United States
Consumer Product Safety Commission

March 2022

CPSC Staff Statement on SEA, Ltd. Report "Rollover Tests of ATVs Outfitted with Proof of Concept Occupant Protection Devices (OPDs)"[1]

The report titled, "Rollover Tests of ATVs Outfitted with Proof of Concept Occupant Protection Devices (OPDs)," presents the results of laboratory simulation of ATV rollover events conducted by SEA, Ltd. (SEA), on six adult, single-rider ATVs that had been equipped with proof of concept occupant protection devices. SEA previously studied the feasibility and effectiveness of using aftermarket OPDs on ATVs by conducting autonomous dynamic rollovers (on a groomed dirt surface) and sled rollovers (using a physical rollover simulator) of ATVs outfitted with aftermarket OPDs. The previous work was conducted for CPSC under Task Orders 1 and 2 of CPSC contract 61320618D0003.[2]

This follow up work was conducted under Task Order 3 of contract 61320618D0003, which tasked SEA to use rollover simulator to evaluate proof-of-concept (POC) designs of occupant protection devices (OPDs) that mitigate injury to the driver of an ATV when a rollover or rearward pitch-over event occurs. Specifically, Task Order 3 tasked SEA to produce four design concept OPDs and conduct laboratory simulated rollover testing to evaluate the occupant protection performance. Results of this exploratory testing show that rear-mounted OPDs can reduce the potential for injury in lateral rollover events and that POC OPDs reduced maximum roll angles and roll rate. In addition, POC OCDs reduced interactions between the ATV and the test dummy because the OPDs provided protective clearance when the ATV rolled above the test dummy and provided clearance distance after the ATV rolled past the test dummy.

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[3]
- Effects on Vehicle Characteristics of Two Persons Riding ATVs[4]
- Effects on ATV Vehicle Characteristics of Rider Active Weight Shift[5]
- Vehicle Characteristics Measurements of ATVs Tested on Groomed Dirt[6]

---

[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] *Rollover Tests of ATVs Outfitted with Occupant Protection Devices (OPDs) – Results from Tests on Six 2014-2015 Model Year Vehicles,* CPSC Contract 61320618D0003, SEA, Ltd. Report to CPSC, January 2020. https://www.cpsc.gov/s3fs-public/SEA-Report-to-CPSC-ATVs-OPDs-final-redacted_0.pdf?VRu656v4QtP5rKIiw0kuSQP_hW49TVDK

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

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

[5] Available at: https://cpsc.gov/s3fs-public/SEA-Report-to-CPSC-Rider-Active-ATV-Study-December-2017.pdf?1nQBCXYgr.fkZoAR3axu7hkJ9l7mbSUI.

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

- ATV Attribute Modification Study: Results of Baseline and Modified Vehicle Testing[7]
- ATV Rollover Tests and Verification of a Physical Rollover Simulator[8]
- Rollover Tests of ATVs Outfitted with Occupant Protection Devices (OPDs)[1]

[7] Available at: https://cpsc.gov/s3fs-public/ATV%20Attribute%20Modification%20Study%20-%20%20Results%20of%20Baseline%20and%20Modified%20Vehicle%20Testing_0.pdf?ch3Lu_.tpLpARkMCeX25aC0AlMNMzIHS.
[8] Available at: https://cpsc.gov/s3fs-public/SEA%20Report%20to%20CPSC%20-%20ATV%20Rollover%20Simulator%20%286b%20cleared%29_Redacted.pdf?mlCsq67xfdq8x94QejoFtK37zwXdLLJV

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

Results from Tests on Six 2014-2015 Model Year Vehicles

for:
U.S. Consumer Product Safety Commission

April 2021

7001 Buffalo Parkway
Columbus, Ohio 43229

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

Results from Tests on Six 2014-2015 Model Year Vehicles

for:
U.S. Consumer Product Safety Commission

"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."

Report prepared by Gary J. Heydinger, Ph.D., P.E.,
with support from Scott Zagorski, Ph.D., P.E., Dale Andreatta, Ph.D., P.E.,
Joe Yapp, Jim Nowjack, Hank Jebode, Jon Coyle and Alex Trazkovich, Ph.D., P.E.

S·E·A

7001 Buffalo Parkway
Columbus, Ohio 43229

TABLE OF CONTENTS

1. OVERVIEW

This report contains results from measurements made by SEA, Ltd. (SEA) for the U.S. Consumer Product Safety Commission (CPSC) under CPSC contract 61320618D0003, a contract that covers general testing and evaluation of all-terrain vehicles (ATVs). Prior to conducting work under CPSC contract 61320618D0003, SEA completed a five-year long, multi-task contract of testing and evaluating ATVs for the CPSC under U.S. Department of Health and Human Services (HHS) contract HHSP233201400030I. Six reports covering the laboratory and dynamic field testing under this previous contract are listed in the footnotes below.[9,10,11,12,13,14]

This report covers work completed under Task Order 3 of contract 61320618D0003. The objective of Task Order 3 was the following:

- Use rollover simulator to evaluate potential rollover technology that mitigates injury to ATV occupants. The contractor shall evaluate proof-of-concept (POC) designs of occupant protection devices (OPDs) that mitigate injury to the driver of an ATV when a rollover or rearward pitch-over event occurs.

Specific tasks for Task Order 3 include:

- Produce four design concept OPDs and conduct laboratory simulated rollover testing, on the previously validated physical rollover simulator, to evaluate the occupant protection performance. Select six ATVs from the set of vehicles provided by CPSC and outfit and test each vehicle with two design concepts from the pool of four design concepts produced. The two concepts for each vehicle will be installed and tested separately. Each vehicle will have a unique set of two concepts with which the vehicle will be tested, and each concept will be tested on three separate vehicles. Therefore, there will be 12 sets of tests in total.

