more severe and result in more chaotic vehicle motions than the minimum energy rollover events, so it is reasonable to expect that maximum roll rates and maximum roll angles would not be as close during the sled and dynamic moderate energy rollover tests as they are during the minimum energy rollover tests. The maximum roll angles for Vehicles F and J are close to the ranges of the maximum roll angles for the other four vehicles tested during both the minimum and moderate energy events.

Figure 6 shows the final roll angles for all of the sled and dynamic rollover tests. The final roll angles for all of the dynamic minimum energy tests were less than the final roll angles for all of the dynamic moderate energy tests. With the exception of Vehicle E, the final roll angles for all of the sled minimum energy tests were less than the final roll angles for all of the sled moderate energy tests. The final roll angles for Vehicles F and J are within the ranges of the final roll angles for the other four vehicles tested during both the minimum and moderate energy events.

Figures 7-10 contain plots of roll rate versus roll angle for the dynamic and sled rollover tests of Vehicles A, E, G and L. Results from the minimum energy rollovers are shown by the red lines and blue lines are used for the moderate energy results. The sled test results have solid lines while the dynamic test results have dashed lines. The roll motions of the vehicles were influenced by their impacts and interactions with the ATD and the ground as they progressed through the rollover events. Looking at phase plots of roll rate versus roll angle demonstrates the indistinct nature of the final roll angles. As mentioned, Vehicle E had a lower final roll angle for its moderate energy sled test than for its minimum energy sled test. Figure 8 clearly shows that the moderate energy sled test had markedly greater maximum roll rate and maximum roll angle than the minimum energy sled test, yet the vehicle ultimately rolled back to a smaller final angle for the moderate energy test. Figure 8 also shows that the maximum and final roll angle outcomes for the dynamic and sled moderate energy rollover tests of Vehicle E are quite different, even though the roll angle and roll rates up to about 170º of roll angle were similar.

For Vehicle A (Figure 7) the final roll angle outcomes for both dynamic and sled moderate energy tests were close to 180º. Vehicle A experienced a maximum roll angle close to 220º during its moderate energy dynamic test and a little over 280º during its moderate energy sled test, yet it rolled back to near 180º for both tests.

Figures 9 and 10 show that during moderate energy tests Vehicles G and L did not roll back from their maximum roll angles to their to final roll angles as far as Vehicles A and E did. In both the sled and dynamic moderate energy tests, Vehicle G had a final roll angle near 270º and Vehicle L had a final roll angle near 360º.

The steering motor gearbox and the steel tubular guard used to protect the steer motor during the dynamic rollovers was designed so that its height would not protrude above a line connecting the rear of the rear rack and the handlebars, in order to not interfere with the roll motion of the vehicle during the rollovers. However, during some of the dynamic tests, mainly during the moderate energy rollover tests, the guard mounted on the front rack did gouge into the dirt surface and likely influenced the roll motion of the vehicles, meaning the roll motions could have been different if the guard was not on the vehicle. In some cases when the vehicle rolled past 180º, the guard gouging likely contributed to the rear of the vehicles raising higher than they would have if the guard was not present. For future dynamic rollover tests, the steer motor gearbox and guard should be lowered, or the steering controller should be completely reconfigured, to mitigate the potential for this test equipment to interfere with the roll motions of the vehicle.

Figure 11 contains a graph of roll rate versus roll angle for all of the minimum energy rollovers, while Figure 12 contains a graph for the all of the moderate energy rollovers. These graphs highlight the distinctions between minimum energy rollover and moderate energy rollover maximum roll rates and maximum roll angles. They also show that the sled rollover test results generally compare well with results from the dynamic rollover tests.

4.2 Discussion of ATD Response During Sled and Dynamic Rollover Tests

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

The overall motion of the ATD as it detached from the ATV was consistent between the dynamic and sled tests. During all of 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. During the dynamic tests, after the right side the ATD contacted the ground, the ATD generally rotated to a facedown posture, and at the end of the dynamic rollover events was usually facing down, but in a couple of cases it was on its right side but somewhat facing down. During the sled tests, after the right side the ATD contacted the ground, the ATD generally rotated to a face up posture, and at the end of the sled rollover events was usually facing up, but in a couple of cases it was on its right side but somewhat facing up. The forward velocity of the ATV and ATD during the dynamic tests caused the ATD to rotate to a facedown orientation. For the sled tests, at the start of each test the front wheels of the ATV were positioned 20º to the left to simulate the characteristic handlebar position and yaw orientation of the ATD on the ATV. Possibly lessening this angle in future sled tests should reduce the tendency for the ATD to rotate face up after impacting the ground. Despite the rotation of the ATD being different during the dynamic and sled tests, the overall 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 of the dynamic and sled rollover events, the maximum peaks in the head accelerations and rates occurred when the ATD head 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 access injury potential during automotive crashes, it is also used by researchers conducting studies not involving automotive crashes, and it is used in this study of ATV rollovers to assess potential head injury levels, as well as to verify that the ATD head impacts with the ground were comparable in the dynamic and sled rollover tests conducted.

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 range duration ranges are commonly used, and they are denoted as HIC_{15} and HIC_{36}, 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 of the dynamic and sled tests conducted, all of the HIC values occurred when the time duration range was centered around at 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 13 and 14 are graphs of HIC_{15} values and HIC_{36} values, respectively, for all of the sled and dynamic minimum and moderate energy rollover tests. 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. Vehicles F and J, the vehicles tested only on the sled, have HIC values in the ranges of the HIC values calculated from tests conducted using the other vehicles.

The HIC_{15} values are consistently greater than the HIC_{36} values. Having HIC_{15} values greater than HIC_{36} values means that the ATD head impacts that caused the peaks in the resultant head accelerations were relatively short lived. NHTSA's standard for performance requirements for the protection of vehicle occupants in frontal crashes (Federal Motor Vehicle Safety Standard 208[13]) specifies that maximum calculated HIC_{15} values shall not exceed 700 and that the HIC_{36} values

[13] *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**

shall not exceed 1,000. General consensus in the technical literature is 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.[14]

The HIC_{15} values averaged 146 for all of minimum energy rollovers, and 272 for all of the moderate energy rollovers, shown on Figure 13. For the HIC_{36} values shown on Figure 14, the minimum energy rollovers averaged 87 and the moderate energy rollovers averaged 191. The average HIC values are at levels that would suggest that moderate or severe head injuries are likely to not occur during rollover events like those conducted in the study. However, six of the HIC_{15} values computed during the moderate energy rollover tests were near or above 250, suggesting that concussions could have occurred during these rollover events. 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.

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. Current commercially available Occupant Protective Devices (OPDs) for ATV's feature structures that extend upward from the vehicle to provide an occupant space when the vehicle is overturned. Conducting tests similar to those conducted in this study, but using an ATV equipped with an upward extended OPD, are likely to result in similar head-strike outcomes. That is, these OPDs will not influence how the ATD releases laterally from the vehicle, so similar head-strike events and HIC values are anticipated. Likewise, during rollover maneuvers of the type conducted in this study, the potential for neck injuries that could occur during the time of initial head strike with the ground will generally not differ whether or not an upward extended OPD is on the vehicle.

4.3 Discussion of ATV Interactions with ATD During Rollover Tests

Tables 8-10 are presented to provide a baseline for comparison – other than HIC values – that could be used to evaluate the safety benefits of equipping an ATV with an OPD during J-Turn-steering induced rollover events. Table 8 (for the minimum energy rollovers) and Table 9 (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. The summary descriptions include comments on ATV to ATD interactions that occurred during the rollover events, as well as comments on the rest position of the ATV relative to the ATD at the final rest position at the end of each run. In addition to the descriptive summaries, Tables 8 and 9 list the maximum and final roll angles during the rollover events, and they contain a photograph showing the final rest position for each test.

Table 10 is a compilation, based on the summary descriptions in Tables 8 and 9, of 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 whether or not the ATV came to rest on top of the ATD's pelvis, abdomen, thorax or head at the end of the run. Significant interaction is defined here to be the occurrence of having a significant portion of the ATV – subjectively estimated to be 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.

[14] 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.

Certainly ATV impacts to a rider's upper and/or lower limbs could result in significant 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.

Table 10 shows that during three of the eight dynamic rollover tests the ATV made significant interaction with the ATD, and that significant interaction occurred during nine of the twelve sled rollover tests. Significant interaction occurred during all six of the moderate energy sled rollovers, but during only one of the four moderate energy dynamic rollovers. As mentioned, during some of the dynamic tests, mainly during the moderate energy rollover tests, the guard mounted on the front rack to protect the steering motor and gearbox did gouge into the dirt surface and likely influenced the roll motion of the vehicles. In some cases when the vehicle rolled past 180º, the guard gouging likely contributed to the rear of the vehicles raising higher than they would have if the guard was not present. It is likely that the influence of this guard reduced the number of significant interactions during the dynamic moderate energy rollovers. For future dynamic rollover tests, the steer motor gearbox and guard should be lowered, or the steering controller should be completely reconfigured, to mitigate the potential for this test equipment to interfere with interactions between the ATV and ATD.

The ATV came to rest on the ATD's pelvis, abdomen, thorax or head at the end of two of the eight dynamic rollover tests and at the end of one of the twelve sled rollover tests. In total, the ATV came to rest on top of the ATD in 15% (3 of 20) of the rollover tests conducted in this study. These rest position outcomes, and the occurrences of significant interactions between the ATV and ADT, provide a baseline for evaluating the effectiveness of potentially reducing injuries by equipping ATVs with OPDs, during maneuvers similar to those conducted in this study.

4.4 Summary

Based on comparisons to full-scale dynamic rollover tests conducted on a groomed dirt surface, the ATV rollover simulator has been shown to be a reliable tool for reproducing ATV and ATD responses in ATV rollover events. Both minimum energy and moderate energy rollovers were verified, indicating that the sled has features (operating processes and parameters) that can be tuned to simulate a specific type of rollover test maneuver.

Vehicle response results – accelerations and roll motions – from rollover tests conducted on the rollover simulator compared well with vehicle response results from full-scale dynamic tests. For both the dynamic and sled tests, clear distinctions in vehicle responses between the minimum energy and moderate energy rollovers were recognized.

An ATD secure and release system has been developed that provides a means of supporting the posture of the ATV during the run-up phase of rollover events, provides a reliable handhold strength of the ATD's hands to the ATV hand grips, and provides a repeatable method for releasing the bulk of the ATD from the ATV based on the roll angle of the vehicle. The ATD secure and release system was used during the dynamic and sled rollover events, and based on ATD responses during these tests the consistency of the system was verified.

The overall motion of the ATD as it detached from the ATV was consistent between the dynamic and sled tests. During all of 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 overall 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.

Vehicle responses from minimum and moderate energy rollover tests conducted on the roll simulator for Vehicles F and J were consistent with sled responses from tests conducted on the other four vehicles. Also, HIC values from tests conducted using Vehicles F and J are in the ranges of HIC values from tests conducted using the other four vehicles. This indicates that the sled can be used to generate meaningful rollover test results without knowledge of the ATV and ATD responses measured during full-scale dynamic rollover tests.

Lastly, the overall results from this study provide a baseline for evaluating the safety benefits of equipping an ATV with an OPD during J-Turn-steering induced rollover events.

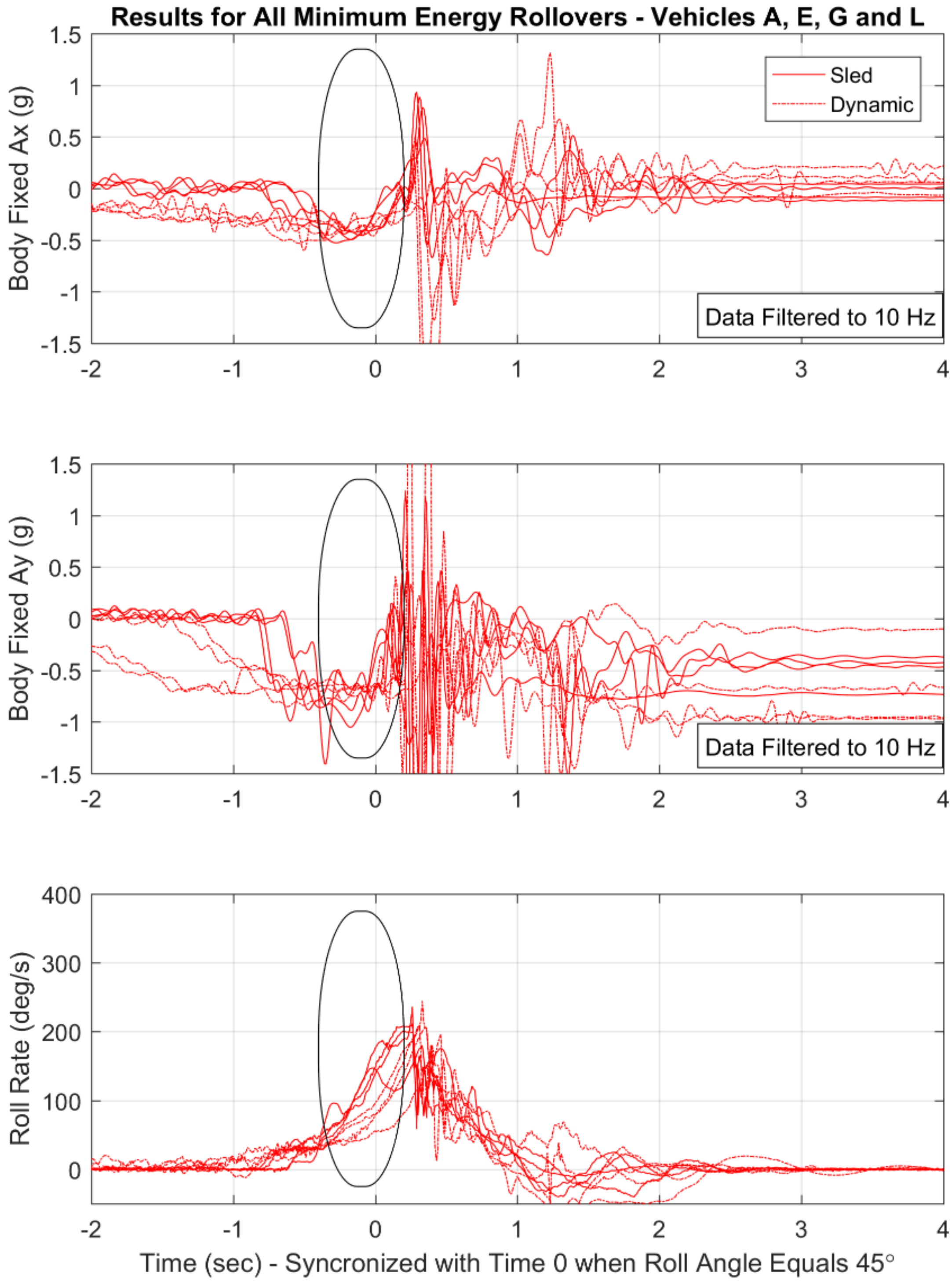


Figure 1: Ax, Ay and Roll Rate from Sled and Dynamic Minimum Energy Rollovers

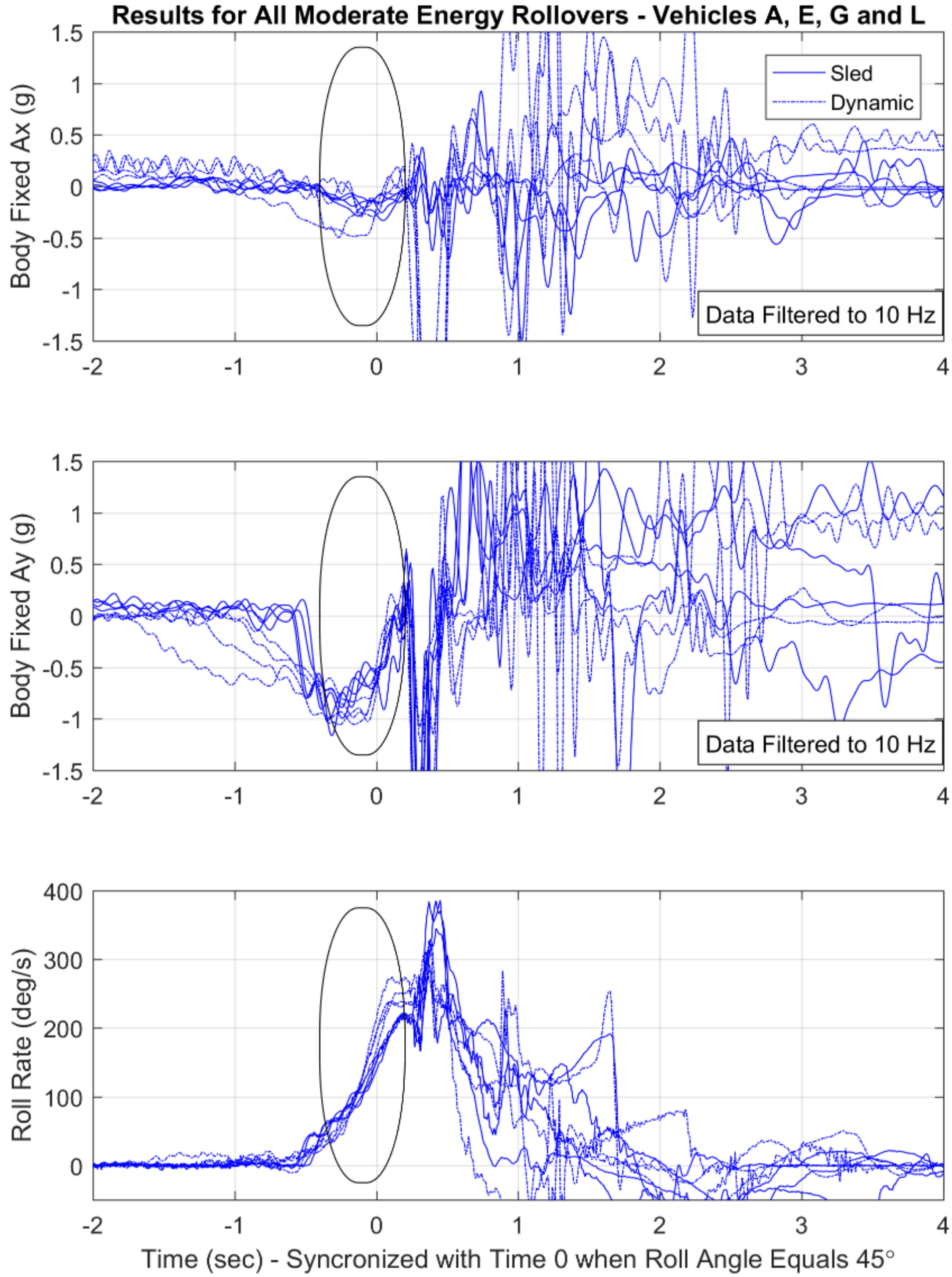


Figure 2: Ax, Ay and Roll Rate from Sled and Dynamic Moderate Energy Rollovers

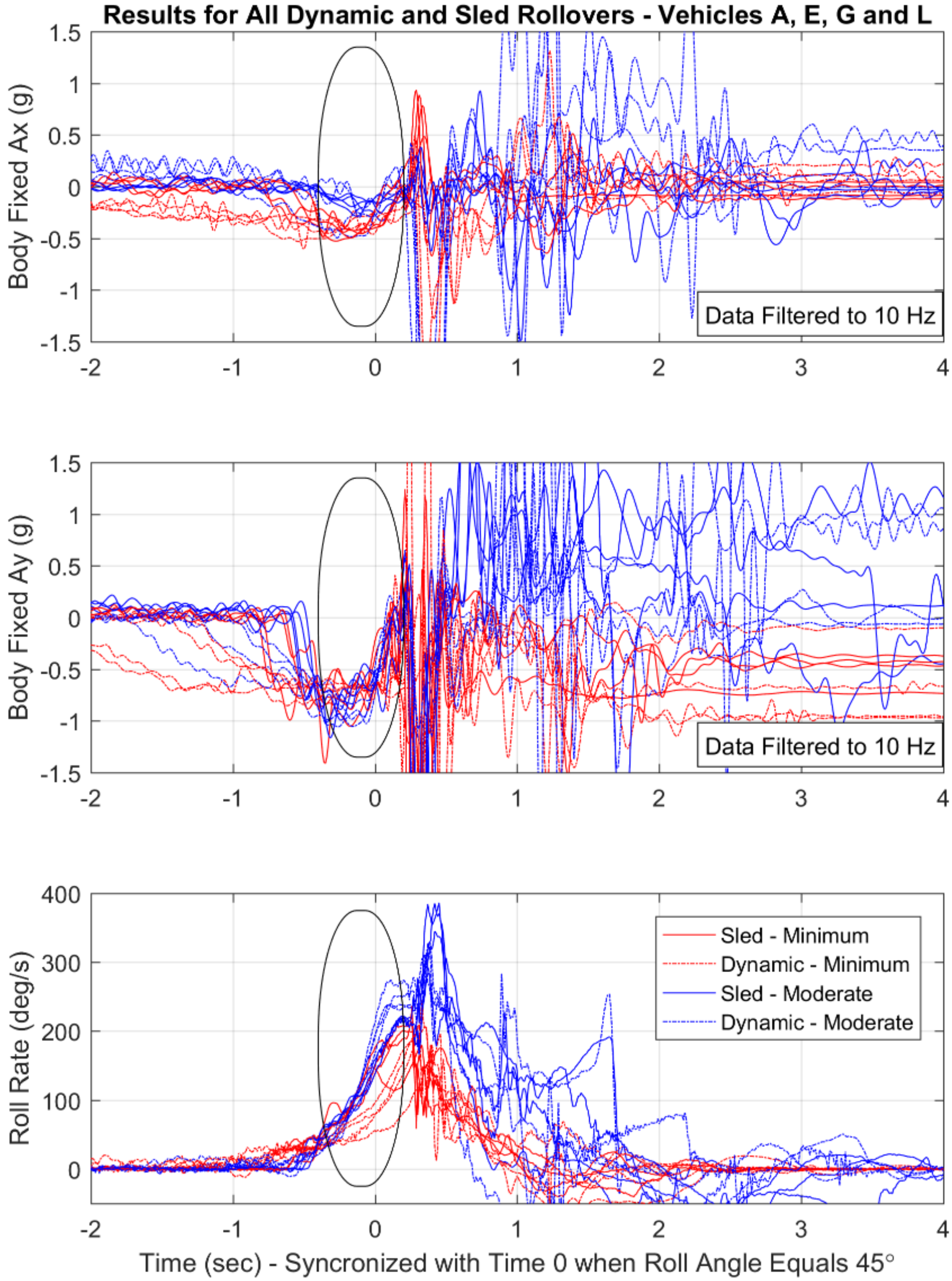


Figure 3: Ax, Ay and Roll Rate from Sled and Dynamic Minimum and Moderate Energy Rollovers

Table 7: Maximum Roll Rate, Maximum Roll Angle and Final Roll Angle for all Dynamic and Sled Rollovers							
Vehicle Letter	**Event**	**Dynamic Rollovers**			**Sled Rollovers**		
		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)**
A	Minimum Energy	244.6	177.9	174.1	236.2	154.8	144.4
	Moderate Energy	311.0	217.5	184.9	386.3	283.5	168.2
	Moderate Energy w/Trip	264.0	269.9	267.8	NA	NA	NA
E	Minimum Energy	206.3	148.3	102.5	201.2	157.9	151.9
	Moderate Energy	327.7	299.3	266.1	344.9	202.3	139.2
	Moderate Energy w/Trip	278.4	294.4	272.4	NA	NA	NA
F	Minimum Energy	NA	NA	NA	208.4	148.5	141.8
	Moderate Energy	NA	NA	NA	393.9	281.6	253.1
G	Minimum Energy	209.4	141.8	137.3	211.3	164.5	148.4
	Moderate Energy	327.7	294.1	273.2	284.9	297.7	277.1
	Moderate Energy w/Trip	409.1	378.2	368.1	NA	NA	NA
J	Minimum Energy	NA	NA	NA	186.4	131.9	94.6
	Moderate Energy	NA	NA	NA	306.4	274.8	241.0
L	Minimum Energy	196.2	114.2	92.0	180.0	137.2	135.0
	Moderate Energy	310.8	366.4	358.9	385.3	371.0	360.6
	Moderate Energy w/Trip	345.4	376.0	361.7	NA	NA	NA

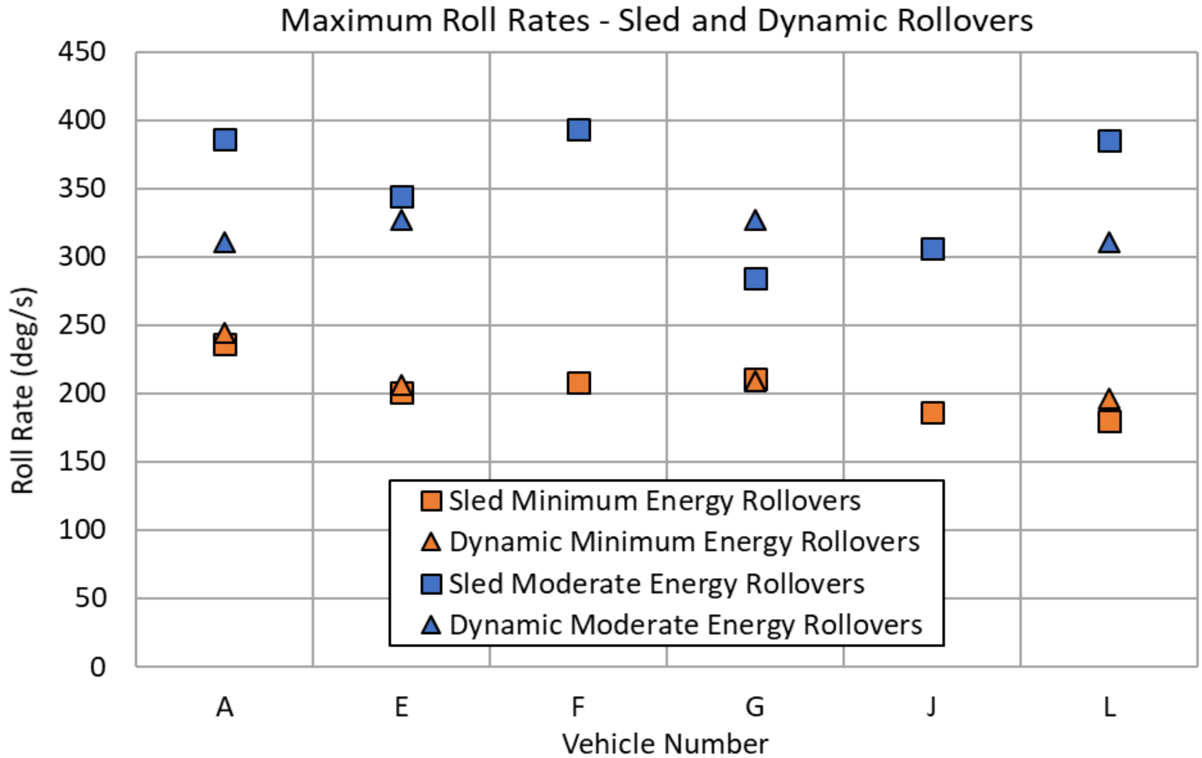


Figure 4: Maximum Roll Rates from Sled and Dynamic Minimum and Moderate Energy Rollovers

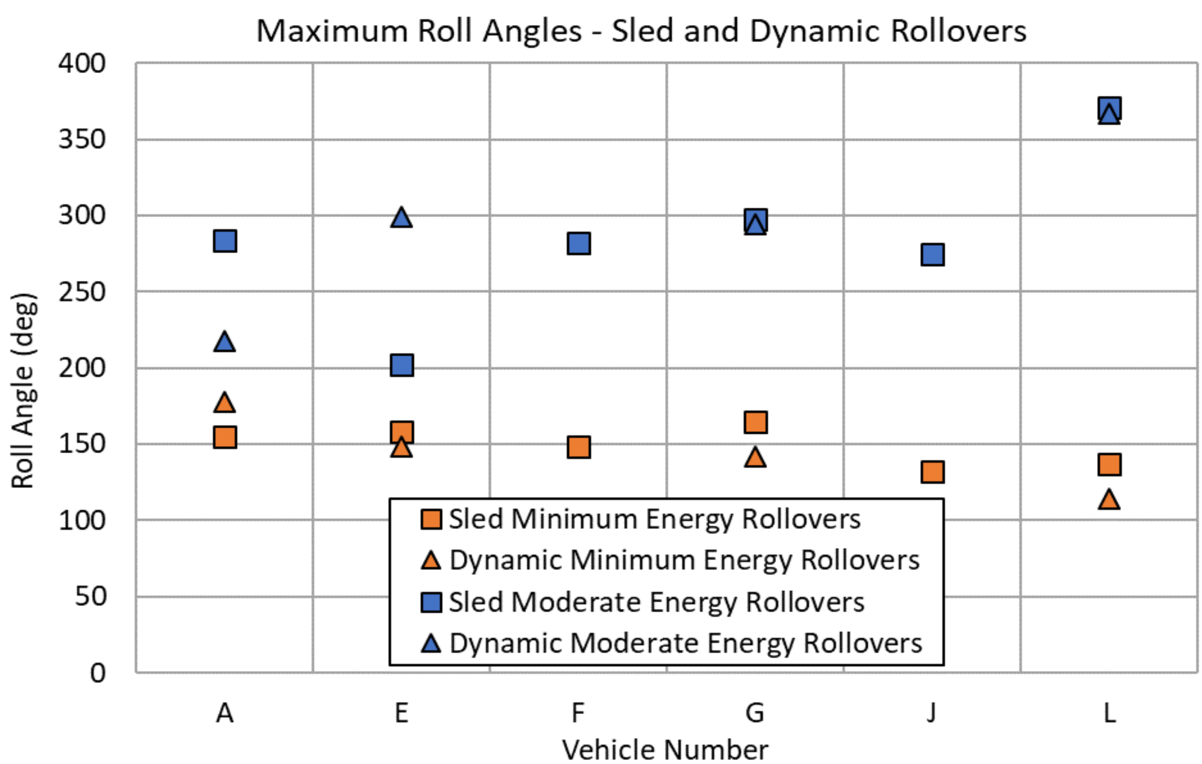


Figure 5: Maximum Roll Angles from Sled and Dynamic Minimum and Moderate Energy Rollovers

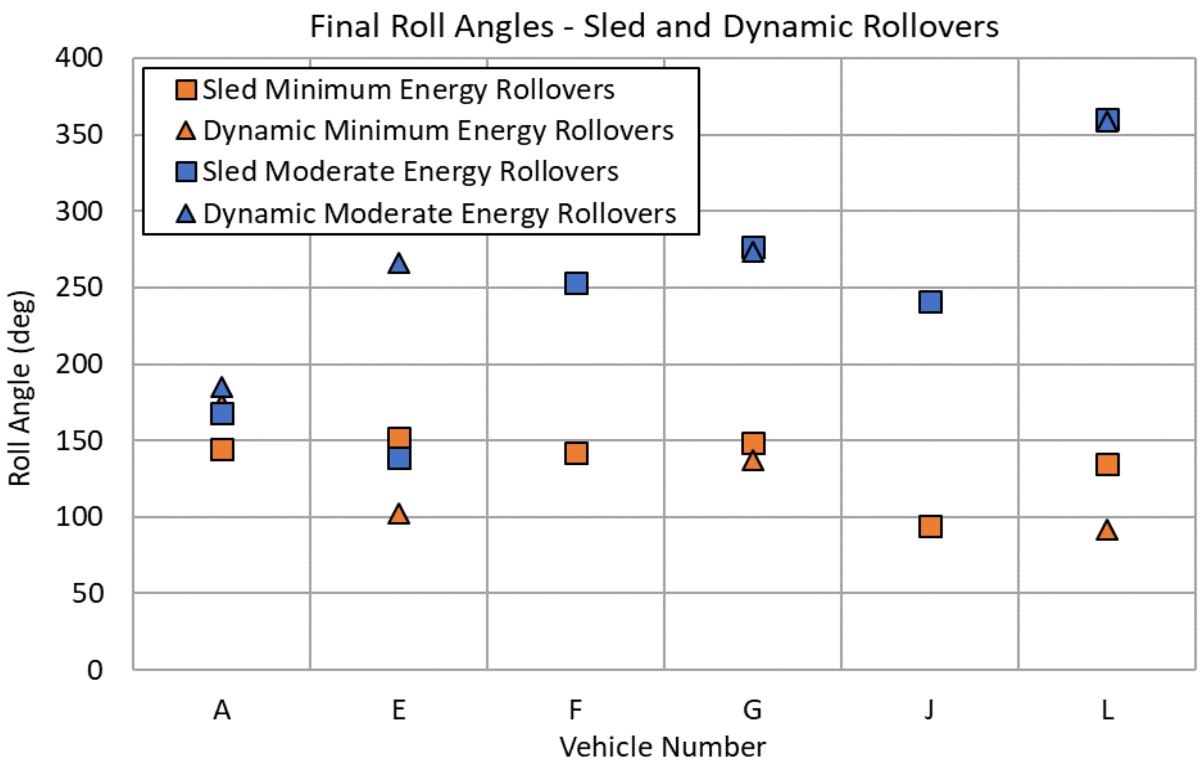


Figure 6: Final Roll Angles from Sled and Dynamic Minimum and Moderate Energy Rollovers

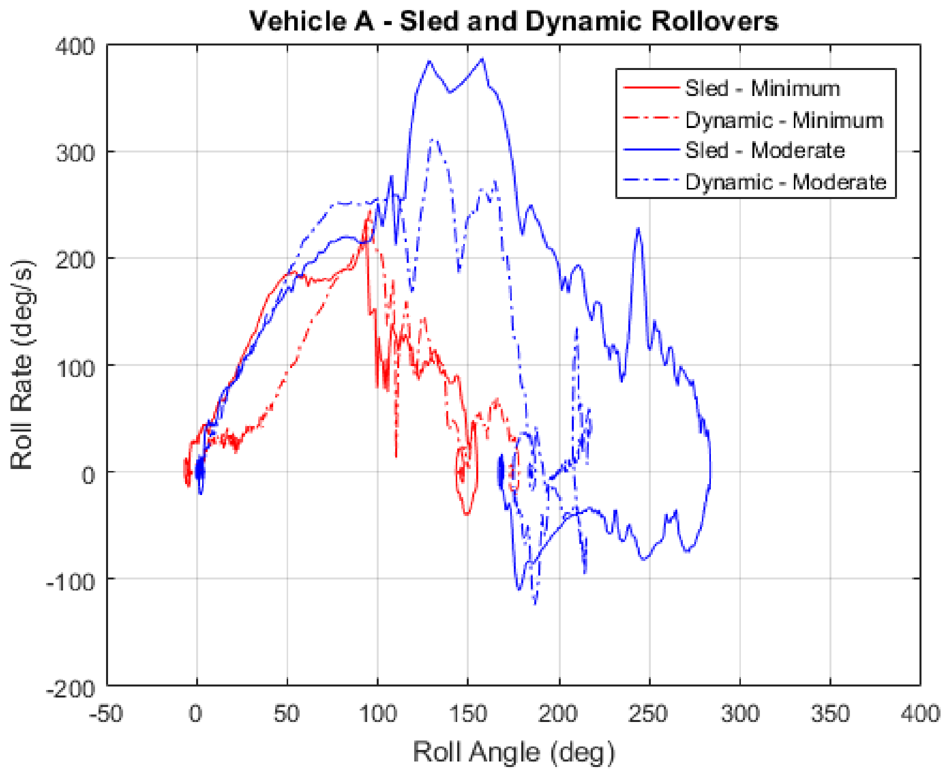


Figure 7: Roll Rate versus Roll Angle – Sled and Dynamic Runs – Vehicle A

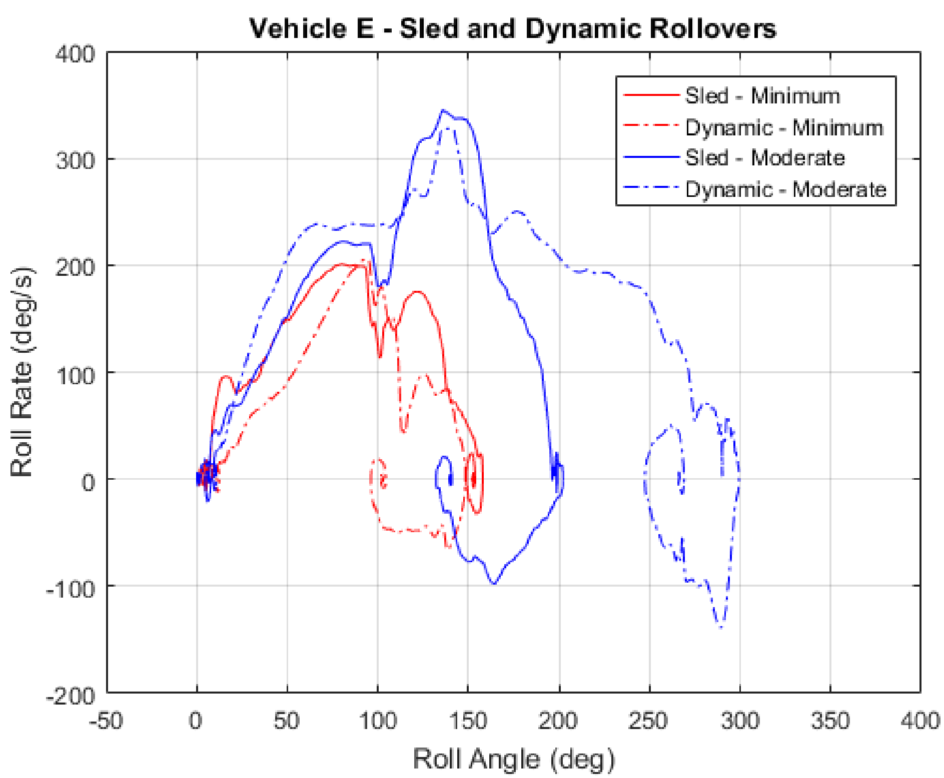


Figure 8: Roll Rate versus Roll Angle – Sled and Dynamic Runs – Vehicle E

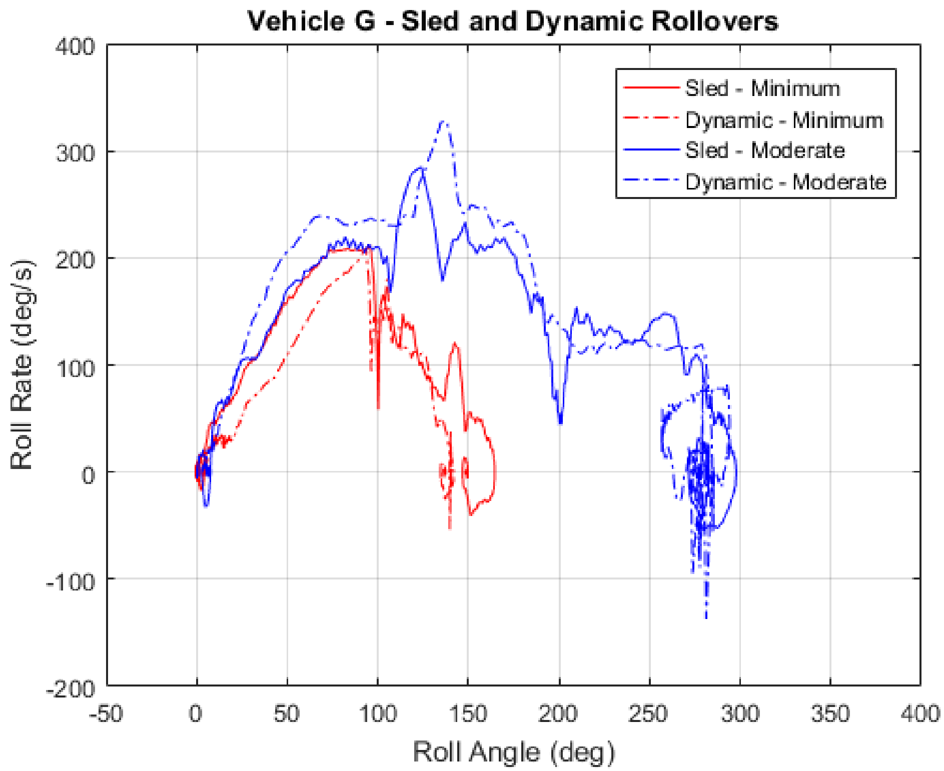


Figure 9: Roll Rate versus Roll Angle – Sled and Dynamic Runs – Vehicle G

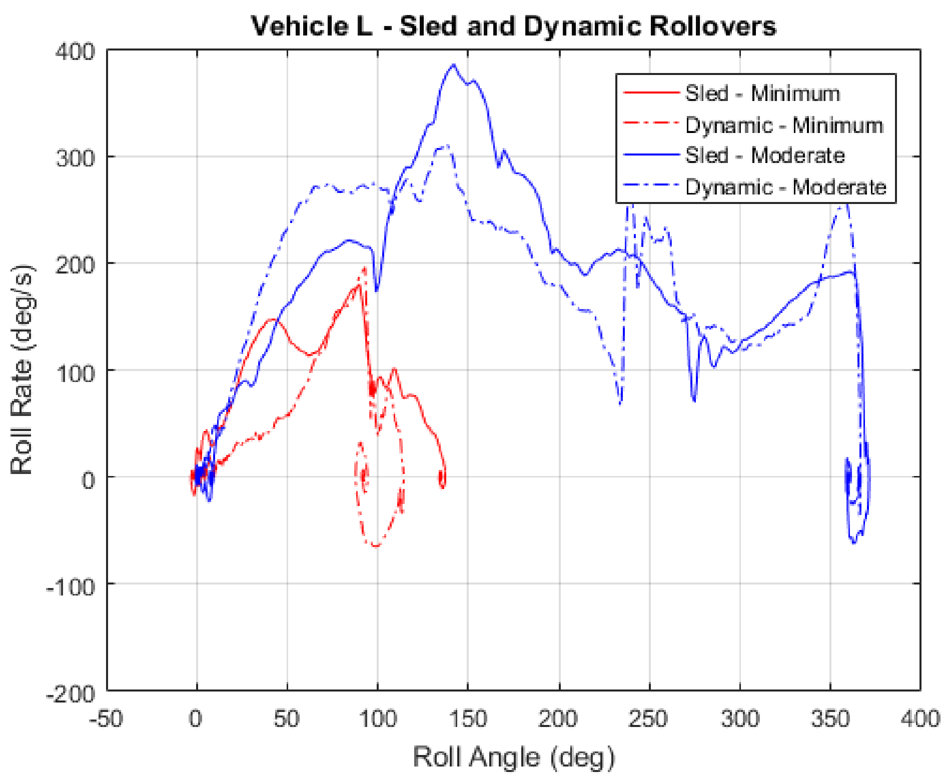


Figure 10: Roll Rate versus Roll Angle – Sled and Dynamic Runs – Vehicle L

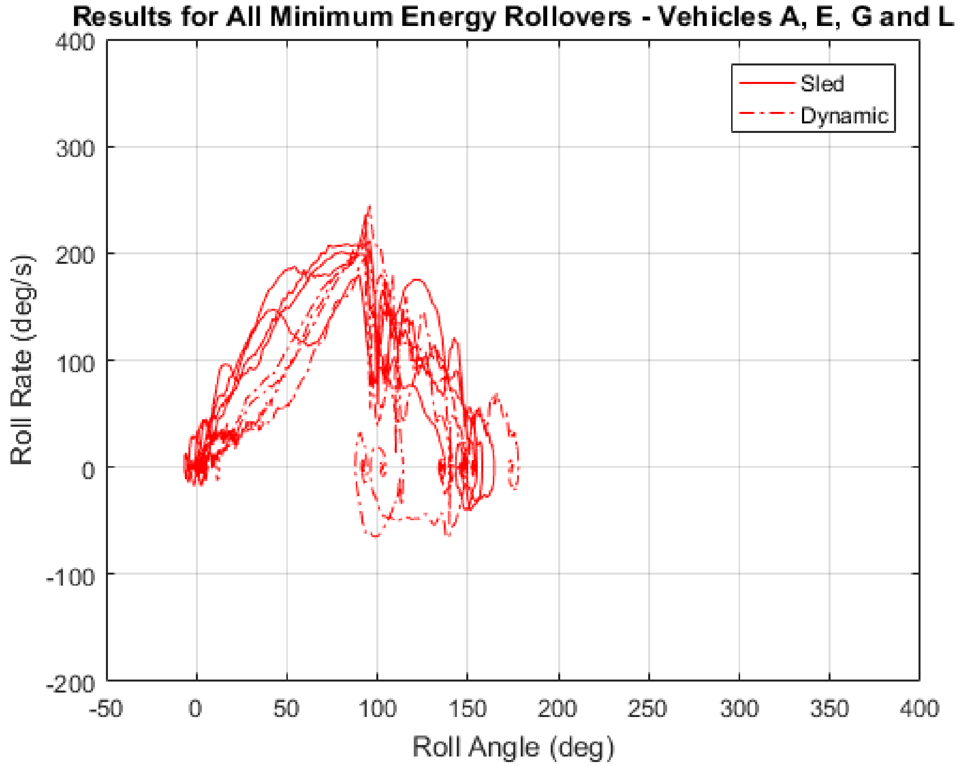


Figure 11: Roll Rate versus Roll Angle – All Minimum Energy Runs

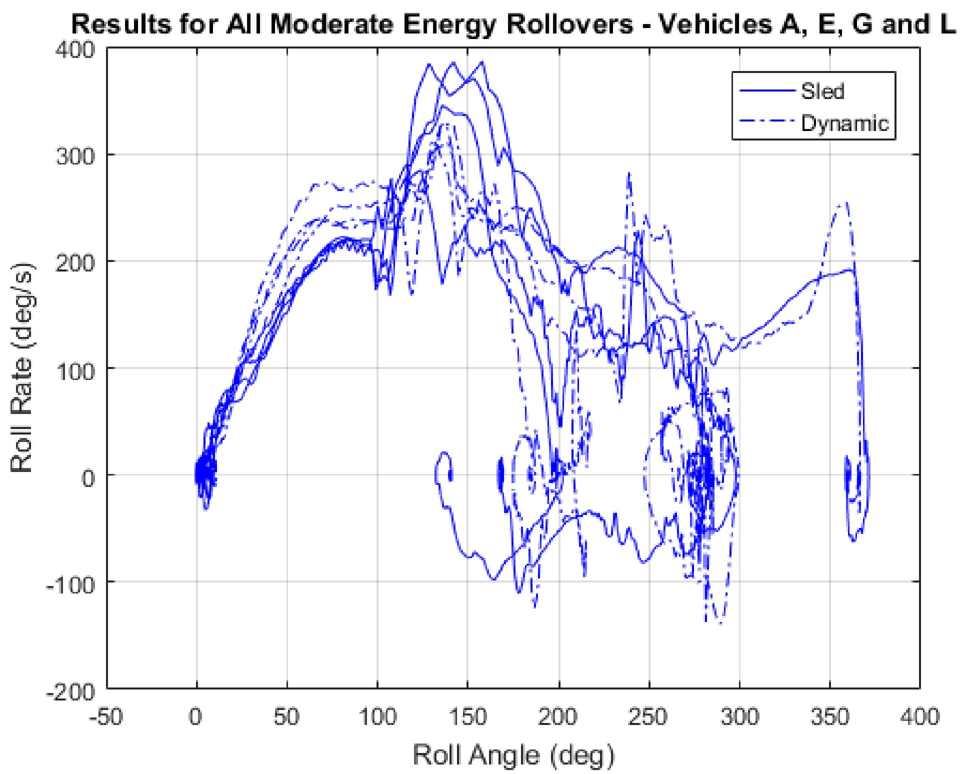


Figure 12: Roll Rate versus Roll Angle – All Moderate Energy Runs

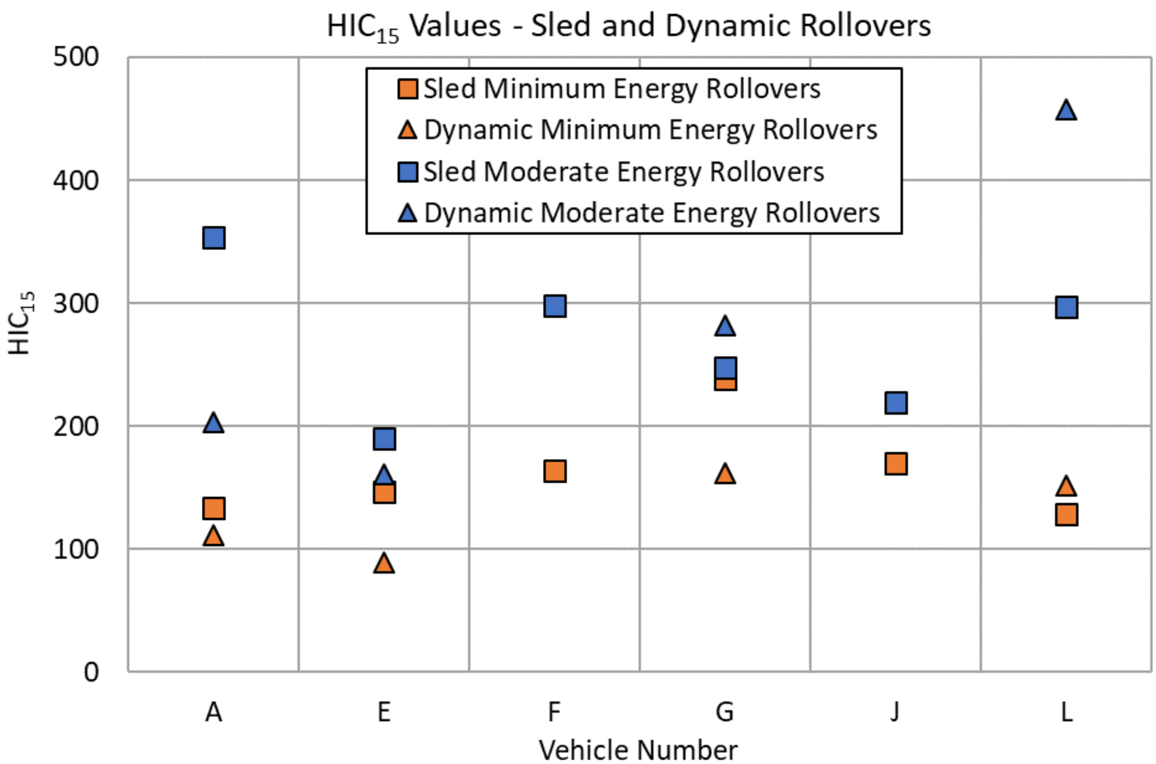


Figure 13: HIC$_{15}$ Values from Sled and Dynamic Minimum and Moderate Energy Rollovers

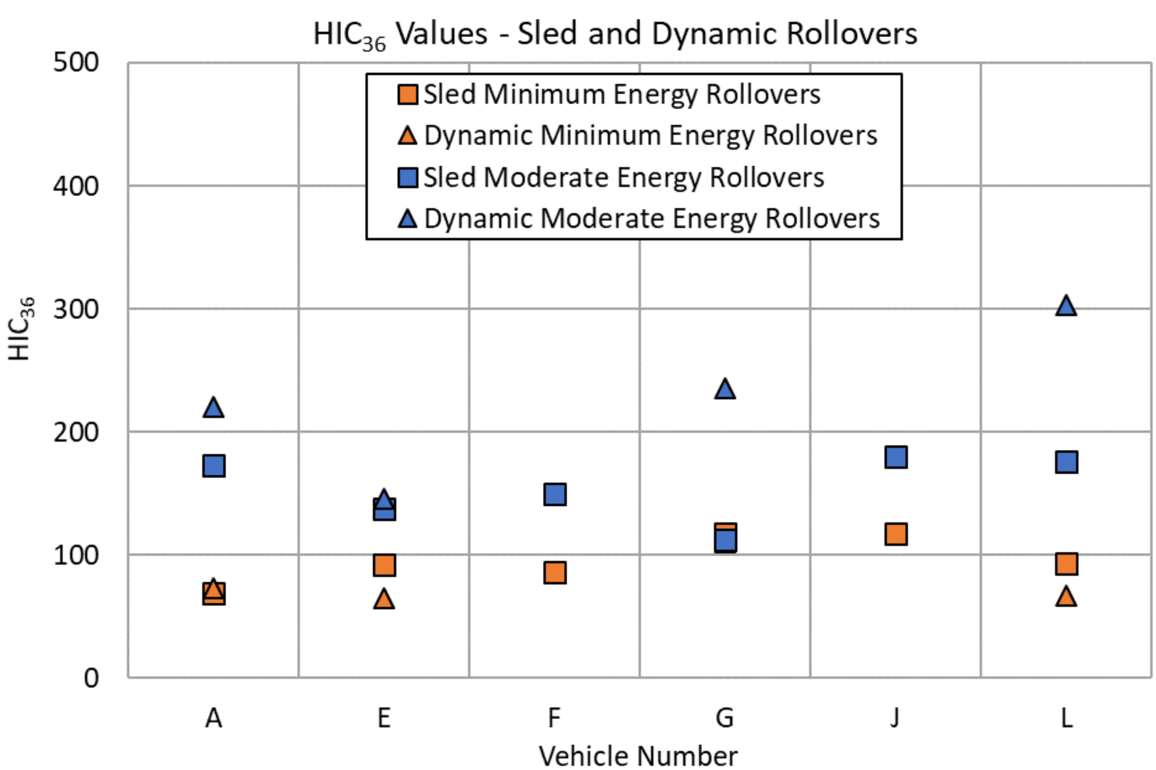


Figure 14: HIC$_{36}$ Values from Sled and Dynamic Minimum and Moderate Energy Rollovers

Table 8: ATV Dynamic and Sled Minimum Energy Rollovers – Description of Significant ATV and ADT Interactions and Rest Position Photographs				
Vehicle	**Dynamic Rollovers**		**Sled Rollovers**	
A	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.	
E	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 of 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.	
G	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 of the ATD and came to rest on the ATD's right leg.	

Table 8: ATV Dynamic and Sled Minimum Energy Rollovers – Description of Significant ATV and ADT Interactions and Rest Position Photographs (Continued)				
Vehicle	**Dynamic Rollovers**		**Sled Rollovers**	
L	Max Roll 114° – Final Roll 92° The ATV seat rolled up against the ATD's buttocks near its maximum roll angle. No part of the ATD was pinned beneath the ATV at rest.		Max Roll 137° – Final Roll 135° The ATV seat rolled up against the ATD's buttocks prior to its maximum roll angle. No part of the ATD was pinned beneath the ATV at rest.	
F	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.	
J	NA	NA	Max Roll 132° – Final Roll 95° The ATV seat rolled up close to the ATD's buttocks near its maximum roll angle. There was minimum contact between the ATV and ADT once the ATD released from the ATV. No part of the ATD was pinned beneath the ATV at rest.	

Table 9: ATV Dynamic and Sled Moderate Energy Rollovers – Description of Significant ATV and ADT Interactions and Rest Position Photographs

Vehicle	Dynamic Rollovers		Sled Rollovers	
A	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 the ATD as it went from 180° to 284°, and then rolled off of the ATD at its final rest position.	
E	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 the ATD near its maximum roll angle. The ATV's rear rack came to rest on the ATD's right foot.	
G	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 the ATD's body and head at a little past 180° of roll angle. The ATV then rolled mostly off of, and back onto, the ATD before coming to rest with its left side resting on the ATD's left leg and left arm.	

**Table 9: ATV Dynamic and Sled Moderate Energy Rollovers –
Description of Significant ATV and ADT Interactions and Rest Position Photographs (Continued)**

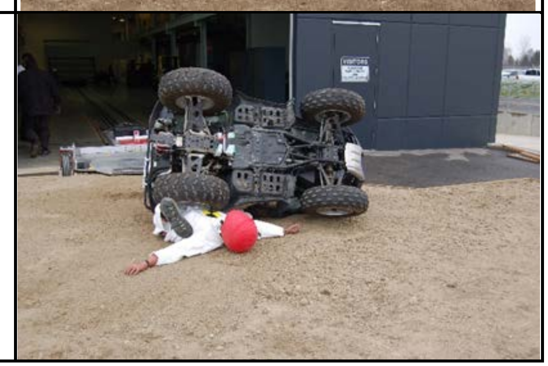
Vehicle	Dynamic Rollovers		Sled Rollovers	
L	Max Roll 366° – Final Roll 359° Near 270° of roll angle, the ATV landed on the ATD’s right leg. The ATV came to rest with its left footwell above the ATD’s head.		Max Roll 371° – Final Roll 361° The ATV rolled onto the ATD’s body (but not its head) near 270° of roll angle. The ATV come to rest with its left rear tire on the ATD's left foot.	
F	**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.	
J	**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 the ATD's pelvis.	

Table 10: Summary of Significant ATV and ADT Interactions During Rollovers and at Final Rest Position					
		Dynamic Rollovers		Sled Rollovers	
Vehicle	Rollover Type	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	Significant ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head
A	Minimum Energy	X	X	X	O
	Moderate Energy	X	X	X	O
E	Minimum Energy	X	O	X	O
	Moderate Energy	O	O	X	O
G	Minimum Energy	O	O	X	O
	Moderate Energy	O	O	X	O
L	Minimum Energy	O	O	O	O
	Moderate Energy	O	O	X	O
F	Minimum Energy	NA	NA	O	O
	Moderate Energy	NA	NA	X	X
J	Minimum Energy	NA	NA	O	O
	Moderate Energy	NA	NA	X	O
Percent Occurrence		37.5% (3/8)	25.0% (2/8)	75.0% (9/12)	8.3% (1/12)

AOS Camera 1 - Roll Angle = 30° - Time = 1.28 sec

AOS Camera 1 - Roll Angle = 45° - Time = 1.54 sec

AOS Camera 1 - Roll Angle = 90° - Time = 1.85 sec

AOS Camera 2 - Roll Angle = 30° - Time = 1.28 sec

AOS Camera 2 - Roll Angle = 45° - Time = 1.54 sec

AOS Camera 2 - Roll Angle = 90° - Time = 1.85 sec

Vehicle A - Dynamic Minimum Energy Rollover

AOS Camera 1 - ATD Head Strike - Time = 1.97 sec

AOS Camera 1 - Max Angle = 177.9° - Time = 3.24 sec

AOS Camera 1 - End of Run - Roll Angle = 174.1°

AOS Camera 2 - ATD Head Strike - Time = 1.97 sec

AOS Camera 2 - Max Angle = 177.9° - Time = 3.24 sec

AOS Camera 2 - End of Run - Roll Angle = 174.1°

Vehicle A - Dynamic Minimum Energy Rollover

RT Camera 1 - Roll Angle = 30° - Time = 1.28 sec

RT Camera 1 - Roll Angle = 45° - Time = 1.54 sec

RT Camera 1 - Roll Angle = 90° - Time = 1.85 sec

RT Camera 2 - Roll Angle = 30° - Time = 1.28 sec

RT Camera 2 - Roll Angle = 45° - Time = 1.54 sec

RT Camera 2 - Roll Angle = 90° - Time = 1.85 sec

Vehicle A - Dynamic Minimum Energy Rollover

RT Camera 1 - ATD Head Strike - Time = 1.97 sec

RT Camera 1 - Max Angle = 177.9° - Time = 3.24 sec

RT Camera 1 - End of Run - Roll Angle = 174.1°

RT Camera 2 - ATD Head Strike - Time = 1.97 sec

RT Camera 2 - Max Angle = 177.9° - Time = 3.24 sec

RT Camera 2 - End of Run - Roll Angle = 174.1°

Vehicle A - Dynamic Minimum Energy Rollover

Drone Camera - Roll Angle = 30° - Time = 1.28 sec

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

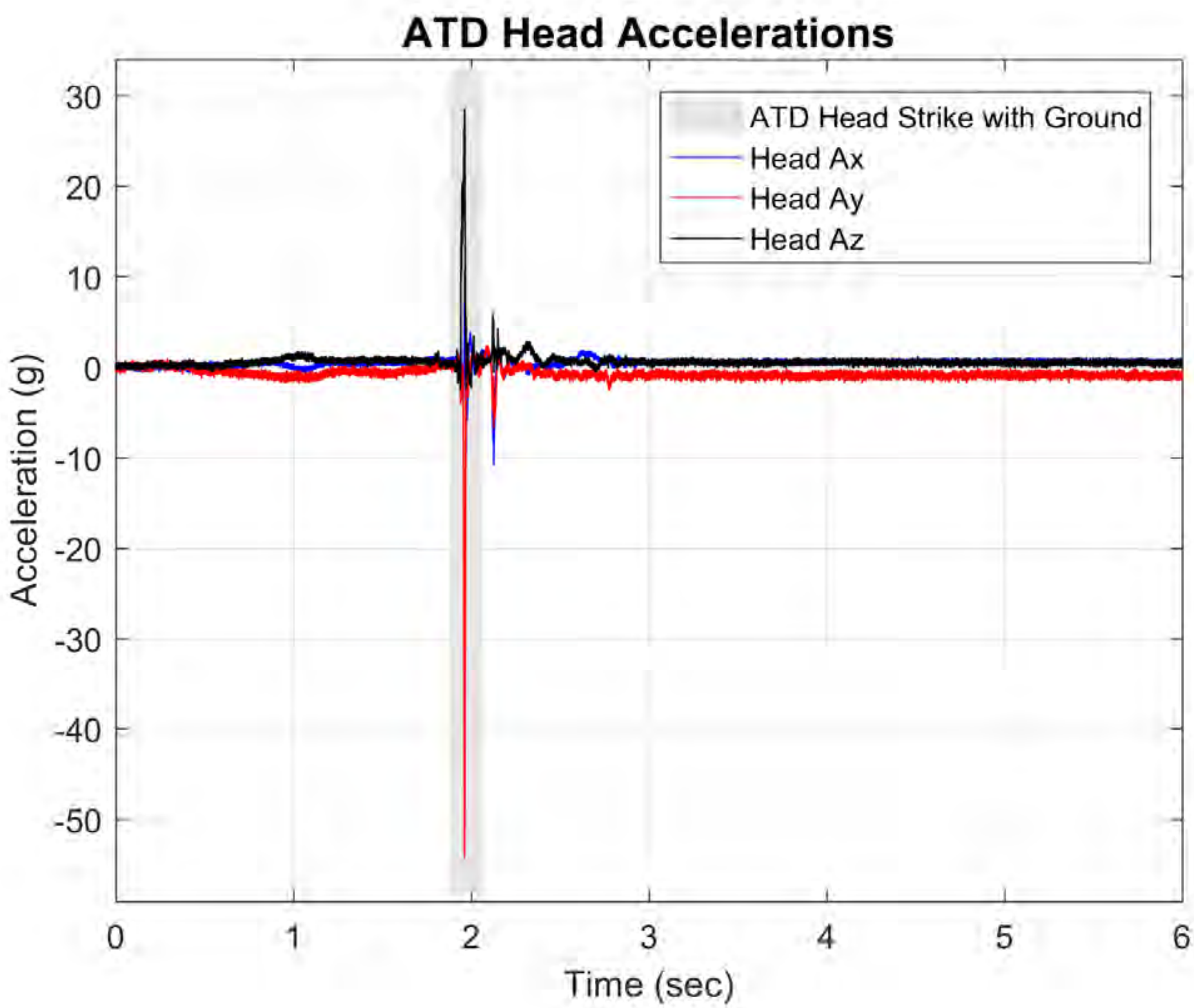
Drone Camera - Roll Angle = 90° - Time = 1.85 sec

Drone Camera - ATD Head Strike - Time = 1.97 sec

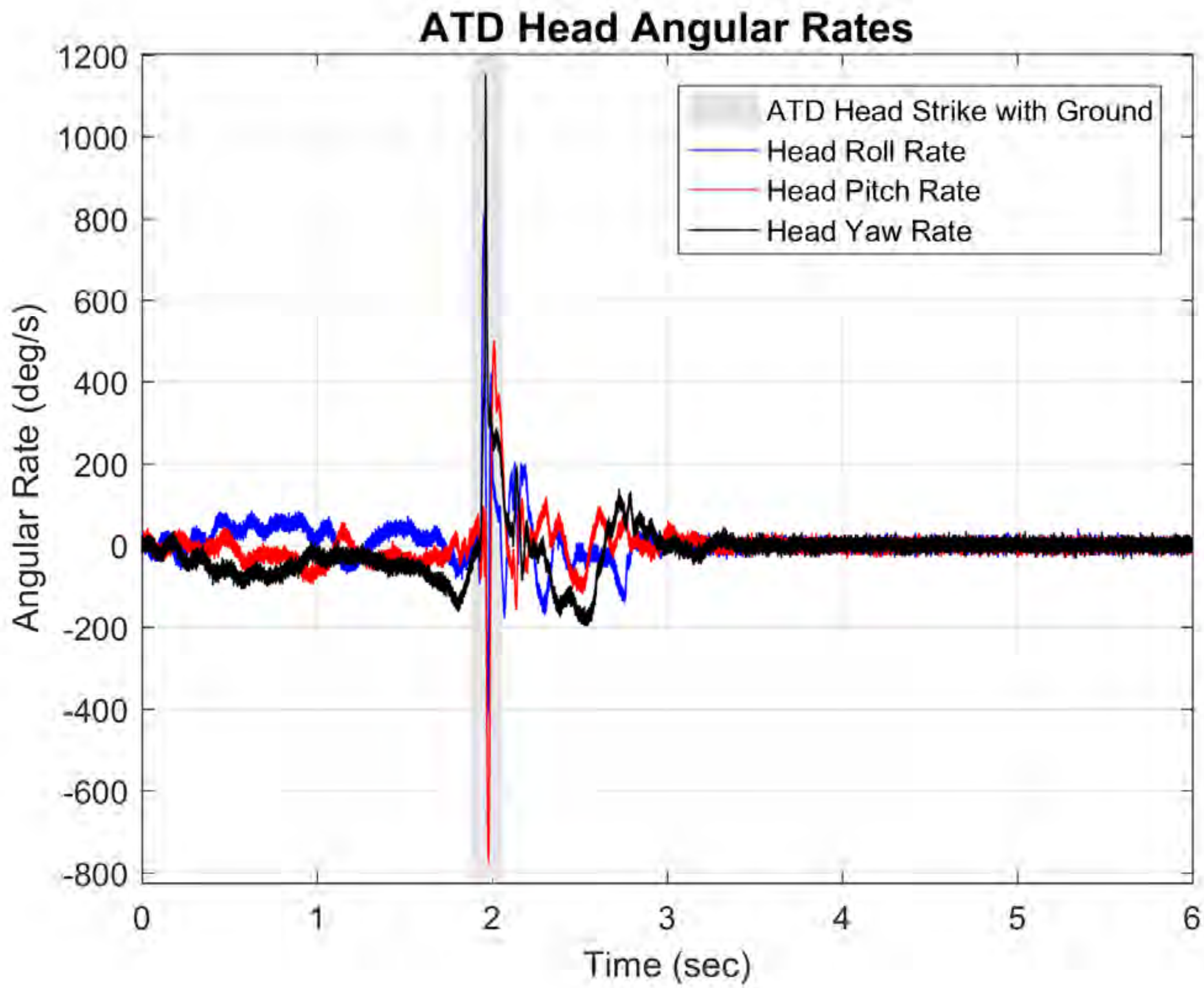
Drone Camera - Max Angle = 177.9° - Time = 3.24 sec

Drone Camera - End of Run - Roll Angle = 174.1°

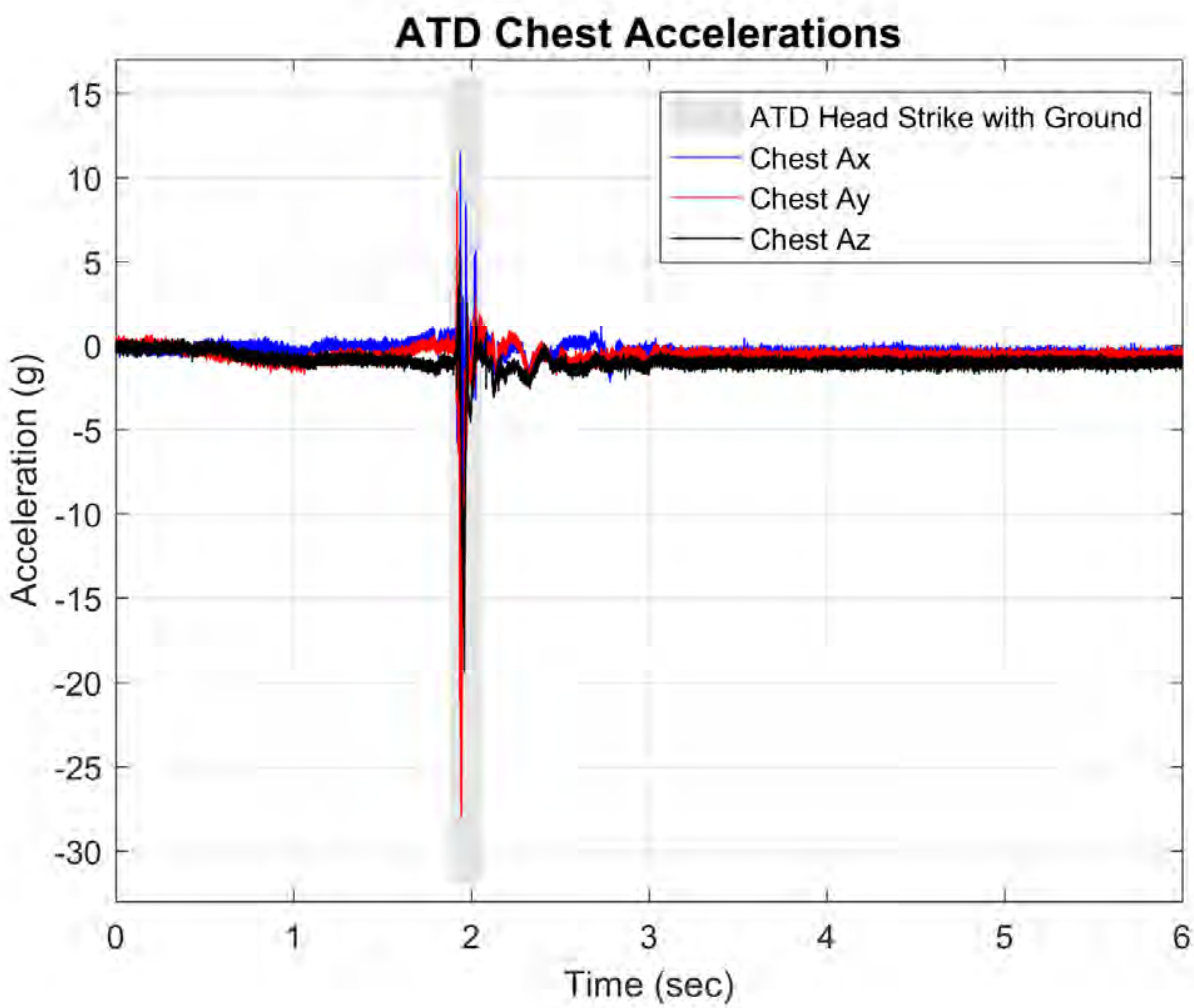
Vehicle A - Dynamic Minimum Energy Rollover



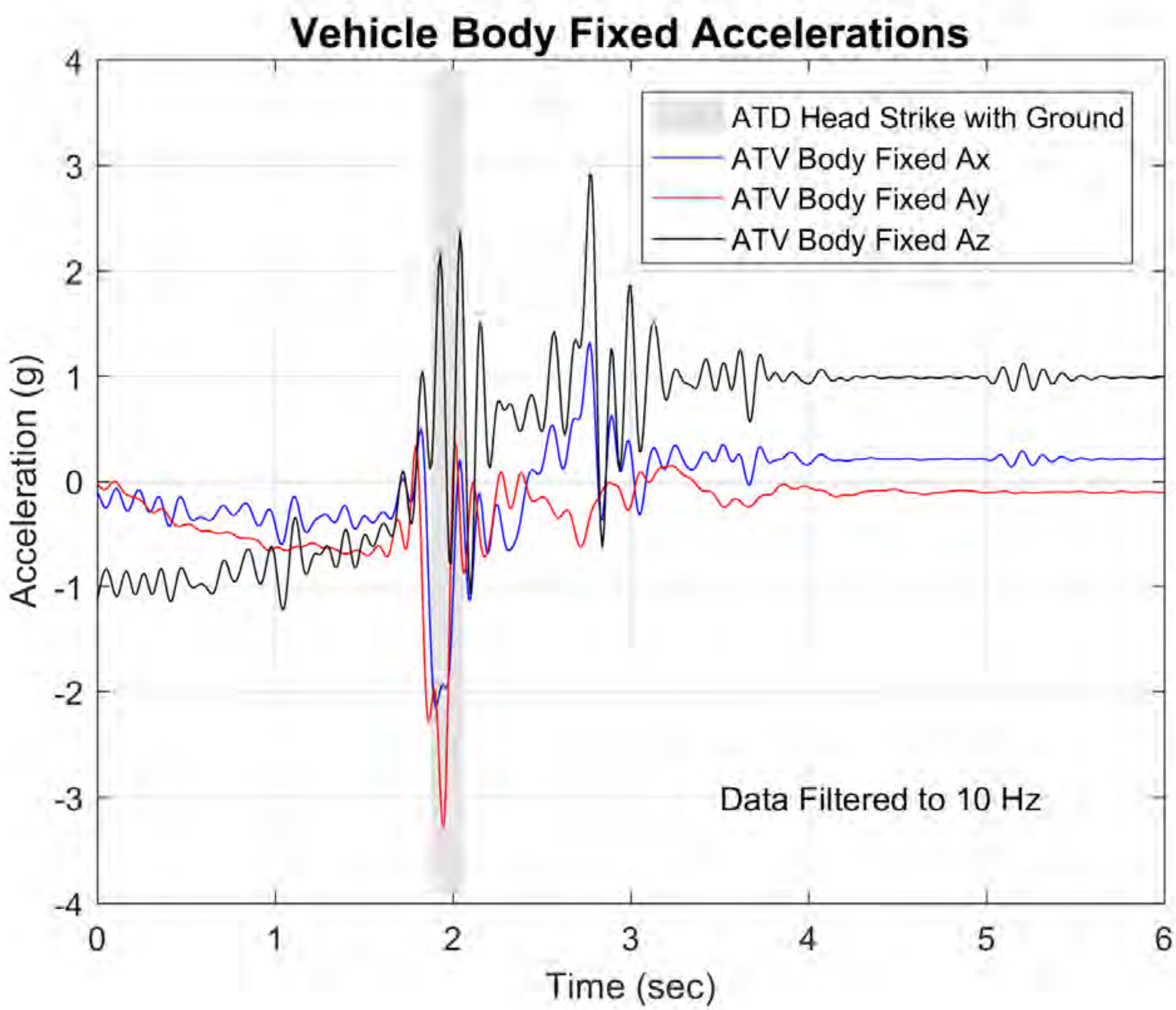
Vehicle A - Dynamic Minimum Energy Rollover



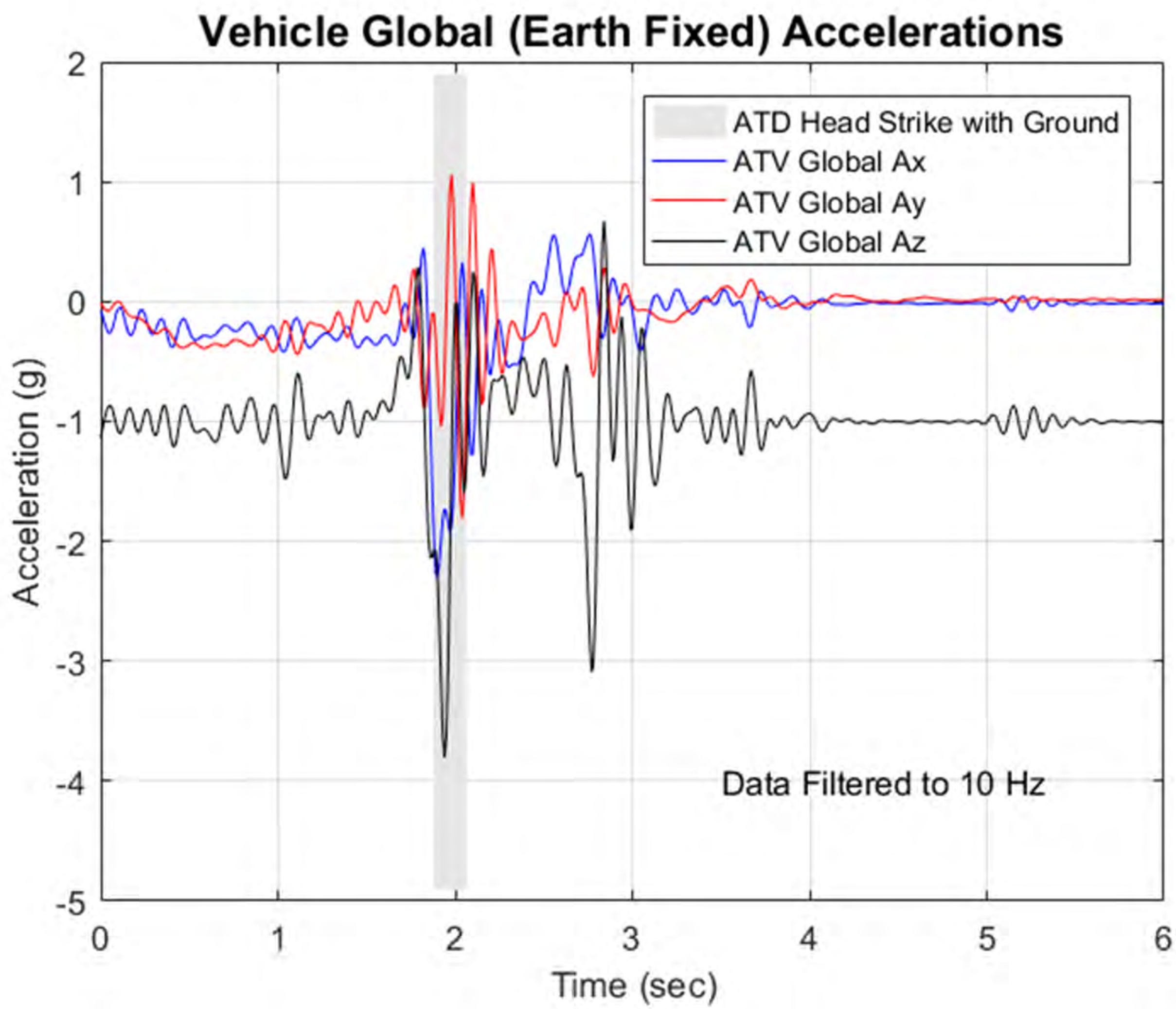
Vehicle A - Dynamic Minimum Energy Rollover



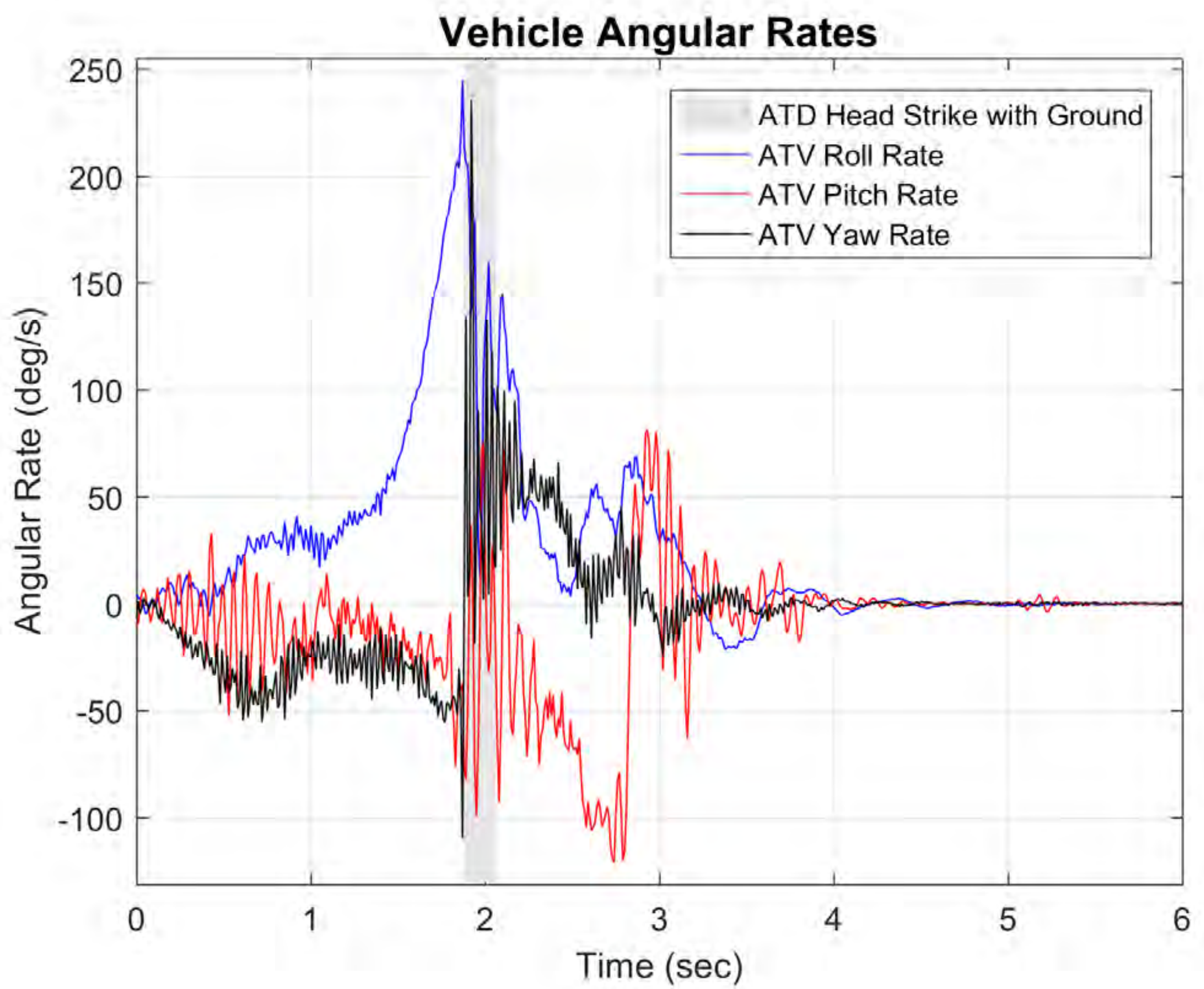
Vehicle A - Dynamic Minimum Energy Rollover



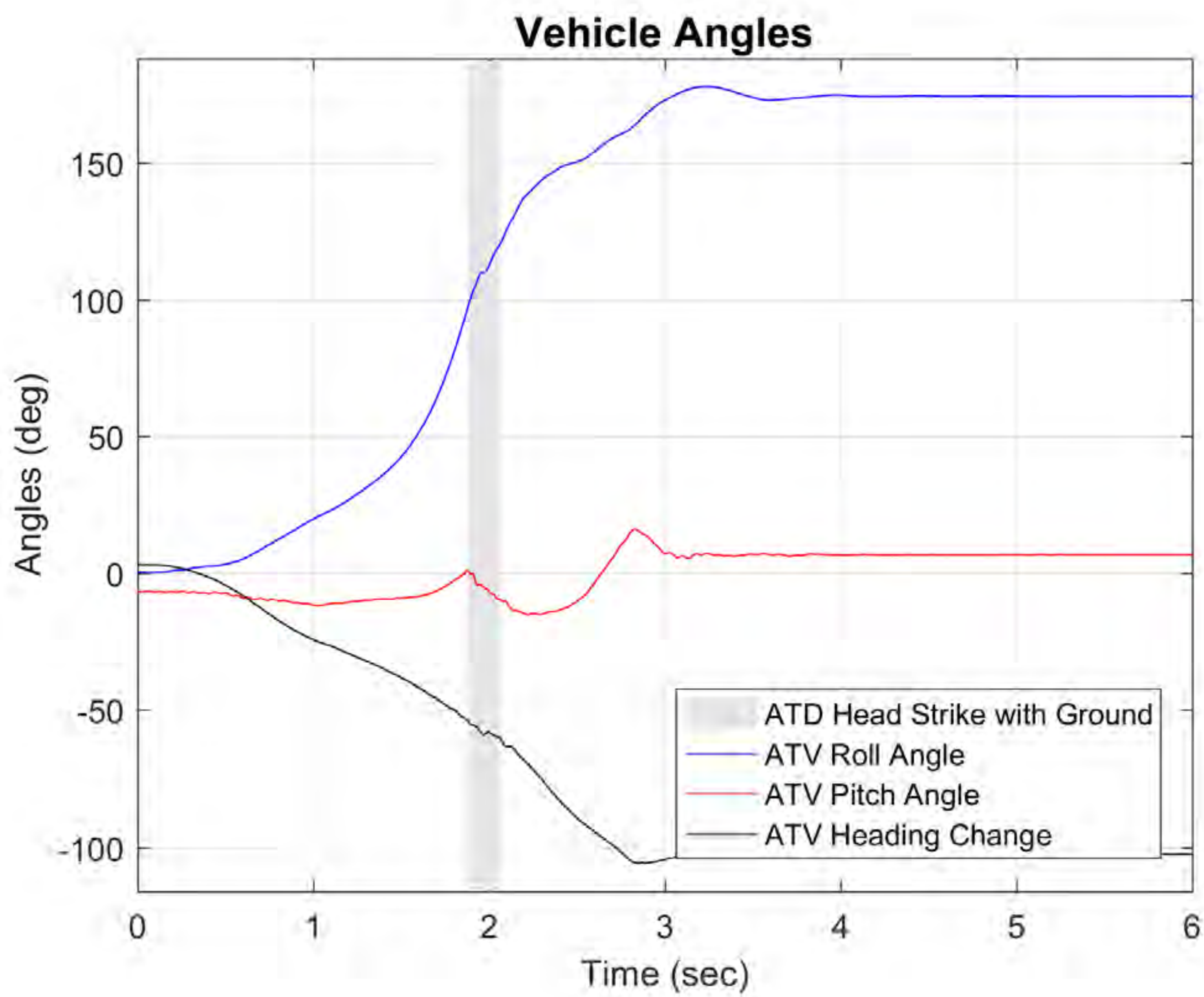
Vehicle A - Dynamic Minimum Energy Rollover



Vehicle A - Dynamic Minimum Energy Rollover



Vehicle A - Dynamic Minimum Energy Rollover



Vehicle A - Dynamic Minimum Energy Rollover

AOS Camera 1 - Roll Angle = 30° - Time = 0.97 sec

AOS Camera 1 - Roll Angle = 45° - Time = 1.08 sec

AOS Camera 1 - Roll Angle = 90° - Time = 1.27 sec

AOS Camera 2 - Roll Angle = 30° - Time = 0.97 sec

AOS Camera 2 - Roll Angle = 45° - Time = 1.08 sec

AOS Camera 2 - Roll Angle = 90° - Time = 1.27 sec

Vehicle A - Dynamic Moderate Energy Rollover

AOS Camera 1 - ATD Head Strike - Time = 1.43 sec

AOS Camera 1 - Roll Angle = 180° - Time = 1.66 sec

AOS Camera 1 - Max Angle = 217.5° - Time = 2.38 sec

AOS Camera 2 - ATD Head Strike - Time = 1.43 sec

AOS Camera 2 - Roll Angle = 180° - Time = 1.66 sec

AOS Camera 2 - Max Angle = 217.5° - Time = 2.38 sec

Vehicle A - Dynamic Moderate Energy Rollover

AOS Camera 1 - End of Run - Roll Angle = 184.9°

AOS Camera 2 - End of Run - Roll Angle = 184.9°

Vehicle A - Dynamic Moderate Energy Rollover

RT Camera 1 - Roll Angle = 30° - Time = 0.97 sec

RT Camera 1 - Roll Angle = 45° - Time = 1.08 sec

RT Camera 1 - Roll Angle = 90° - Time = 1.27 sec

RT Camera 2 - Roll Angle = 30° - Time = 0.97 sec

RT Camera 2 - Roll Angle = 45° - Time = 1.08 sec

RT Camera 2 - Roll Angle = 90° - Time = 1.27 sec

Vehicle A - Dynamic Moderate Energy Rollover

RT Camera 1 - ATD Head Strike - Time = 1.43 sec

RT Camera 1 - Roll Angle = 180° - Time = 1.66 sec

RT Camera 1 - Max Angle = 217.5° - Time = 2.38 sec

RT Camera 2 - ATD Head Strike - Time = 1.43 sec

RT Camera 2 - Roll Angle = 180° - Time = 1.66 sec

RT Camera 2 - Max Angle = 217.5° - Time = 2.38 sec

Vehicle A - Dynamic Moderate Energy Rollover

RT Camera 1 - End of Run - Roll Angle = 184.9°

RT Camera 2 - End of Run - Roll Angle = 184.9°

Vehicle A - Dynamic Moderate Energy Rollover

Drone Camera - Roll Angle = 30° - Time = 0.97 sec

Drone Camera - Roll Angle = 45° - Time = 1.08 sec

Drone Camera - Roll Angle = 90° - Time = 1.27 sec

Drone Camera - ATD Head Strike - Time = 1.43 sec

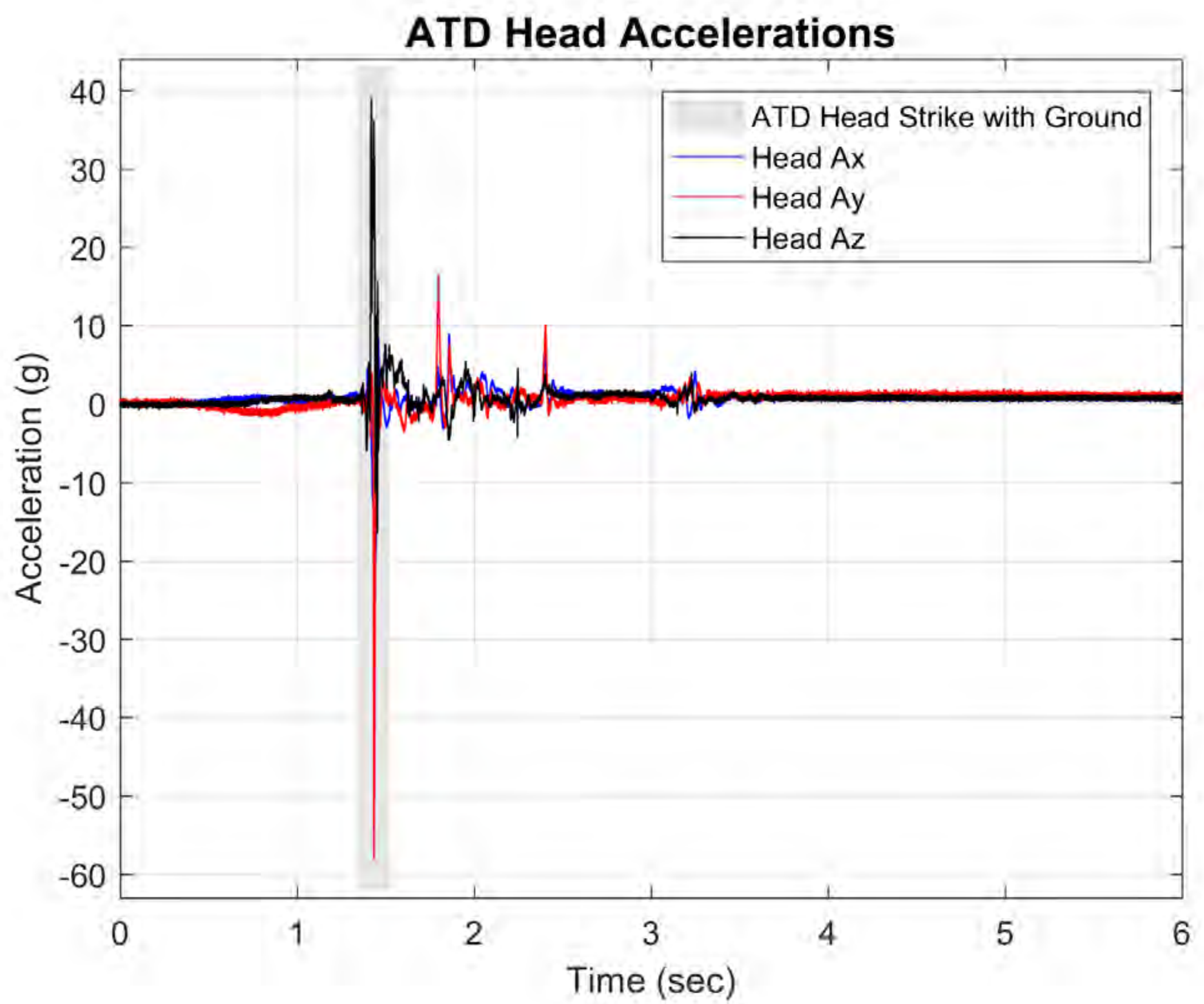
Drone Camera - Roll Angle = 180° - Time = 1.66 sec

Drone Camera - Max Angle = 217.5° - Time = 2.38 sec

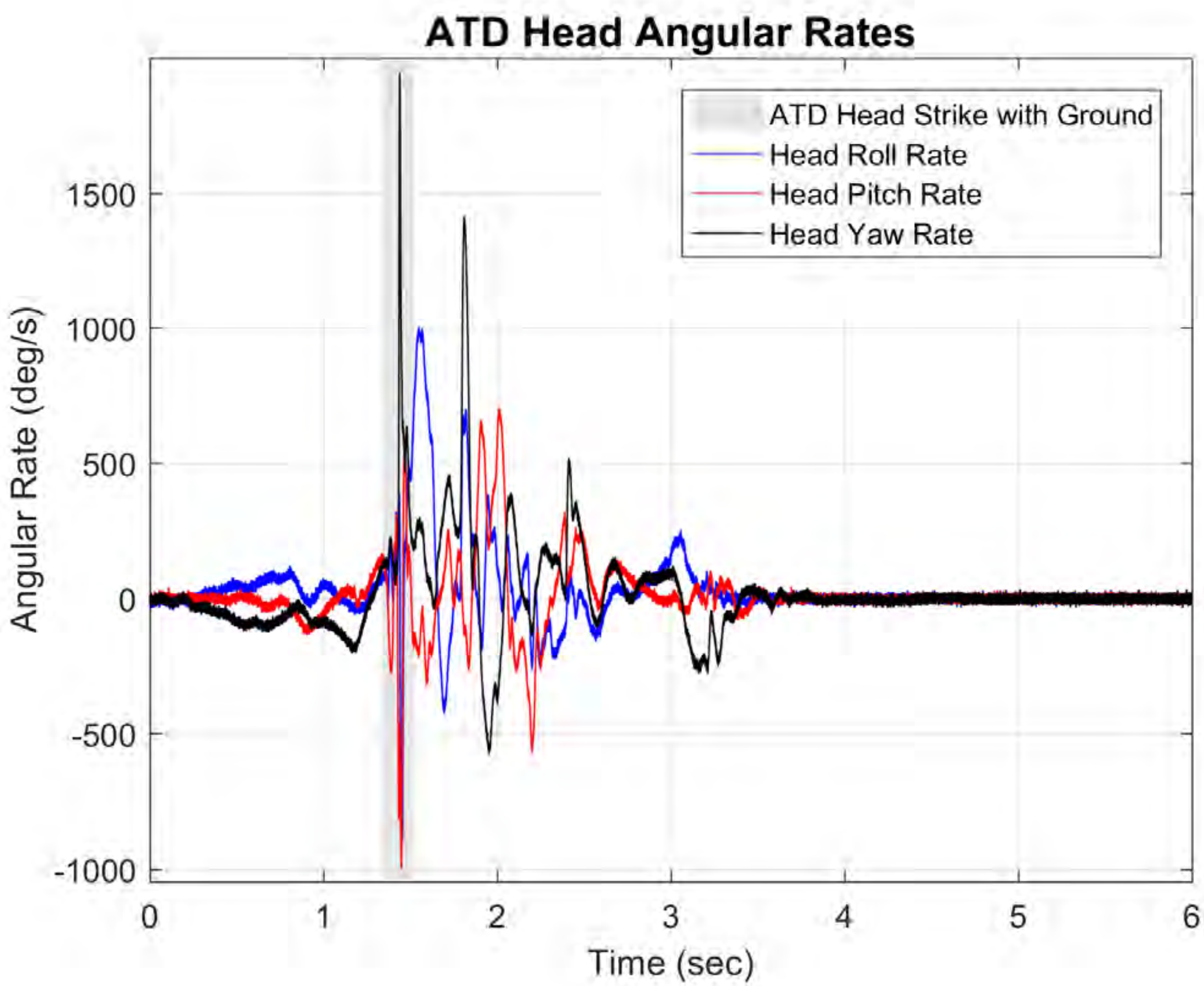
Vehicle A - Dynamic Moderate Energy Rollover