---

[9] *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, January 2017. **https://www.cpsc.gov/s3fs-public/SEA_Report_to_CPSC_Vehicle_Characteristics_Measurements_of_All_Terrain_Vehicles.pdf**

[10] *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**

[11] *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, January 2018. **https://www.cpsc.gov/s3fs-public/SEA-Report-to-CPSC-Rider-Active-ATV-Study-December-2017.pdf?1nQBCXYgr.fkZoAR3axu7hkJ9l7mbSUl**

[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, February 2018. **https://www.cpsc.gov/s3fs-public/SEA-Report-to-CPSC-Groomed-Dirt-ATV-Study.pdf?eK1E6h7IXBtznyCDatWHofAoHHmwD_nr**

[13] *ATV Attribute Modification Study: Results of Baseline and Modified Vehicle Testing Results from Tests on Three 2014-2015 Model Year Vehicles*, HHS Contract HHSP233201400030I, SEA, Ltd. Report to CPSC, April 2018. **https://www.cpsc.gov/s3fs-public/ATV%20Attribute%20Modification%20Study%20-%20%20Results%20of%20Baseline%20and%20Modified%20Vehicle%20Testing_0.pdf?ch3Lu_.tpLpARkMCeX25aC0AlMNMzIHS**

[14] *ATV Rollover Tests and Verification of a Physical Rollover Simulator – Results from Tests on Six 2014-2015 Model Year Vehicles*, HHS Contract HHSP233201400030I, SEA, Ltd. Report to CPSC, October 2019. **https://www.cpsc.gov/s3fs-public/SEA%20Report%20to%20CPSC%20-%20ATV%20Rollover%20Simulator%20%286b%20cleared%29_Redacted.pdf?mlCsq67xfdq8x94QejoFtK37zwXdLLJV**

- Modification of vehicles with proof-of-design concepts shall be coordinated by the contractor with input from CPSC staff. The contractor shall be responsible for research, data analysis, design, purchases, and construction of design concepts.

SEA previously conducted autonomous dynamic rollovers (on a groomed dirt surface) and sled rollovers (using a physical rollover simulator) of ATVs outfitted with aftermarket OPDs. This work was conducted for CPSC under Task Orders 1 and 2 of CPSC contract 61320618D0003.[15] This testing was conducted to determine the feasibility and effectiveness of using OPDs on ATVs.

The summary section from the report covering the previous tests with aftermarket OPDs is provided (in italics) below. The tradenames of the aftermarket OPDs evaluated have been replaced with AM #1 and AM #2 in the following reprint of the summary as well as in the remainder of this report.

> *This current rollover study of ATVs outfitted with OPDs, and the previous rollover study of ATVs without OPDs, involved conducting actual (dynamic) and simulated (sled) steering-maneuver-induced lateral rollover events. Two levels of maneuver severity were studied: minimum energy and moderate energy. Except for the dynamic tests on Vehicle A, all the minimum energy rollovers conducted resulted in maximum roll angles less than 180° and all the moderate energy rollovers conducted resulted in more than 180° of roll angle. In both studies, the same anthropometric test device (ATD) secure and release system was used, and the release of the ATD's body from the ATV was initiated when the vehicle roll angle achieved 30°. The dynamic and sled rollover tests conducted are representative of ATV and ATD motions during a subset of potential ATV rollovers, and they are useful for evaluating the feasibility and effectiveness of using OPD devices on ATVs.*
>
> *Results from 52 rollover tests were analyzed, including 16 rollovers with no OPD, 18 rollovers with AM #1 and 18 rollovers with AM #2. In all the dynamic and sled rollover tests conducted, both AM #1 and AM #2 retained their structural integrity, and their general position and orientation on the ATVs tested was not compromised during any of the tests.*
>
> *Tables and graphs of ATV maximum roll rates, maximum roll angles and final roll angles during each rollover have been presented. Plots from selected dynamic and sled rollover tests were used to provide insight into the indeterminate nature of the maximum roll rates, maximum roll angles and final roll angles developed during some of the rollover tests with no OPD, with AM #1 and with AM #2. Variations in roll rate and roll angle outcomes were attributed to how the side of vehicle and/or the OPD structure engage the test surface during the rollover sequence.*
>
> *For the lateral rollover tests used in this and previous study without OPDs, adding OPDs to the ATVs did not measurably influence how the ATD releases laterally from the vehicle.*

---

[15] *Rollover Tests of ATVs Outfitted with Occupant Protection Devices (OPDs) – Results from Tests on Six 2014-2015 Model Year Vehicles,* CPSC Contract 61320618D0003, SEA, Ltd. Report to CPSC, January 2020. **https://www.cpsc.gov/s3fs-public/SEA-Report-to-CPSC-ATVs-OPDs-final-redacted_0.pdf?VRu656v4QtP5rKIiw0kuSQP_hW49TVDK**

Accordingly, the ranges of head injury criteria (HIC) values measured during tests with AM #1 and with AM #2 were found to be generally in the range of HIC values measured with No OPD.

For tests conducted with both AM #1 and AM #2, in all but one of the nine minimim energy rollovers (the one being the only minimum energy rollover with greater than 180° of roll angle) there were no significant ATV to ATD interactions during the rollovers or at rest. Conversely, there were significant interactions during the rollovers in five of the eight minimum energy rollovers conducted with no OPD. AM #1 and AM #2 also reduced the relative interactions during the moderate energy rollovers, but to a lesser extent than they did during the minimum energy rollovers.

Neither AM #1 nor AM #2 reduced the relative number of interactions between the ATV and ATD at final rest during minimum and moderate energy rollovers. For the rollover tests conducted, while the OPDs provided space for the ATV to roll above the ATD during the rollover sequence, thus minimizing ATV to ATD interactions, the OPDs did not reduce the occurrence of the ATV ending up on top of the ATD's Pelvis, Abdomen, Thorax or Head.

The findings of the pilot study using aftermarket OPDs demonstrated that the aftermarket OPDs evaluated appeared effective in eliminating interactions between the ATV and ATD in all the minimum energy sled rollovers conducted and in eliminating interactions in all but one of the minimum energy dynamic rollovers conducted. The aftermarket OPDs appeared effective in reducing the interactions between the ATV and ATD in the moderate energy rollovers, but to a lesser extent than they did during the minimum energy rollovers. For this reason, only moderate energy severity rollovers were conducted in the current study.

The objective for the designs of the POC OPDs was to further reduce interactions between the ATV and ATD during moderate energy sled tests. This objective can largely be achieved by:

- Providing clearance (protective space) for the ATD when the ATV is in an upside-down orientation
- Preventing the ATV from rolling to 180° or far enough past 180° to end with a final roll angle of 270° or more
- Providing clearance between the driver and ATV/OPD in the event of an overturn of 270° of roll or more

The same six vehicles used in the rollover study involving aftermarket OPDs were used in this study, namely, Vehicles A, C, E, F, G and J. All the vehicles have straddle seating, and their intended use is for a single occupant, the driver. All the vehicles have clear warning labels stating, "Never Carry a Passenger" or "Never Carry Passengers." All the vehicles have handlebar (tiller) steering, thumb activated throttles, and hand and foot activated brakes.

Table 1 contains a list of assorted vehicle information for the six vehicles used in this study. The measured curb weights and maximum speeds are listed. Also listed in Table 1 is information on the transmission types (Automatic or Manual) and whether the vehicle has a Solid Rear Axle or Independent Rear Suspension. All the vehicles with solid rear axles are two-wheel drive (2WD) only vehicles. All the vehicles with independent rear suspensions are equipped with selectable four-wheel drive (4WD) or all-wheel drive (AWD).

The sled rollover tests were performed on SEA's laboratory sled, configured for ATV rollover testing, on numerous dates between May 12, 2020 and December 1, 2020. As mentioned, the severity of the rollover tests conducted on the sled are defined as Moderate Energy Rollovers. The intent of the moderate energy rollovers was to produce rollover events for ATVs without OPDs resulting in at least 180 degrees of roll angle. The moderate energy rollovers are the same severity as those used in previous moderate energy rollover tests conducted on the sled. Various sled configuration parameters and configurations were tuned to generate moderate energy sled rollover events that were representative of the moderate energy dynamic rollover events (see previous report[16] and Appendix B for details).

This report has four main sections: Overview, Design of Proof-of-Concept Occupant Protection Devices, Sled Testing and Discussion of Sled Rollover Results, and Comparison of Rollover Events of ATVs without an OPD and Outfitted with Aftermarket and POC OPDs. This report also has five appendices. Appendices A contains results from the sled rollover tests, Appendix B contains a description of the ATV rollover sled, Appendix C contains photographs of the on-vehicle equipment used during the sled tests, Appendix D contains descriptions of the ATD and ATD secure and release, and Appendix E contains a description of the video equipment.

Table 1: Test Vehicle Information

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

[16] Ibid

2. DESIGN OF PROOF-OF-CONCEPT OCCUPANT PROTECTION DEVICES

This section describes the designs of the proof-of-concept (POC) occupant protection devices (OPDs). The overall objective was to create POC designs of OPDs that mitigate injury to the driver of an ATV when a rollover or rearward pitch-over event occurs. The main considerations for the designs were:

- Protect the driver in lateral rollover and rear pitchover overturns
- Provide clearance (protective space) for the ATD when the ATV is in an upside-down orientation
- Provide clearance between the driver and ATV/OPD after an overturn event with a roll angle of 270° or more
- Minimize potential for OPD impact with the driver in an overturn event
- Not restrict access to the ATV
- Not restrict egress from the ATV beyond restrictions present when using currently available rear mounted aftermarket OPDs such as AM #1 and AM #2
- Not interfere with driver-active operation and control of the ATV
- Not restrict driver visibility from front/side
- Be short enough and narrow enough to mitigate potential for impacts with overhead branches and objects near the side of the ATV

Another consideration for an OPD is that its additional weight does not increase the center-of-gravity (CG) height of the vehicle too significantly, thus reducing the overturn stability of the vehicle. While some effort was made to make the POC OPDs light and with low CG locations, this was not a primary design consideration. Rather, the POC OPDs were structurally overdesigned so they could withstand multiple rollover events.

2.1 Preliminary Ideas for POC OPD Designs

Three preliminary POC ideas were considered prior to designing the actual POC OPDs that were eventually fabricated and tested. Table 4 shows the physical configurations of the rudimentary features attached to a modified aftermarket OPD and lists the intended purpose of the attached features. The objective of conducting tests using these rudimentary features was simply to determine the feasibility of the preliminary design ideas.

Table 4: Preliminary-Idea POC OPDs	
Extended Span OPD Provide a wider and higher spanning OPD structure to lessen maximum (and final) roll angles, and to provide a further "throw" of the vehicle if it does roll beyond 180°, thus preventing the vehicle from landing on the operator	
Energy Absorbing OPD Provide some type of spring and/or damper element to absorb energy and lessen peak roll rates and lessen maximum (and final) roll angles	
Low Friction Pivot Point OPD Reduce friction at the top portion of the OPD, and possibly provide a sliding surface so the top of the OPD does not act as a fixed pivot point, thus reducing roll motion and potentially providing further "throw" of the vehicle	

Preliminary POC OPDs were made, by modifying an aftermarket OPD (AM #2), to assess the feasibility of these three ideas. Then each of the three preliminary-idea OPDs were mounted on an ATV and tested during moderate energy sled rollovers.

- The preliminary extended span OPD performed well and prevented the ATV from rolling over and prevented the vehicle from landing on the ATD. During the right-side leading rollover event, the right side (shorter) OPD span dug into the dirt and the vehicle continued to until the right side (longer) OPD span hit the ground and prevented the vehicle from rolling to 180 degrees. The vehicle rolled back to a final roll angle near 90 degrees. The concept behind this preliminary idea OPD – to design an OPD with an extended (vertical and lateral) span – was carried forward to the formal POC design phase. With knowledge that the large dimensions of this device, particularly the extended left side, were very effective in stopping roll, the dimensions for the formal POC OPDs were reduced to make a more practical design.

- The preliminary energy absorbing OPD did not prevent the ATV from rolling over, but it did work to reduce peak roll rates and maximum roll angles compared to the aftermarket OPDs previously tested. The pyramid shaped foam was not intended to be a component of final POC design, rather it was used as a simple way to attach an energy absorbing feature to an existing aftermarket OPD. With knowledge that an OPD with some energy absorbing feature could reduce roll rates during rollover events, this concept was carried forward to the formal POC design stage.

- The preliminary low friction pivot point OPD – mounting a low friction Teflon surface to the outside of the top of an aftermarket OPD – did not prevent rollover, and it did not significantly reduce peak roll rates observed during the sled rollover event using the same aftermarket OPD without any top cover. The Teflon covered top surface engaged the soil in a similar fashion as the uncovered top surface in the comparable moderate energy rollover tests conducted. For this reason, the concept of developing an OPD with a low friction pivot point was not carried forward to the formal POC design stage.