Drone Camera - End of Run - Roll Angle = 184.9°

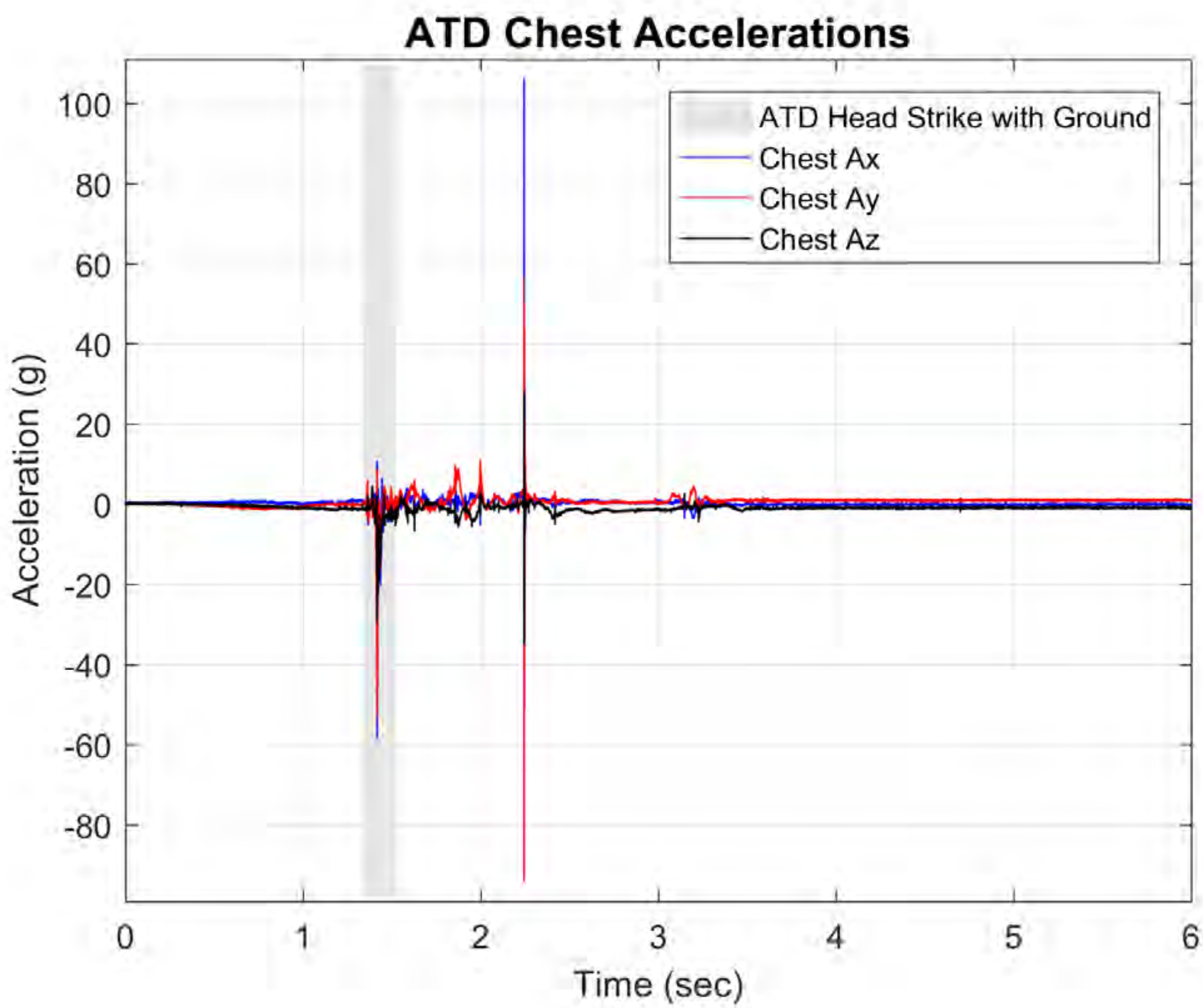
Vehicle A - Dynamic Moderate Energy Rollover



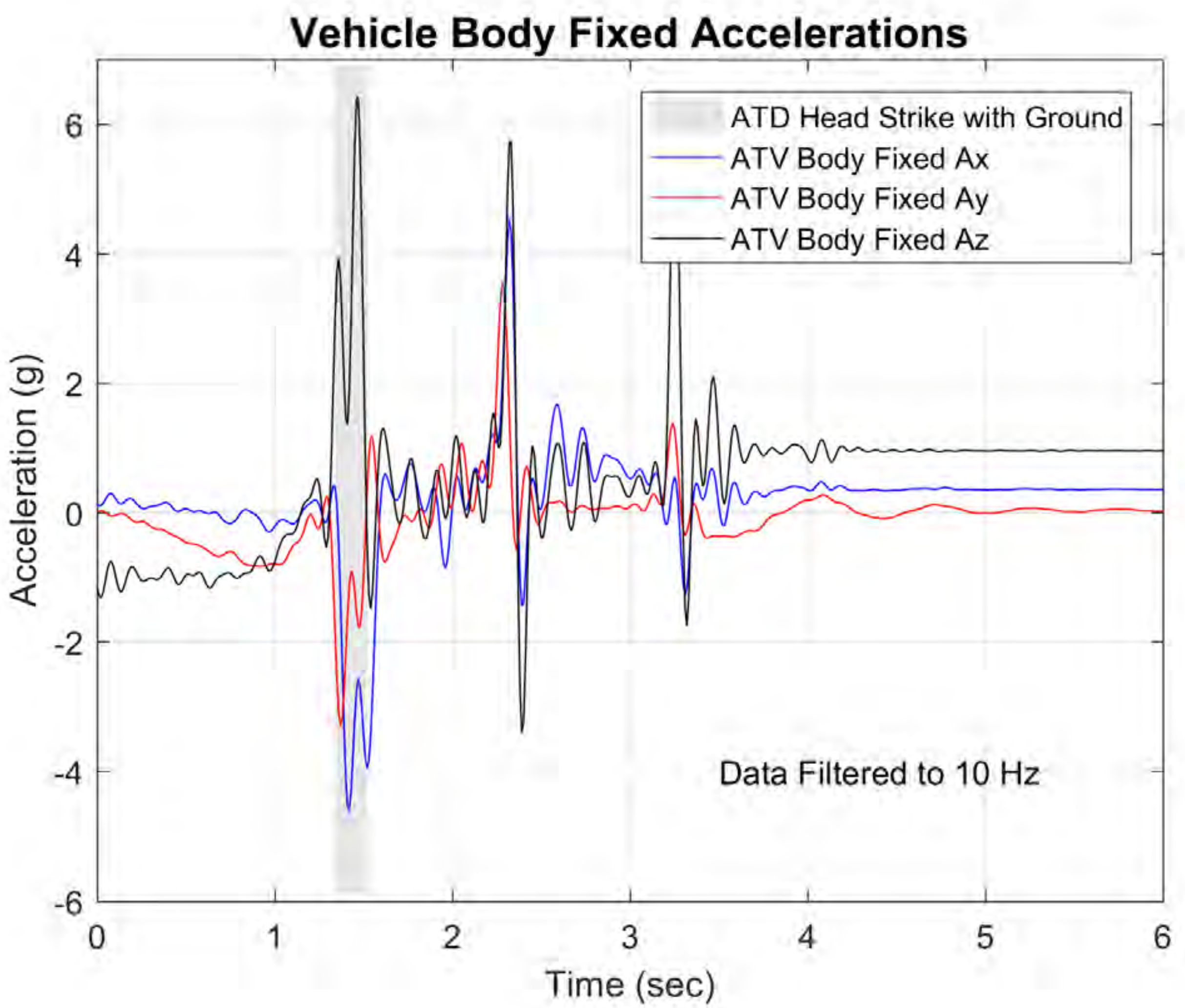
Vehicle A - Dynamic Moderate Energy Rollover



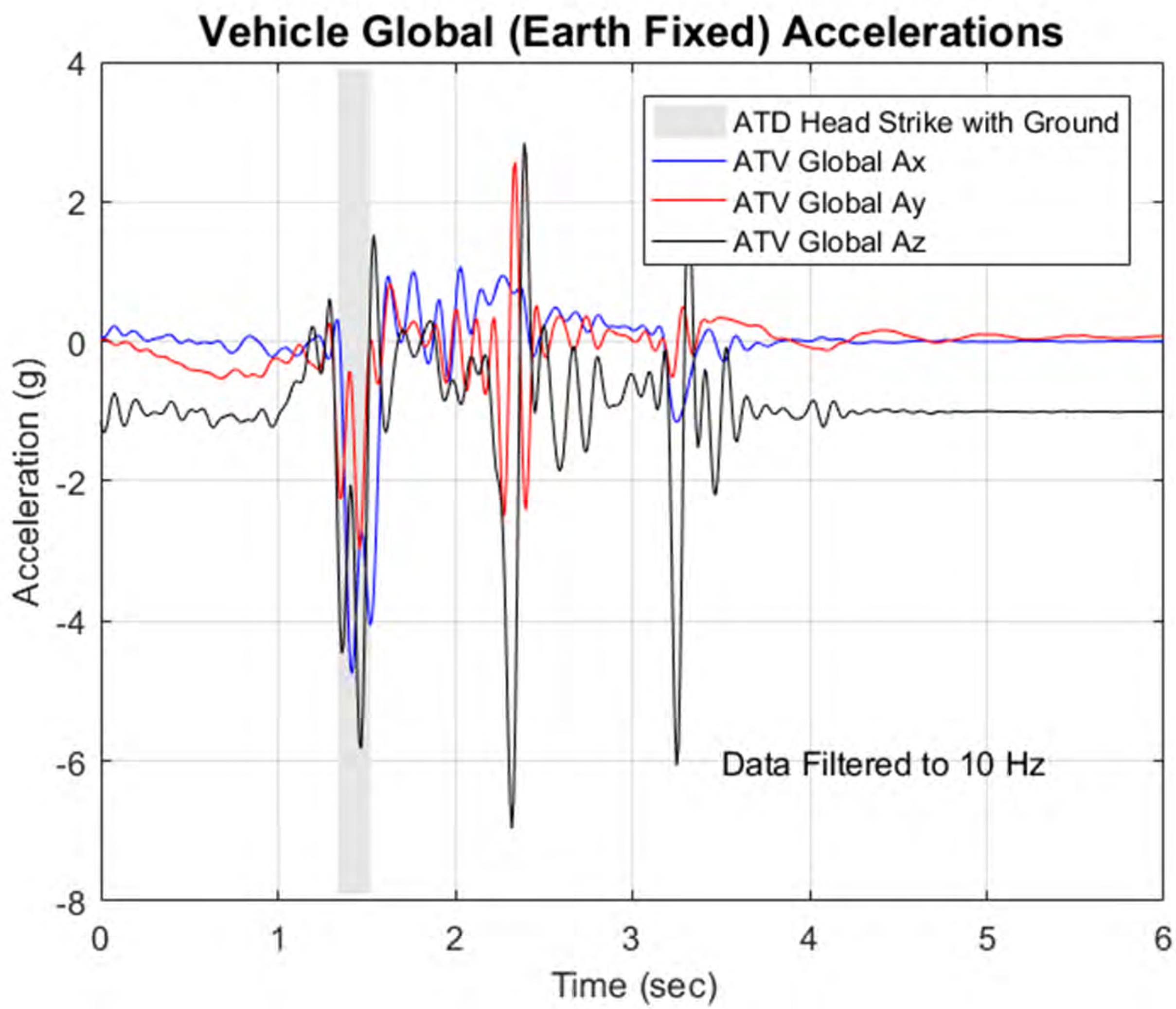
Vehicle A - Dynamic Moderate Energy Rollover



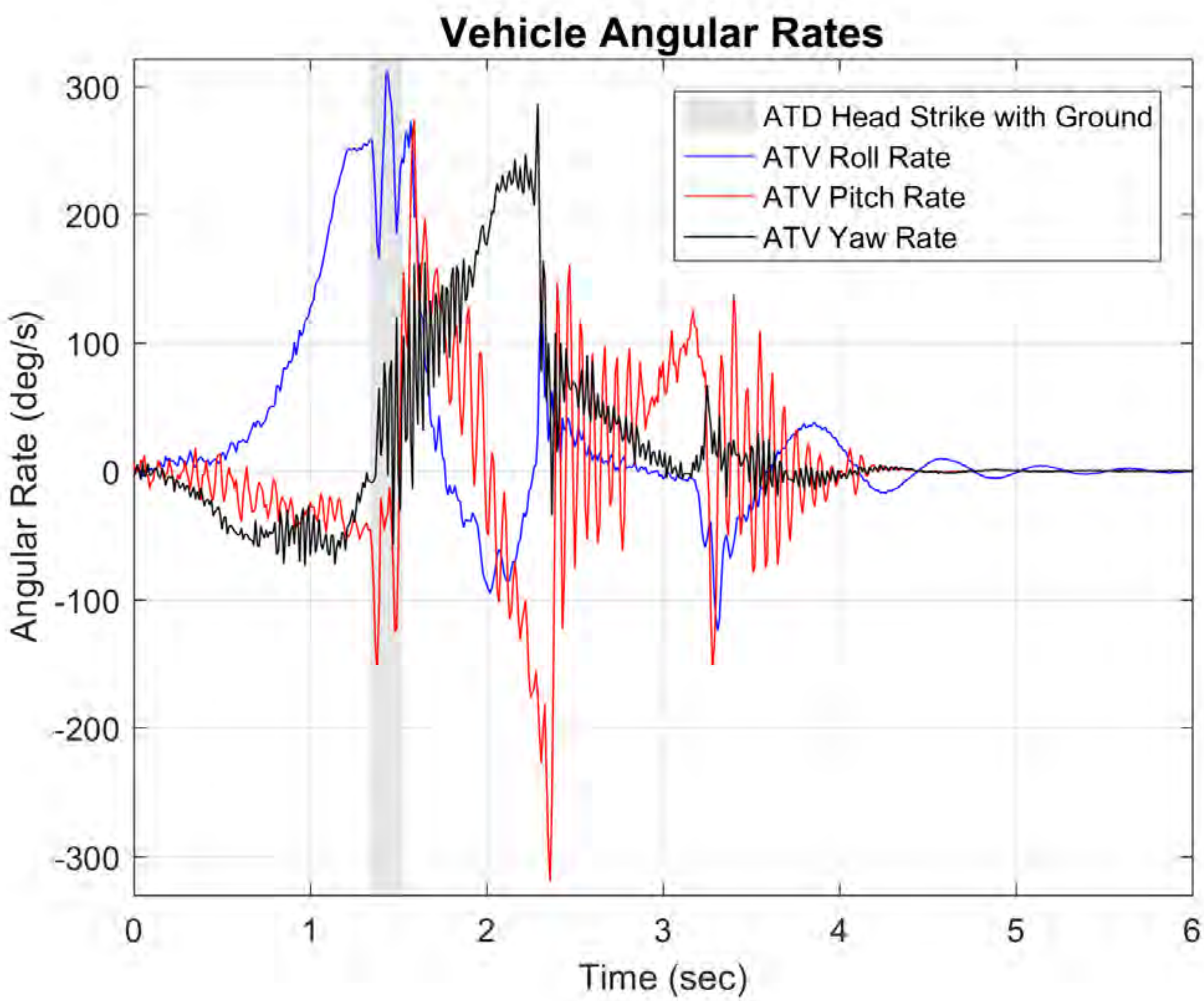
Vehicle A - Dynamic Moderate Energy Rollover



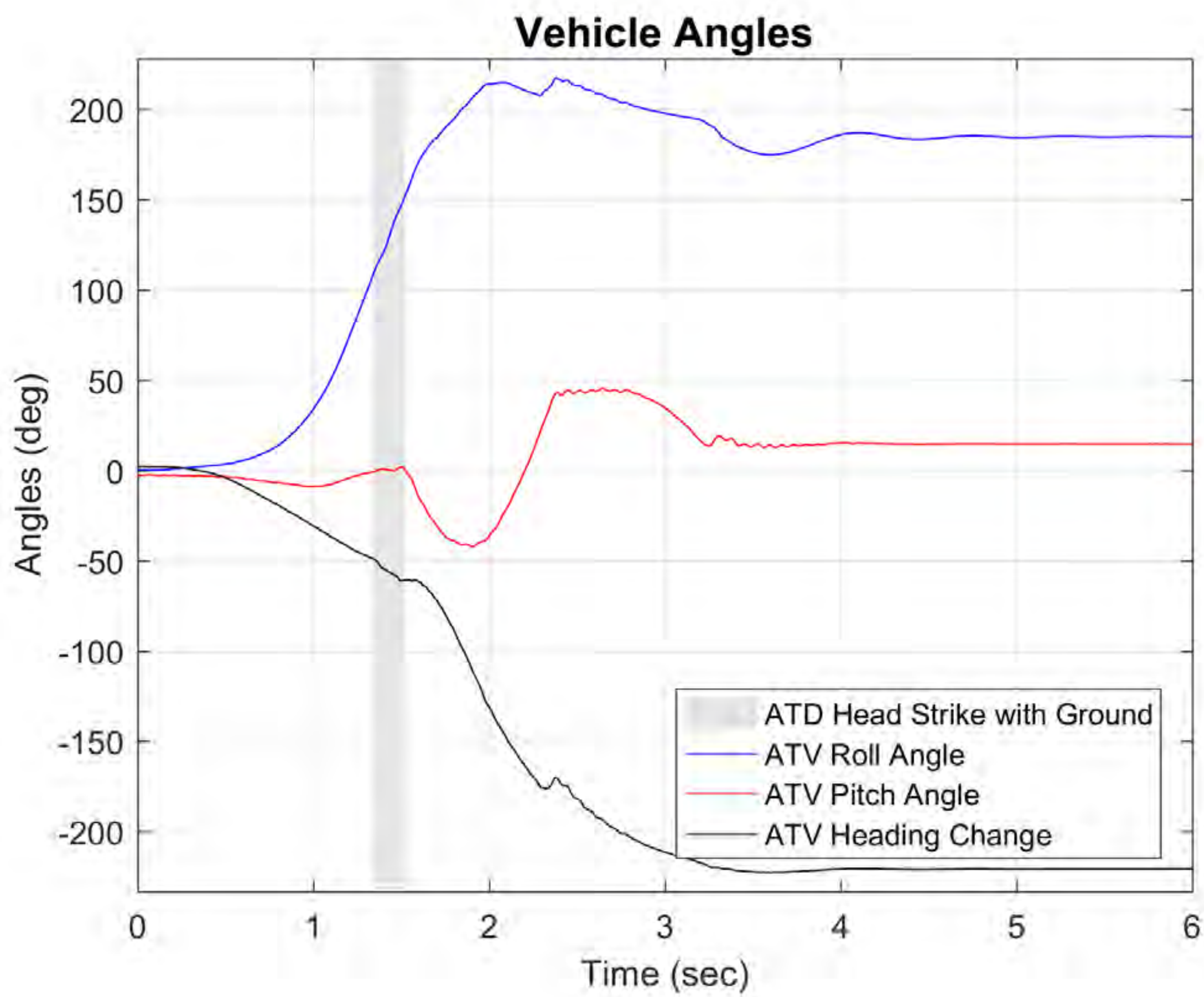
Vehicle A - Dynamic Moderate Energy Rollover



Vehicle A - Dynamic Moderate Energy Rollover



Vehicle A - Dynamic Moderate Energy Rollover



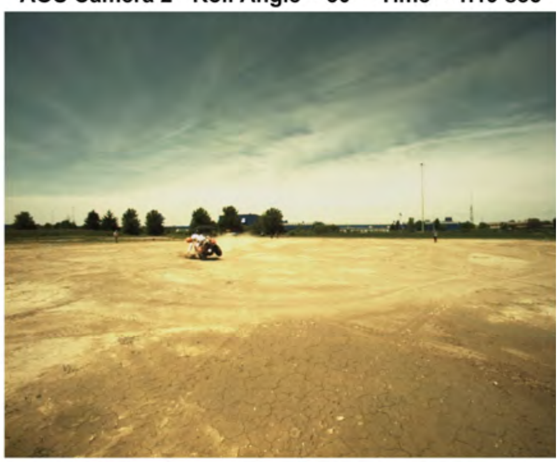
Vehicle A - Dynamic Moderate Energy Rollover

AOS Camera 1 - Roll Angle = 30° - Time = 1.19 sec

AOS Camera 1 - Roll Angle = 45° - Time = 1.3 sec

AOS Camera 1 - Roll Angle = 90° - Time = 1.49 sec

AOS Camera 2 - Roll Angle = 30° - Time = 1.19 sec



AOS Camera 2 - Roll Angle = 45° - Time = 1.3 sec

AOS Camera 2 - Roll Angle = 90° - Time = 1.49 sec

Vehicle A - Dynamic Moderate Energy Rollover with Trip Feature

AOS Camera 1 - ATD Head Strike - Time = 1.65 sec

AOS Camera 1 - Roll Angle = 180° - Time = 2.01 sec

AOS Camera 1 - Max Angle = 269.9° - Time = 4.77 sec

AOS Camera 2 - ATD Head Strike - Time = 1.65 sec

AOS Camera 2 - Roll Angle = 180° - Time = 2.01 sec

AOS Camera 2 - Max Angle = 269.9° - Time = 4.77 sec

Vehicle A - Dynamic Moderate Energy Rollover with Trip Feature

AOS Camera 1 - End of Run - Roll Angle = 267.8°

AOS Camera 2 - End of Run - Roll Angle = 267.8°

Vehicle A - Dynamic Moderate Energy Rollover with Trip Feature

RT Camera 1 - Roll Angle = 30° - Time = 1.19 sec

RT Camera 1 - Roll Angle = 45° - Time = 1.3 sec

RT Camera 1 - Roll Angle = 90° - Time = 1.49 sec

RT Camera 2 - Roll Angle = 30° - Time = 1.19 sec

RT Camera 2 - Roll Angle = 45° - Time = 1.3 sec

RT Camera 2 - Roll Angle = 90° - Time = 1.49 sec

Vehicle A - Dynamic Moderate Energy Rollover with Trip Feature

RT Camera 1 - ATD Head Strike - Time = 1.65 sec

RT Camera 1 - Roll Angle = 180° - Time = 2.01 sec

RT Camera 1 - Max Angle = 269.9° - Time = 4.77 sec

RT Camera 2 - ATD Head Strike - Time = 1.65 sec

RT Camera 2 - Roll Angle = 180° - Time = 2.01 sec

RT Camera 2 - Max Angle = 269.9° - Time = 4.77 sec

Vehicle A - Dynamic Moderate Energy Rollover with Trip Feature

RT Camera 1 - End of Run - Roll Angle = 267.8°

RT Camera 2 - End of Run - Roll Angle = 267.8°

Vehicle A - Dynamic Moderate Energy Rollover with Trip Feature

Drone Camera - Roll Angle = 30° - Time = 1.19 sec

Drone Camera - Roll Angle = 45° - Time = 1.3 sec

Drone Camera - Roll Angle = 90° - Time = 1.49 sec

Drone Camera - ATD Head Strike - Time = 1.65 sec

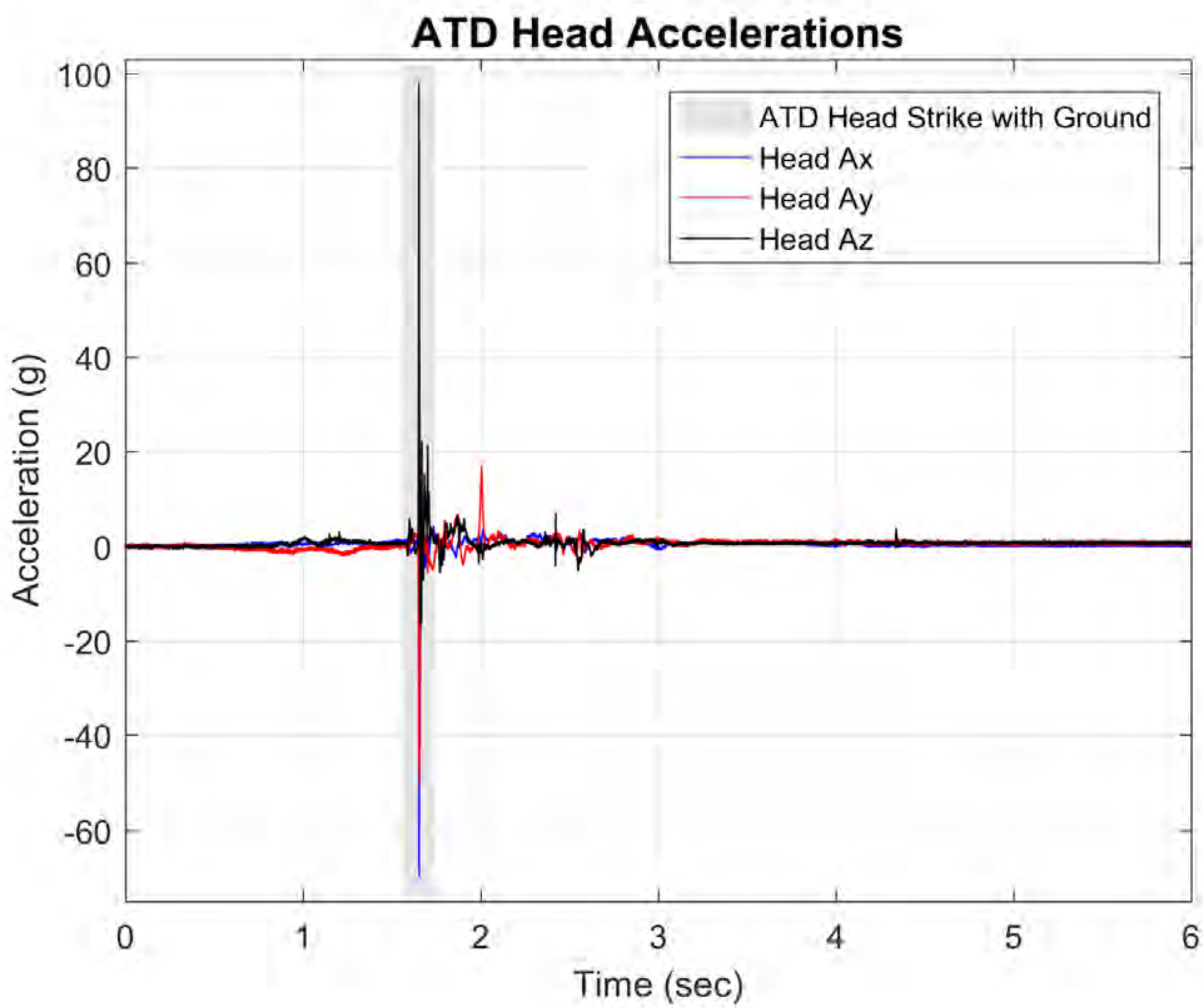
Drone Camera - Roll Angle = 180° - Time = 2.01 sec

Drone Camera - Max Angle = 269.9° - Time = 4.77 sec

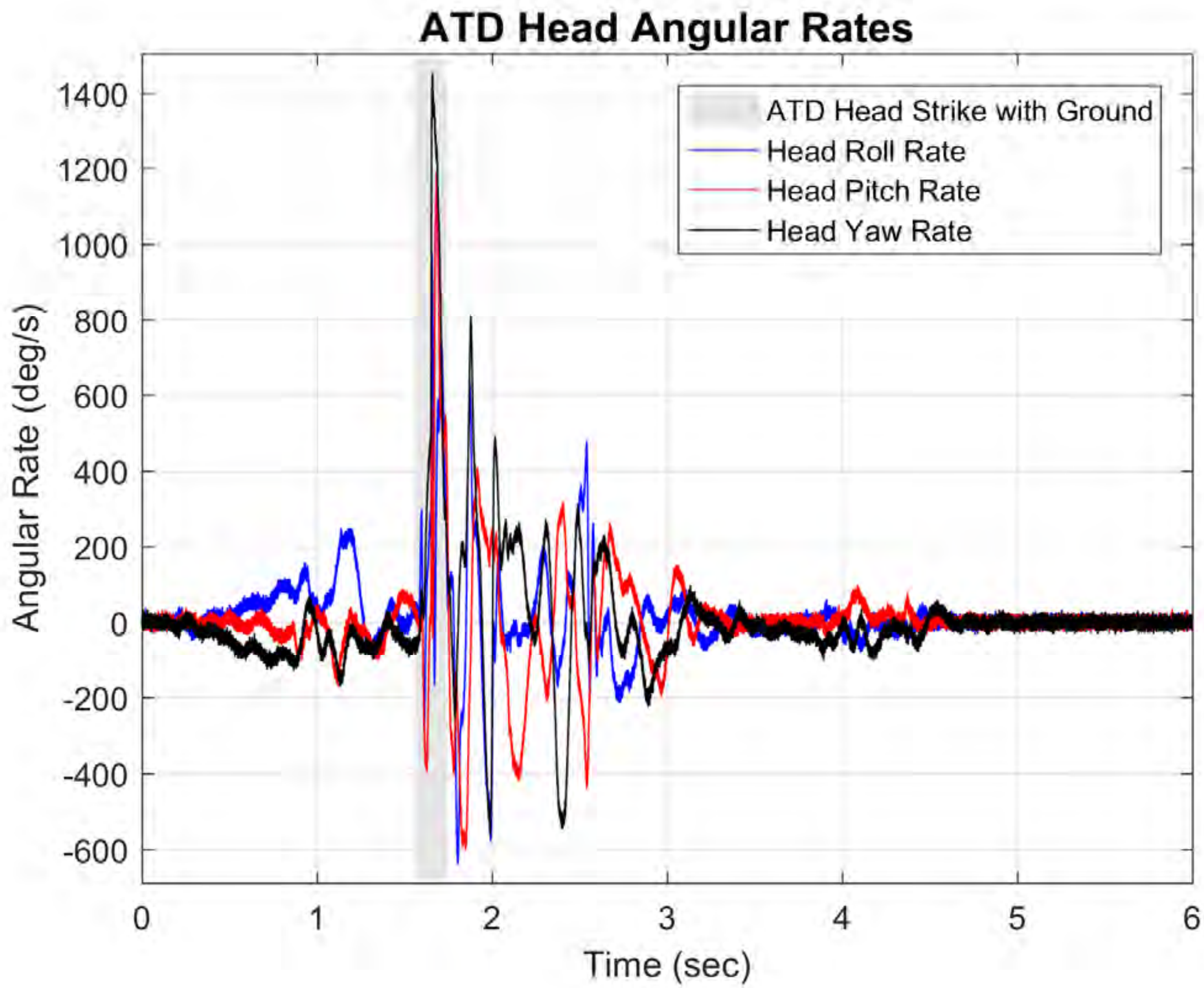
Vehicle A - Dynamic Moderate Energy Rollover with Trip Feature

Drone Camera - End of Run - Roll Angle = 267.8°

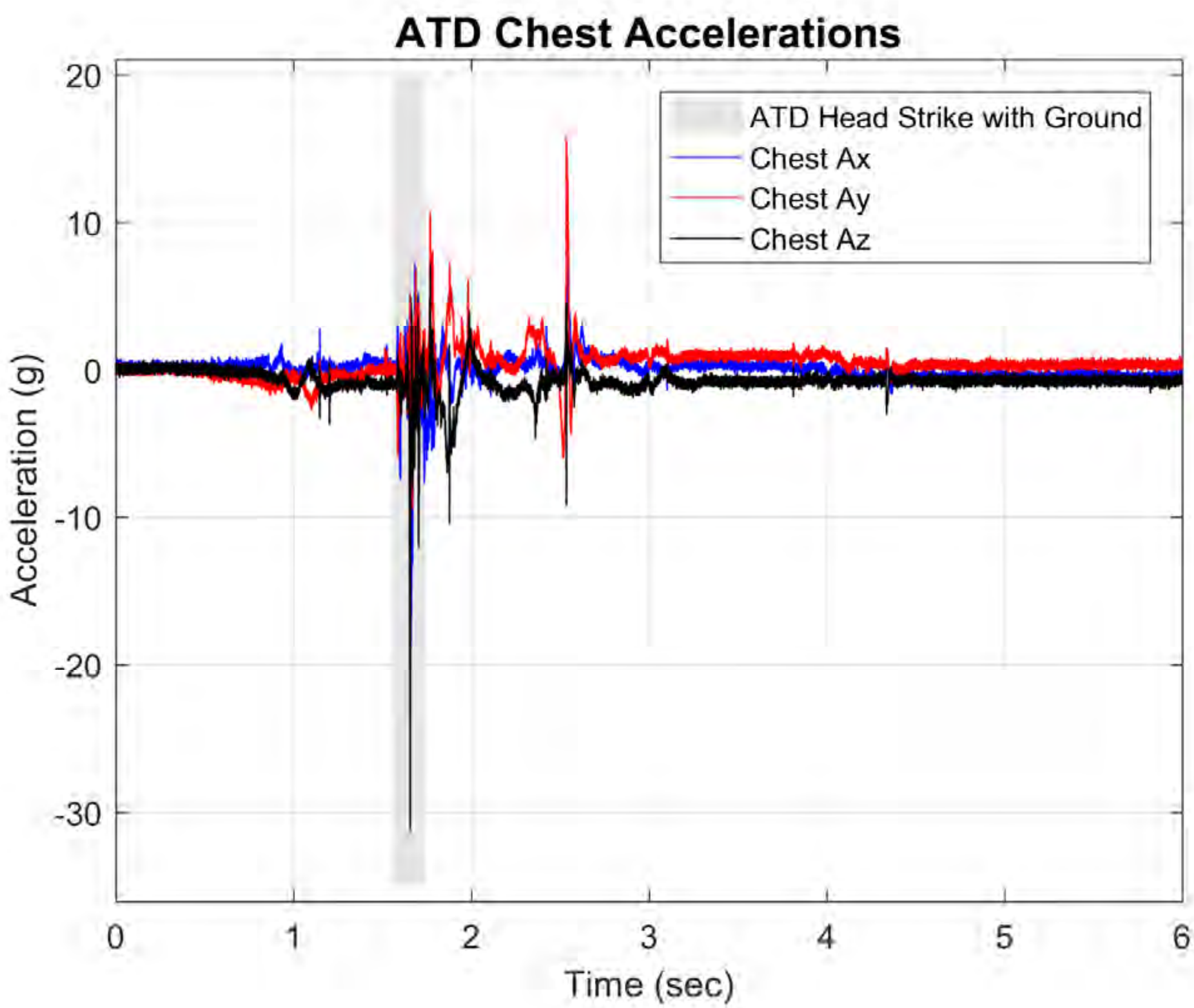
Vehicle A - Dynamic Moderate Energy Rollover with Trip Feature



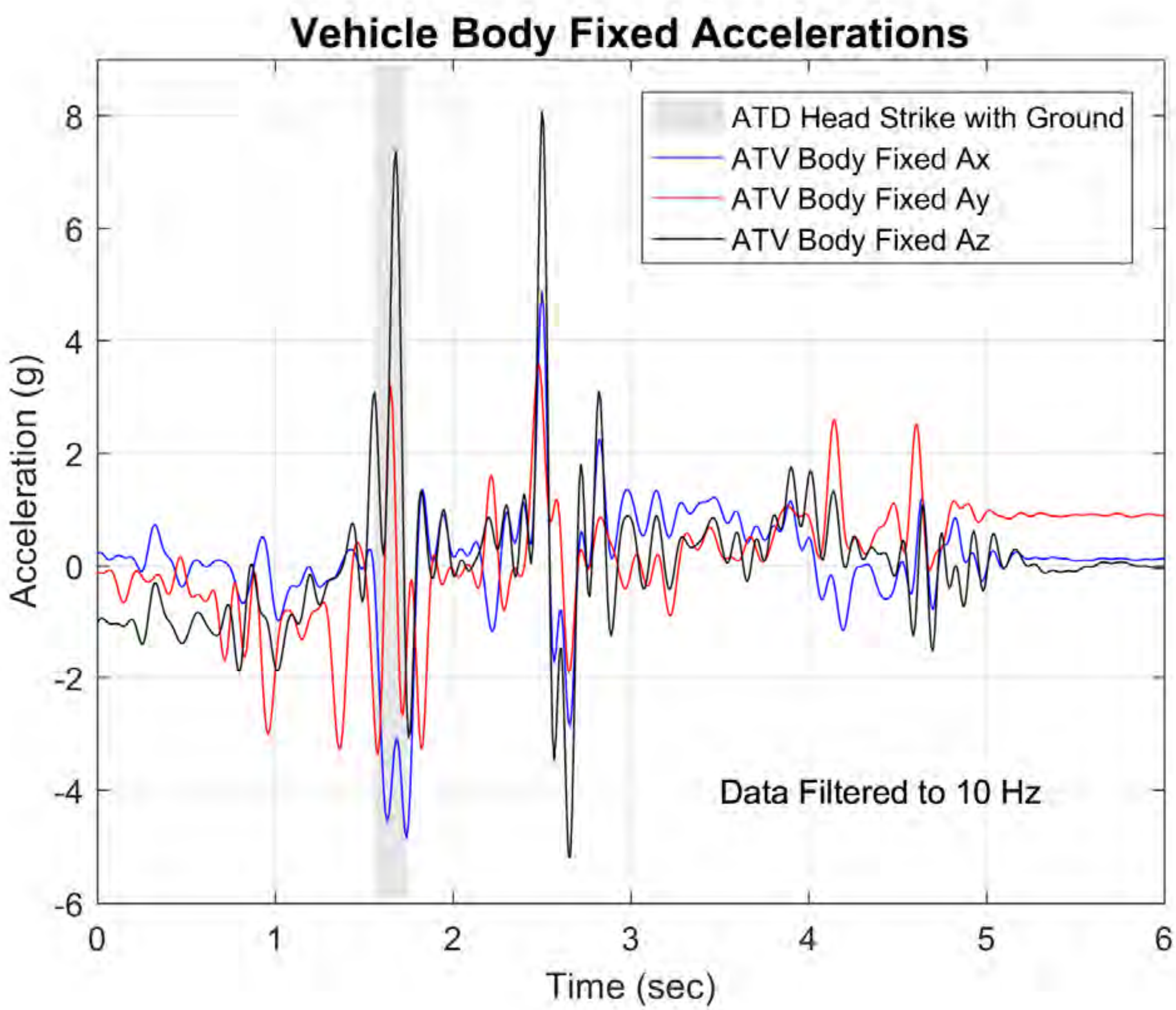
Vehicle A - Dynamic Moderate Energy Rollover with Trip Feature



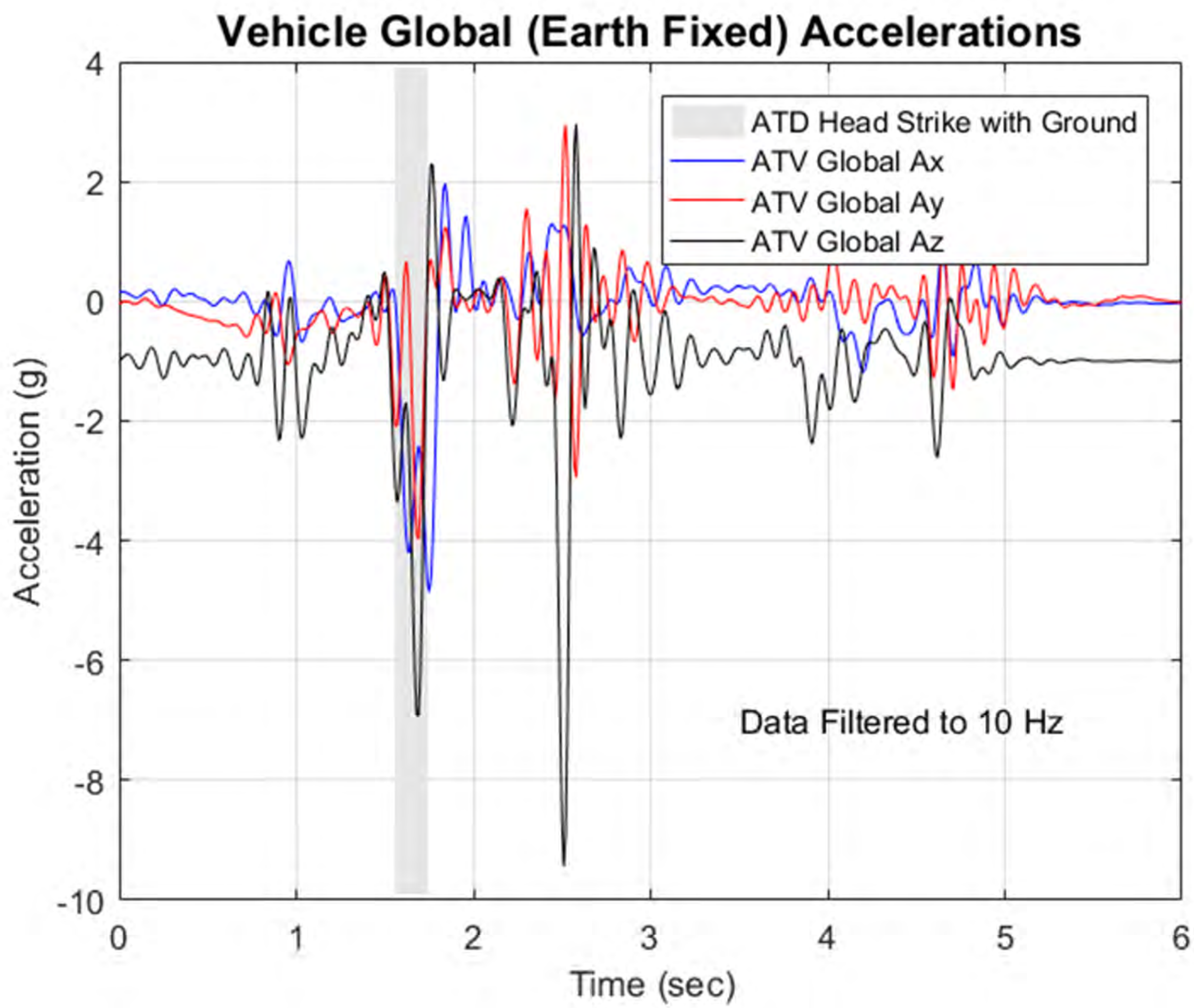
Vehicle A - Dynamic Moderate Energy Rollover with Trip Feature



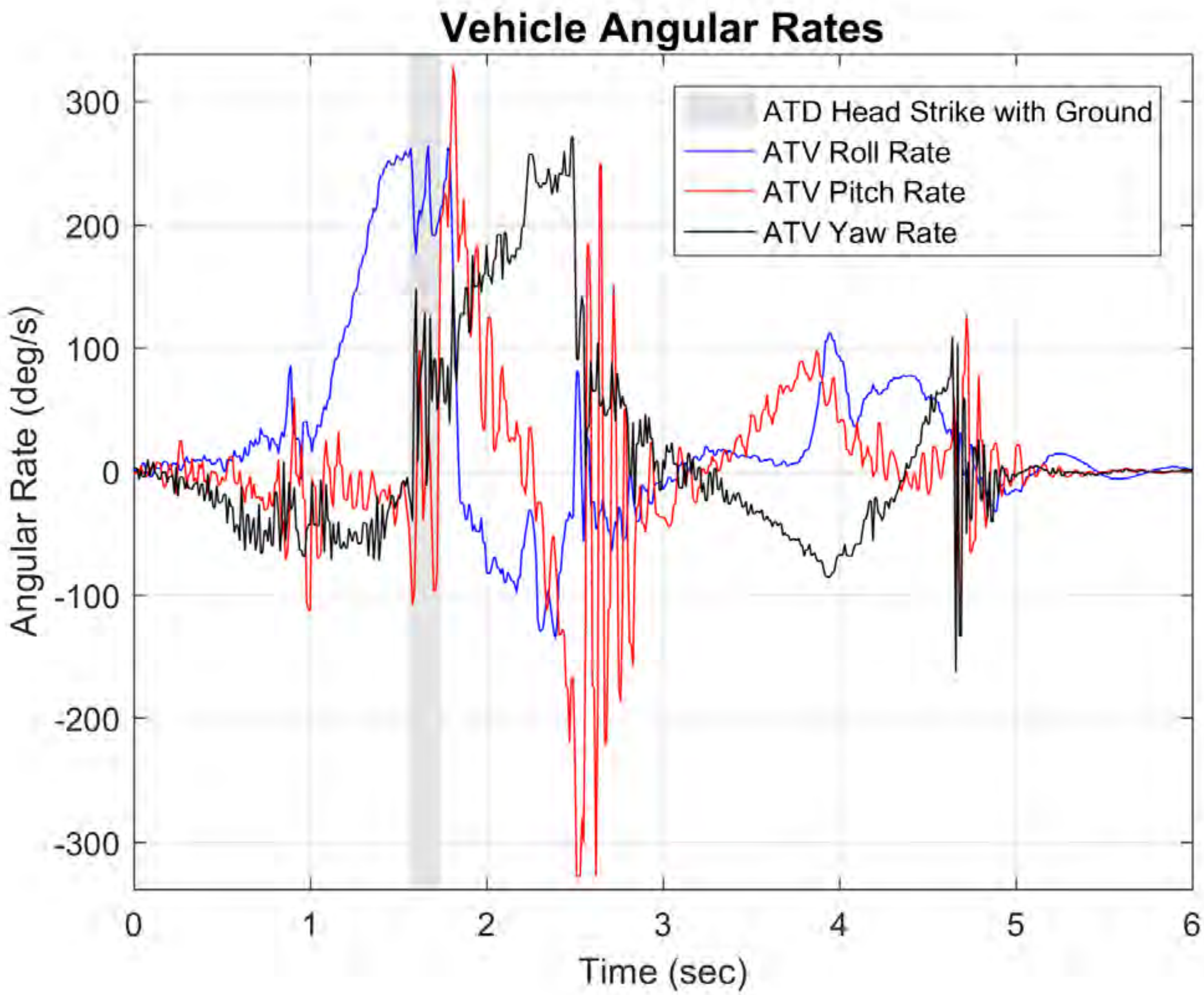
Vehicle A - Dynamic Moderate Energy Rollover with Trip Feature



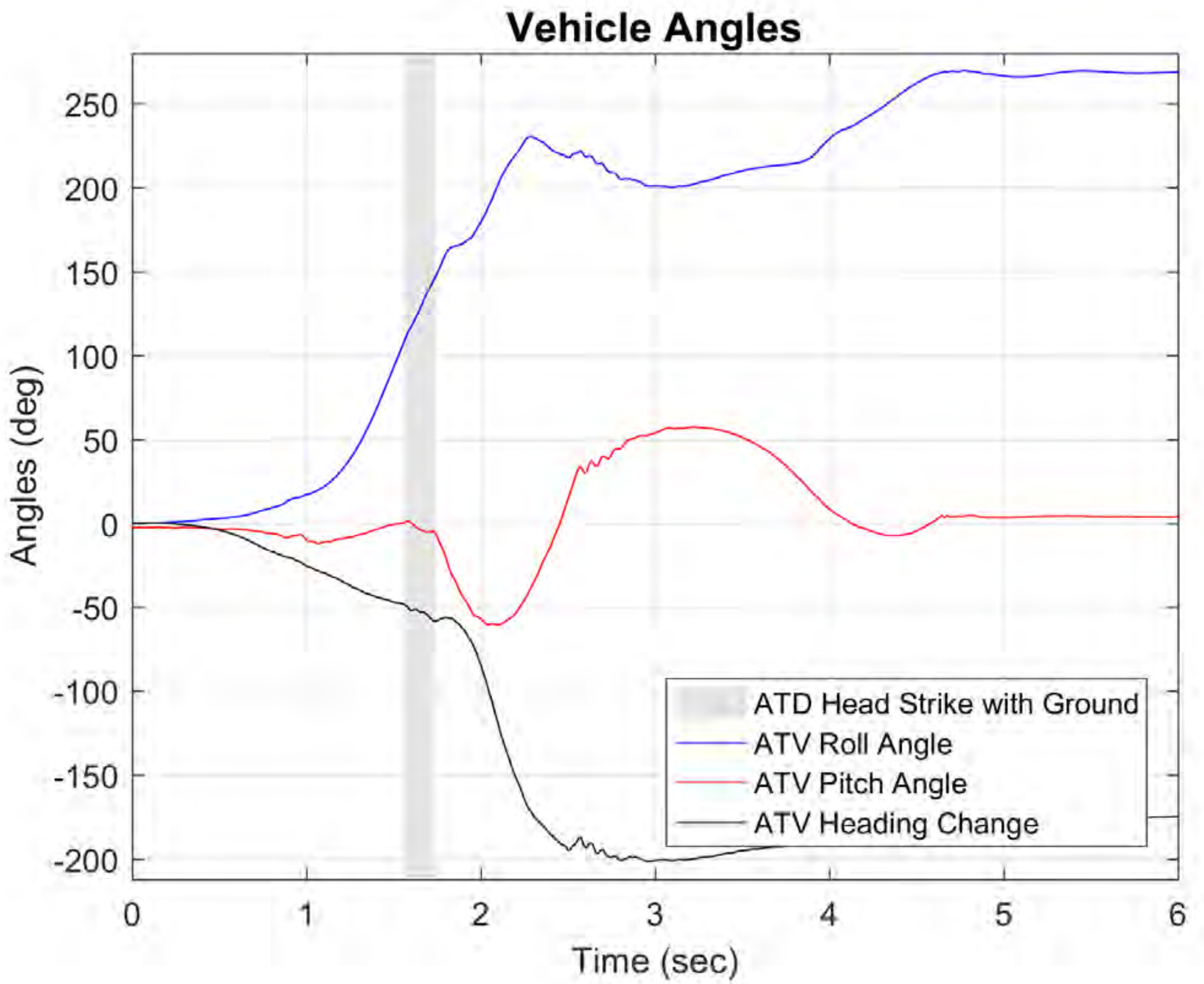
Vehicle A - Dynamic Moderate Energy Rollover with Trip Feature



Vehicle A - Dynamic Moderate Energy Rollover with Trip Feature



Vehicle A - Dynamic Moderate Energy Rollover with Trip Feature



Vehicle A - Dynamic Moderate Energy Rollover with Trip Feature

AOS Camera 1 - Roll Angle = 30° - Time = 2.18 sec

AOS Camera 1 - Roll Angle = 45° - Time = 2.38 sec

AOS Camera 1 - Roll Angle = 90° - Time = 2.72 sec

AOS Camera 2 - Roll Angle = 30° - Time = 2.18 sec

AOS Camera 2 - Roll Angle = 45° - Time = 2.38 sec

AOS Camera 2 - Roll Angle = 90° - Time = 2.72 sec

Vehicle E - Dynamic Minimum Energy Rollover

AOS Camera 1 - ATD Head Strike - Time = 2.84 sec

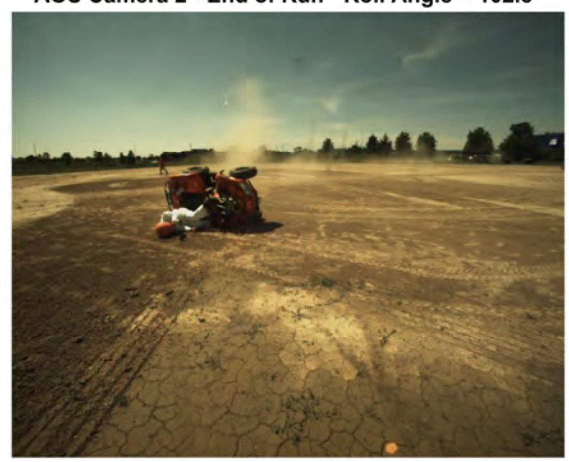
AOS Camera 1 - Max Angle = 148.3° - Time = 3.44 sec

AOS Camera 1 - End of Run - Roll Angle = 102.5°

AOS Camera 2 - ATD Head Strike - Time = 2.84 sec

AOS Camera 2 - Max Angle = 148.3° - Time = 3.44 sec

AOS Camera 2 - End of Run - Roll Angle = 102.5°



Vehicle E - Dynamic Minimum Energy Rollover

RT Camera 1 - Roll Angle = 30° - Time = 2.18 sec

RT Camera 1 - Roll Angle = 45° - Time = 2.38 sec

RT Camera 1 - Roll Angle = 90° - Time = 2.72 sec

RT Camera 2 - Roll Angle = 30° - Time = 2.18 sec

RT Camera 2 - Roll Angle = 45° - Time = 2.38 sec

RT Camera 2 - Roll Angle = 90° - Time = 2.72 sec

Vehicle E - Dynamic Minimum Energy Rollover

RT Camera 1 - ATD Head Strike - Time = 2.84 sec

RT Camera 1 - Max Angle = 148.3° - Time = 3.44 sec

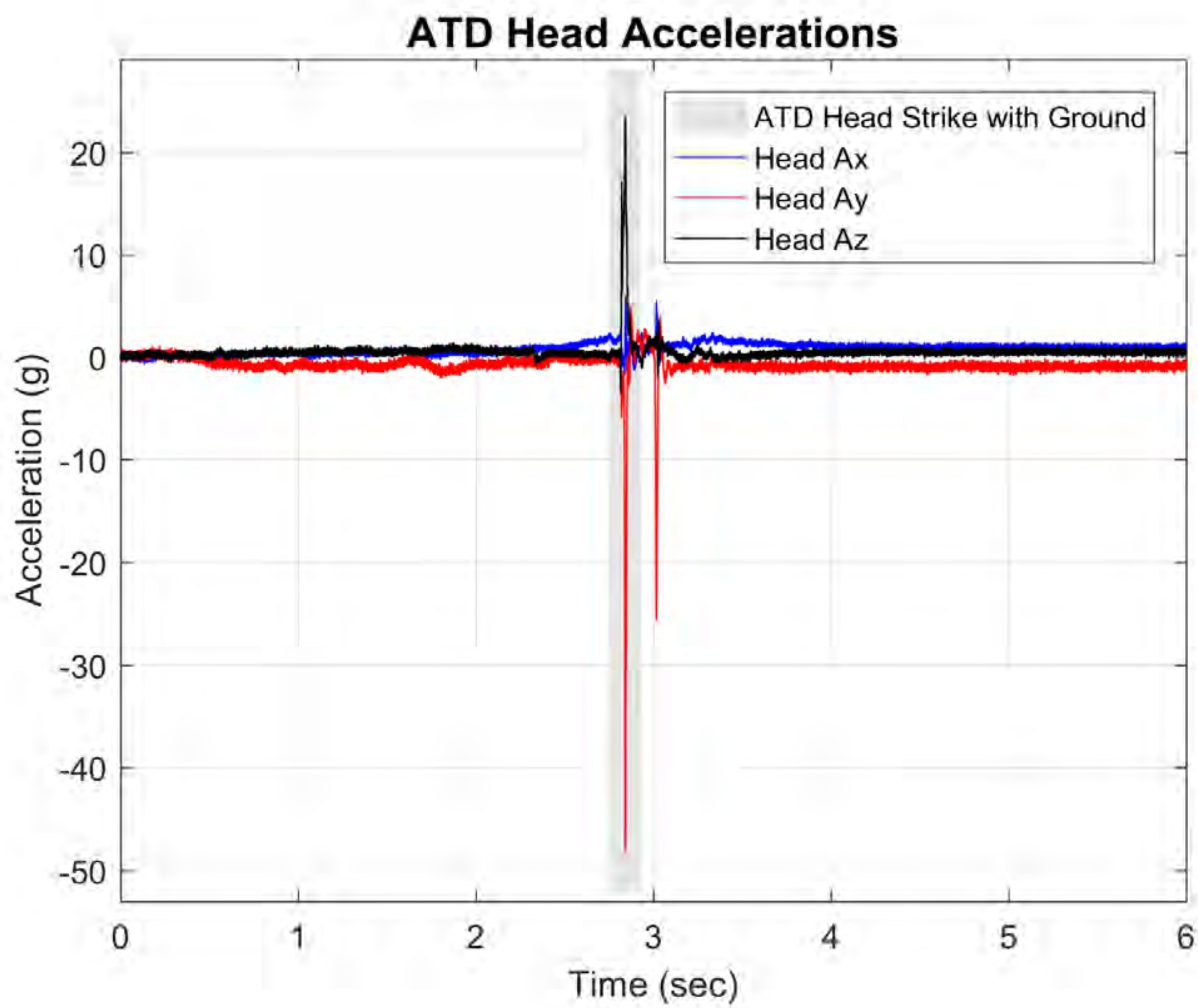
RT Camera 1 - End of Run - Roll Angle = 102.5°

RT Camera 2 - ATD Head Strike - Time = 2.84 sec

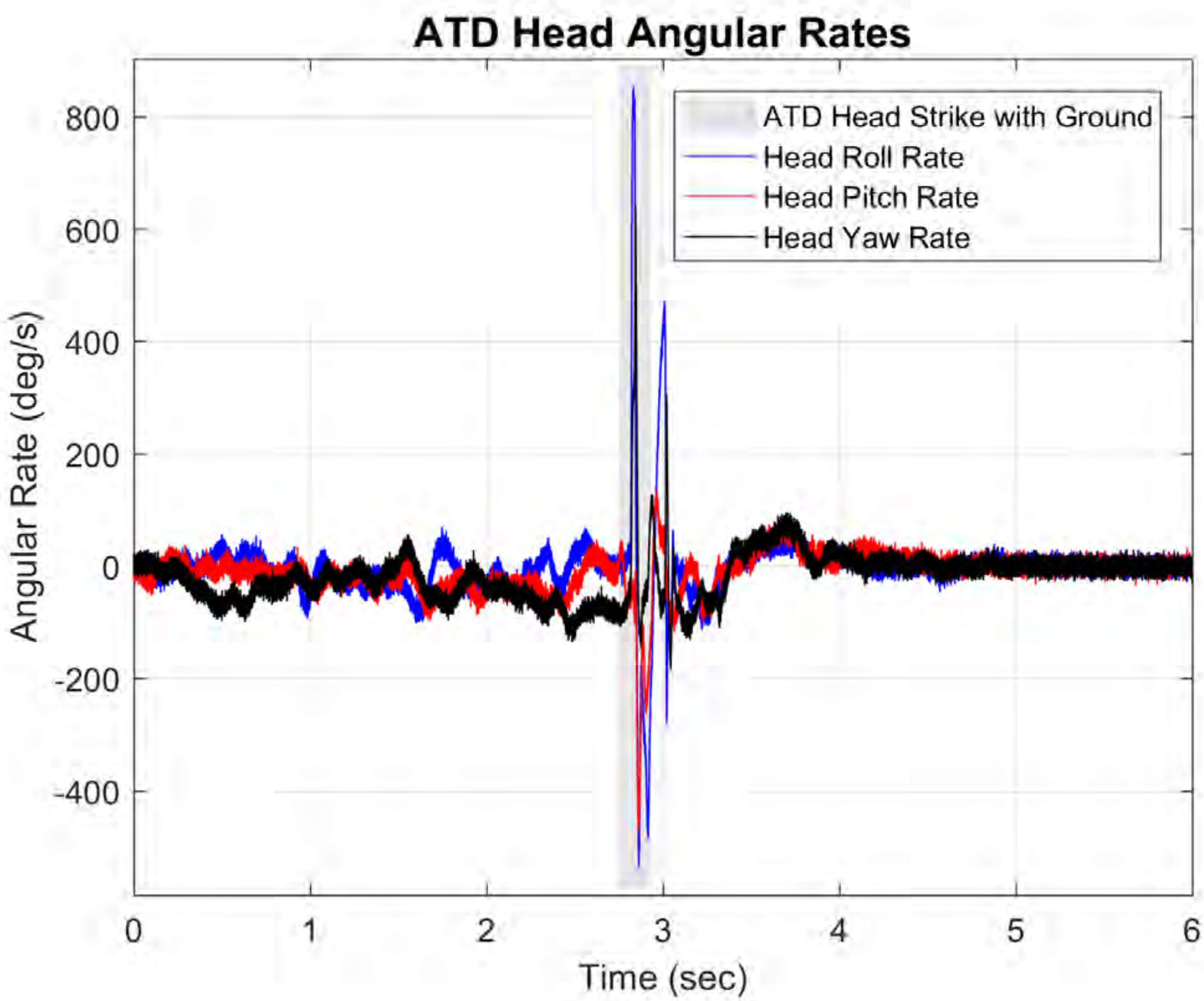
RT Camera 2 - Max Angle = 148.3° - Time = 3.44 sec

RT Camera 2 - End of Run - Roll Angle = 102.5°

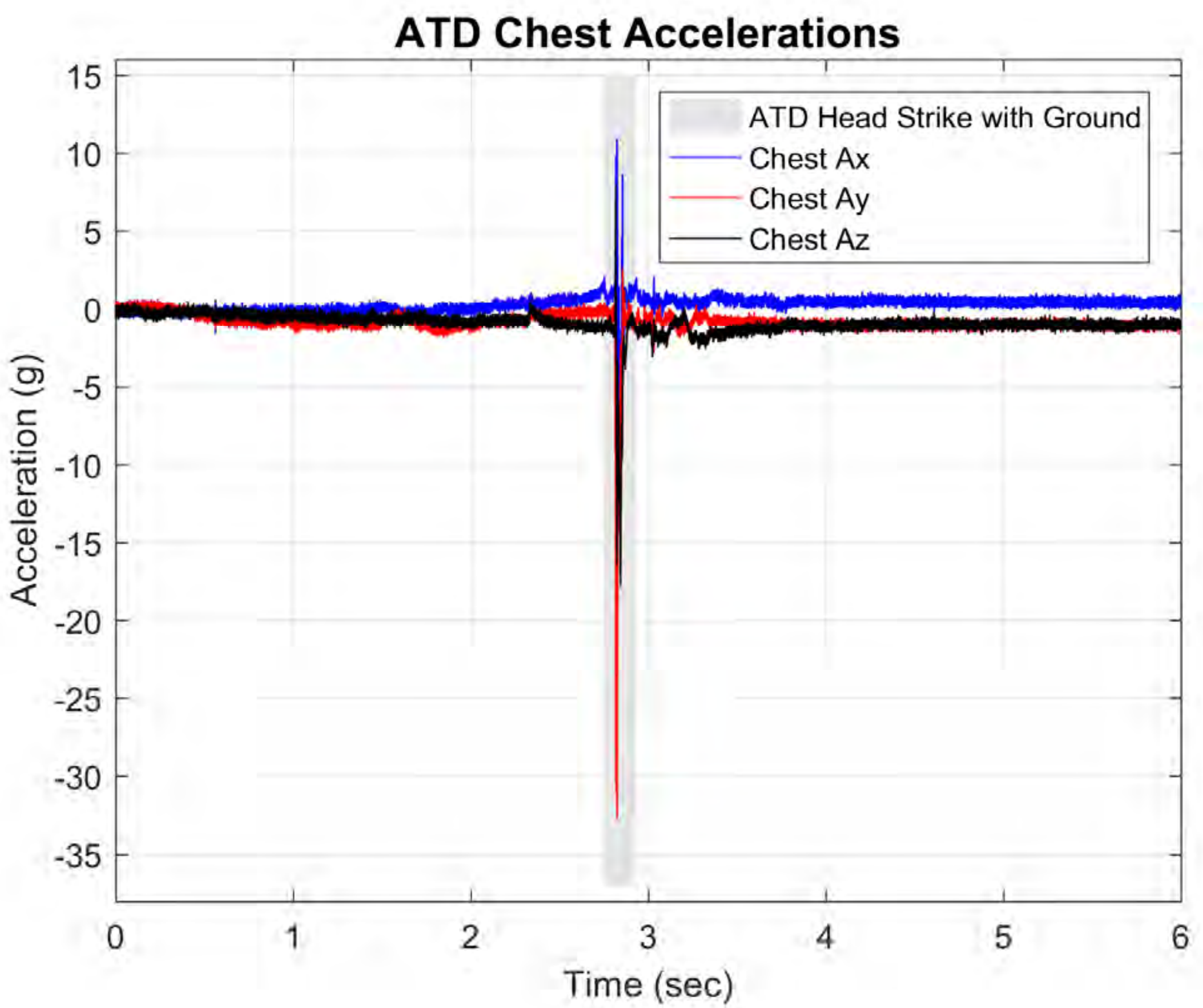
Vehicle E - Dynamic Minimum Energy Rollover



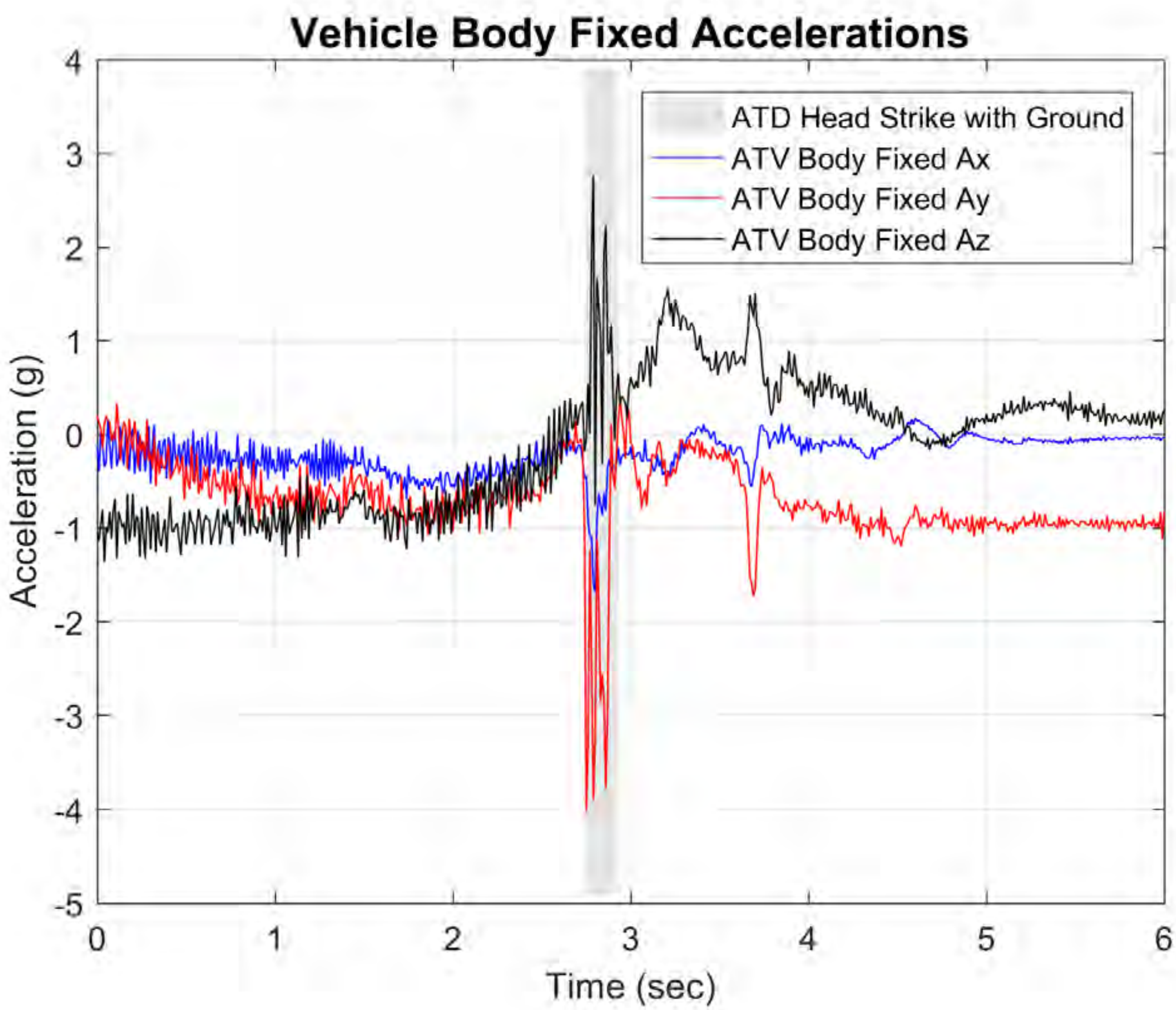
Vehicle E - Dynamic Minimum Energy Rollover



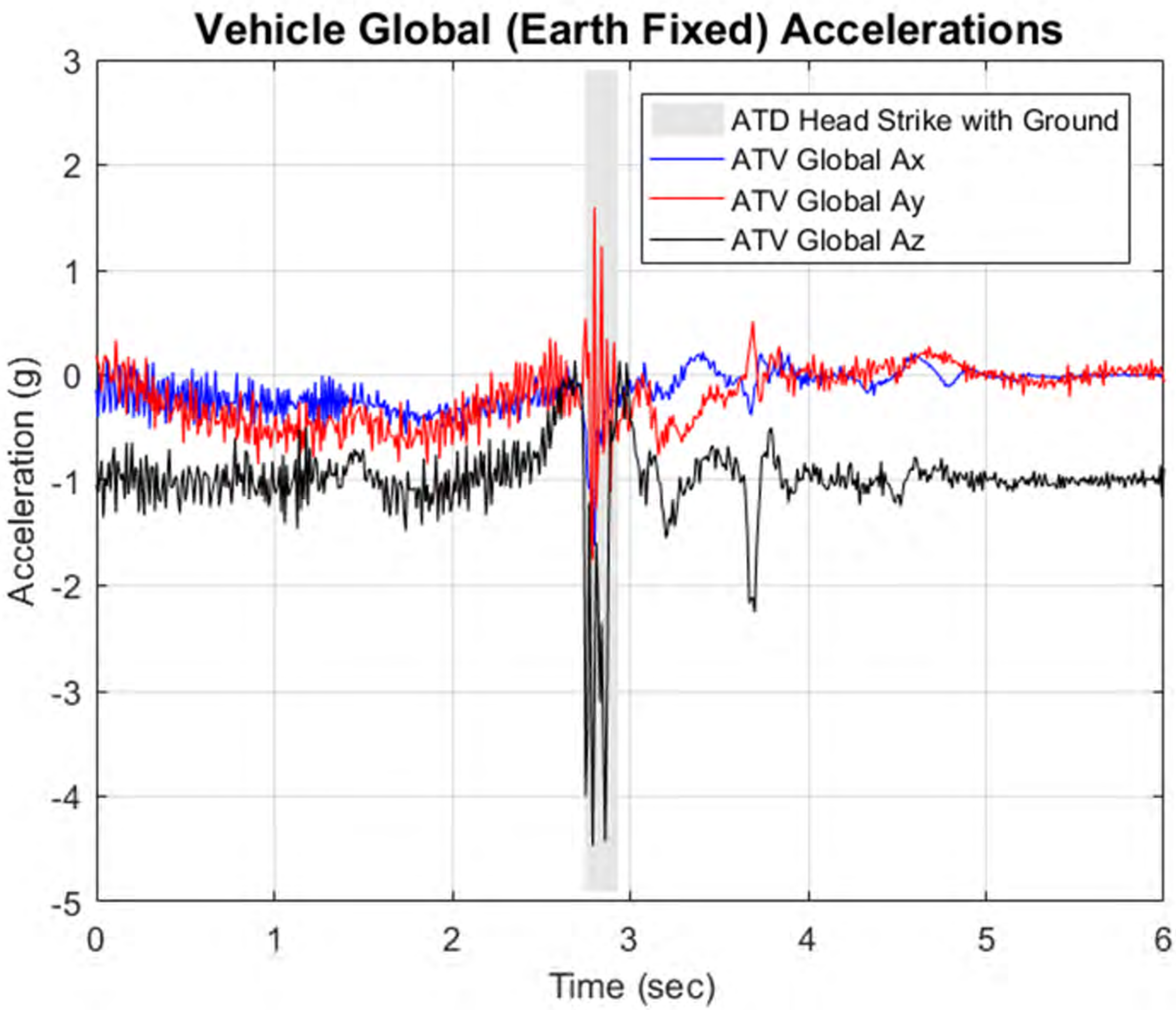
Vehicle E - Dynamic Minimum Energy Rollover



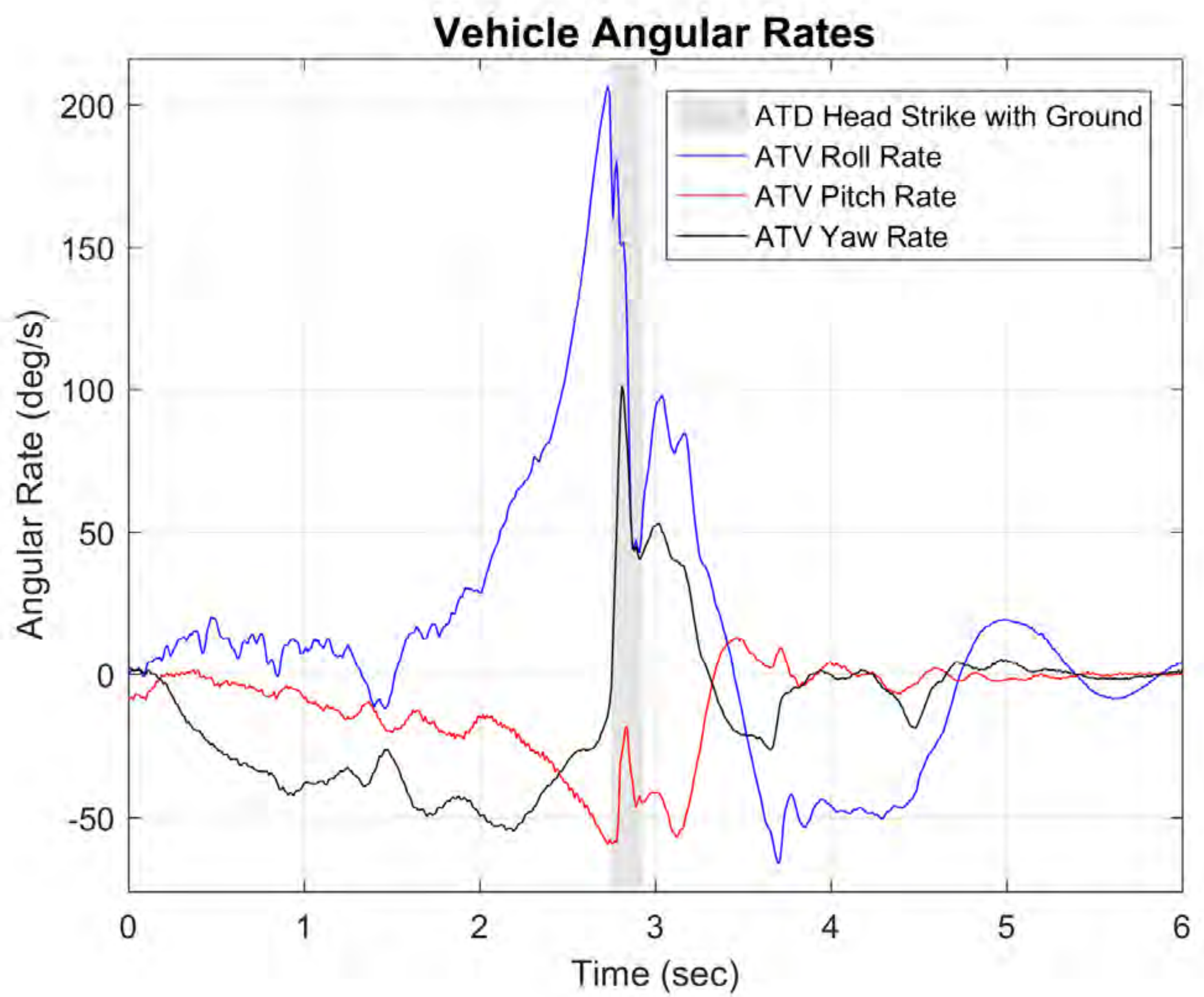
Vehicle E - Dynamic Minimum Energy Rollover



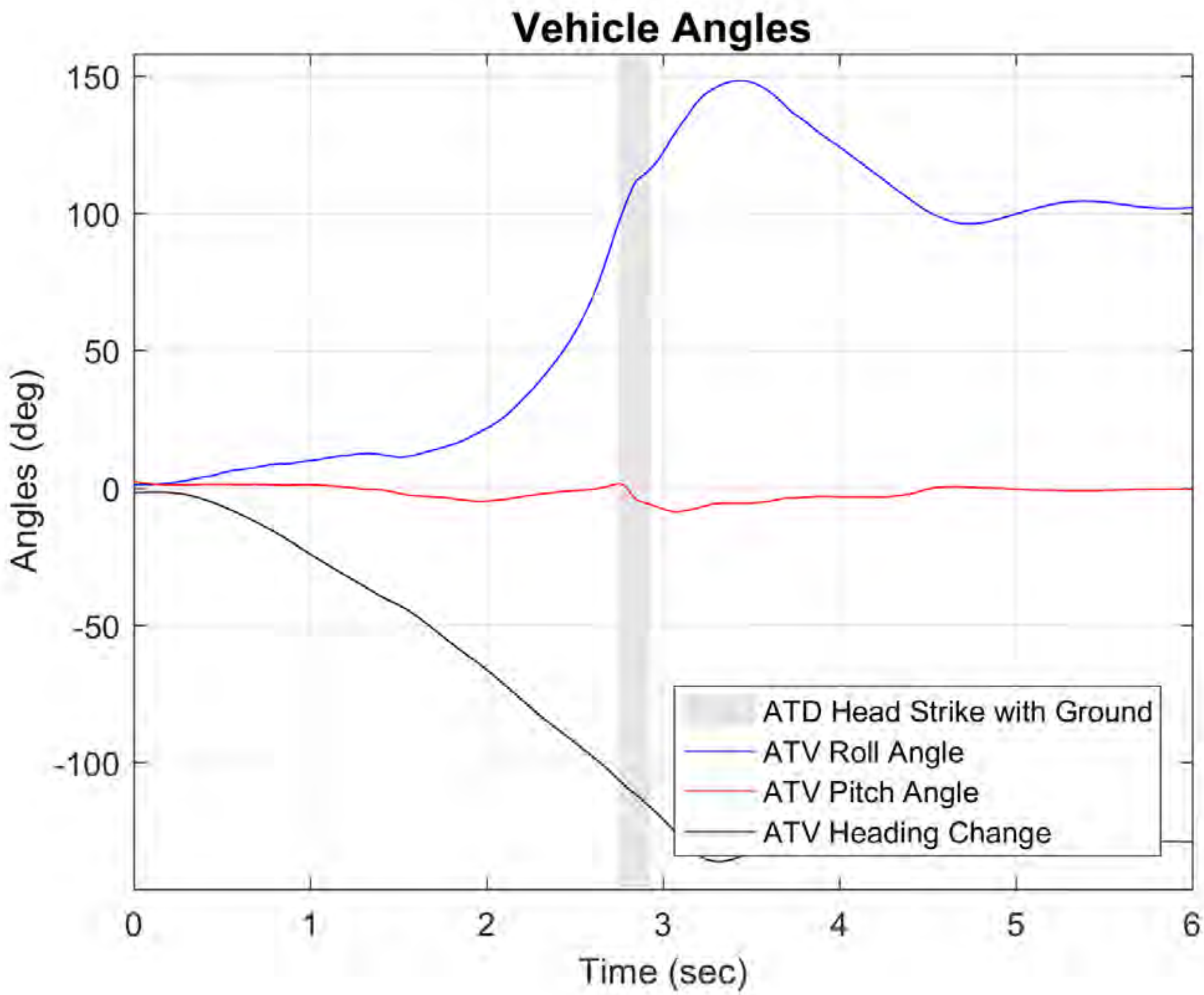
Vehicle E - Dynamic Minimum Energy Rollover



Vehicle E - Dynamic Minimum Energy Rollover



Vehicle E - Dynamic Minimum Energy Rollover



Vehicle E - Dynamic Minimum Energy Rollover

AOS Camera 1 - Roll Angle = 30° - Time = 1.72 sec

AOS Camera 1 - Roll Angle = 45° - Time = 1.82 sec

AOS Camera 1 - Roll Angle = 90° - Time = 2.02 sec

AOS Camera 2 - Roll Angle = 30° - Time = 1.72 sec

AOS Camera 2 - Roll Angle = 45° - Time = 1.82 sec

AOS Camera 2 - Roll Angle = 90° - Time = 2.02 sec

Vehicle E - Dynamic Moderate Energy Rollover

AOS Camera 1 - ATD Head Strike - Time = 2.3 sec

AOS Camera 1 - Roll Angle = 180° - Time = 2.36 sec

AOS Camera 1 - Roll Angle = 270° - Time = 2.76 sec

AOS Camera 2 - ATD Head Strike - Time = 2.3 sec

AOS Camera 2 - Roll Angle = 180° - Time = 2.36 sec

AOS Camera 2 - Roll Angle = 270° - Time = 2.76 sec

Vehicle E - Dynamic Moderate Energy Rollover

AOS Camera 1 - Max Angle = 299.3° - Time = 3.57 sec

AOS Camera 1 - End of Run - Roll Angle = 266.1°

AOS Camera 2 - Max Angle = 299.3° - Time = 3.57 sec

AOS Camera 2 - End of Run - Roll Angle = 266.1°

Vehicle E - Dynamic Moderate Energy Rollover

RT Camera 1 - Roll Angle = 30° - Time = 1.72 sec

RT Camera 1 - Roll Angle = 45° - Time = 1.82 sec

RT Camera 1 - Roll Angle = 90° - Time = 2.02 sec

RT Camera 2 - Roll Angle = 30° - Time = 1.72 sec

RT Camera 2 - Roll Angle = 45° - Time = 1.82 sec

RT Camera 2 - Roll Angle = 90° - Time = 2.02 sec

Vehicle E - Dynamic Moderate Energy Rollover

RT Camera 1 - ATD Head Strike - Time = 2.3 sec

RT Camera 1 - Roll Angle = 180° - Time = 2.36 sec

RT Camera 1 - Roll Angle = 270° - Time = 2.76 sec

RT Camera 2 - ATD Head Strike - Time = 2.3 sec

RT Camera 2 - Roll Angle = 180° - Time = 2.36 sec

RT Camera 2 - Roll Angle = 270° - Time = 2.76 sec

Vehicle E - Dynamic Moderate Energy Rollover

RT Camera 1 - Max Angle = 299.3° - Time = 3.57 sec

RT Camera 1 - End of Run - Roll Angle = 266.1°

RT Camera 2 - Max Angle = 299.3° - Time = 3.57 sec

RT Camera 2 - End of Run - Roll Angle = 266.1°

Vehicle E - Dynamic Moderate Energy Rollover

Drone Camera - Roll Angle = 30° - Time = 1.72 sec

Drone Camera - Roll Angle = 45° - Time = 1.82 sec

Drone Camera - Roll Angle = 90° - Time = 2.02 sec

Drone Camera - ATD Head Strike - Time = 2.3 sec

Drone Camera - Roll Angle = 180° - Time = 2.36 sec

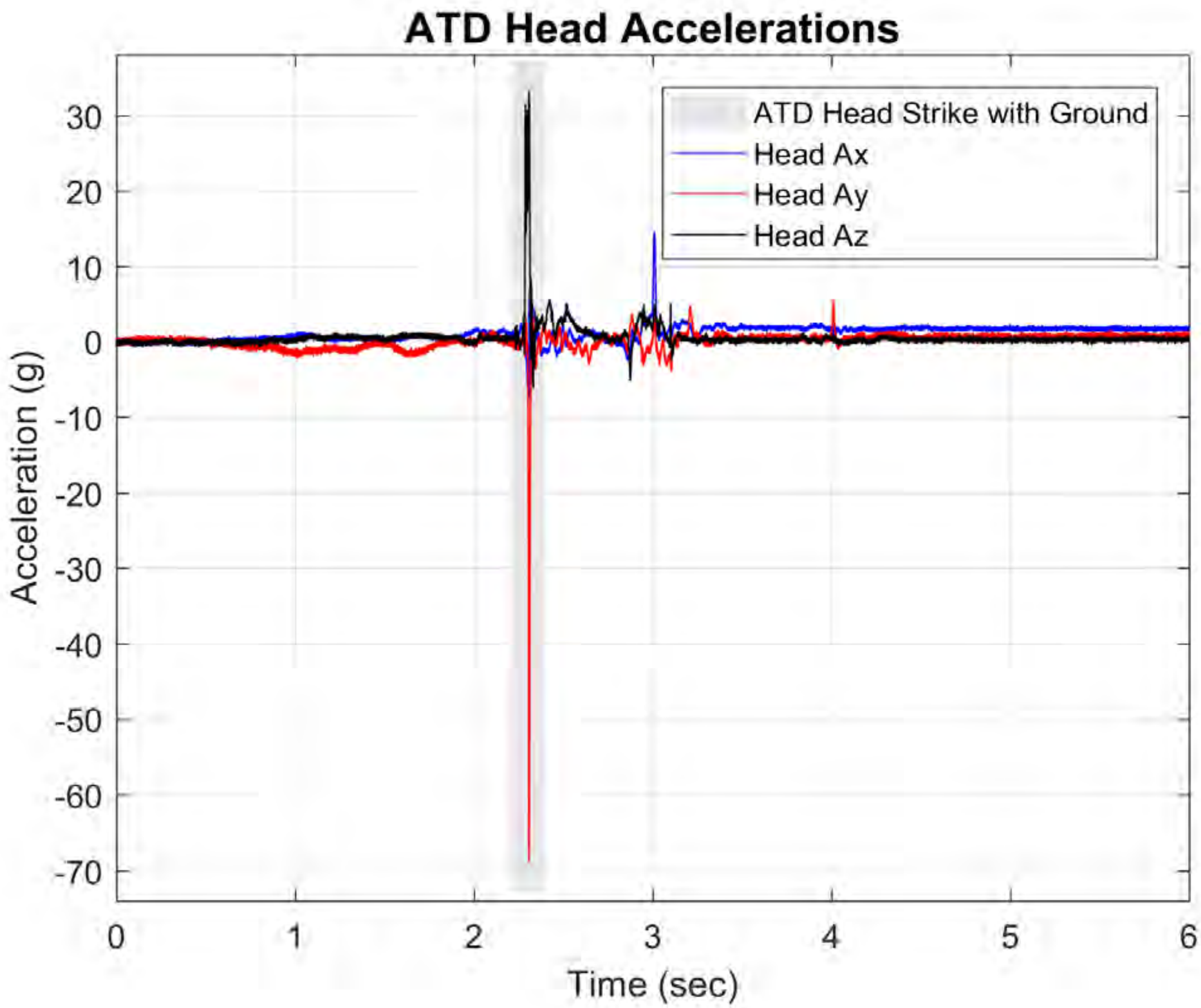
Drone Camera - Roll Angle = 270° - Time = 2.76 sec

Vehicle E - Dynamic Moderate Energy Rollover

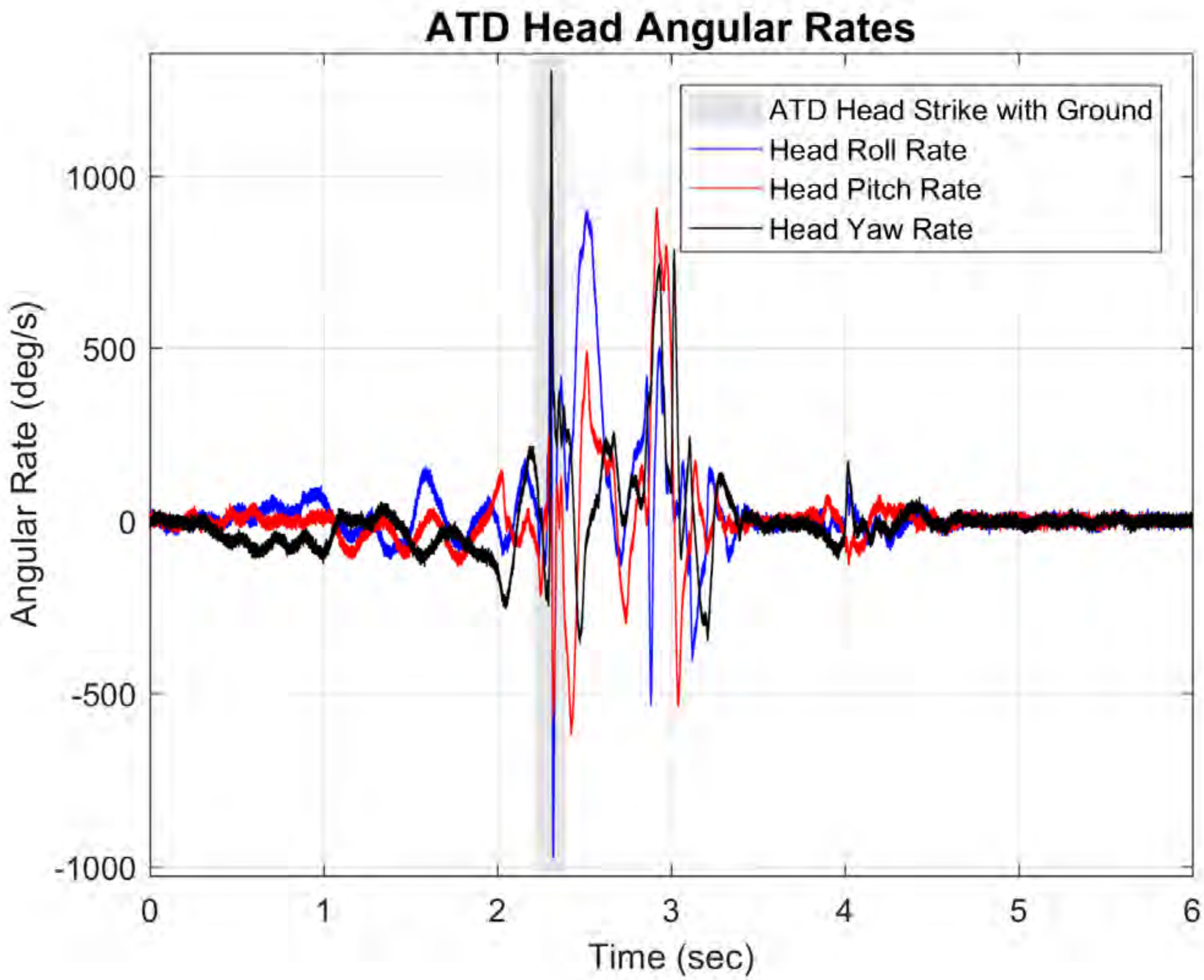
Drone Camera - Max Angle = 299.3° - Time = 3.57 sec

Drone Camera - End of Run - Roll Angle = 266.1°

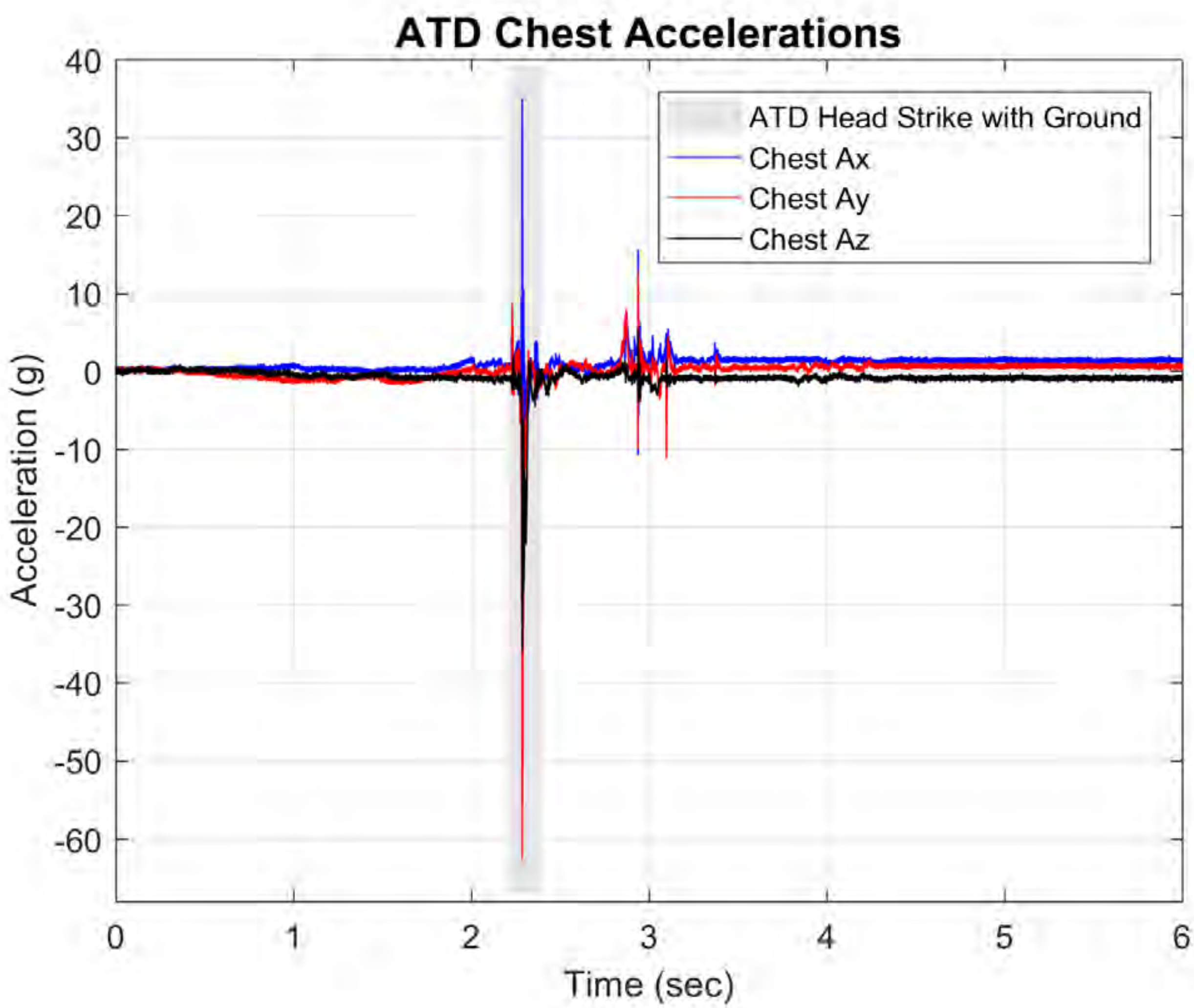
Vehicle E - Dynamic Moderate Energy Rollover



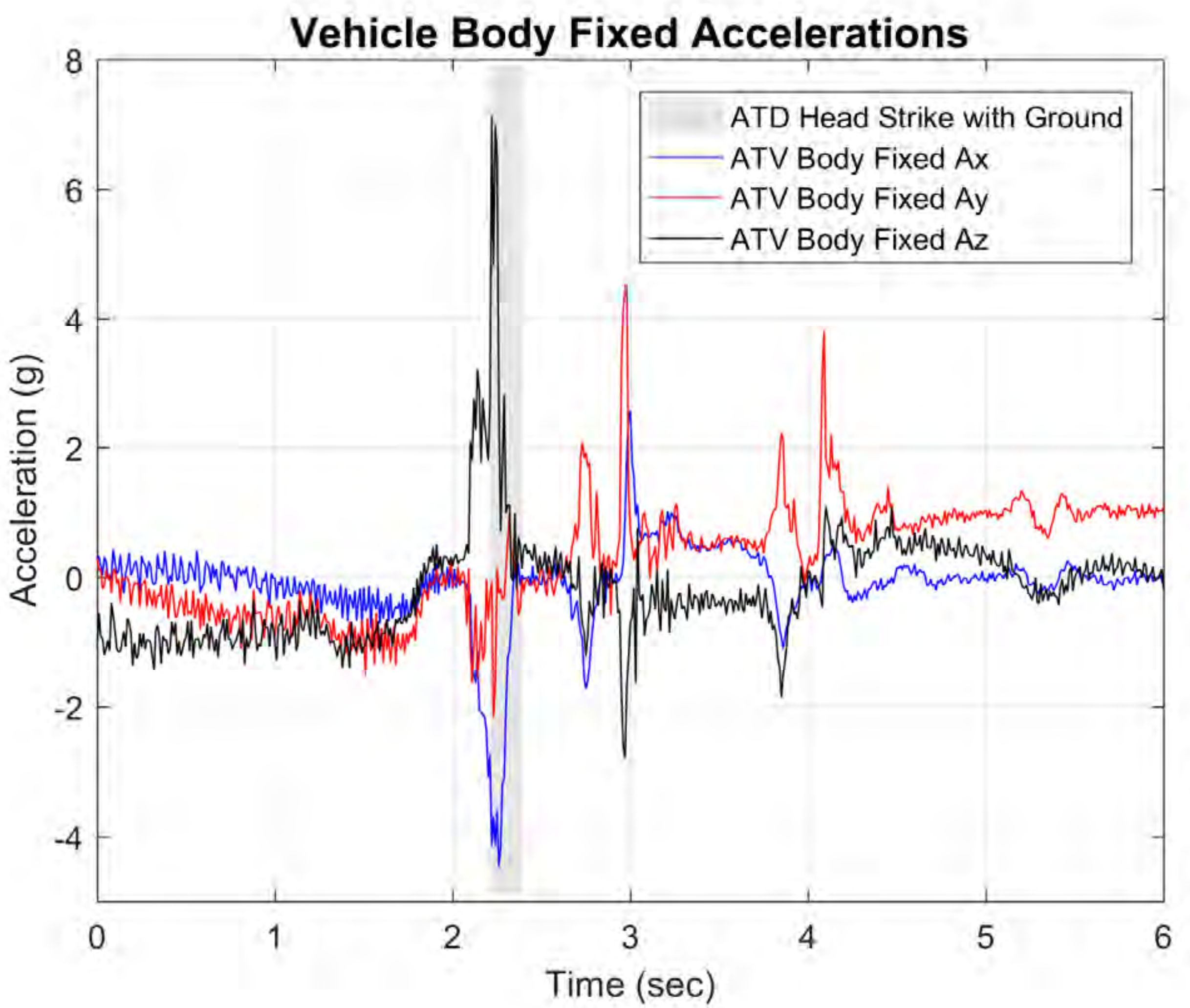
Vehicle E - Dynamic Moderate Energy Rollover



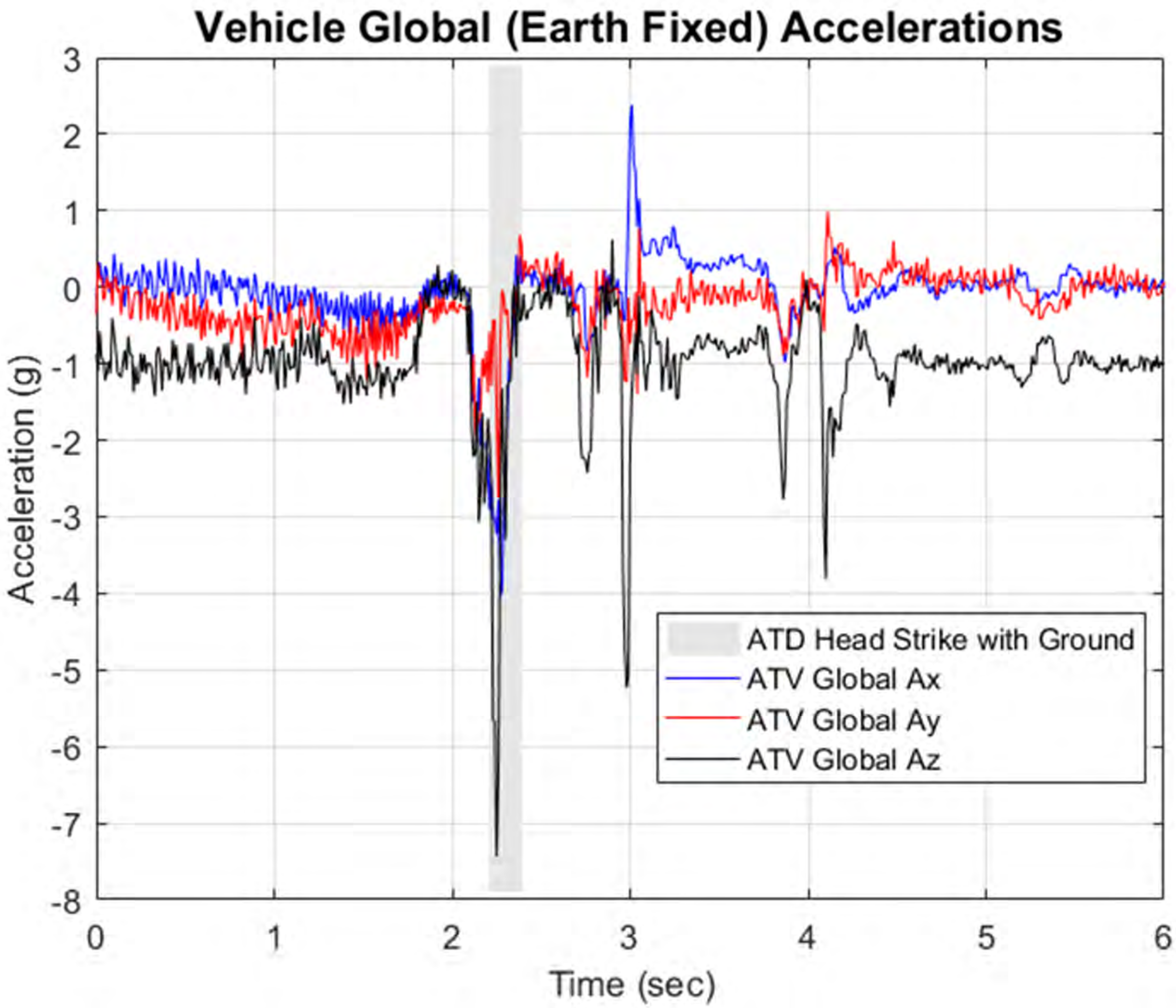
Vehicle E - Dynamic Moderate Energy Rollover