2.2 Vehicle and POC OPD Combinations Tested

The statement of work for this contract specified that four design concepts be produced, and laboratory simulated rollover testing be conducted to evaluate occupant protection performance. Table 5 lists the initial test plan for which each of the four POC design concepts would be used on which three vehicles. The elevation of the preliminary-idea POC OPDs guided the final designs to focus on two main safety improvement concepts: designing a POC OPD with an extended span and designing a POC OPD with energy absorbing features. A test plan was developed to test both concepts in two phases. The first phase was to design and test a basic extended span POC OPD and a basic energy absorbing POC OPD, and these POC designs are referred to as POC #1 and POC #2 respectively. The plan for the second round of testing was to make improvements to both basic designs based on knowledge learned from the first round of testing. The second round extended span POC OPD is referred to as POC #3 and second round energy absorbing POC OPD is referred to as POC #4.

Table 5: Initial Test Plan

Vehicle		A	C	E	F	G	J
First Round of Tests	POC #1 Extended Span	X				X	X
	POC #2 Energy Absorption	X		X	X		
Second Round of Tests	POC #3		X		X	X	
	POC #4		X	X			X

The first-round testing of POC #1 demonstrated that an extended span POC OPD can be designed to prevent ATV rollovers and improve occupant safety in the moderate energy sled tests conducted. The first-round testing of POC #2 demonstrated that basic energy absorption did not prevent a rollover in the moderate energy sled tests conducted for two of the three vehicles tested, but POC #2 did reduce roll rates during the roll sequence and did demonstrate some potential for preventing rollovers and improving safety.

The second-round testing of POC #3 demonstrated that an improved extended span POC OPD (one with deployable telescoping extensions) could be designed to prevent ATV rollovers and improve occupant safety in the moderate energy sled tests conducted. However, the second-round testing of the first vehicle (Vehicle C) using POC #4, a version intended to improve the function of the basic energy absorbing OPD, did not prevent rollover in the moderate energy sled test. Therefore, a decision was made to modify components of POC #4 so it could be used as an additional concept extended span POC OPD (one with deployable scissors extensions), and this version is referred to as POC #5. POC #5 was tested on two vehicles to complete the series of 12 test combinations, as indicated on Table 6. Descriptions of all the POC designs are contained in the following sections.

Table 6: Final Test Series

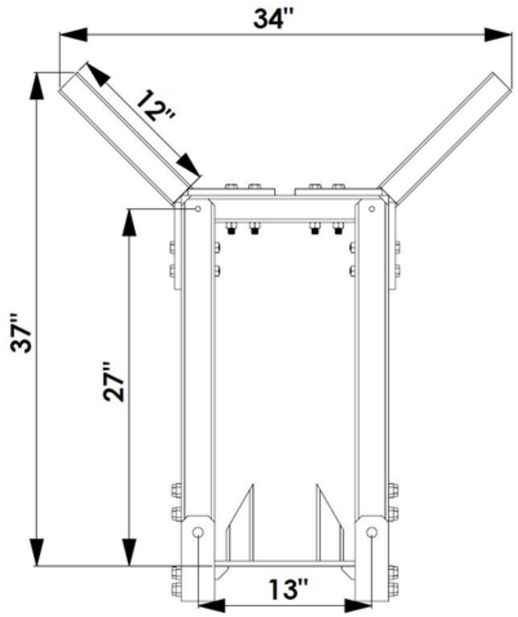
Vehicle		A	C	E	F	G	J
First Round of Tests	POC #1	X				X	X
	POC #2	X		X	X		
Second Round of Tests	POC #3		X		X	X	
	POC #4		X				
	POC #5			X			X

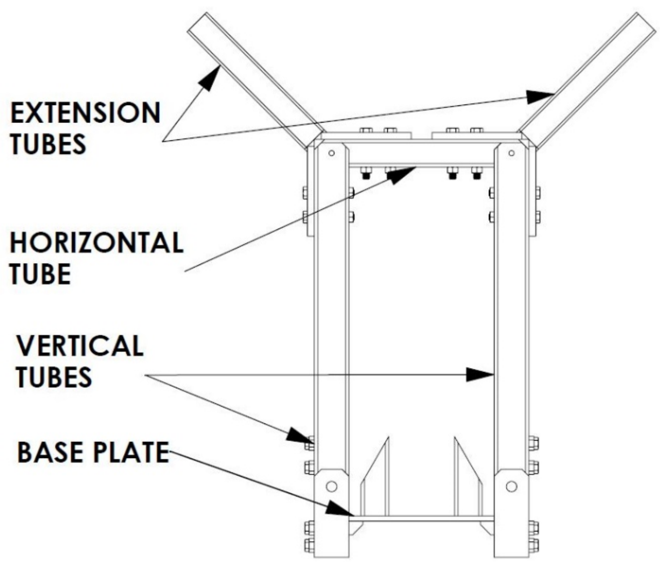
POC #1, POC #3, and POC #5 are Extended Span OPD Concepts
POC #2 and POC #4 are Energy Absorbing OPD Concepts

2.3 Description of POC #1 – Extended Span OPD with Fixed Geometry

A drawing and photograph of POC #1 are shown in Table 7. OPD #1 consists of a frame with two vertical side tubes and a horizontal top tube, and with 12" long extension tubes sticking out from the top corners of the frame at 45° angles. The frame and extension tubes of POC #1 are 2"x2" square steel tubes. The tube wall thickness is 1/4". The same side and horizontal frame members are also used for POC #2. There are pivots built into the connections between these members and the bottom base support; and these pivots allow frame rotation for POC #2. However, the extensions used for POC #1 are bolted firmly onto the frame, and this prevents frame rotation and keeps the frame in its general rectangular shape.

Table 7: POC #1 – Extended Span OPD with Fixed Geometry





The overall height and width of POC #1 are shown on Table 7. POC #1 is too tall and wide to mitigate potential for impacts with overhead branches. However, such a design was intended to reinforce and confirm the concept that extended span OPDs could be developed to better mitigate rollovers in higher energy events compared to the aftermarket OPDs previously evaluated. The overall dimensions of POC #1 with the 12" extensions was expected to be very effective in preventing rollovers during the moderate energy sled tests. Using the fixed geometry of POC #1 was also intended to provide a baseline geometry for designing deployable (using telescoping, swinging or scissors extensions) extended span OPDs in phase two of this study.

POC #1 weighs 93.5 lb. The frame of POC #1 was not designed to have optimum minimal weight, rather it was designed to be strong enough to withstand multiple moderate energy rollover events on the sled to allow for repeated testing.