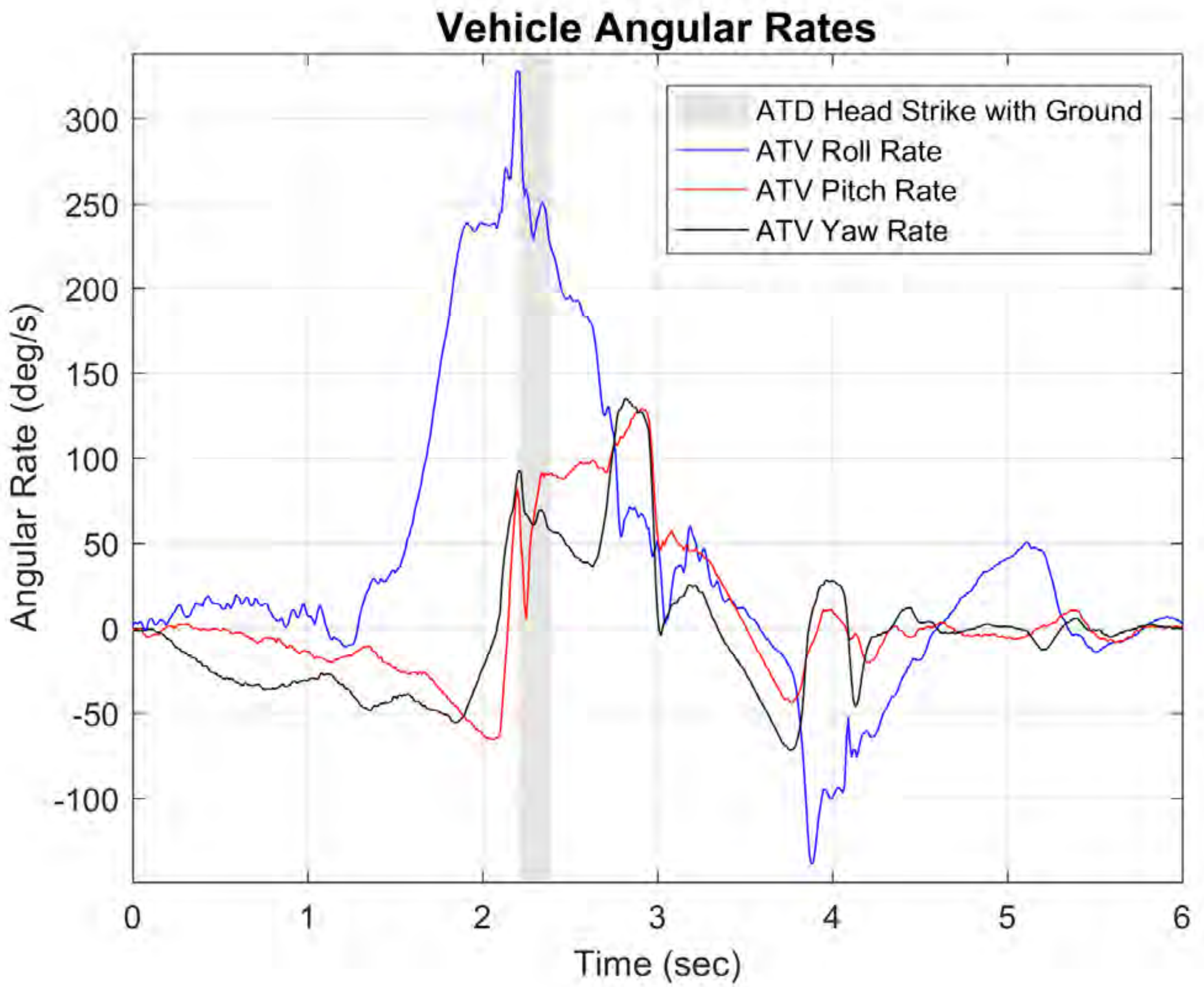
Vehicle E - Dynamic Moderate Energy Rollover



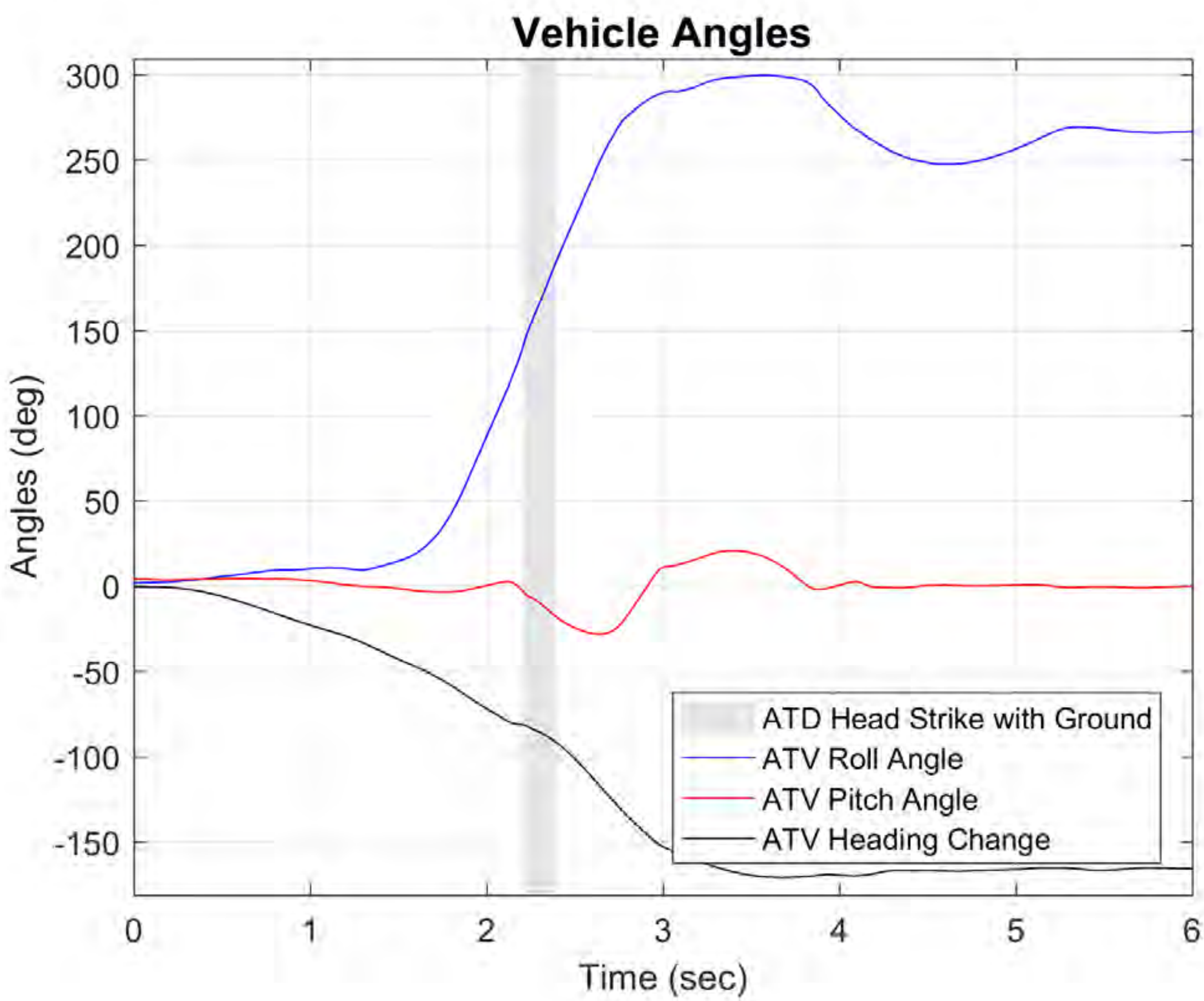
Vehicle E - Dynamic Moderate Energy Rollover



Vehicle E - Dynamic Moderate Energy Rollover



Vehicle E - Dynamic Moderate Energy Rollover



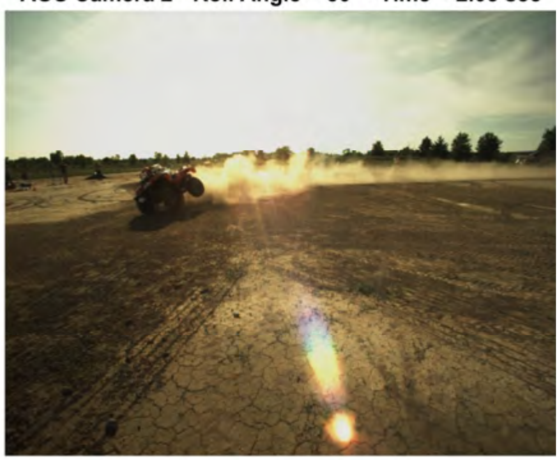
Vehicle E - Dynamic Moderate Energy Rollover

AOS Camera 1 - Roll Angle = 30° - Time = 2.05 sec

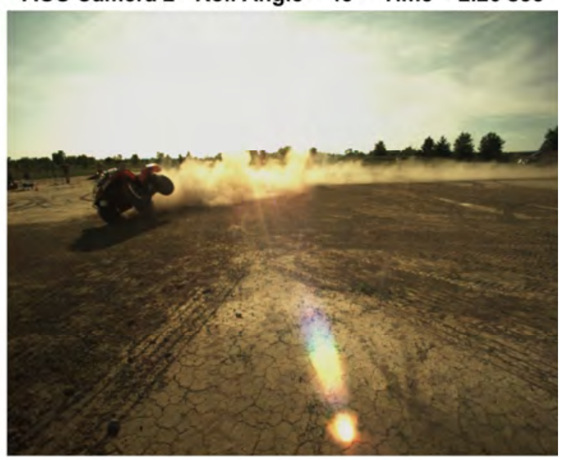
AOS Camera 1 - Roll Angle = 45° - Time = 2.26 sec

AOS Camera 1 - Roll Angle = 90° - Time = 2.54 sec

AOS Camera 2 - Roll Angle = 30° - Time = 2.05 sec



AOS Camera 2 - Roll Angle = 45° - Time = 2.26 sec



AOS Camera 2 - Roll Angle = 90° - Time = 2.54 sec

Vehicle E - Dynamic Moderate Energy Rollover with Trip Feature

AOS Camera 1 - ATD Head Strike - Time = 2.62 sec

AOS Camera 1 - Roll Angle = 180° - Time = 2.97 sec

AOS Camera 1 - Roll Angle = 270° - Time = 3.63 sec

AOS Camera 2 - ATD Head Strike - Time = 2.62 sec

AOS Camera 2 - Roll Angle = 180° - Time = 2.97 sec

AOS Camera 2 - Roll Angle = 270° - Time = 3.63 sec

Vehicle E - Dynamic Moderate Energy Rollover with Trip Feature

AOS Camera 1 - Max Angle = 294.4° - Time = 4.15 sec

AOS Camera 1 - End of Run - Roll Angle = 272.4°

AOS Camera 2 - Max Angle = 294.4° - Time = 4.15 sec

AOS Camera 2 - End of Run - Roll Angle = 272.4°

Vehicle E - Dynamic Moderate Energy Rollover with Trip Feature

RT Camera 1 - Roll Angle = 30° - Time = 2.05 sec

RT Camera 1 - Roll Angle = 45° - Time = 2.26 sec

RT Camera 1 - Roll Angle = 90° - Time = 2.54 sec

RT Camera 2 - Roll Angle = 30° - Time = 2.05 sec

RT Camera 2 - Roll Angle = 45° - Time = 2.26 sec

RT Camera 2 - Roll Angle = 90° - Time = 2.54 sec

Vehicle E - Dynamic Moderate Energy Rollover with Trip Feature

RT Camera 1 - ATD Head Strike - Time = 2.62 sec

RT Camera 1 - Roll Angle = 180° - Time = 2.97 sec

RT Camera 1 - Roll Angle = 270° - Time = 3.63 sec

RT Camera 2 - ATD Head Strike - Time = 2.62 sec

RT Camera 2 - Roll Angle = 180° - Time = 2.97 sec

RT Camera 2 - Roll Angle = 270° - Time = 3.63 sec

Vehicle E - Dynamic Moderate Energy Rollover with Trip Feature

RT Camera 1 - Max Angle = 294.4° - Time = 4.15 sec

RT Camera 1 - End of Run - Roll Angle = 272.4°

RT Camera 2 - Max Angle = 294.4° - Time = 4.15 sec

RT Camera 2 - End of Run - Roll Angle = 272.4°

Vehicle E - Dynamic Moderate Energy Rollover with Trip Feature

Drone Camera - Roll Angle = 30° - Time = 2.05 sec

Drone Camera - Roll Angle = 45° - Time = 2.26 sec

Drone Camera - Roll Angle = 90° - Time = 2.54 sec

Drone Camera - ATD Head Strike - Time = 2.62 sec

Drone Camera - Roll Angle = 180° - Time = 2.97 sec

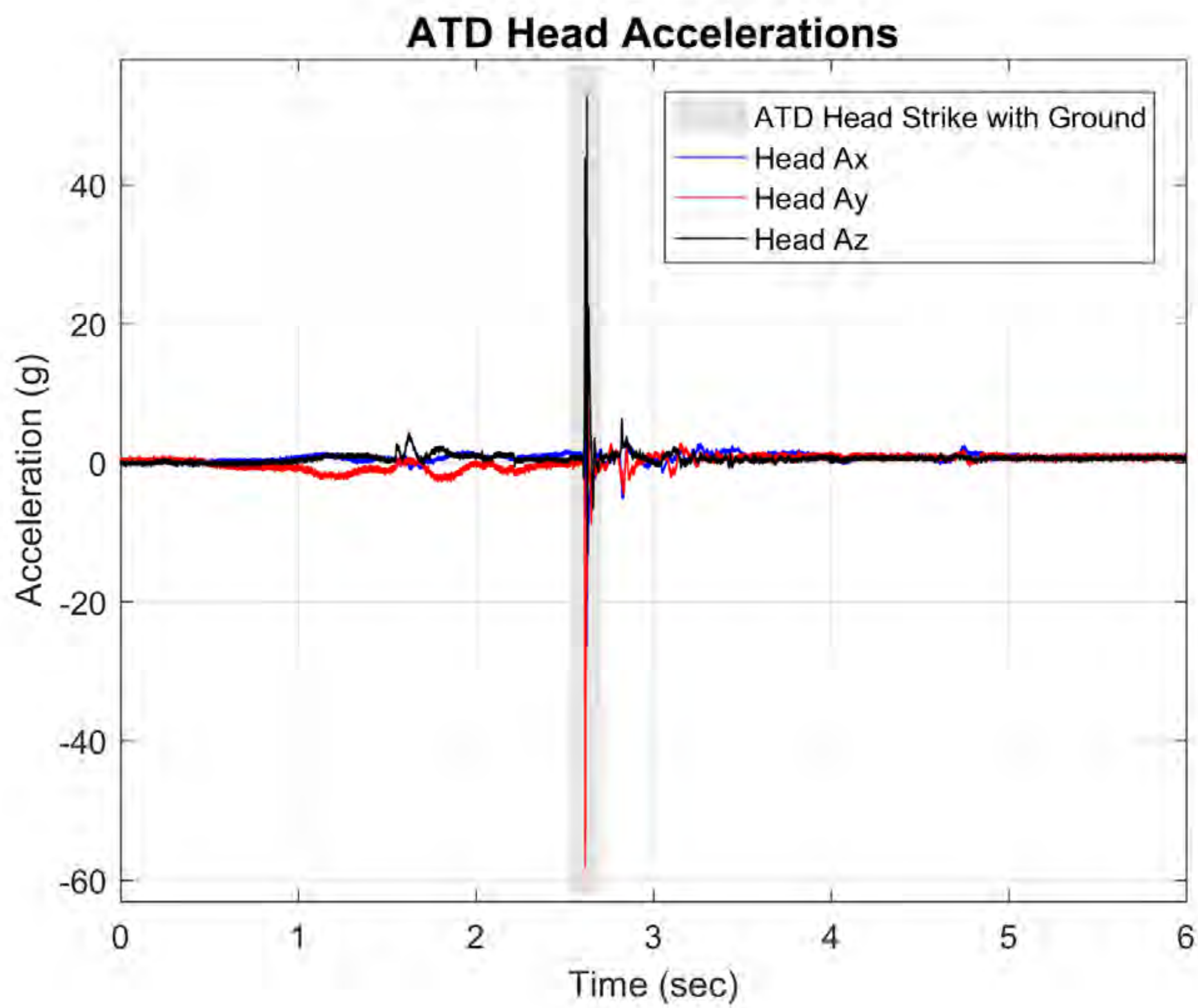
Drone Camera - Roll Angle = 270° - Time = 3.63 sec

Vehicle E - Dynamic Moderate Energy Rollover with Trip Feature

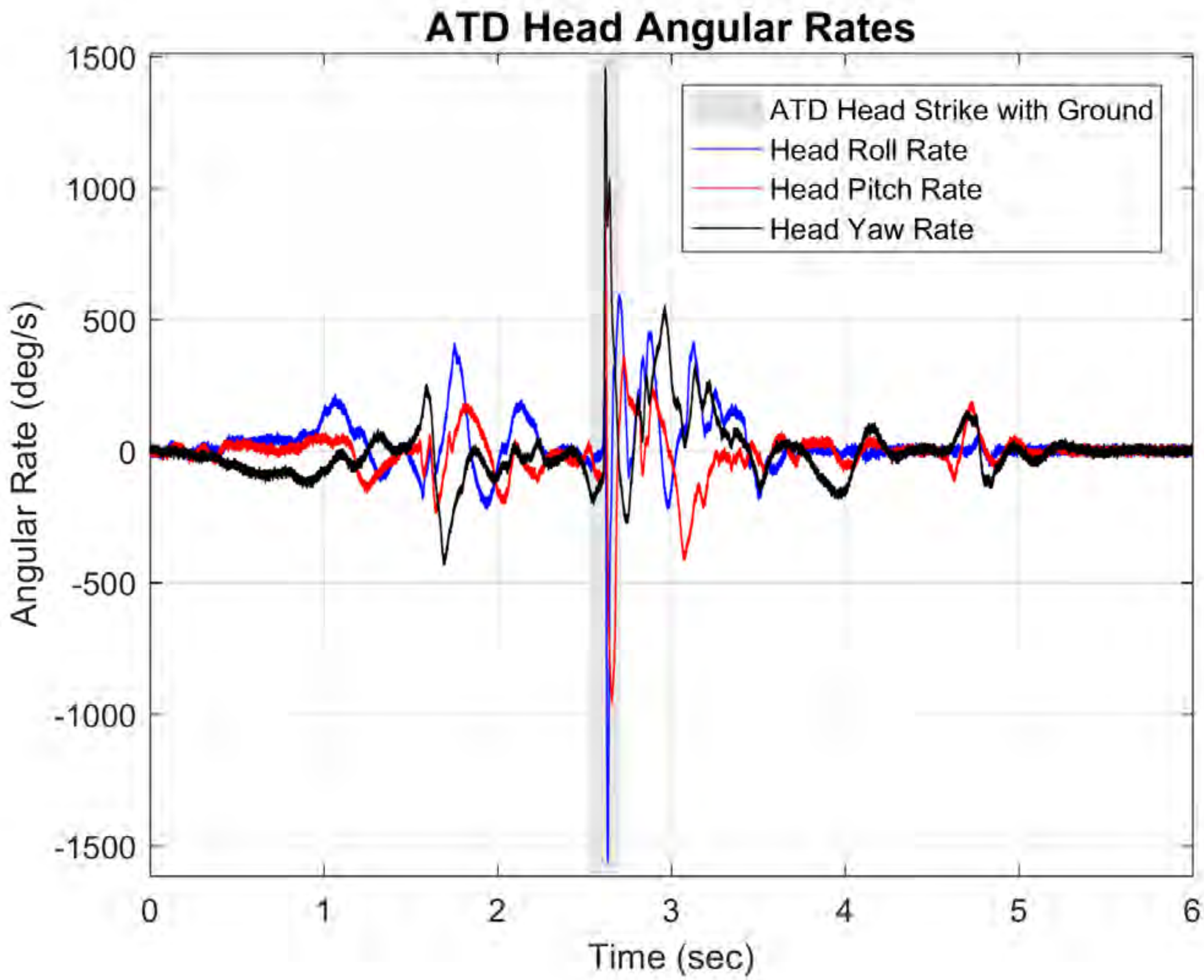
Drone Camera - Max Angle = 294.4° - Time = 4.15 sec

Drone Camera - End of Run - Roll Angle = 272.4°

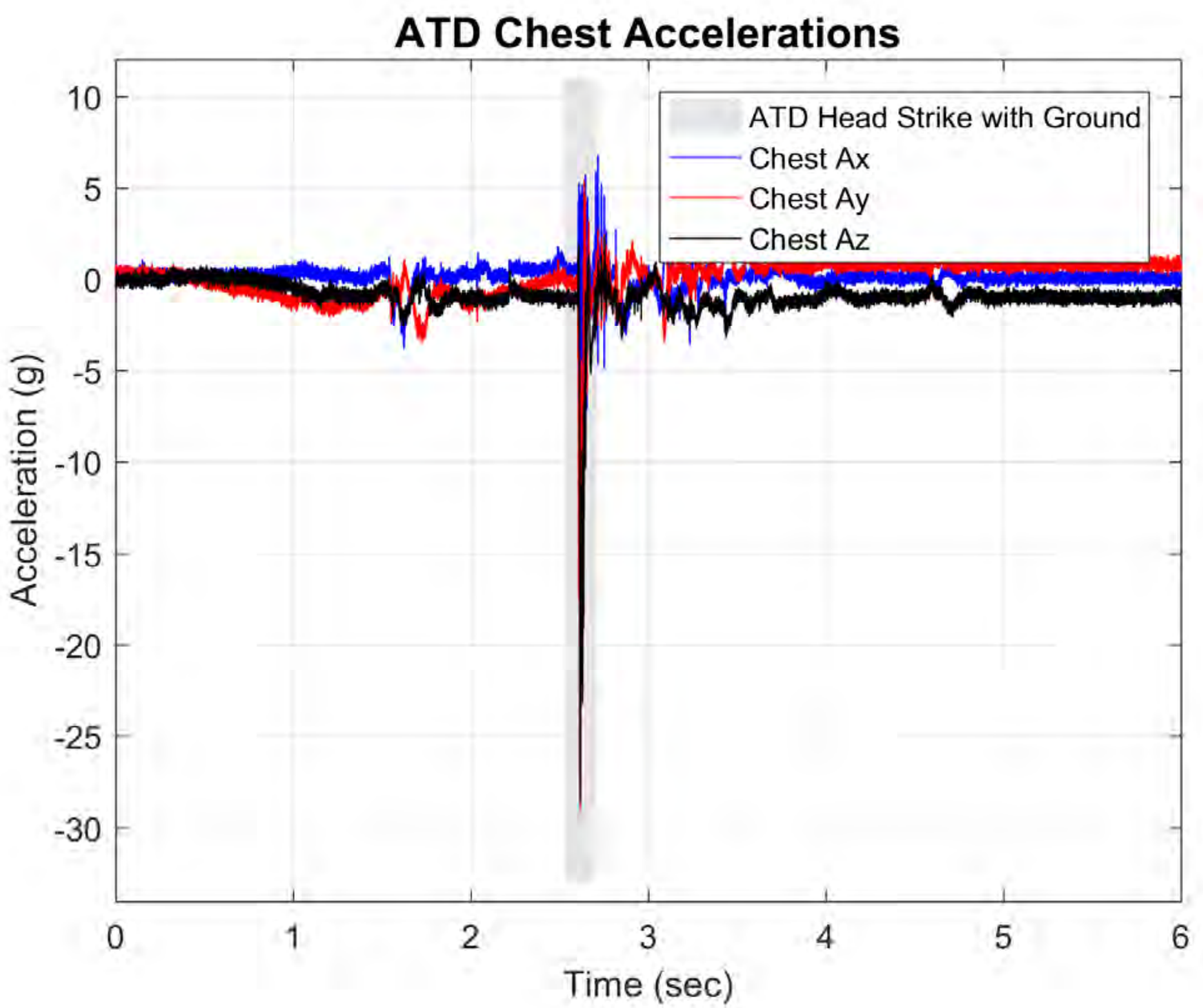
Vehicle E - Dynamic Moderate Energy Rollover with Trip Feature



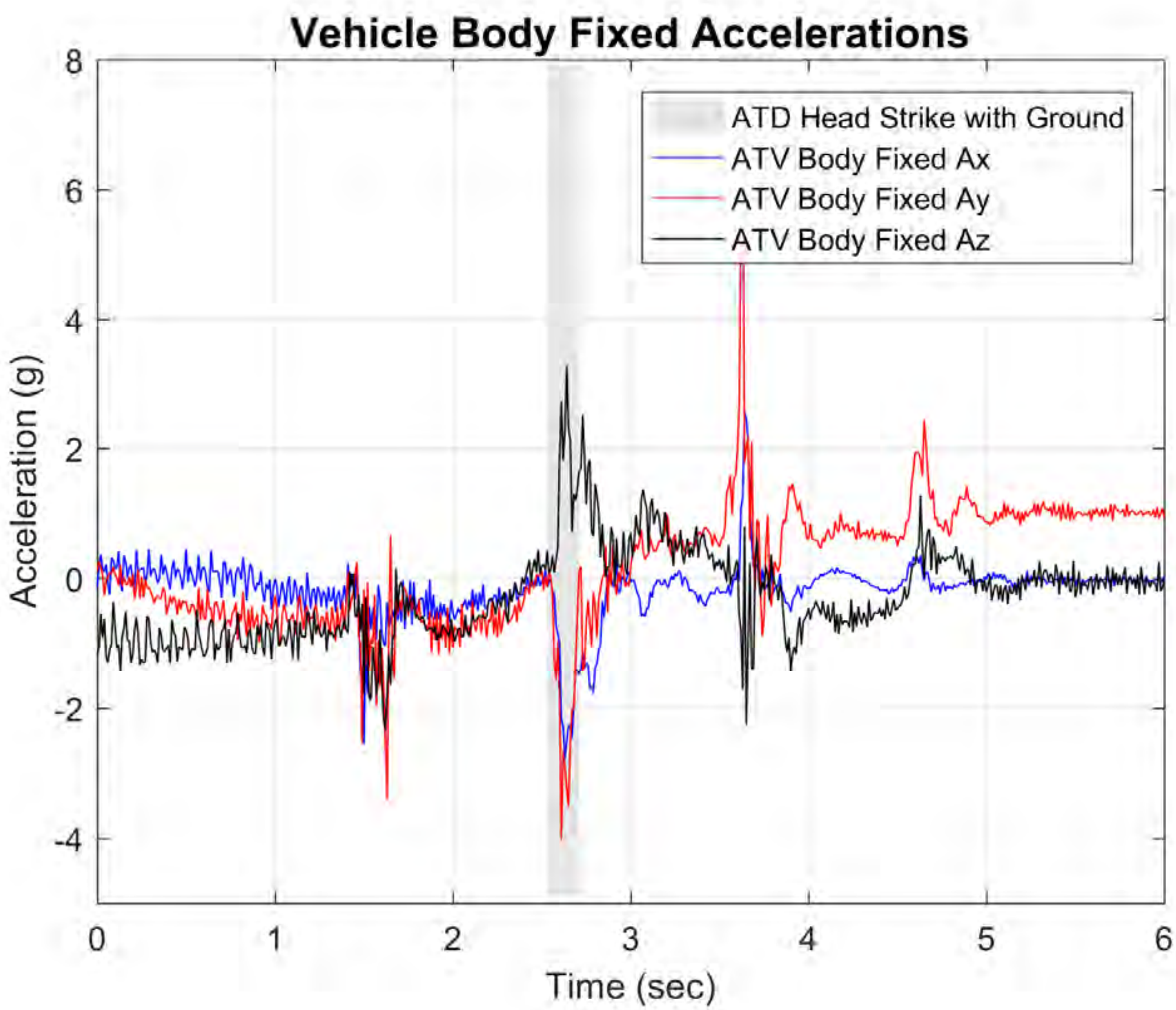
Vehicle E - Dynamic Moderate Energy Rollover with Trip Feature



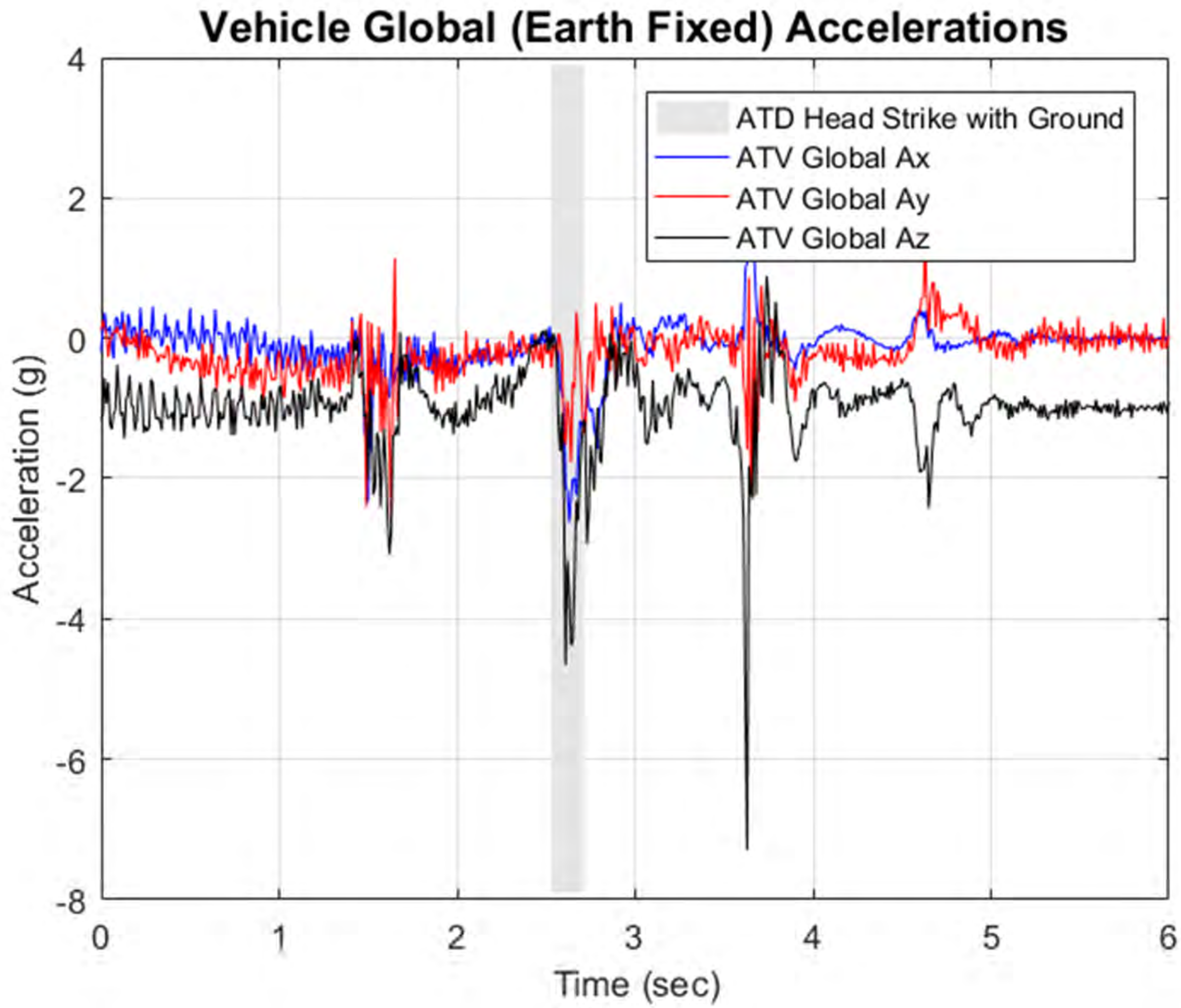
Vehicle E - Dynamic Moderate Energy Rollover with Trip Feature



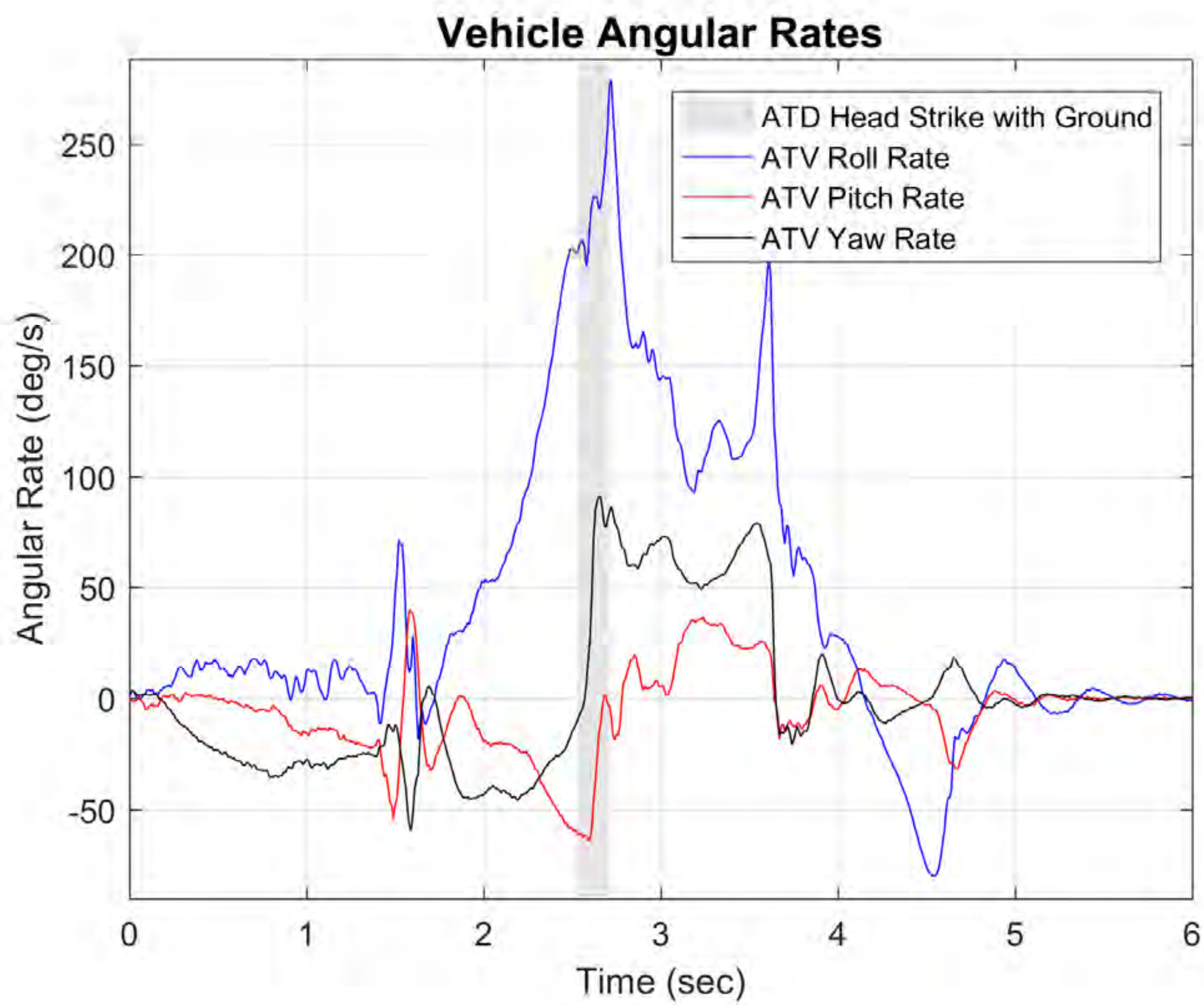
Vehicle E - Dynamic Moderate Energy Rollover with Trip Feature



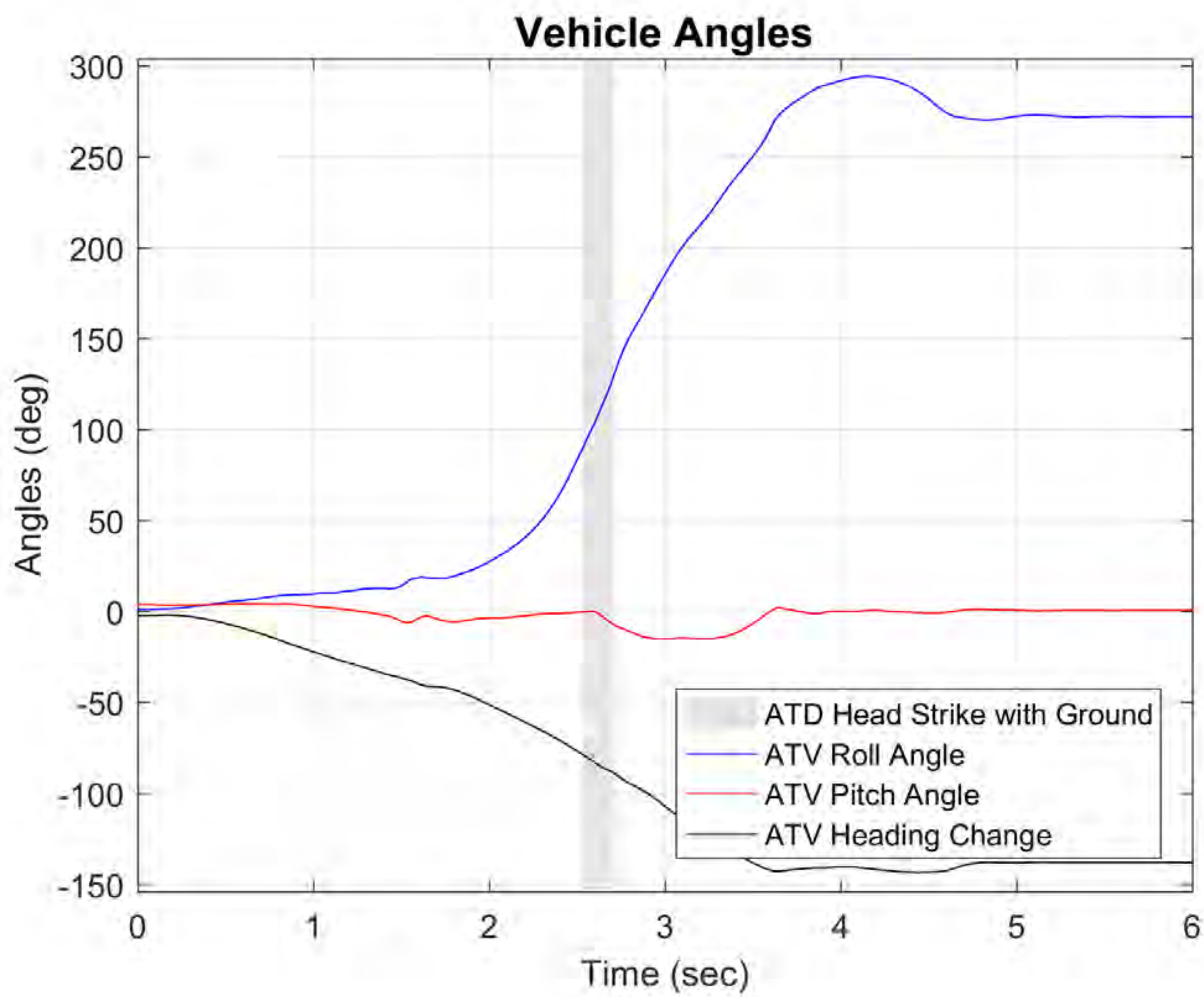
Vehicle E - Dynamic Moderate Energy Rollover with Trip Feature



Vehicle E - Dynamic Moderate Energy Rollover with Trip Feature



Vehicle E - Dynamic Moderate Energy Rollover with Trip Feature



Vehicle E - Dynamic Moderate Energy Rollover with Trip Feature

AOS Camera 1 - Roll Angle = 30° - Time = 1.26 sec

AOS Camera 1 - Roll Angle = 45° - Time = 1.44 sec

AOS Camera 1 - Roll Angle = 90° - Time = 1.74 sec

AOS Camera 2 - Roll Angle = 30° - Time = 1.26 sec

AOS Camera 2 - Roll Angle = 45° - Time = 1.44 sec

AOS Camera 2 - Roll Angle = 90° - Time = 1.74 sec

Vehicle G - Dynamic Minimum Energy Rollover

AOS Camera 1 - ATD Head Strike - Time = 1.82 sec

AOS Camera 1 - Max Angle = 141.8° - Time = 2.42 sec

AOS Camera 1 - End of Run - Roll Angle = 137.3°

AOS Camera 2 - ATD Head Strike - Time = 1.82 sec

AOS Camera 2 - Max Angle = 141.8° - Time = 2.42 sec

AOS Camera 2 - End of Run - Roll Angle = 137.3°

Vehicle G - Dynamic Minimum Energy Rollover

RT Camera 1 - Roll Angle = 30° - Time = 1.26 sec

RT Camera 1 - Roll Angle = 45° - Time = 1.44 sec

RT Camera 1 - Roll Angle = 90° - Time = 1.74 sec

RT Camera 2 - Roll Angle = 30° - Time = 1.26 sec

RT Camera 2 - Roll Angle = 45° - Time = 1.44 sec

RT Camera 2 - Roll Angle = 90° - Time = 1.74 sec

Vehicle G - Dynamic Minimum Energy Rollover

RT Camera 1 - ATD Head Strike - Time = 1.82 sec

RT Camera 1 - Max Angle = 141.8° - Time = 2.42 sec

RT Camera 1 - End of Run - Roll Angle = 137.3°

RT Camera 2 - ATD Head Strike - Time = 1.82 sec

RT Camera 2 - Max Angle = 141.8° - Time = 2.42 sec

RT Camera 2 - End of Run - Roll Angle = 137.3°

Vehicle G - Dynamic Minimum Energy Rollover

Drone Camera - Roll Angle = 30° - Time = 1.26 sec

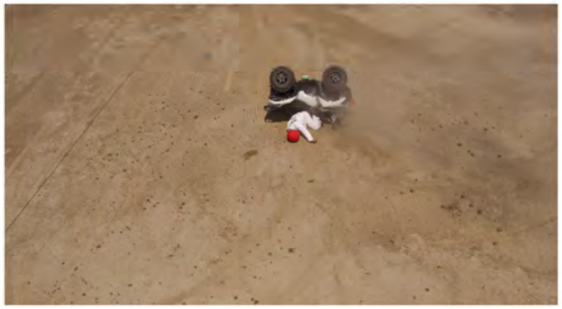
Drone Camera - Roll Angle = 45° - Time = 1.44 sec

Drone Camera - Roll Angle = 90° - Time = 1.74 sec

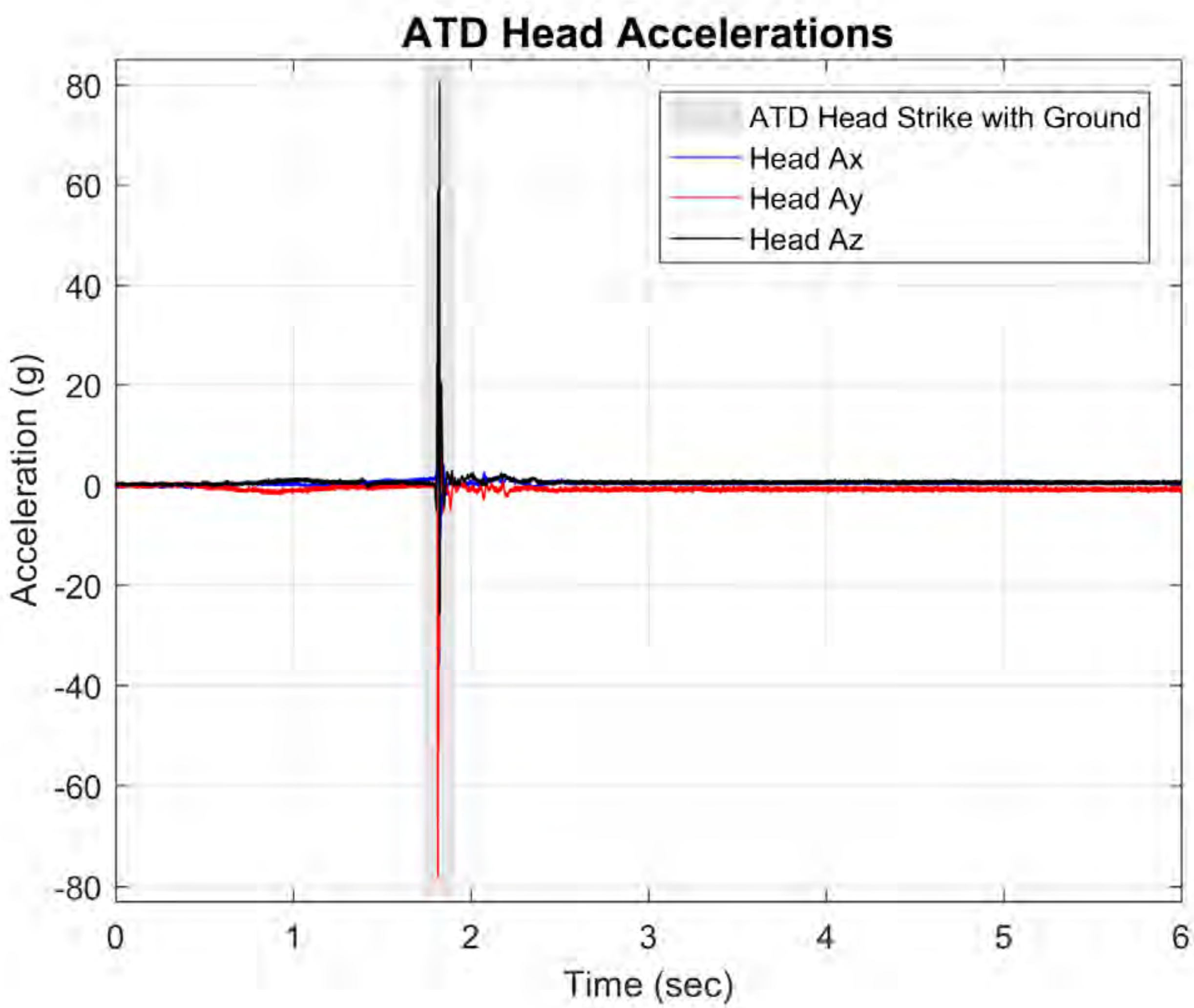
Drone Camera - ATD Head Strike - Time = 1.82 sec

Drone Camera - Max Angle = 141.8° - Time = 2.42 sec

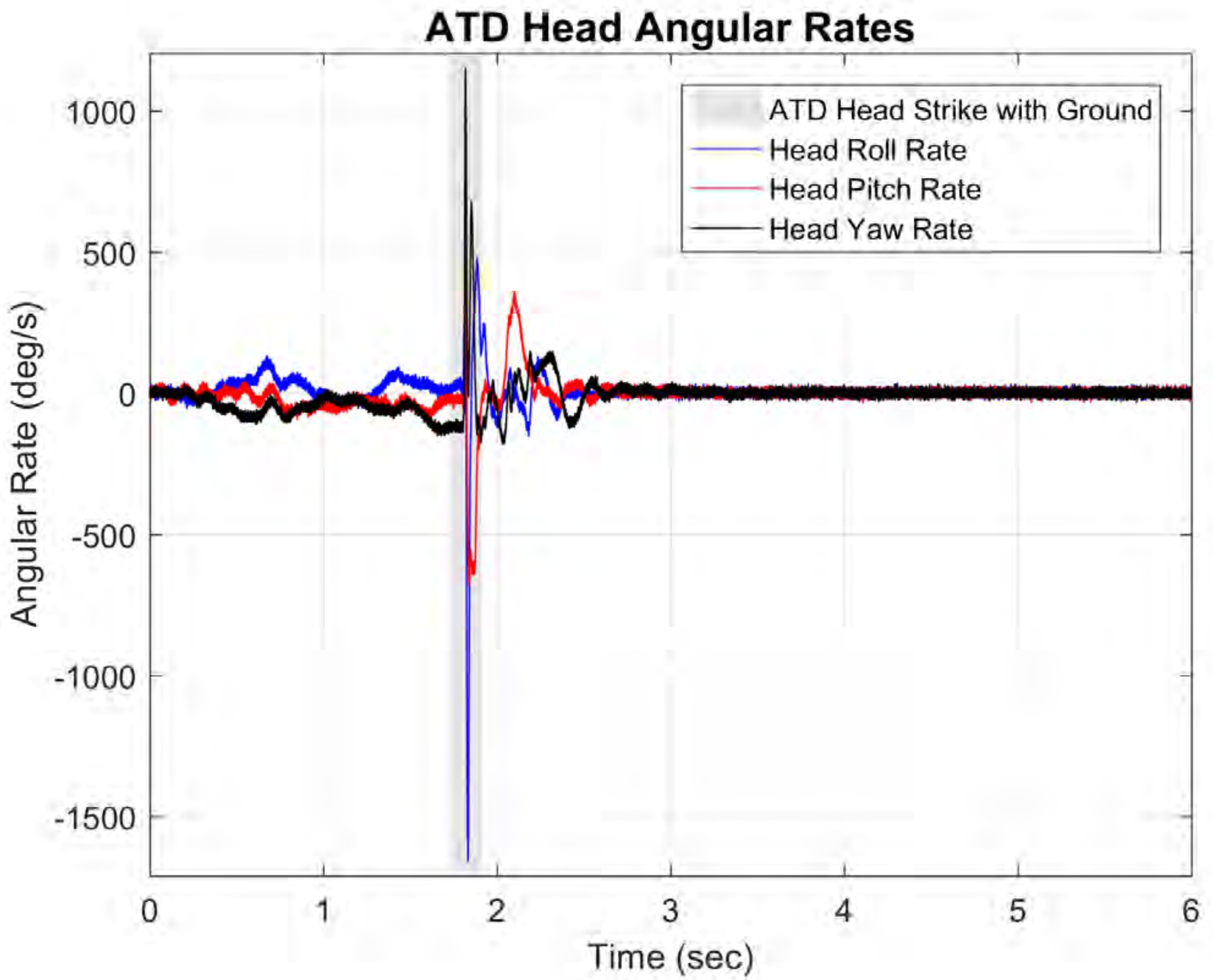
Drone Camera - End of Run - Roll Angle = 137.3°



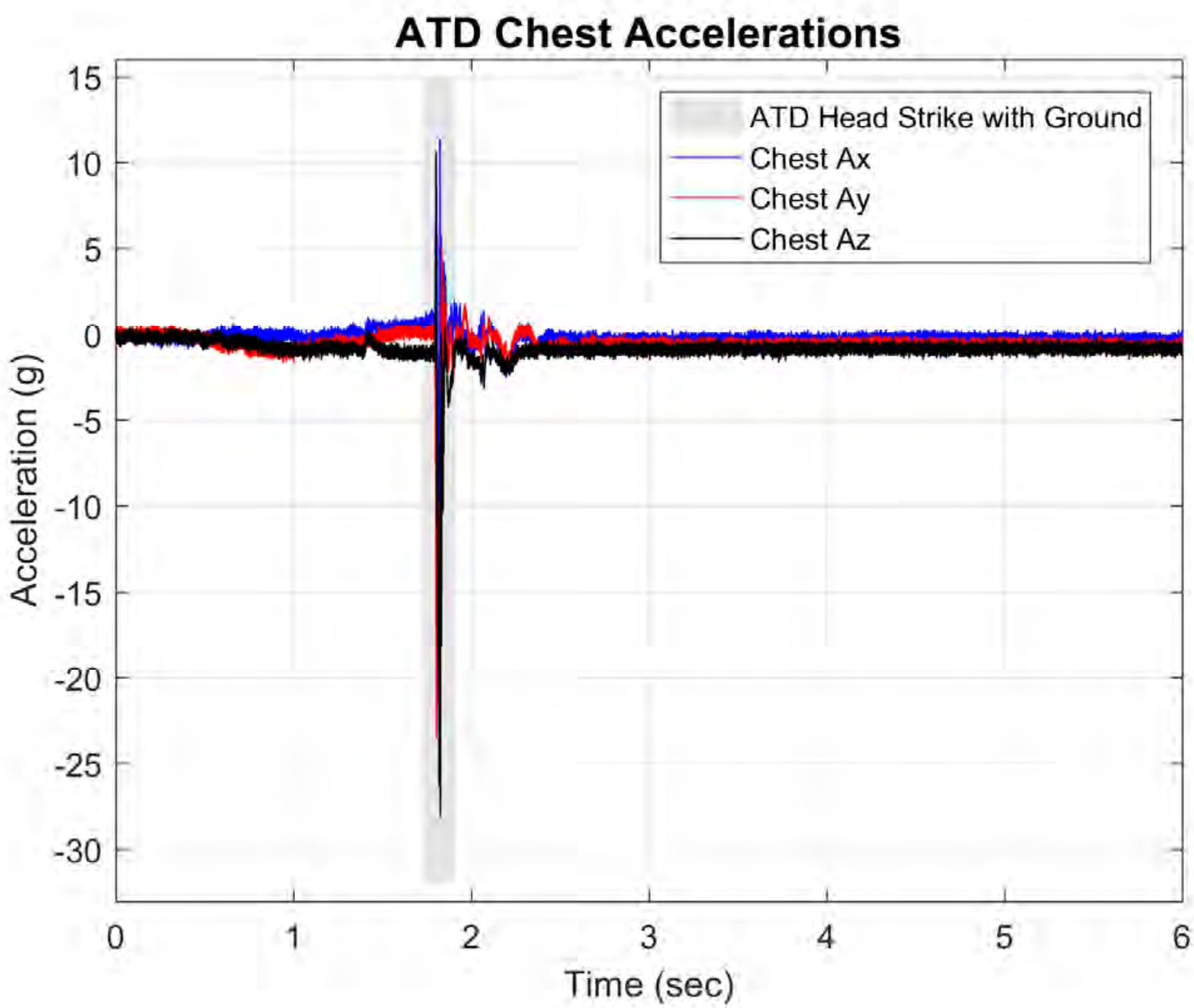
Vehicle G - Dynamic Minimum Energy Rollover



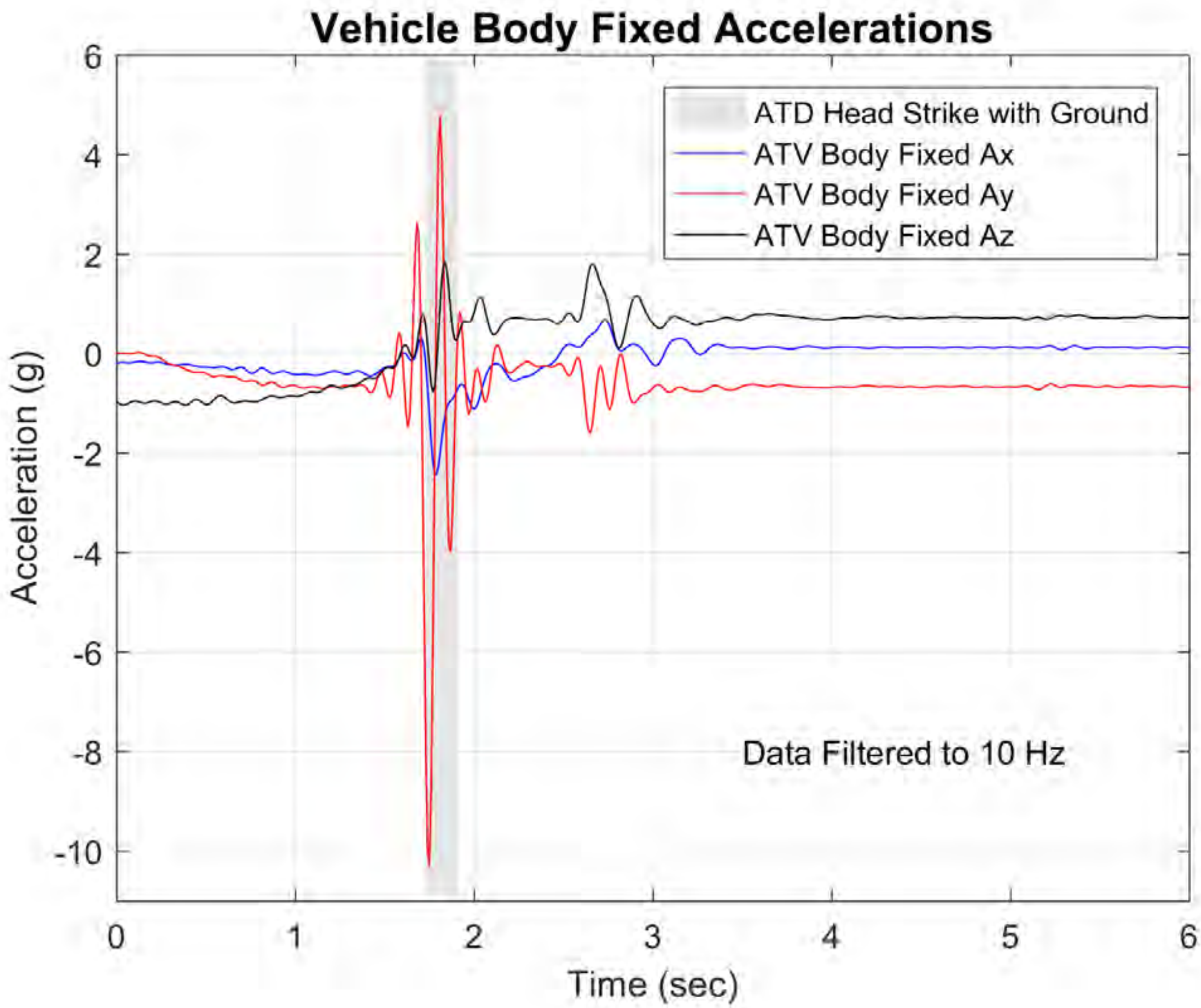
Vehicle G - Dynamic Minimum Energy Rollover



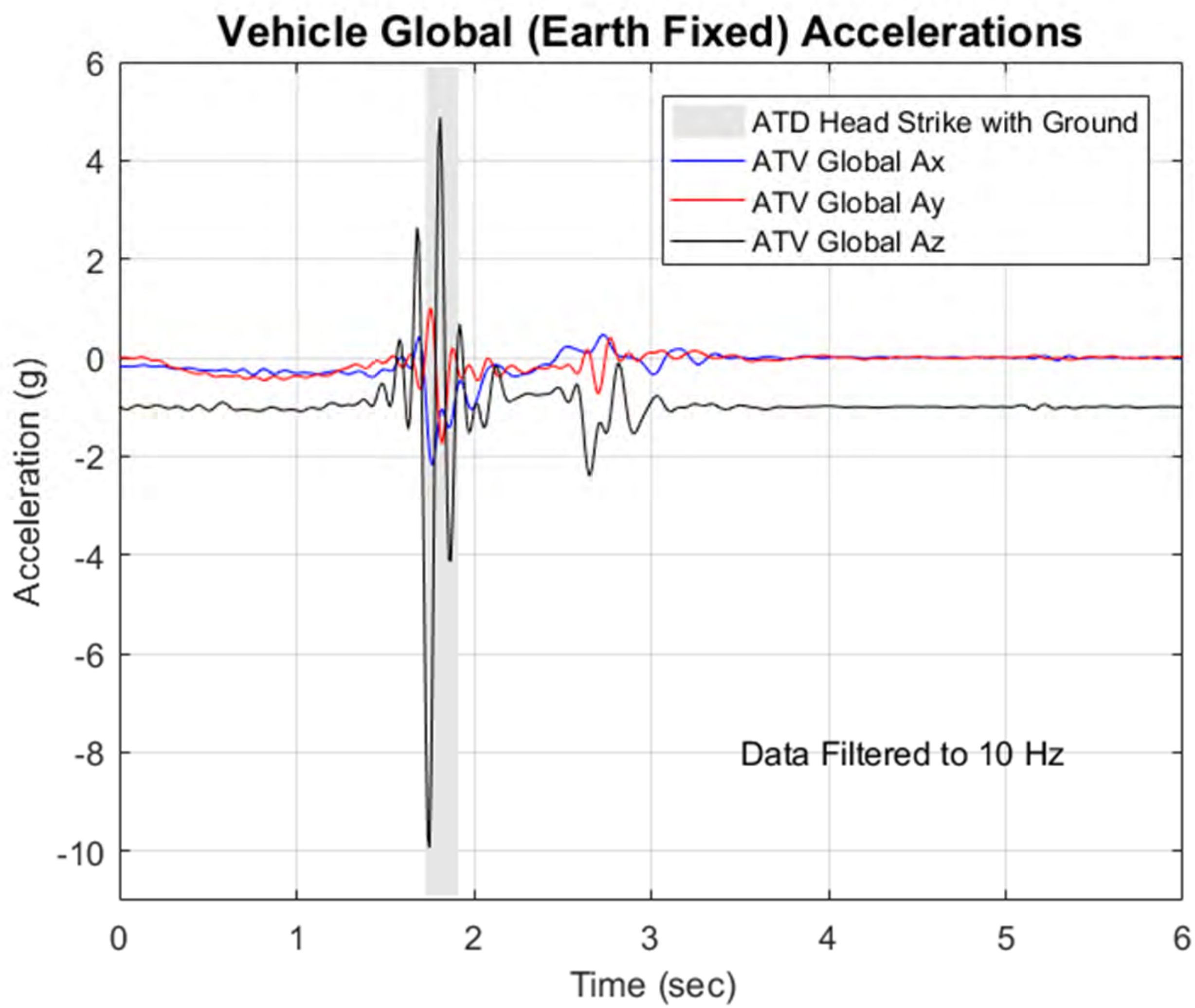
Vehicle G - Dynamic Minimum Energy Rollover



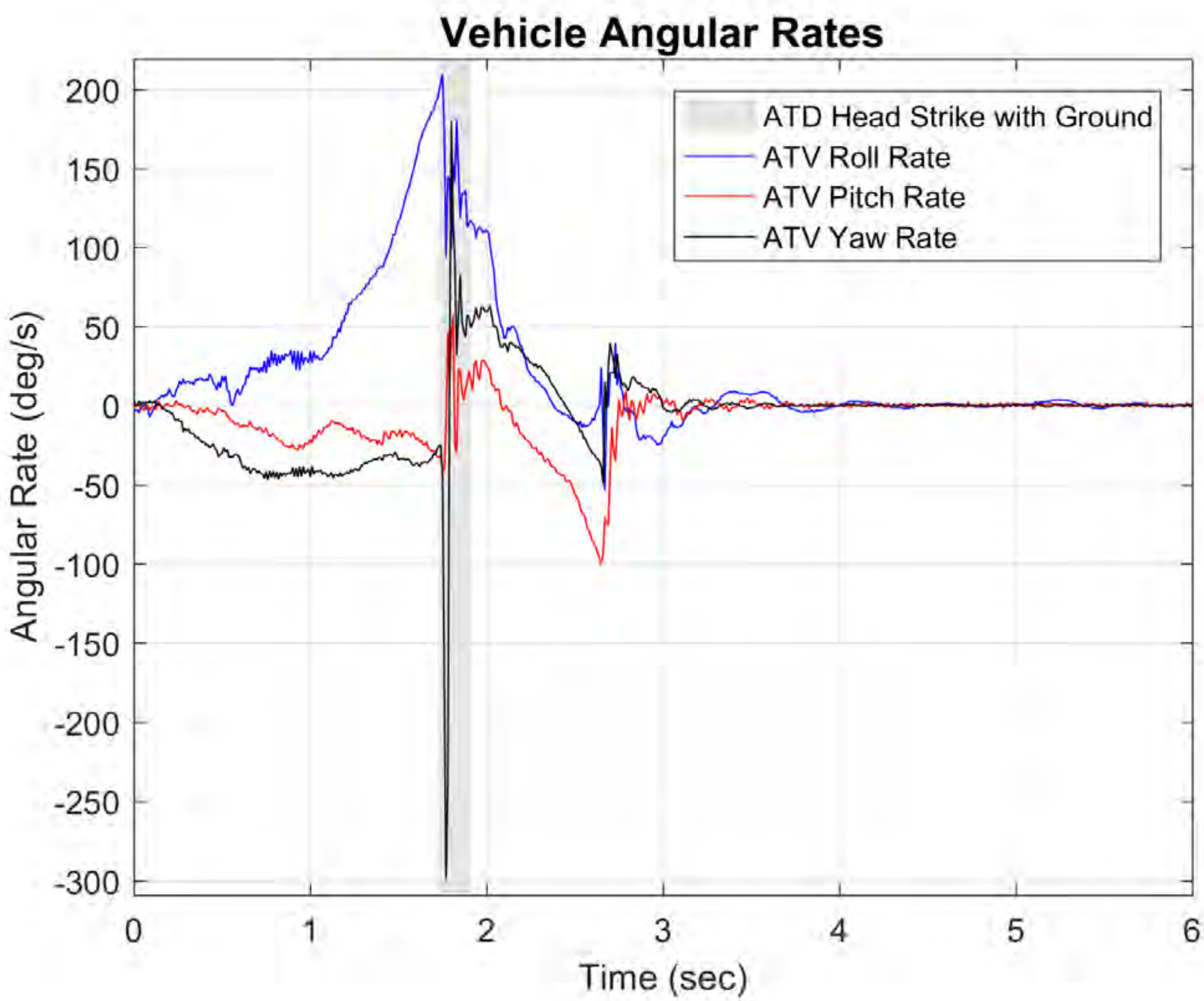
Vehicle G - Dynamic Minimum Energy Rollover



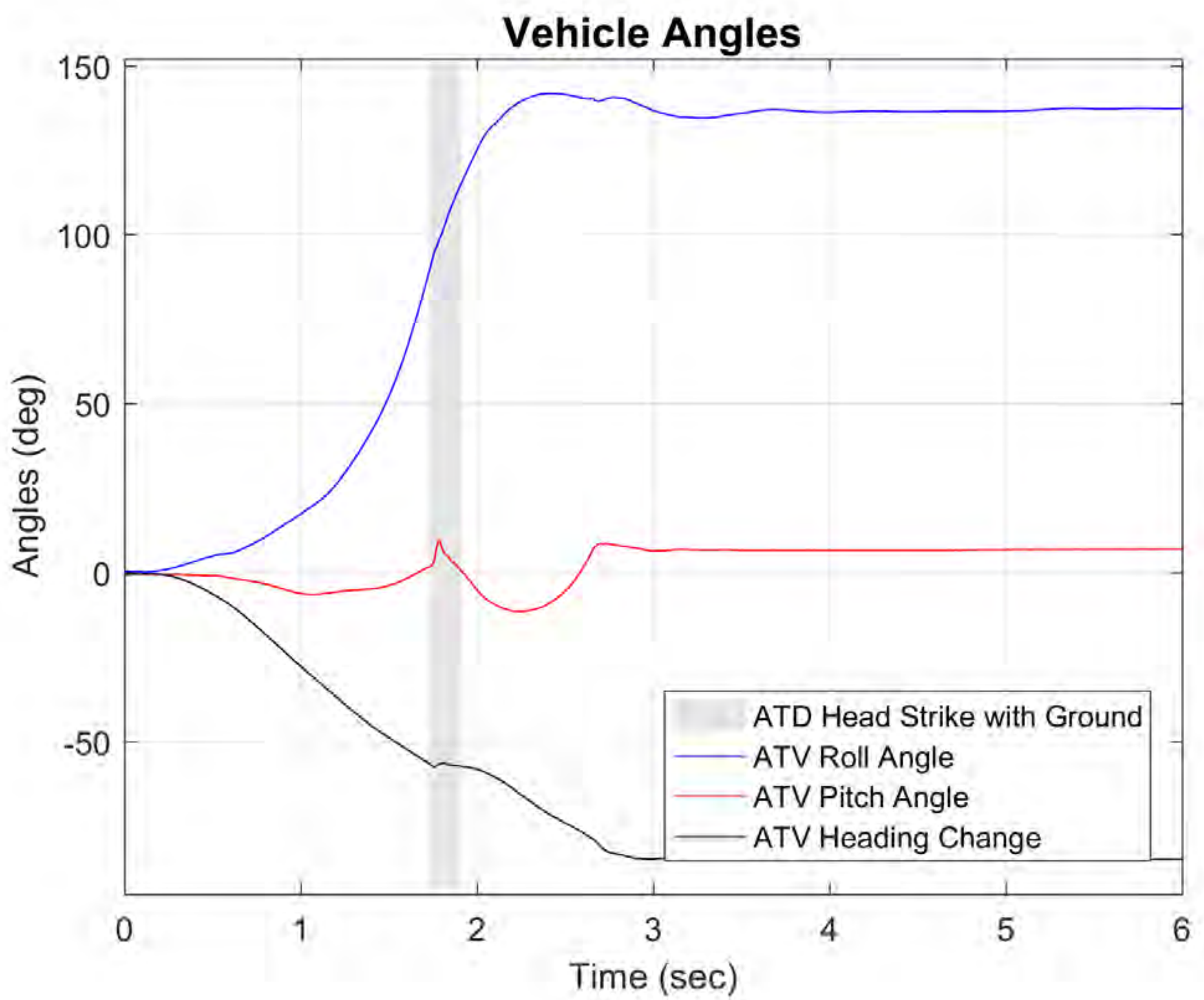
Vehicle G - Dynamic Minimum Energy Rollover



Vehicle G - Dynamic Minimum Energy Rollover



Vehicle G - Dynamic Minimum Energy Rollover



Vehicle G - Dynamic Minimum Energy Rollover

AOS Camera 1 - Roll Angle = 30° - Time = 1.06 sec

AOS Camera 1 - Roll Angle = 45° - Time = 1.14 sec

AOS Camera 1 - Roll Angle = 90° - Time = 1.34 sec

AOS Camera 2 - Roll Angle = 30° - Time = 1.06 sec

AOS Camera 2 - Roll Angle = 45° - Time = 1.14 sec

AOS Camera 2 - Roll Angle = 90° - Time = 1.34 sec

Vehicle G - Dynamic Moderate Energy Rollover

AOS Camera 1 - ATD Head Strike - Time = 1.54 sec

AOS Camera 1 - Roll Angle = 180° - Time = 1.69 sec

AOS Camera 1 - Roll Angle = 270° - Time = 2.1 sec

AOS Camera 2 - ATD Head Strike - Time = 1.54 sec

AOS Camera 2 - Roll Angle = 180° - Time = 1.69 sec

AOS Camera 2 - Roll Angle = 270° - Time = 2.1 sec

Vehicle G - Dynamic Moderate Energy Rollover

AOS Camera 1 - Max Angle = 294.1° - Time = 3.34 sec

AOS Camera 1 - End of Run - Roll Angle = 273.2°

AOS Camera 2 - Max Angle = 294.1° - Time = 3.34 sec

AOS Camera 2 - End of Run - Roll Angle = 273.2°

Vehicle G - Dynamic Moderate Energy Rollover

RT Camera 1 - Roll Angle = 30° - Time = 1.06 sec

RT Camera 1 - Roll Angle = 45° - Time = 1.14 sec

RT Camera 1 - Roll Angle = 90° - Time = 1.34 sec

RT Camera 2 Video Not Available

RT Camera 2 Video Not Available

RT Camera 2 Video Not Available

Vehicle G - Dynamic Moderate Energy Rollover

RT Camera 1 - ATD Head Strike - Time = 1.54 sec

RT Camera 1 - Roll Angle = 180° - Time = 1.69 sec

RT Camera 1 - Roll Angle = 270° - Time = 2.1 sec

RT Camera 2 Video Not Available

RT Camera 2 Video Not Available

RT Camera 2 Video Not Available

Vehicle G - Dynamic Moderate Energy Rollover

RT Camera 1 - Max Angle = 294.1° - Time = 3.34 sec

RT Camera 1 - End of Run - Roll Angle = 273.2°

RT Camera 2 Video Not Available

RT Camera 2 Video Not Available

Vehicle G - Dynamic Moderate Energy Rollover

Drone Camera - Roll Angle = 30° - Time = 1.06 sec

Drone Camera - Roll Angle = 45° - Time = 1.14 sec

Drone Camera - Roll Angle = 90° - Time = 1.34 sec

Drone Camera - ATD Head Strike - Time = 1.54 sec

Drone Camera - Roll Angle = 180° - Time = 1.69 sec

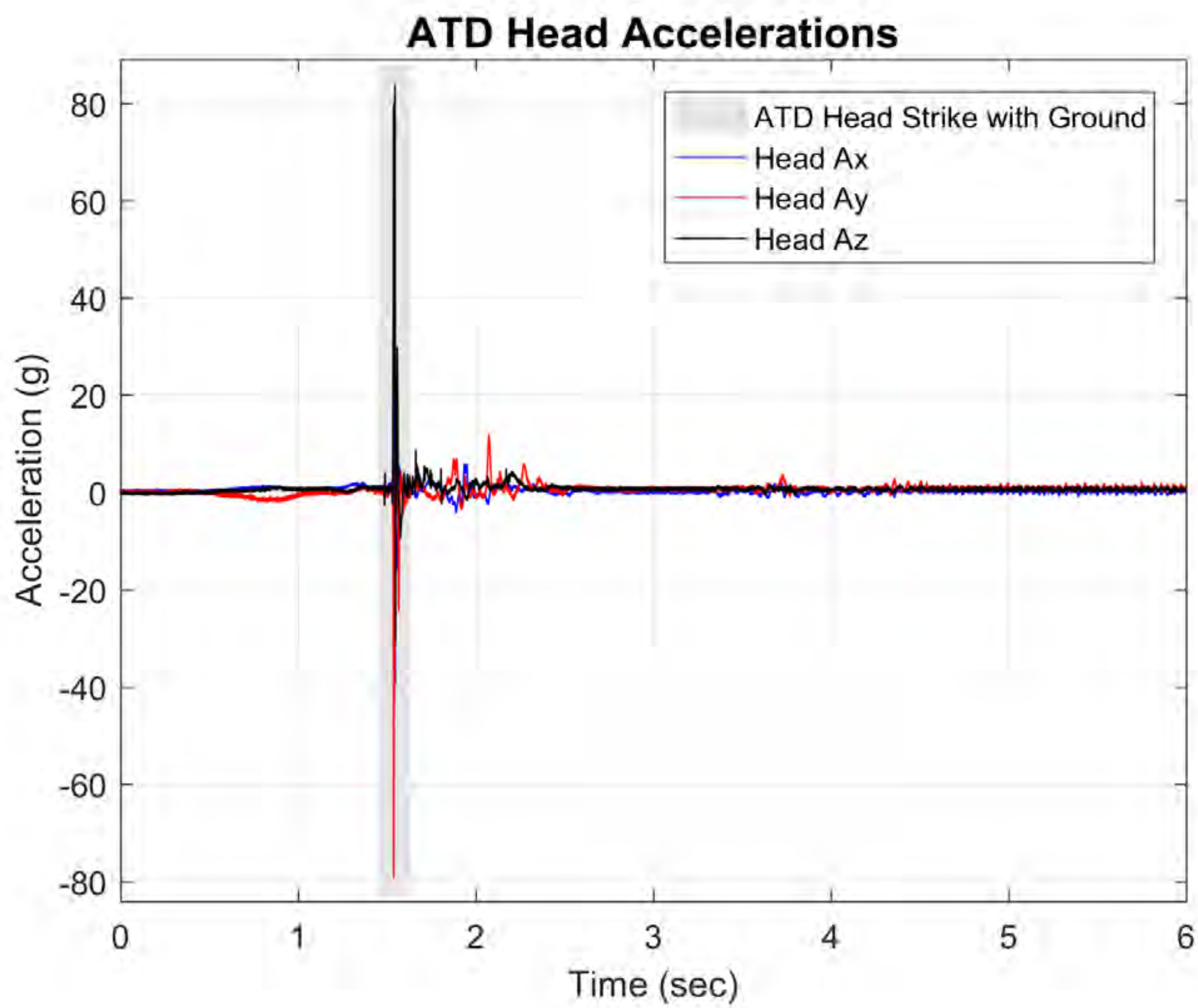
Drone Camera - Roll Angle = 270° - Time = 2.1 sec

Vehicle G - Dynamic Moderate Energy Rollover

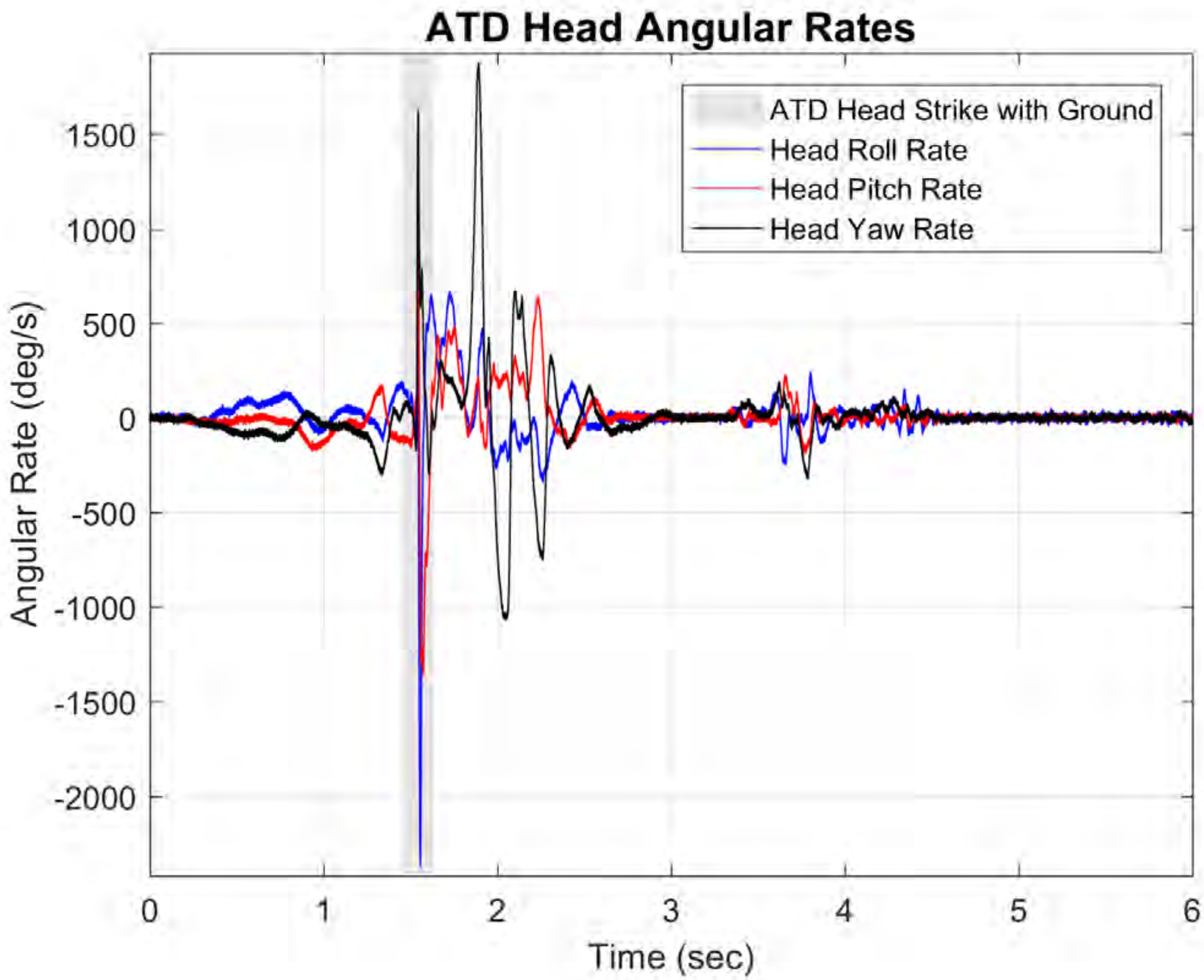
Drone Camera - Max Angle = 294.1° - Time = 3.34 sec

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

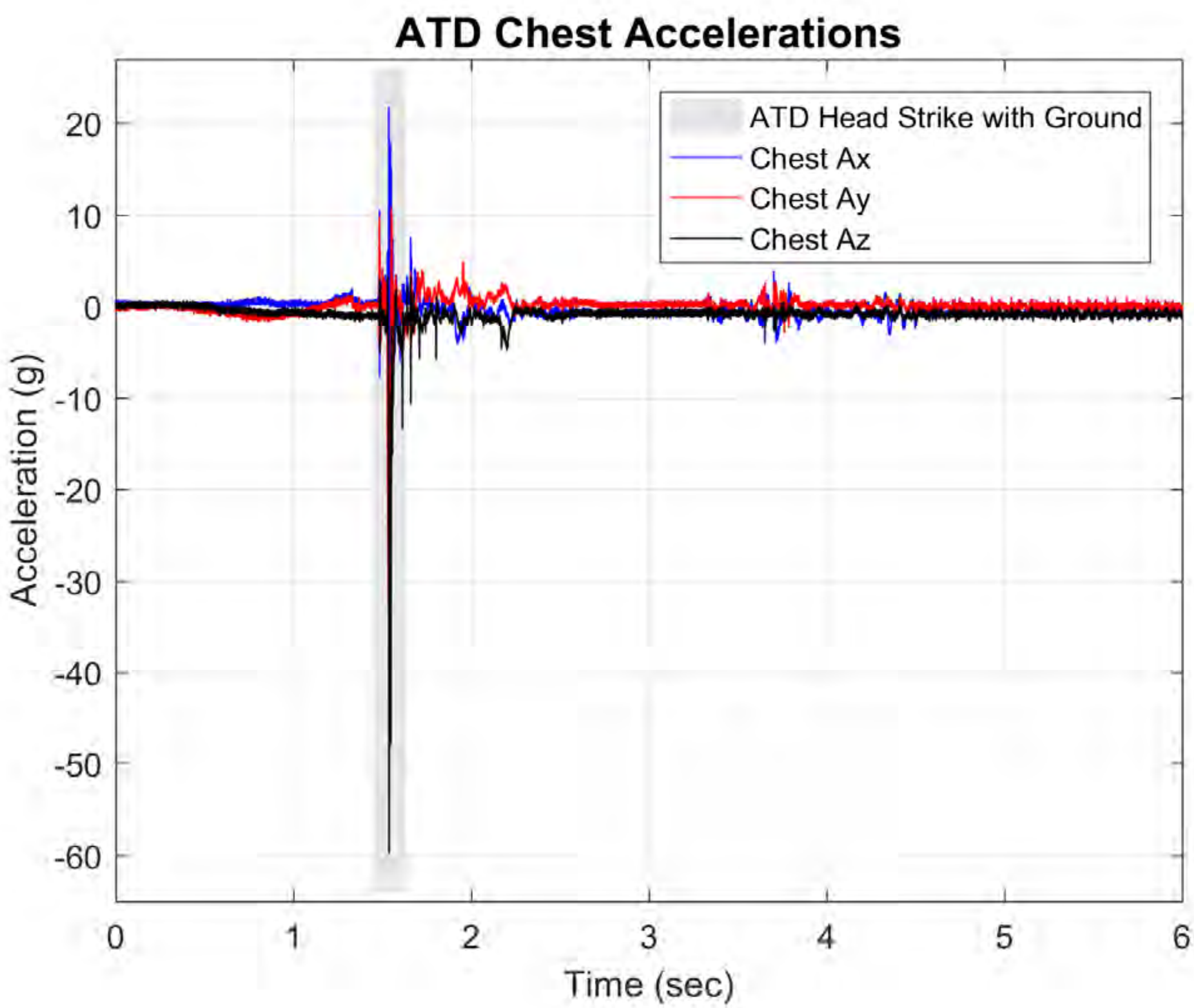
Vehicle G - Dynamic Moderate Energy Rollover



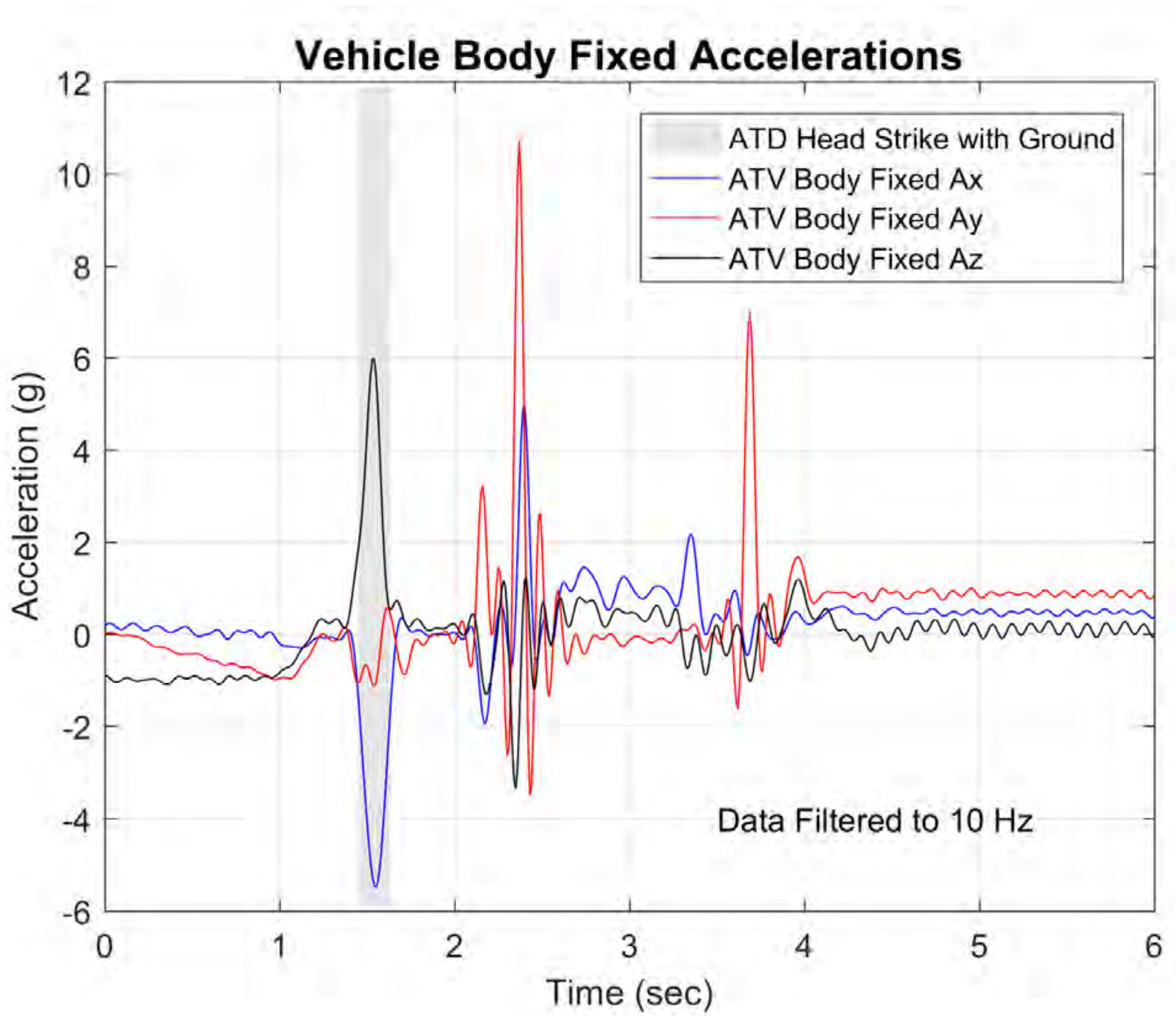
Vehicle G - Dynamic Moderate Energy Rollover



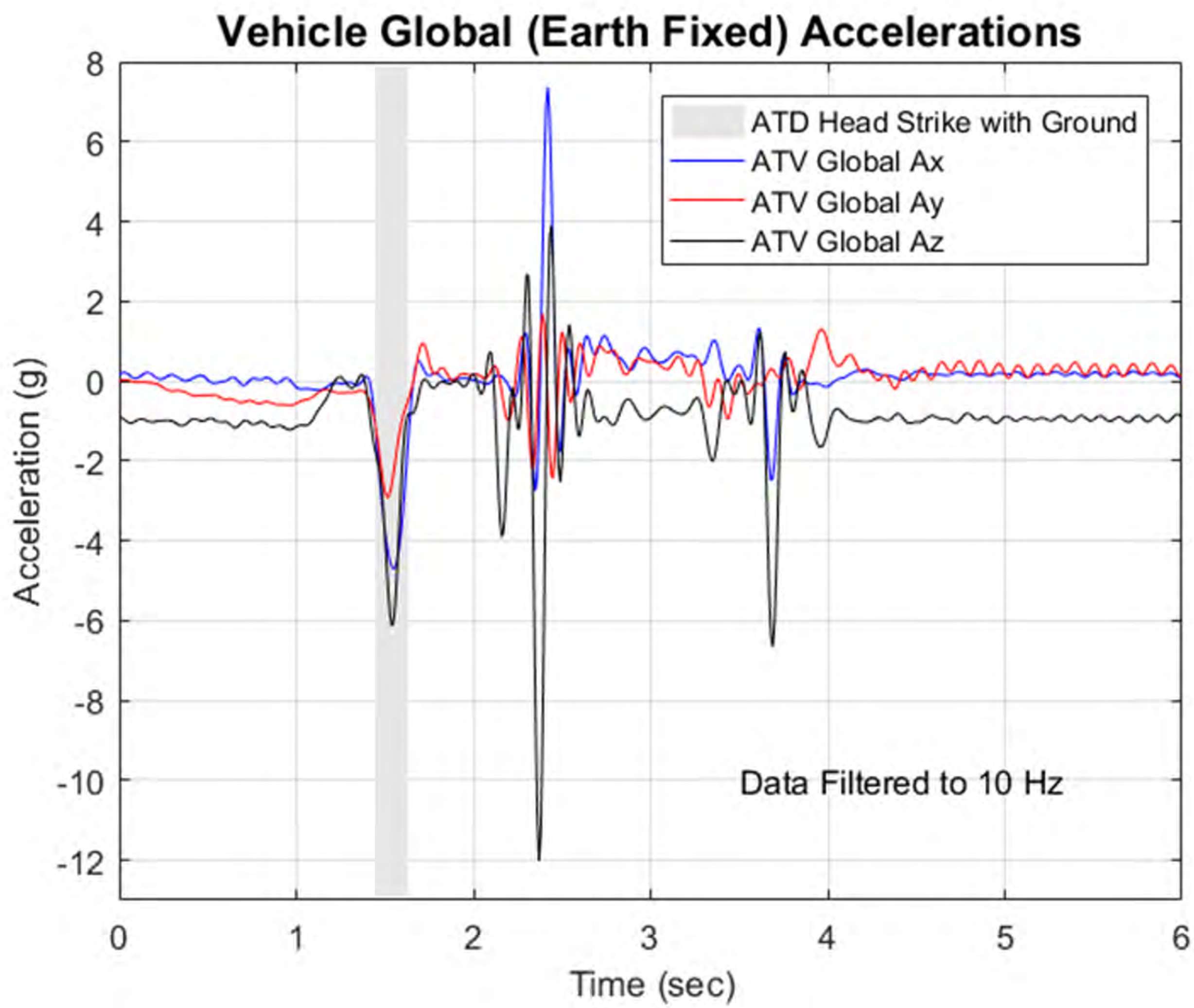
Vehicle G - Dynamic Moderate Energy Rollover



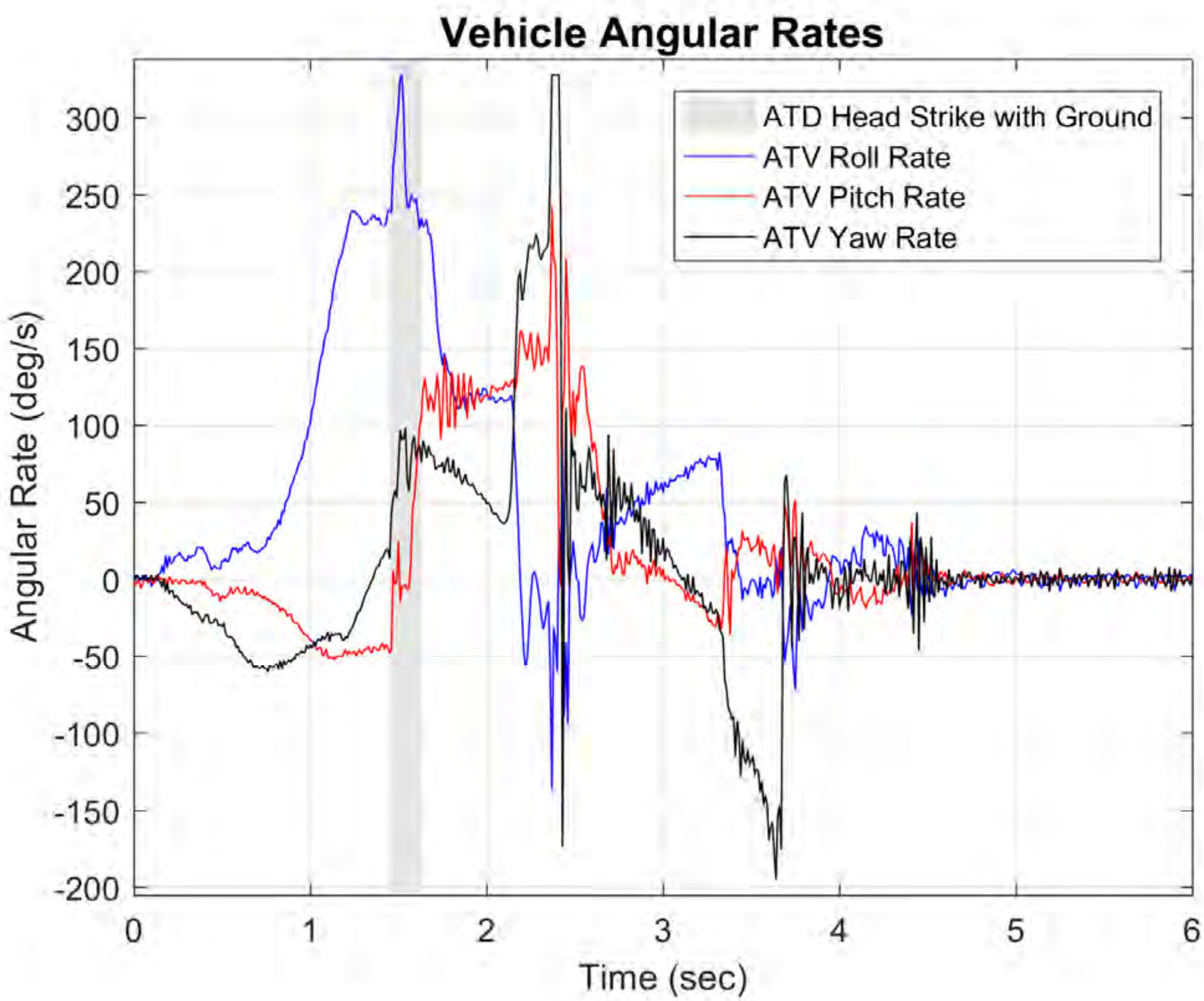
Vehicle G - Dynamic Moderate Energy Rollover



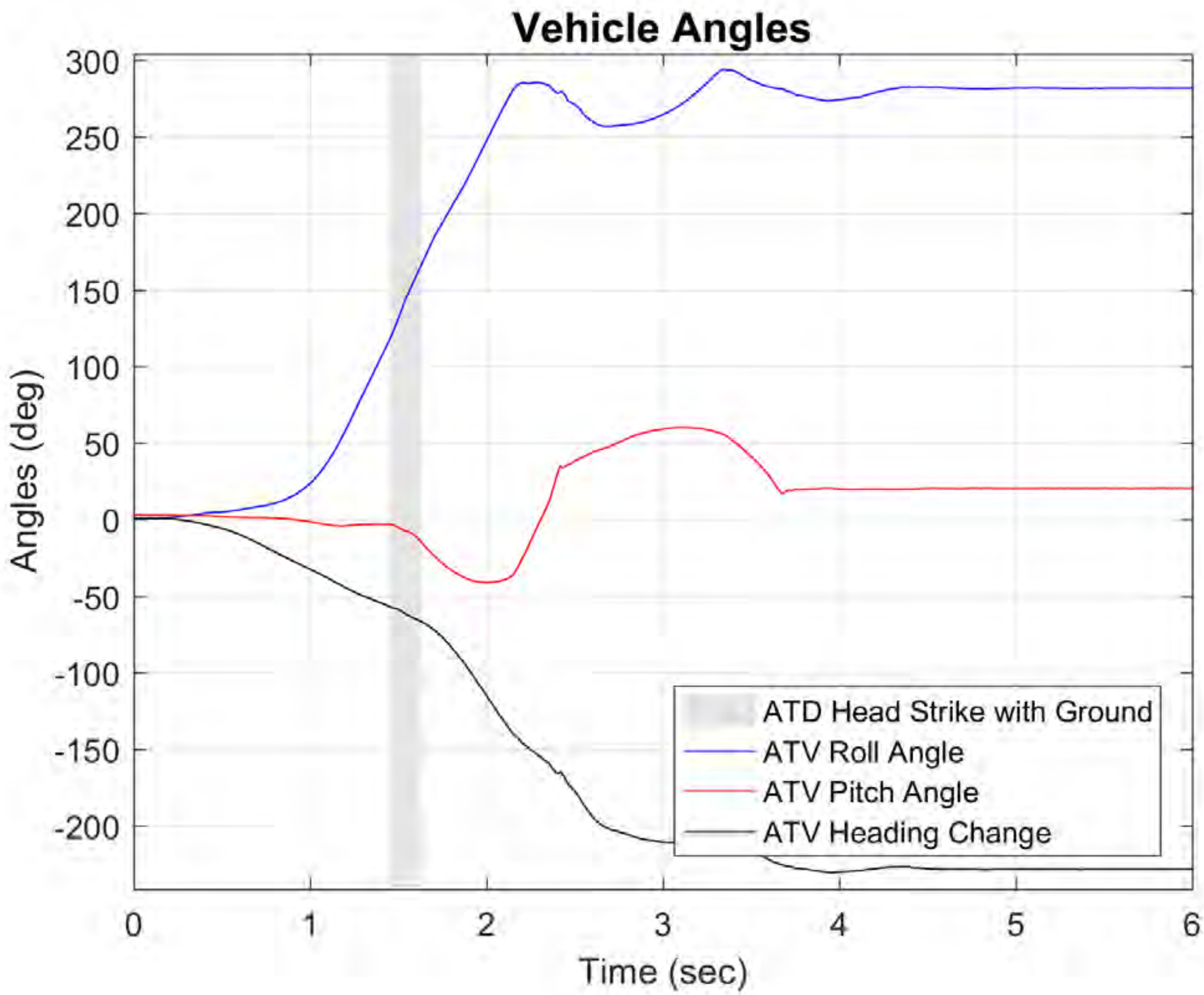
Vehicle G - Dynamic Moderate Energy Rollover