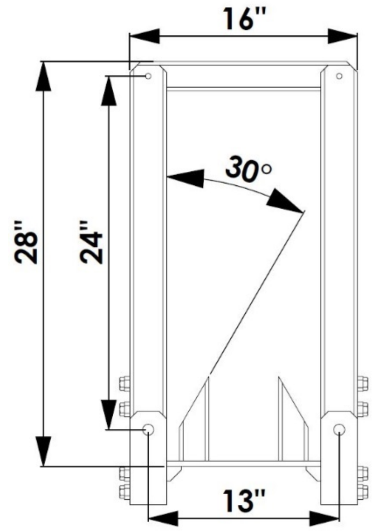
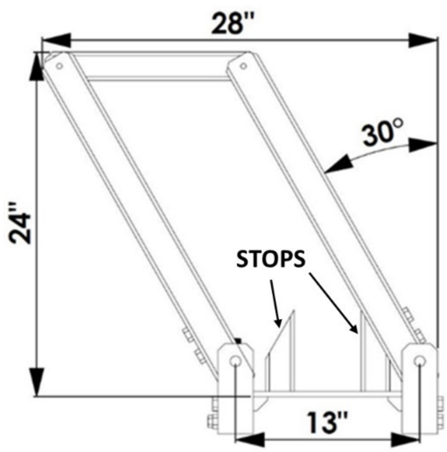
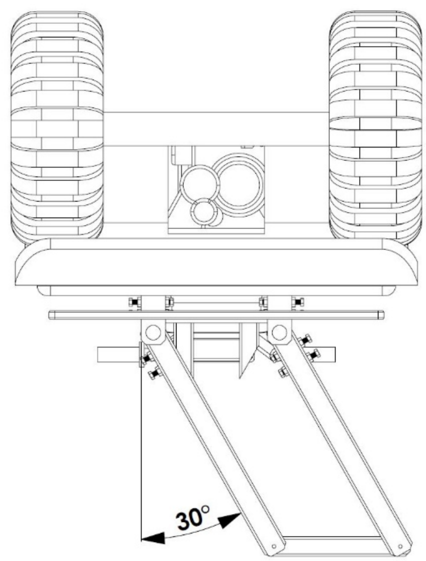
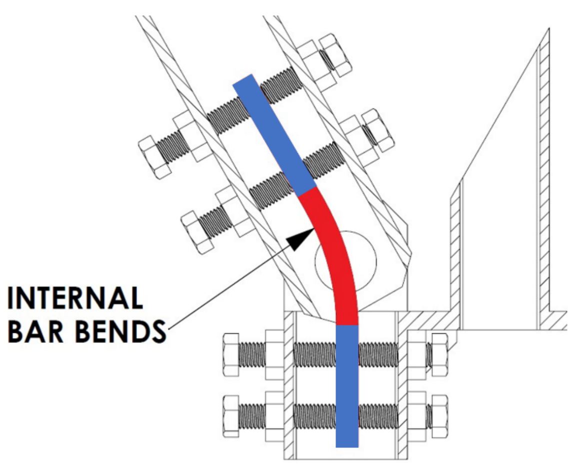
Originally, the base of POC #1 was attached to the rear rack of the ATV, and steel tubes inserted through the base and attached to the ATV hitch were used to support the OPD. This attachment configuration, visible in the photograph in Table 7, is like the configuration used for one of the aftermarket OPDs tested in the previous study. However, after some welds in the steel tubes broke after several tests, this attachment configuration was abandoned. For all subsequent tests (and for all other POC designs), the POC OPDs were attached directly to the bases, with the bases attached directly to the tops of the rear racks of the ATVs.

2.4 Description of POC #2 – Energy Absorbing OPD

Table 8 contains drawings and a photograph of POC #2. As mentioned, the same side and horizontal frame members used for POC #1 were used for POC #2. With the POC #1 extension tubes removed, the top pivots of POC #2 are free to rotate. The energy absorbing components of POC #2 are the internal bendable bars near the bottom pivots shown in Table 8. A preliminary estimate was that the bendable bars should start to bend when the side (lateral) force at the top of POC #2 is half the weight of the ATV. In theory, the force to bend the bars is proportional to their width times thickness squared. The material for the bars is hot rolled steel, a material which can deform through a large deflection at nearly constant stress. Bars of various thickness from 1/4" to 5/8" were fabricated. Several different bar sizes were used with each ATV tested with POC #2, to determine the bar size that would provide the best energy absorption and reduction in roll motion for the specific ATV being tested. When high enough lateral force is applied to the top portion of the frame, the internal bars will bend (plastically deform) and the 4-bar linkage frame will rotate into a parallelogram shape.

The steel stops of POC #2 prevent the bars from bending more than 30° and prevent the frame from rotating more than 30°. The middle row right side schematic in Table 8 shows an ATV at 180° roll angle equipped with a POC #2 frame rotated to 30°. Frame rotation also provides rollover resistance by moving the tip-over point of the OPD outward, to the right in the image in Table 8 of an ATV rolling in the clockwise direction. POC #2 frame rotation effectively makes the OPD wider and reduces the chance of the vehicle rolling past the 180° roll position.

POC #2 weighs 71.5 lb, but again the frame was not designed to have optimum minimal weight, rather it was designed to be strong enough to withstand multiple moderate energy rollover events on the sled to allow for repeated testing.

<table>
<tr><th colspan="2">Table 8: POC #2 – Energy Absorbing OPD</th></tr>
<tr><td>
</td><td></td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>
</td><td>A bendable bar is inside both lower hinges.

The bent zone is shown in red, with the unbent parts of the bar in blue.

Bar of various thickness provided varying amounts of energy absorbing capacity.