Vehicle G - Dynamic Moderate Energy Rollover



Vehicle G - Dynamic Moderate Energy Rollover



Vehicle G - Dynamic Moderate Energy Rollover

AOS Camera 1 - Roll Angle = 30° - Time = 1.22 sec

AOS Camera 1 - Roll Angle = 45° - Time = 1.33 sec

AOS Camera 1 - Roll Angle = 90° - Time = 1.59 sec

AOS Camera 2 - Roll Angle = 30° - Time = 1.22 sec

AOS Camera 2 - Roll Angle = 45° - Time = 1.33 sec

AOS Camera 2 - Roll Angle = 90° - Time = 1.59 sec

Vehicle G - Dynamic Moderate Energy Rollover with Trip Feature

AOS Camera 1 - ATD Head Strike - Time = 1.71 sec

AOS Camera 1 - Roll Angle = 180° - Time = 1.95 sec

AOS Camera 1 - Roll Angle = 270° - Time = 2.2 sec

AOS Camera 2 - ATD Head Strike - Time = 1.71 sec

AOS Camera 2 - Roll Angle = 180° - Time = 1.95 sec

AOS Camera 2 - Roll Angle = 270° - Time = 2.2 sec

Vehicle G - Dynamic Moderate Energy Rollover with Trip Feature

AOS Camera 1 - Roll Angle = 360° - Time = 2.51 sec

AOS Camera 1 - Max Angle = 378.2° - Time = 2.67 sec

AOS Camera 1 - End of Run - Roll Angle = 368.1°

AOS Camera 2 - Roll Angle = 360° - Time = 2.51 sec

AOS Camera 2 - Max Angle = 378.2° - Time = 2.67 sec

AOS Camera 2 - End of Run - Roll Angle = 368.1°

Vehicle G - Dynamic Moderate Energy Rollover with Trip Feature

RT Camera 1 - Roll Angle = 30° - Time = 1.22 sec

RT Camera 1 - Roll Angle = 45° - Time = 1.33 sec

RT Camera 1 - Roll Angle = 90° - Time = 1.59 sec

RT Camera 2 - Roll Angle = 30° - Time = 1.22 sec

RT Camera 2 - Roll Angle = 45° - Time = 1.33 sec

RT Camera 2 - Roll Angle = 90° - Time = 1.59 sec

Vehicle G - Dynamic Moderate Energy Rollover with Trip Feature

RT Camera 1 - ATD Head Strike - Time = 1.71 sec

RT Camera 1 - Roll Angle = 180° - Time = 1.95 sec

RT Camera 1 - Roll Angle = 270° - Time = 2.2 sec

RT Camera 2 - ATD Head Strike - Time = 1.71 sec

RT Camera 2 - Roll Angle = 180° - Time = 1.95 sec

RT Camera 2 - Roll Angle = 270° - Time = 2.2 sec

Vehicle G - Dynamic Moderate Energy Rollover with Trip Feature

RT Camera 1 - Roll Angle = 360° - Time = 2.51 sec

RT Camera 1 - Max Angle = 378.2° - Time = 2.67 sec

RT Camera 1 - End of Run - Roll Angle = 368.1°

RT Camera 2 - Roll Angle = 360° - Time = 2.51 sec

RT Camera 2 - Max Angle = 378.2° - Time = 2.67 sec

RT Camera 2 - End of Run - Roll Angle = 368.1°

Vehicle G - Dynamic Moderate Energy Rollover with Trip Feature

Drone Camera - Roll Angle = 30° - Time = 1.22 sec

Drone Camera - Roll Angle = 45° - Time = 1.33 sec

Drone Camera - Roll Angle = 90° - Time = 1.59 sec

Drone Camera - ATD Head Strike - Time = 1.71 sec

Drone Camera - Roll Angle = 180° - Time = 1.95 sec

Drone Camera - Roll Angle = 270° - Time = 2.2 sec

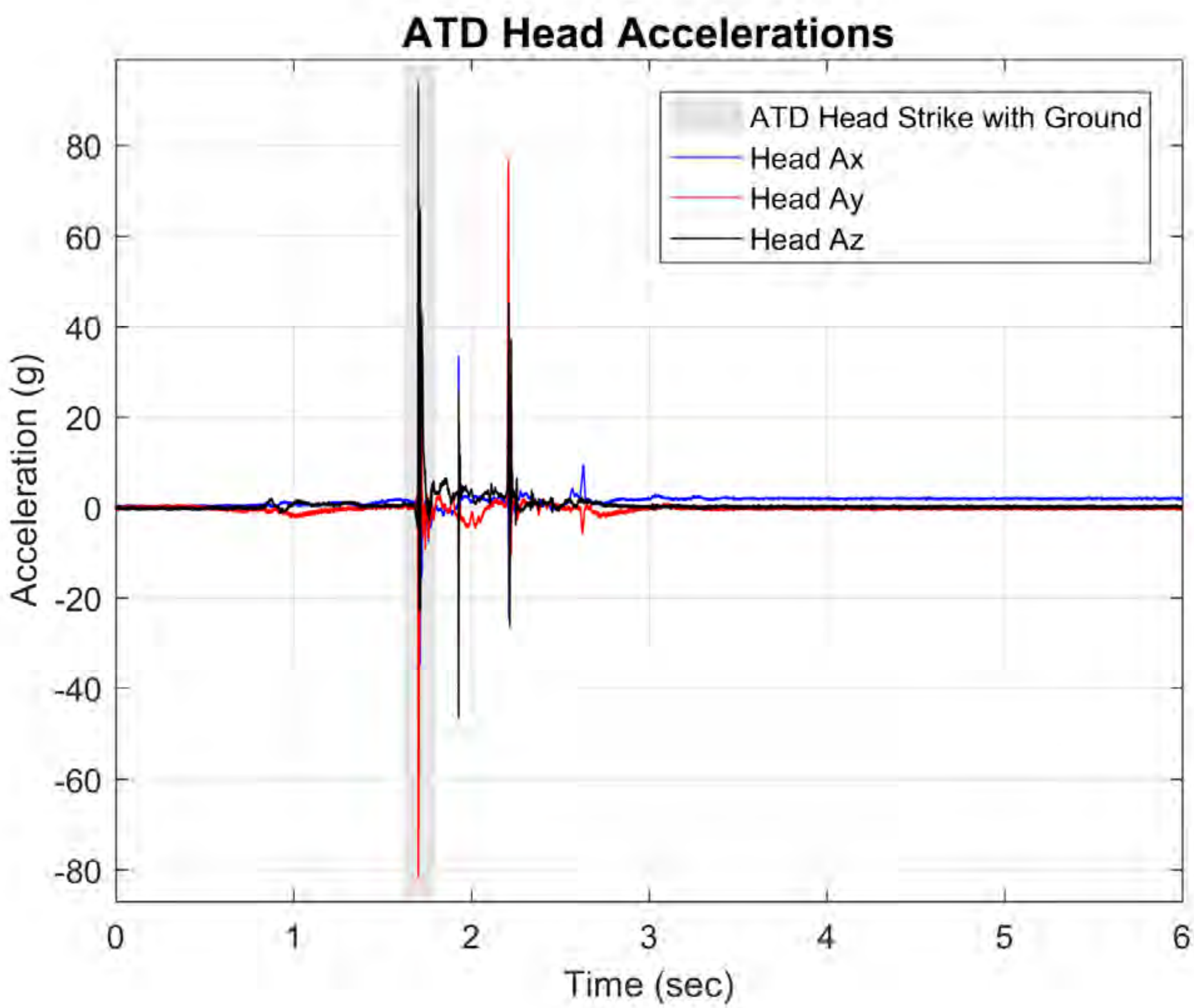
Vehicle G - Dynamic Moderate Energy Rollover with Trip Feature

Drone Camera - Roll Angle = 360° - Time = 2.51 sec

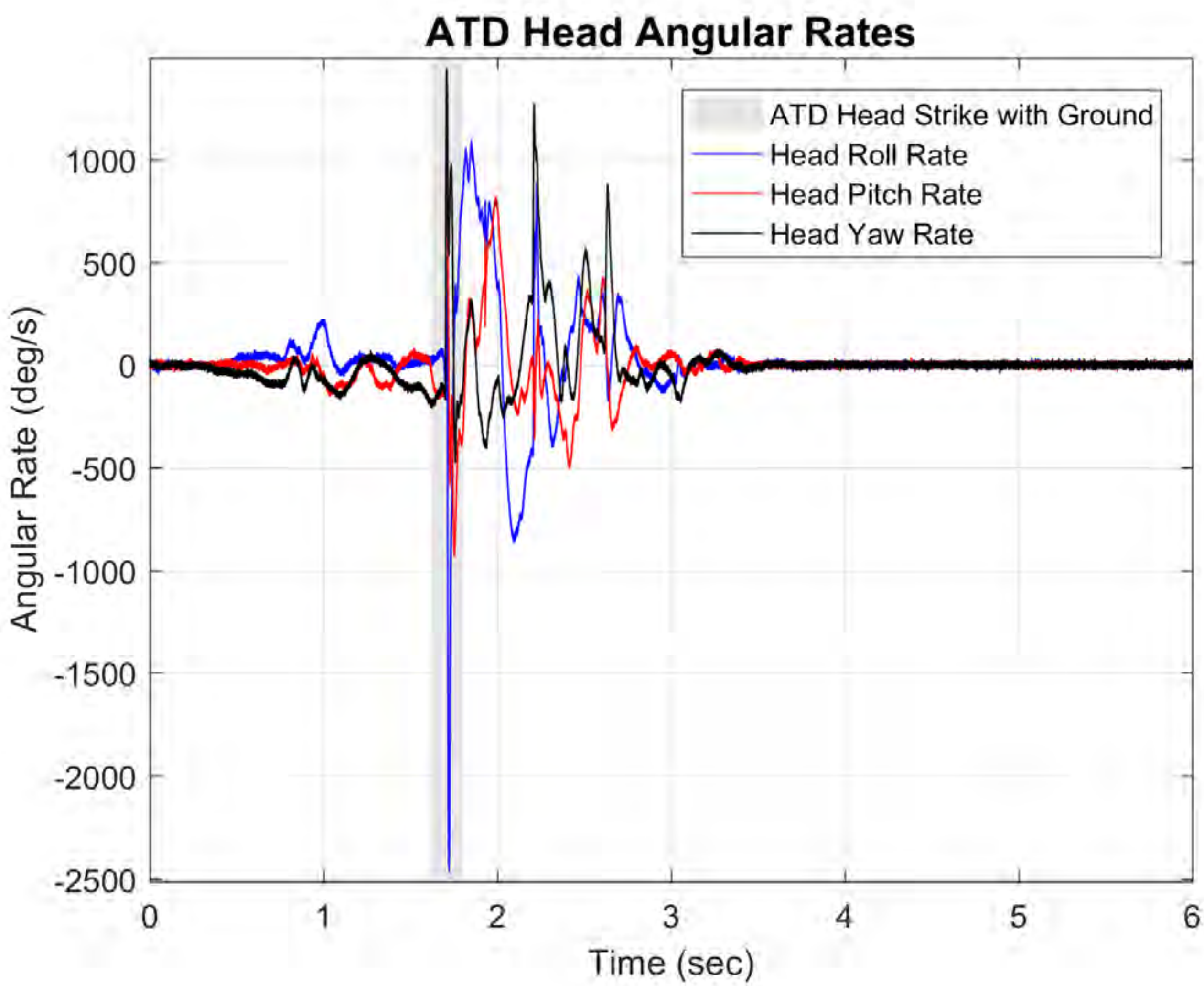
Drone Camera - Max Angle = 378.2° - Time = 2.67 sec

Drone Camera - End of Run - Roll Angle = 368.1°

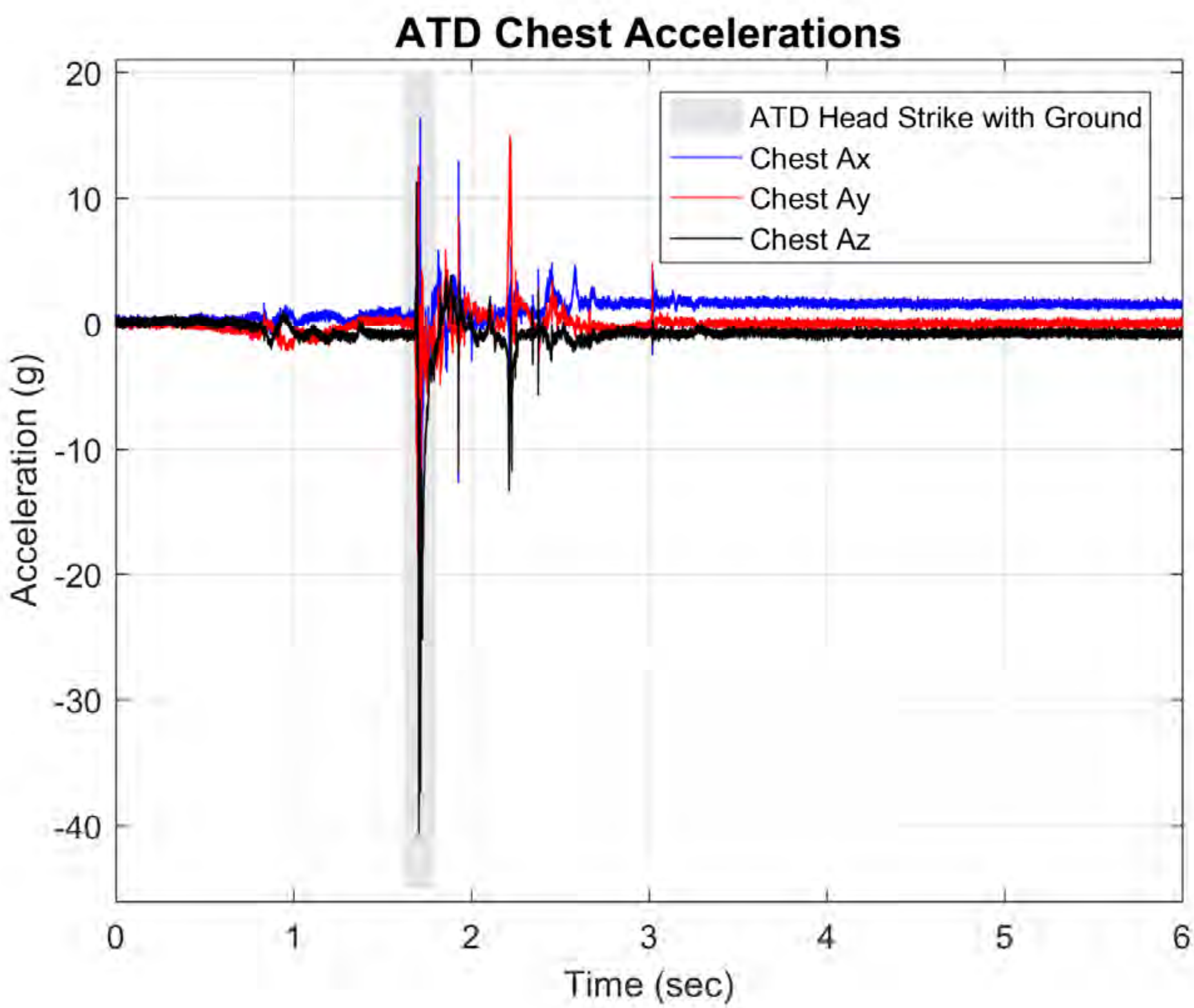
Vehicle G - Dynamic Moderate Energy Rollover with Trip Feature



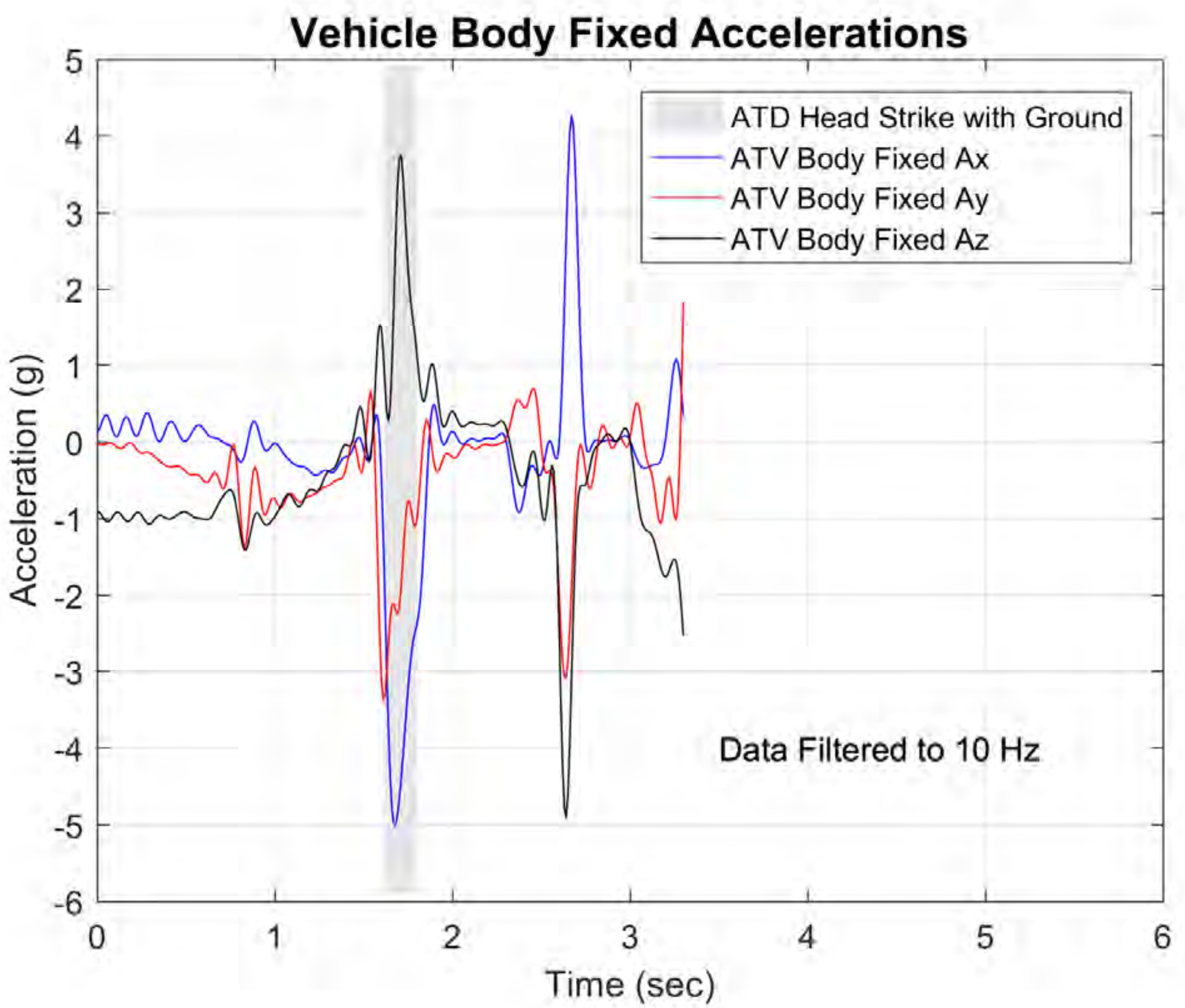
Vehicle G - Dynamic Moderate Energy Rollover with Trip Feature



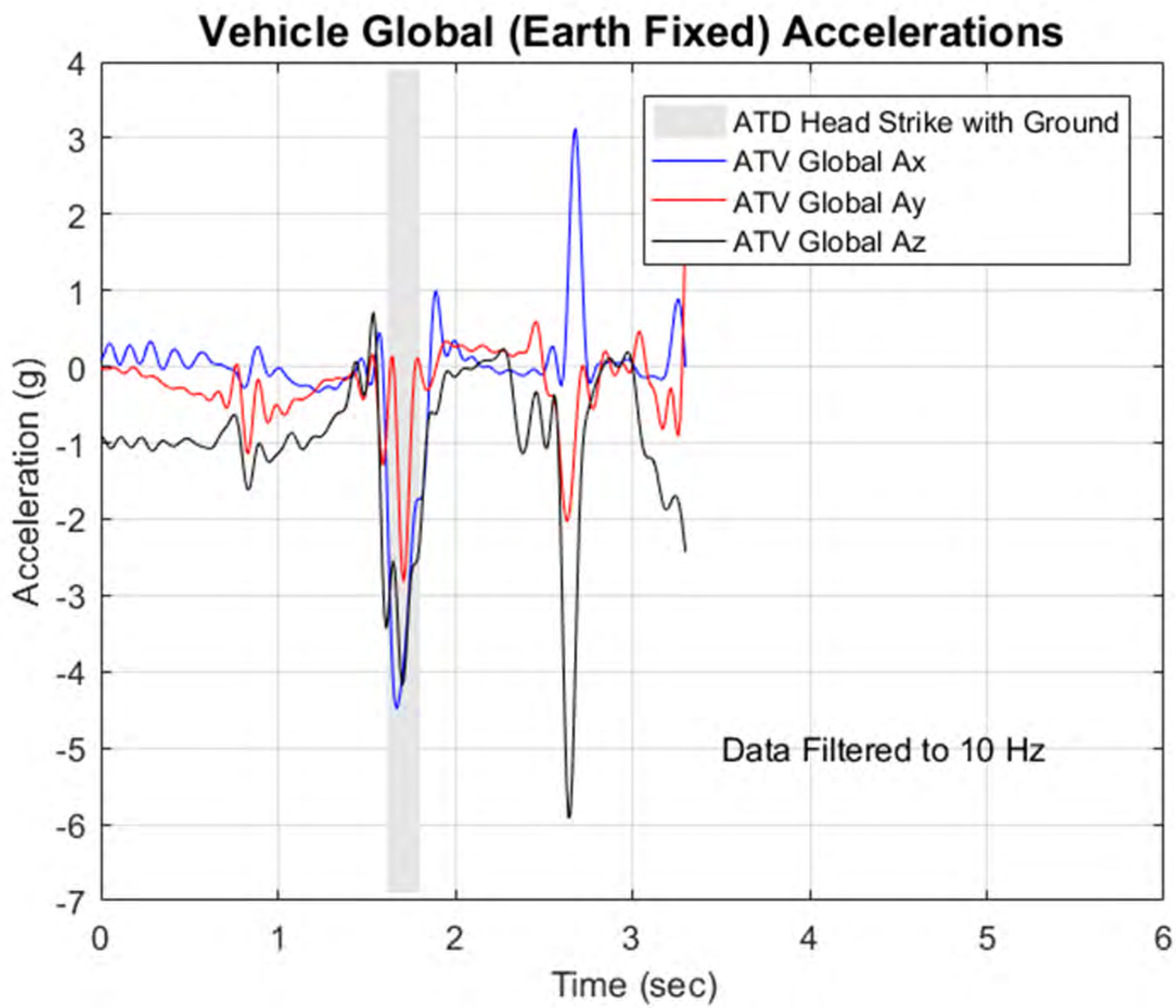
Vehicle G - Dynamic Moderate Energy Rollover with Trip Feature



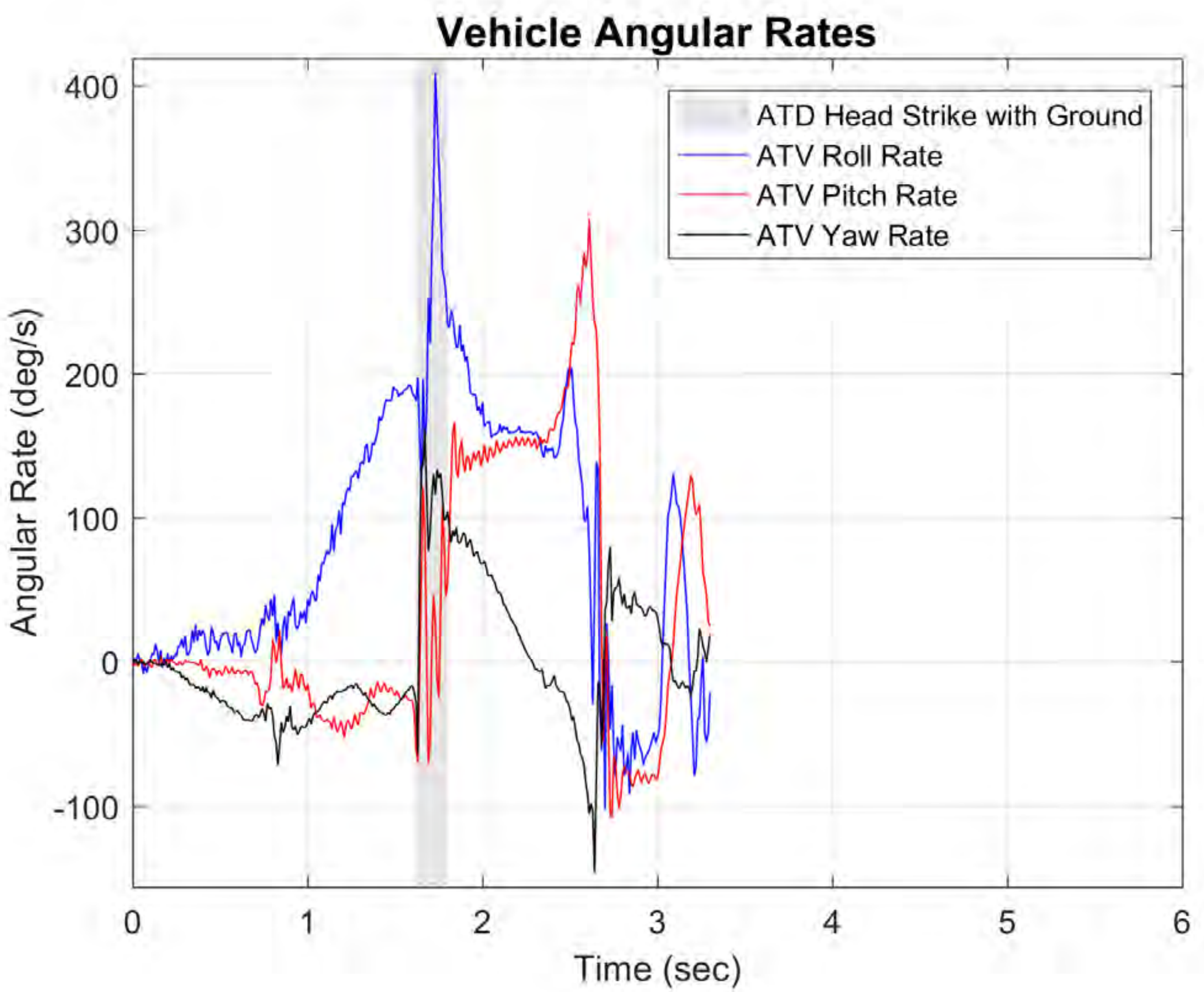
Vehicle G - Dynamic Moderate Energy Rollover with Trip Feature



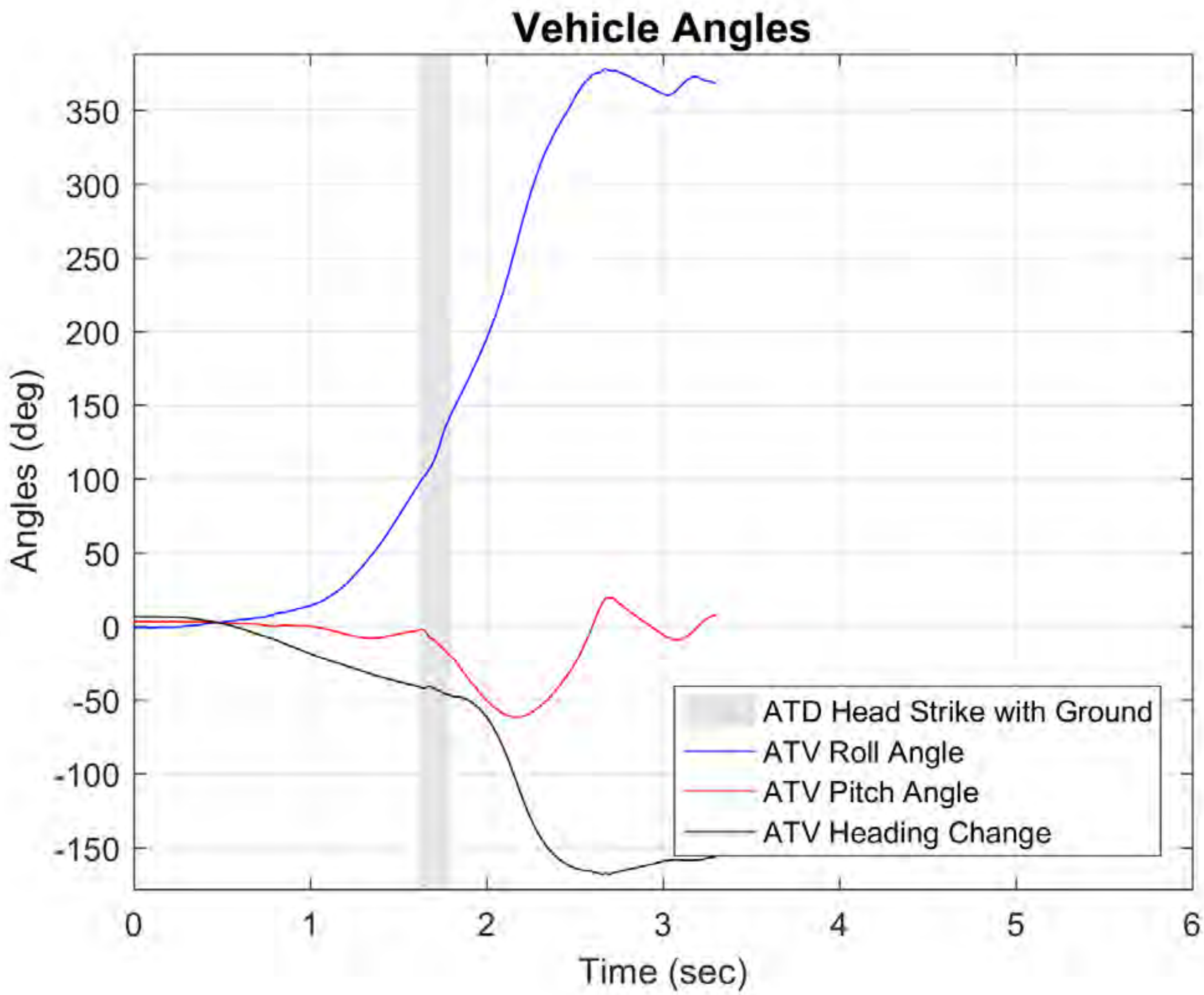
Vehicle G - Dynamic Moderate Energy Rollover with Trip Feature



Vehicle G - Dynamic Moderate Energy Rollover with Trip Feature



Vehicle G - Dynamic Moderate Energy Rollover with Trip Feature



Vehicle G - Dynamic Moderate Energy Rollover with Trip Feature

AOS Camera 1 - Roll Angle = 30° - Time = 2.01 sec

AOS Camera 1 - Roll Angle = 45° - Time = 2.35 sec

AOS Camera 1 - ATD Head Strike - Time = 2.72 sec

AOS Camera 2 - Roll Angle = 30° - Time = 2.01 sec

AOS Camera 2 - Roll Angle = 45° - Time = 2.35 sec

AOS Camera 2 - ATD Head Strike - Time = 2.72 sec

Vehicle L - Dynamic Minimum Energy Rollover

AOS Camera 1 - Roll Angle = 90° - Time = 2.8 sec

AOS Camera 1 - Max Angle = 114.2° - Time = 3.26 sec

AOS Camera 1 - End of Run - Roll Angle = 92.0°

AOS Camera 2 - Roll Angle = 90° - Time = 2.8 sec

AOS Camera 2 - Max Angle = 114.2° - Time = 3.26 sec

AOS Camera 2 - End of Run - Roll Angle = 92.0°

Vehicle L - Dynamic Minimum Energy Rollover

RT Camera 1 - Roll Angle = 30° - Time = 2.01 sec

RT Camera 1 - Roll Angle = 45° - Time = 2.35 sec

RT Camera 1 - ATD Head Strike - Time = 2.72 sec

RT Camera 2 - Roll Angle = 30° - Time = 2.01 sec

RT Camera 2 - Roll Angle = 45° - Time = 2.35 sec

RT Camera 2 - ATD Head Strike - Time = 2.72 sec

Vehicle L - Dynamic Minimum Energy Rollover

RT Camera 1 - Roll Angle = 90° - Time = 2.8 sec

RT Camera 1 - Max Angle = 114.2° - Time = 3.26 sec

RT Camera 1 - End of Run - Roll Angle = 92.0°

RT Camera 2 - Roll Angle = 90° - Time = 2.8 sec

RT Camera 2 - Max Angle = 114.2° - Time = 3.26 sec

RT Camera 2 - End of Run - Roll Angle = 92.0°

Vehicle L - Dynamic Minimum Energy Rollover

Drone Camera - Roll Angle = 30° - Time = 2.01 sec

Drone Camera - Roll Angle = 45° - Time = 2.35 sec

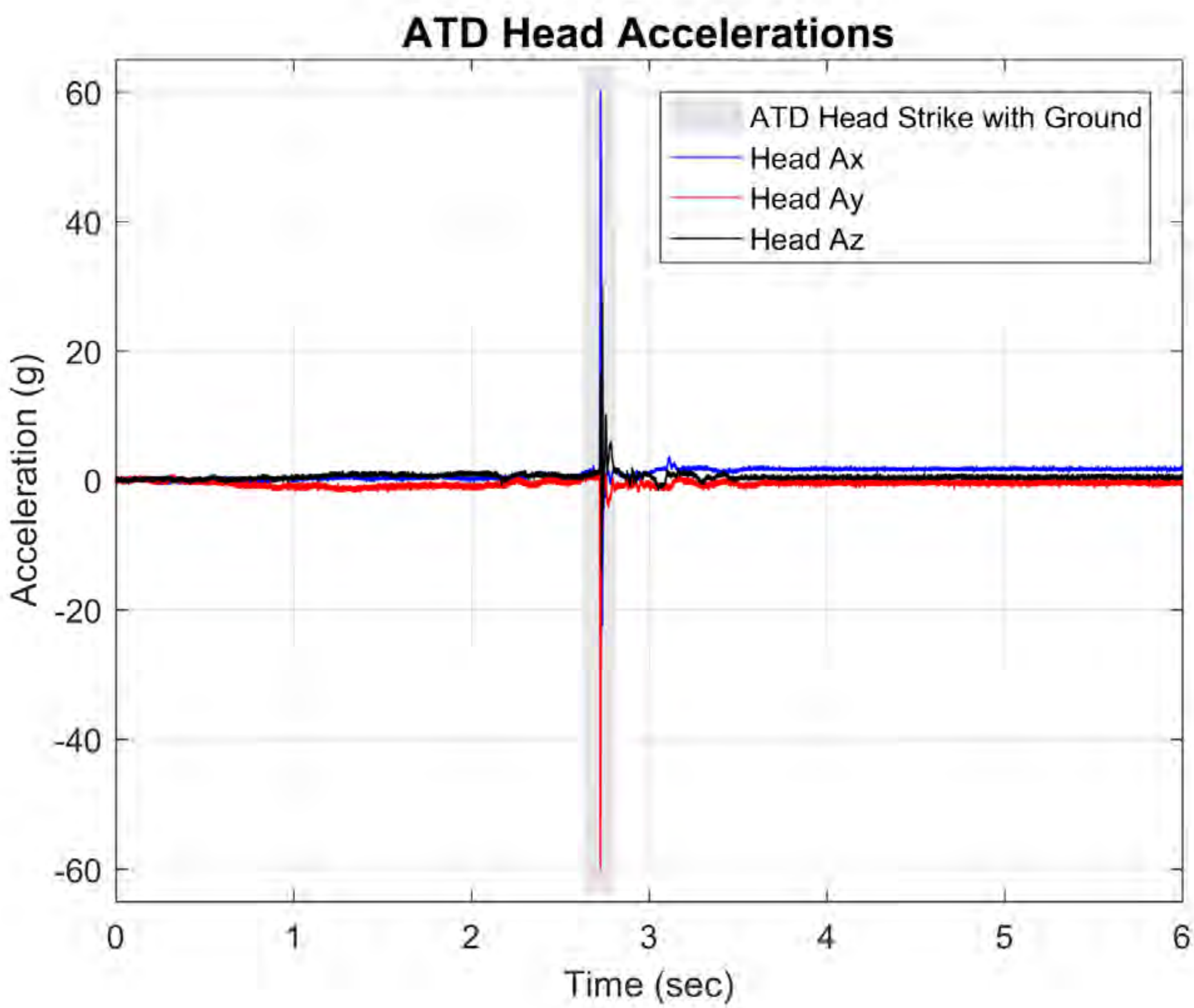
Drone Camera - ATD Head Strike - Time = 2.72 sec

Drone Camera - Roll Angle = 90° - Time = 2.8 sec

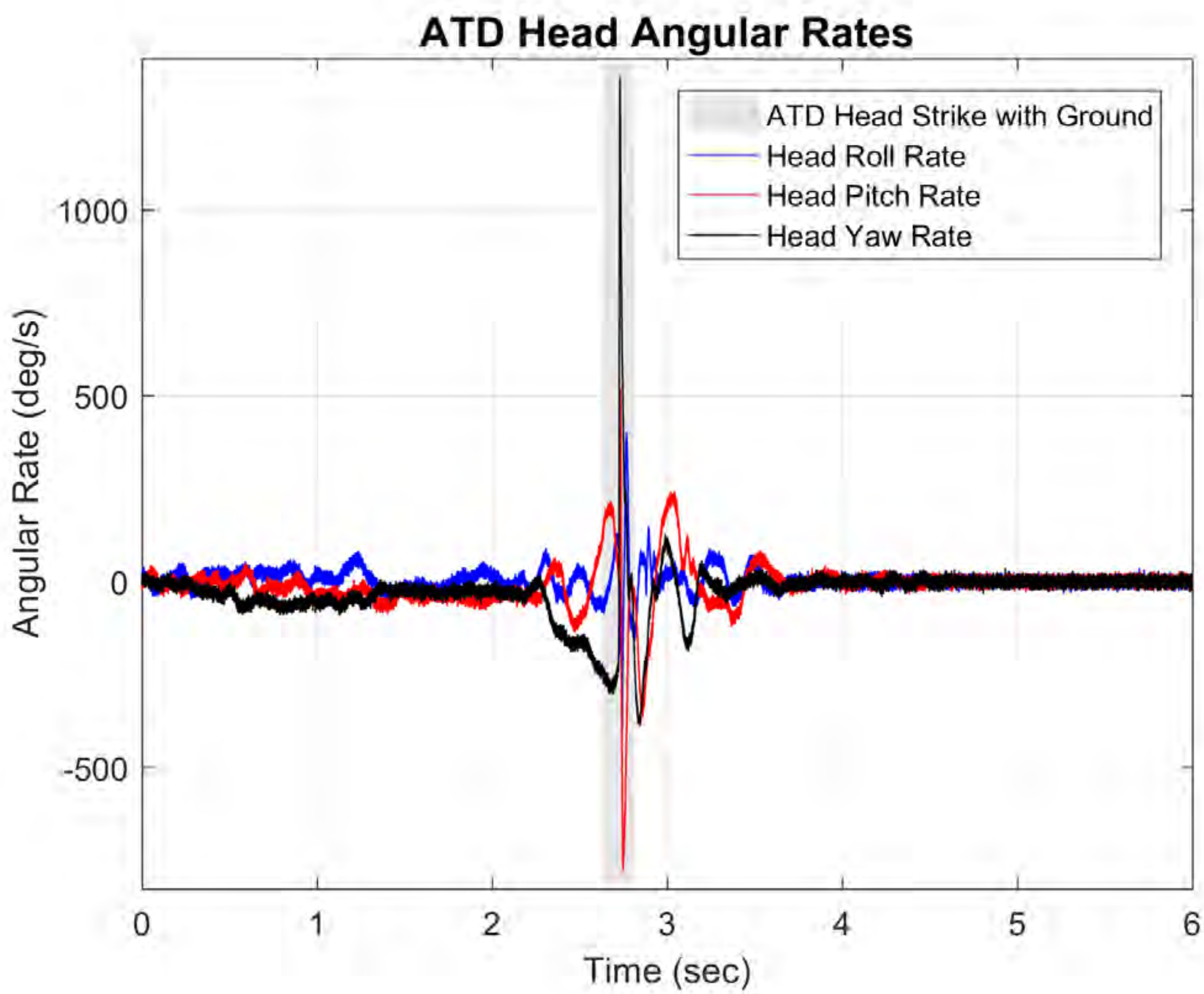
Drone Camera - Max Angle = 114.2° - Time = 3.26 sec

Drone Camera - End of Run - Roll Angle = 92.0°

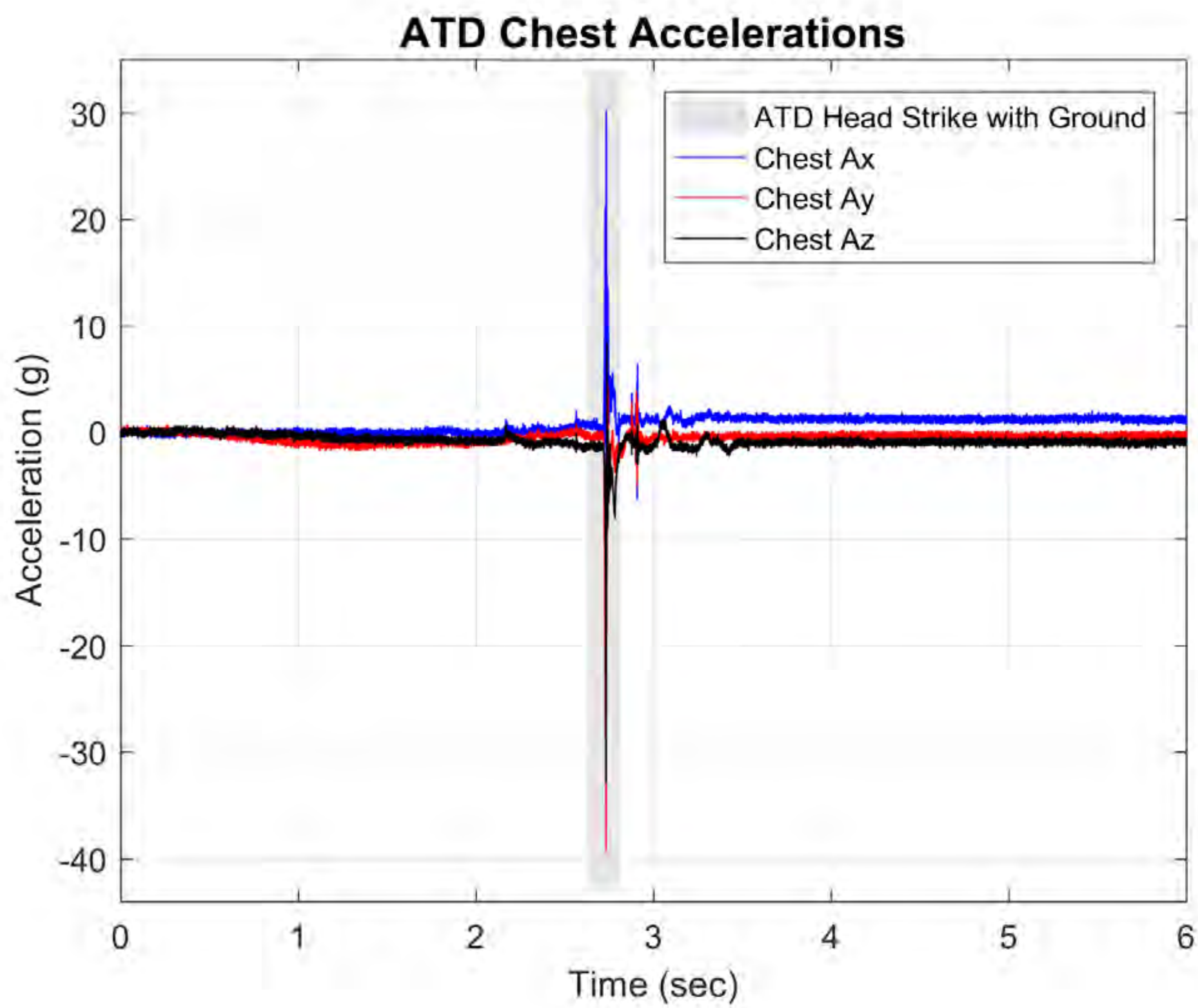
Vehicle L - Dynamic Minimum Energy Rollover



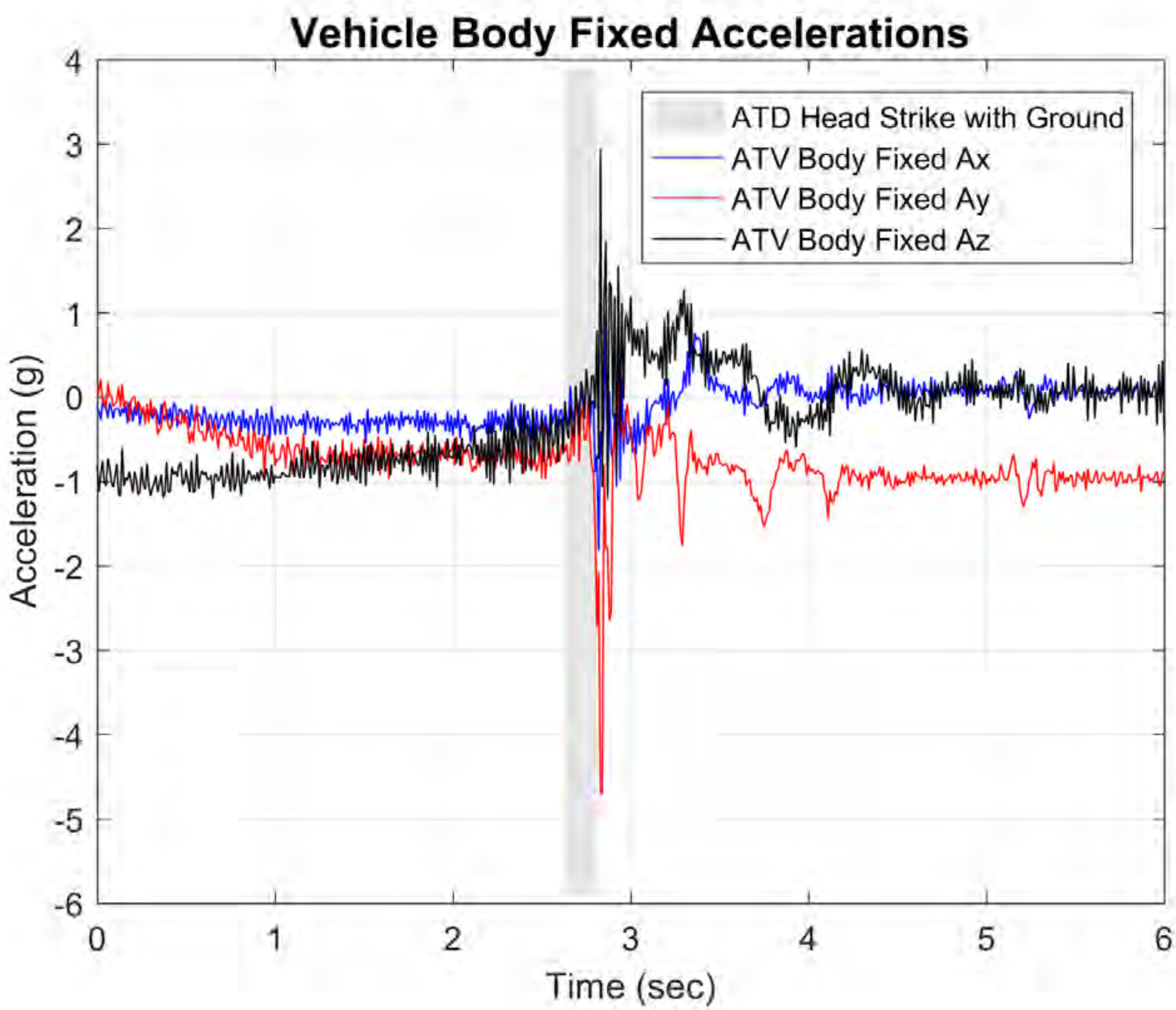
Vehicle L - Dynamic Minimum Energy Rollover



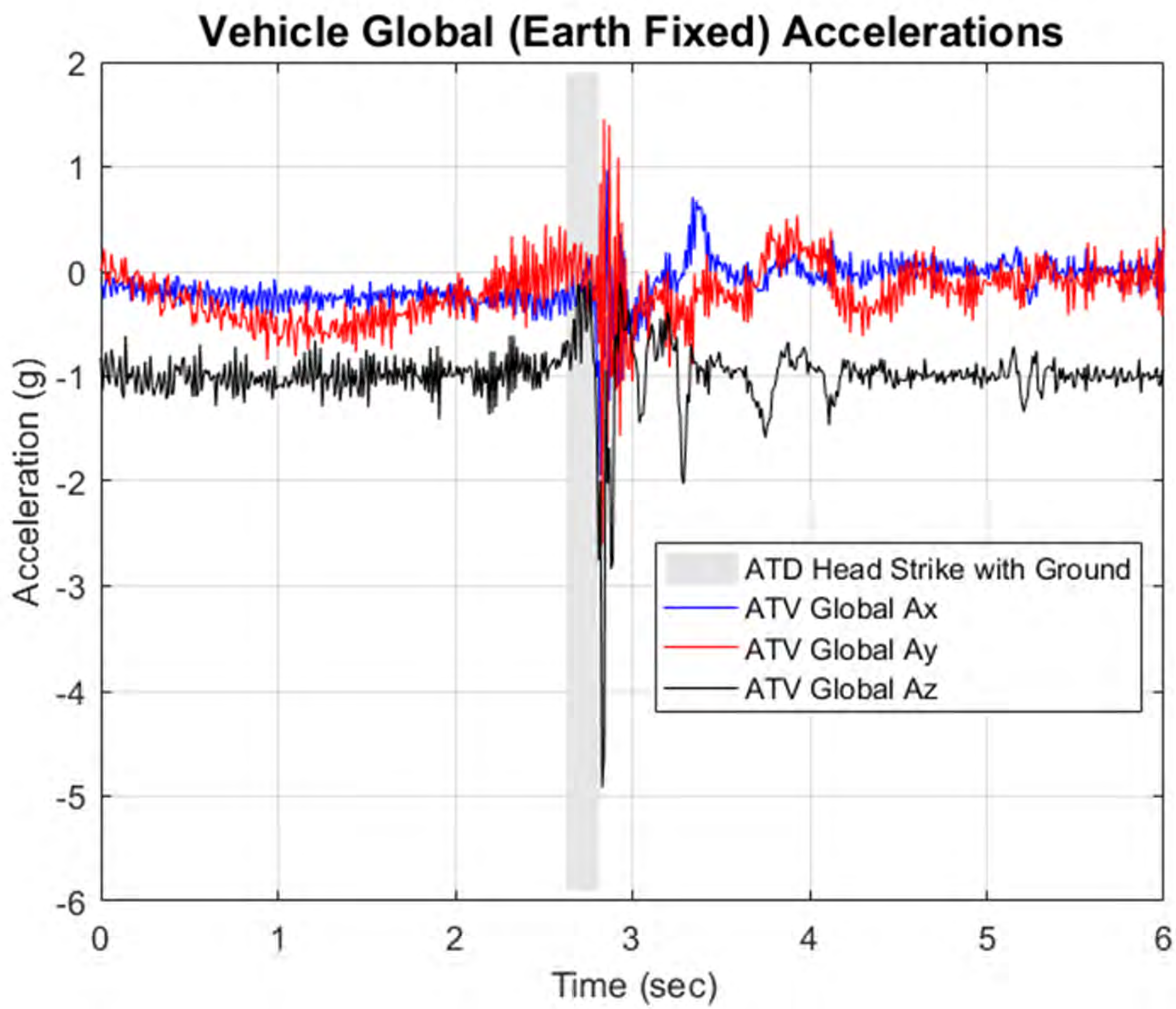
Vehicle L - Dynamic Minimum Energy Rollover



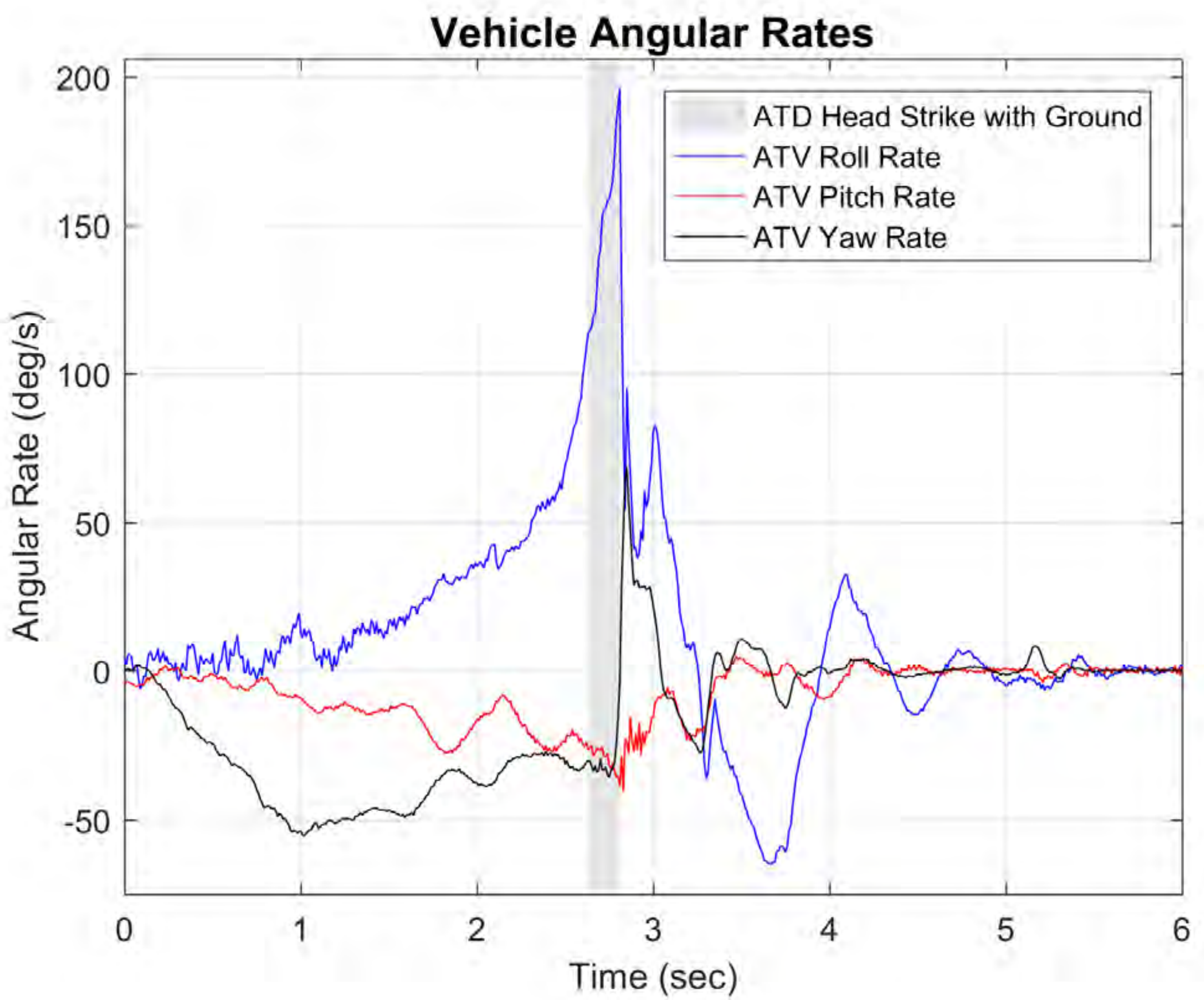
Vehicle L - Dynamic Minimum Energy Rollover



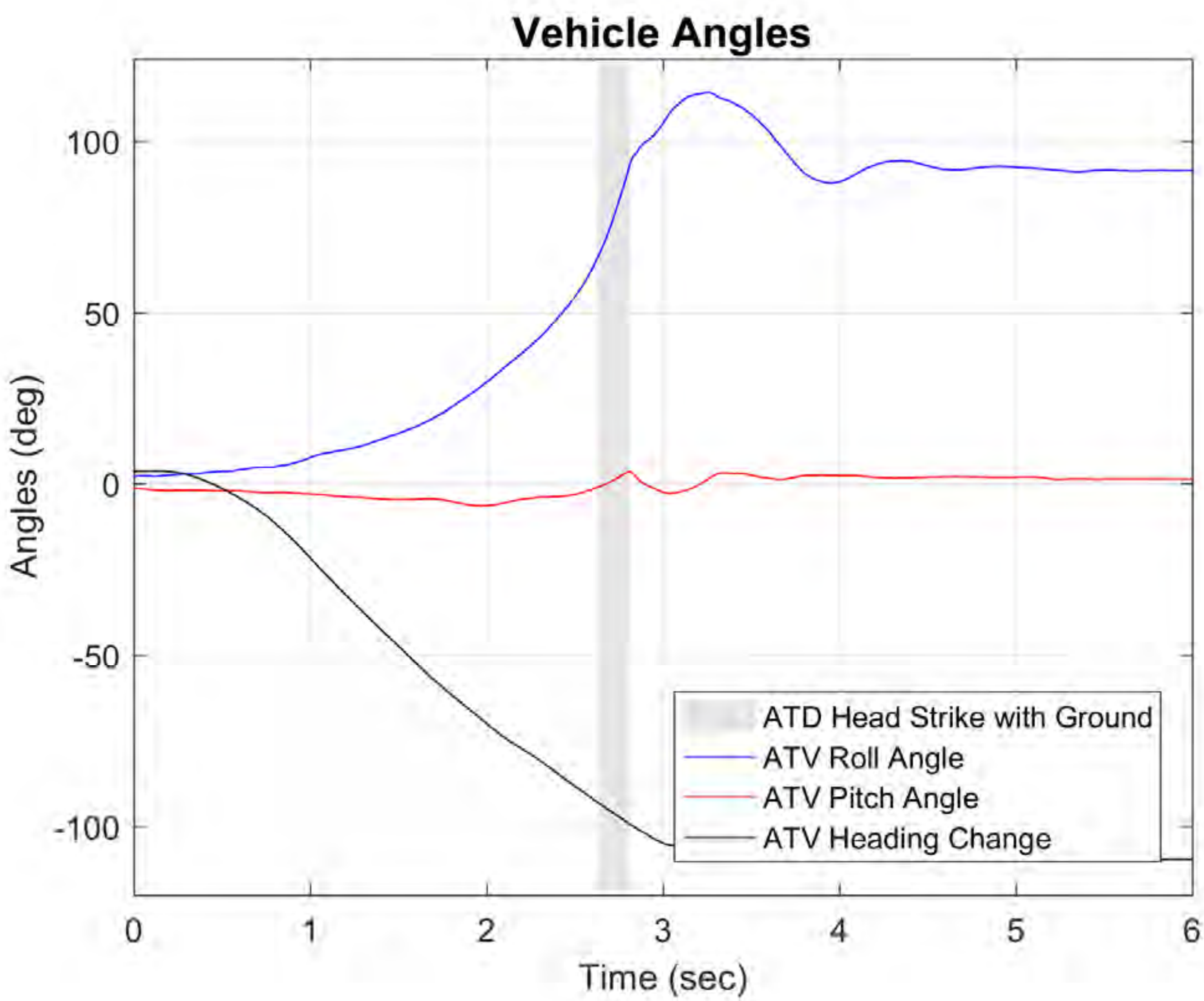
Vehicle L - Dynamic Minimum Energy Rollover



Vehicle L - Dynamic Minimum Energy Rollover



Vehicle L - Dynamic Minimum Energy Rollover



Vehicle L - Dynamic Minimum Energy Rollover

AOS Camera 1 - Roll Angle = 30° - Time = 1.34 sec

AOS Camera 1 - Roll Angle = 45° - Time = 1.42 sec

AOS Camera 1 - Roll Angle = 90° - Time = 1.6 sec

AOS Camera 2 - Roll Angle = 30° - Time = 1.34 sec

AOS Camera 2 - Roll Angle = 45° - Time = 1.42 sec

AOS Camera 2 - Roll Angle = 90° - Time = 1.6 sec

Vehicle L - Dynamic Moderate Energy Rollover

AOS Camera 1 - ATD Head Strike - Time = 1.84 sec

AOS Camera 1 - Roll Angle = 180° - Time = 1.94 sec

AOS Camera 1 - Roll Angle = 270° - Time = 2.47 sec

AOS Camera 2 - ATD Head Strike - Time = 1.84 sec

AOS Camera 2 - Roll Angle = 180° - Time = 1.94 sec

AOS Camera 2 - Roll Angle = 270° - Time = 2.47 sec

Vehicle L - Dynamic Moderate Energy Rollover

AOS Camera 1 - Roll Angle = 360° - Time = 3.08 sec

AOS Camera 1 - Max Angle = 366.4° - Time = 3.12 sec

AOS Camera 1 - End of Run - Roll Angle = 358.9°

AOS Camera 2 - Roll Angle = 360° - Time = 3.08 sec

AOS Camera 2 - Max Angle = 366.4° - Time = 3.12 sec

AOS Camera 2 - End of Run - Roll Angle = 358.9°

Vehicle L - Dynamic Moderate Energy Rollover

RT Camera 1 - Roll Angle = 30° - Time = 1.34 sec

RT Camera 1 - Roll Angle = 45° - Time = 1.42 sec

RT Camera 1 - Roll Angle = 90° - Time = 1.6 sec

RT Camera 2 - Roll Angle = 30° - Time = 1.34 sec

RT Camera 2 - Roll Angle = 45° - Time = 1.42 sec

RT Camera 2 - Roll Angle = 90° - Time = 1.6 sec

Vehicle L - Dynamic Moderate Energy Rollover

RT Camera 1 - ATD Head Strike - Time = 1.84 sec

RT Camera 1 - Roll Angle = 180° - Time = 1.94 sec

RT Camera 1 - Roll Angle = 270° - Time = 2.47 sec

RT Camera 2 - ATD Head Strike - Time = 1.84 sec

RT Camera 2 - Roll Angle = 180° - Time = 1.94 sec

RT Camera 2 - Roll Angle = 270° - Time = 2.47 sec

Vehicle L - Dynamic Moderate Energy Rollover

RT Camera 1 - Roll Angle = 360° - Time = 3.08 sec

RT Camera 1 - Max Angle = 366.4° - Time = 3.12 sec

RT Camera 1 - End of Run - Roll Angle = 358.9°

RT Camera 2 - Roll Angle = 360° - Time = 3.08 sec

RT Camera 2 - Max Angle = 366.4° - Time = 3.12 sec

RT Camera 2 - End of Run - Roll Angle = 358.9°

Vehicle L - Dynamic Moderate Energy Rollover

Drone Camera - Roll Angle = 30° - Time = 1.34 sec

Drone Camera - Roll Angle = 45° - Time = 1.42 sec

Drone Camera - Roll Angle = 90° - Time = 1.6 sec

Drone Camera - ATD Head Strike - Time = 1.84 sec

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

Drone Camera - Roll Angle = 270° - Time = 2.47 sec

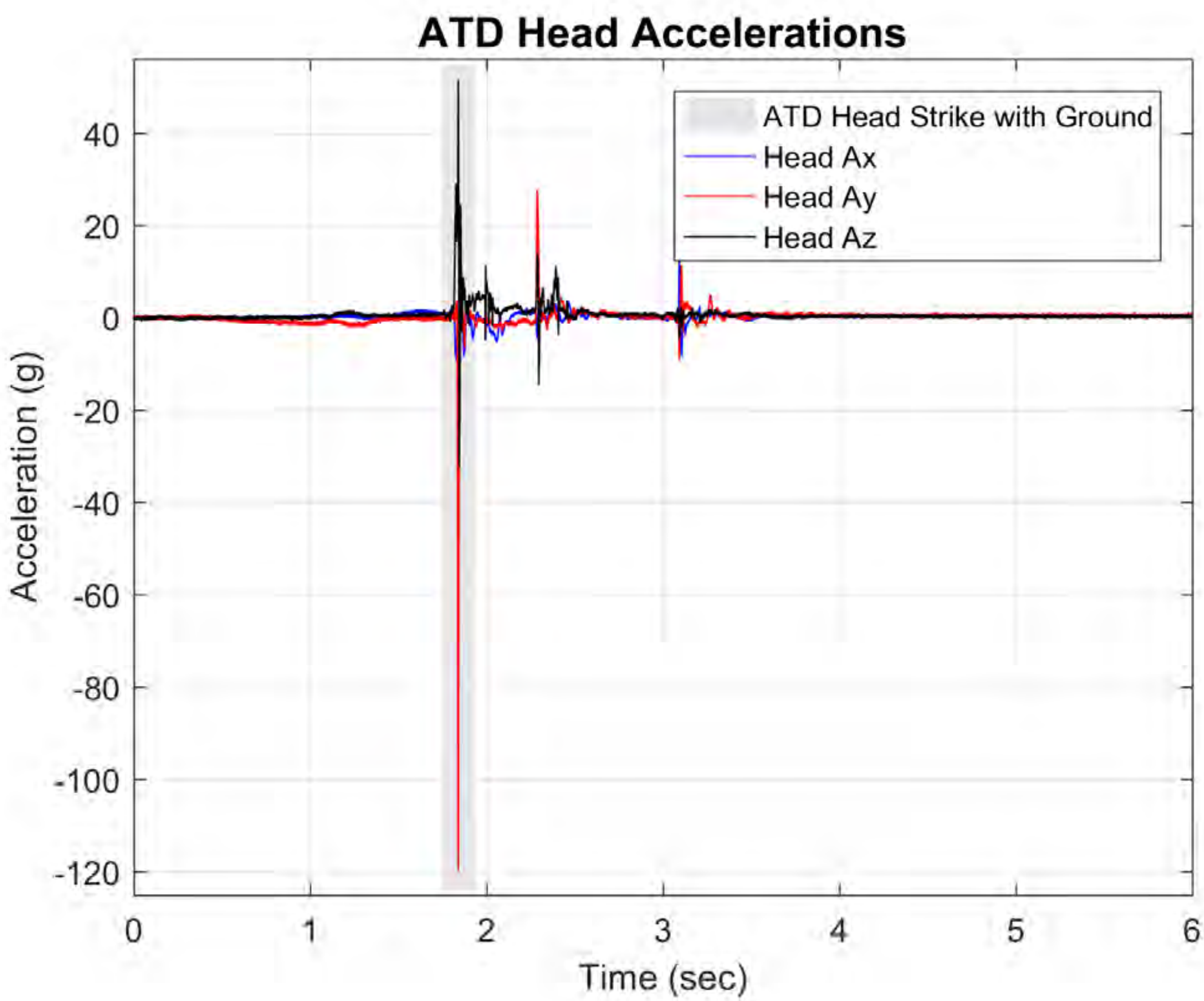
Vehicle L - Dynamic Moderate Energy Rollover

Drone Camera - Roll Angle = 360° - Time = 3.08 sec

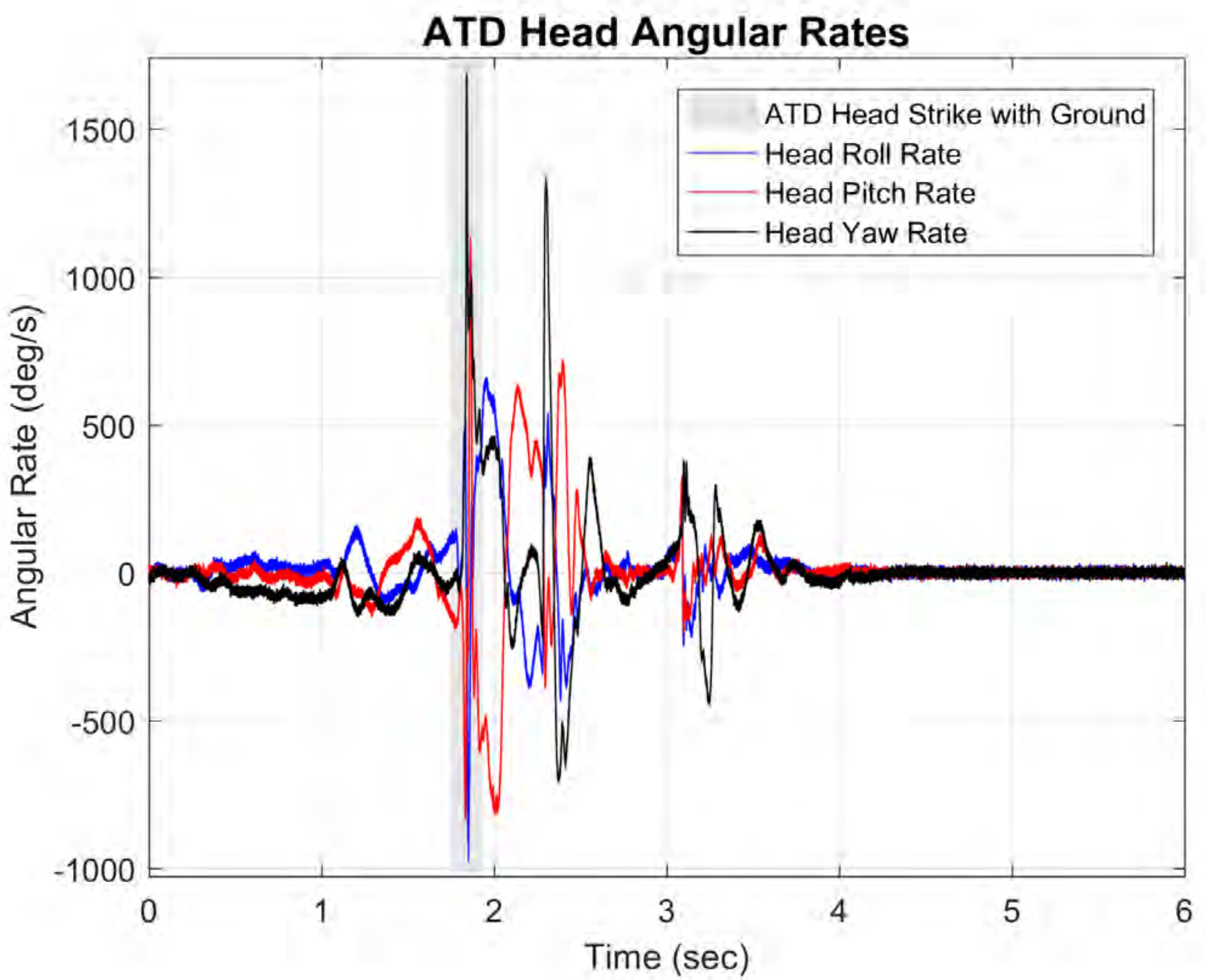
Drone Camera - Max Angle = 366.4° - Time = 3.12 sec

Drone Camera - End of Run - Roll Angle = 358.9°

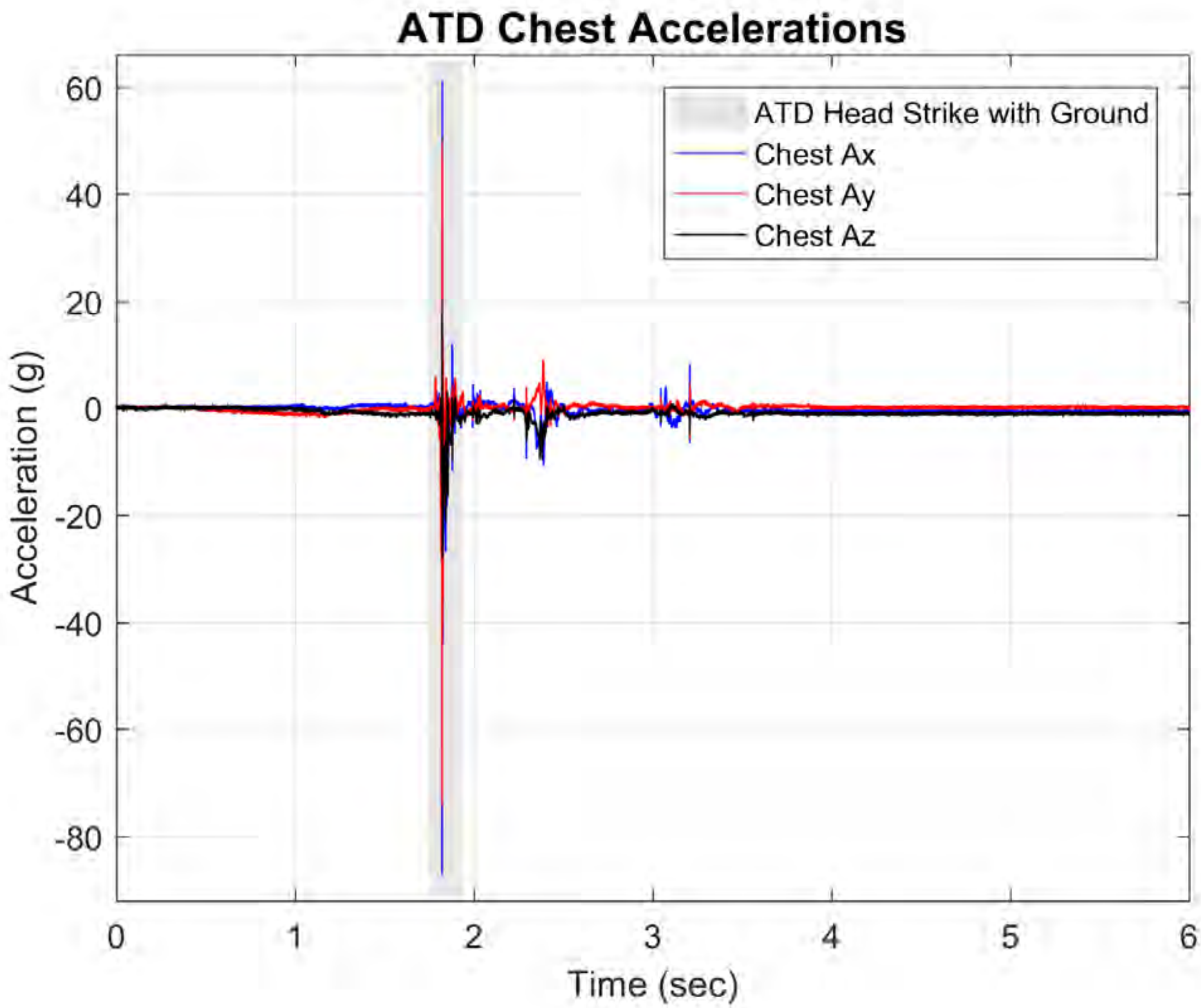
Vehicle L - Dynamic Moderate Energy Rollover



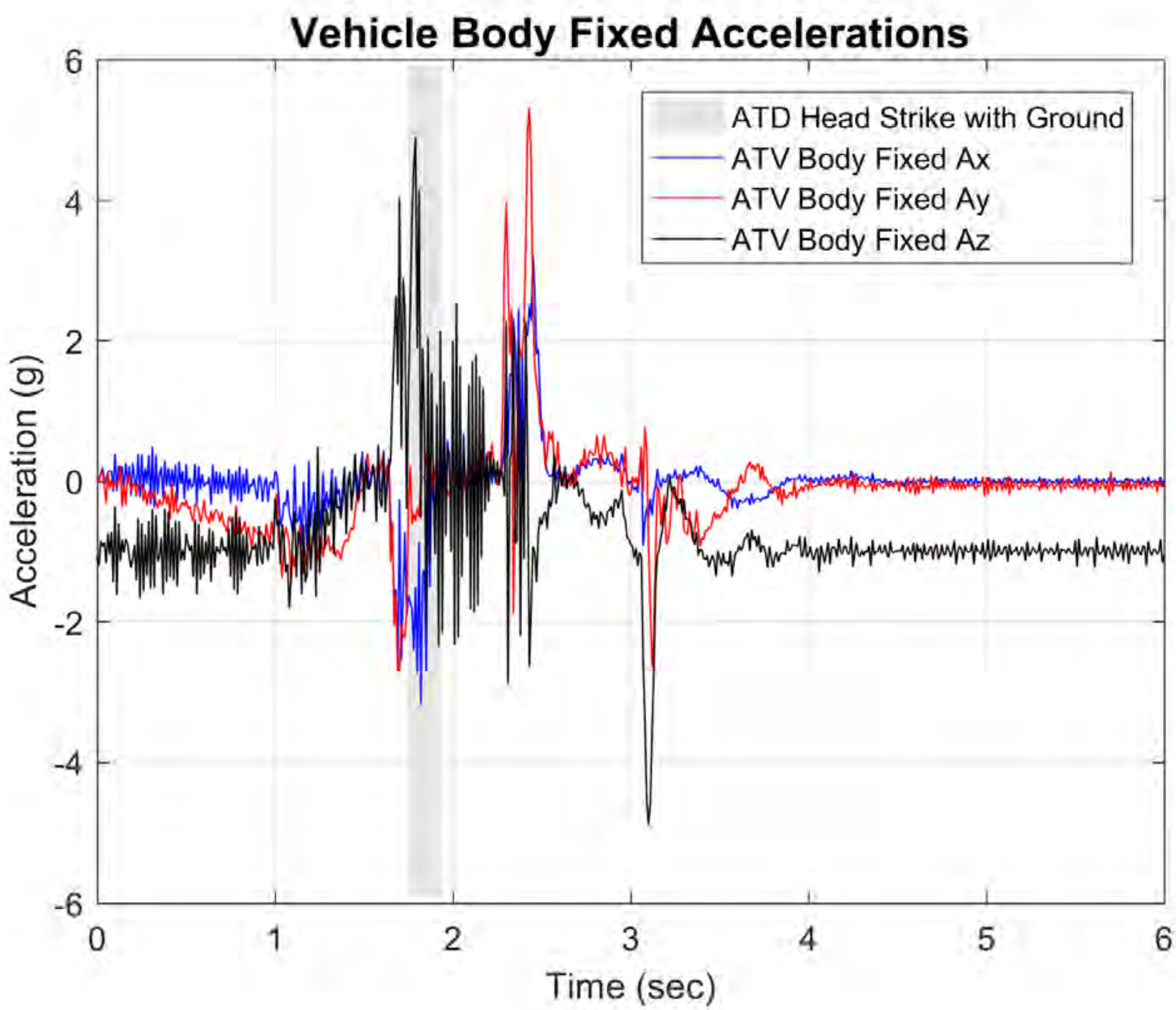
Vehicle L - Dynamic Moderate Energy Rollover



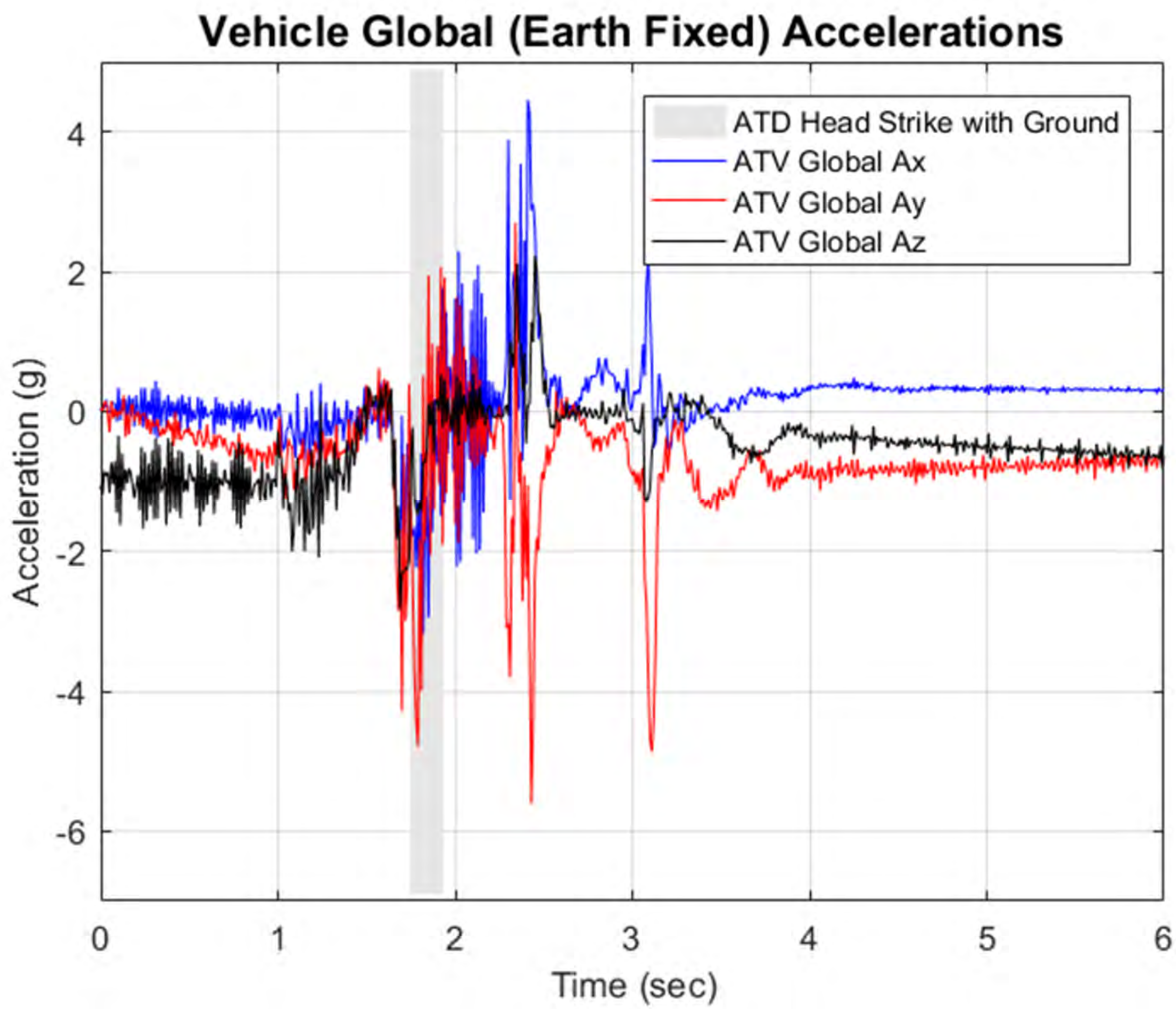
Vehicle L - Dynamic Moderate Energy Rollover



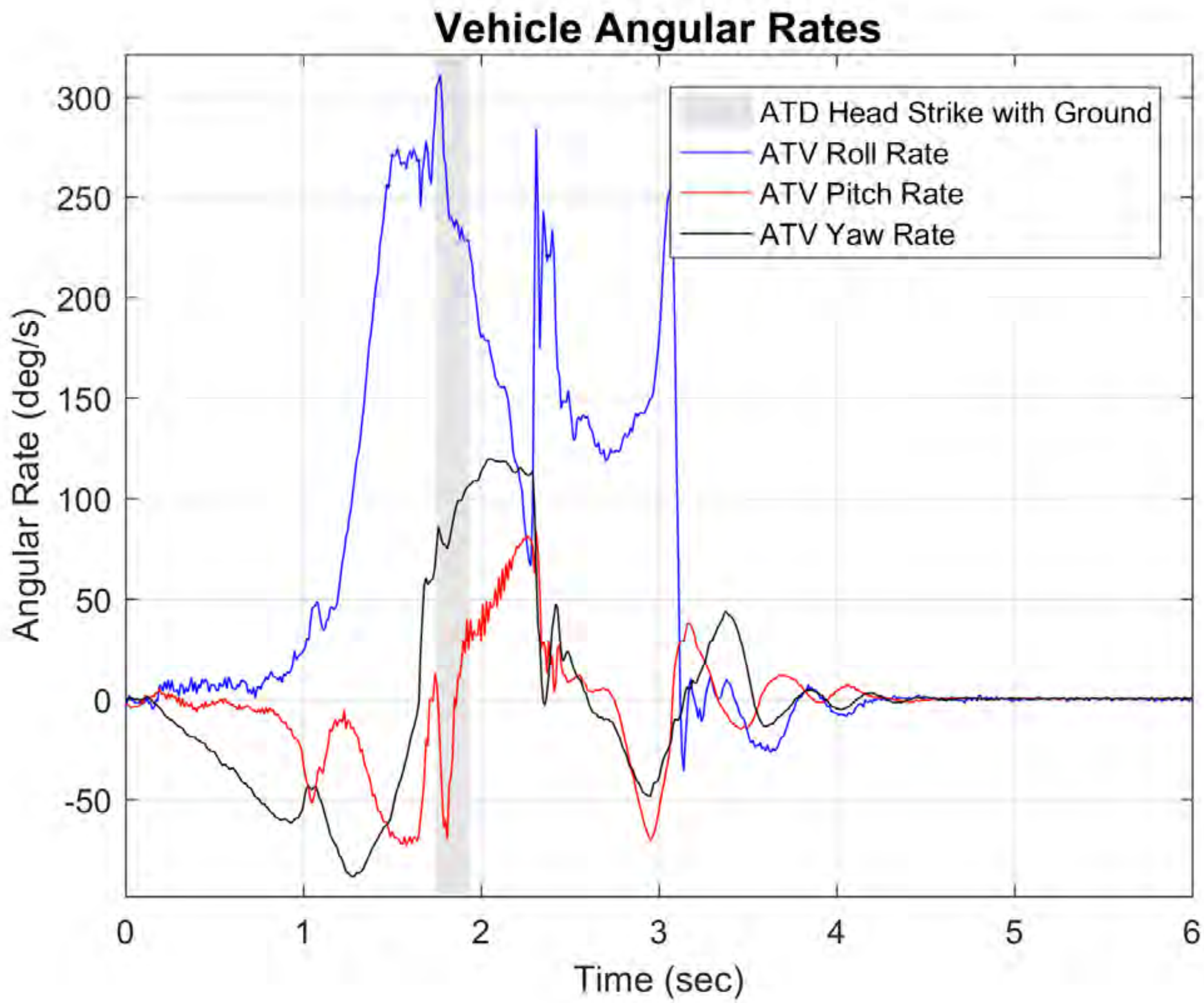
Vehicle L - Dynamic Moderate Energy Rollover



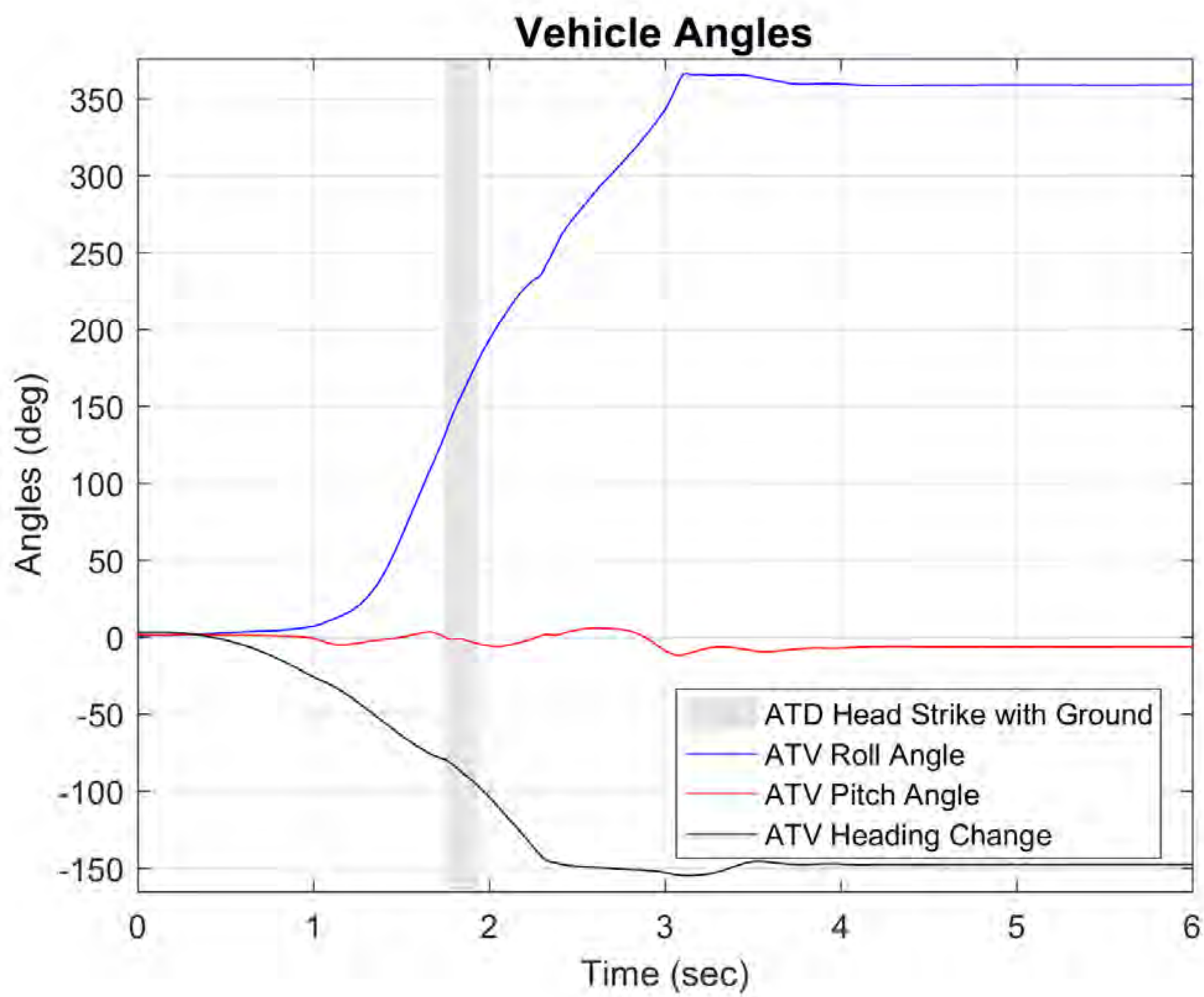
Vehicle L - Dynamic Moderate Energy Rollover



Vehicle L - Dynamic Moderate Energy Rollover



Vehicle L - Dynamic Moderate Energy Rollover



Vehicle L - Dynamic Moderate Energy Rollover

AOS Camera 1 - Roll Angle = 30° - Time = 1.39 sec

AOS Camera 1 - Roll Angle = 45° - Time = 1.48 sec

AOS Camera 1 - Roll Angle = 90° - Time = 1.67 sec

AOS Camera 2 - Roll Angle = 30° - Time = 1.39 sec

AOS Camera 2 - Roll Angle = 45° - Time = 1.48 sec

AOS Camera 2 - Roll Angle = 90° - Time = 1.67 sec

Vehicle L - Dynamic Moderate Energy Rollover with Trip Feature

AOS Camera 1 - ATD Head Strike - Time = 1.95 sec

AOS Camera 1 - Roll Angle = 180° - Time = 2.09 sec

AOS Camera 1 - Roll Angle = 270° - Time = 2.46 sec

AOS Camera 2 - ATD Head Strike - Time = 1.95 sec

AOS Camera 2 - Roll Angle = 180° - Time = 2.09 sec

AOS Camera 2 - Roll Angle = 270° - Time = 2.46 sec

Vehicle L - Dynamic Moderate Energy Rollover with Trip Feature

AOS Camera 1 - Roll Angle = 360° - Time = 2.97 sec

AOS Camera 1 - Max Angle = 373.6° - Time = 3.21 sec

AOS Camera 1 - End of Run - Roll Angle = 361.7°

AOS Camera 2 - Roll Angle = 360° - Time = 2.97 sec

AOS Camera 2 - Max Angle = 373.6° - Time = 3.21 sec

AOS Camera 2 - End of Run - Roll Angle = 361.7°

Vehicle L - Dynamic Moderate Energy Rollover with Trip Feature

RT Camera 1 - Roll Angle = 30° - Time = 1.39 sec

RT Camera 1 - Roll Angle = 45° - Time = 1.48 sec

RT Camera 1 - Roll Angle = 90° - Time = 1.67 sec

RT Camera 2 - Roll Angle = 30° - Time = 1.39 sec

RT Camera 2 - Roll Angle = 45° - Time = 1.48 sec

RT Camera 2 - Roll Angle = 90° - Time = 1.67 sec

Vehicle L - Dynamic Moderate Energy Rollover with Trip Feature

RT Camera 1 - ATD Head Strike - Time = 1.95 sec

RT Camera 1 - Roll Angle = 180° - Time = 2.09 sec

RT Camera 1 - Roll Angle = 270° - Time = 2.46 sec

RT Camera 2 - ATD Head Strike - Time = 1.95 sec

RT Camera 2 - Roll Angle = 180° - Time = 2.09 sec

RT Camera 2 - Roll Angle = 270° - Time = 2.46 sec

Vehicle L - Dynamic Moderate Energy Rollover with Trip Feature

RT Camera 1 - Roll Angle = 360° - Time = 2.97 sec

RT Camera 1 - Max Angle = 373.6° - Time = 3.21 sec

RT Camera 1 - End of Run - Roll Angle = 361.7°

RT Camera 2 - Roll Angle = 360° - Time = 2.97 sec

RT Camera 2 - Max Angle = 373.6° - Time = 3.21 sec

RT Camera 2 - End of Run - Roll Angle = 361.7°

Vehicle L - Dynamic Moderate Energy Rollover with Trip Feature

Drone Camera - Roll Angle = 30° - Time = 1.39 sec

Drone Camera - Roll Angle = 45° - Time = 1.48 sec

Drone Camera - Roll Angle = 90° - Time = 1.67 sec

Drone Camera - ATD Head Strike - Time = 1.95 sec

Drone Camera - Roll Angle = 180° - Time = 2.09 sec

Drone Camera - Roll Angle = 270° - Time = 2.46 sec

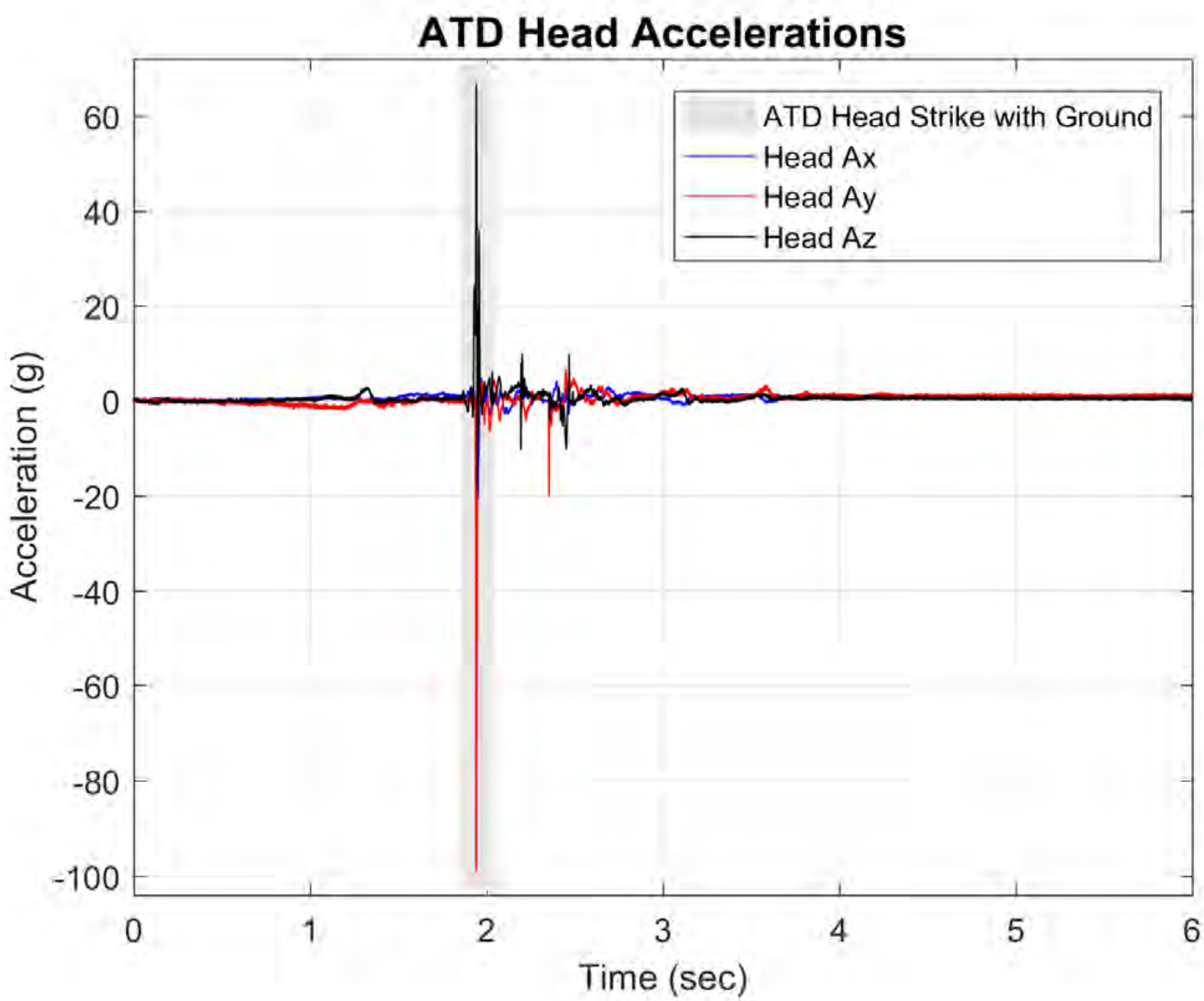
Vehicle L - Dynamic Moderate Energy Rollover with Trip Feature