Bar thickness can be tuned to the size of the vehicle.</td></tr>
</table>

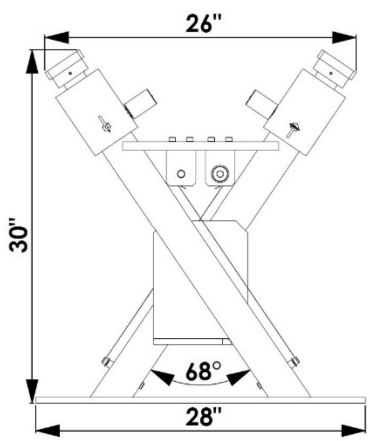
2.5 Description of POC #3 – Extended Span OPD with Telescoping Extensions

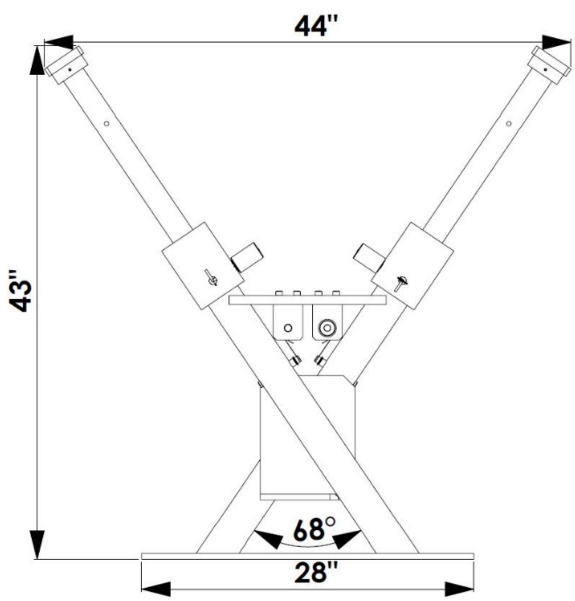
Table 9 contains drawings and photographs of POC #3, with the telescoping extensions retracted and extended. The extensions are made of 2" outer diameter aluminum tubes with 1/4" wall thickness. When retracted, these extensions fit inside 3" outer diameter aluminum tubes with 1/2" wall thickness. The retracted dimensions of POC #3 are representative of an OPD sized to mitigate potential for impacts with overhead branches while the extended dimensions are intended to mitigate rollovers. POC #3 includes a proof-of-concept feature to deploy the extensions at the onset of a potential rollover event. In this case, a 12V electrically actuated tubular solenoid (Magnet-Schultz model MSA/1942 S-07804) is used to lock the position of the extensions in their retracted state, and to initiate release of them when the vehicle rolls to an angle of 30°. Constant force (nominally 25 lb) coil springs (similar to the self-retracting tapes in tape measures, only stronger) are used to extend the extensions. The extensions are manually pushed into the outer tubes thus extending the constant force springs. When inserted into an outer tube, the solenoid shaft locks the extension to its retracted position. When extended, spring loaded locking pins lock the extensions, so they do not get recompressed due to ground forces. The extensions need to deploy and lock quickly, so they are ready when needed, when the vehicle roll angle is somewhat just beyond 90°. Using 25 lb constant force springs and low friction bushings between the extension and outer tubes, POC #3 extensions fully extend and lock in about 0.3 seconds. This timing was good, as the extension extended and locked properly during tests of all three ATVs using POC #3.

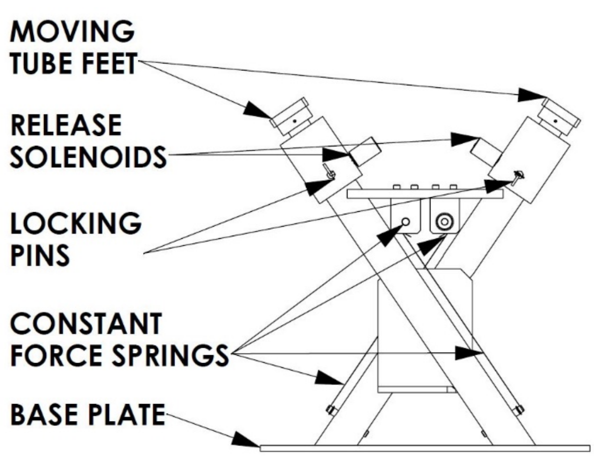
In this case, the roll angle measurement used to trigger deployment of the extensions at 30° of roll angle is the same one used to sense the timing for release of the ATD hip and neck cables (which also triggers at 30° roll angle). Thresholds of vehicle states other than roll angle, such as vehicle speed, lateral acceleration or roll rate could be used alone or combination to trigger the extensions. Of course, this requires sensors on the vehicle to make the measurements, some processor to monitor the sensors and send a deployment signal, and some device (e.g., a solenoid) to unlock the extensions. Also, energy sources other than constant force springs (e.g., an energized gas cylinder or a rapid chemical reaction inflator) could be used to deploy the extensions. While there are numerous design possibilities for a telescoping extended span OPD, POC #3 does demonstrate the proof of concept.

POC #3, which weighs 78.0 lb, was designed to be strong enough to withstand multiple moderate energy rollovers and not designed to have optimum minimal weight to allow for repeated testing.

Table 9: POC #3 – Extended Span OPD with Telescoping Extensions







2.6 Description of POC #4 – Energy Absorbing OPD with Energy Deflecting Feature

The second phase energy absorbing OPD, POC #4, is shown in the diagrams and photographs in Table 10. The two vertical side members of POC #4 are made of 3/8" thick aluminum plates welded together to form U-channels. The width of the main portion of the front and rear of each side member is 3 3/8", and the side of each side member is 4 1/8" wide. Both vertical sides are connected to the base plate with pivots. Like POC #2, both vertical sides of POC #4 can rotate inward if enough inward lateral force is applied to the side. Unlike POC #2, during a rollover event only the downward side (ground strike side) of POC #4 rotates while the other side remains fixed.

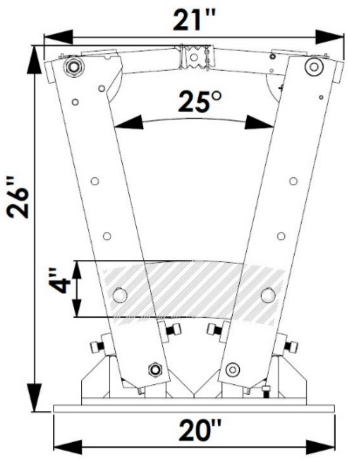
There are two energy absorbing features in the POC #4 design. It is designed to use permanent deformation of bendable bars to absorb energy, like POC #2. POC #4 is also designed to have an energy absorbing solid synthetic rubber (Neoprene) spring member, with 4"x3" cross section, installed between the vertical sides. As the vehicle rolls, the downward side gets pushed inward, and this bends the bars and/or compresses the rubber, depending on which energy absorbing features are installed at the time. The rubber spring was also intended to deflect stored energy (energy stored from being compressed) back to the downward side, to help retard the roll motion.

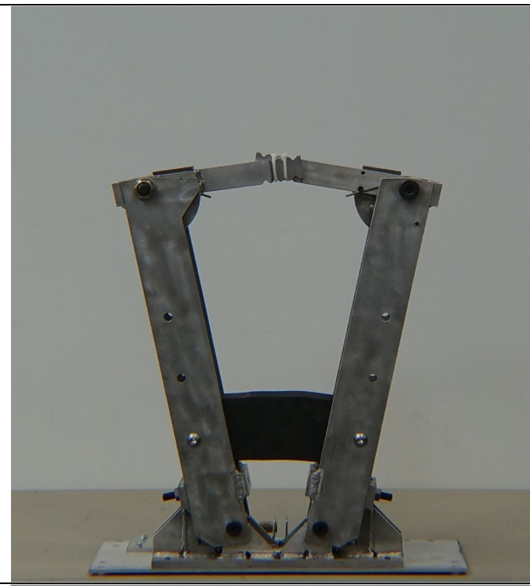
POC #4 has passive spring activated swinging extensions mounted at the top of both sides. They are passive in the sense that there is no external source of energy. The swinging extensions are held in place using cable ties. The swinging extensions are 10" long and made of 3/4" x 1 1/2" aluminum bars. When the downward side strikes the ground causing the side to rotate inward, the cable ties break, and the extensions are free to swing open, at which point spring loaded locking pins lock them in a position near fully open. The extensions help retard the roll motion by increasing the effective span of the OPD. The overall dimensions of POC #4, with the extensions folded in and with them extended, are shown in Table 10. The springs used to open the swinging extensions are not strong enough to cause extension of the downward side to fully open when the top portion of the side is in contact with the ground. However, the upward side swinging arms fully extends and locks before it encounters the ground.

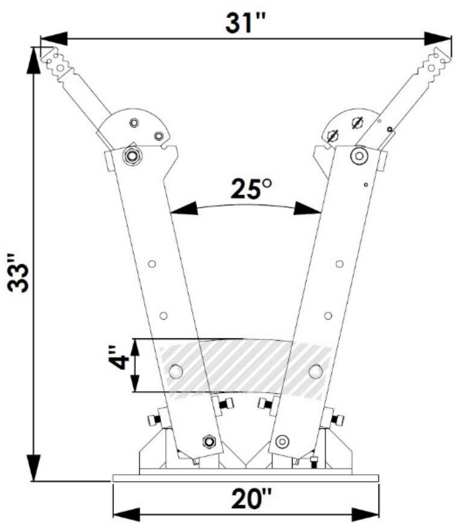
Bars of various thickness from 3/8" to 3/4" were fabricated for use with POC #4, and three different sizes of rubber members were designed and fabricated. The smallest rubber member is mounted between the sides in the lowest available position, as shown in Table 10. The two larger members were designed to fit between the sides at the two higher hole locations in the sides, above the lowest position. Bench tests indicated that when approximately 1,200 lb of force were applied laterally to the top of POC #4 with only the smallest rubber spring (no bendable bars), the rubber spring would compress to one half of its original length. Ultimately only the smallest rubber member was used for the tests of POC #4.

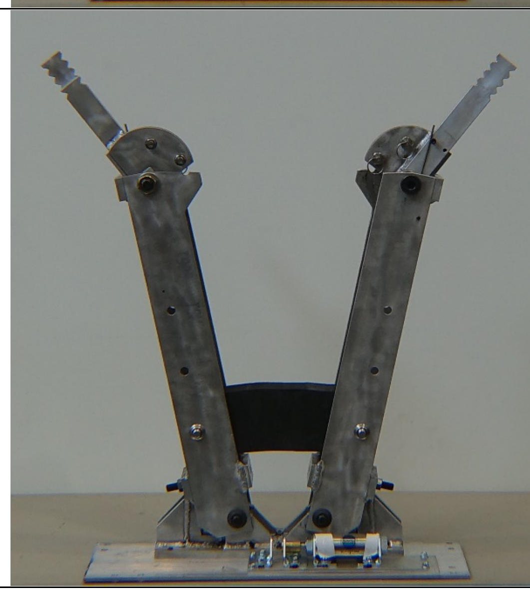
The metal parts of POC #4 weigh 37.0 lb and the smallest rubber spring weighs 7.2 lb.

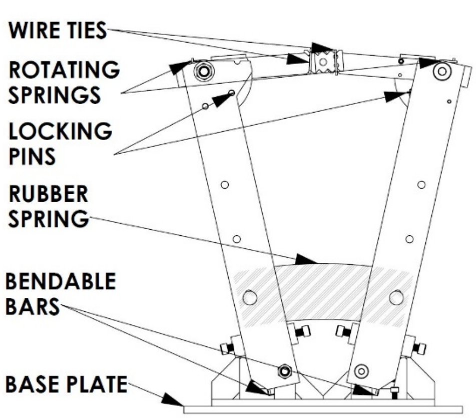
Table 10: POC #4 – Energy Absorbing OPD with Energy Deflecting Feature

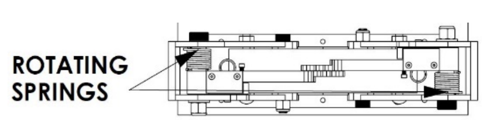












Top View

2.7 Description of POC #5 – Extended Span OPD with Scissors Extensions

As mentioned, the second-round testing of the first vehicle (Vehicle C) using POC #4 did not prevent rollover in the moderate energy sled test. Therefore, the decision was made to abandon making further modifications to an energy absorbing OPD and to instead modify components of POC #4 so it could be used as an additional concept of an extended span OPD. POC #5 is the modified version with passively deployed scissors extensions. Unlike POC #3, which uses a constant spring force energy source to deploy the telescoping extensions and uses a roll angle sensor in combination with an electronic solenoid to trigger deployment, deployment of the scissor mechanism of POC #5 is passive and purely mechanical. As with POC #4, spring loaded locking pins lock the extensions in their extended position.