Drone Camera - Roll Angle = 360° - Time = 2.97 sec

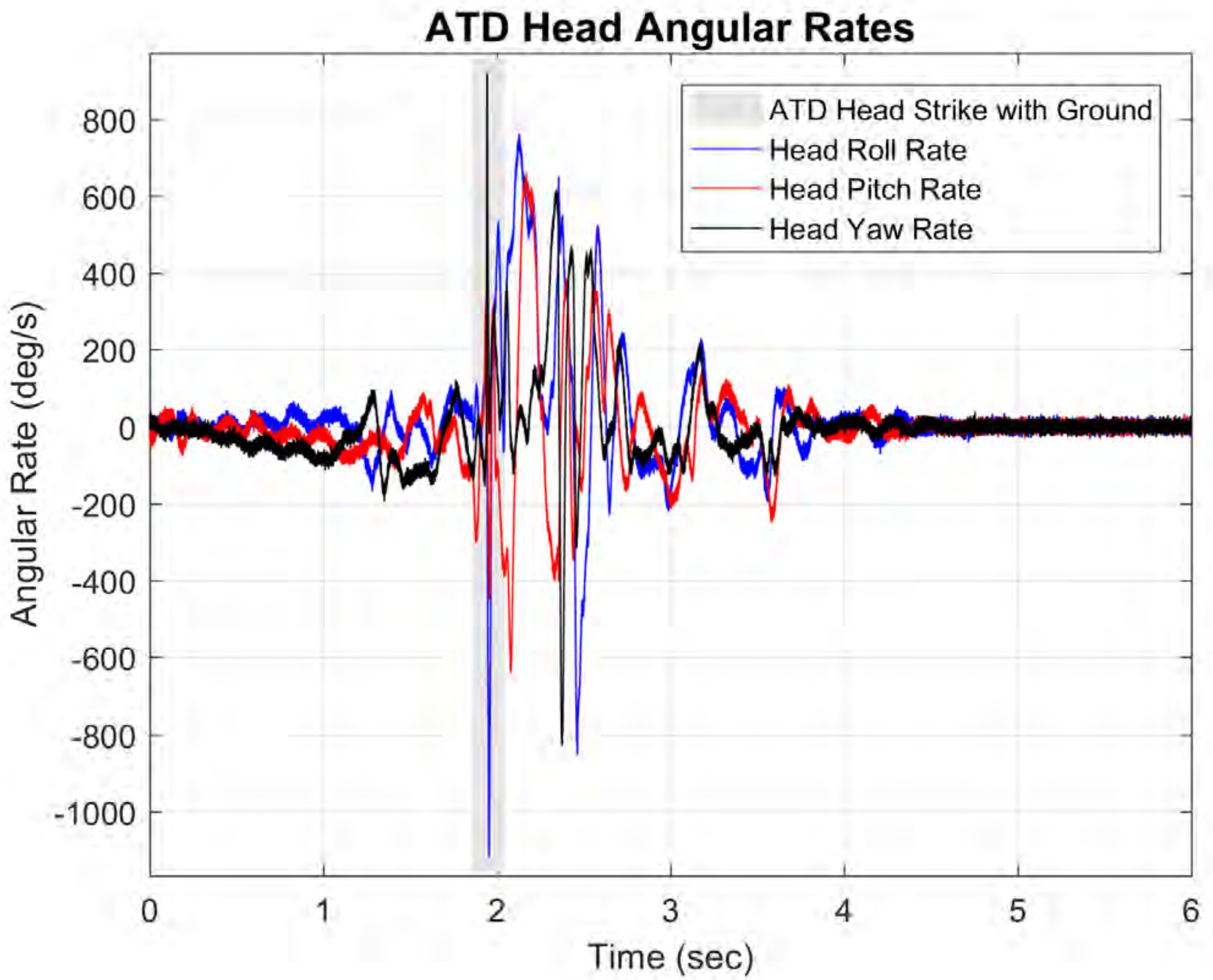
Drone Camera - Max Angle = 373.6° - Time = 3.21 sec

Drone Camera - End of Run - Roll Angle = 361.7°

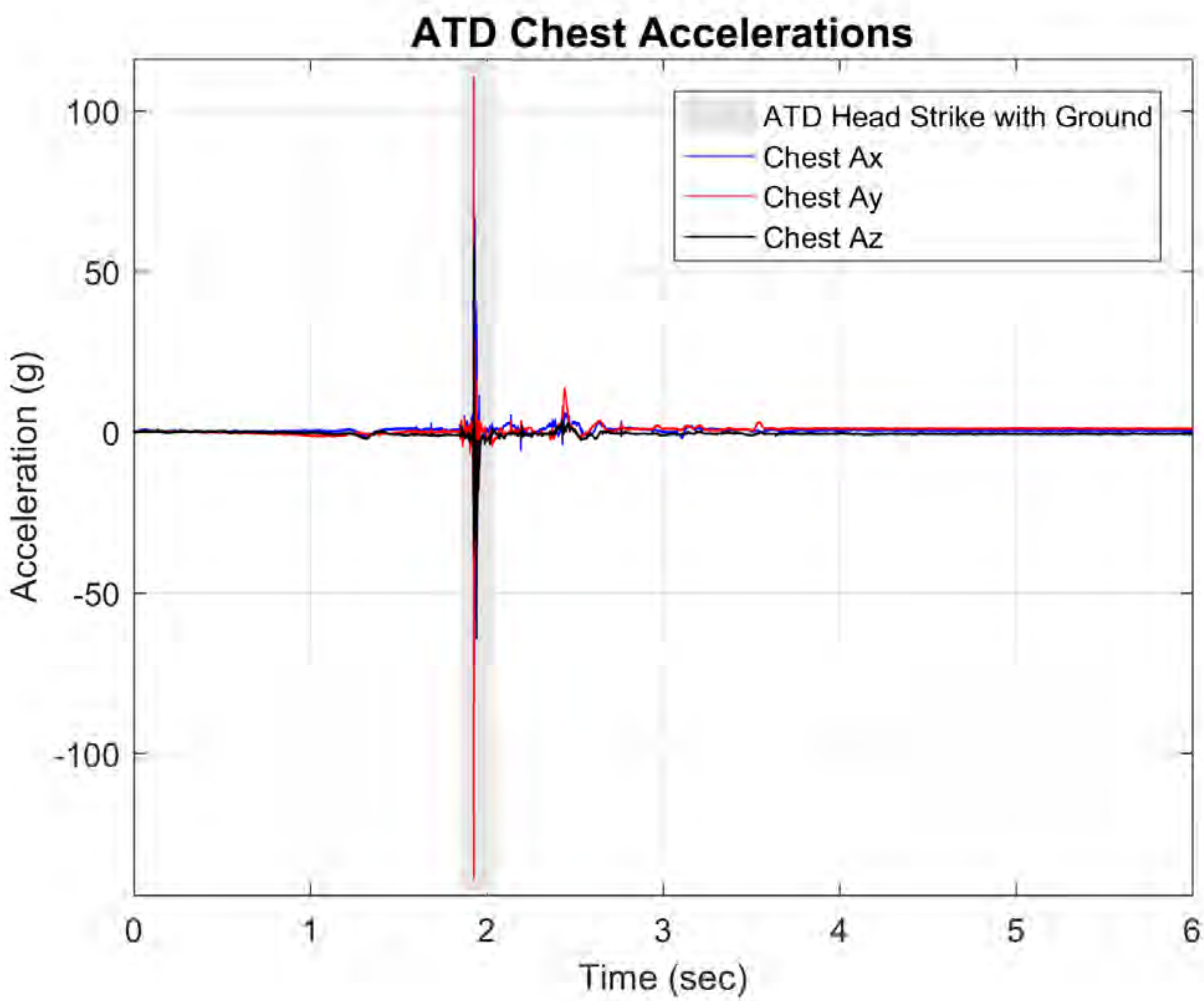
Vehicle L - Dynamic Moderate Energy Rollover with Trip Feature



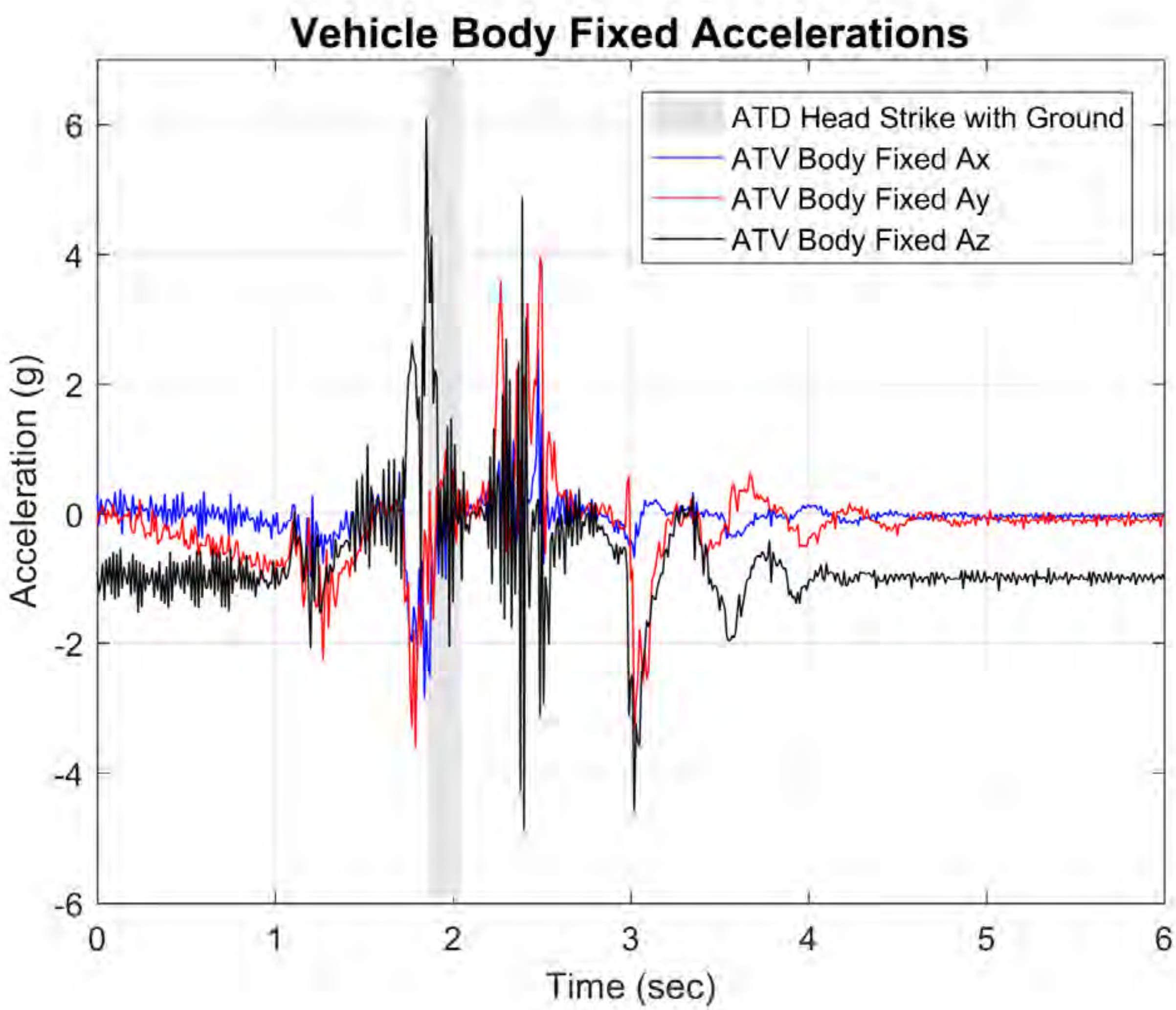
Vehicle L - Dynamic Moderate Energy Rollover with Trip Feature



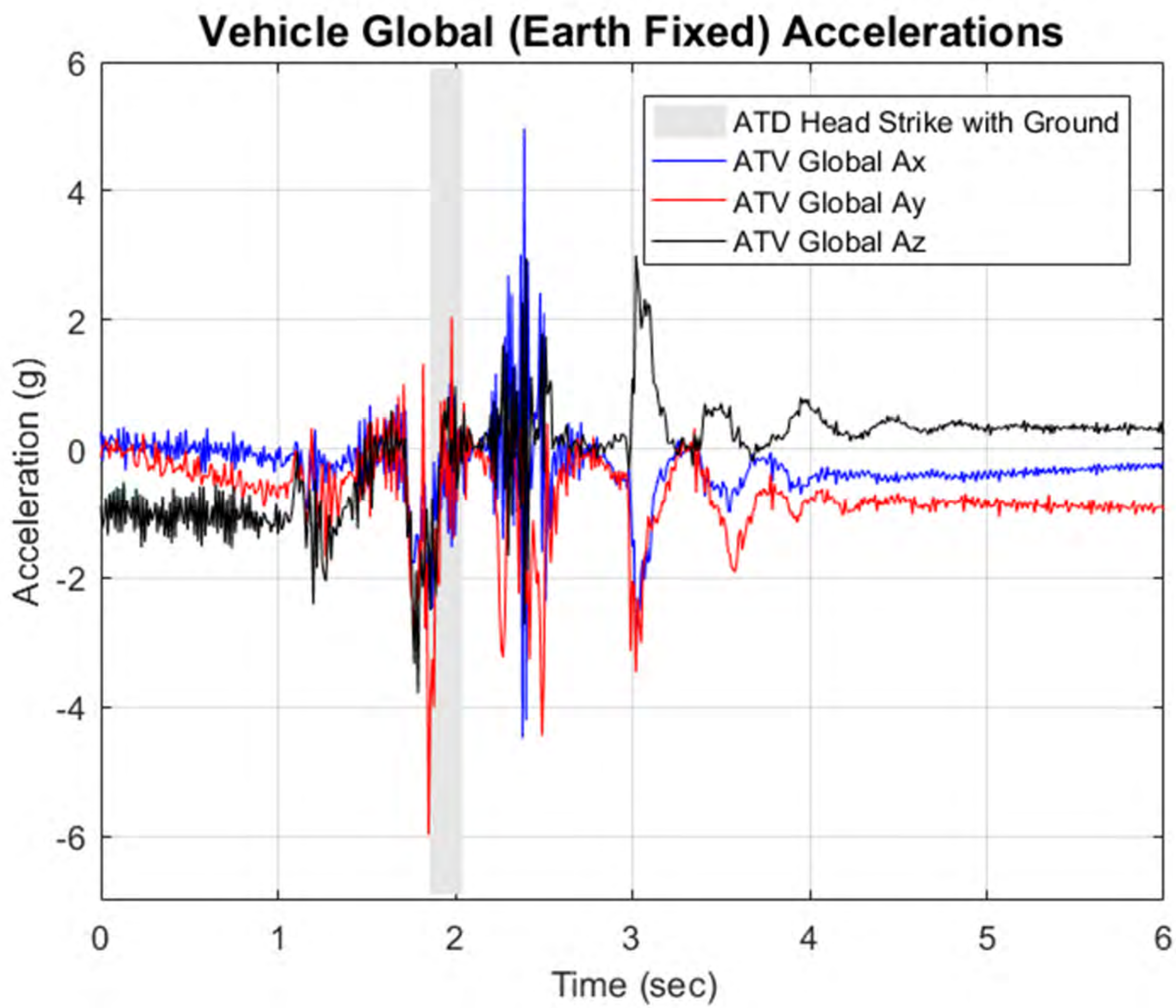
Vehicle L - Dynamic Moderate Energy Rollover with Trip Feature



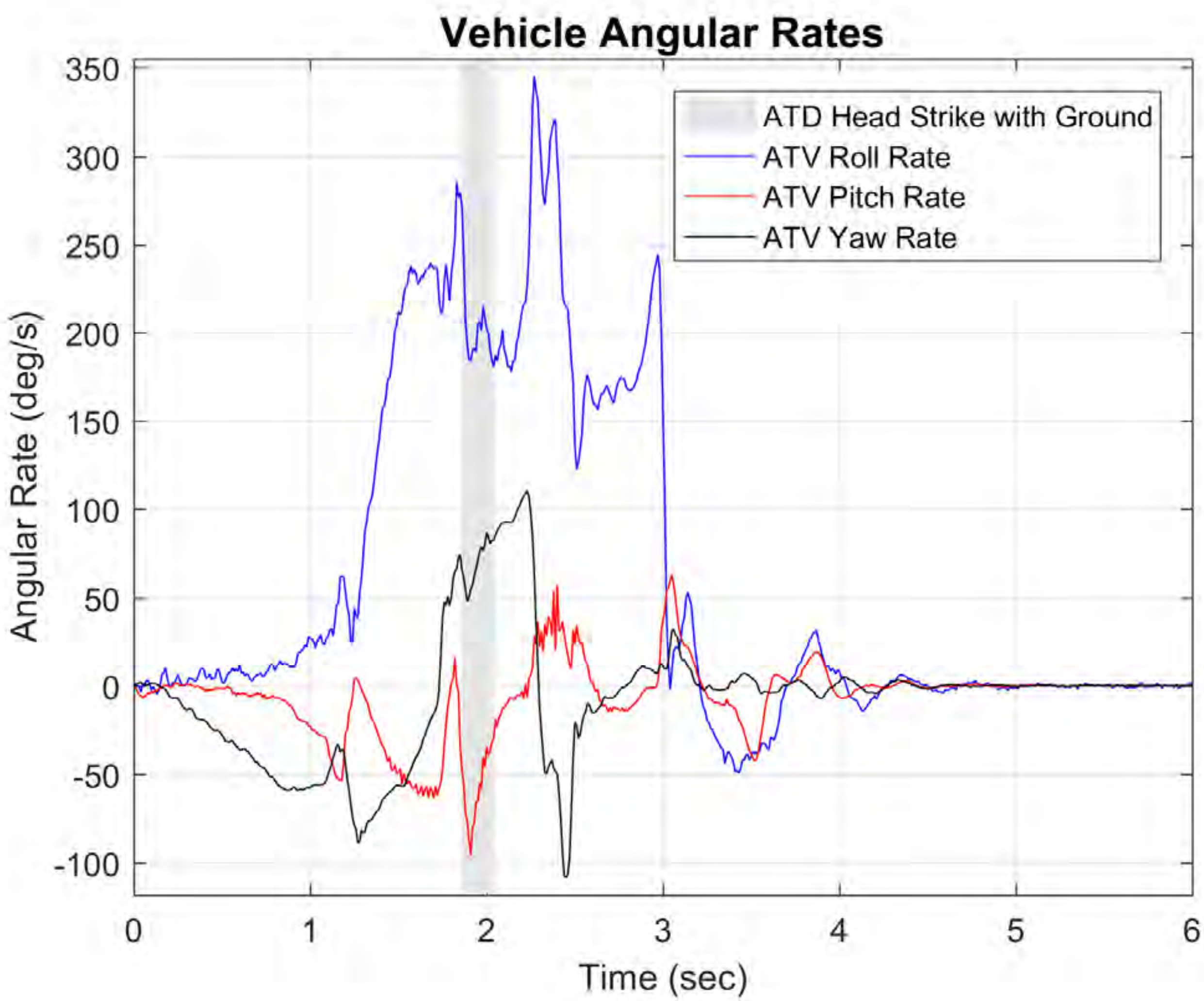
Vehicle L - Dynamic Moderate Energy Rollover with Trip Feature



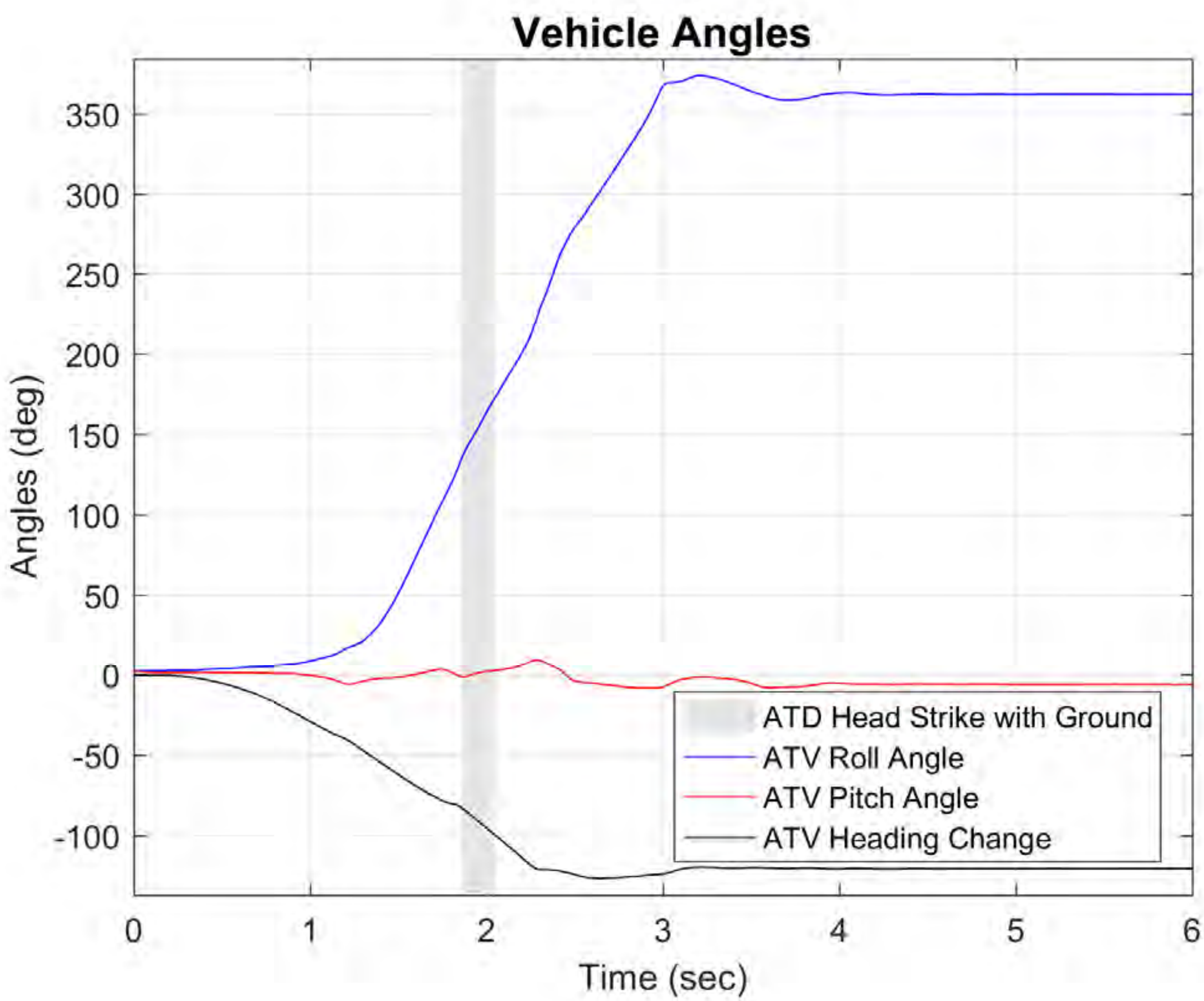
Vehicle L - Dynamic Moderate Energy Rollover with Trip Feature



Vehicle L - Dynamic Moderate Energy Rollover with Trip Feature



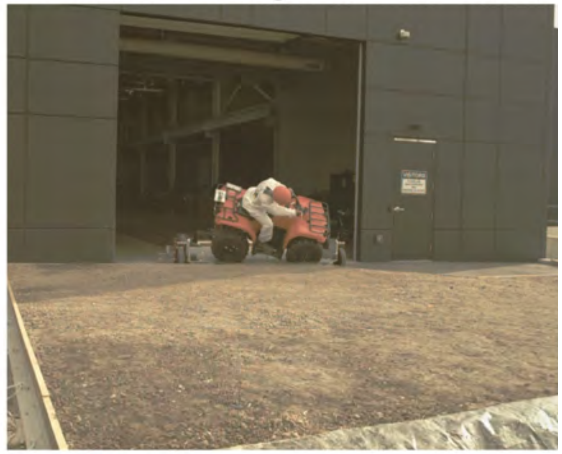
Vehicle L - Dynamic Moderate Energy Rollover with Trip Feature



Vehicle L - Dynamic Moderate Energy Rollover with Trip Feature

AOS Camera 1 - Roll Angle = 30° - Time = 0.73 sec

AOS Camera 1 - Roll Angle = 45° - Time = 0.82 sec



AOS Camera 1 - Roll Angle = 90° - Time = 1.07 sec

AOS Camera 2 - Roll Angle = 30° - Time = 0.73 sec

AOS Camera 2 - Roll Angle = 45° - Time = 0.82 sec

AOS Camera 2 - Roll Angle = 90° - Time = 1.07 sec

Vehicle A - Sled Minimum Energy Rollover

AOS Camera 1 - ATD Head Strike - Time = 1.23 sec

AOS Camera 1 - Max Angle = 154.8° - Time = 1.85 sec

AOS Camera 1 - End of Run - Roll Angle = 144.4°

AOS Camera 2 - ATD Head Strike - Time = 1.23 sec

AOS Camera 2 - Max Angle = 154.8° - Time = 1.85 sec

AOS Camera 2 - End of Run - Roll Angle = 144.4°

Vehicle A - Sled Minimum Energy Rollover

RT Camera 1 - Roll Angle = 30° - Time = 0.73 sec

RT Camera 1 - Roll Angle = 45° - Time = 0.82 sec

RT Camera 1 - Roll Angle = 90° - Time = 1.07 sec

RT Camera 2 - Roll Angle = 30° - Time = 0.73 sec

RT Camera 2 - Roll Angle = 45° - Time = 0.82 sec

RT Camera 2 - Roll Angle = 90° - Time = 1.07 sec

Vehicle A - Sled Minimum Energy Rollover

RT Camera 1 - ATD Head Strike - Time = 1.23 sec

RT Camera 1 - Max Angle = 154.8° - Time = 1.85 sec

RT Camera 1 - End of Run - Roll Angle = 144.4°

RT Camera 2 - ATD Head Strike - Time = 1.23 sec

RT Camera 2 - Max Angle = 154.8° - Time = 1.85 sec

RT Camera 2 - End of Run - Roll Angle = 144.4°

Vehicle A - Sled Minimum Energy Rollover

Drone Camera - Roll Angle = 30° - Time = 0.73 sec

Drone Camera - Roll Angle = 45° - Time = 0.82 sec

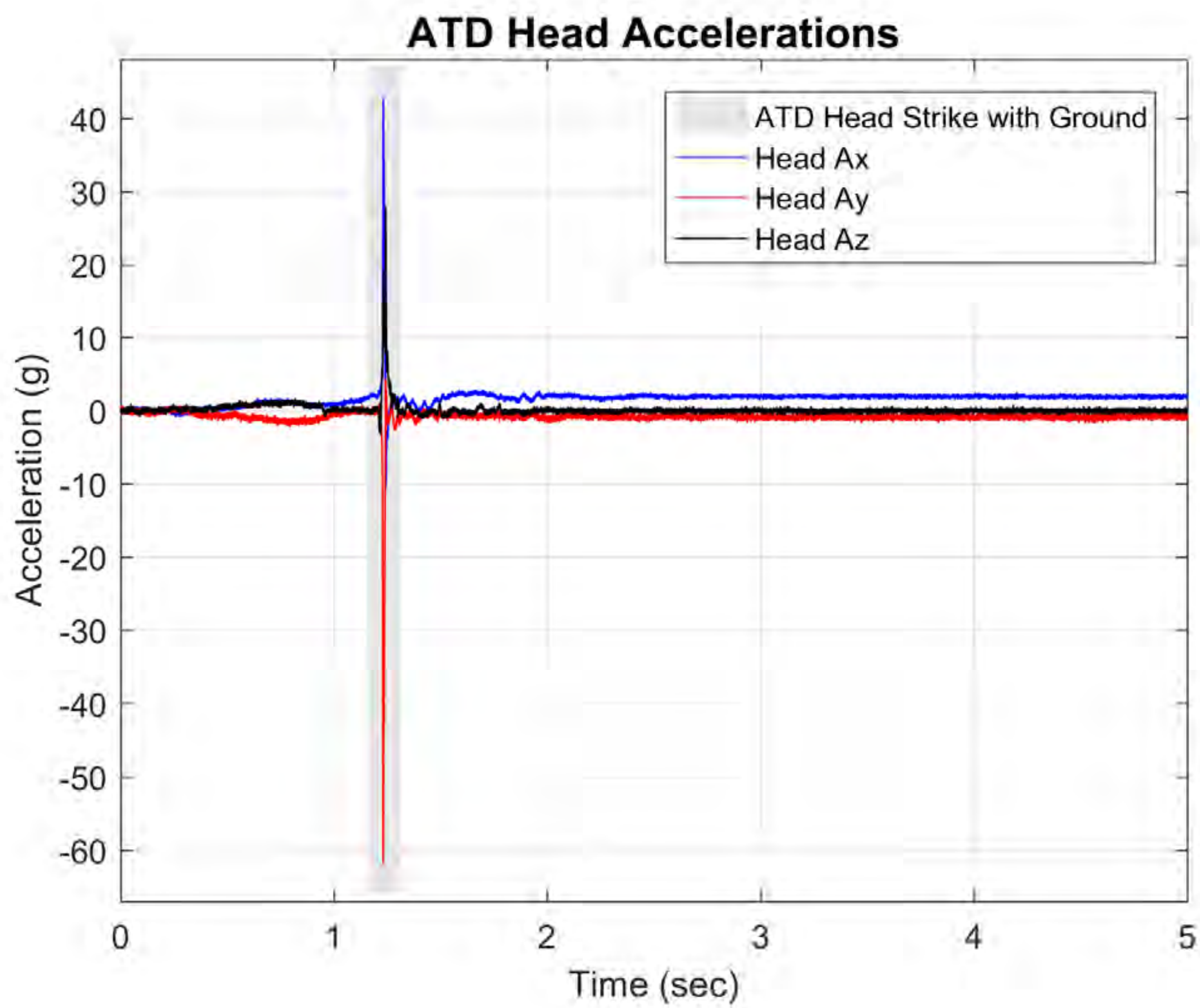
Drone Camera - Roll Angle = 90° - Time = 1.07 sec

Drone Camera - ATD Head Strike - Time = 1.23 sec

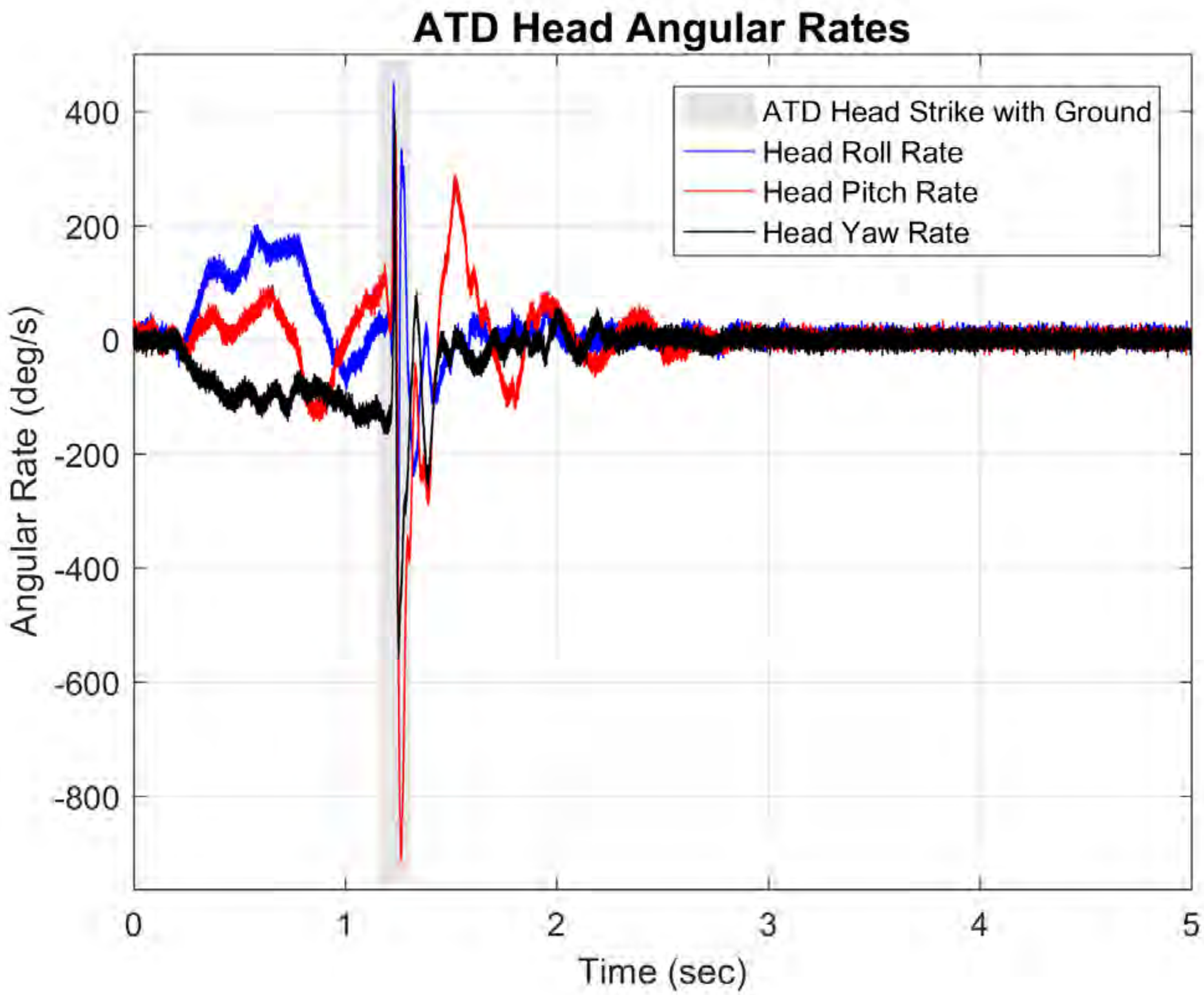
Drone Camera - Max Angle = 154.8° - Time = 1.85 sec

Drone Camera - End of Run - Roll Angle = 144.4°

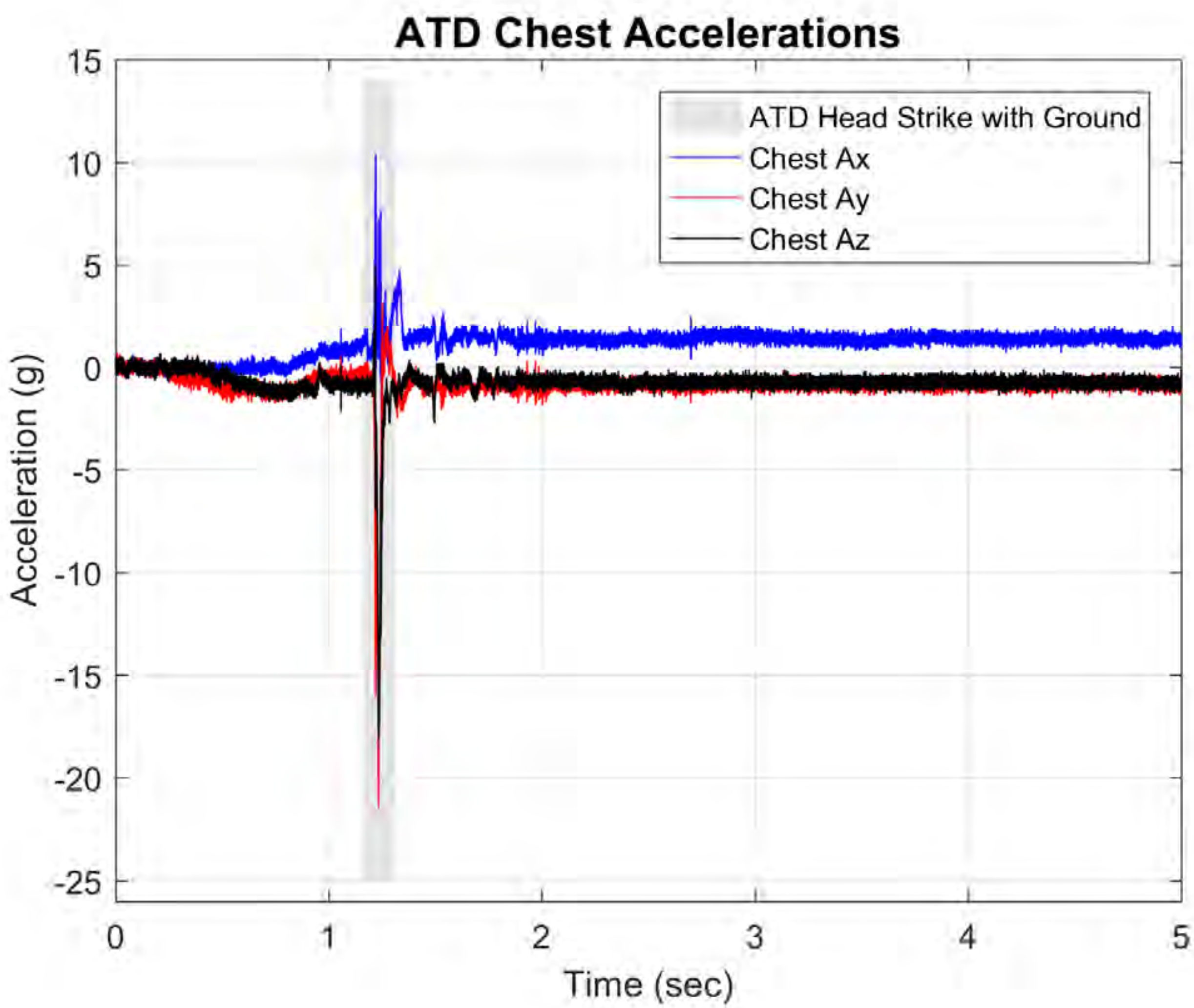
Vehicle A - Sled Minimum Energy Rollover



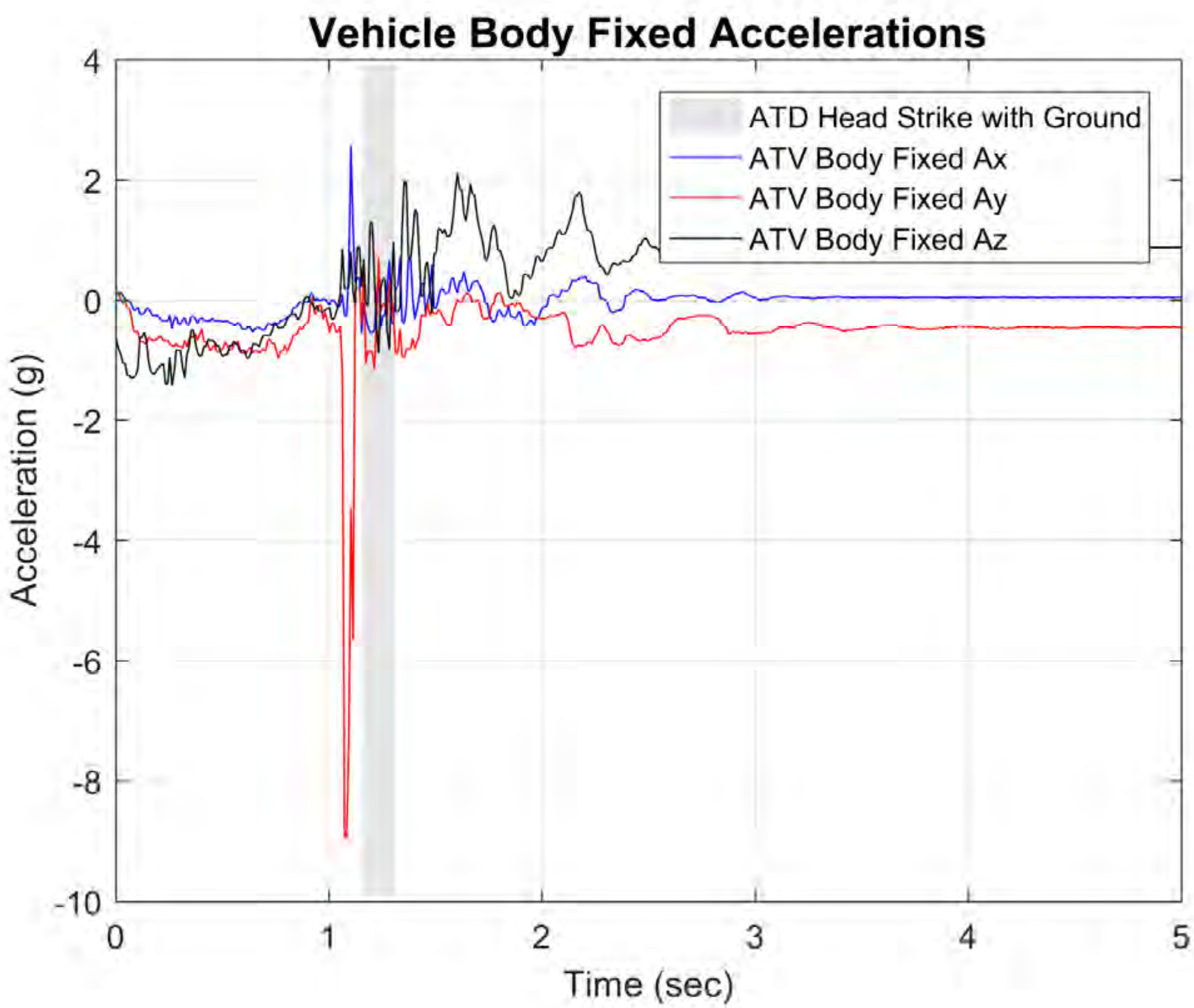
Vehicle A - Sled Minimum Energy Rollover



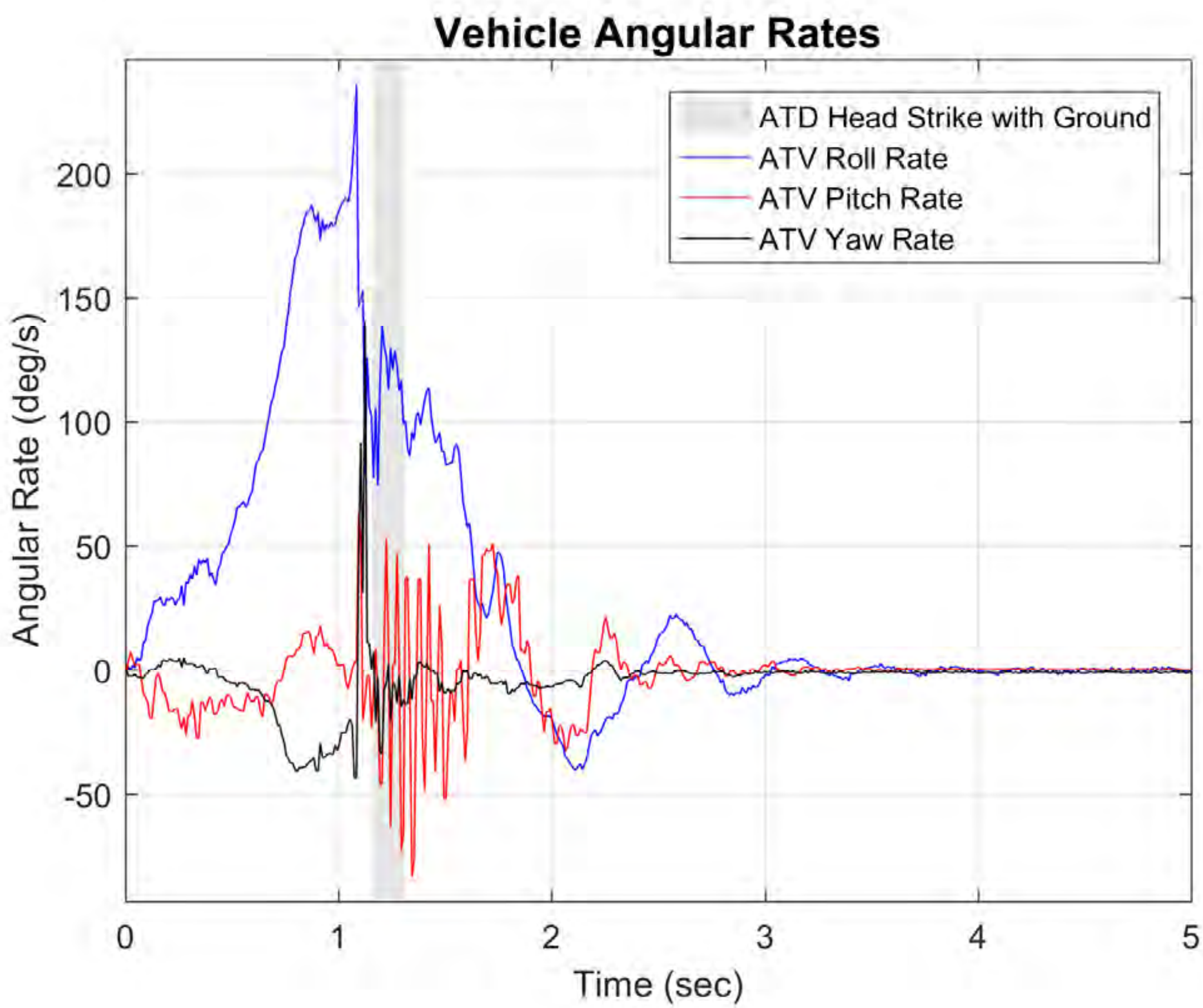
Vehicle A - Sled Minimum Energy Rollover



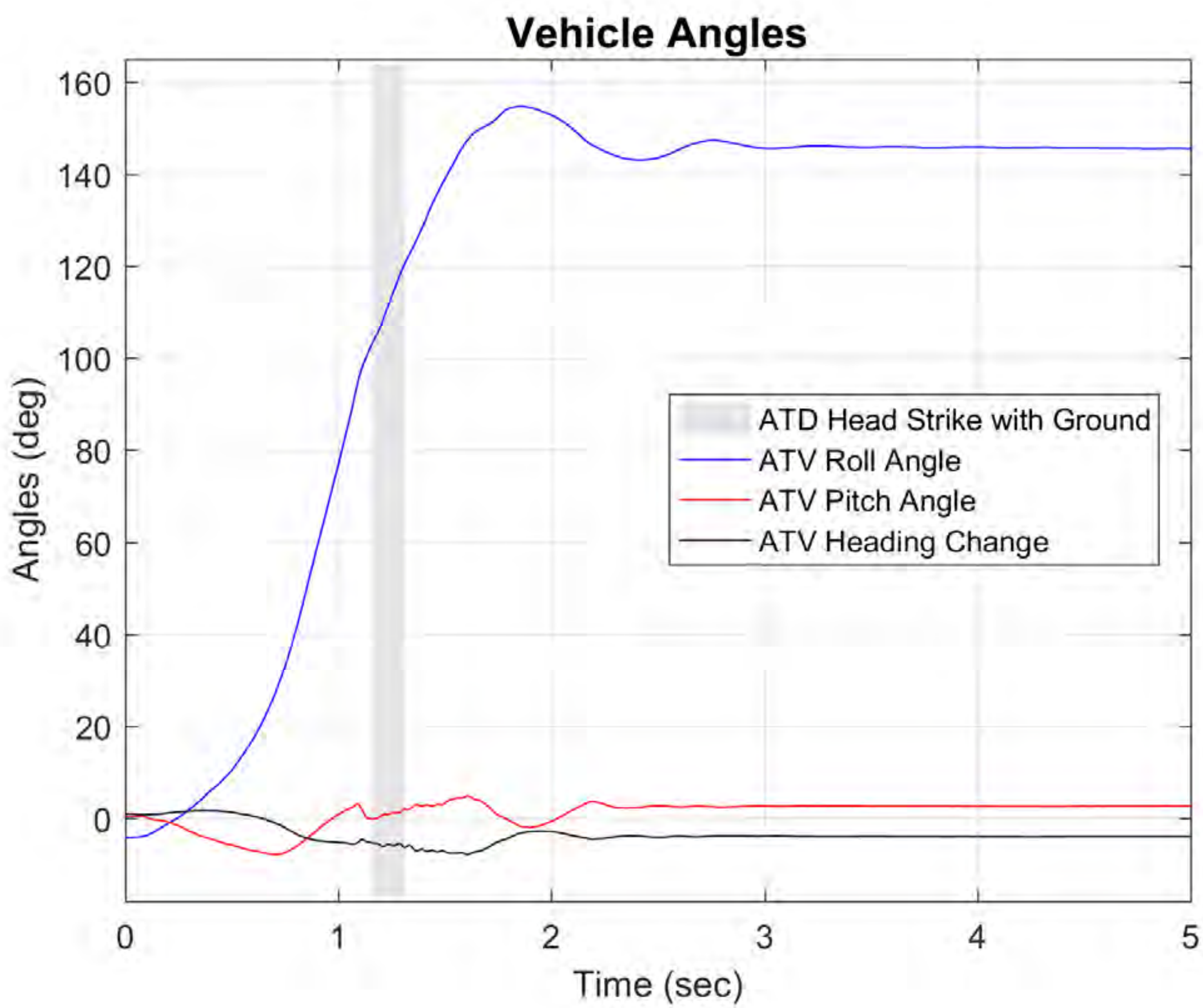
Vehicle A - Sled Minimum Energy Rollover



Vehicle A - Sled Minimum Energy Rollover



Vehicle A - Sled Minimum Energy Rollover



Vehicle A - Sled Minimum Energy Rollover

AOS Camera 1 - Roll Angle = 30° - Time = 0.51 sec

AOS Camera 1 - Roll Angle = 45° - Time = 0.62 sec

AOS Camera 1 - Roll Angle = 90° - Time = 0.85 sec

AOS Camera 2 - Roll Angle = 30° - Time = 0.51 sec

AOS Camera 2 - Roll Angle = 45° - Time = 0.62 sec

AOS Camera 2 - Roll Angle = 90° - Time = 0.85 sec

Vehicle A - Sled Moderate Energy Rollover

AOS Camera 1 - ATD Head Strike - Time = 0.97 sec

AOS Camera 1 - Roll Angle = 180° - Time = 1.15 sec

AOS Camera 1 - Max Angle = 283.5° - Time = 2.06 sec

AOS Camera 2 - ATD Head Strike - Time = 0.97 sec

AOS Camera 2 - Roll Angle = 180° - Time = 1.15 sec

AOS Camera 2 - Max Angle = 283.5° - Time = 2.06 sec

Vehicle A - Sled Moderate Energy Rollover

AOS Camera 1 - End of Run - Roll Angle = 168.2°

AOS Camera 2 - End of Run - Roll Angle = 168.2°

Vehicle A - Sled Moderate Energy Rollover

RT Camera 1 - Roll Angle = 30° - Time = 0.51 sec

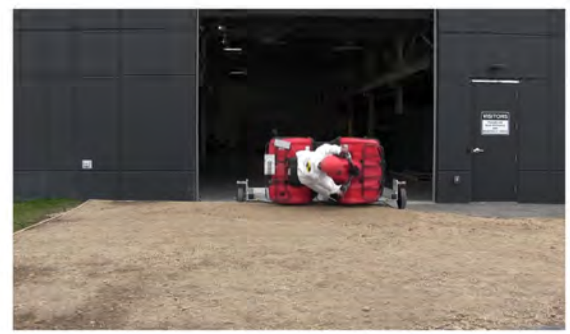
RT Camera 1 - Roll Angle = 45° - Time = 0.62 sec

RT Camera 1 - Roll Angle = 90° - Time = 0.85 sec

RT Camera 2 - Roll Angle = 30° - Time = 0.51 sec

RT Camera 2 - Roll Angle = 45° - Time = 0.62 sec

RT Camera 2 - Roll Angle = 90° - Time = 0.85 sec



Vehicle A - Sled Moderate Energy Rollover

RT Camera 1 - ATD Head Strike - Time = 0.97 sec

RT Camera 1 - Roll Angle = 180° - Time = 1.15 sec

RT Camera 1 - Max Angle = 283.5° - Time = 2.06 sec

RT Camera 2 - ATD Head Strike - Time = 0.97 sec

RT Camera 2 - Roll Angle = 180° - Time = 1.15 sec

RT Camera 2 - Max Angle = 283.5° - Time = 2.06 sec

Vehicle A - Sled Moderate Energy Rollover

RT Camera 1 - End of Run - Roll Angle = 168.2°

RT Camera 2 - End of Run - Roll Angle = 168.2°

Vehicle A - Sled Moderate Energy Rollover

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

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

Drone Camera - Roll Angle = 90° - Time = 0.85 sec

Drone Camera - ATD Head Strike - Time = 0.97 sec

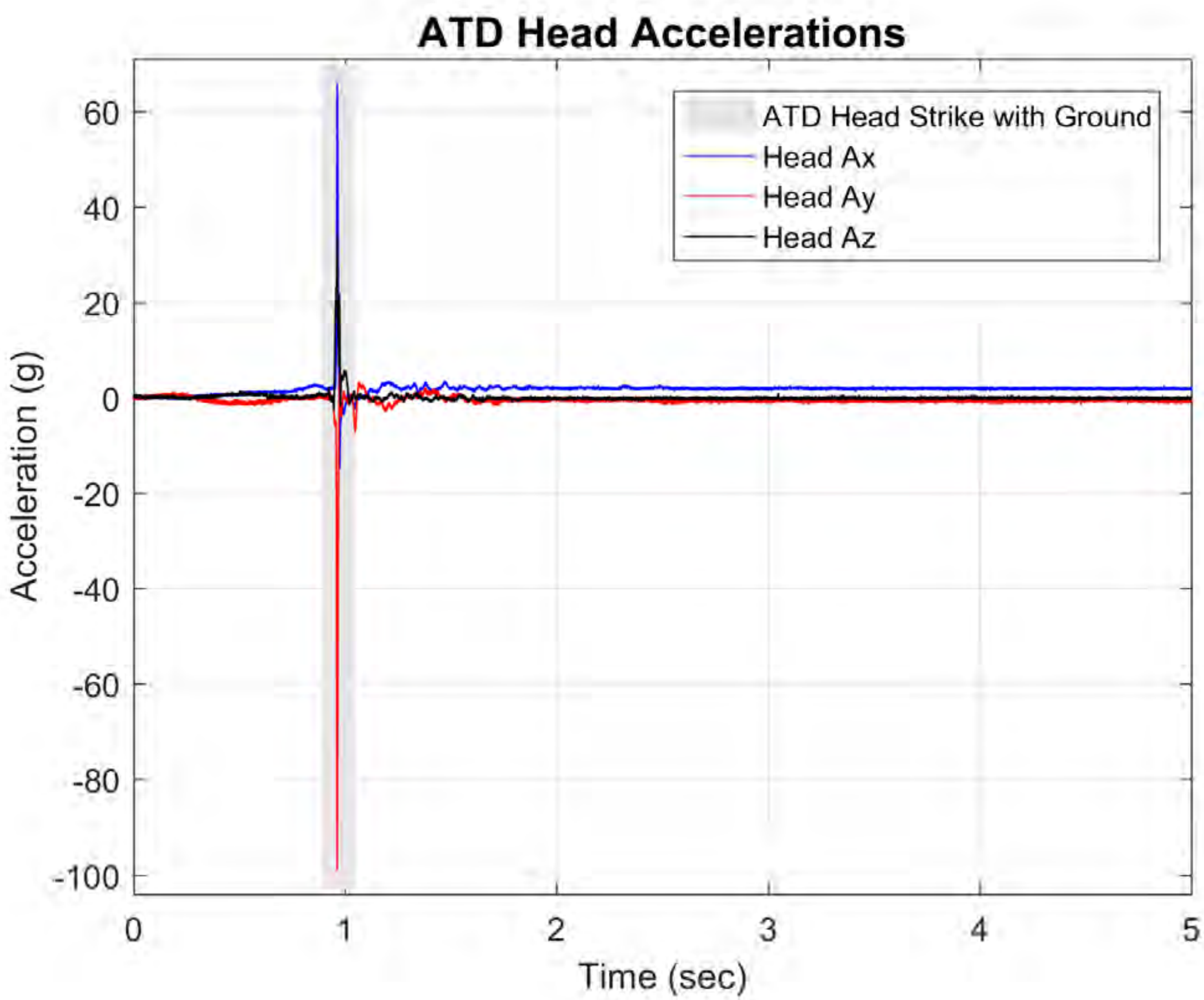
Drone Camera - Roll Angle = 180° - Time = 1.15 sec

Drone Camera - Max Angle = 283.5° - Time = 2.06 sec

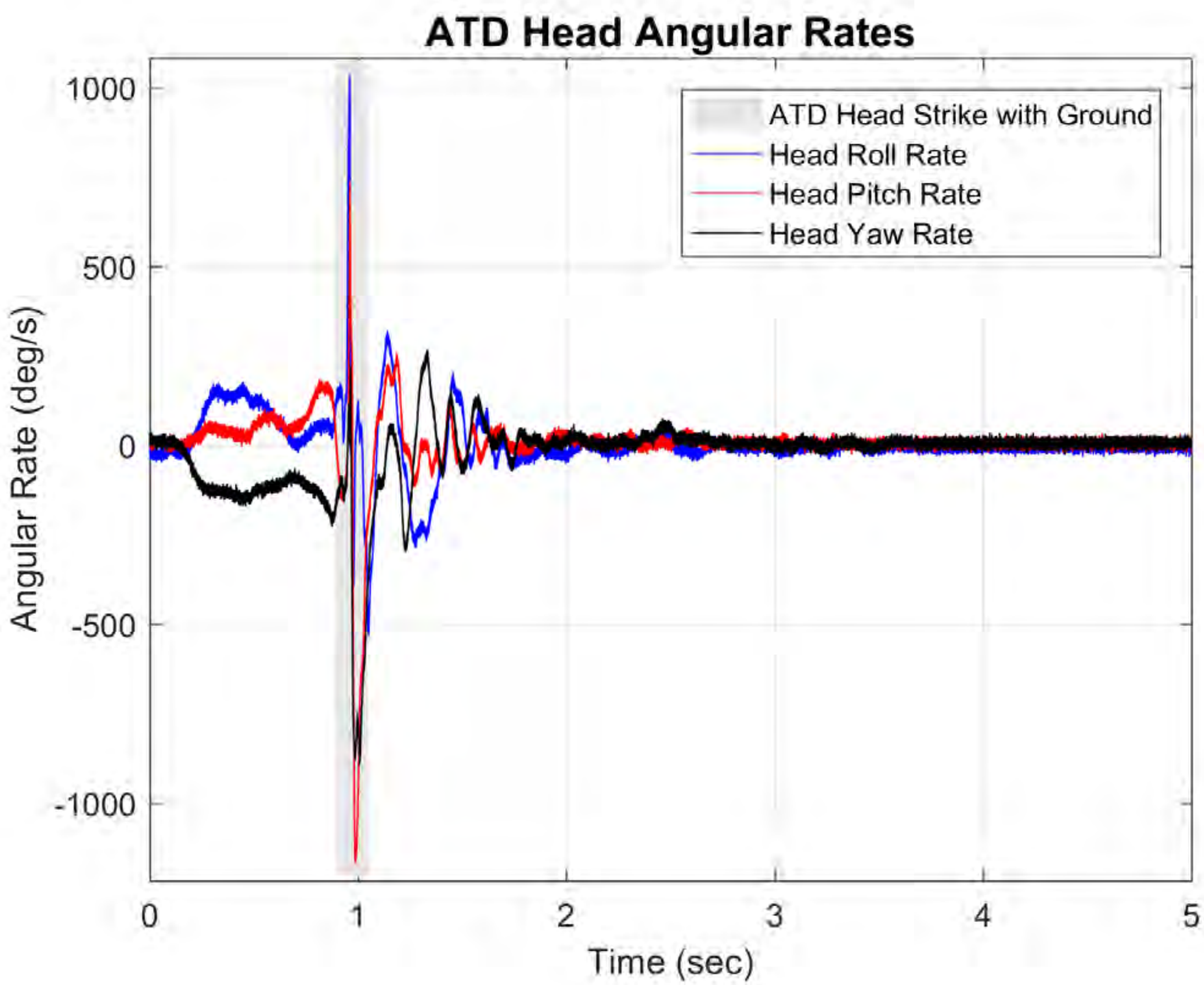
Vehicle A - Sled Moderate Energy Rollover

Drone Camera - End of Run - Roll Angle = 168.2°

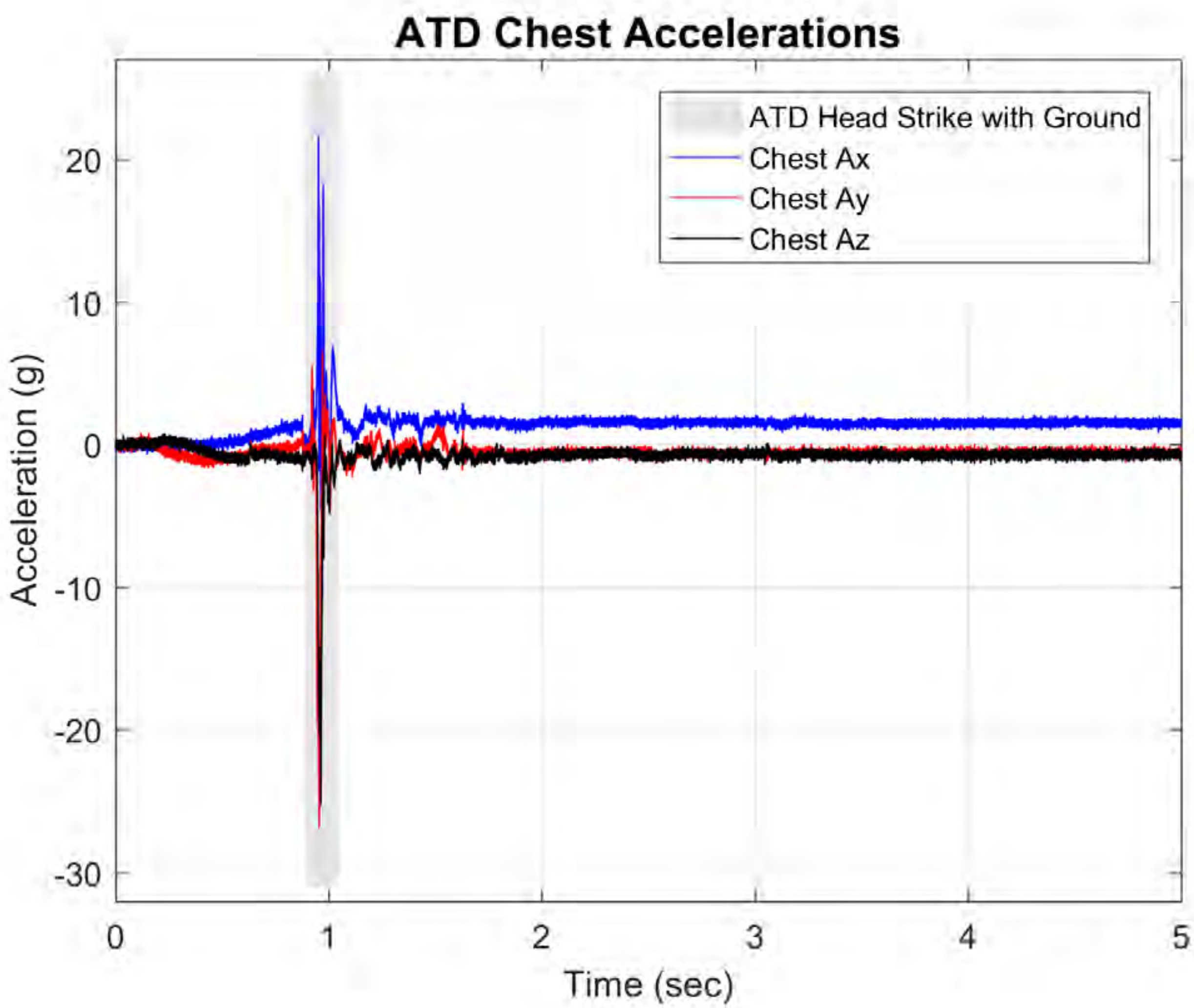
Vehicle A - Sled Moderate Energy Rollover



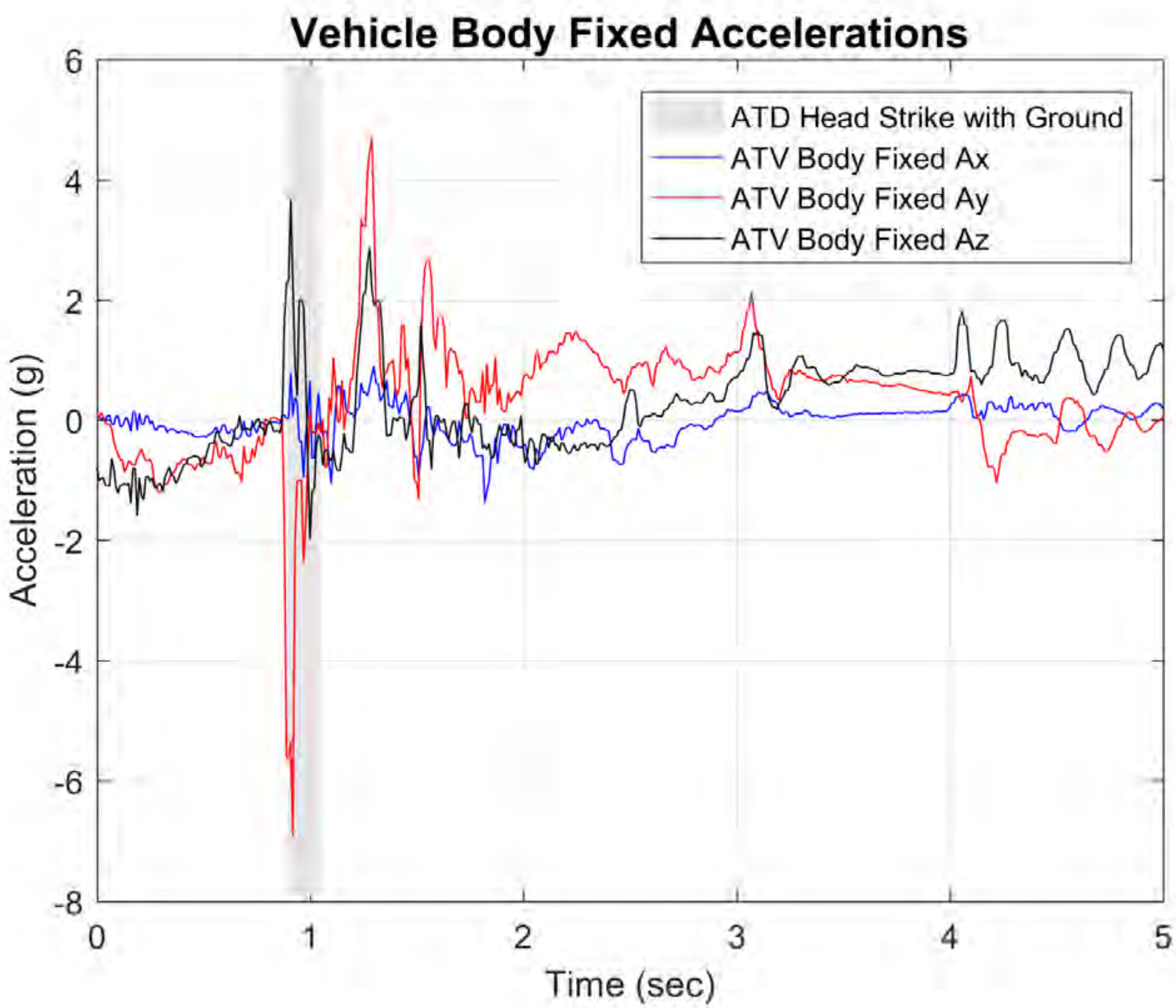
Vehicle A - Sled Moderate Energy Rollover



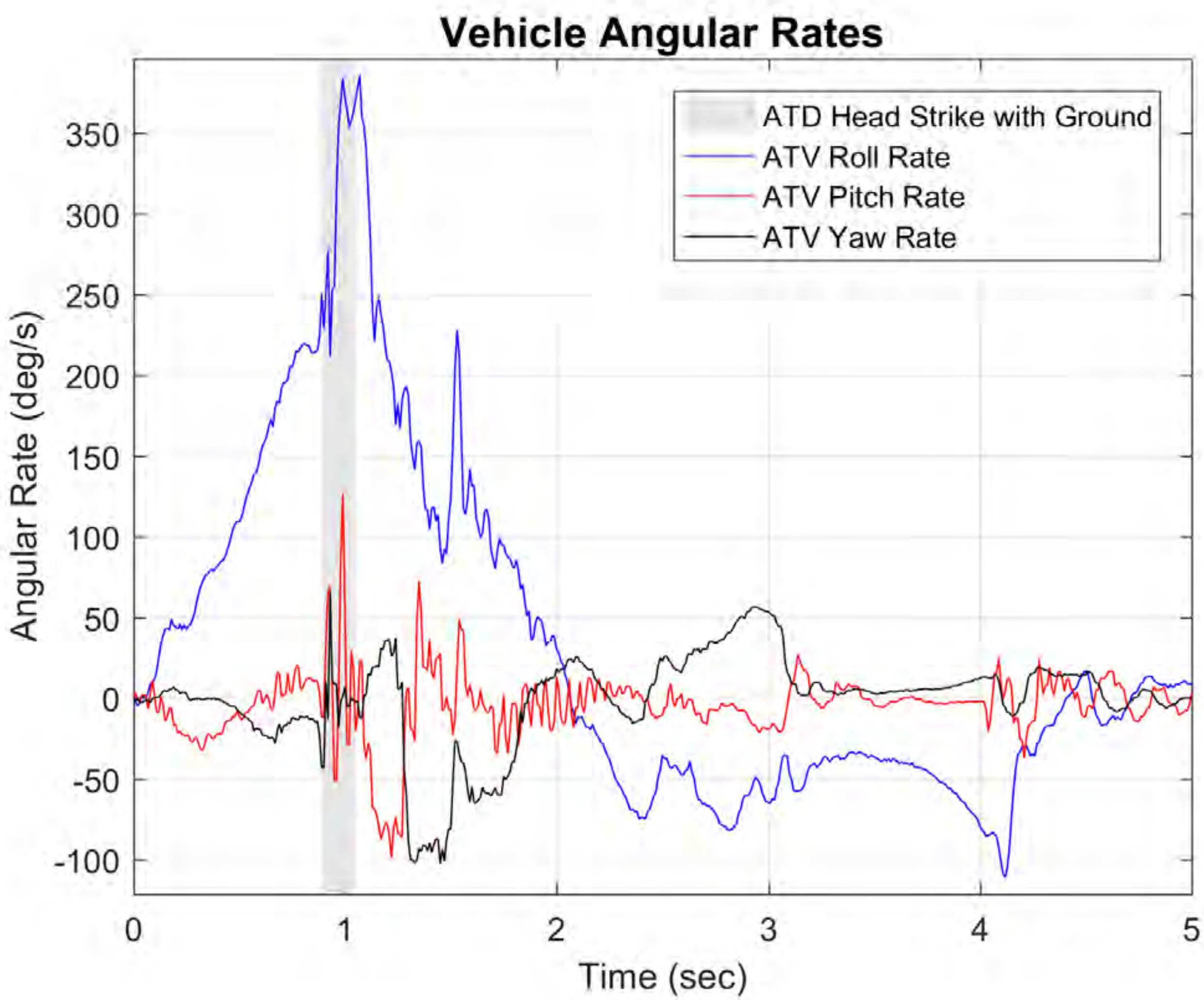
Vehicle A - Sled Moderate Energy Rollover



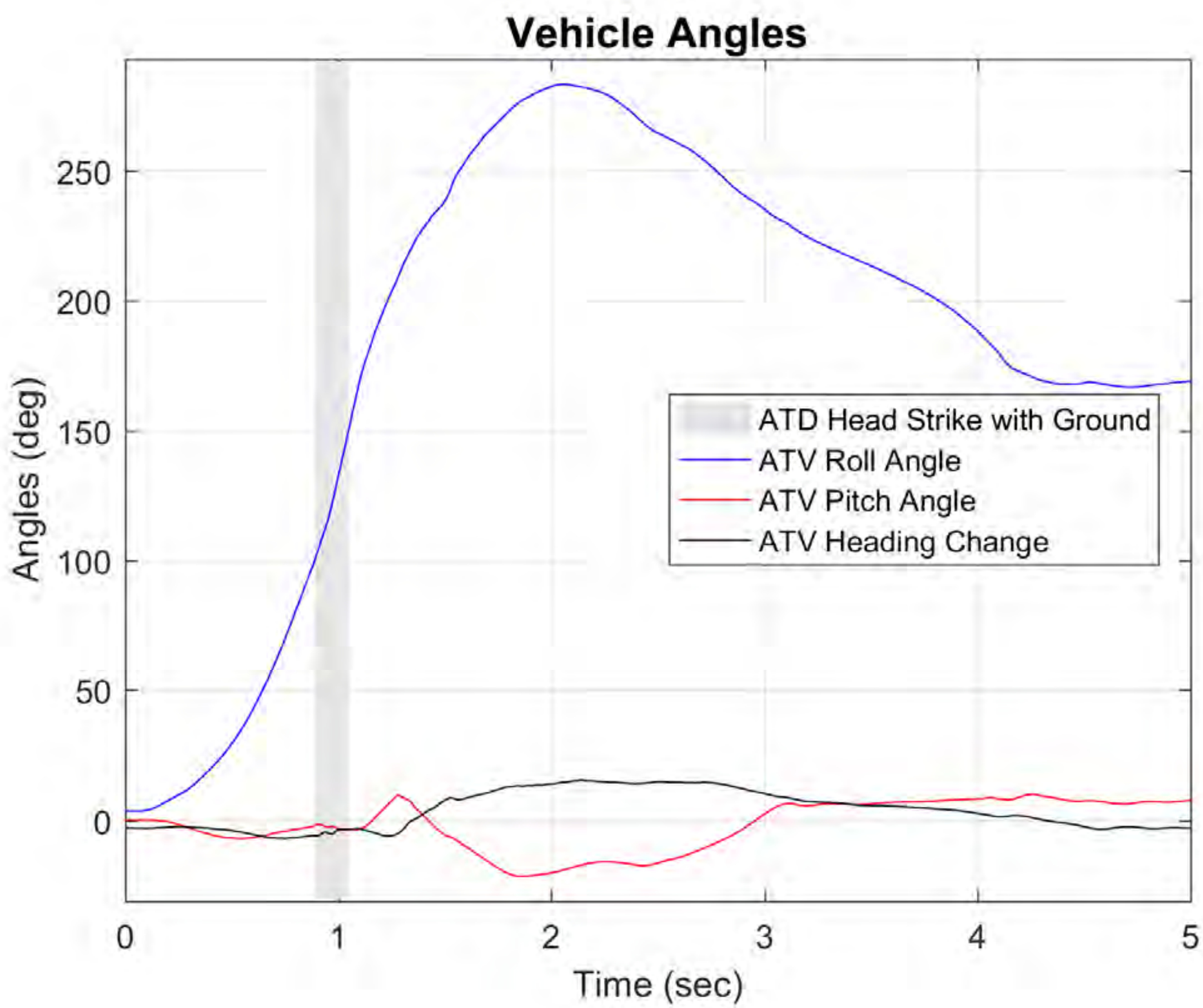
Vehicle A - Sled Moderate Energy Rollover



Vehicle A - Sled Moderate Energy Rollover



Vehicle A - Sled Moderate Energy Rollover



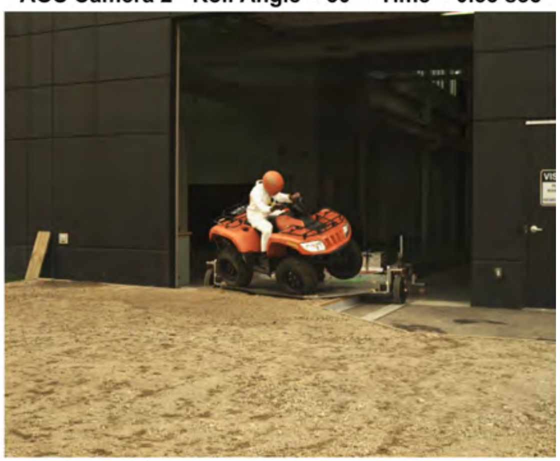
Vehicle A - Sled Moderate Energy Rollover

AOS Camera 1 - Roll Angle = 30° - Time = 0.53 sec

AOS Camera 1 - Roll Angle = 45° - Time = 0.66 sec

AOS Camera 1 - Roll Angle = 90° - Time = 0.91 sec

AOS Camera 2 - Roll Angle = 30° - Time = 0.53 sec



AOS Camera 2 - Roll Angle = 45° - Time = 0.66 sec

AOS Camera 2 - Roll Angle = 90° - Time = 0.91 sec

Vehicle E - Sled Minimum Energy Rollover

AOS Camera 1 - ATD Head Strike - Time = 0.99 sec

AOS Camera 1 - Max Angle = 157.9° - Time = 1.7 sec

AOS Camera 1 - End of Run - Roll Angle = 151.9°

AOS Camera 2 - ATD Head Strike - Time = 0.99 sec

AOS Camera 2 - Max Angle = 157.9° - Time = 1.7 sec

AOS Camera 2 - End of Run - Roll Angle = 151.9°

Vehicle E - Sled Minimum Energy Rollover

RT Camera 1 - Roll Angle = 30° - Time = 0.53 sec

RT Camera 1 - Roll Angle = 45° - Time = 0.66 sec

RT Camera 1 - Roll Angle = 90° - Time = 0.91 sec

RT Camera 2 - Roll Angle = 30° - Time = 0.53 sec

RT Camera 2 - Roll Angle = 45° - Time = 0.66 sec

RT Camera 2 - Roll Angle = 90° - Time = 0.91 sec

Vehicle E - Sled Minimum Energy Rollover

RT Camera 1 - ATD Head Strike - Time = 0.99 sec

RT Camera 1 - Max Angle = 157.9° - Time = 1.7 sec

RT Camera 1 - End of Run - Roll Angle = 151.9°

RT Camera 2 - ATD Head Strike - Time = 0.99 sec

RT Camera 2 - Max Angle = 157.9° - Time = 1.7 sec

RT Camera 2 - End of Run - Roll Angle = 151.9°

Vehicle E - Sled Minimum Energy Rollover

Drone Camera - Roll Angle = 30° - Time = 0.53 sec

Drone Camera - Roll Angle = 45° - Time = 0.66 sec

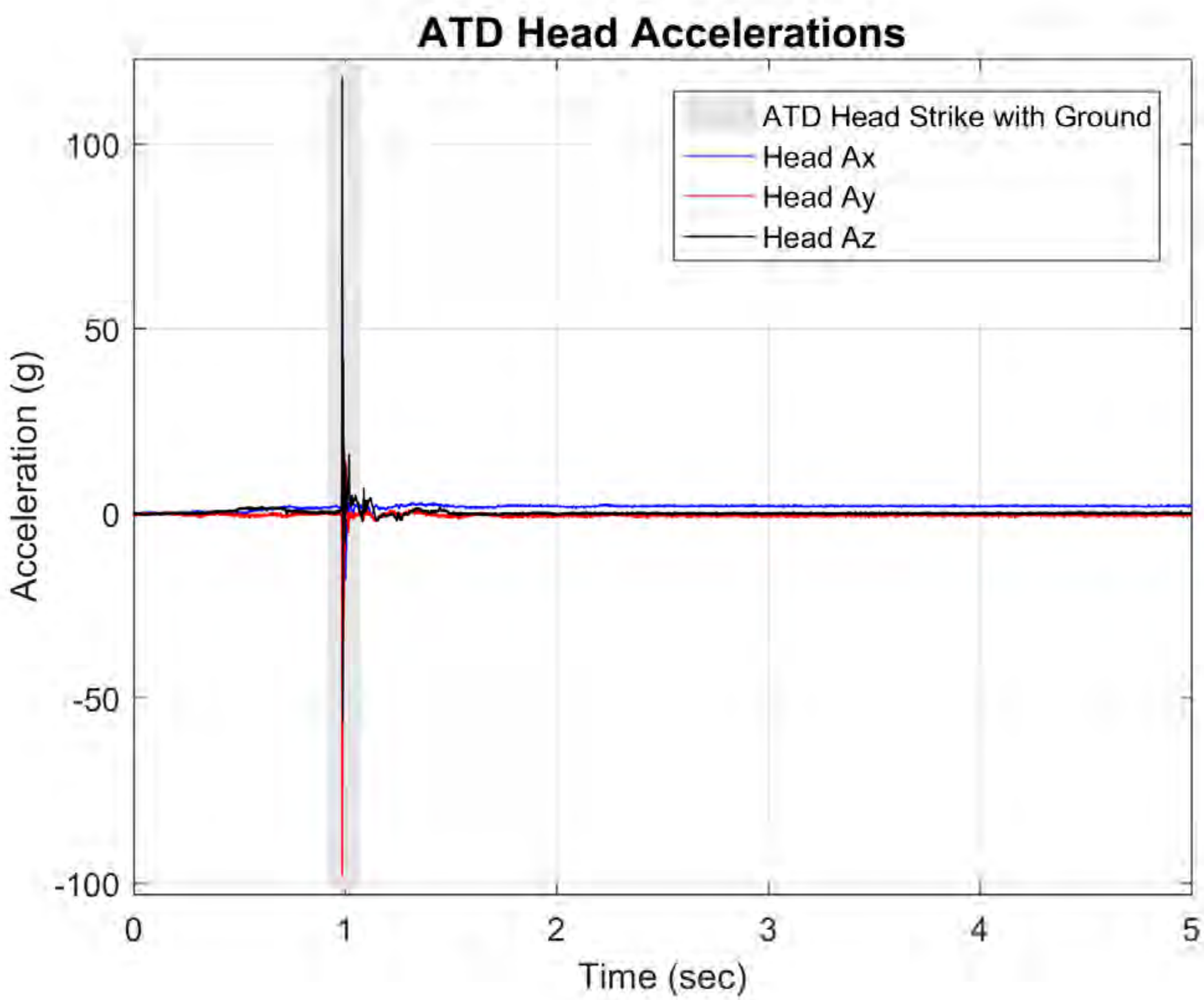
Drone Camera - Roll Angle = 90° - Time = 0.91 sec

Drone Camera - ATD Head Strike - Time = 0.99 sec

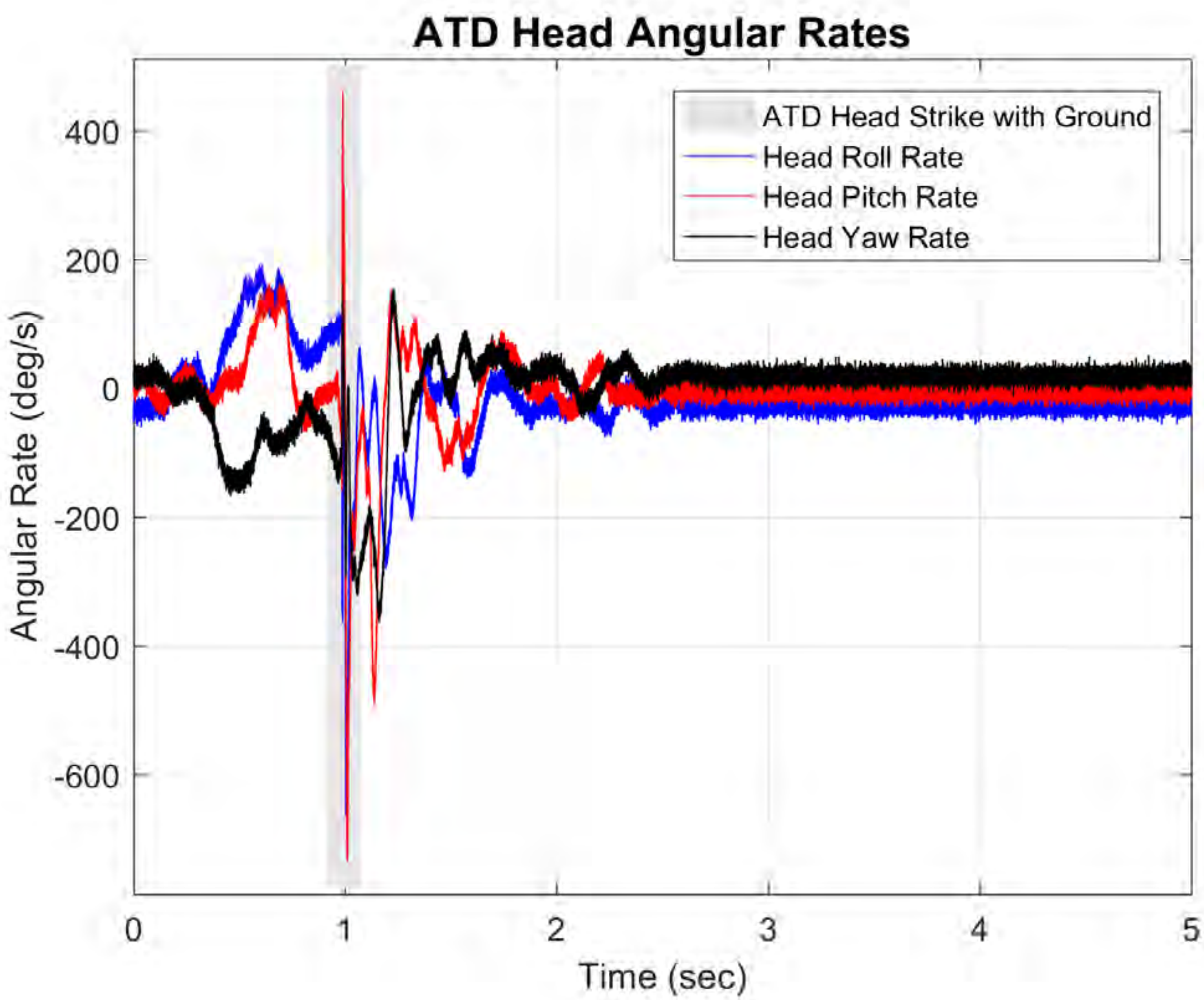
Drone Camera - Max Angle = 157.9° - Time = 1.7 sec

Drone Camera - End of Run - Roll Angle = 151.9°

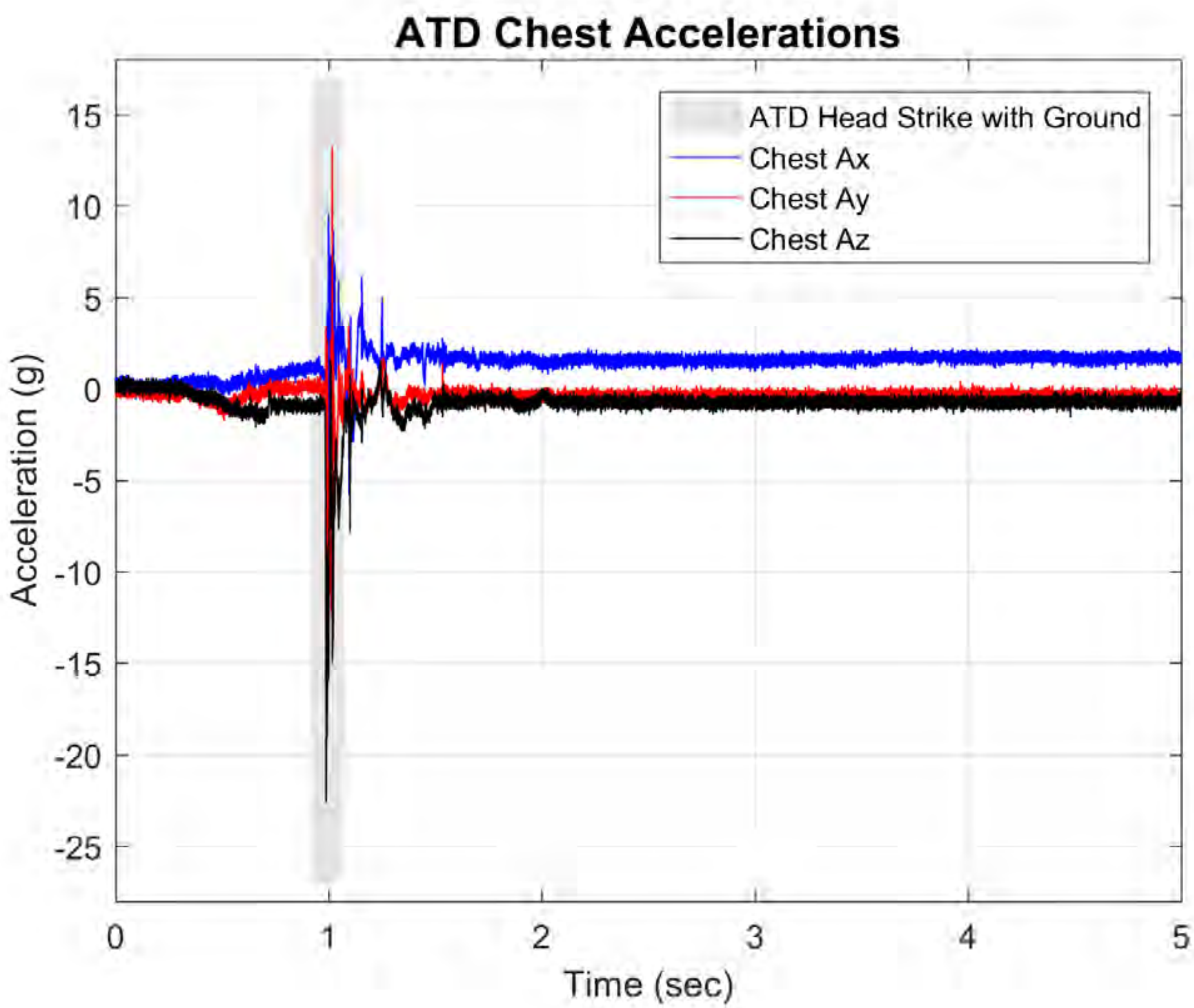
Vehicle E - Sled Minimum Energy Rollover



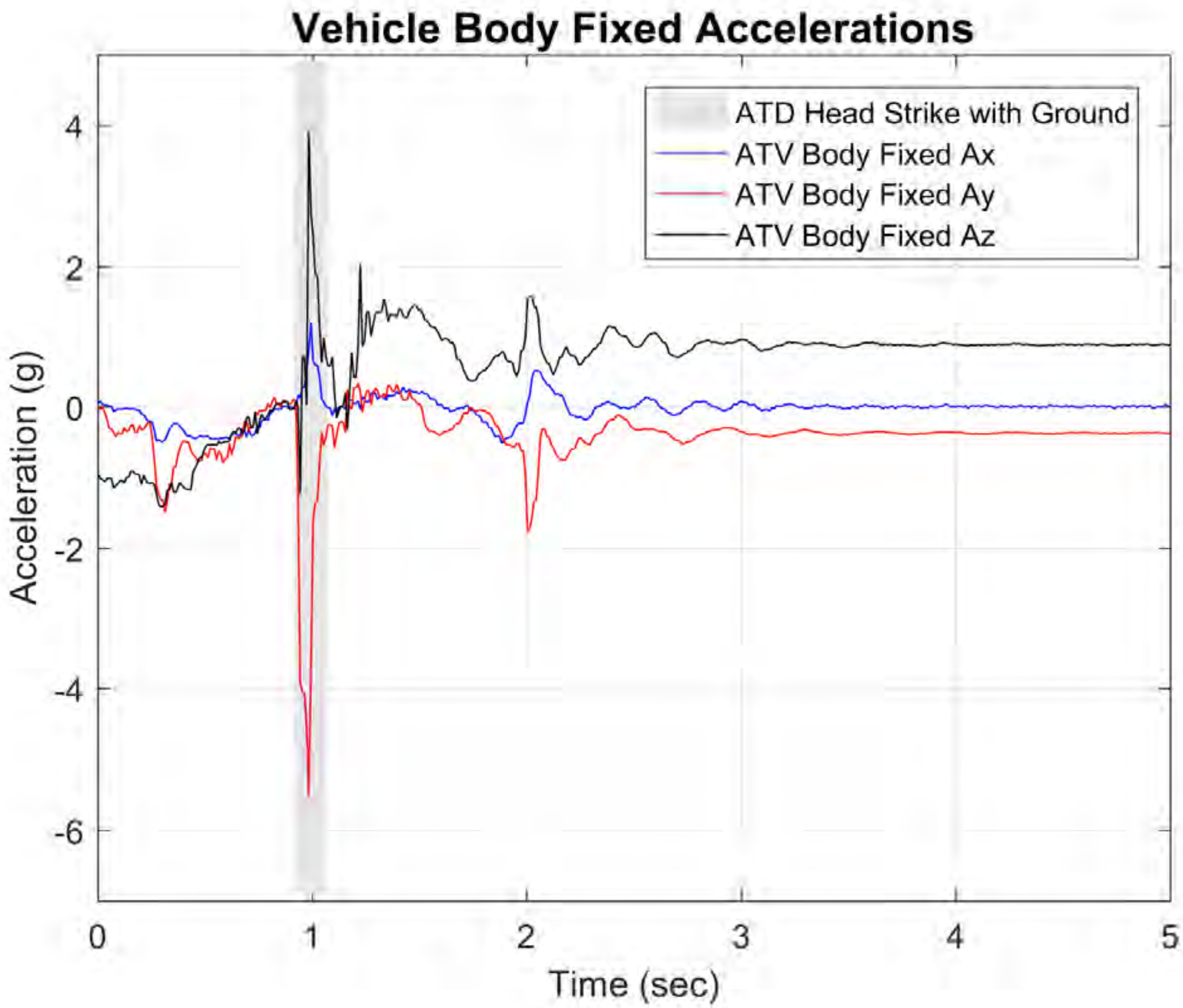
Vehicle E - Sled Minimum Energy Rollover



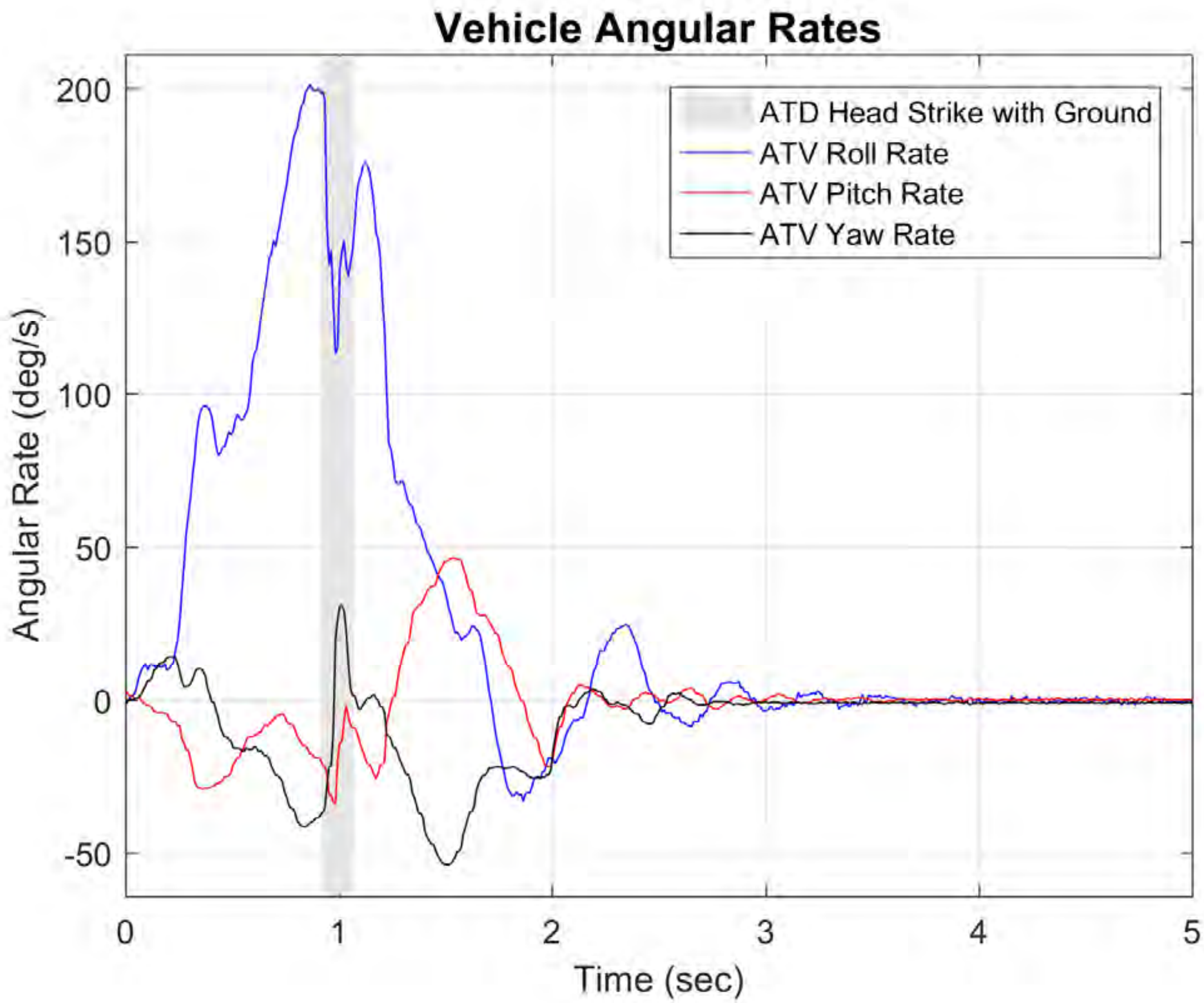
Vehicle E - Sled Minimum Energy Rollover



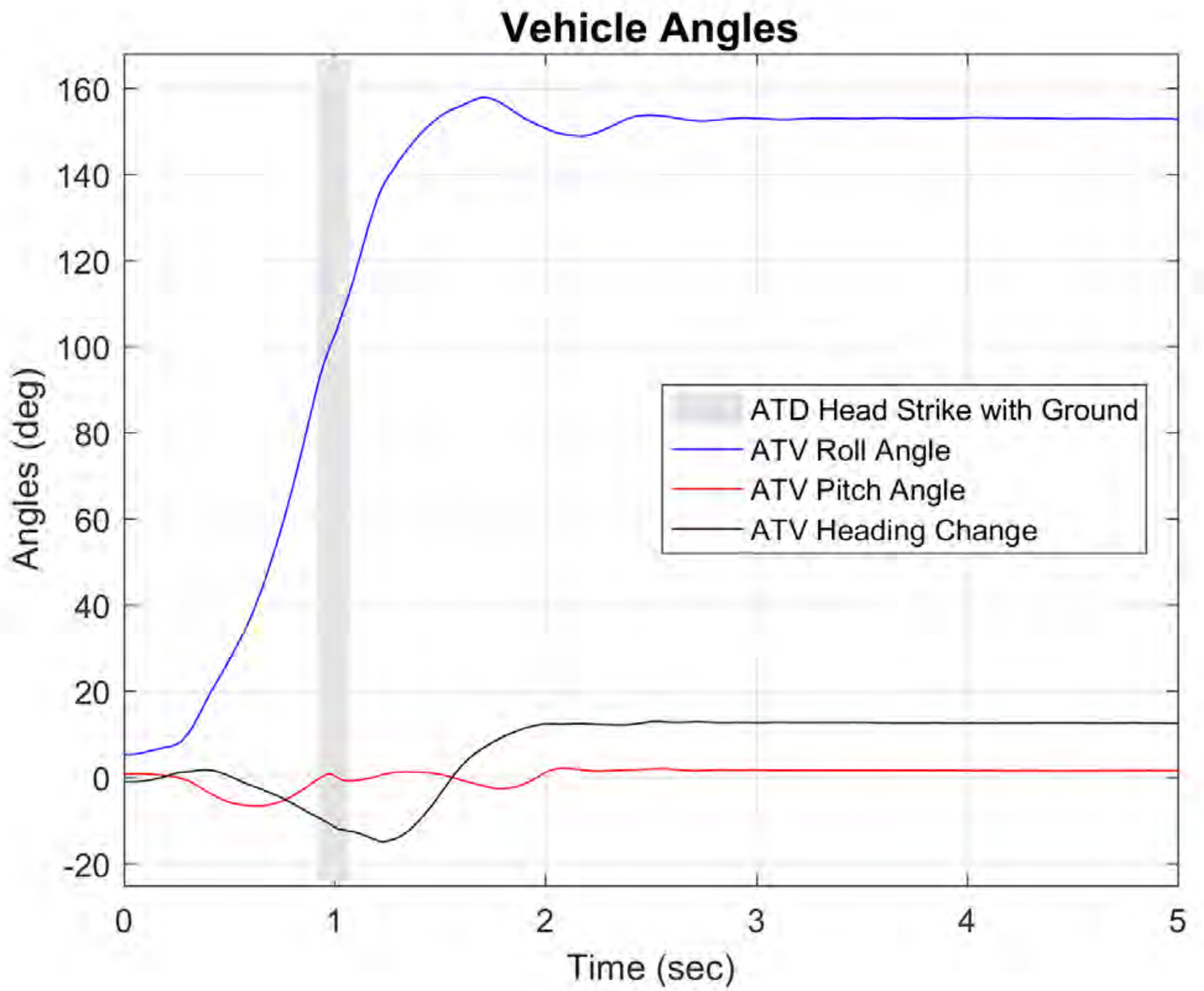
Vehicle E - Sled Minimum Energy Rollover



Vehicle E - Sled Minimum Energy Rollover



Vehicle E - Sled Minimum Energy Rollover



Vehicle E - Sled Minimum Energy Rollover

AOS Camera 1 - Roll Angle = 30° - Time = 0.51 sec

AOS Camera 1 - Roll Angle = 45° - Time = 0.64 sec

AOS Camera 1 - Roll Angle = 90° - Time = 0.88 sec

AOS Camera 2 - Roll Angle = 30° - Time = 0.51 sec

AOS Camera 2 - Roll Angle = 45° - Time = 0.64 sec

AOS Camera 2 - Roll Angle = 90° - Time = 0.88 sec

Vehicle E - Sled Moderate Energy Rollover

AOS Camera 1 - ATD Head Strike - Time = 1.04 sec

AOS Camera 1 - Roll Angle = 180° - Time = 1.25 sec

AOS Camera 1 - Max Angle = 202.3° - Time = 2.16 sec

AOS Camera 2 - ATD Head Strike - Time = 1.04 sec

AOS Camera 2 - Roll Angle = 180° - Time = 1.25 sec

AOS Camera 2 - Max Angle = 202.3° - Time = 2.16 sec

Vehicle E - Sled Moderate Energy Rollover

AOS Camera 1 - End of Run - Roll Angle = 139.2°

AOS Camera 2 - End of Run - Roll Angle = 139.2°

Vehicle E - Sled Moderate Energy Rollover

RT Camera 1 - Roll Angle = 30° - Time = 0.51 sec

RT Camera 1 - Roll Angle = 45° - Time = 0.64 sec

RT Camera 1 - Roll Angle = 90° - Time = 0.88 sec

RT Camera 2 - Roll Angle = 30° - Time = 0.51 sec

RT Camera 2 - Roll Angle = 45° - Time = 0.64 sec

RT Camera 2 - Roll Angle = 90° - Time = 0.88 sec

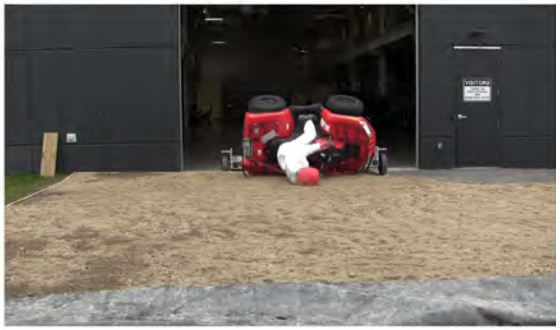
Vehicle E - Sled Moderate Energy Rollover

RT Camera 1 - ATD Head Strike - Time = 1.04 sec

RT Camera 1 - Roll Angle = 180° - Time = 1.25 sec

RT Camera 1 - Max Angle = 202.3° - Time = 2.16 sec

RT Camera 2 - ATD Head Strike - Time = 1.04 sec



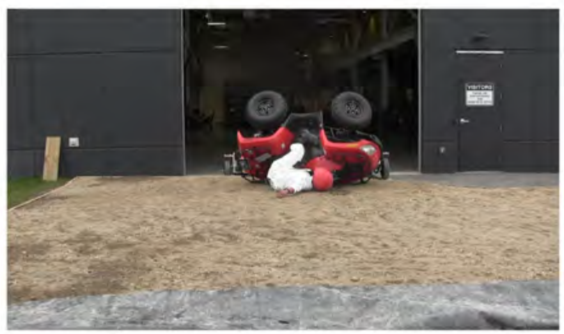
RT Camera 2 - Roll Angle = 180° - Time = 1.25 sec

RT Camera 2 - Max Angle = 202.3° - Time = 2.16 sec

Vehicle E - Sled Moderate Energy Rollover

RT Camera 1 - End of Run - Roll Angle = 139.2°

RT Camera 2 - End of Run - Roll Angle = 139.2°



Vehicle E - Sled Moderate Energy Rollover

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

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

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

Drone Camera - ATD Head Strike - Time = 1.04 sec

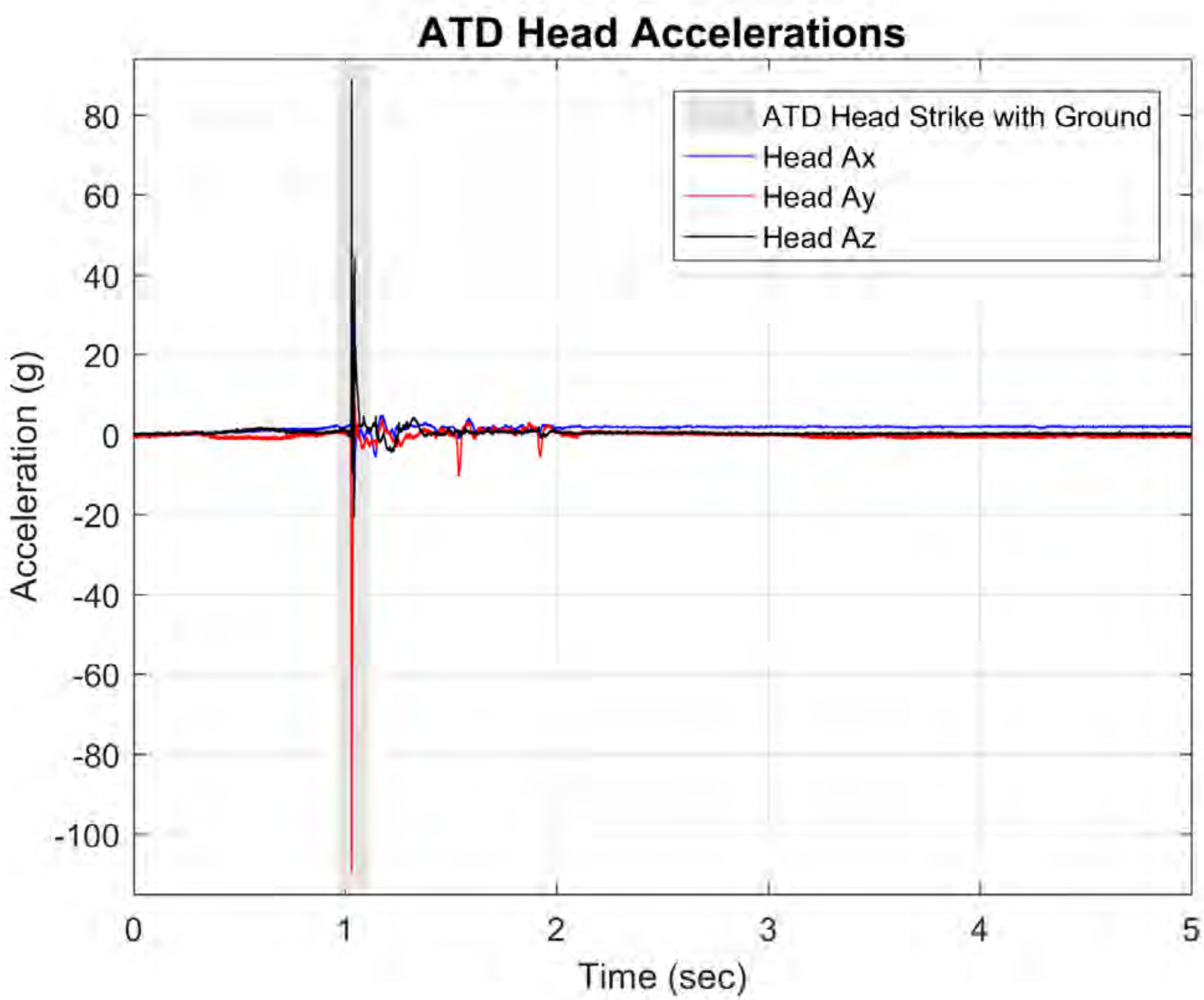
Drone Camera - Roll Angle = 180° - Time = 1.25 sec

Drone Camera - Max Angle = 202.3° - Time = 2.16 sec

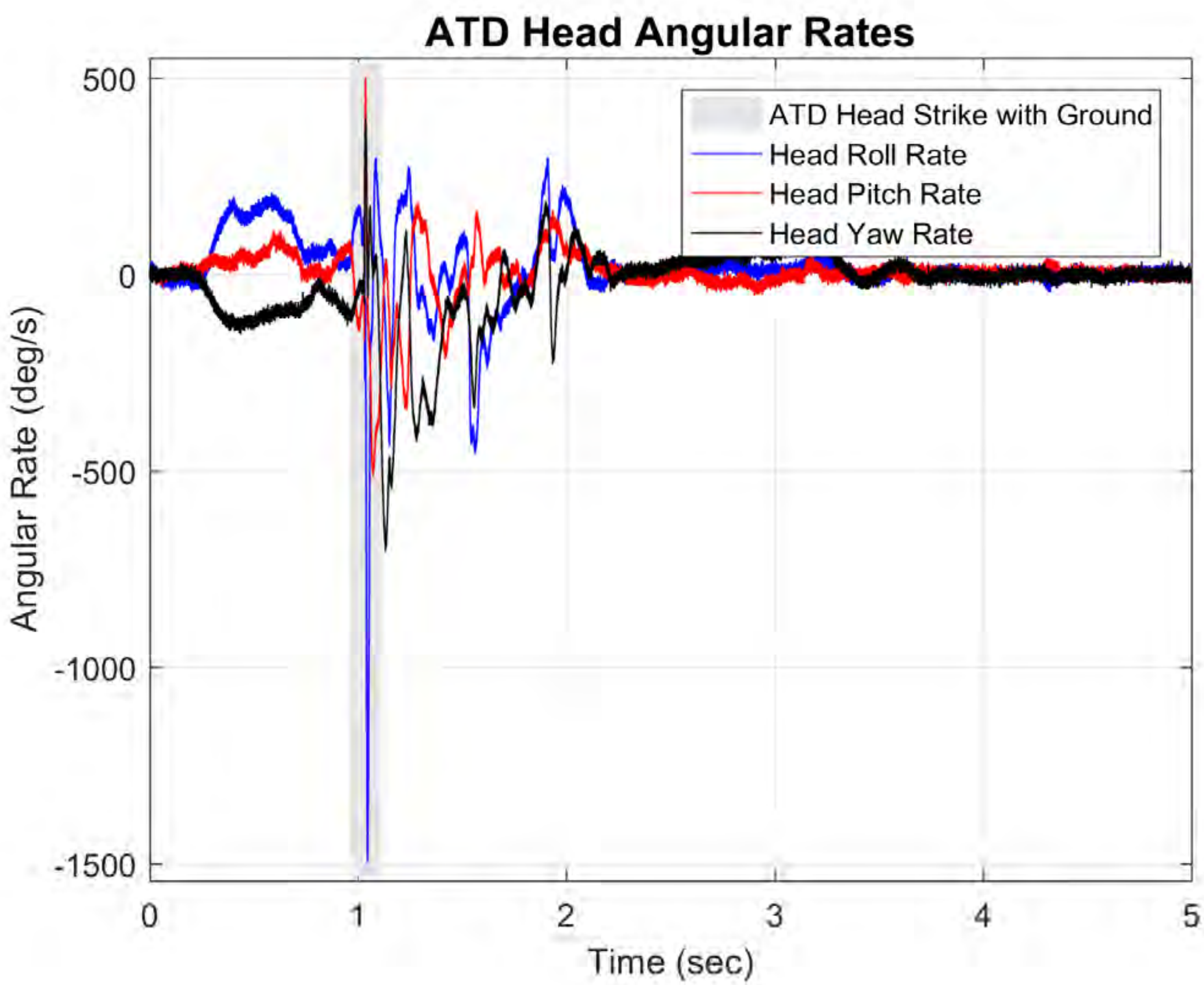
Vehicle E - Sled Moderate Energy Rollover

Drone Camera - End of Run - Roll Angle = 139.2°

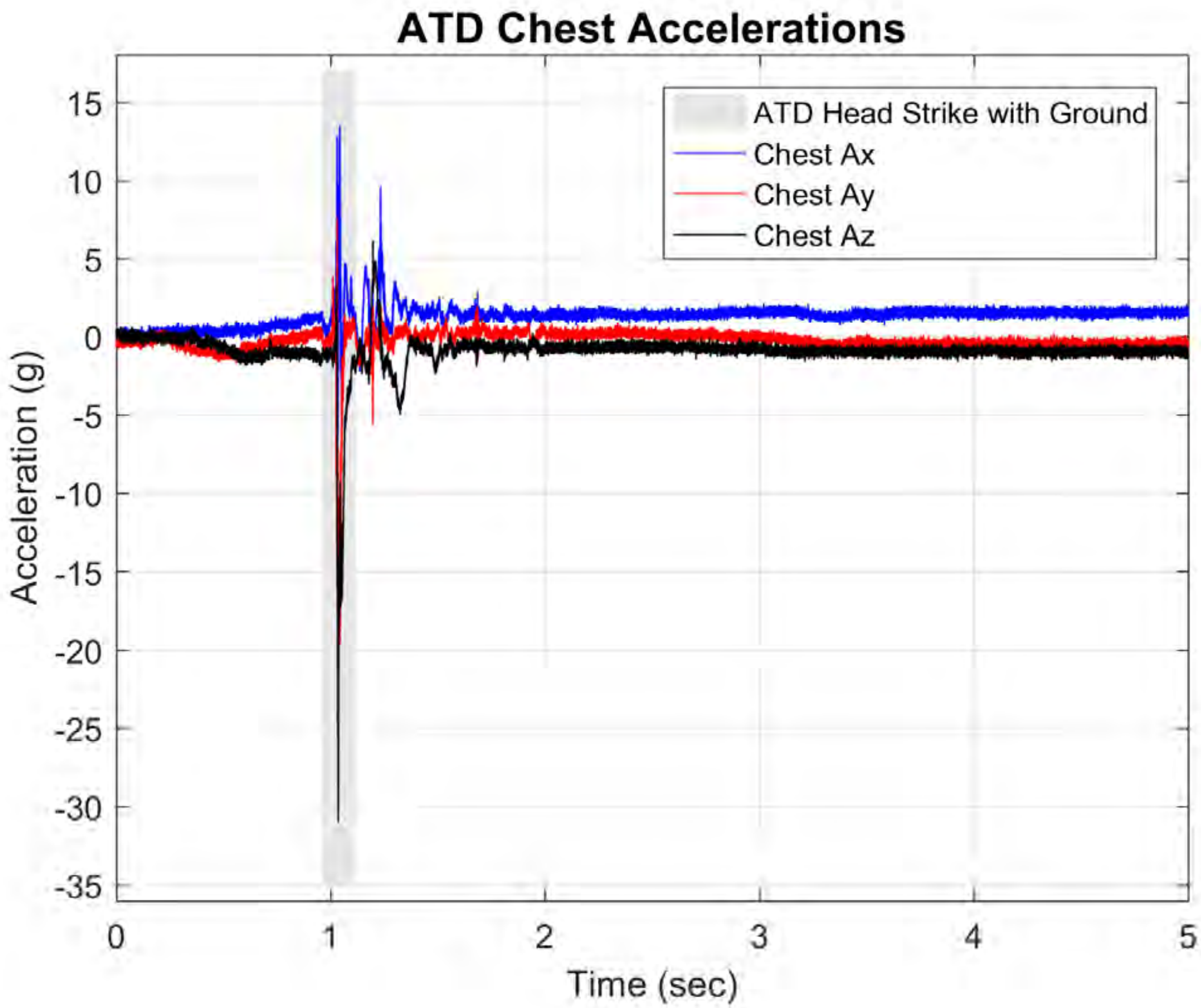
Vehicle E - Sled Moderate Energy Rollover



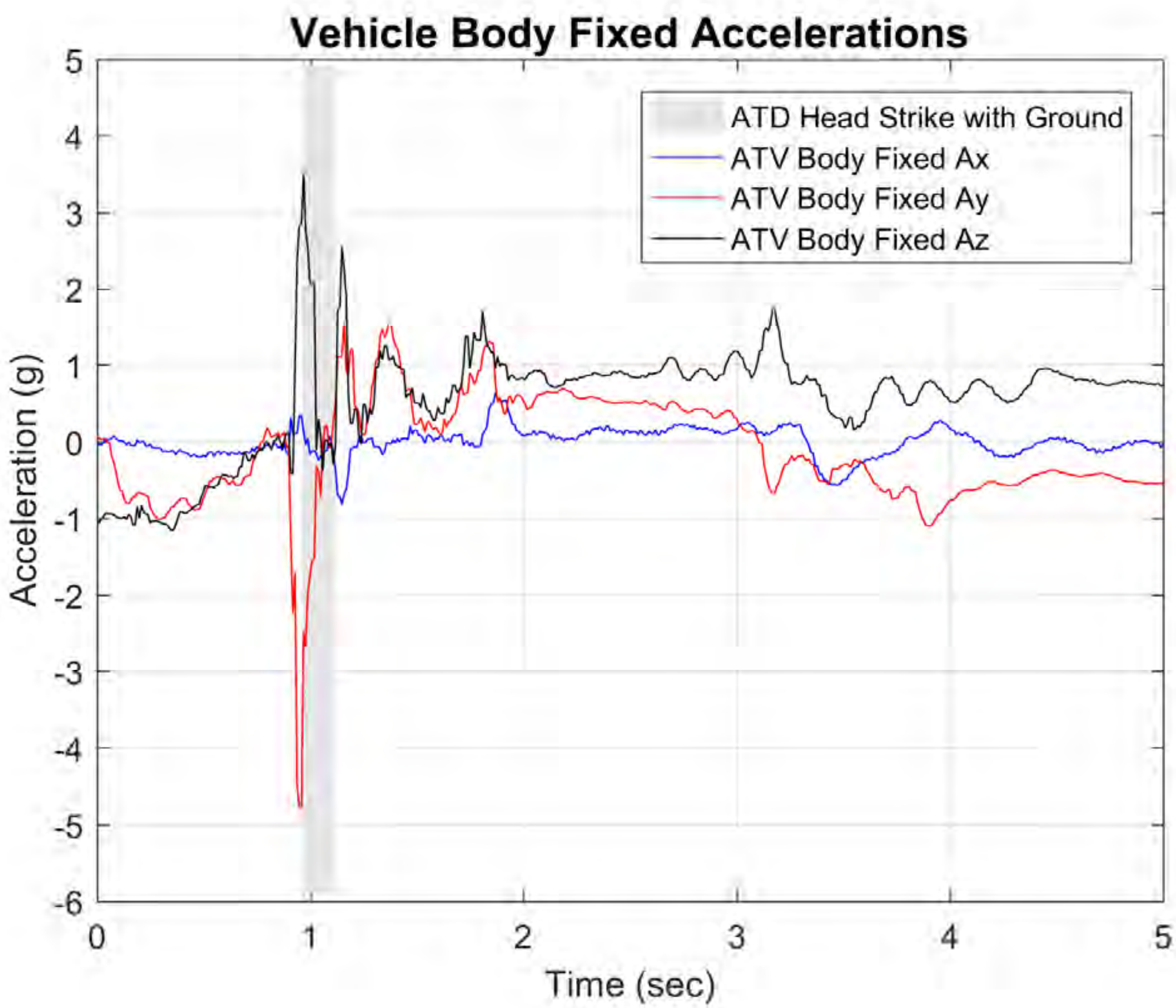
Vehicle E - Sled Moderate Energy Rollover



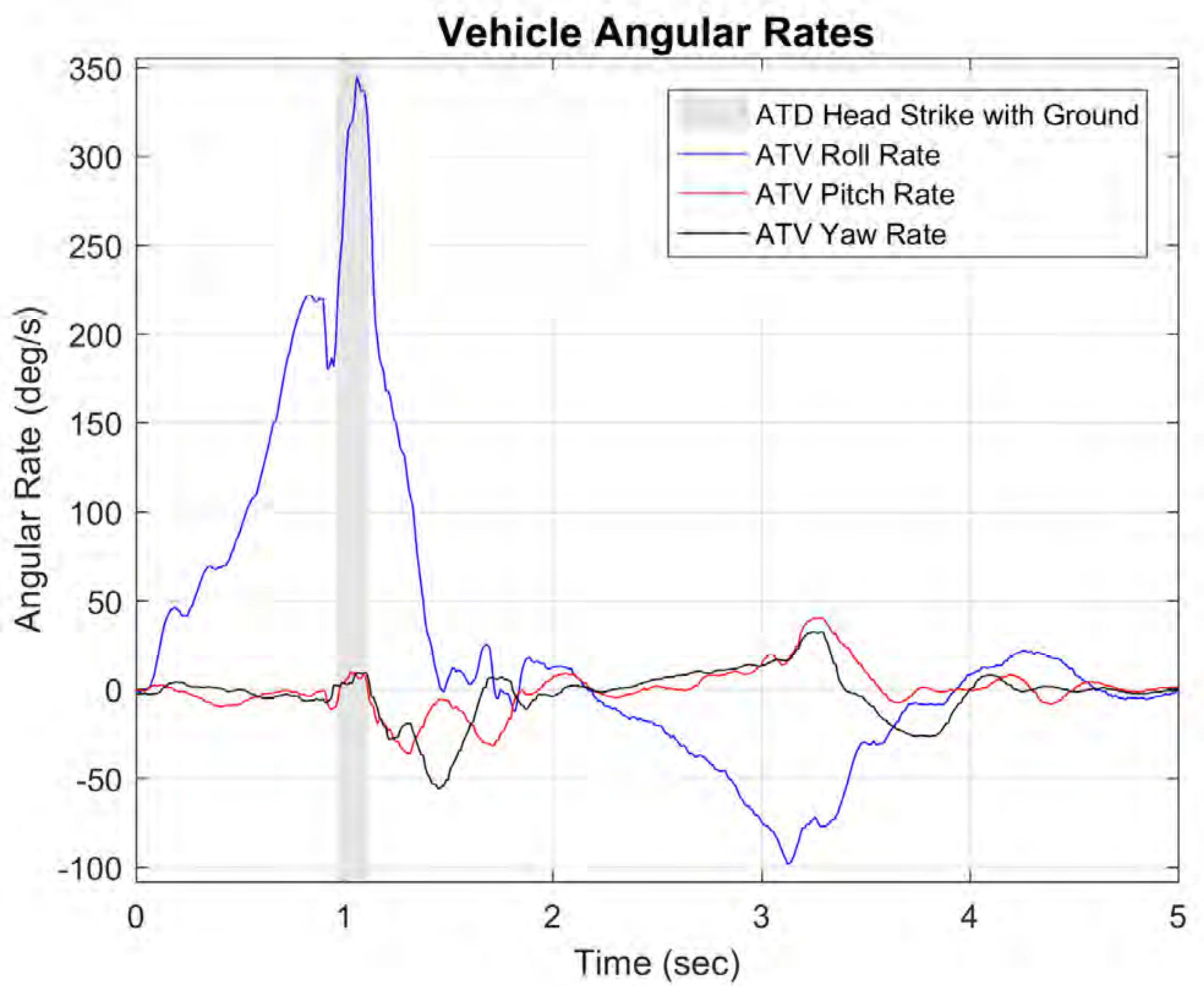
Vehicle E - Sled Moderate Energy Rollover



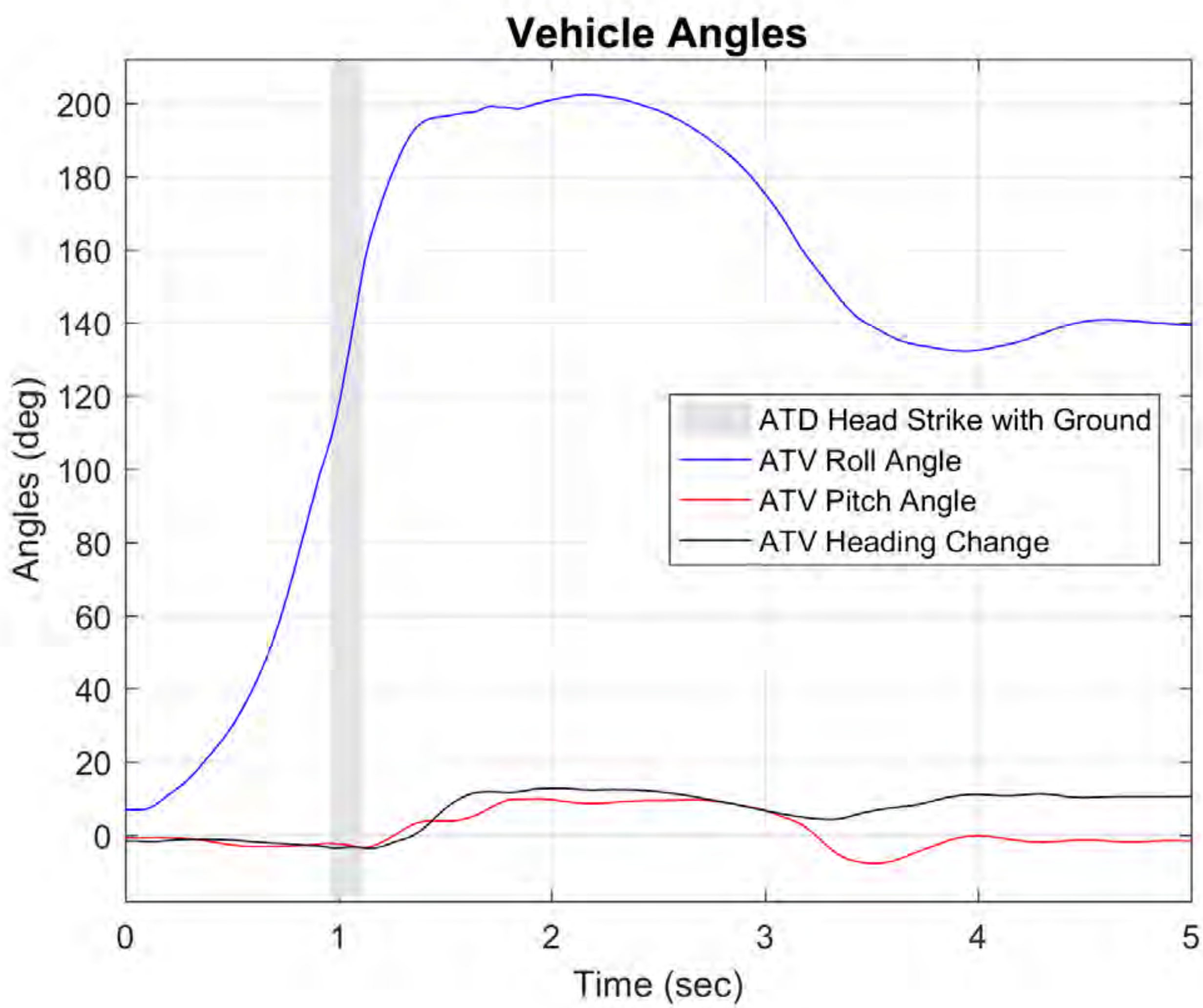
Vehicle E - Sled Moderate Energy Rollover



Vehicle E - Sled Moderate Energy Rollover



Vehicle E - Sled Moderate Energy Rollover



Vehicle E - Sled Moderate Energy Rollover

AOS Camera 1 - Roll Angle = 30° - Time = 0.67 sec

AOS Camera 1 - Roll Angle = 45° - Time = 0.77 sec

AOS Camera 1 - Roll Angle = 90° - Time = 1.01 sec

AOS Camera 2 - Roll Angle = 30° - Time = 0.67 sec

AOS Camera 2 - Roll Angle = 45° - Time = 0.77 sec

AOS Camera 2 - Roll Angle = 90° - Time = 1.01 sec

Vehicle F - Sled Minimum Energy Rollover

AOS Camera 1 - ATD Head Strike - Time = 1.13 sec

AOS Camera 1 - Max Angle = 148.5° - Time = 1.7 sec

AOS Camera 1 - End of Run - Roll Angle = 141.8°

AOS Camera 2 - ATD Head Strike - Time = 1.13 sec

AOS Camera 2 - Max Angle = 148.5° - Time = 1.7 sec

AOS Camera 2 - End of Run - Roll Angle = 141.8°

Vehicle F - Sled Minimum Energy Rollover

RT Camera 1 - Roll Angle = 30° - Time = 0.67 sec

RT Camera 1 - Roll Angle = 45° - Time = 0.77 sec

RT Camera 1 - Roll Angle = 90° - Time = 1.01 sec

RT Camera 2 - Roll Angle = 30° - Time = 0.67 sec

RT Camera 2 - Roll Angle = 45° - Time = 0.77 sec

RT Camera 2 - Roll Angle = 90° - Time = 1.01 sec

Vehicle F - Sled Minimum Energy Rollover

RT Camera 1 - ATD Head Strike - Time = 1.13 sec

RT Camera 1 - Max Angle = 148.5° - Time = 1.7 sec

RT Camera 1 - End of Run - Roll Angle = 141.8°

RT Camera 2 - ATD Head Strike - Time = 1.13 sec

RT Camera 2 - Max Angle = 148.5° - Time = 1.7 sec

RT Camera 2 - End of Run - Roll Angle = 141.8°

Vehicle F - Sled Minimum Energy Rollover

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

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

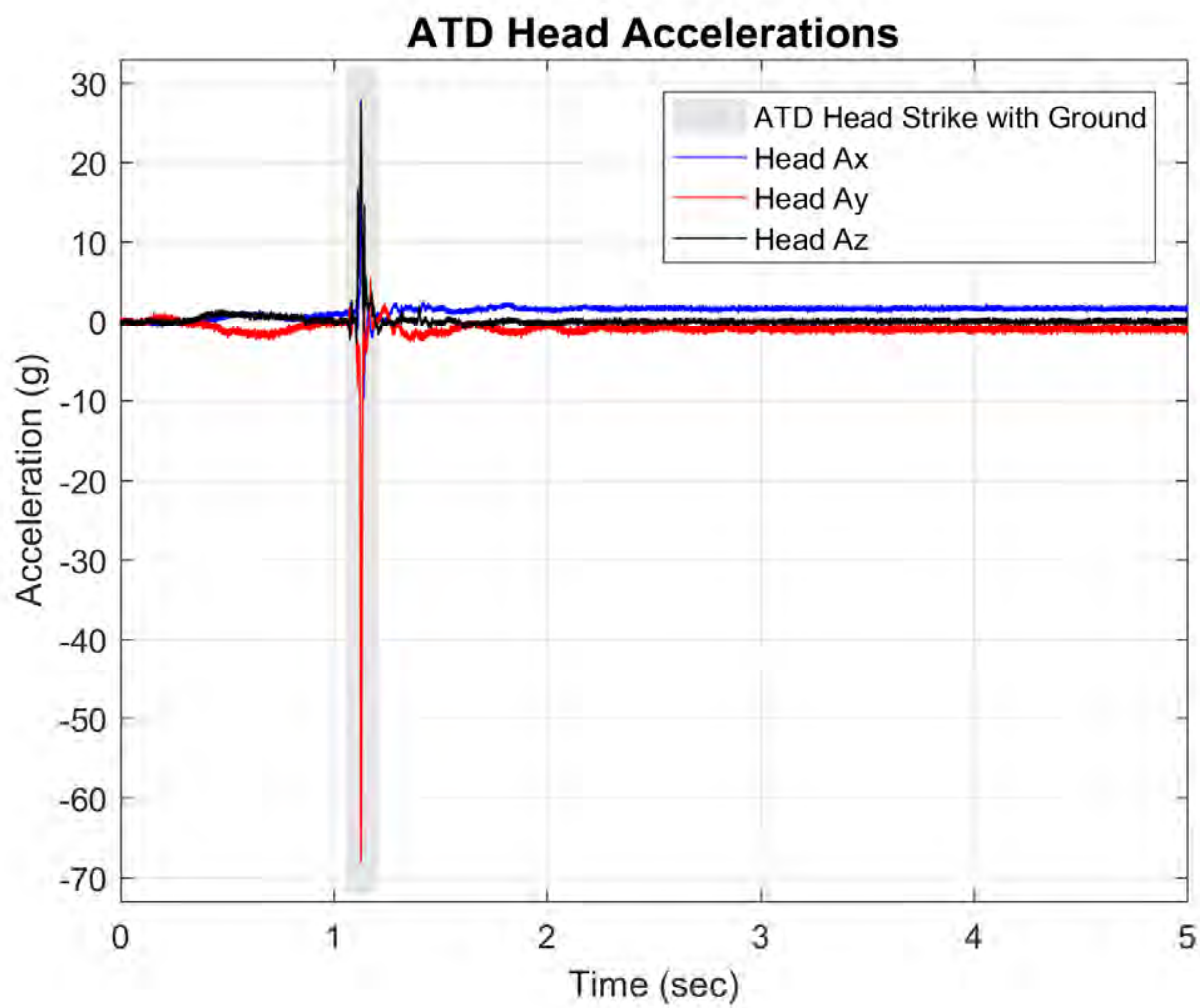
Drone Camera - Roll Angle = 90° - Time = 1.01 sec

Drone Camera - ATD Head Strike - Time = 1.13 sec

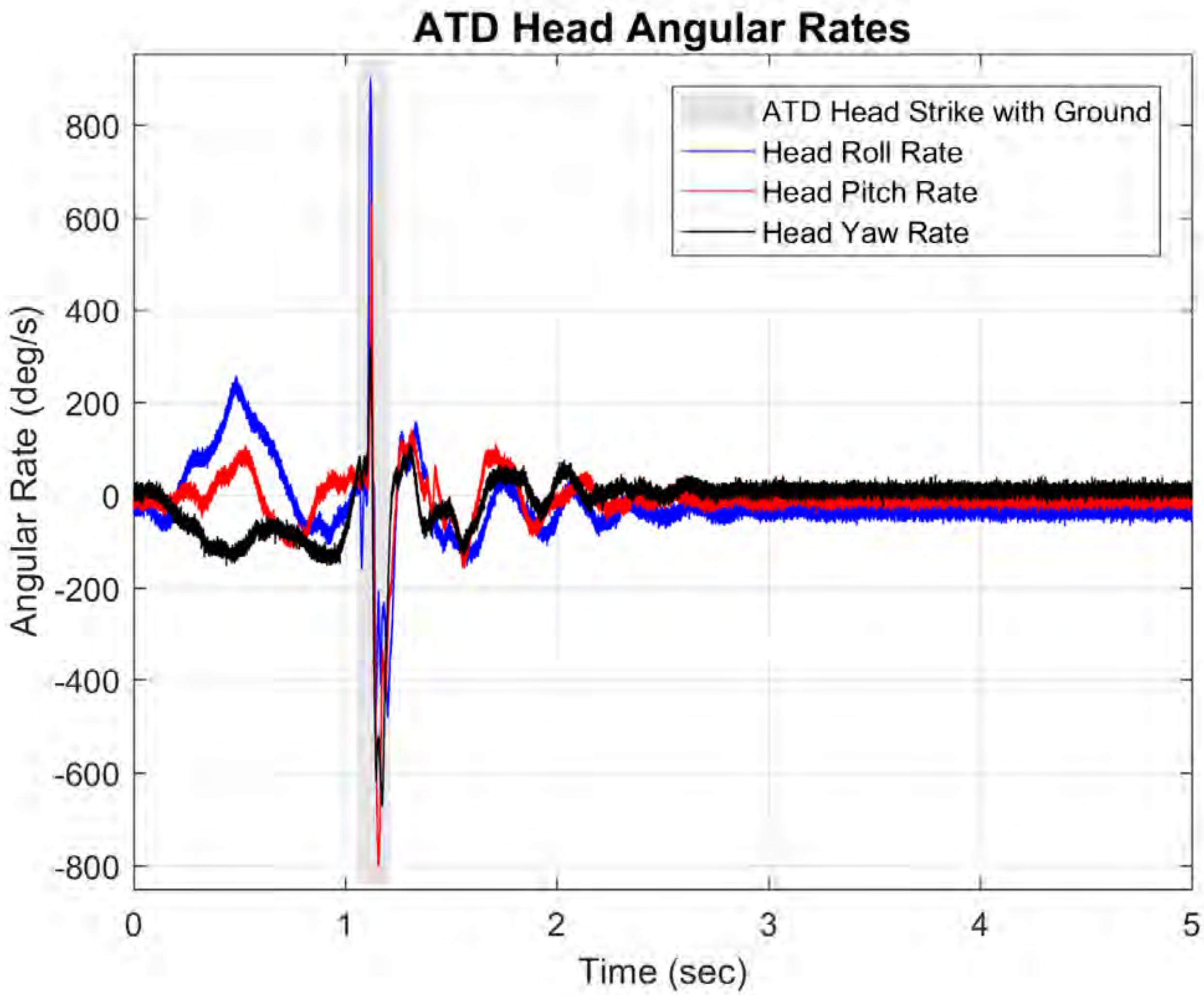
Drone Camera - Max Angle = 148.5° - Time = 1.7 sec

Drone Camera - End of Run - Roll Angle = 141.8°

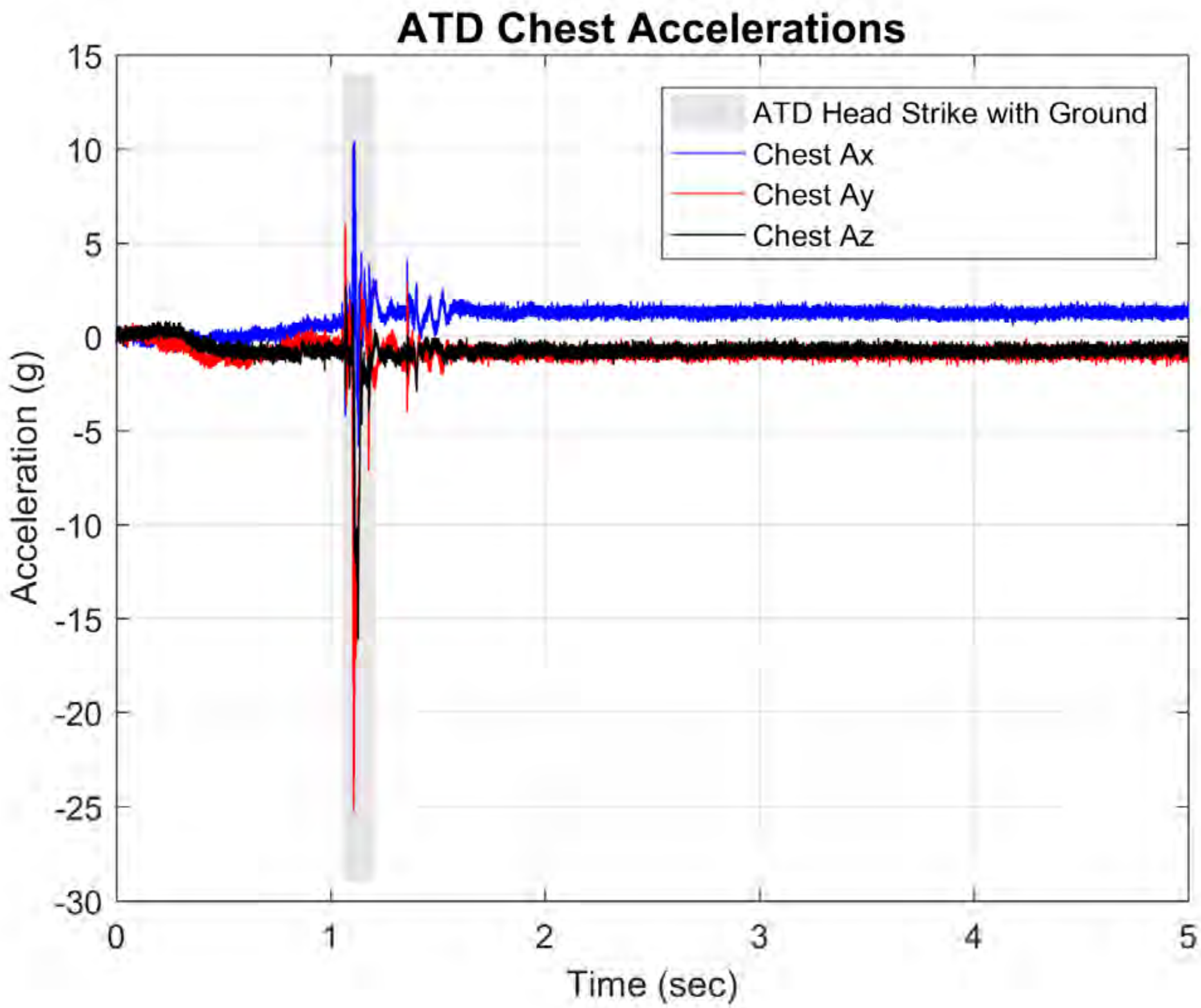
Vehicle F - Sled Minimum Energy Rollover



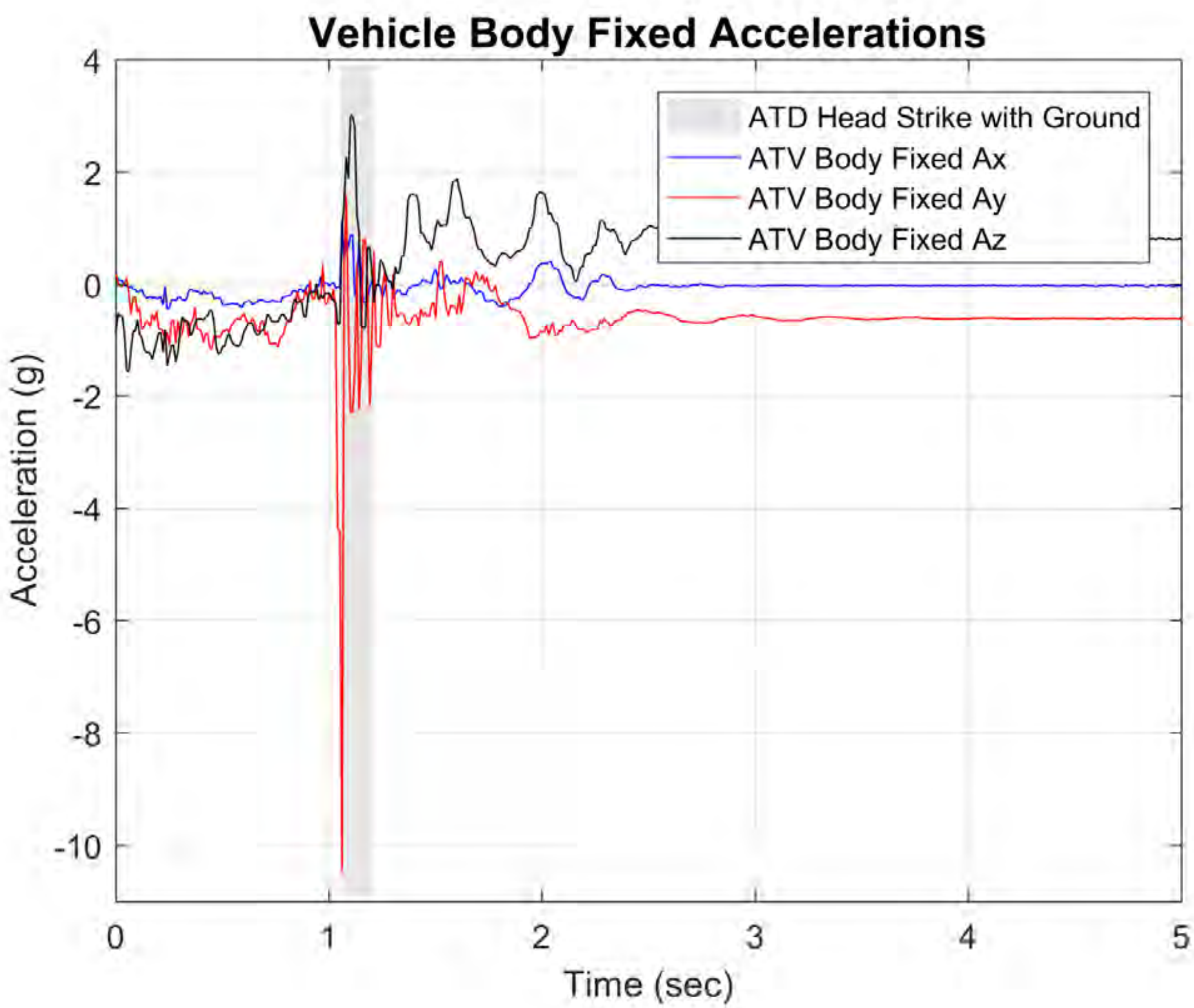
Vehicle F - Sled Minimum Energy Rollover



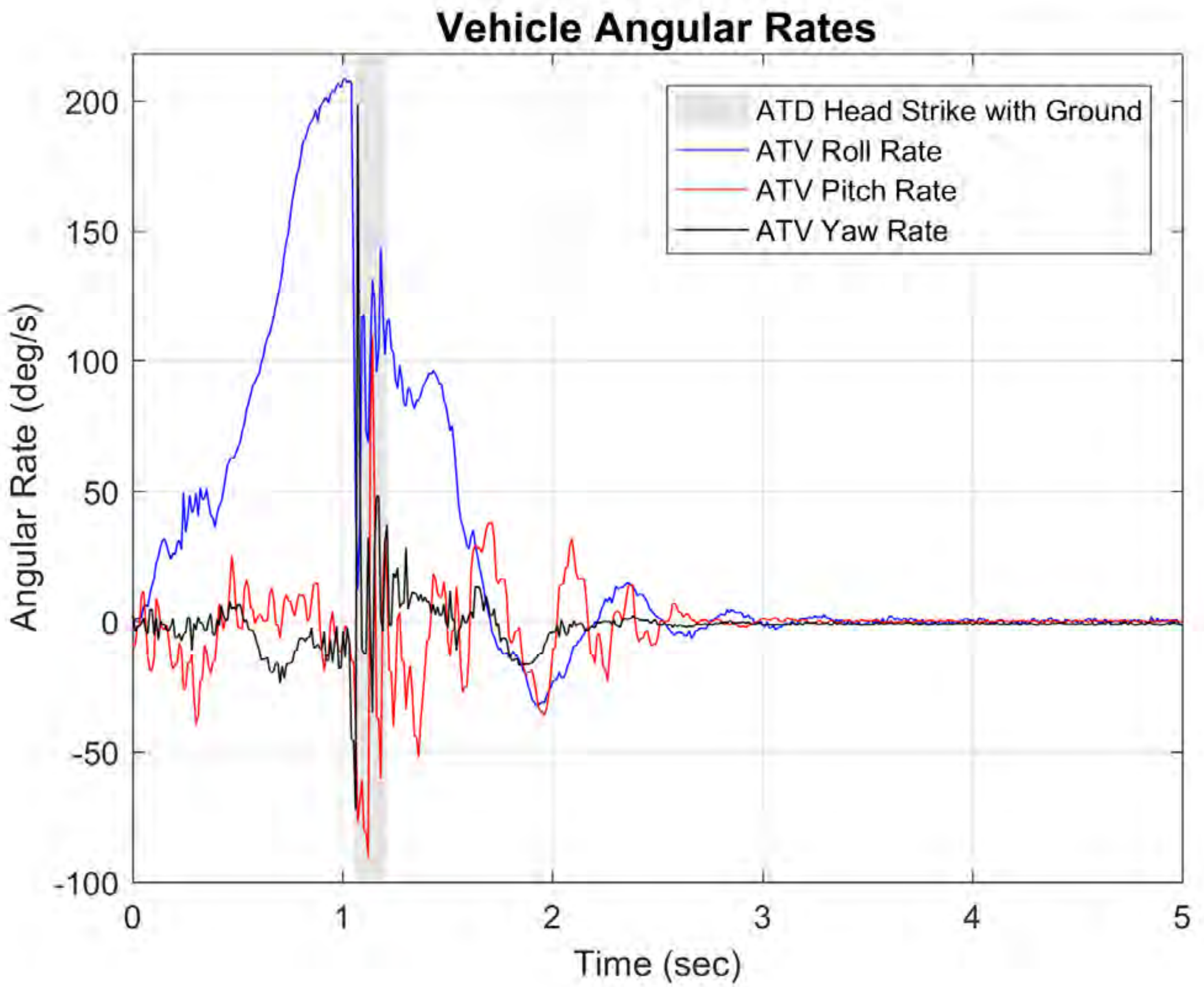
Vehicle F - Sled Minimum Energy Rollover



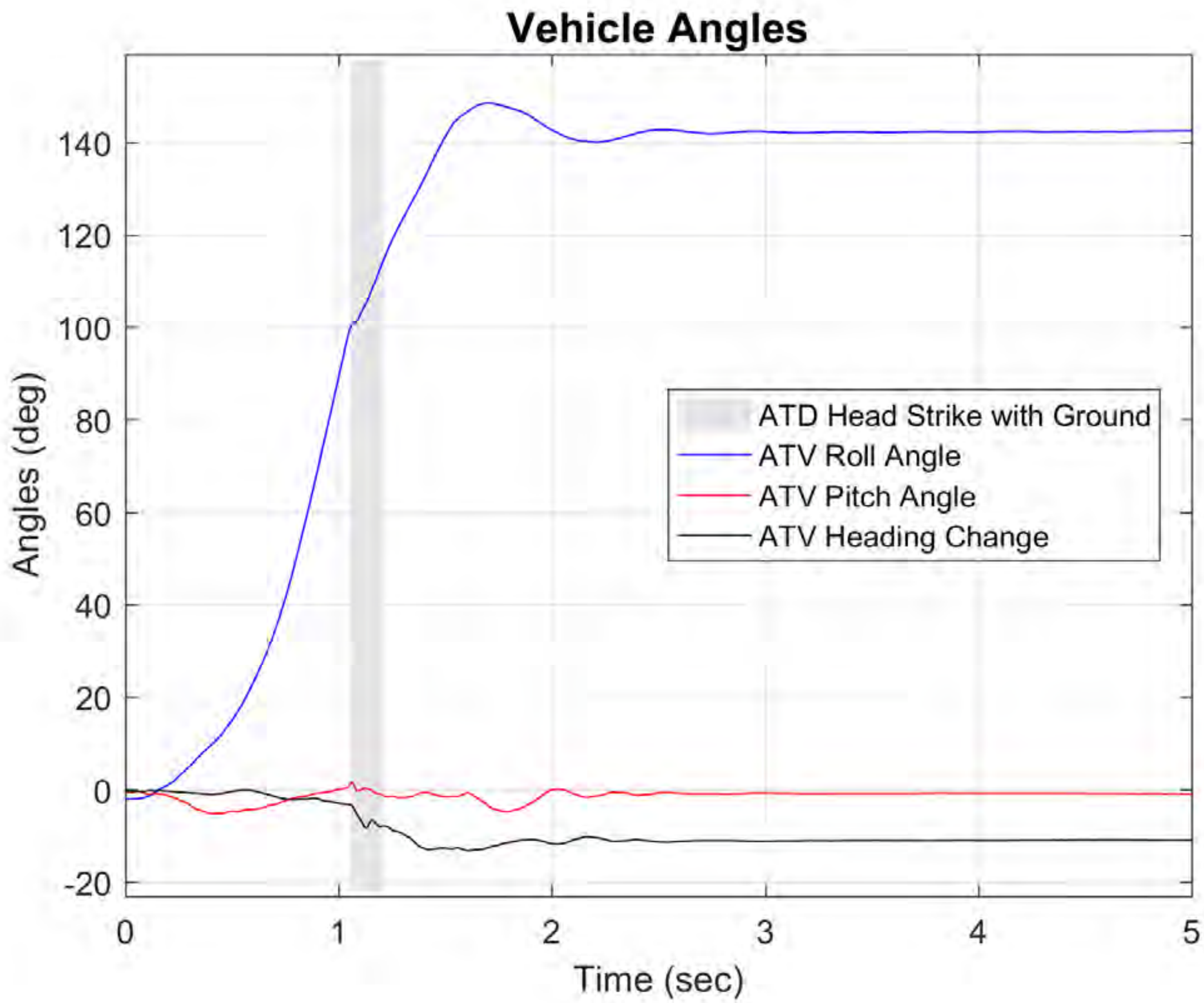
Vehicle F - Sled Minimum Energy Rollover



Vehicle F - Sled Minimum Energy Rollover



Vehicle F - Sled Minimum Energy Rollover



Vehicle F - Sled Minimum Energy Rollover

AOS Camera 1 - Roll Angle = 30° - Time = 0.53 sec

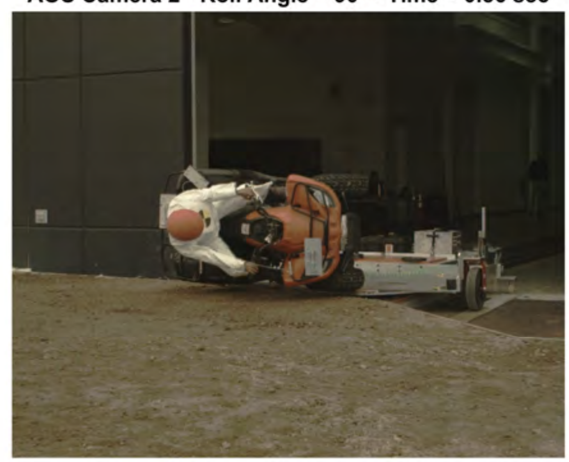
AOS Camera 1 - Roll Angle = 45° - Time = 0.64 sec

AOS Camera 1 - Roll Angle = 90° - Time = 0.86 sec

AOS Camera 2 - Roll Angle = 30° - Time = 0.53 sec

AOS Camera 2 - Roll Angle = 45° - Time = 0.64 sec

AOS Camera 2 - Roll Angle = 90° - Time = 0.86 sec



Vehicle F - Sled Moderate Energy Rollover

AOS Camera 1 - ATD Head Strike - Time = 1.02 sec

AOS Camera 1 - Roll Angle = 180° - Time = 1.18 sec

AOS Camera 1 - Max Angle = 281.6° - Time = 2.48 sec

AOS Camera 2 - ATD Head Strike - Time = 1.02 sec

AOS Camera 2 - Roll Angle = 180° - Time = 1.18 sec

AOS Camera 2 - Max Angle = 281.6° - Time = 2.48 sec

Vehicle F - Sled Moderate Energy Rollover

AOS Camera 1 - End of Run - Roll Angle = 253.1°

AOS Camera 2 - End of Run - Roll Angle = 253.1°

Vehicle F - Sled Moderate Energy Rollover

RT Camera 1 - Roll Angle = 30° - Time = 0.53 sec

RT Camera 1 - Roll Angle = 45° - Time = 0.64 sec

RT Camera 1 - Roll Angle = 90° - Time = 0.86 sec

RT Camera 2 - Roll Angle = 30° - Time = 0.53 sec

RT Camera 2 - Roll Angle = 45° - Time = 0.64 sec

RT Camera 2 - Roll Angle = 90° - Time = 0.86 sec

Vehicle F - Sled Moderate Energy Rollover

RT Camera 1 - ATD Head Strike - Time = 1.02 sec

RT Camera 1 - Roll Angle = 180° - Time = 1.18 sec

RT Camera 1 - Max Angle = 281.6° - Time = 2.48 sec

RT Camera 2 - ATD Head Strike - Time = 1.02 sec

RT Camera 2 - Roll Angle = 180° - Time = 1.18 sec

RT Camera 2 - Max Angle = 281.6° - Time = 2.48 sec

Vehicle F - Sled Moderate Energy Rollover

RT Camera 1 - End of Run - Roll Angle = 253.1°

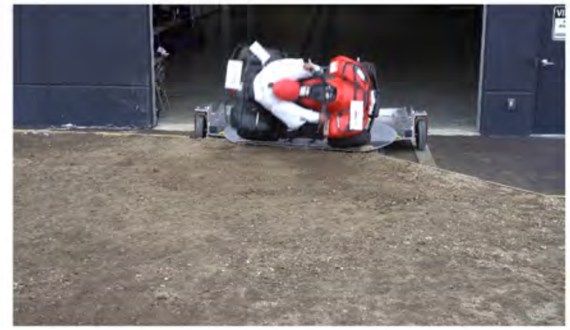
RT Camera 2 - End of Run - Roll Angle = 253.1°

Vehicle F - Sled Moderate Energy Rollover

Drone Camera - Roll Angle = 30° - Time = 0.53 sec

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

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



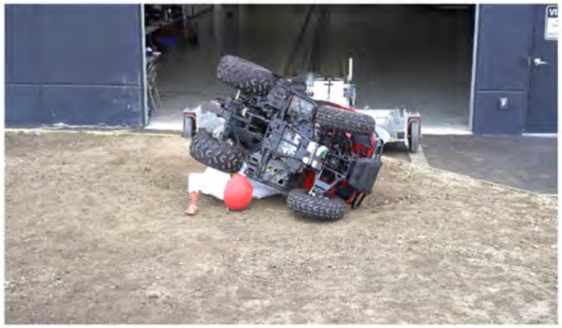
Drone Camera - ATD Head Strike - Time = 1.02 sec

Drone Camera - Roll Angle = 180° - Time = 1.18 sec

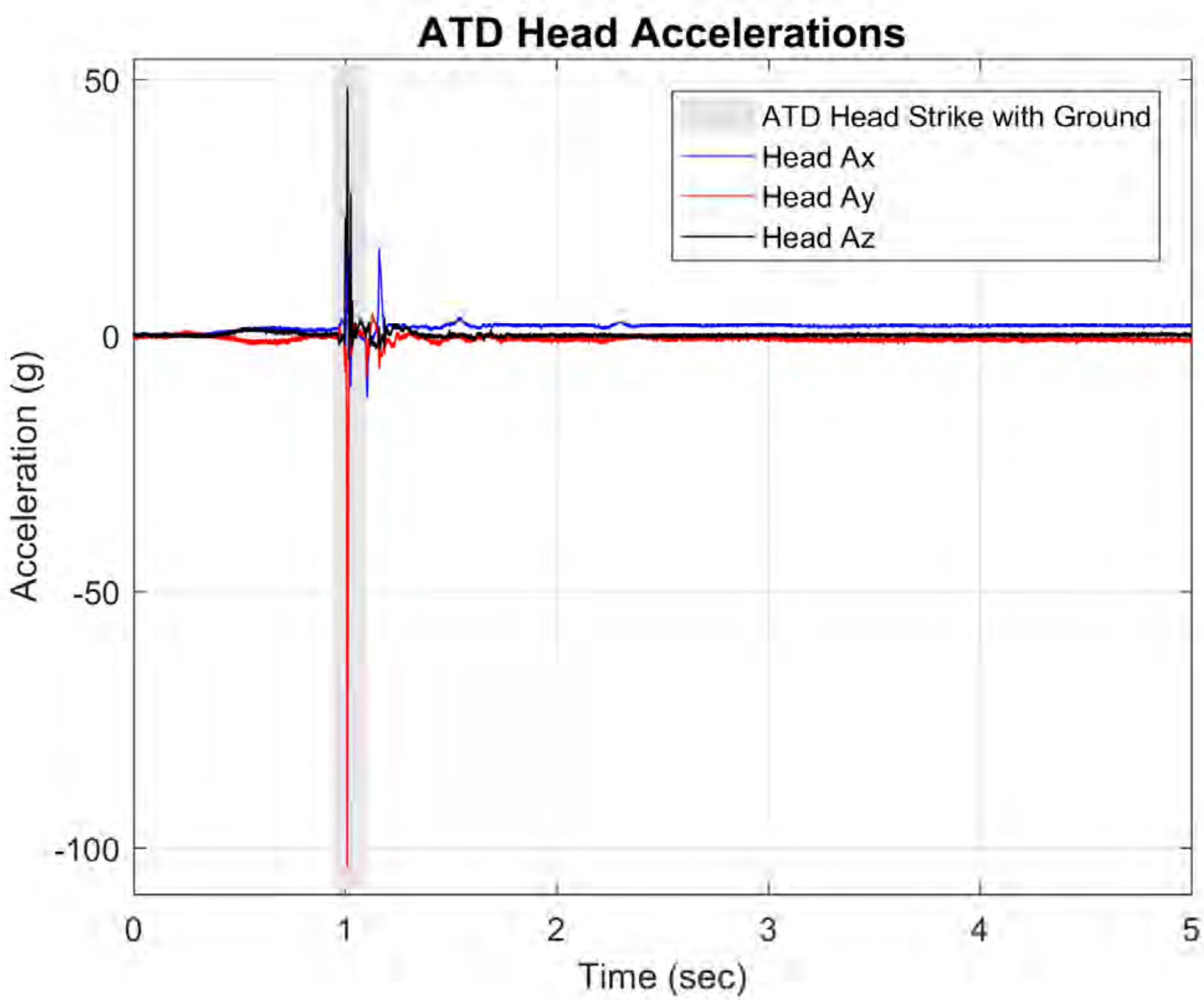
Drone Camera - Max Angle = 281.6° - Time = 2.48 sec

Vehicle F - Sled Moderate Energy Rollover

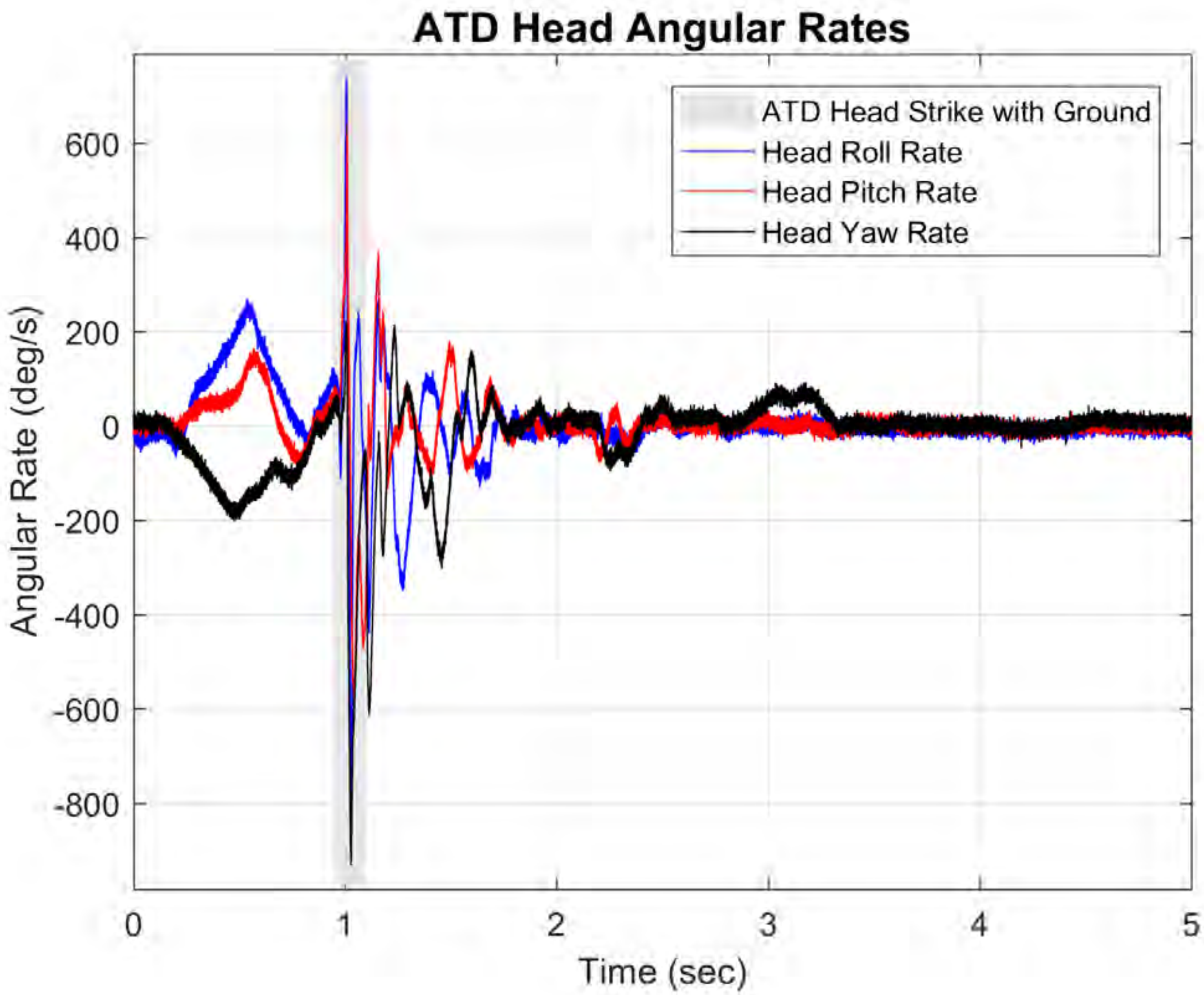
Drone Camera - End of Run - Roll Angle = 253.1°



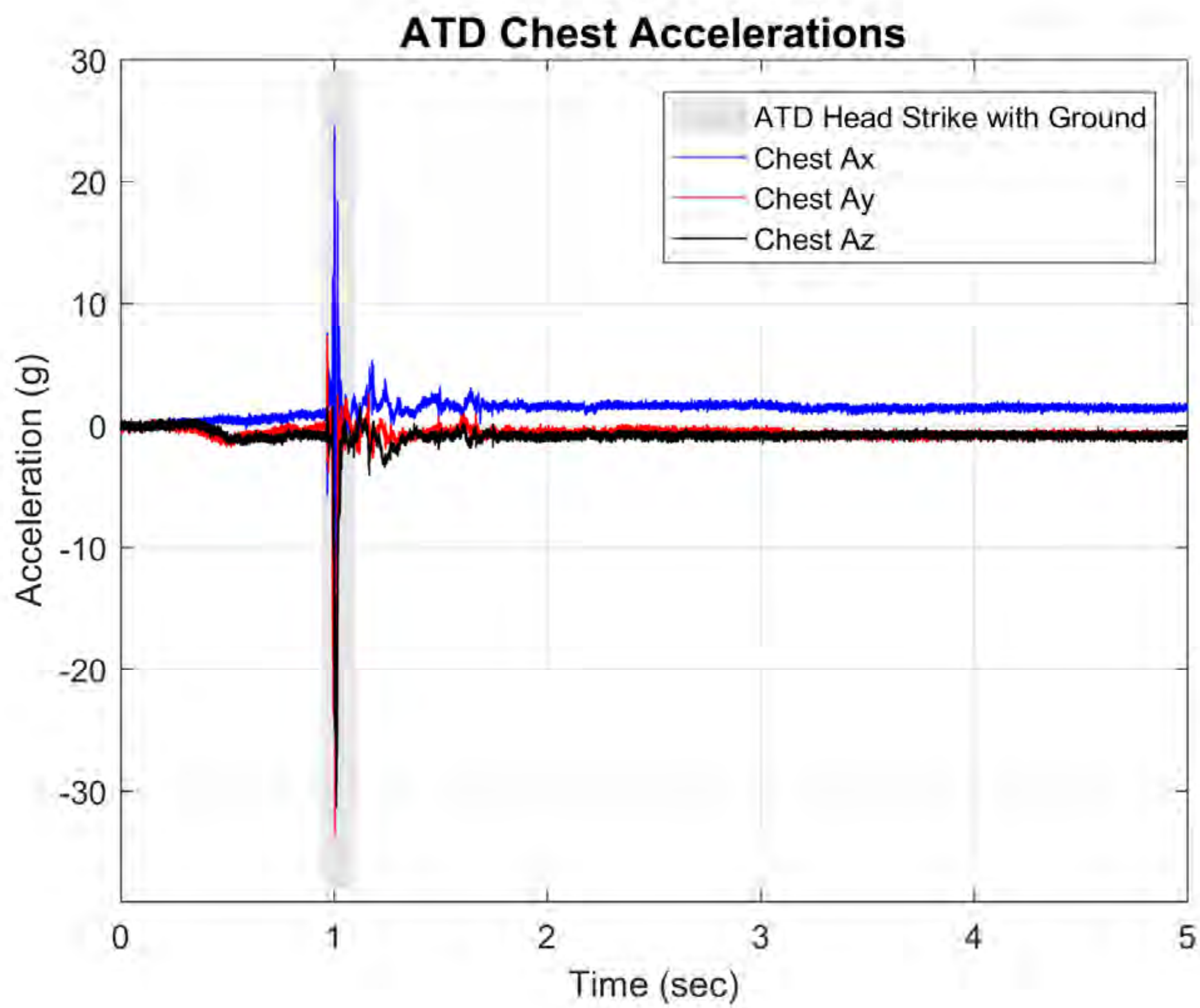
Vehicle F - Sled Moderate Energy Rollover



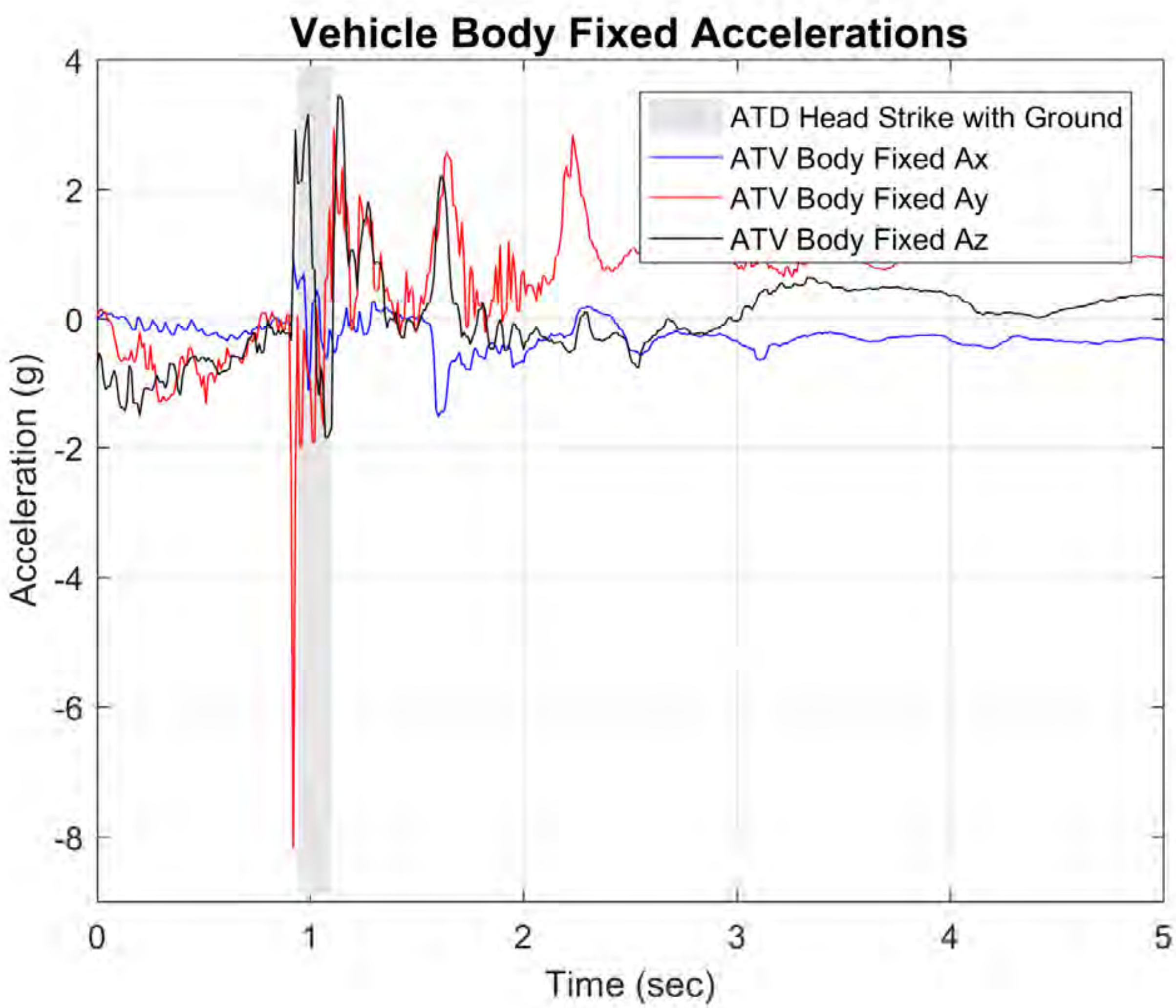
Vehicle F - Sled Moderate Energy Rollover



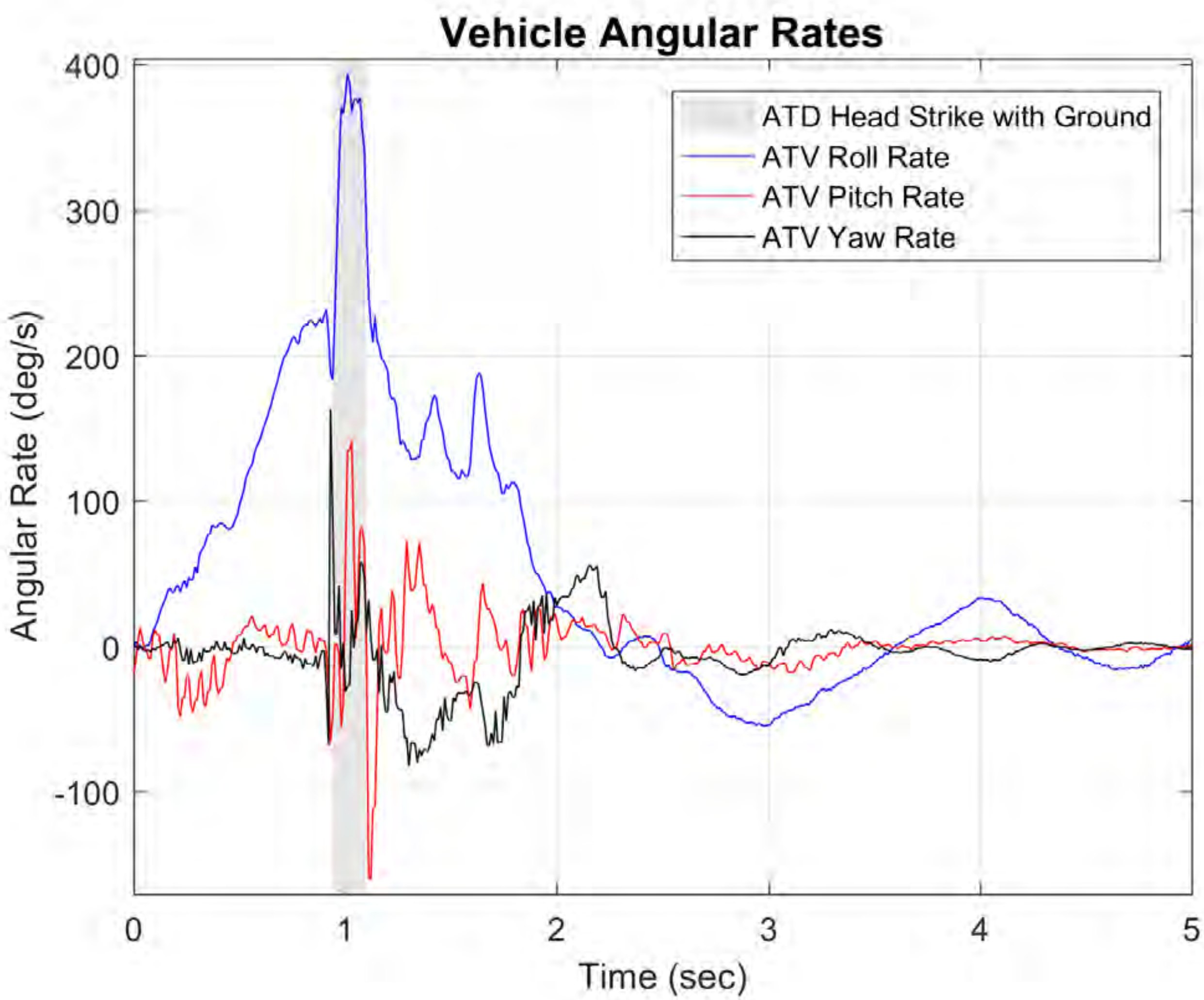
Vehicle F - Sled Moderate Energy Rollover



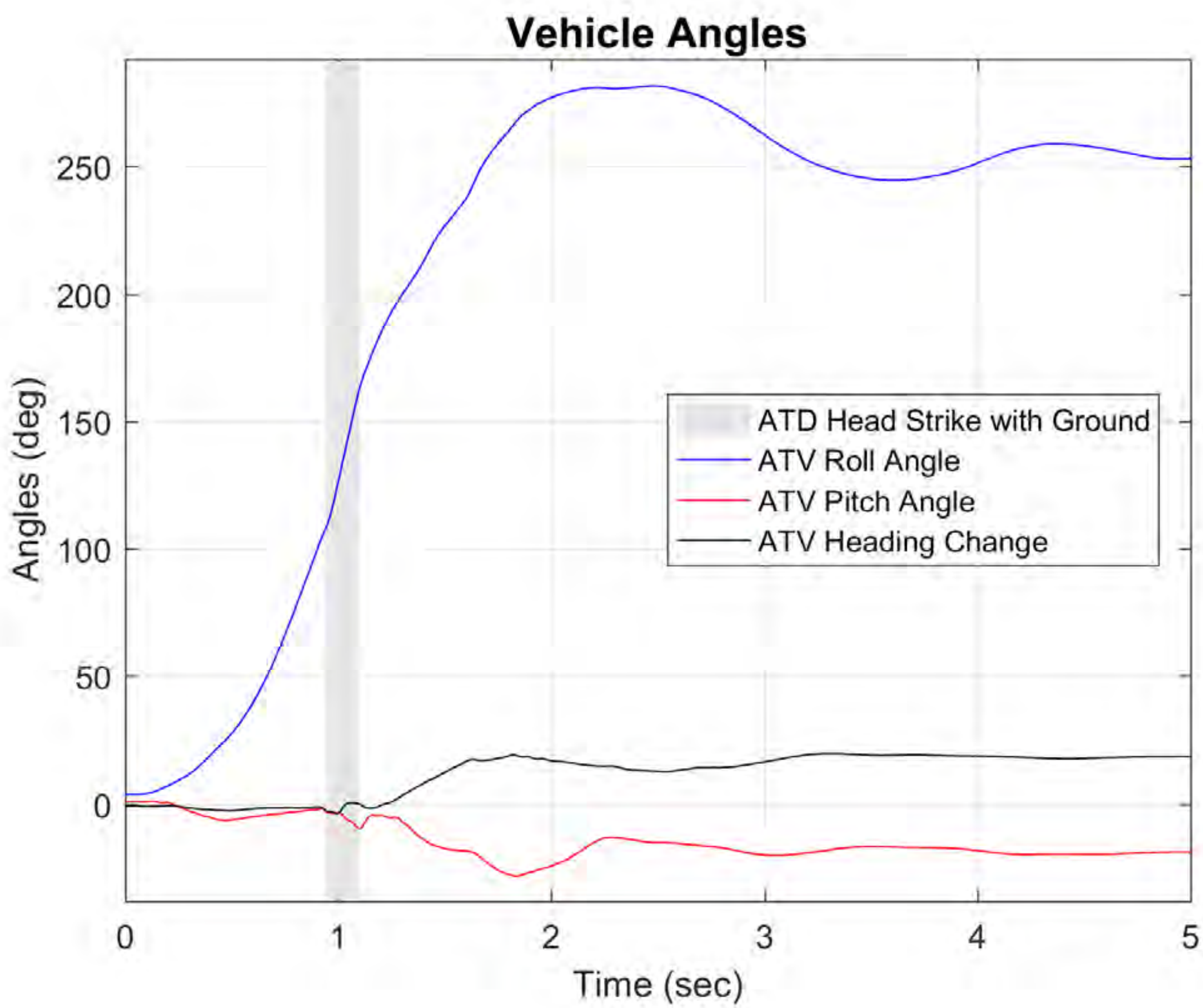
Vehicle F - Sled Moderate Energy Rollover



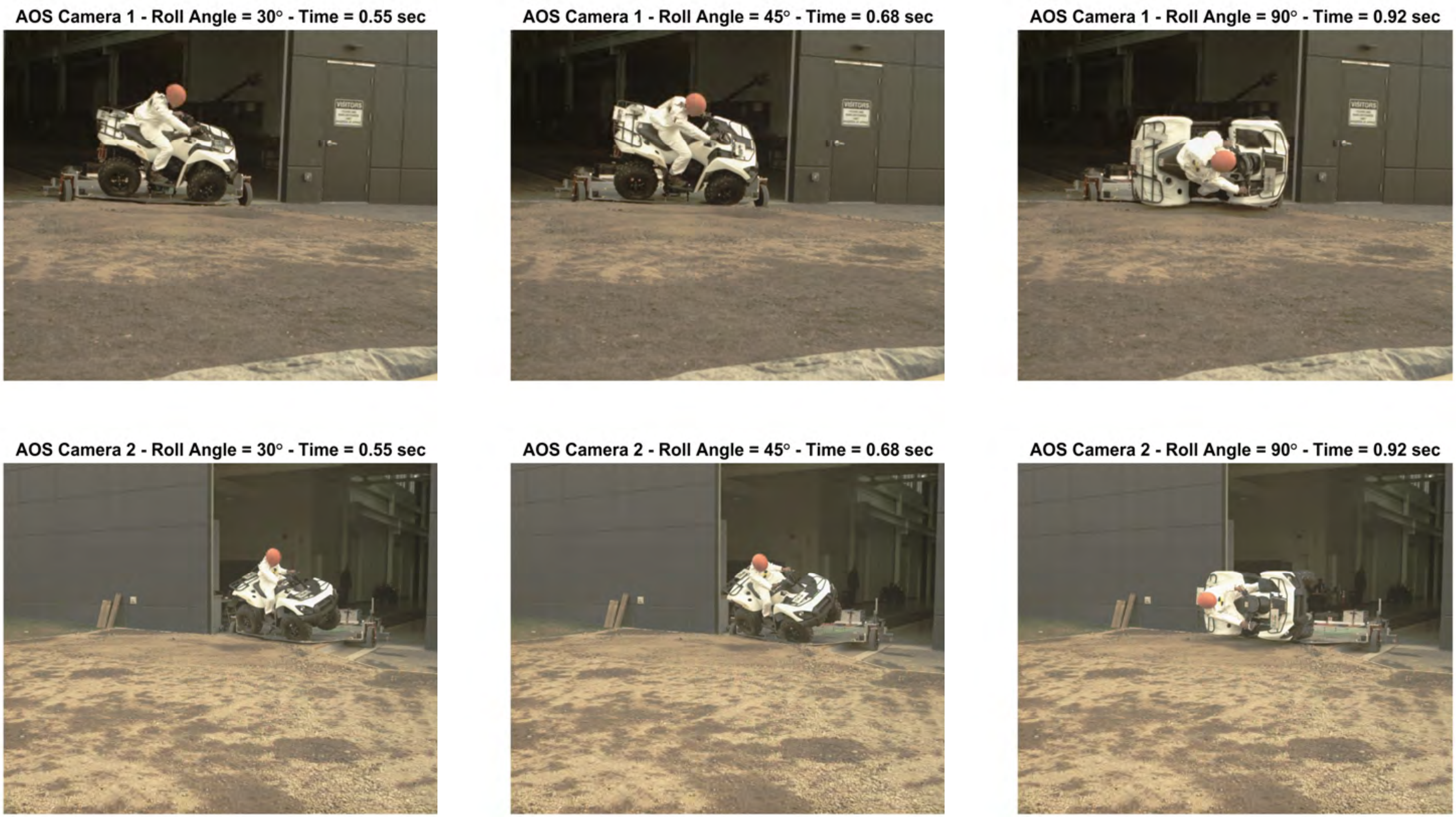
Vehicle F - Sled Moderate Energy Rollover



Vehicle F - Sled Moderate Energy Rollover



Vehicle F - Sled Moderate Energy Rollover



Vehicle G - Sled Minimum Energy Rollover

AOS Camera 1 - ATD Head Strike - Time = 1.08 sec

AOS Camera 1 - Max Angle = 164.5° - Time = 1.96 sec

AOS Camera 1 - End of Run - Roll Angle = 148.4°

AOS Camera 2 - ATD Head Strike - Time = 1.08 sec

AOS Camera 2 - Max Angle = 164.5° - Time = 1.96 sec

AOS Camera 2 - End of Run - Roll Angle = 148.4°

Vehicle G - Sled Minimum Energy Rollover

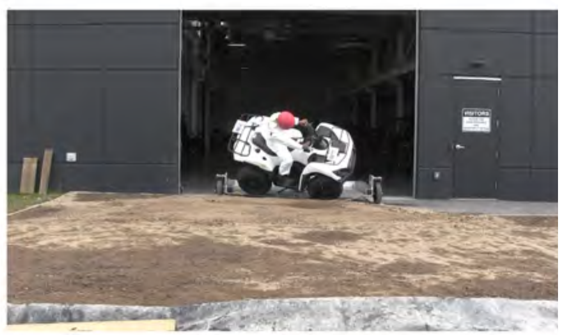
RT Camera 1 - Roll Angle = 30° - Time = 0.55 sec

RT Camera 1 - Roll Angle = 45° - Time = 0.68 sec

RT Camera 1 - Roll Angle = 90° - Time = 0.92 sec

RT Camera 2 - Roll Angle = 30° - Time = 0.55 sec

RT Camera 2 - Roll Angle = 45° - Time = 0.68 sec



RT Camera 2 - Roll Angle = 90° - Time = 0.92 sec

Vehicle G - Sled Minimum Energy Rollover

RT Camera 1 - ATD Head Strike - Time = 1.08 sec

RT Camera 1 - Max Angle = 164.5° - Time = 1.96 sec

RT Camera 1 - End of Run - Roll Angle = 148.4°

RT Camera 2 - ATD Head Strike - Time = 1.08 sec

RT Camera 2 - Max Angle = 164.5° - Time = 1.96 sec

RT Camera 2 - End of Run - Roll Angle = 148.4°

Vehicle G - Sled Minimum Energy Rollover

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

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

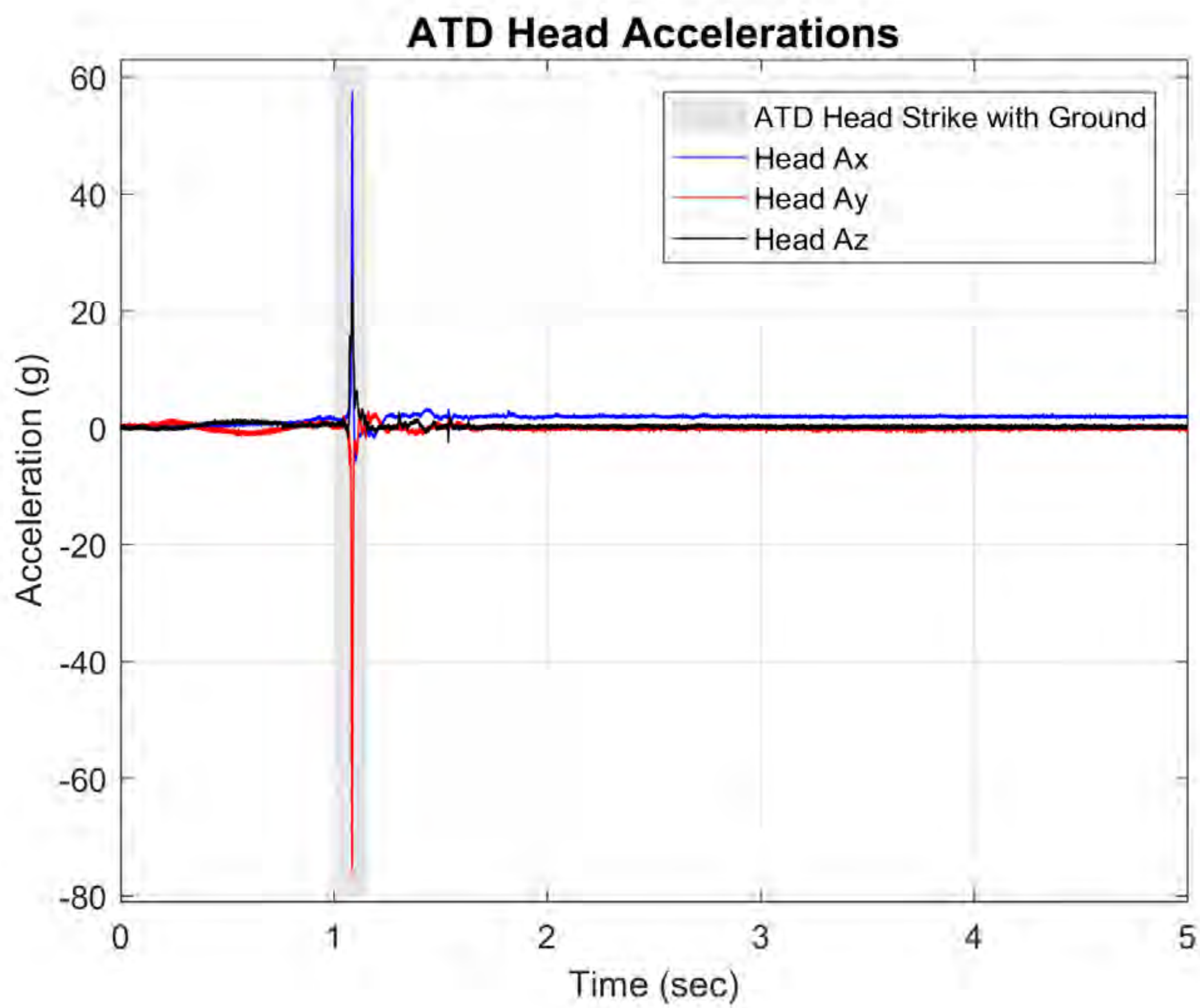
Drone Camera - Roll Angle = 90° - Time = 0.92 sec

Drone Camera - ATD Head Strike - Time = 1.08 sec

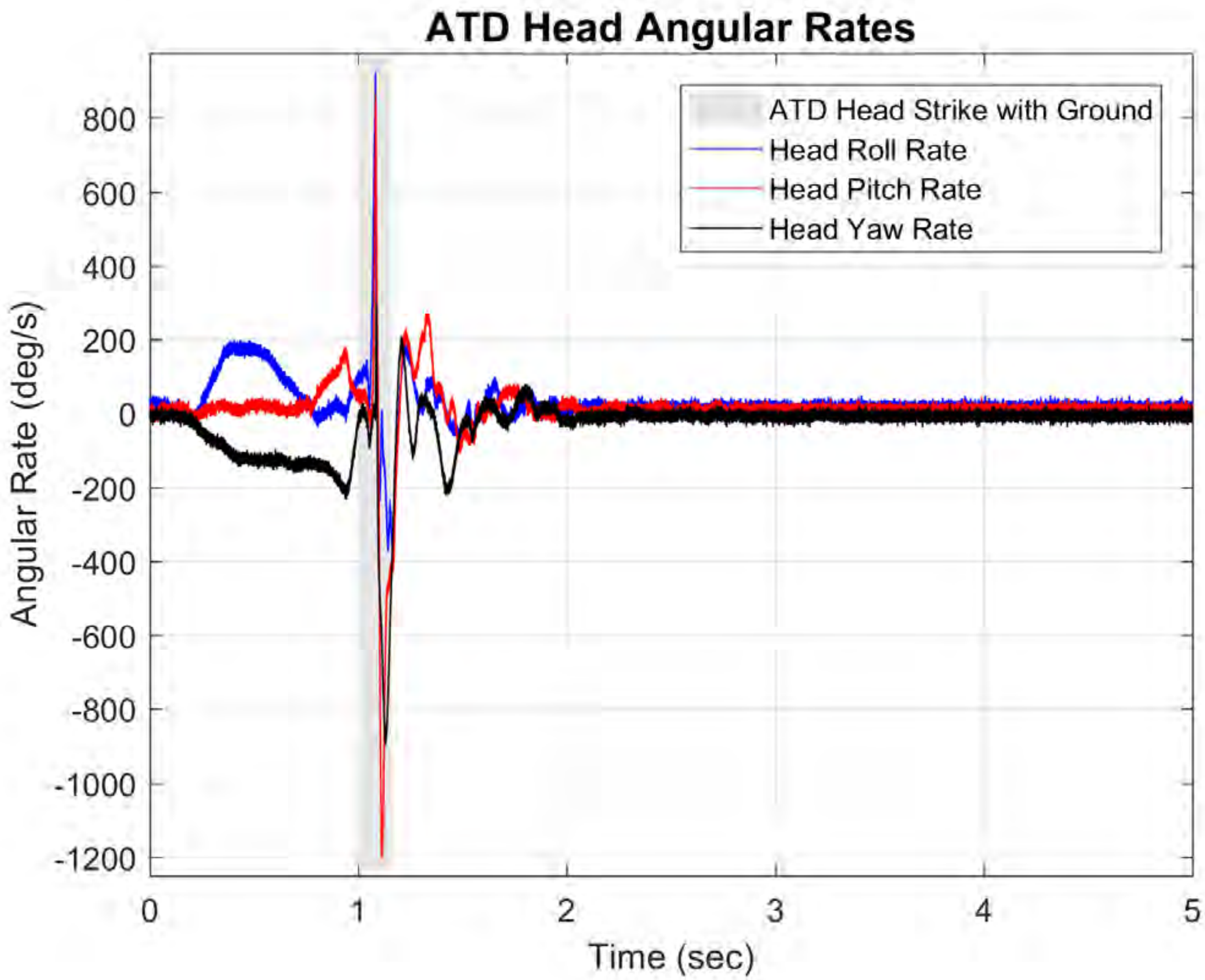
Drone Camera - Max Angle = 164.5° - Time = 1.96 sec

Drone Camera - End of Run - Roll Angle = 148.4°

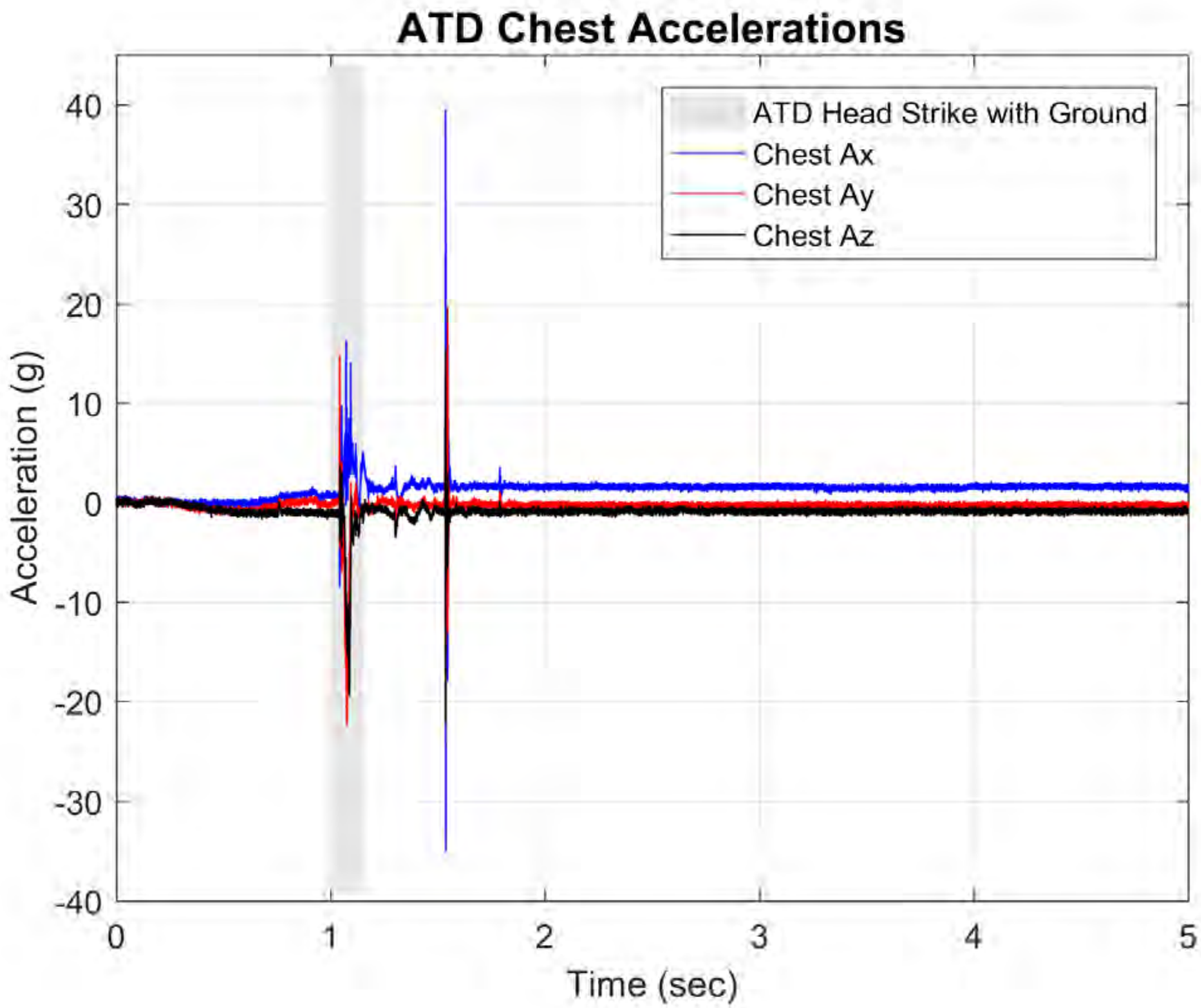
Vehicle G - Sled Minimum Energy Rollover



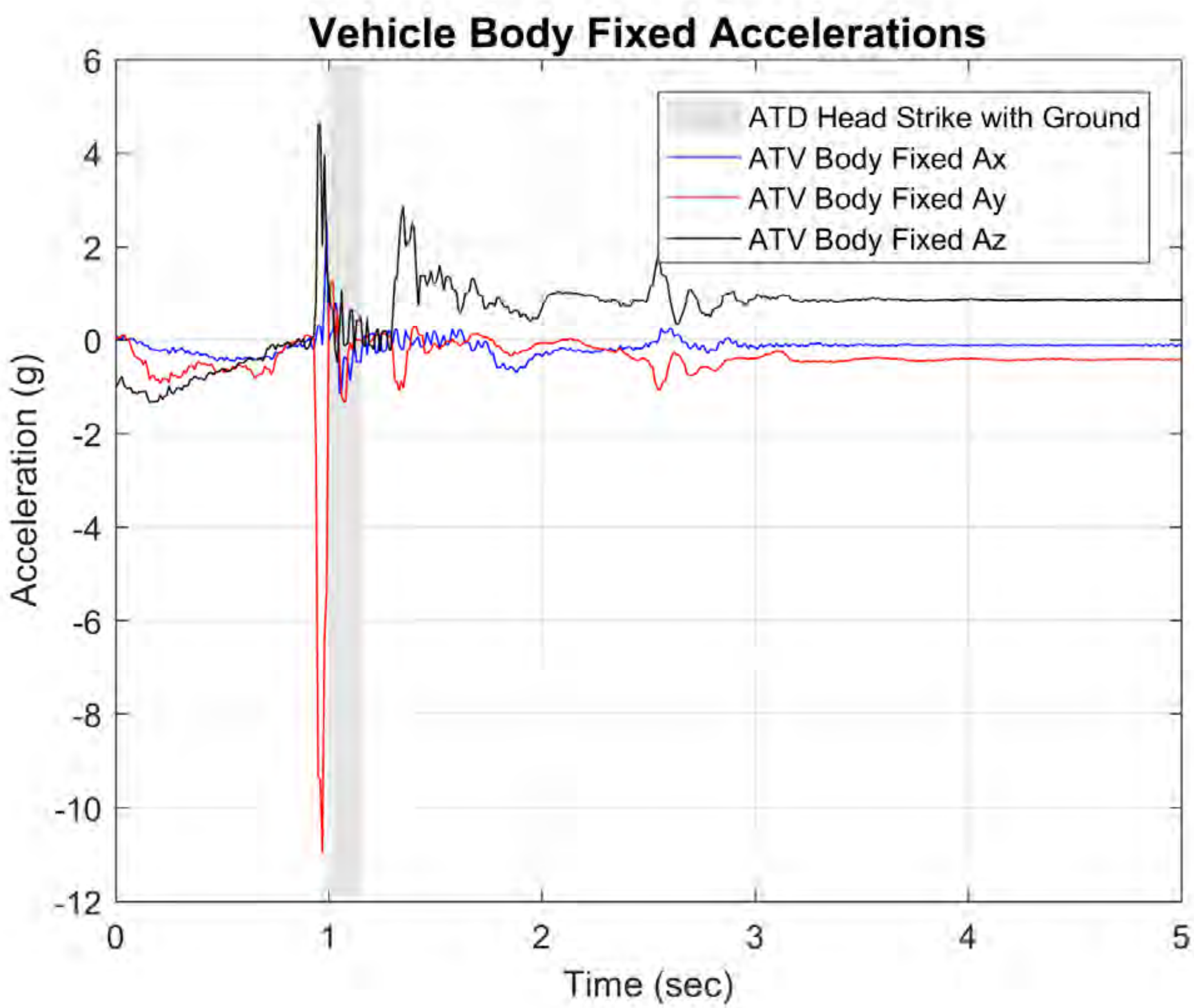
Vehicle G - Sled Minimum Energy Rollover



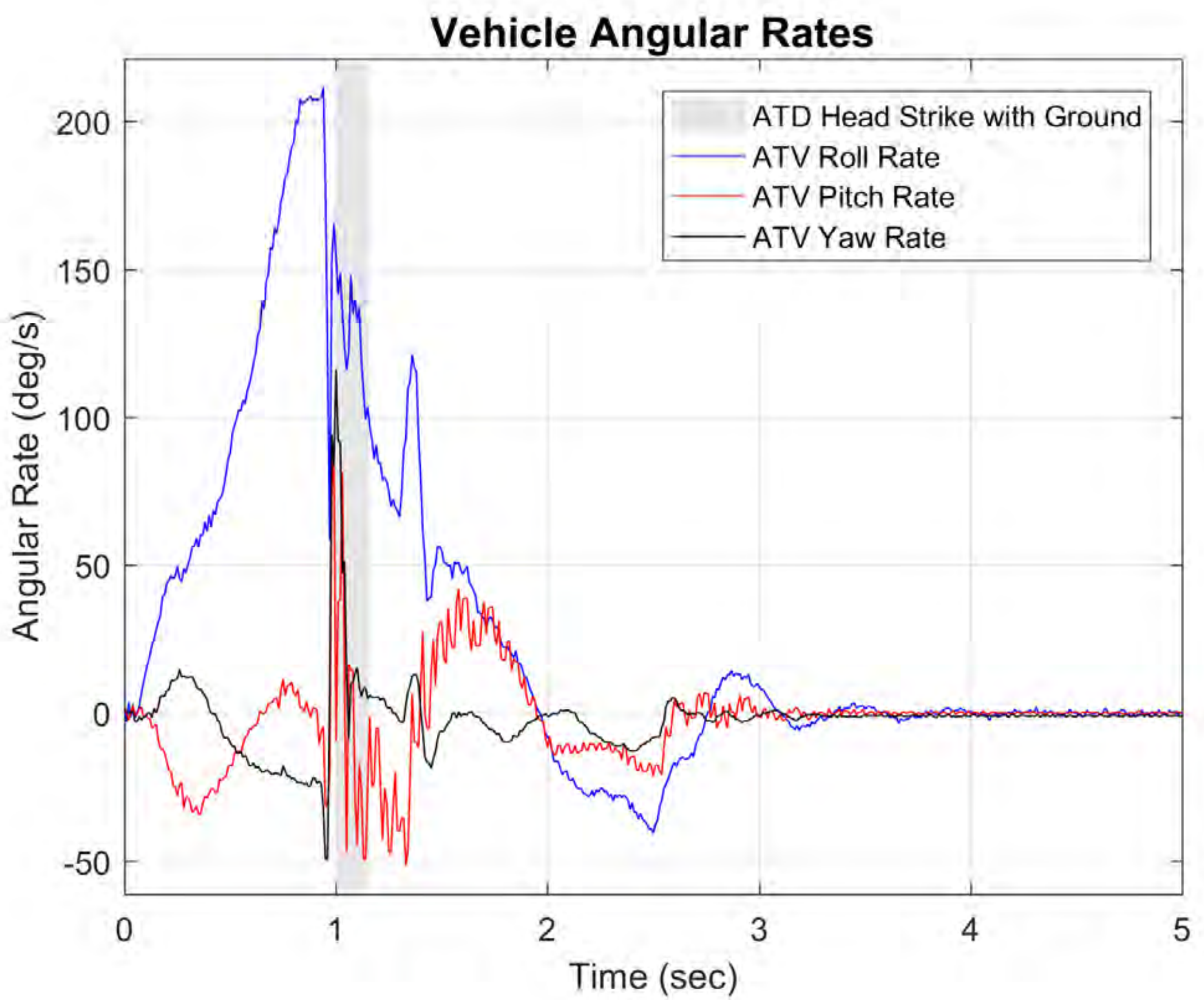
Vehicle G - Sled Minimum Energy Rollover



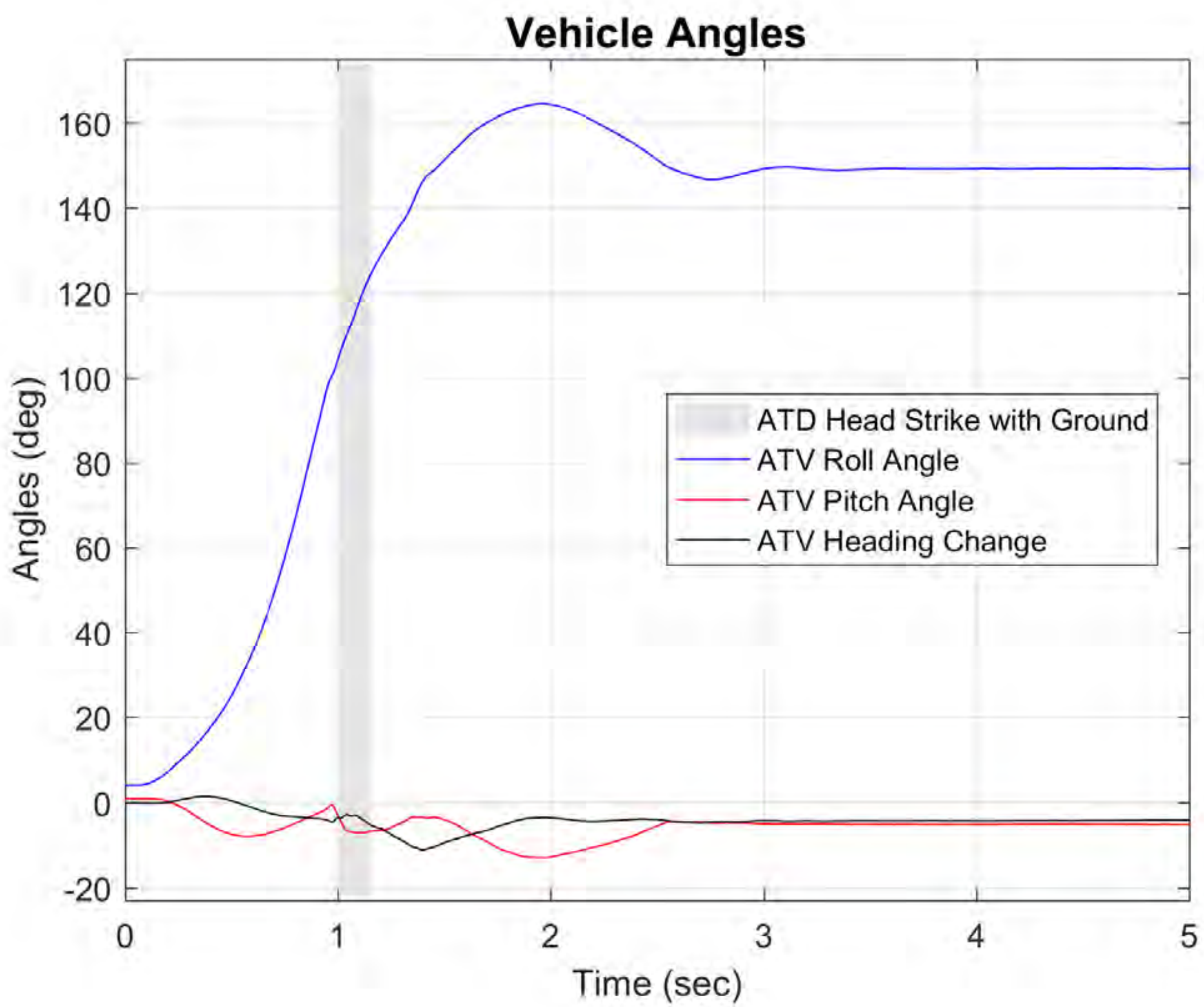
Vehicle G - Sled Minimum Energy Rollover



Vehicle G - Sled Minimum Energy Rollover



Vehicle G - Sled Minimum Energy Rollover



Vehicle G - Sled Minimum Energy Rollover

AOS Camera 1 - Roll Angle = 30° - Time = 0.41 sec

AOS Camera 1 - Roll Angle = 45° - Time = 0.53 sec

AOS Camera 1 - Roll Angle = 90° - Time = 0.76 sec

AOS Camera 2 - Roll Angle = 30° - Time = 0.41 sec

AOS Camera 2 - Roll Angle = 45° - Time = 0.53 sec

AOS Camera 2 - Roll Angle = 90° - Time = 0.76 sec

Vehicle G - Sled Moderate Energy Rollover

AOS Camera 1 - ATD Head Strike - Time = 0.88 sec

AOS Camera 1 - Roll Angle = 180° - Time = 1.18 sec

AOS Camera 1 - Max Angle = 297.7° - Time = 2.56 sec

AOS Camera 2 - ATD Head Strike - Time = 0.88 sec

AOS Camera 2 - Roll Angle = 180° - Time = 1.18 sec

AOS Camera 2 - Max Angle = 297.7° - Time = 2.56 sec

Vehicle G - Sled Moderate Energy Rollover

AOS Camera 1 - End of Run - Roll Angle = 277.1°

AOS Camera 2 - End of Run - Roll Angle = 277.1°

Vehicle G - Sled Moderate Energy Rollover

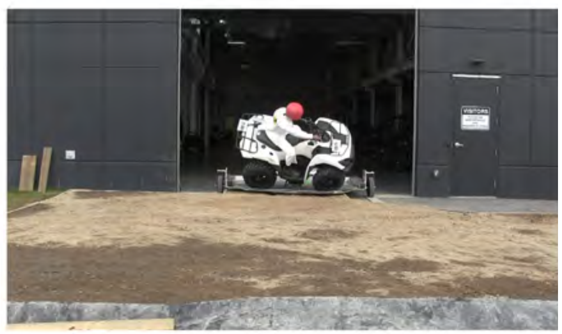
RT Camera 1 - Roll Angle = 30° - Time = 0.41 sec

RT Camera 1 - Roll Angle = 45° - Time = 0.53 sec

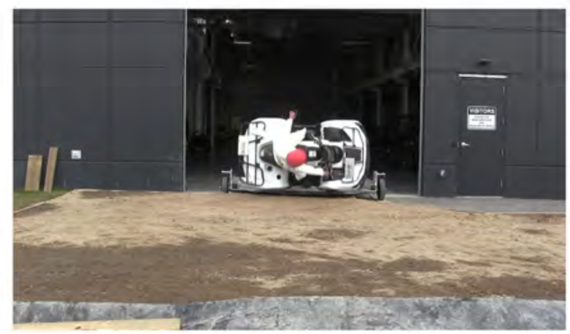
RT Camera 1 - Roll Angle = 90° - Time = 0.76 sec

RT Camera 2 - Roll Angle = 30° - Time = 0.41 sec

RT Camera 2 - Roll Angle = 45° - Time = 0.53 sec



RT Camera 2 - Roll Angle = 90° - Time = 0.76 sec



Vehicle G - Sled Moderate Energy Rollover

RT Camera 1 - ATD Head Strike - Time = 0.88 sec

RT Camera 1 - Roll Angle = 180° - Time = 1.18 sec

RT Camera 1 - Max Angle = 297.7° - Time = 2.56 sec

RT Camera 2 - ATD Head Strike - Time = 0.88 sec

RT Camera 2 - Roll Angle = 180° - Time = 1.18 sec

RT Camera 2 - Max Angle = 297.7° - Time = 2.56 sec

Vehicle G - Sled Moderate Energy Rollover

RT Camera 1 - End of Run - Roll Angle = 277.1°

RT Camera 2 - End of Run - Roll Angle = 277.1°

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 = 0.76 sec

Drone Camera - ATD Head Strike - Time = 0.88 sec

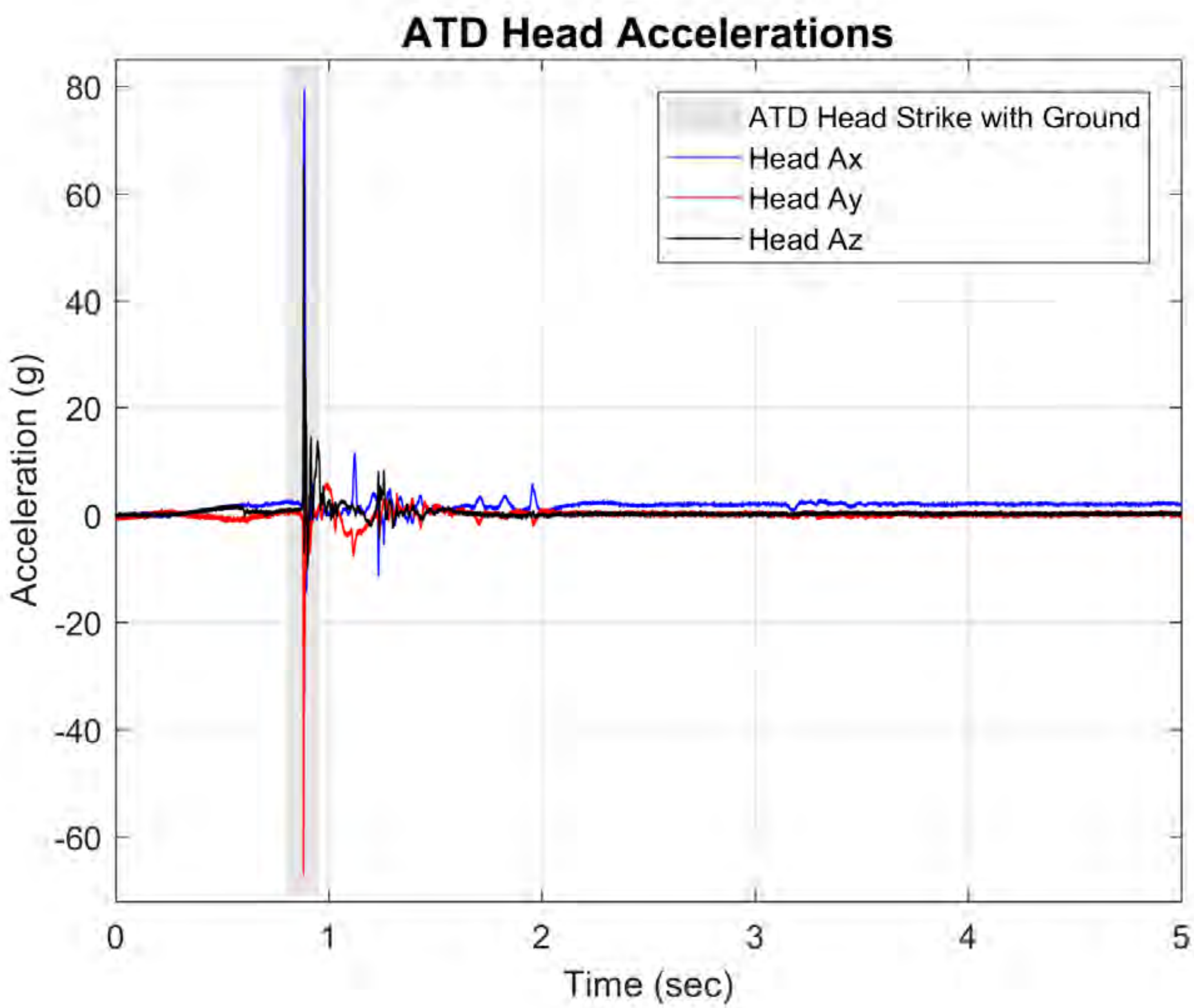
Drone Camera - Roll Angle = 180° - Time = 1.18 sec

Drone Camera - Max Angle = 297.7° - Time = 2.56 sec

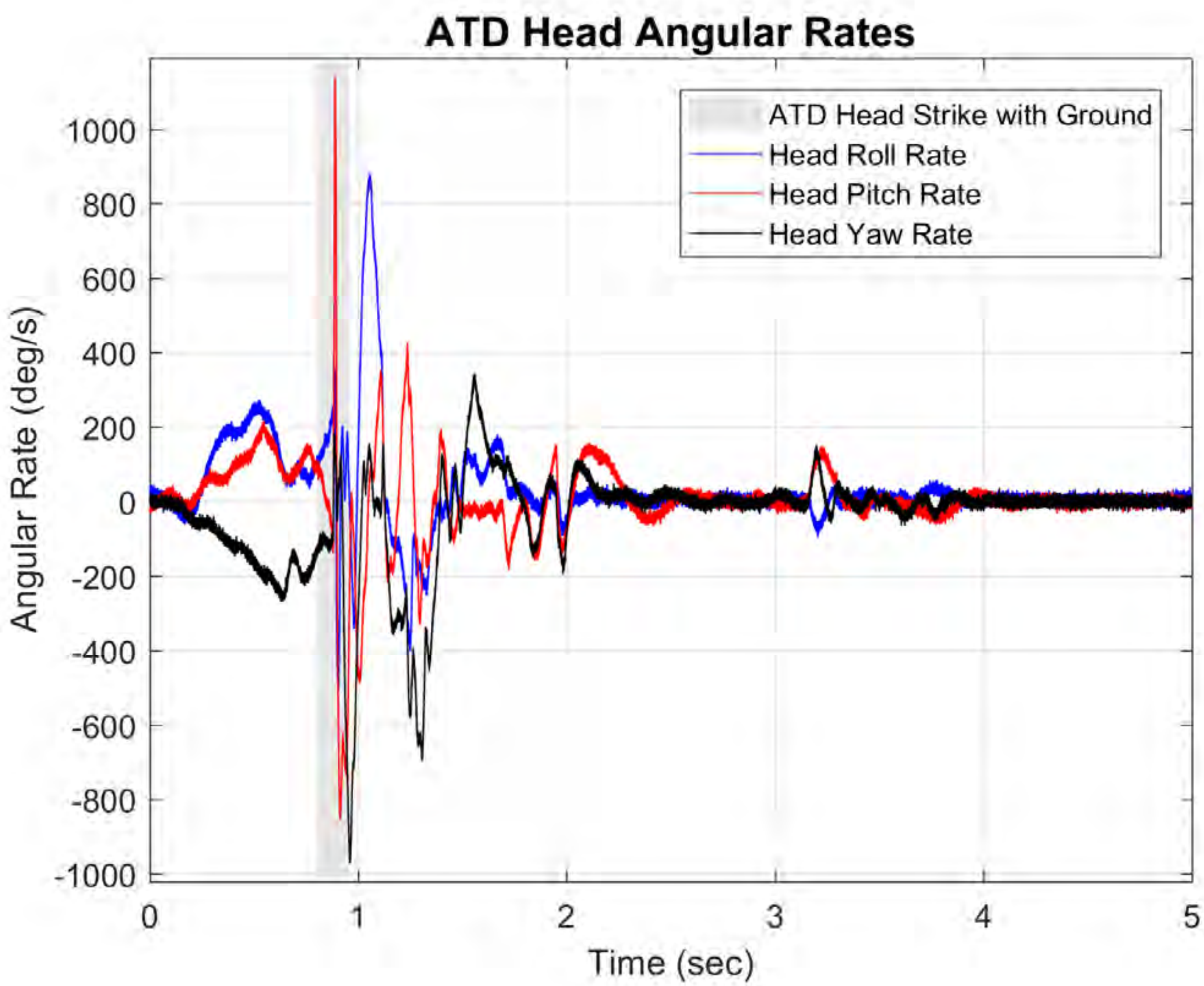
Vehicle G - Sled Moderate Energy Rollover

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

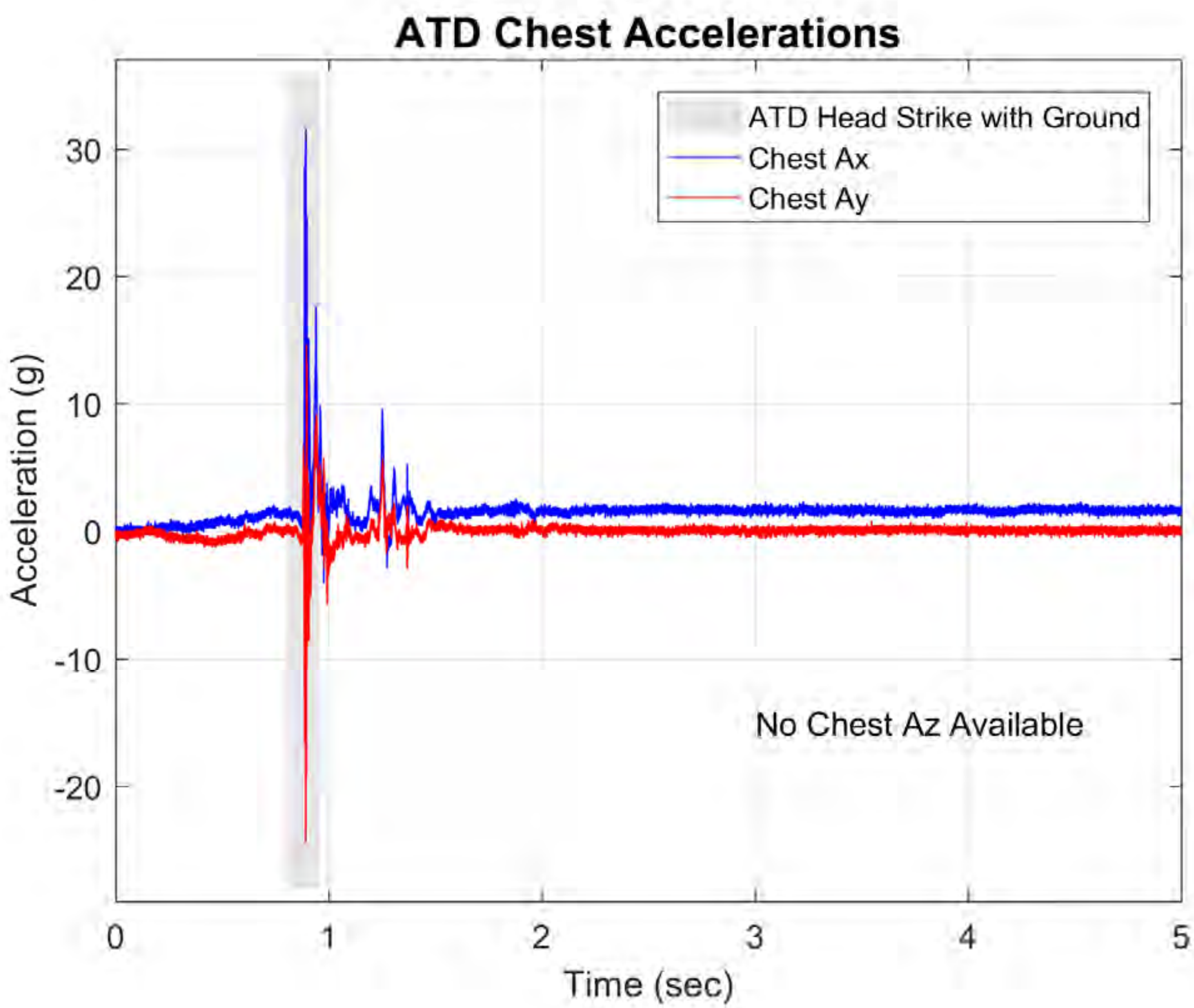
Vehicle G - Sled Moderate Energy Rollover



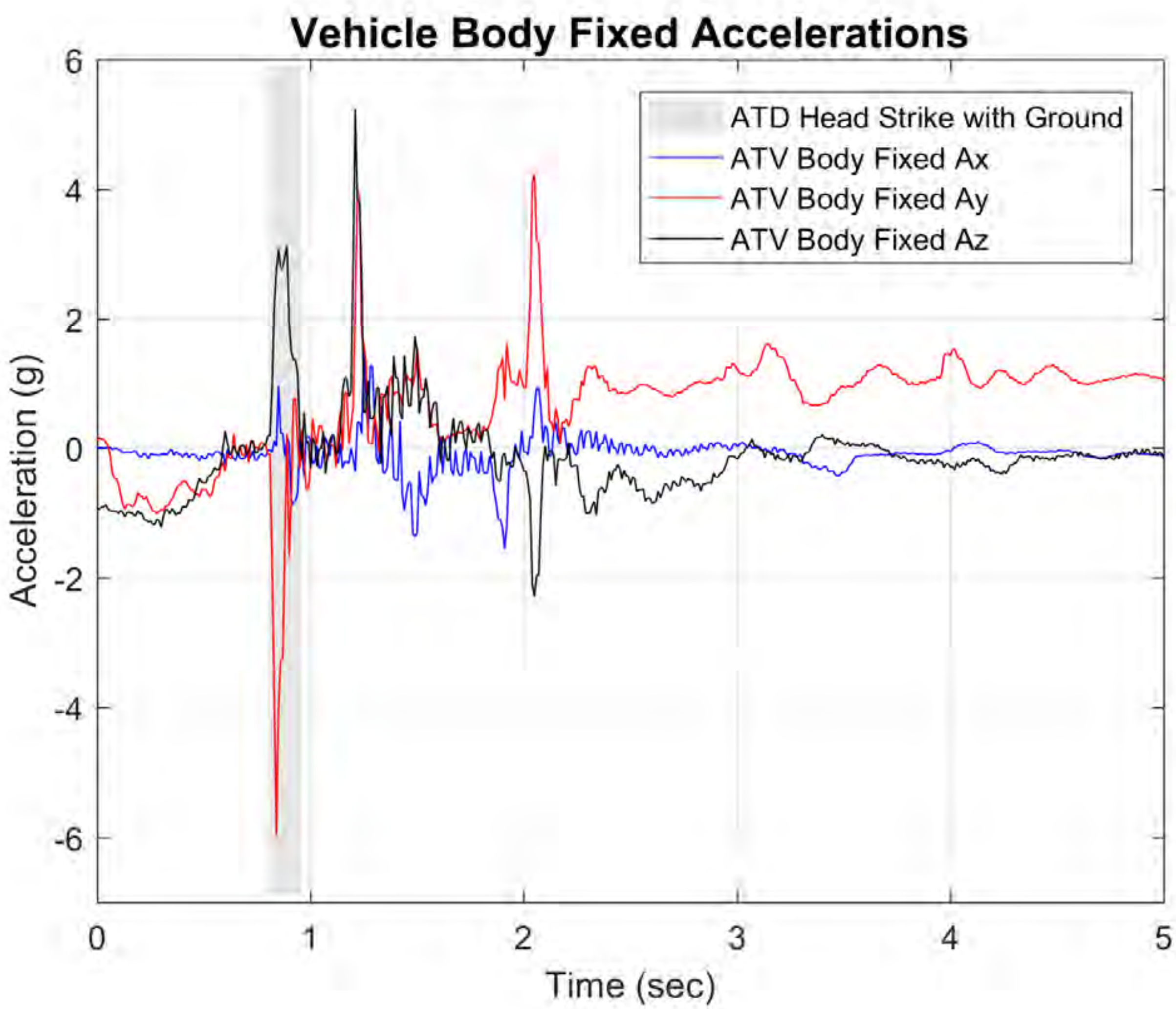
Vehicle G - Sled Moderate Energy Rollover



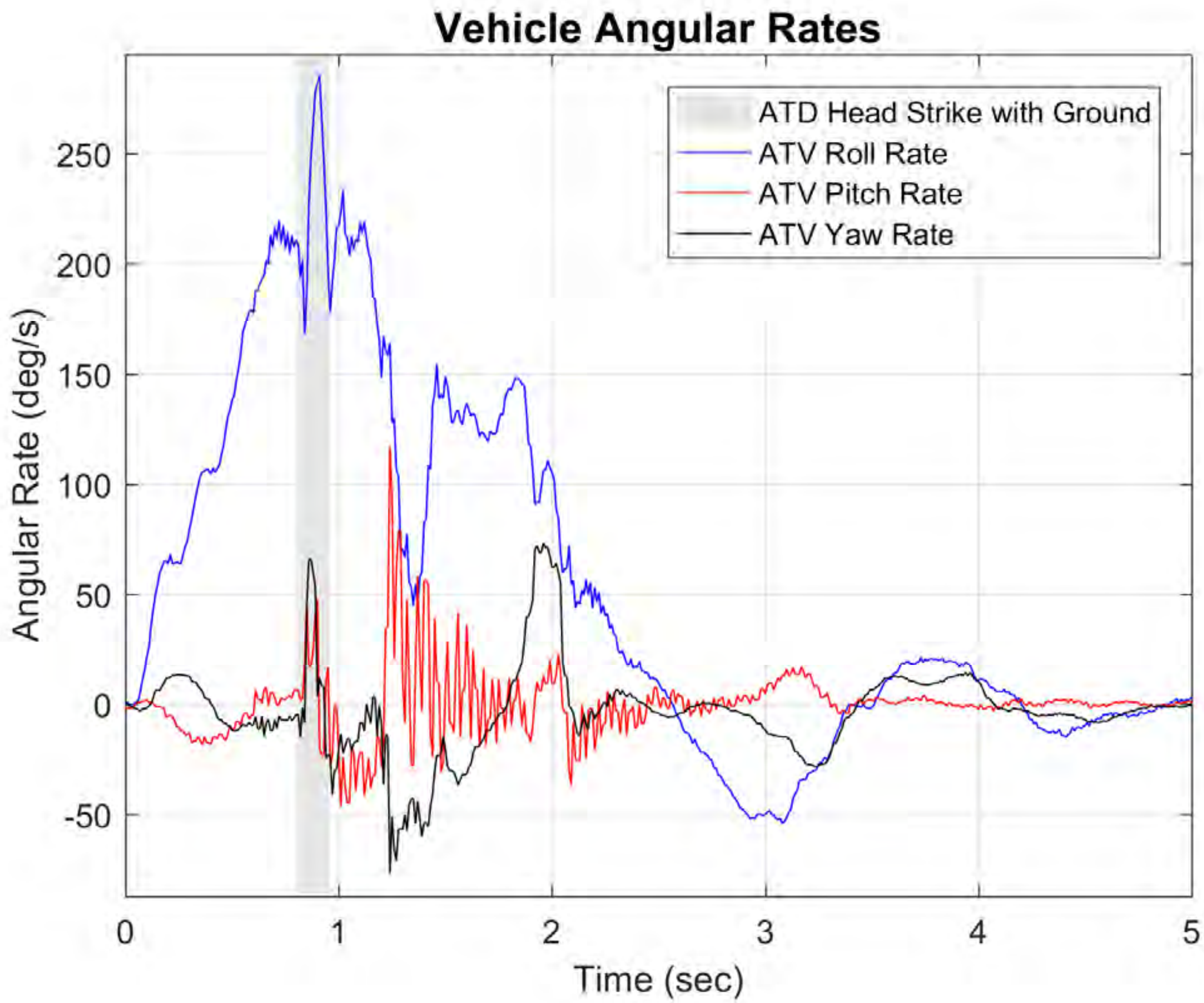
Vehicle G - Sled Moderate Energy Rollover



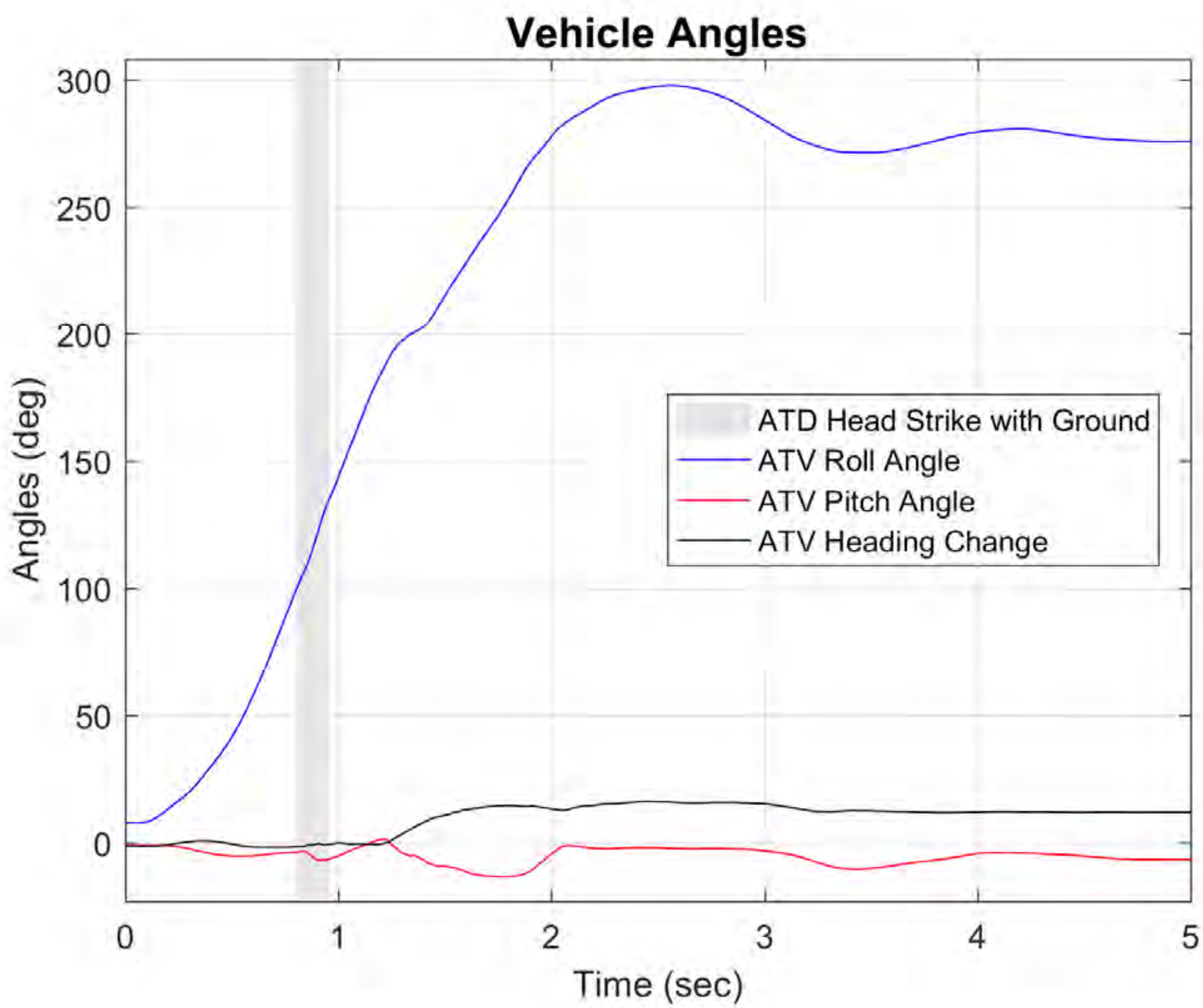
Vehicle G - Sled Moderate Energy Rollover



Vehicle G - Sled Moderate Energy Rollover



Vehicle G - Sled Moderate Energy Rollover



Vehicle G - Sled Moderate Energy Rollover

AOS Camera 1 - Roll Angle = 30° - Time = 0.69 sec

AOS Camera 1 - Roll Angle = 45° - Time = 0.78 sec

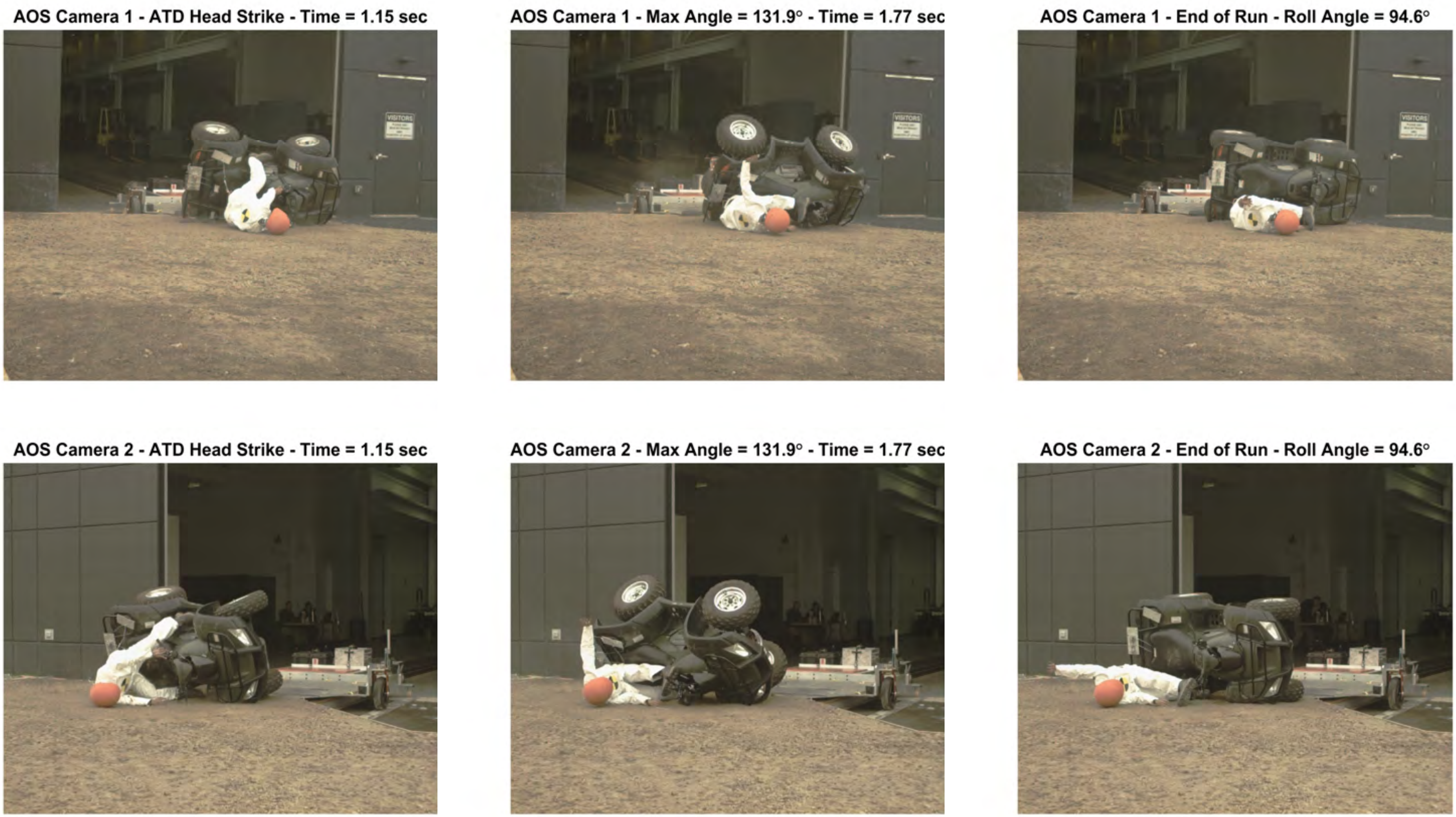
AOS Camera 1 - Roll Angle = 90° - Time = 1.03 sec

AOS Camera 2 - Roll Angle = 30° - Time = 0.69 sec

AOS Camera 2 - Roll Angle = 45° - Time = 0.78 sec

AOS Camera 2 - Roll Angle = 90° - Time = 1.03 sec

Vehicle J - Sled Minimum Energy Rollover



Vehicle J - Sled Minimum Energy Rollover

RT Camera 1 - Roll Angle = 30° - Time = 0.69 sec

RT Camera 1 - Roll Angle = 45° - Time = 0.78 sec

RT Camera 1 - Roll Angle = 90° - Time = 1.03 sec

RT Camera 2 - Roll Angle = 30° - Time = 0.69 sec

RT Camera 2 - Roll Angle = 45° - Time = 0.78 sec

RT Camera 2 - Roll Angle = 90° - Time = 1.03 sec

Vehicle J - Sled Minimum Energy Rollover

RT Camera 1 - ATD Head Strike - Time = 1.15 sec

RT Camera 1 - Max Angle = 131.9° - Time = 1.77 sec

RT Camera 1 - End of Run - Roll Angle = 94.6°

RT Camera 2 - ATD Head Strike - Time = 1.15 sec

RT Camera 2 - Max Angle = 131.9° - Time = 1.77 sec

RT Camera 2 - End of Run - Roll Angle = 94.6°

Vehicle J - Sled Minimum Energy Rollover

Drone Camera - Roll Angle = 30° - Time = 0.69 sec

Drone Camera - Roll Angle = 45° - Time = 0.78 sec

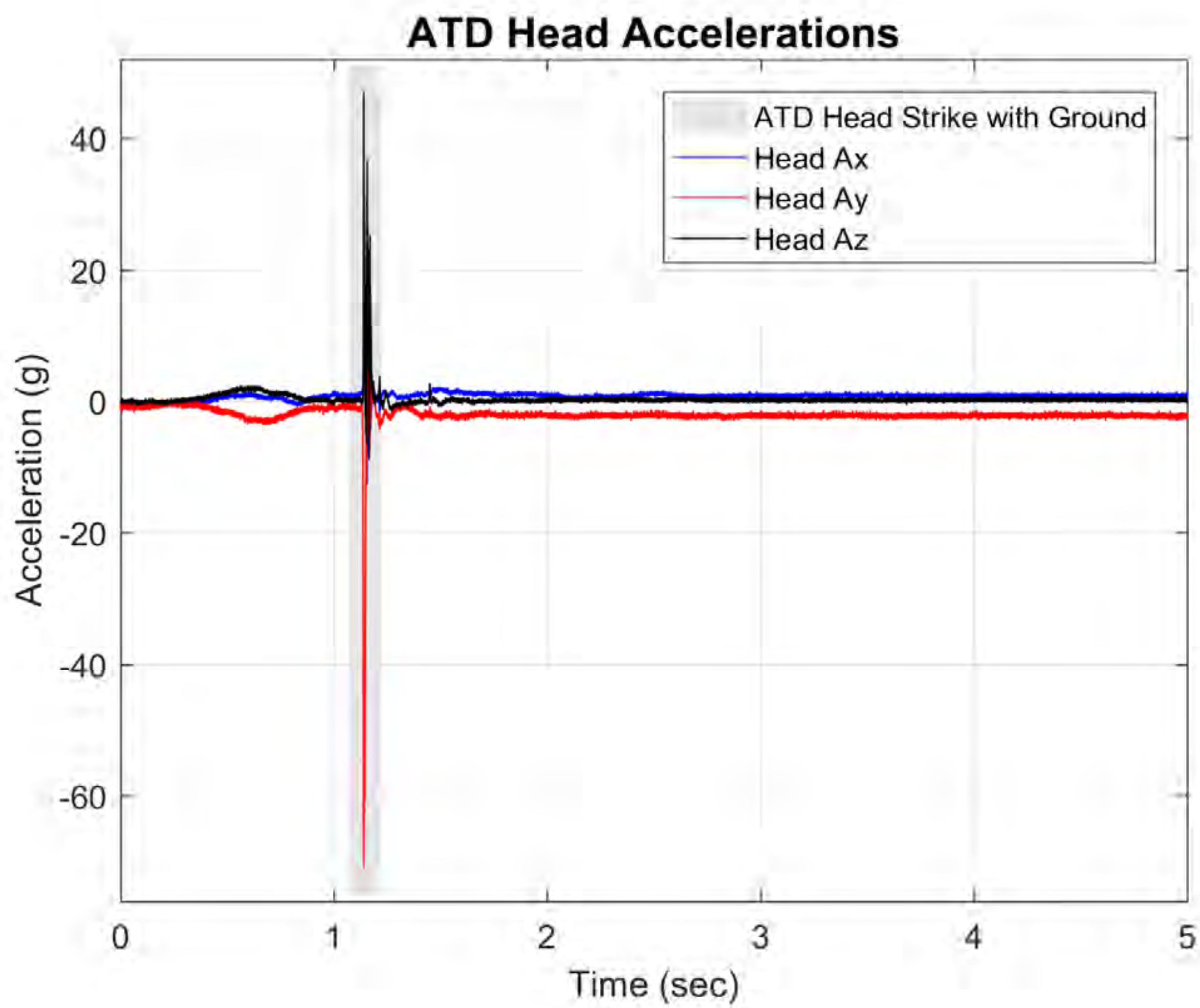
Drone Camera - Roll Angle = 90° - Time = 1.03 sec

Drone Camera - ATD Head Strike - Time = 1.15 sec

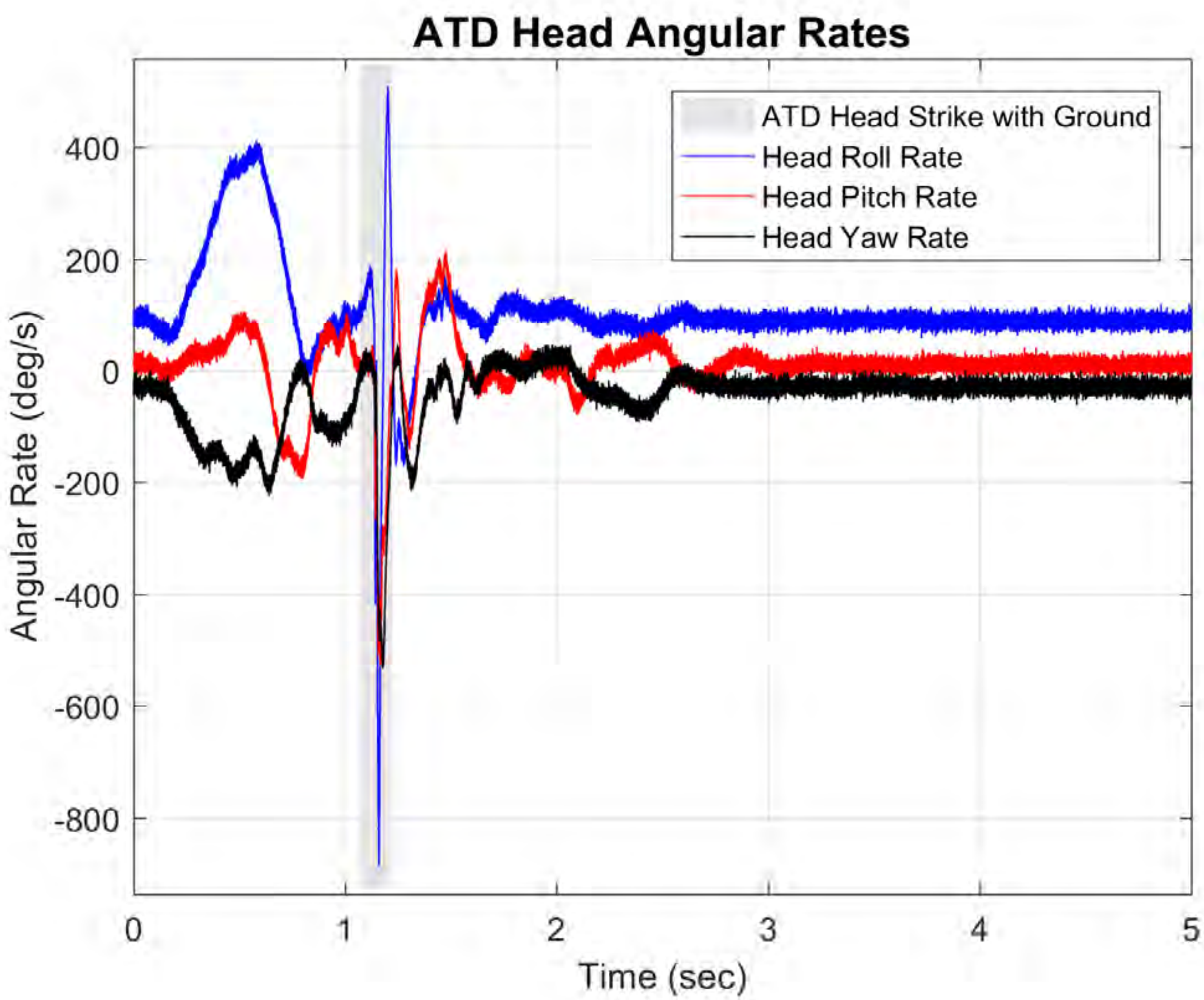
Drone Camera - Max Angle = 131.9° - Time = 1.77 sec

Drone Camera - End of Run - Roll Angle = 94.6°

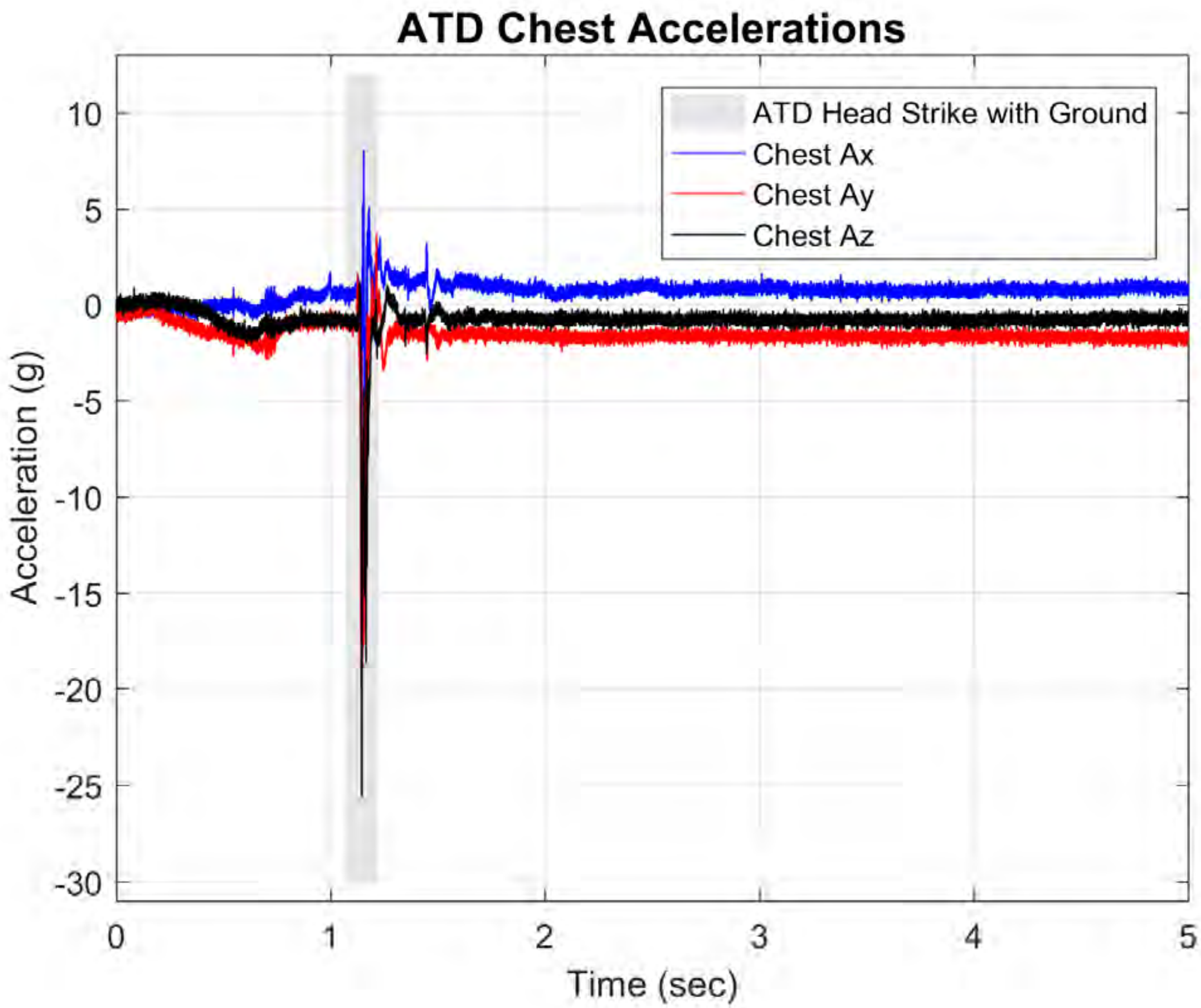
Vehicle J - Sled Minimum Energy Rollover



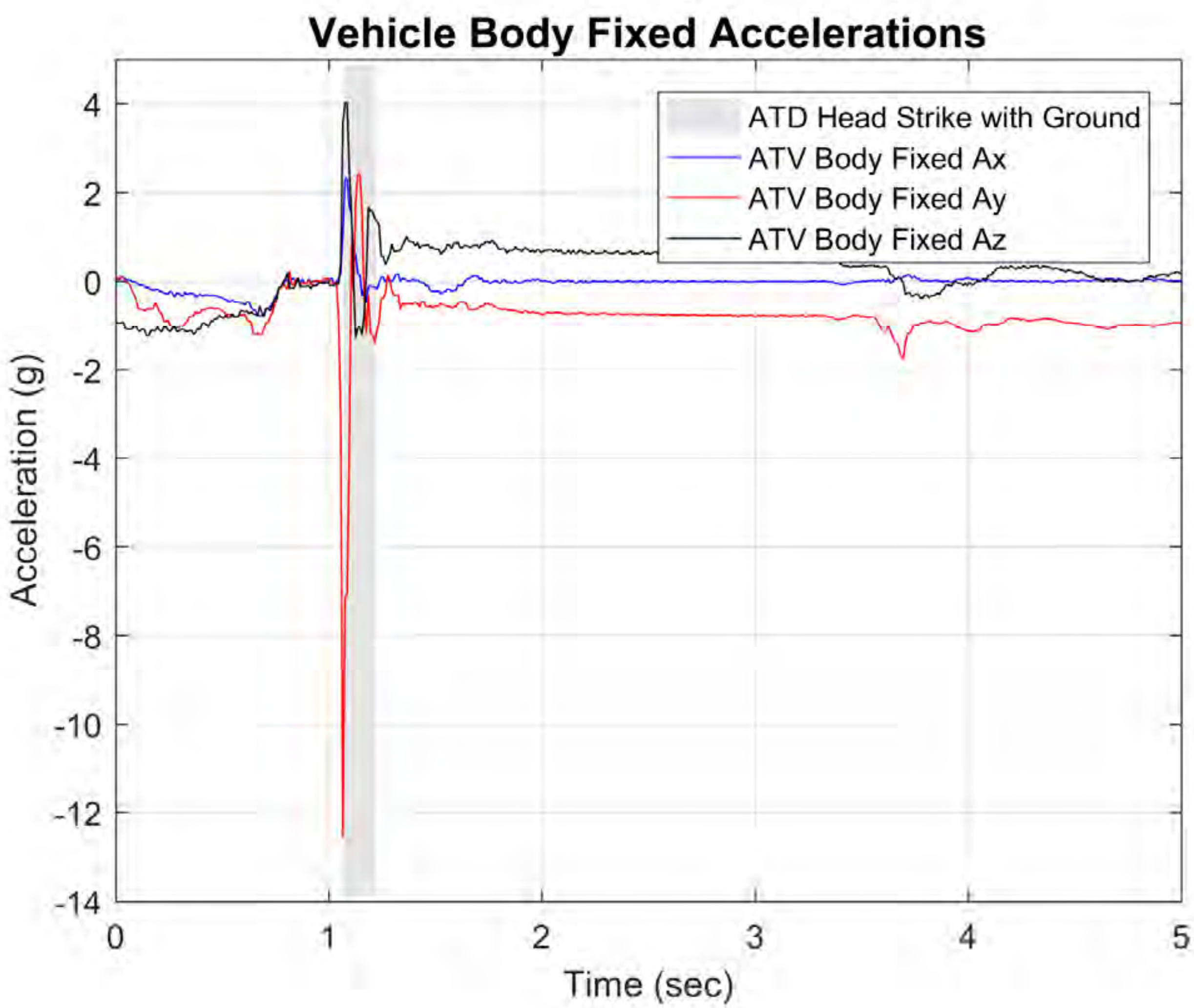
Vehicle J - Sled Minimum Energy Rollover



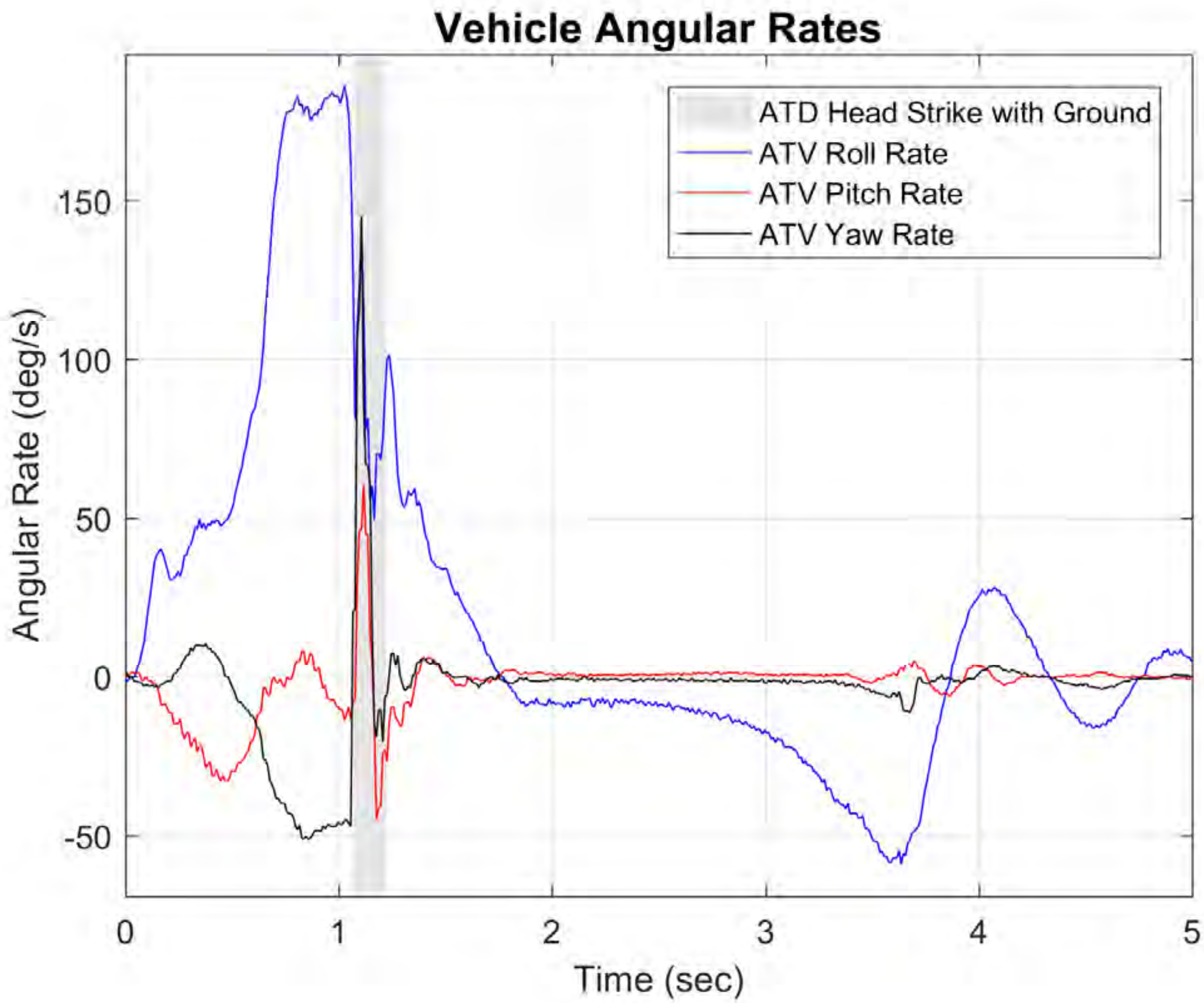
Vehicle J - Sled Minimum Energy Rollover



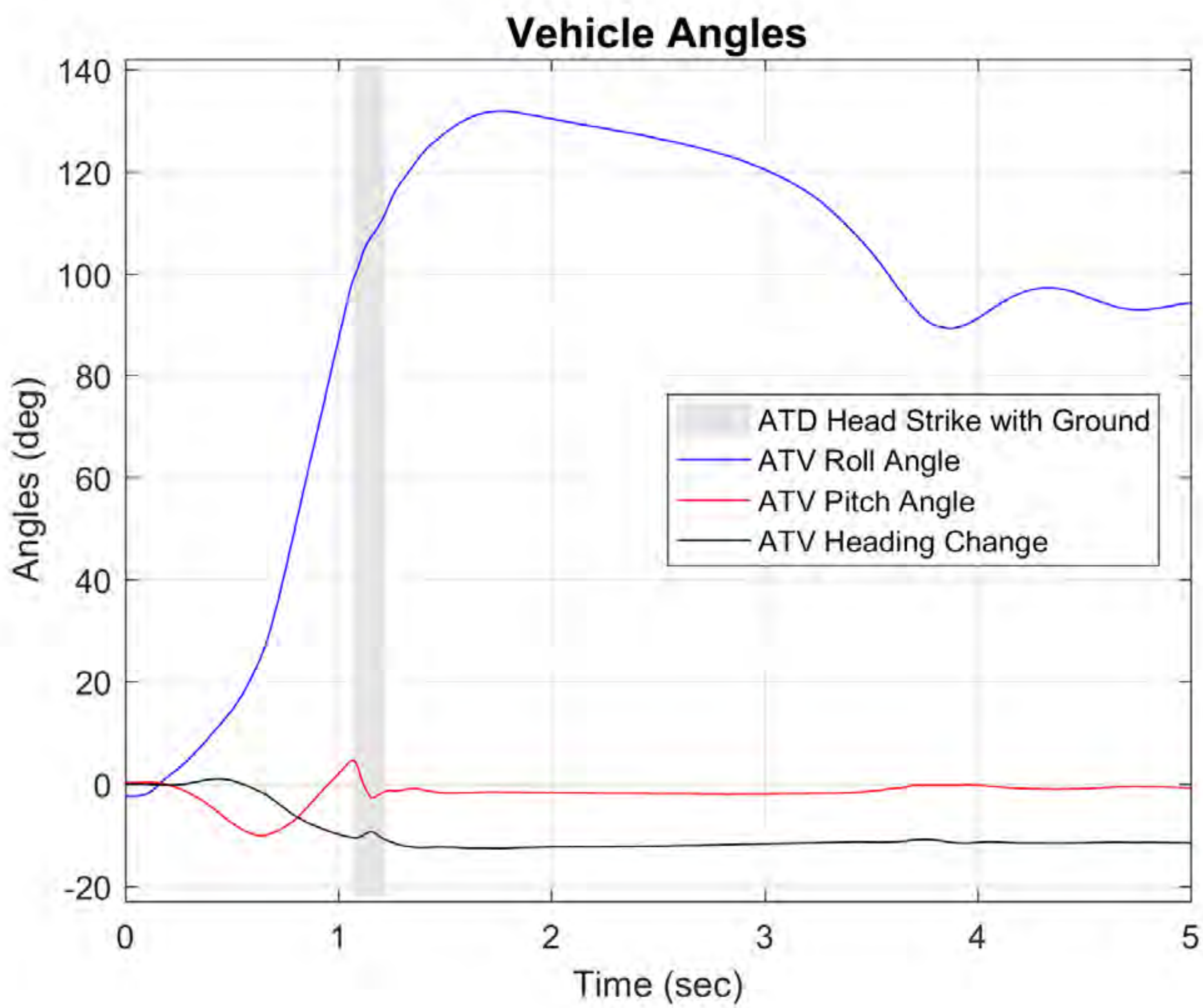
Vehicle J - Sled Minimum Energy Rollover



Vehicle J - Sled Minimum Energy Rollover



Vehicle J - Sled Minimum Energy Rollover



Vehicle J - Sled Minimum Energy Rollover

AOS Camera 1 - Roll Angle = 30° - Time = 0.46 sec

AOS Camera 1 - Roll Angle = 45° - Time = 0.58 sec

AOS Camera 1 - Roll Angle = 90° - Time = 0.81 sec

AOS Camera 2 - Roll Angle = 30° - Time = 0.46 sec

AOS Camera 2 - Roll Angle = 45° - Time = 0.58 sec

AOS Camera 2 - Roll Angle = 90° - Time = 0.81 sec

Vehicle J - Sled Moderate Energy Rollover

AOS Camera 1 - ATD Head Strike - Time = 1.01 sec

AOS Camera 1 - Roll Angle = 180° - Time = 1.17 sec

AOS Camera 1 - Max Angle = 274.8° - Time = 1.98 sec

AOS Camera 2 - ATD Head Strike - Time = 1.01 sec

AOS Camera 2 - Roll Angle = 180° - Time = 1.17 sec

AOS Camera 2 - Max Angle = 274.8° - Time = 1.98 sec

Vehicle J - Sled Moderate Energy Rollover

AOS Camera 1 - End of Run - Roll Angle = 241.0°

AOS Camera 2 - End of Run - Roll Angle = 241.0°

Vehicle J - Sled Moderate Energy Rollover

RT Camera 1 - Roll Angle = 30° - Time = 0.46 sec

RT Camera 1 - Roll Angle = 45° - Time = 0.58 sec

RT Camera 1 - Roll Angle = 90° - Time = 0.81 sec

RT Camera 2 - Roll Angle = 30° - Time = 0.46 sec

RT Camera 2 - Roll Angle = 45° - Time = 0.58 sec

RT Camera 2 - Roll Angle = 90° - Time = 0.81 sec

Vehicle J - Sled Moderate Energy Rollover

RT Camera 1 - ATD Head Strike - Time = 1.01 sec

RT Camera 1 - Roll Angle = 180° - Time = 1.17 sec

RT Camera 1 - Max Angle = 274.8° - Time = 1.98 sec

RT Camera 2 - ATD Head Strike - Time = 1.01 sec

RT Camera 2 - Roll Angle = 180° - Time = 1.17 sec

RT Camera 2 - Max Angle = 274.8° - Time = 1.98 sec

Vehicle J - Sled Moderate Energy Rollover

RT Camera 1 - End of Run - Roll Angle = 241.0°

RT Camera 2 - End of Run - Roll Angle = 241.0°

Vehicle J - 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 = 0.81 sec

Drone Camera - ATD Head Strike - Time = 1.01 sec

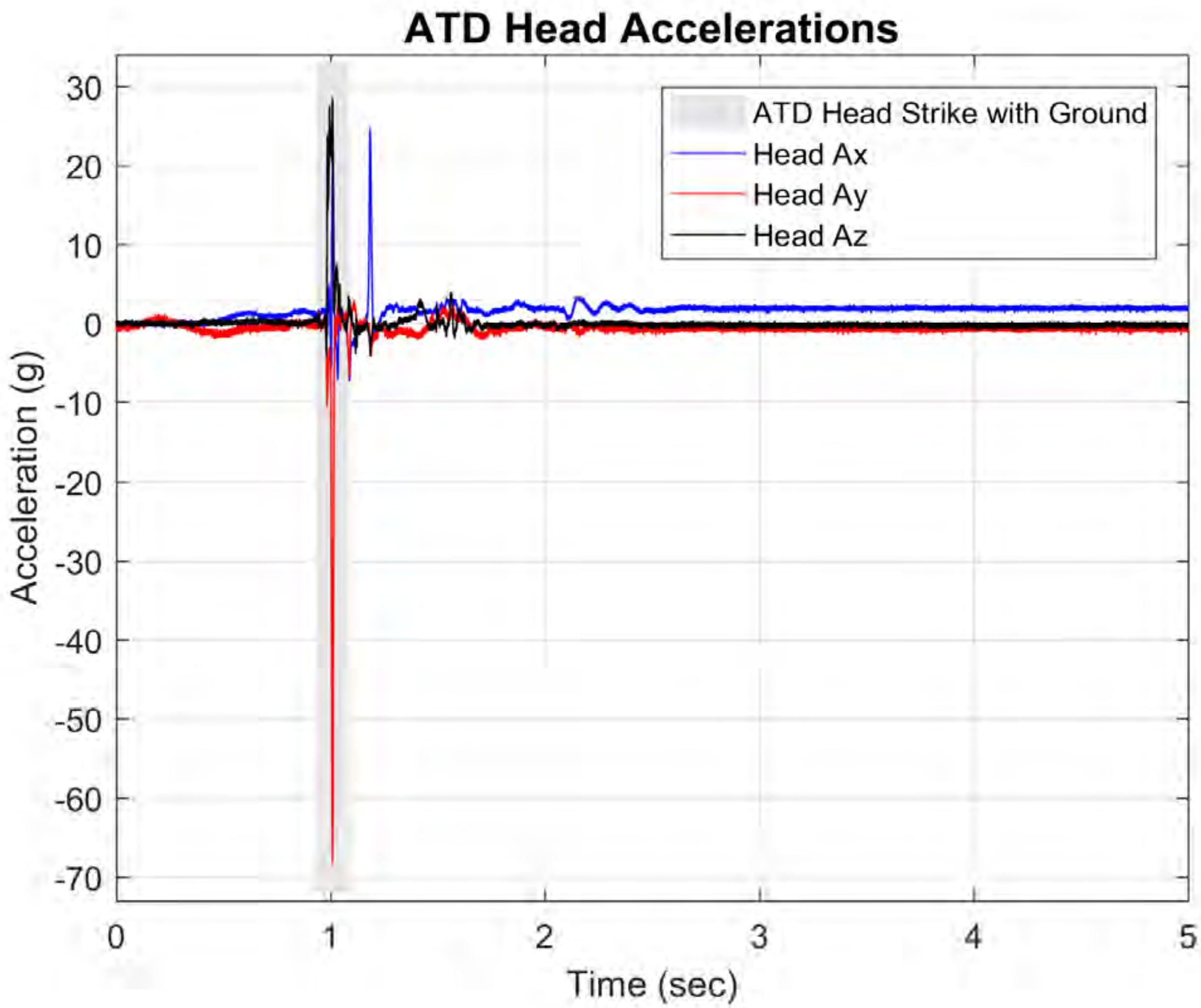
Drone Camera - Roll Angle = 180° - Time = 1.17 sec

Drone Camera - Max Angle = 274.8° - Time = 1.98 sec

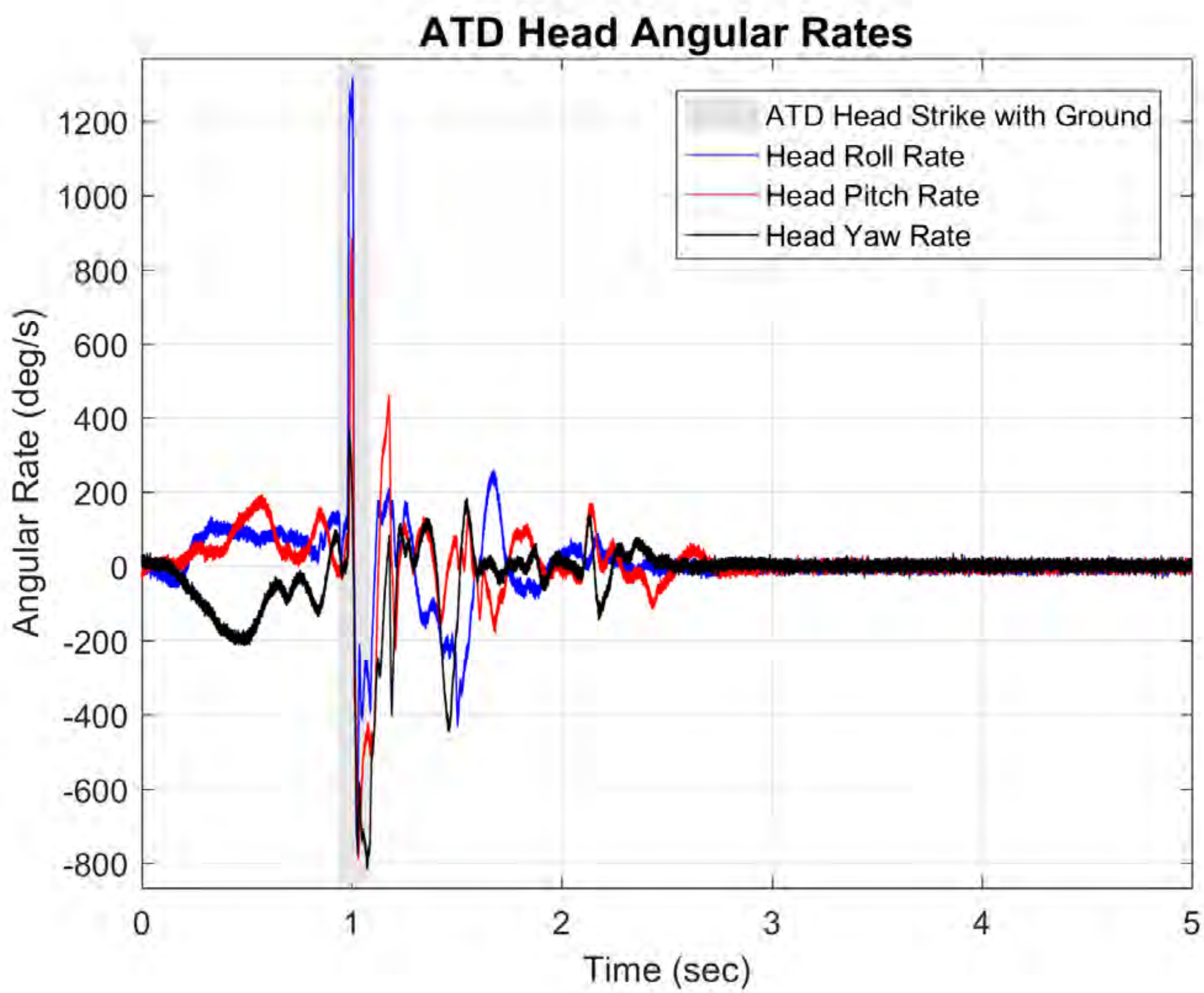
Vehicle J - Sled Moderate Energy Rollover

Drone Camera - End of Run - Roll Angle = 241.0°

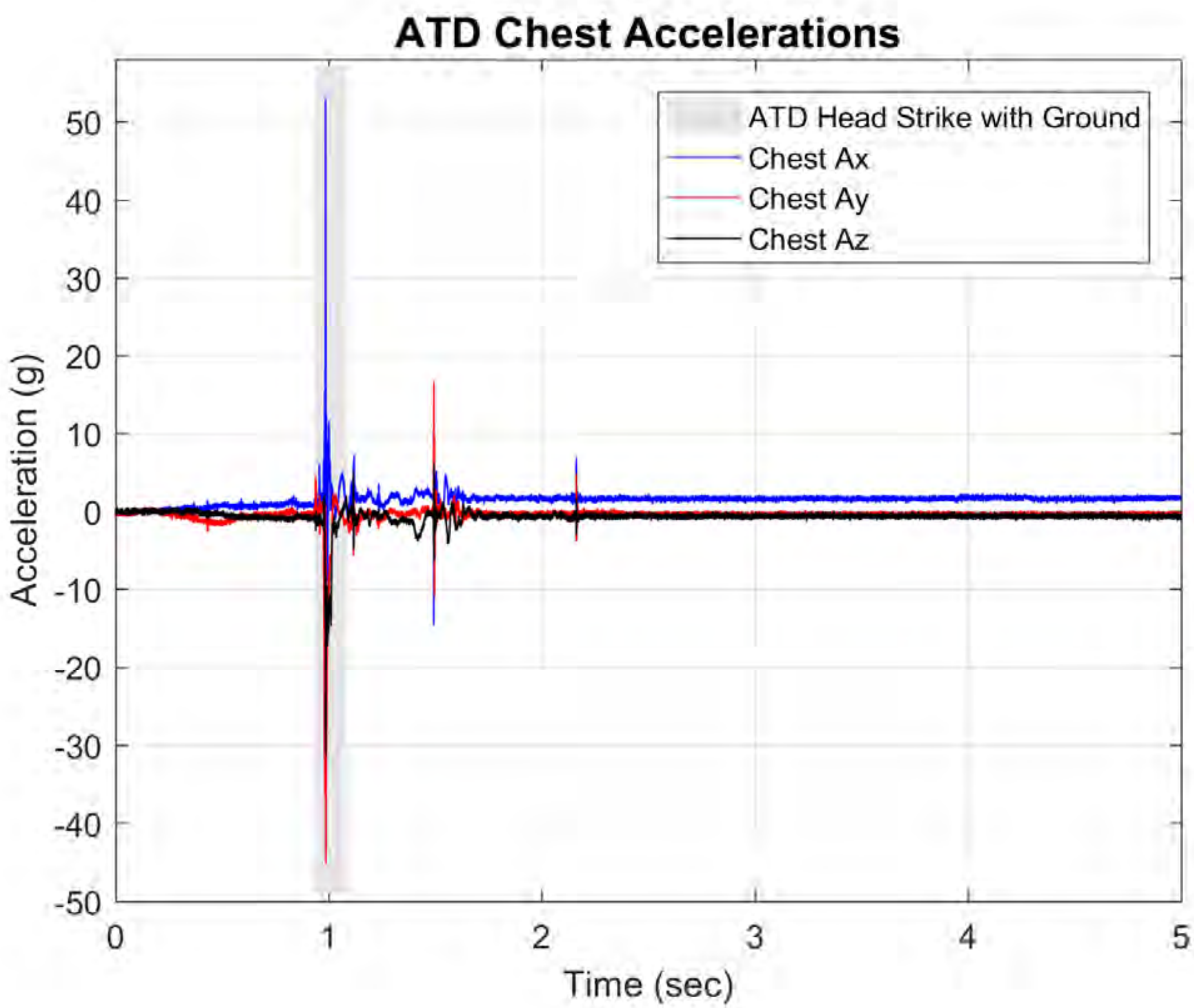
Vehicle J - Sled Moderate Energy Rollover



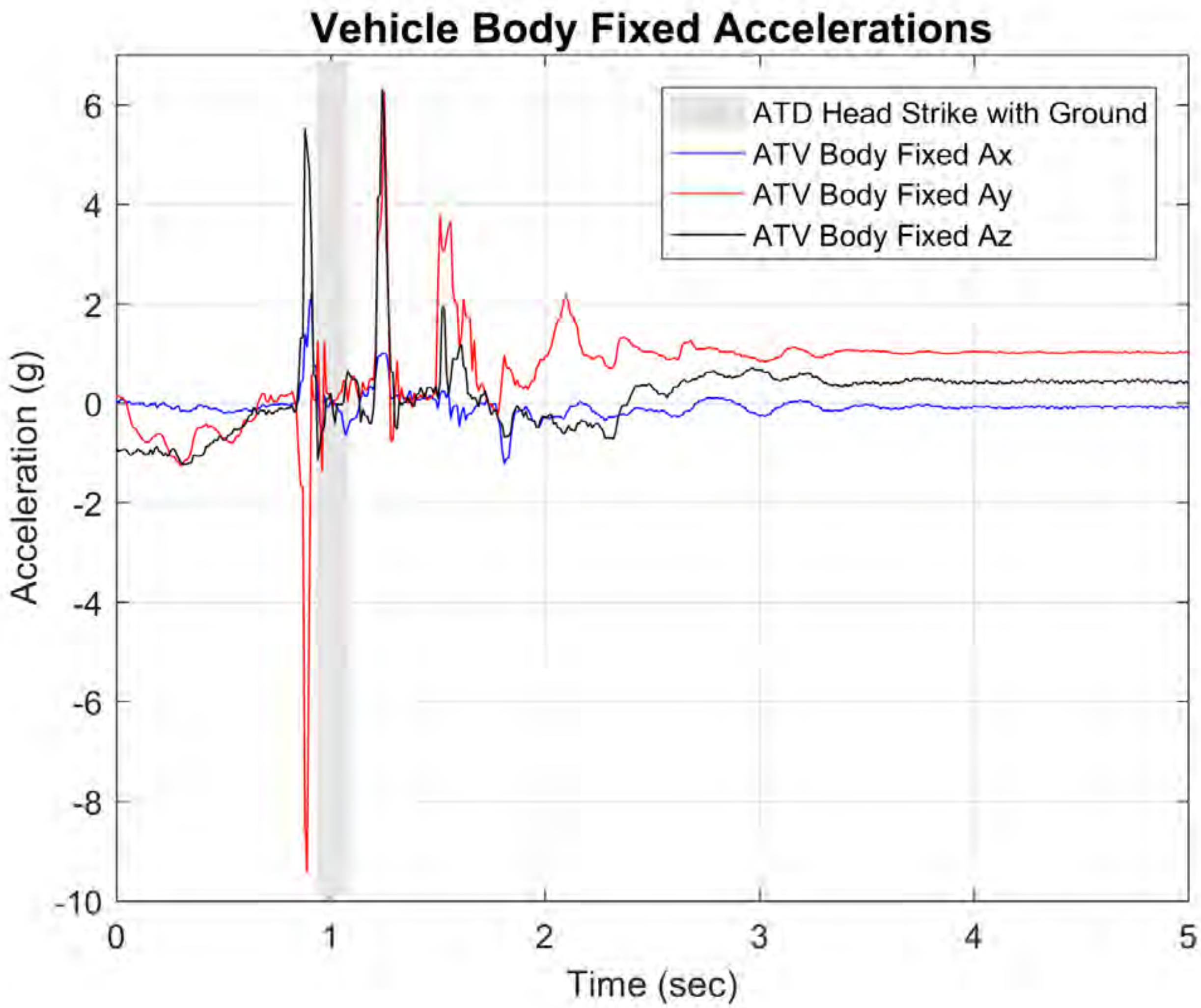
Vehicle J - Sled Moderate Energy Rollover



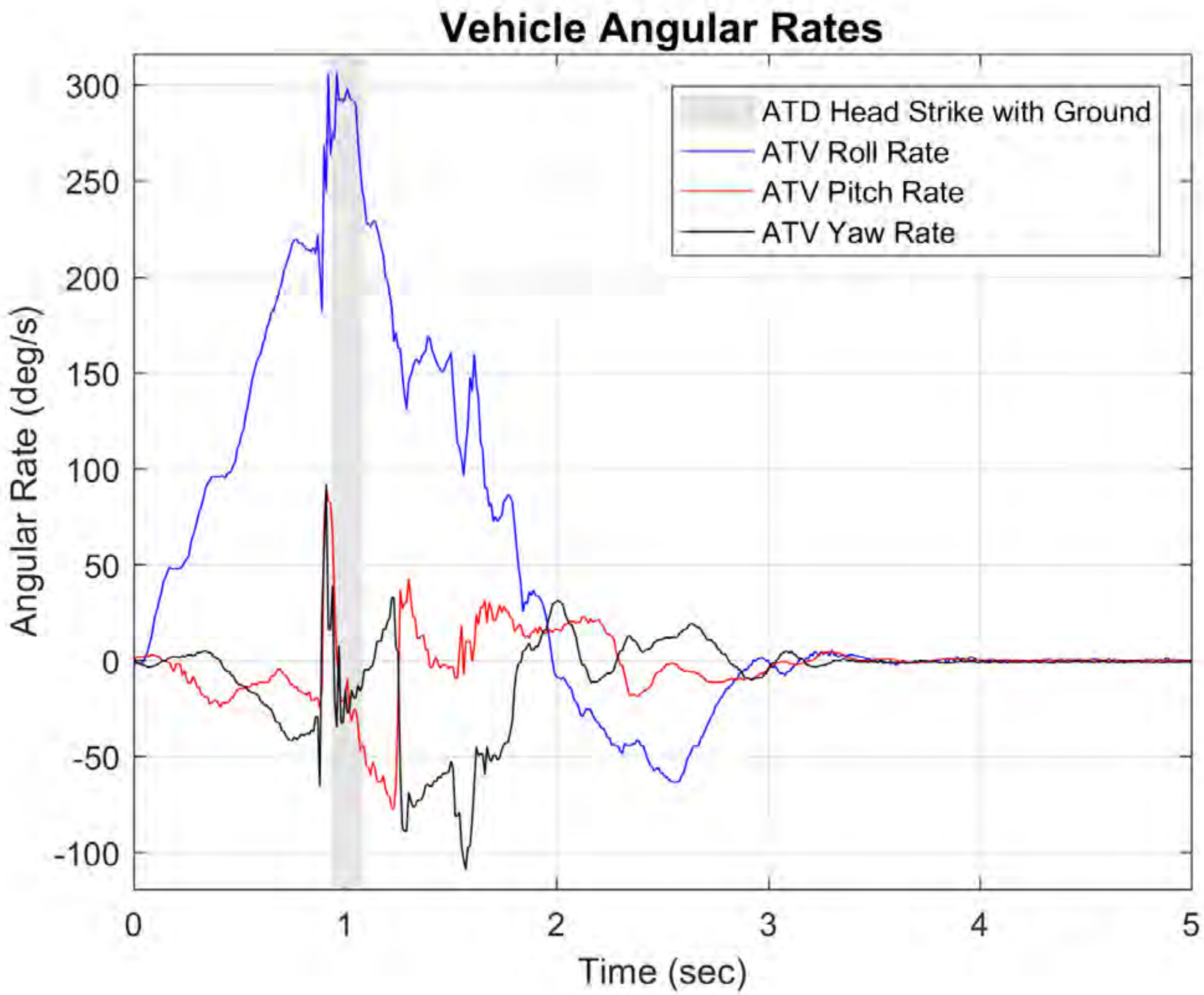
Vehicle J - Sled Moderate Energy Rollover



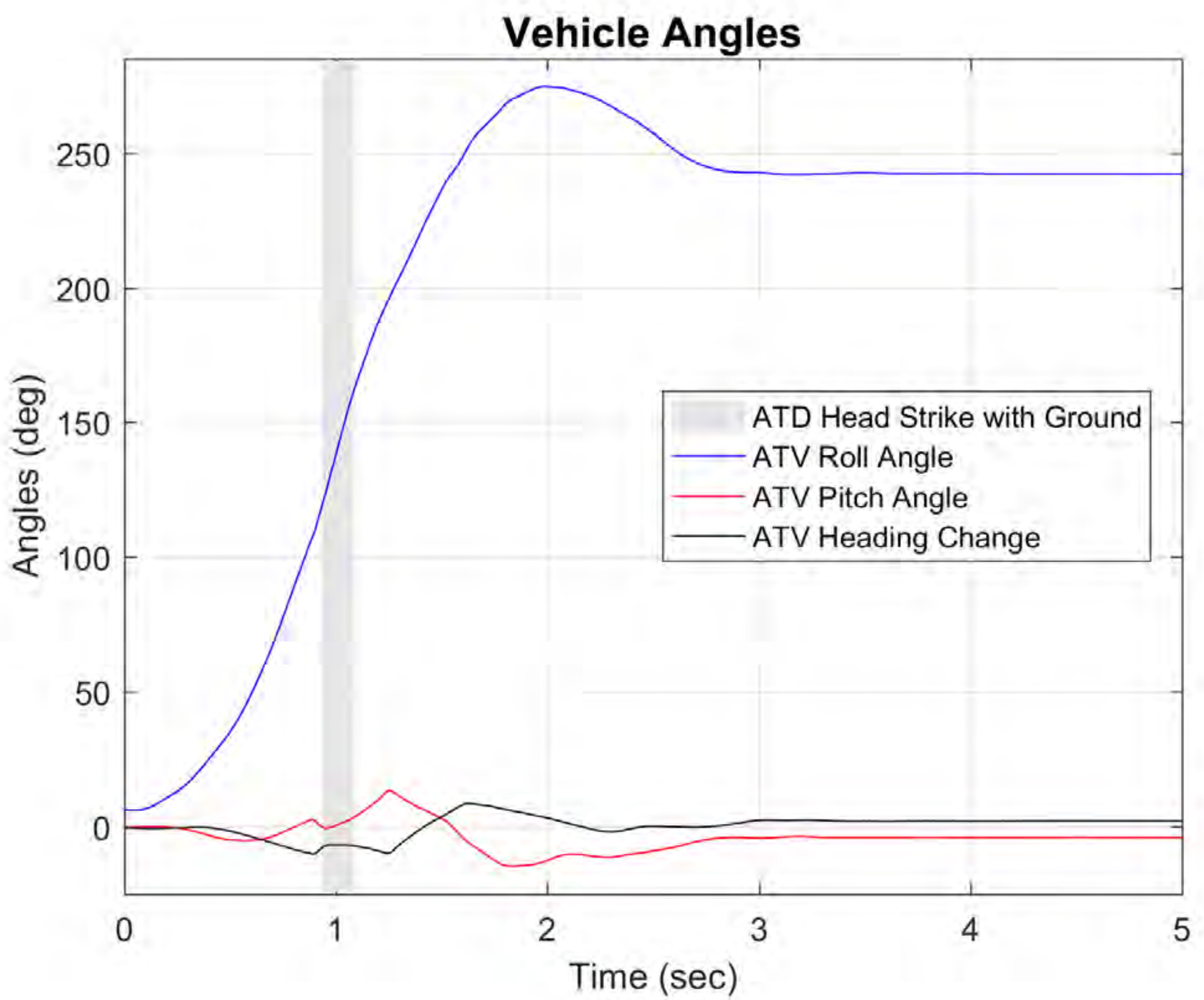
Vehicle J - Sled Moderate Energy Rollover



Vehicle J - Sled Moderate Energy Rollover



Vehicle J - Sled Moderate Energy Rollover



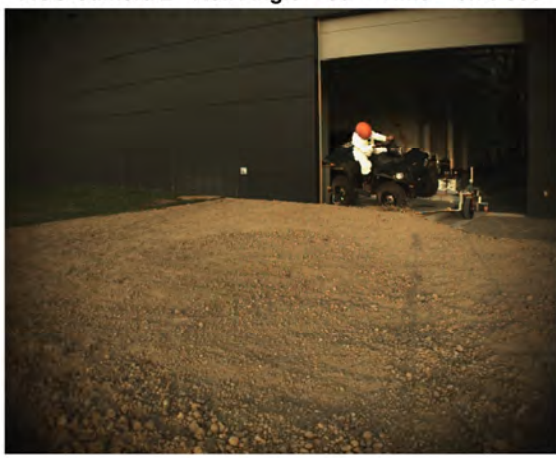
Vehicle J - Sled Moderate Energy Rollover

AOS Camera 1 - Roll Angle = 30° - Time = 0.76 sec

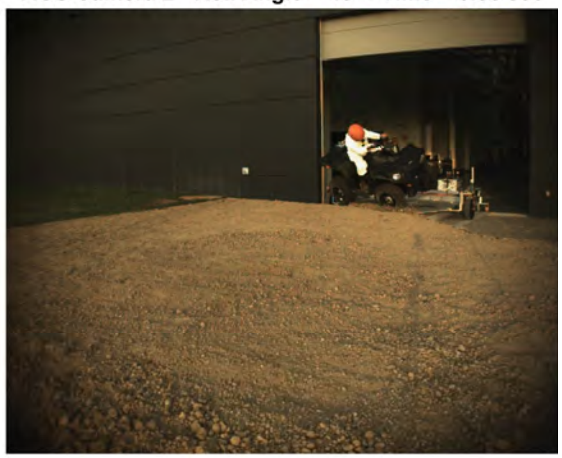
AOS Camera 1 - Roll Angle = 45° - Time = 0.86 sec

AOS Camera 1 - Roll Angle = 90° - Time = 1.2 sec

AOS Camera 2 - Roll Angle = 30° - Time = 0.76 sec



AOS Camera 2 - Roll Angle = 45° - Time = 0.86 sec



AOS Camera 2 - Roll Angle = 90° - Time = 1.2 sec

Vehicle L - Sled Minimum Energy Rollover

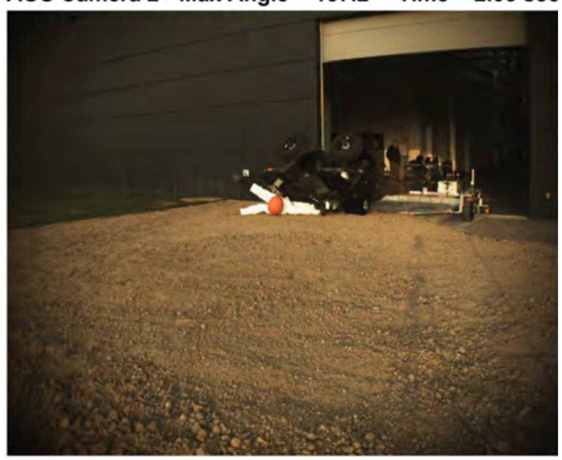
AOS Camera 1 - ATD Head Strike - Time = 1.28 sec

AOS Camera 1 - Max Angle = 137.2° - Time = 2.03 sec

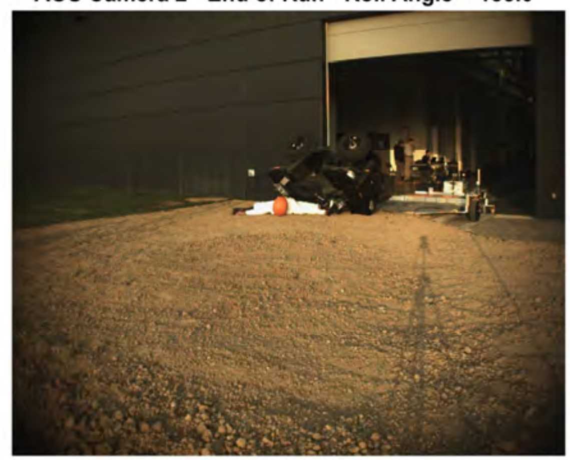
AOS Camera 1 - End of Run - Roll Angle = 135.0°

AOS Camera 2 - ATD Head Strike - Time = 1.28 sec

AOS Camera 2 - Max Angle = 137.2° - Time = 2.03 sec



AOS Camera 2 - End of Run - Roll Angle = 135.0°



Vehicle L - Sled Minimum Energy Rollover

RT Camera 1 - Roll Angle = 30° - Time = 0.76 sec

RT Camera 1 - Roll Angle = 45° - Time = 0.86 sec

RT Camera 1 - Roll Angle = 90° - Time = 1.2 sec

RT Camera 2 - Roll Angle = 30° - Time = 0.76 sec

RT Camera 2 - Roll Angle = 45° - Time = 0.86 sec

RT Camera 2 - Roll Angle = 90° - Time = 1.2 sec

Vehicle L - Sled Minimum Energy Rollover

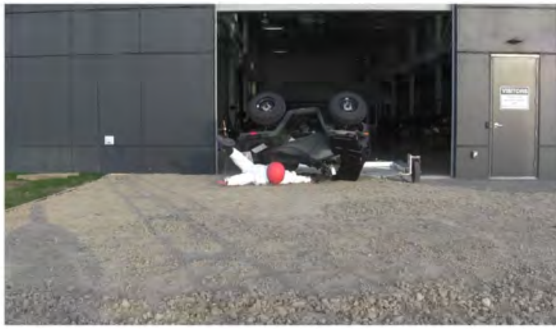
RT Camera 1 - ATD Head Strike - Time = 1.28 sec

RT Camera 1 - Max Angle = 137.2° - Time = 2.03 sec

RT Camera 1 - End of Run - Roll Angle = 135.0°

RT Camera 2 - ATD Head Strike - Time = 1.28 sec

RT Camera 2 - Max Angle = 137.2° - Time = 2.03 sec



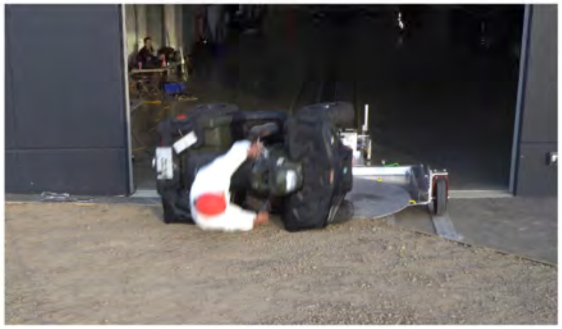
RT Camera 2 - End of Run - Roll Angle = 135.0°

Vehicle L - Sled Minimum Energy Rollover

Drone Camera - Roll Angle = 30° - Time = 0.76 sec

Drone Camera - Roll Angle = 45° - Time = 0.86 sec

Drone Camera - Roll Angle = 90° - Time = 1.2 sec

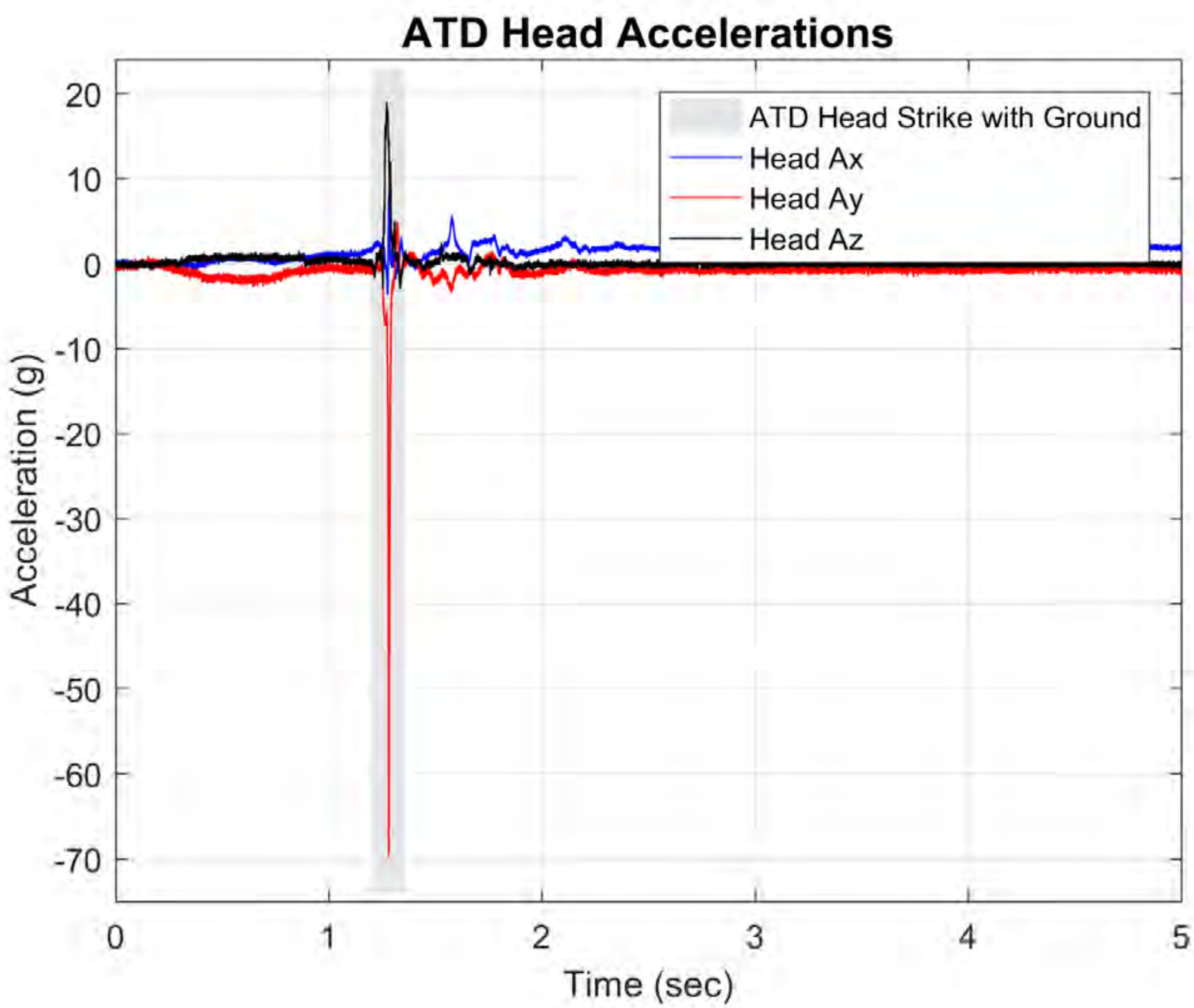


Drone Camera - ATD Head Strike - Time = 1.28 sec

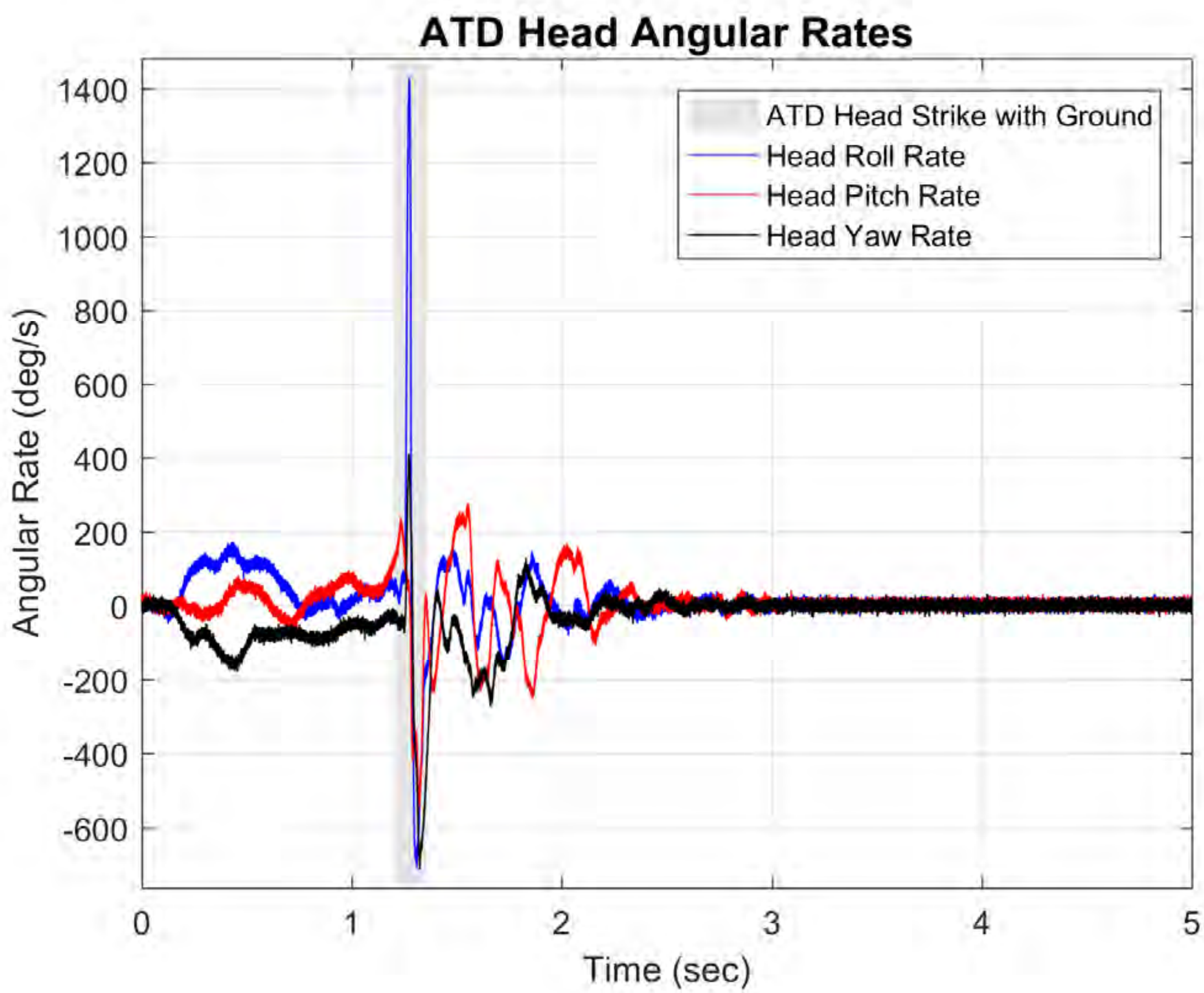
Drone Camera - Max Angle = 137.2° - Time = 2.03 sec

Drone Camera - End of Run - Roll Angle = 135.0°

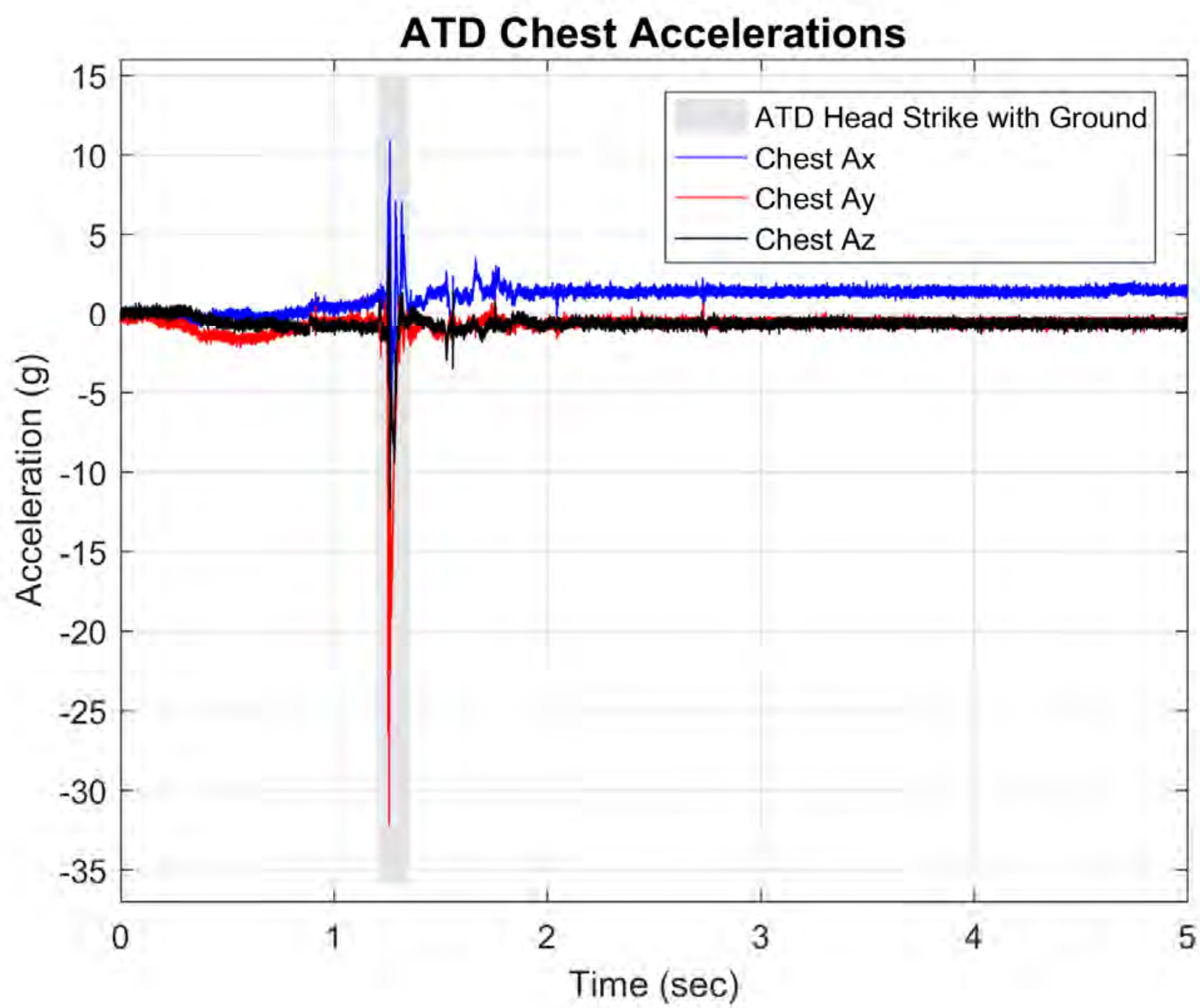
Vehicle L - Sled Minimum Energy Rollover



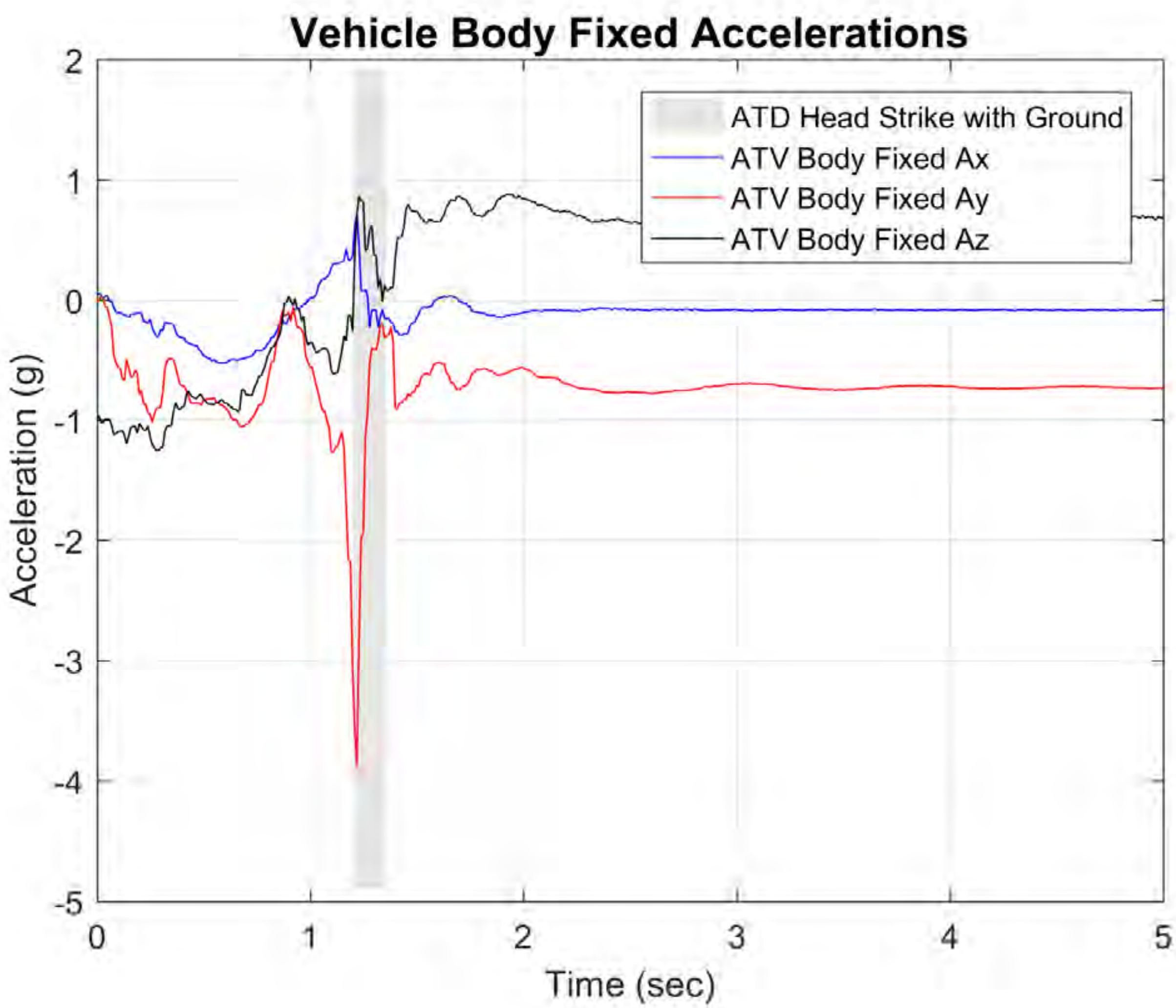
Vehicle L - Sled Minimum Energy Rollover



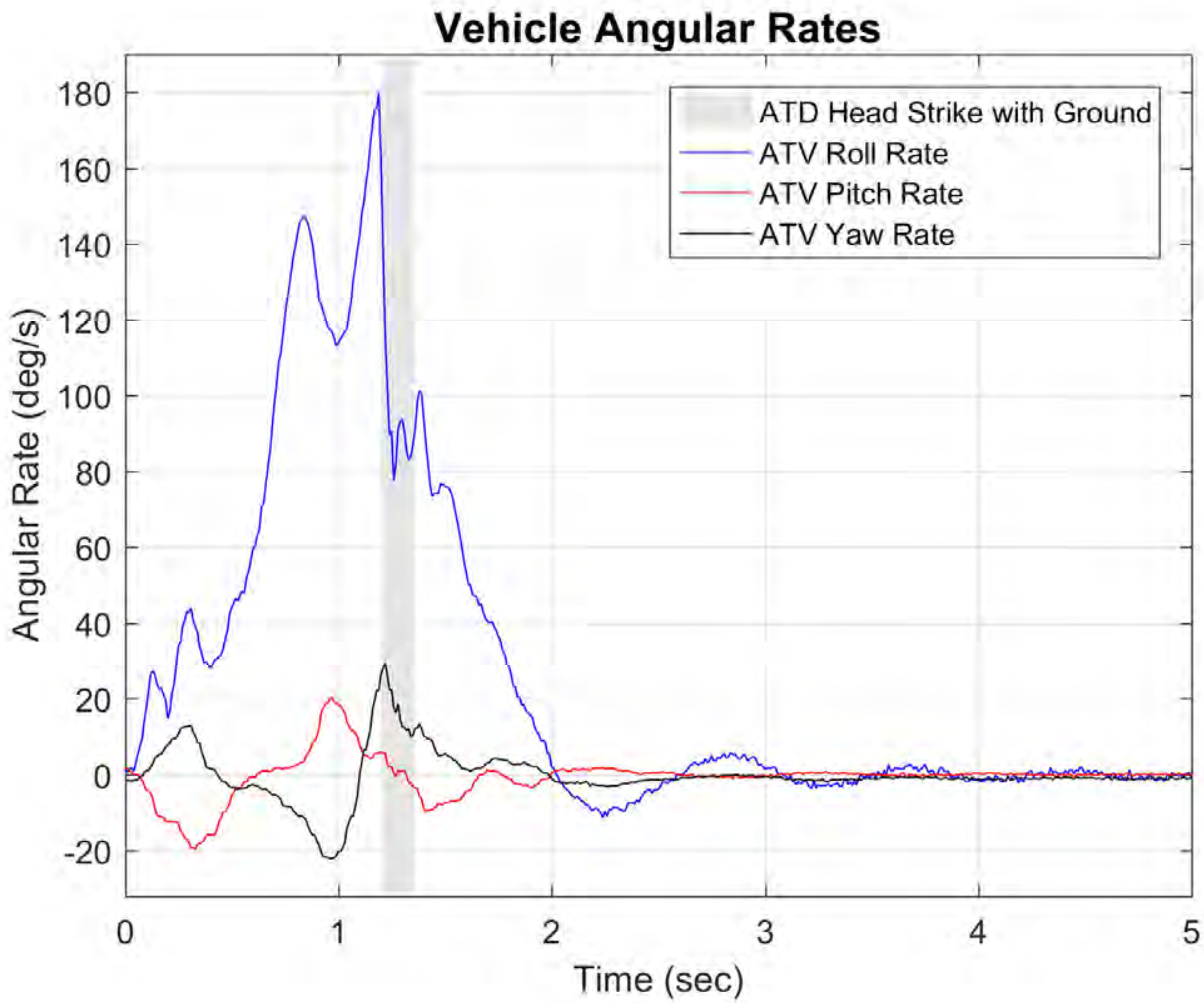
Vehicle L - Sled Minimum Energy Rollover



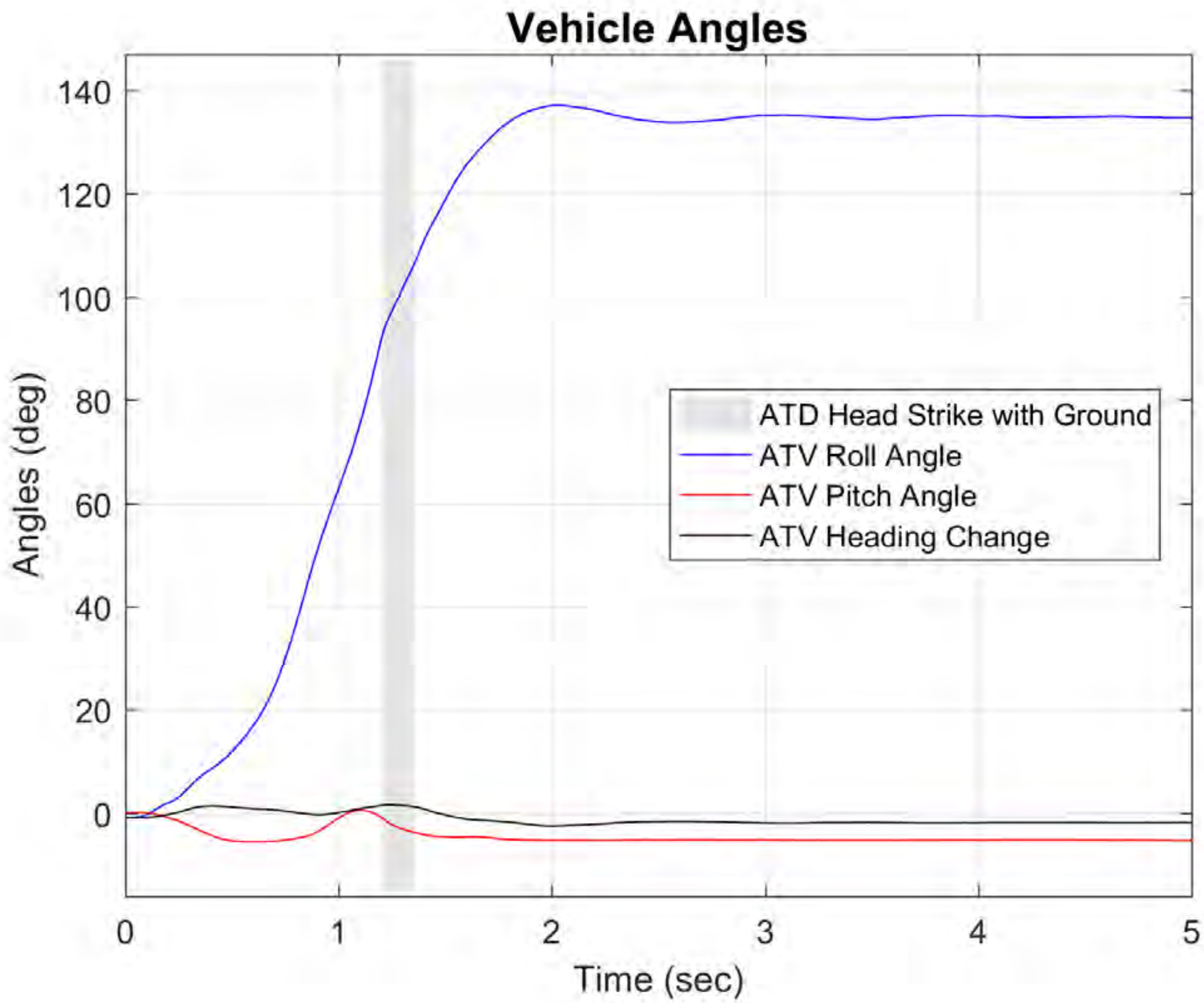
Vehicle L - Sled Minimum Energy Rollover



Vehicle L - Sled Minimum Energy Rollover



Vehicle L - Sled Minimum Energy Rollover



Vehicle L - Sled Minimum Energy Rollover

AOS Camera 1 - Roll Angle = 30° - Time = 0.42 sec

AOS Camera 1 - Roll Angle = 45° - Time = 0.56 sec

AOS Camera 1 - Roll Angle = 90° - Time = 0.79 sec

AOS Camera 2 - Roll Angle = 30° - Time = 0.42 sec

AOS Camera 2 - Roll Angle = 45° - Time = 0.56 sec

AOS Camera 2 - Roll Angle = 90° - Time = 0.79 sec

Vehicle L - Sled Moderate Energy Rollover

AOS Camera 1 - ATD Head Strike - Time = 0.91 sec

AOS Camera 1 - Roll Angle = 180° - Time = 1.1 sec

AOS Camera 1 - Roll Angle = 270° - Time = 1.56 sec

AOS Camera 2 - ATD Head Strike - Time = 0.91 sec

AOS Camera 2 - Roll Angle = 180° - Time = 1.1 sec

AOS Camera 2 - Roll Angle = 270° - Time = 1.56 sec

Vehicle L - Sled Moderate Energy Rollover

AOS Camera 1 - Roll Angle = 360° - Time = 2.21 sec

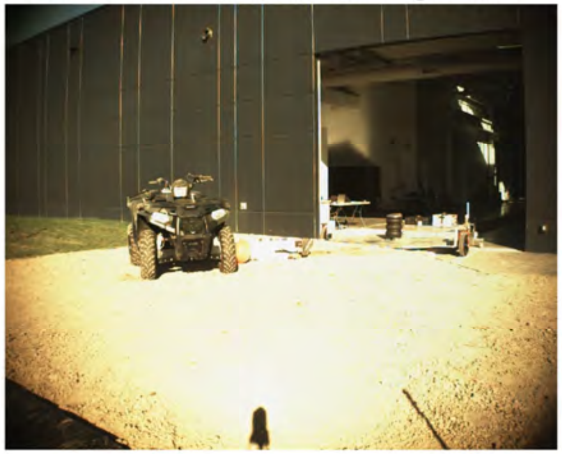
AOS Camera 1 - Max Angle = 371.0° - Time = 2.4 sec

AOS Camera 1 - End of Run - Roll Angle = 360.6°

AOS Camera 2 - Roll Angle = 360° - Time = 2.21 sec

AOS Camera 2 - Max Angle = 371.0° - Time = 2.4 sec

AOS Camera 2 - End of Run - Roll Angle = 360.6°



Vehicle L - Sled Moderate Energy Rollover

RT Camera 1 - Roll Angle = 30° - Time = 0.42 sec

RT Camera 1 - Roll Angle = 45° - Time = 0.56 sec

RT Camera 1 - Roll Angle = 90° - Time = 0.79 sec

RT Camera 2 - Roll Angle = 30° - Time = 0.42 sec

RT Camera 2 - Roll Angle = 45° - Time = 0.56 sec

RT Camera 2 - Roll Angle = 90° - Time = 0.79 sec

Vehicle L - Sled Moderate Energy Rollover

RT Camera 1 - ATD Head Strike - Time = 0.91 sec

RT Camera 1 - Roll Angle = 180° - Time = 1.1 sec

RT Camera 1 - Roll Angle = 270° - Time = 1.56 sec

RT Camera 2 - ATD Head Strike - Time = 0.91 sec

RT Camera 2 - Roll Angle = 180° - Time = 1.1 sec

RT Camera 2 - Roll Angle = 270° - Time = 1.56 sec

Vehicle L - Sled Moderate Energy Rollover

RT Camera 1 - Roll Angle = 360° - Time = 2.21 sec

RT Camera 1 - Max Angle = 371° - Time = 2.4 sec

RT Camera 1 - End of Run - Roll Angle = 360.6°

RT Camera 2 - Roll Angle = 360° - Time = 2.21 sec

RT Camera 2 - Max Angle = 371° - Time = 2.4 sec

RT Camera 2 - End of Run - Roll Angle = 360.6°

Vehicle L - Sled Moderate Energy Rollover

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

Drone Camera - Roll Angle = 45° - Time = 0.56 sec

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

Drone Camera - ATD Head Strike - Time = 0.91 sec

Drone Camera - Roll Angle = 180° - Time = 1.1 sec

Drone Camera - Roll Angle = 270° - Time = 1.56 sec

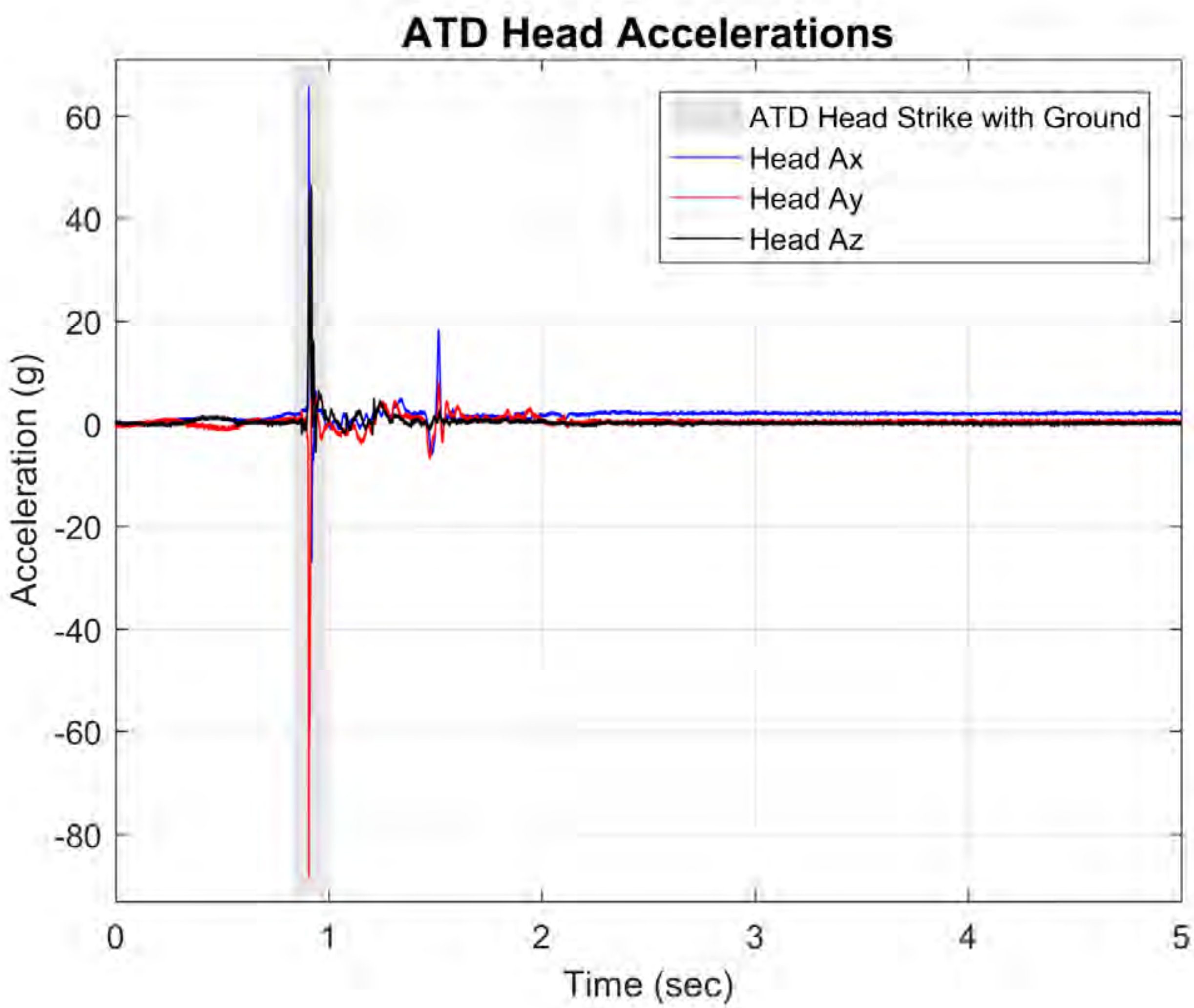
Vehicle L - Sled Moderate Energy Rollover

Drone Camera - Roll Angle = 360° - Time = 2.21 sec

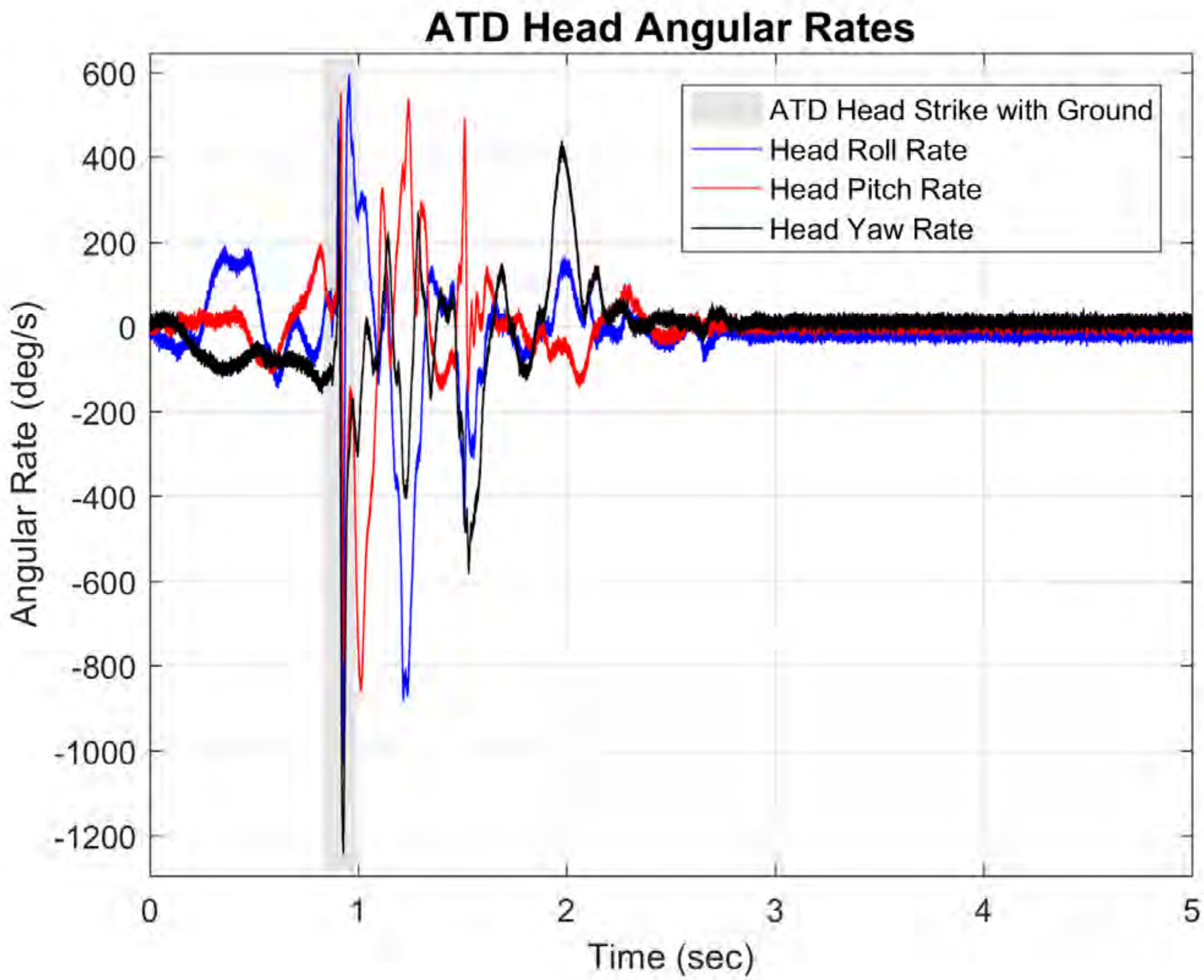
Drone Camera - Max Angle = 371° - Time = 2.4 sec

Drone Camera - End of Run - Roll Angle = 360.6°

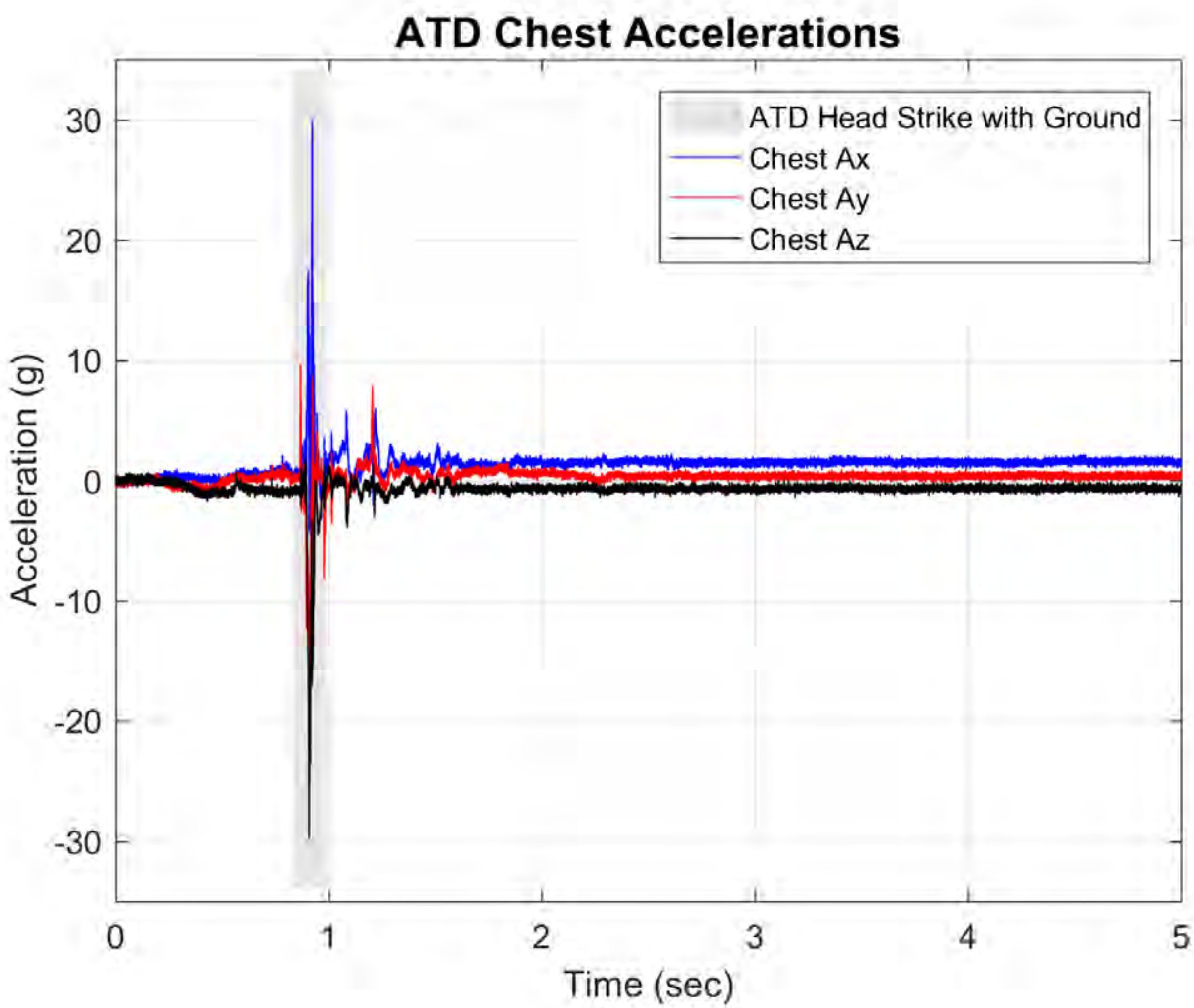
Vehicle L - Sled Moderate Energy Rollover



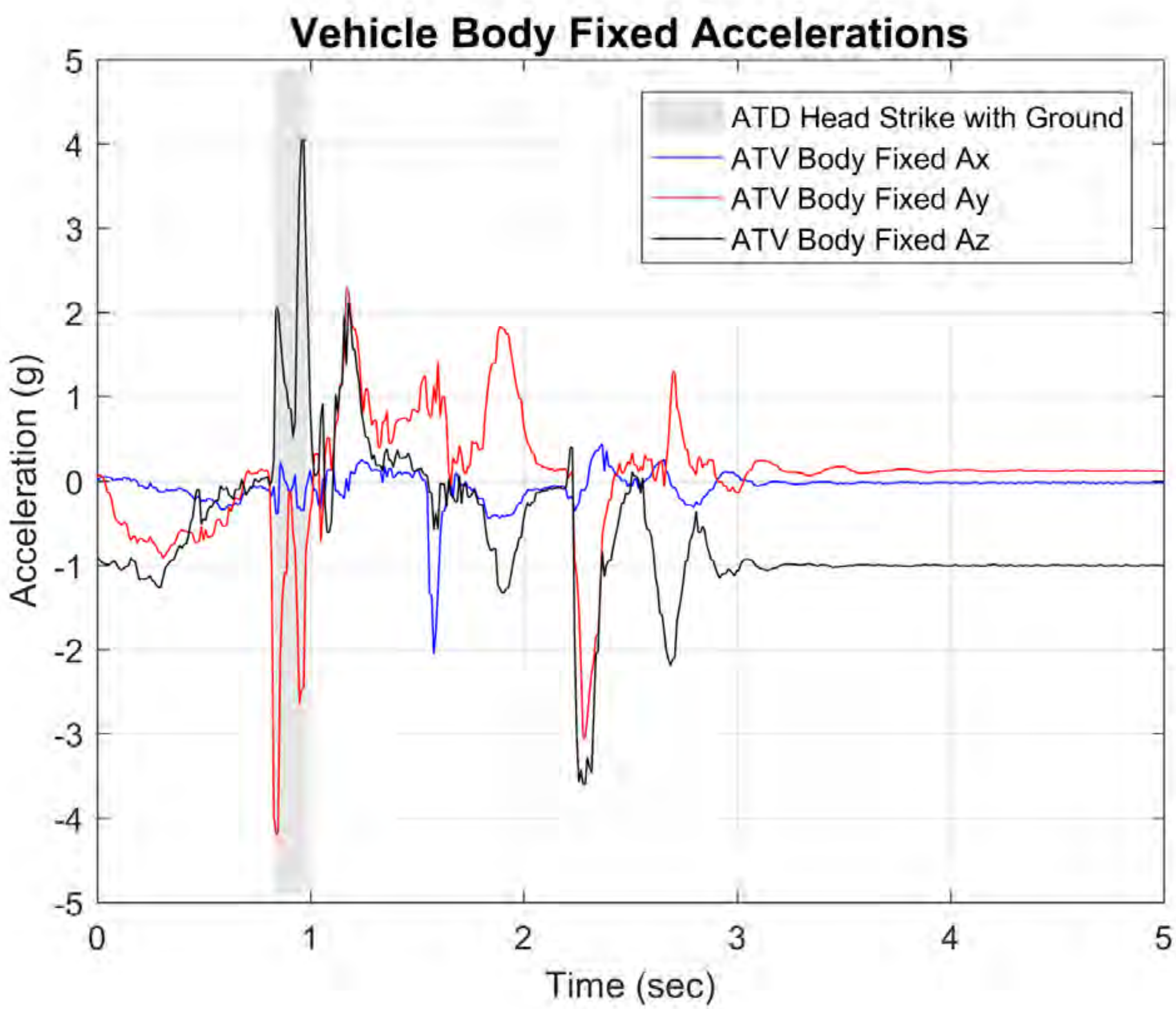
Vehicle L - Sled Moderate Energy Rollover



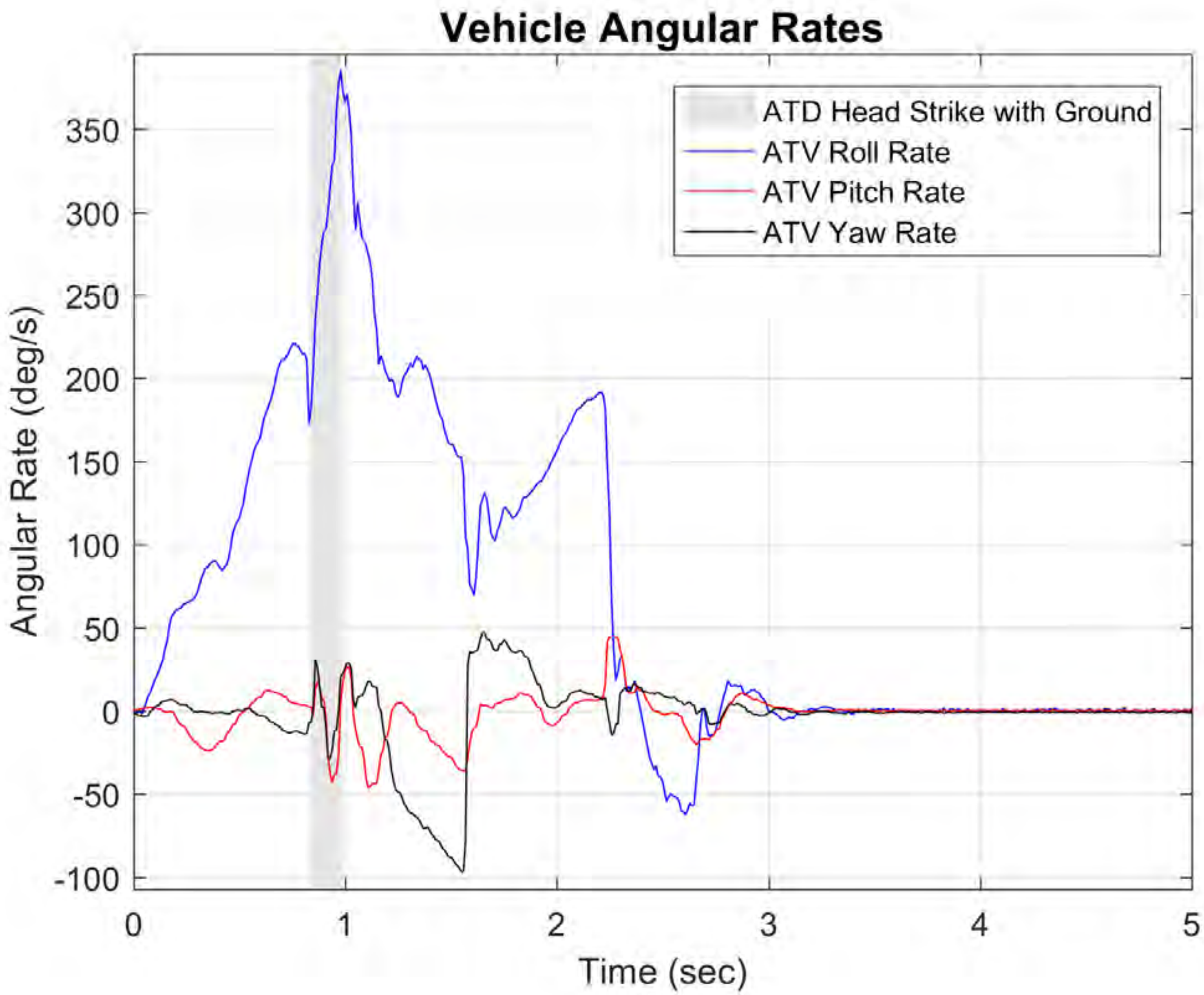
Vehicle L - Sled Moderate Energy Rollover



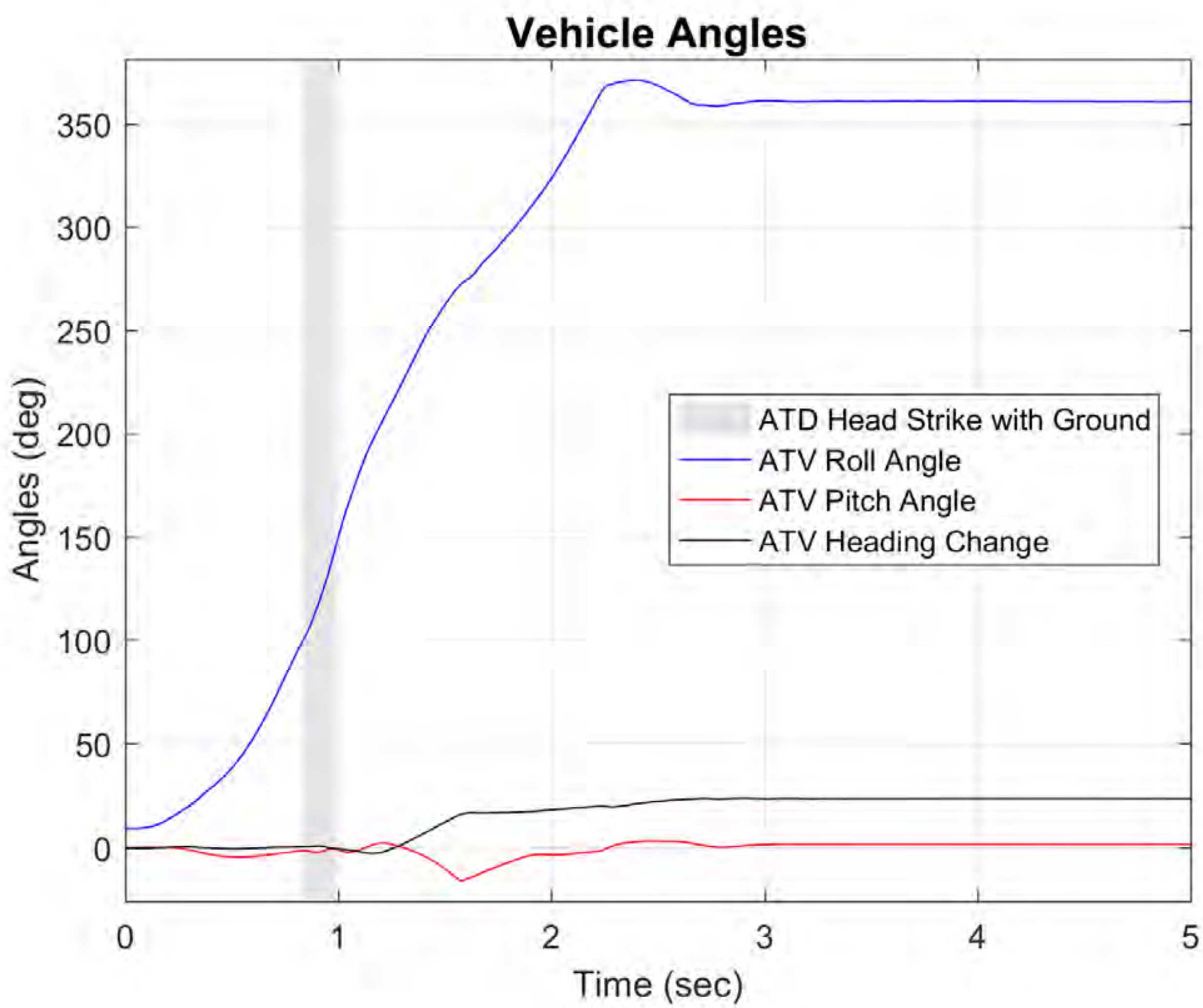
Vehicle L - Sled Moderate Energy Rollover



Vehicle L - Sled Moderate Energy Rollover



Vehicle L - Sled Moderate Energy Rollover



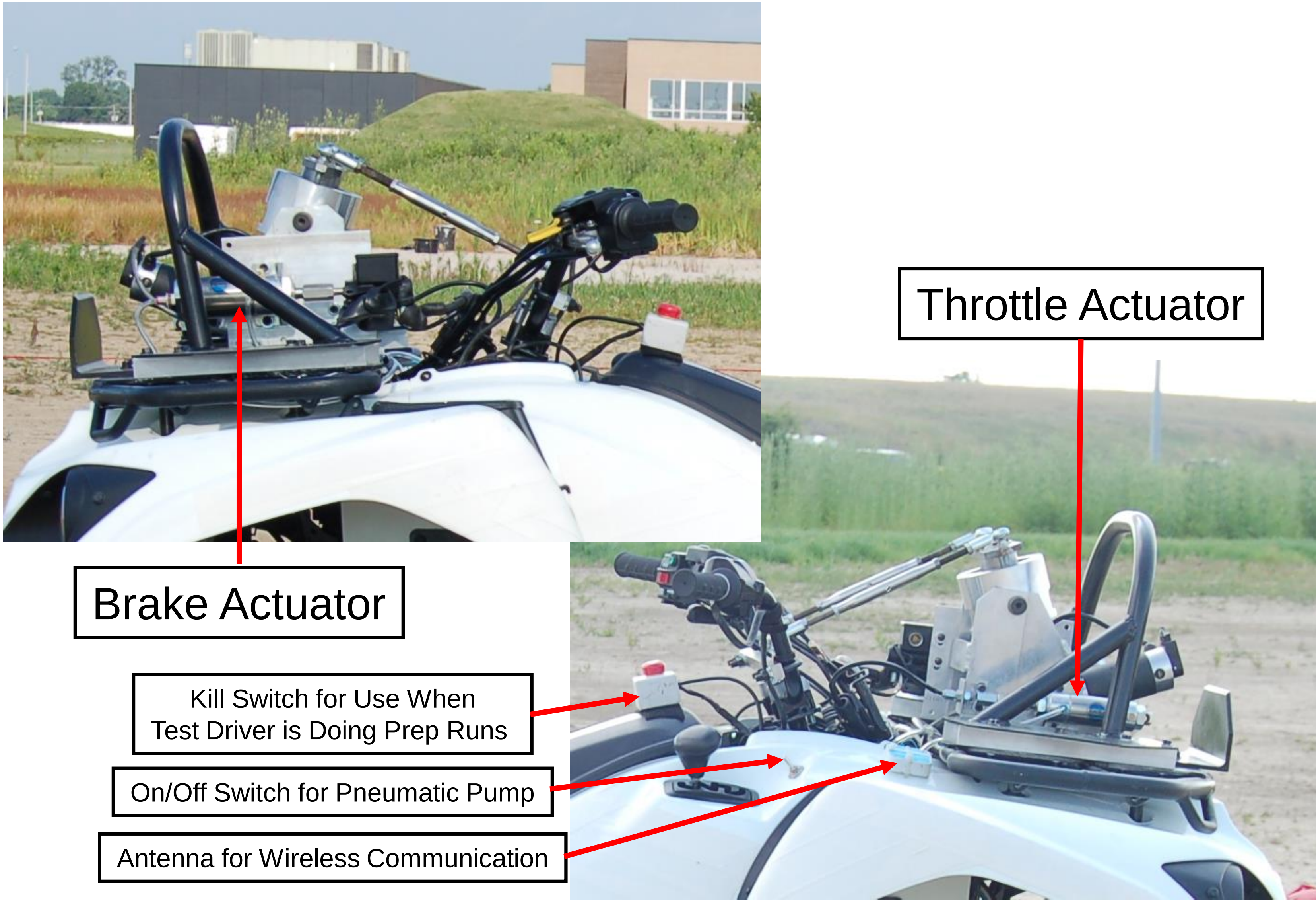
Vehicle L - Sled Moderate Energy Rollover

Side View of Test Vehicle Prepared for Dynamic Rollover Testing

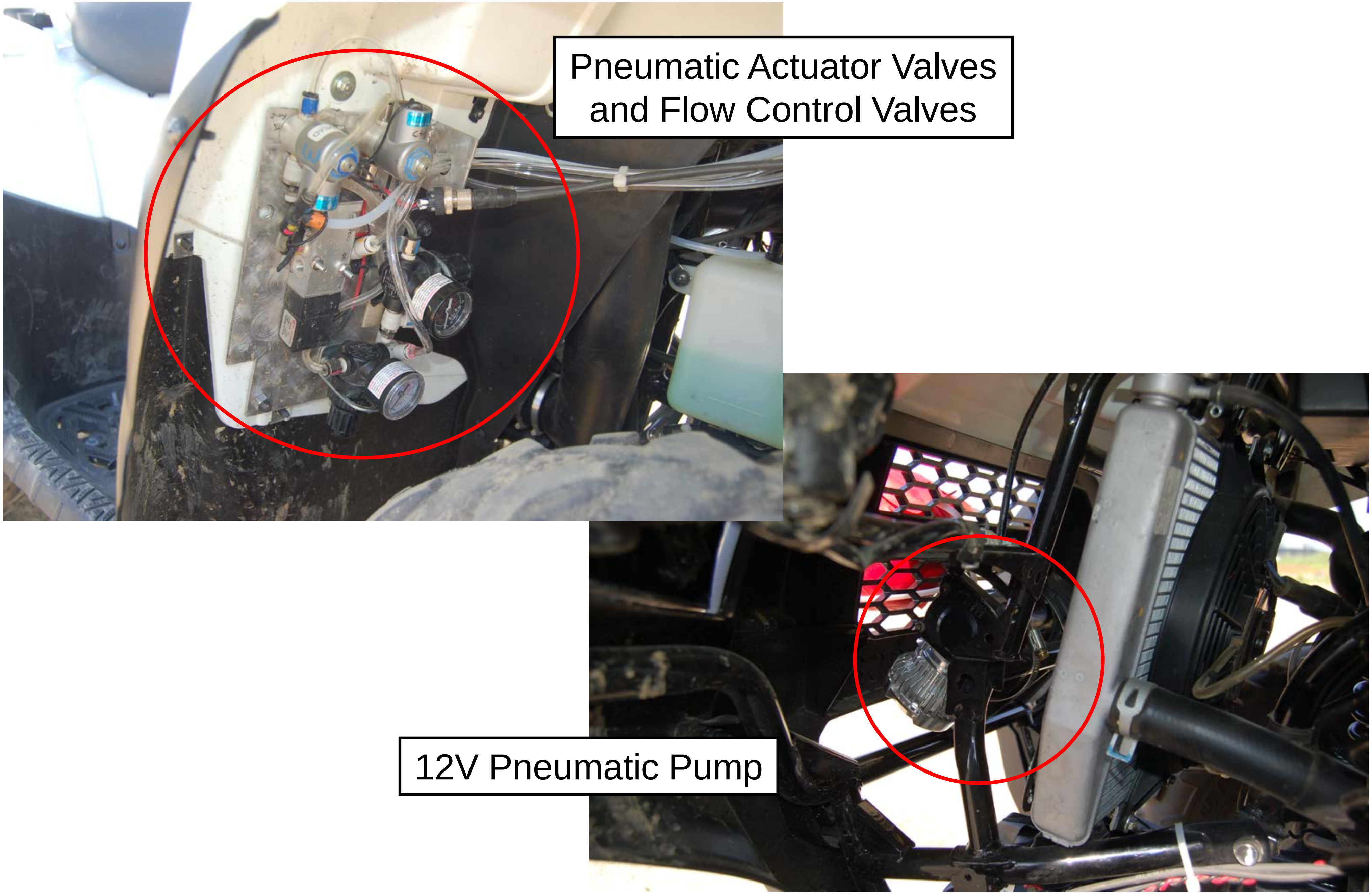
Side View of Test Vehicle Prepared for Dynamic Rollover Testing with ATD Secured on Vehicle

ATV Dynamic Rollover Steering Controller Motor and Protective Guard

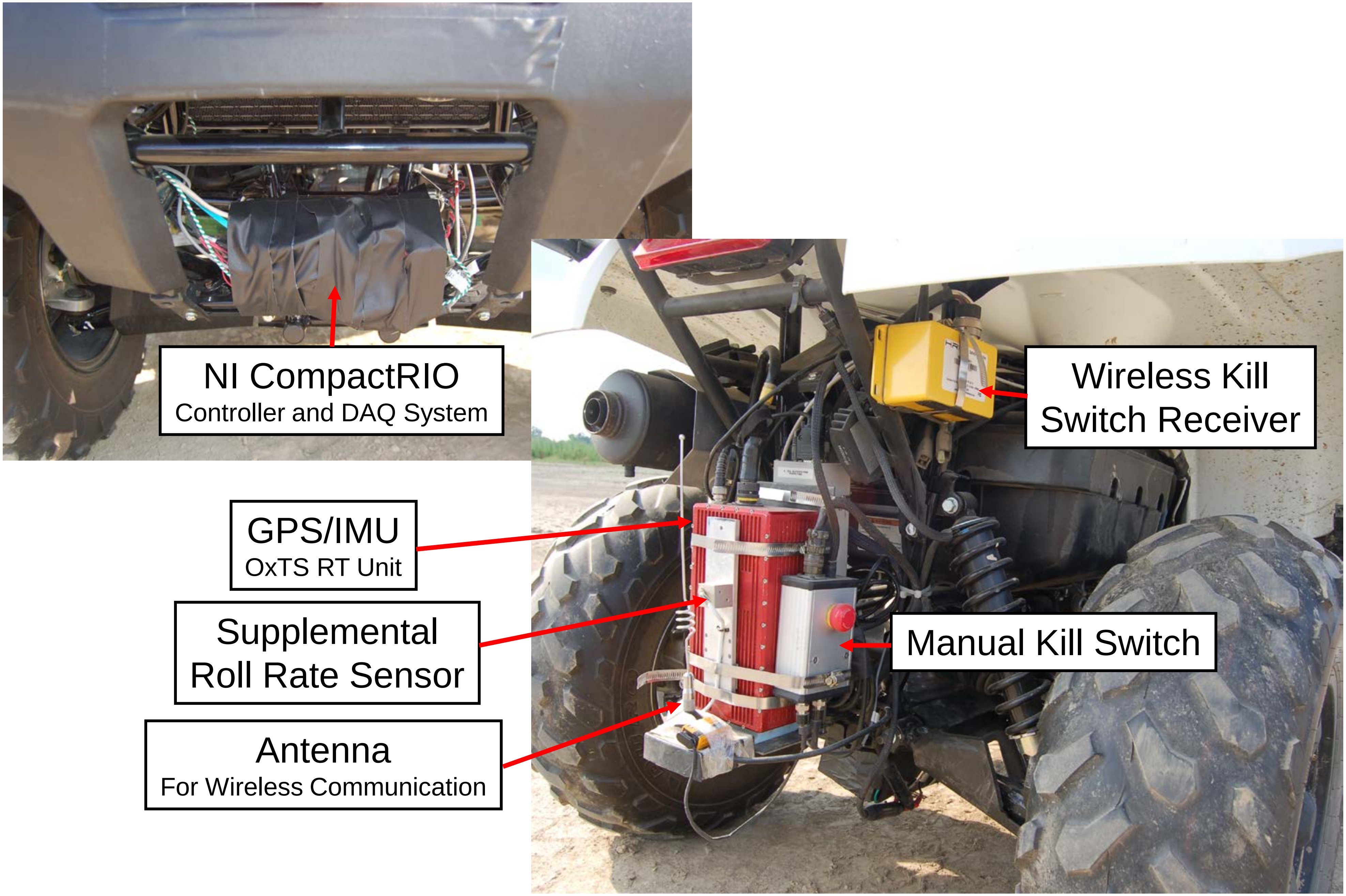
ATV Dynamic Rollover Brake and Throttle Pneumatic Actuators



ATV Dynamic and Sled Rollover Pneumatic Valves and Pump

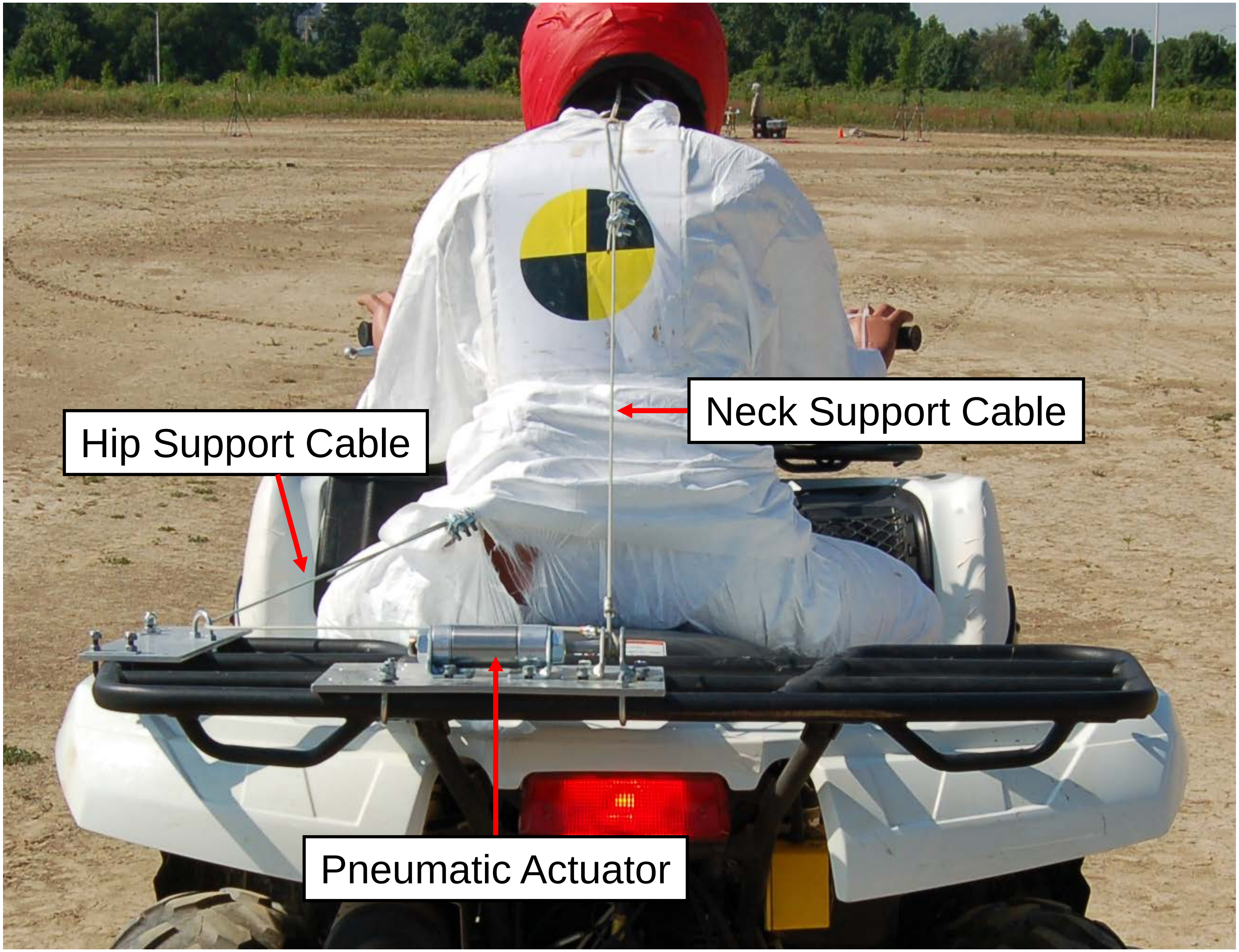


ATV Dynamic Rollover Controller/DAQ, Sensors and Kill Circuit Switches

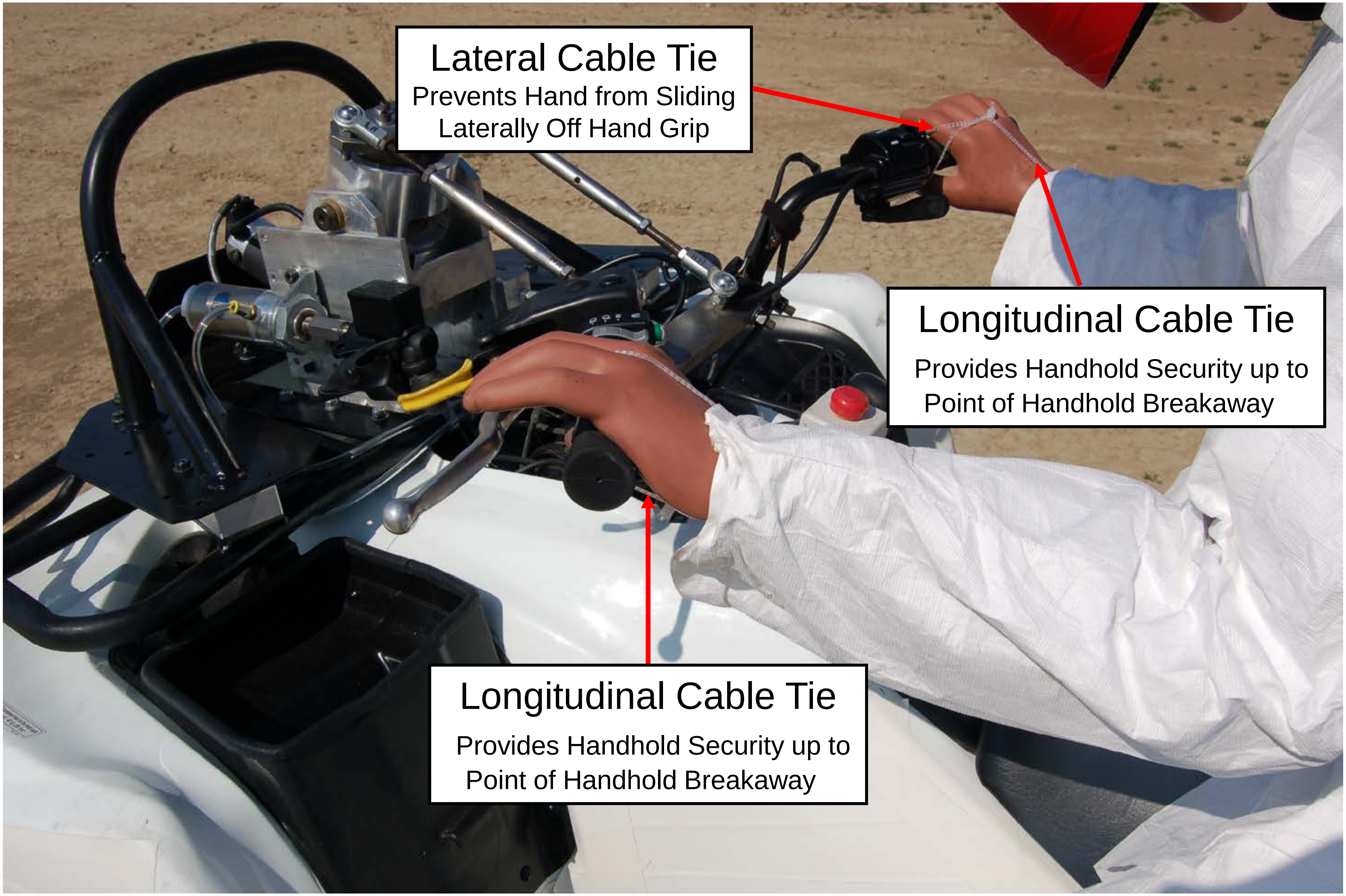


Batteries and RT Antenna Mounting used for ATV Dynamic Rollover

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



ATV Dynamic and Sled 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:

- Two triggerable cameras were connected to a ribbon switch (position trigger) that was used to time synchronize the video image data to the vehicle data. These cameras are capable of recording video at high speeds, but they were set to record video at 25 frames per second (fps). This correlates to one frame every 0.04 seconds. Using higher frame rates reduces the resolution of the video images, so 25 fps was selected as it provided relatively good images. (The lenses used on the cameras for the dynamic rollover tests were replaced for the sled rollover tests, and they provided much clearer images during the sled tests.)

- Two fixed-frame rate cameras were used to collect real-time (RT) images of the rollover events, and provide for convenient real-time playback of the rollover events immediately after each run. These cameras have a fixed frame rate of 30 fps.

- 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 these high speed 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 pit 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 1 and 2 were set up to be roughly orthogonal to one another. RT Camera 1 and HS Camera 1 were set up very close to one another, as were RT Camera 2 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 Name Used for Video Image Results	**Manufacturer**	**Model**	**Frame Rate (fps)**
Camera 1 & Camera 2	--	--	25
RT Camera 1 & RT Camera 2	--	--	30
NA	--	--	600
Drone Camera (Dynamic Rollovers of Vehicle A)	--	--	60
Drone Camera (Dynamic Rollovers of Vehicles E, G and L)	--	--	24
Drone Camera (All Sled Rollovers)	--	--	30

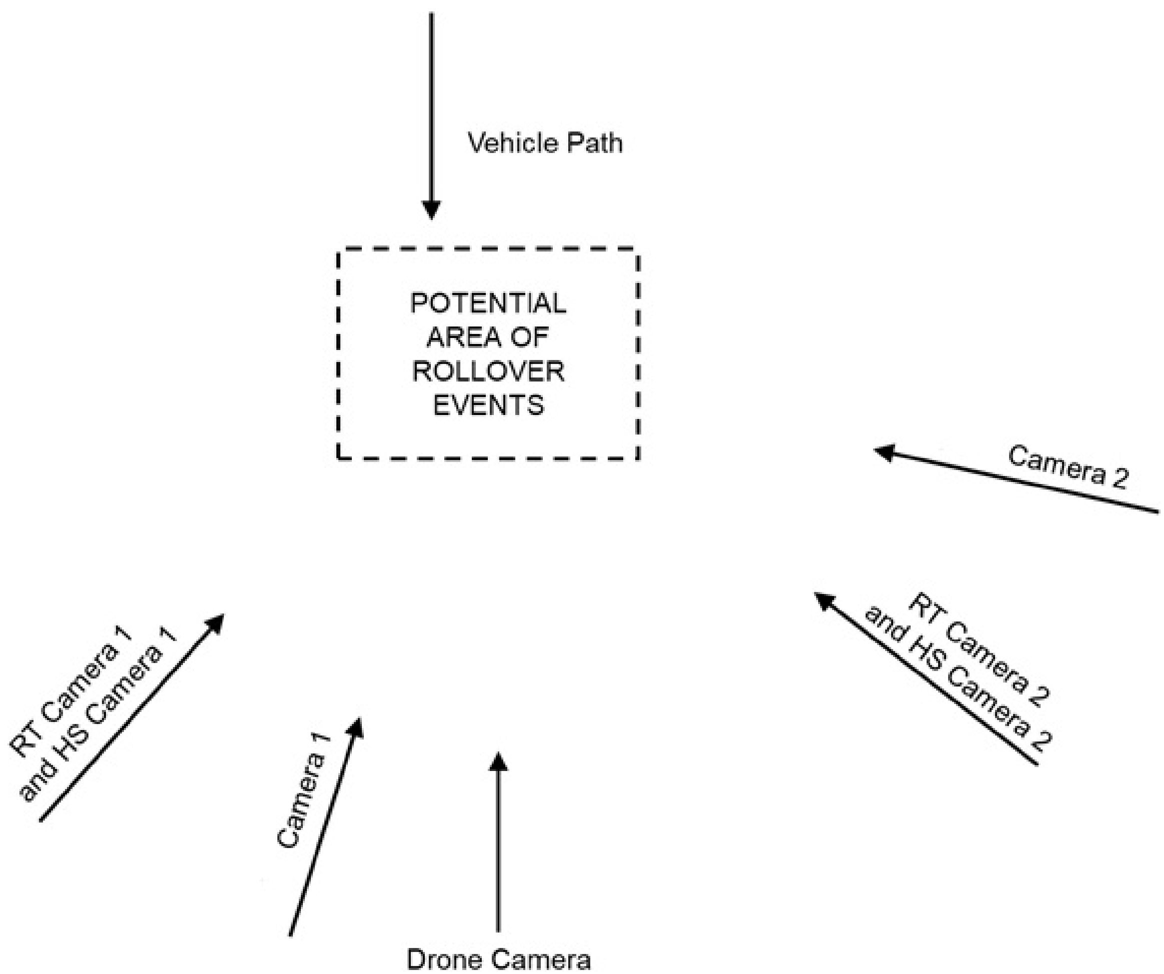


Figure D.1: Representative Orientation of Cameras During Dynamic and Sled Tests

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

For all of the dynamic and sled rollover tests, an instrumented Hybrid III 50th percentile male Anthropometric Test Device (ATD) with a standing pelvis was used as the surrogate driver. A DOT approved large HJC model CL-33 open face helmet with a full-face shield 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 of 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[1,2], 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:

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

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

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

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_{15} and HIC_{36}, 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.[3] 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

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[1] 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.

[2] 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.

[3] 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 significant 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.[4] 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 50th 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, Velcro, 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, Velcro 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 (Cable Ties Plus SKU number CP-08472-NA) were found 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, during the left-turn turning portion of the maneuver, the ATD's right hand slide to the right and off of 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 of 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 Velcro strap, placed loosely

[4] 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 of the dynamic and sled tests conducted, a specified roll angle of 30º 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 45º of roll angle.

During a couple of sled tests on the fourth vehicle in the test sequence (Vehicle J), 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 (on Vehicles F and G), a pneumatic actuator system similar to 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 30º 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 30º of roll angle with full release occurring around 45º of roll angle. After about 45º 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 90º 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.

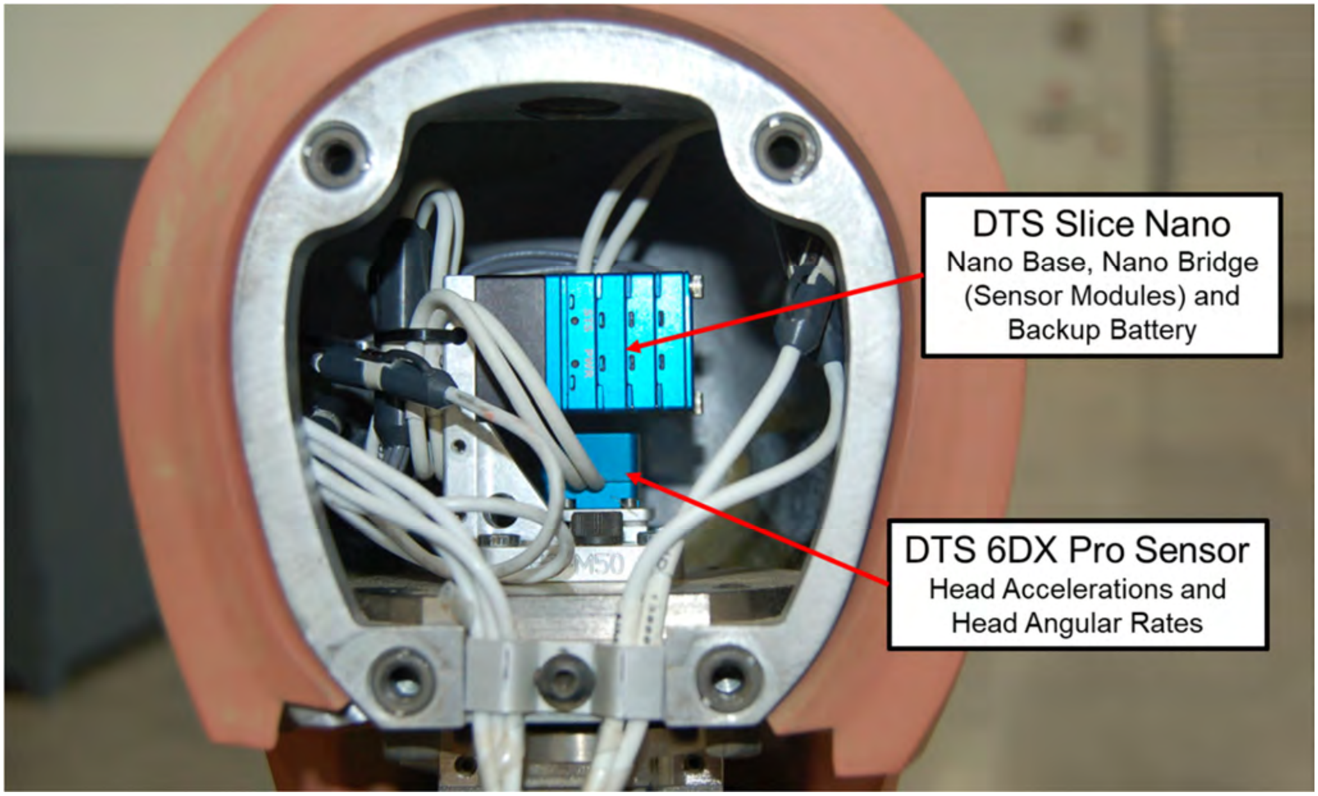

Figure E.1: Instrumentation in ATD Head

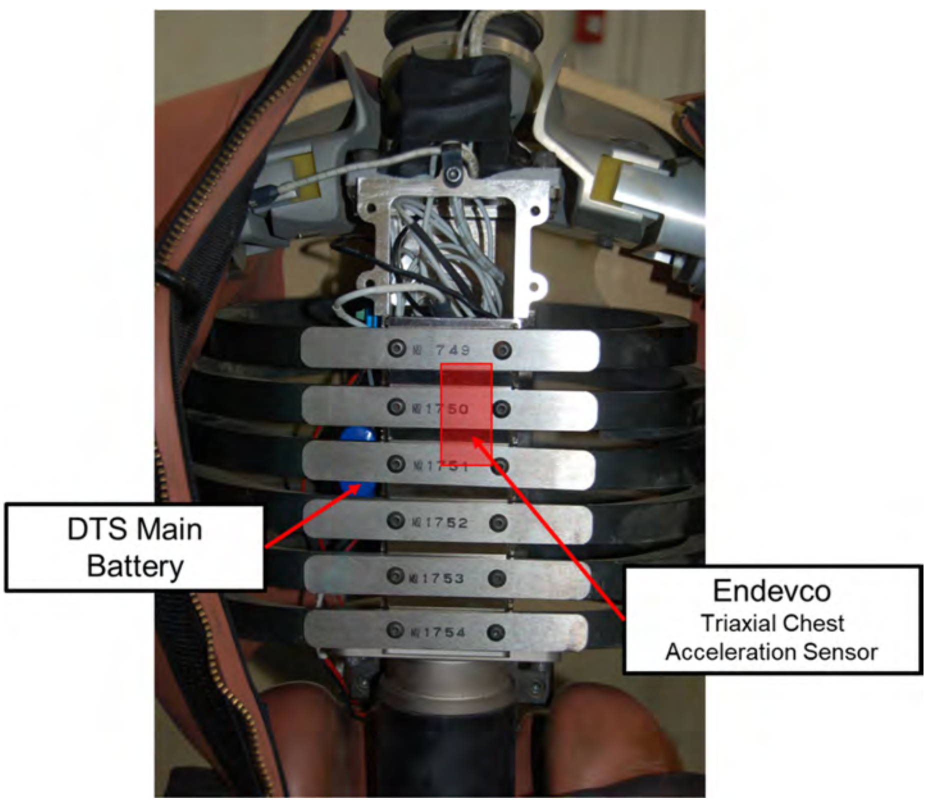

Figure E.2: Instrumentation in ATD Chest

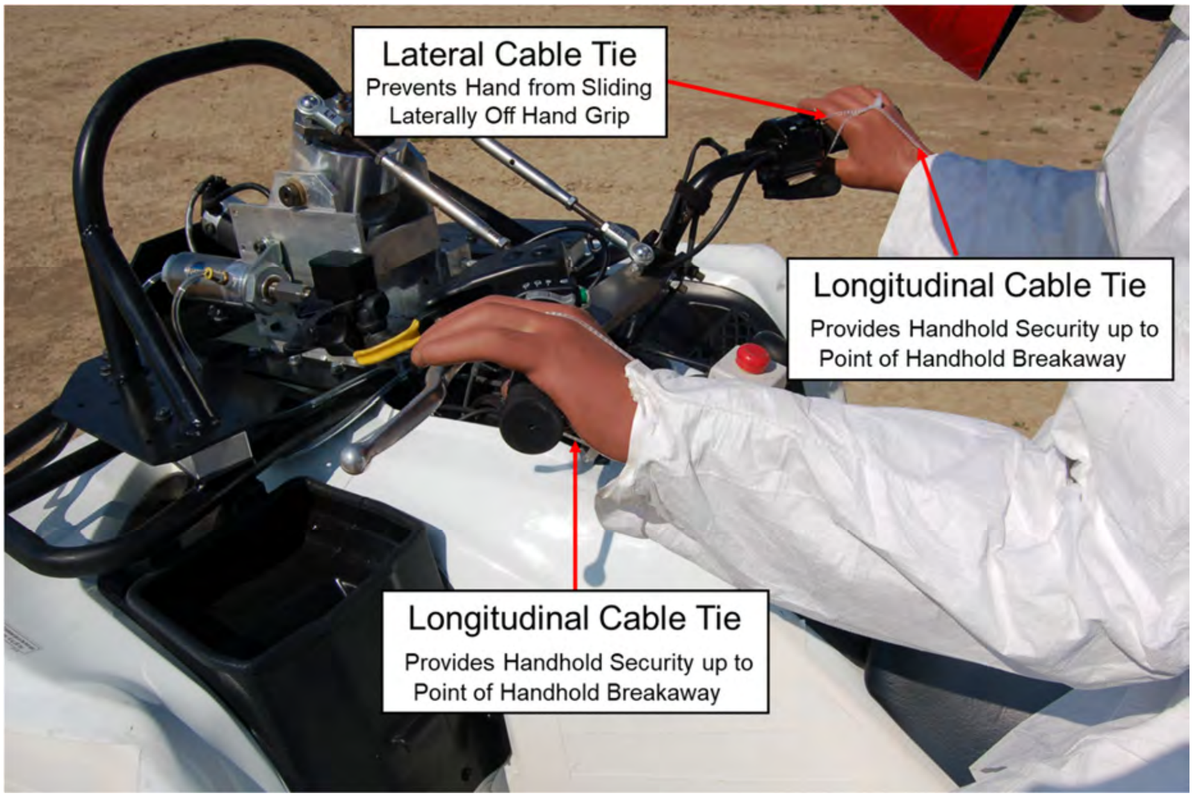

Figure E.3: Cable Tie Arrangement used to Secure the ATD's Hands to the Hand Grips

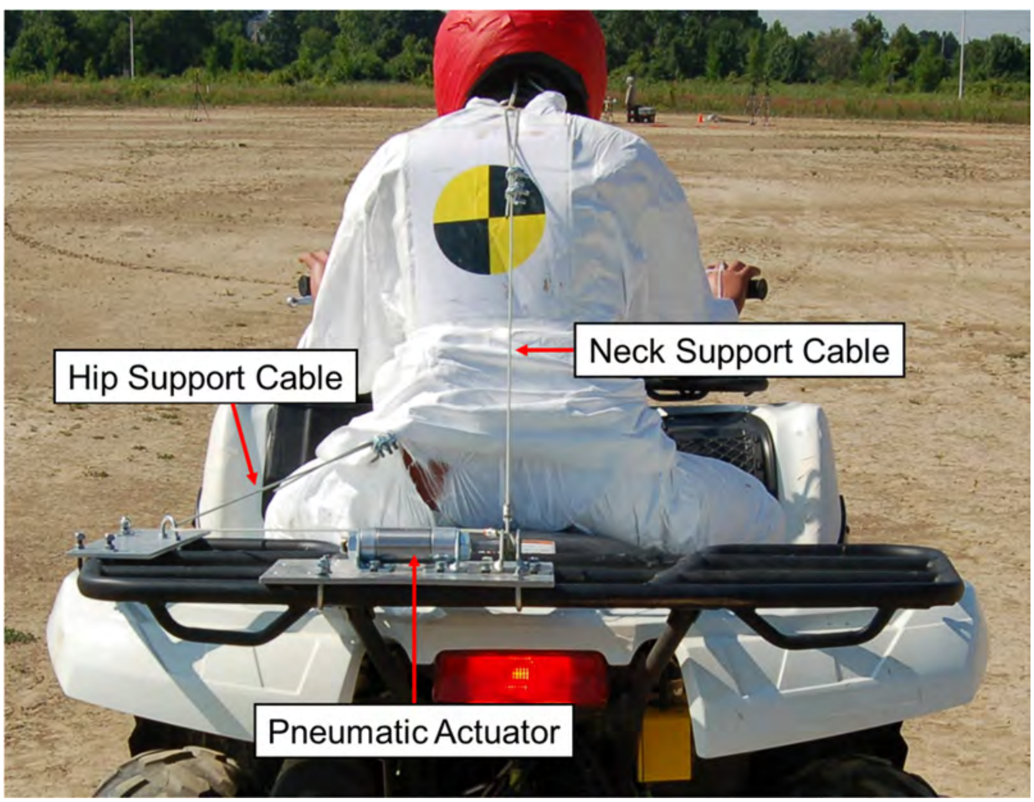

Figure E.4: Wire Rope Cable Arrangement used to Secure the ATD's Hip and Neck

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

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

Figure E.7: Pneumatically Released Handhold used on Right Hand (Sled Vehicles F and G)

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 rollover testing on Recreational Off-Highway Vehicles (ROVs).[1,2,3,4] 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 of 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 of 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 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.

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[1] Zagorski, S.B., *Modeling, Control and State Estimation of a Roll Simulator*, PhD Dissertation, The Ohio State University, 2012.

[2] 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

[3] 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.

[4] 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.

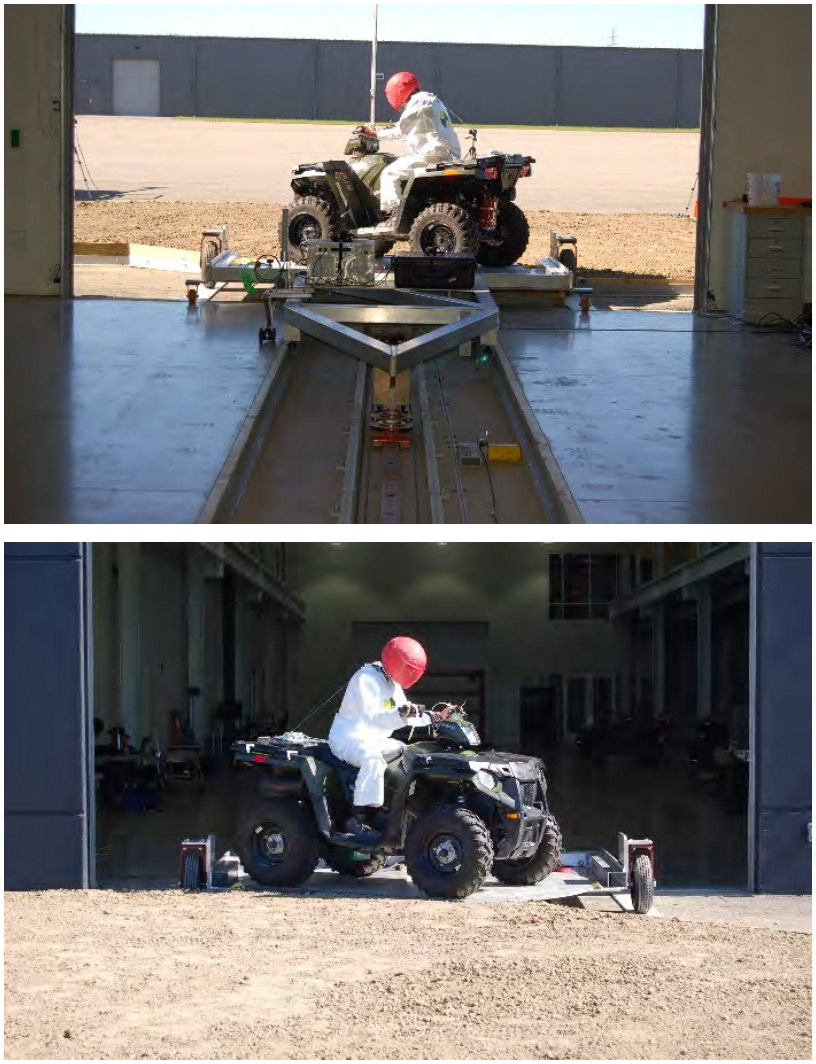

Figure F.1: Views of ATV Rollover Simulator Along the Direction of Sled Translation

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

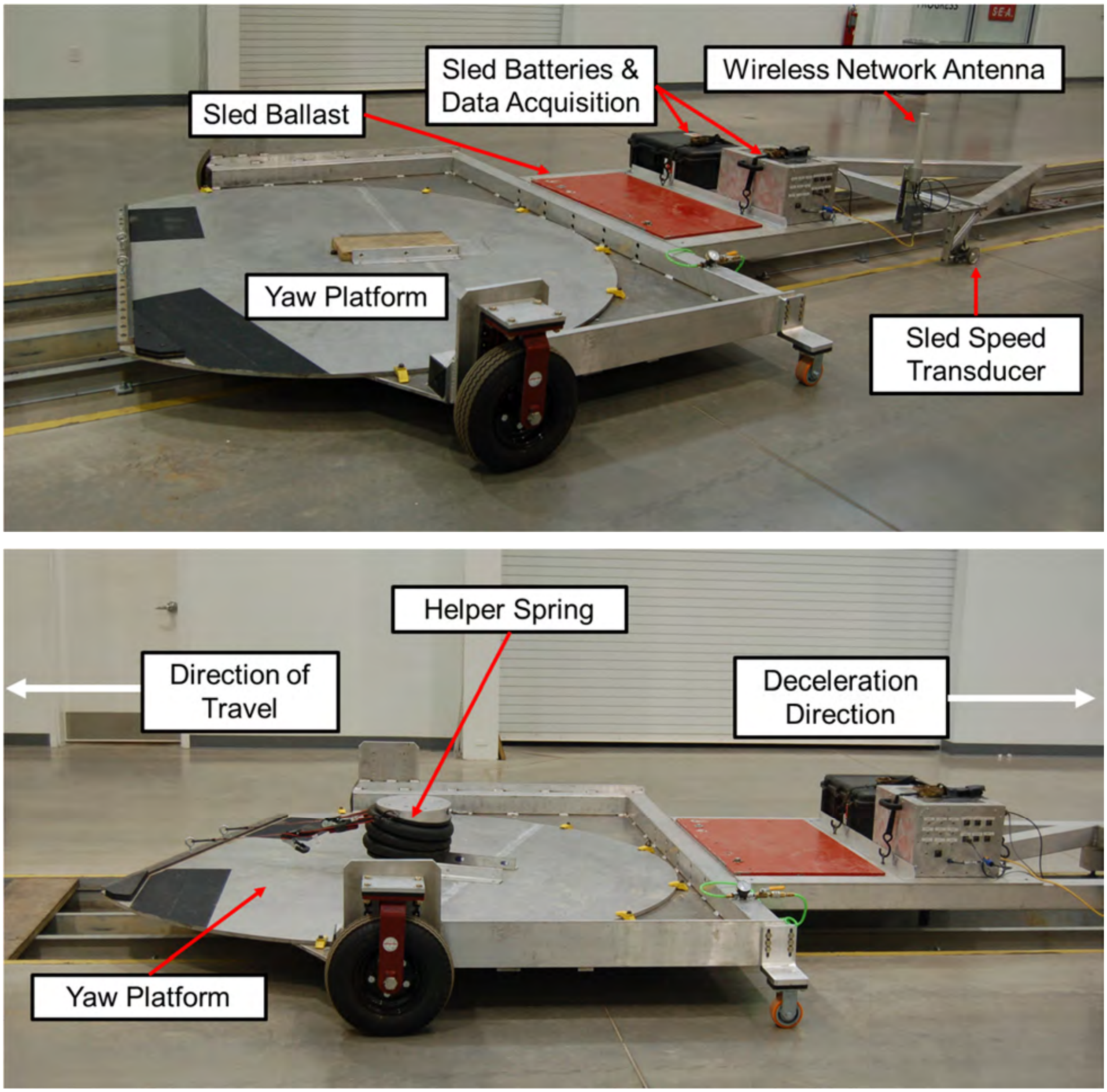

Figure F.3: ATV Rollover Sled Components
Top: Without Helper Spring – Bottom: With Helper Spring

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. Sled entry speed was adjusted such that enough kinetic energy was in the system to produce the ranges of peak roll rate (180-250 deg/s for minimum energy rollovers and over 250 deg/s in the moderate energy rollovers) and ranges of maximum roll angle (90°-180° for minimum energy rollovers and over 180° for moderate energy rollovers). Given the total weight of the sled with ATV and ATD, a nominal sled entry speed of 21 ft/sec was used for the minimum energy rollovers and a 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 of 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 roll over. 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° (so as 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 of 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 of 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. Nevertheless, the trip rail was used to make sure this did not happen. The trip rail does not have a significant influence on 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 20°, 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 initialy rolled in the direction of the rollover helps generate greater roll energy in the test, and results in greater maximum roll rates and roll angles during the rollover events. 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 ATV. 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.

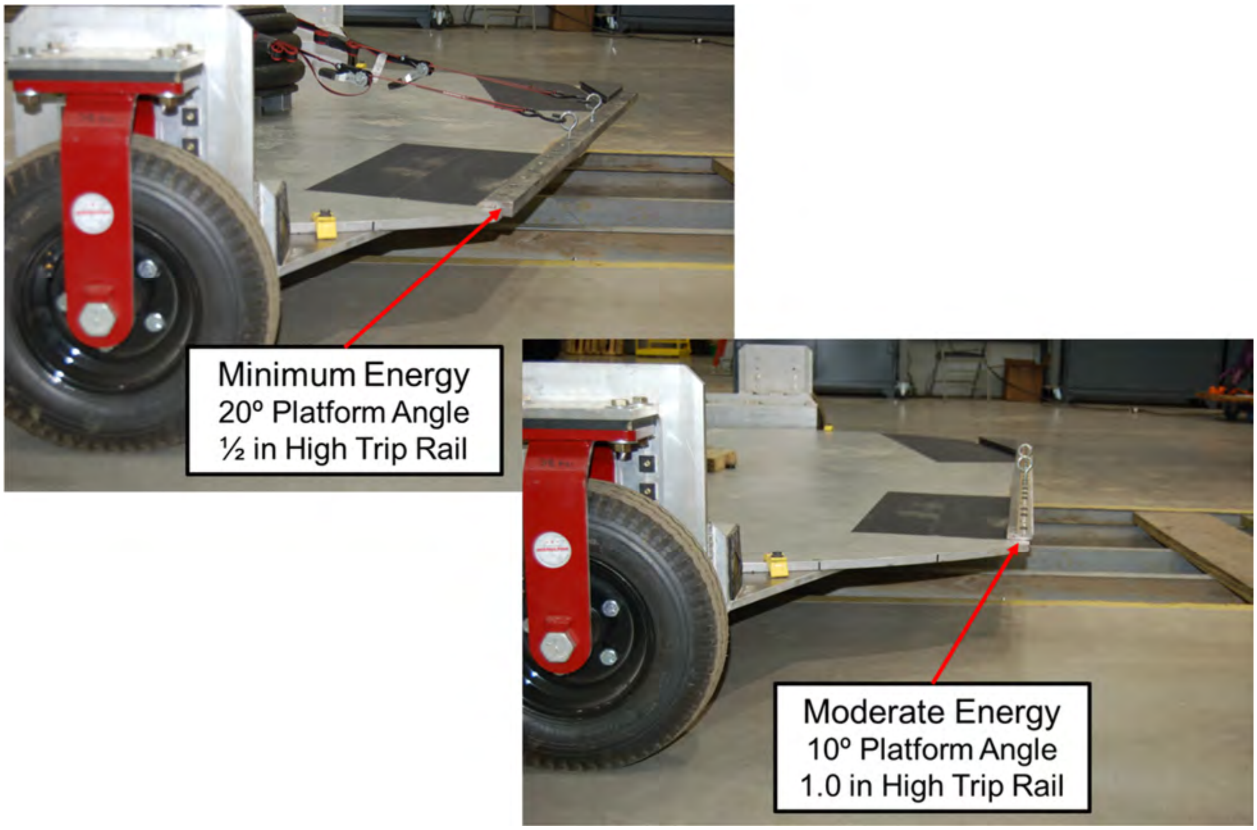

Figure F.4: Platform Yaw Angles and Trip Rails used for Minimum Energy and Moderate Energy ATV Sled Rollovers

Figure F.5: Photo Showing Steer Angle Block

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