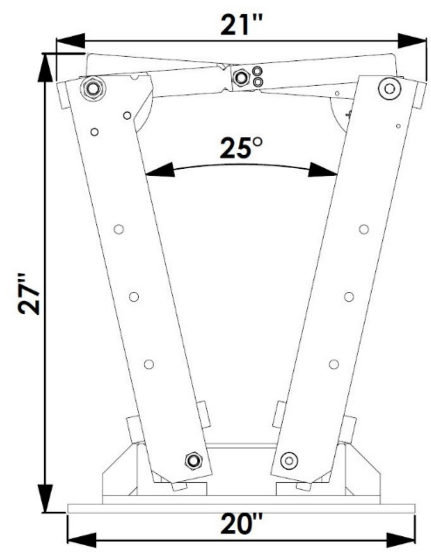
Table 11 contains drawings and photographs of POC #5, with the scissors extensions in their down (closed) and locked extended (open) positions. The side members with their pivots at the base are the same components used for POC #4. Also, the same swinging arms used for POC #4 are used, but these were extended in length to 17" and they were joined together using a mechanical pivot near their midspan (as shown in Table 10). The springs used to swing open the extensions for POC #4 were not needed for POC #5 as gravity keeps the side members of POC #5 in their open position, and this keeps the scissors extension arms in their lowest (closed) position.

The pivots at the tops and bottoms of the side members and the pivot between the extension arms are shoulder bolts through holes, which have low friction. During the moderate energy sled rollover events, the centrifugal force exerted on the scissors mechanism because of the roll motion causes the scissors to begin to open by about 45° of roll motion. In some tests conducted using POC #5, the scissors mechanism opened fully, and the locking pin locked the mechanism open, prior to the time the downward side contacted the ground. If the mechanism does not lock in the open position, it can close as the vehicle rolls toward 180° of roll angle and the benefit of the extended span will be lost. To assist the scissors mechanism to open fully and lock, a round nylon puck was attached to the top of downward side. The puck, shown in the photographs of POC #5 but not in the drawings, engages the ground sooner than the side would without the puck, and this ensures that the scissor mechanism will lock in the open position.

POC #5 worked well on the first vehicle tested, as the vehicle did not roll beyond 180° in the moderate energy sled test. However, the second vehicle tested using POC #5 did rollover to 270° because the leading narrow extension arm penetrated completely into the ground and this reduced the effectiveness of the extended span. To lessen ground penetration of the arms, 4" long feet made of 1 5/8" x 1 5/8" steel U-channel were added to the ends of the arms. These rounded-edge U-channel feet worked to lessen ground penetration for tests on the second vehicle, and POC #5 (with feet) again prevented the vehicle from rolling beyond 180°. Figure 12 contains diagrams and photographs of POC #5 with the feet added.

The overall height and width dimensions with the scissors closed and with the scissors locked open are given on Table 11 for POC #5 without feet and Table 12 for POC #5 with feet. The overall weight of POC #5 is close to the weight of POC #4 without the rubber spring, 37.0 lb. The overall size and weight of POC #5, as well as the arrangement and geometry of the scissors mechanism, could be optimized to further improve the benefits of this passive extended span OPD. Nonetheless, POC #5 did demonstrate the feasibility of this concept.

Table 11: POC #5 – Extended Span OPD with Scissors Extensions



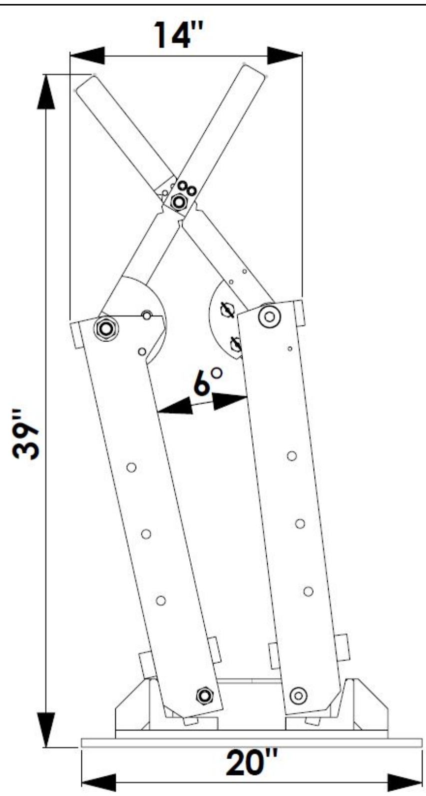
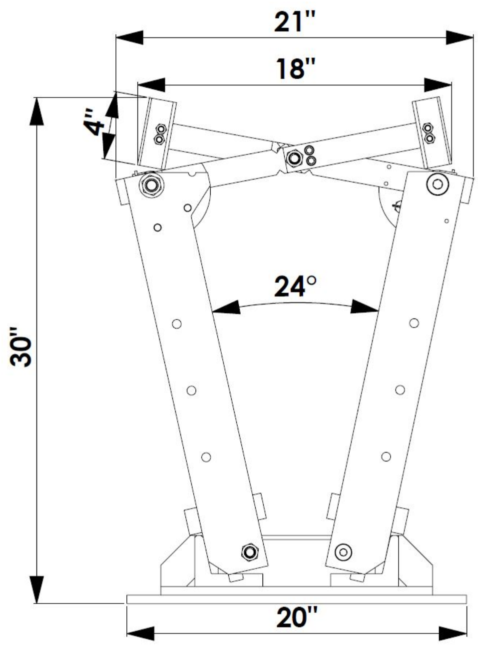
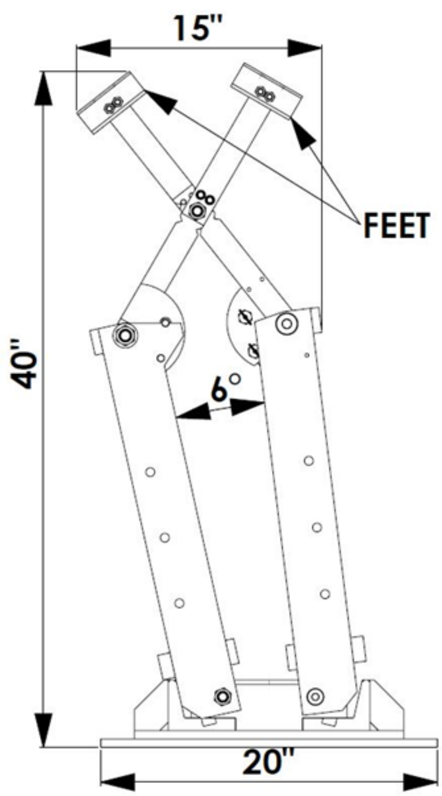
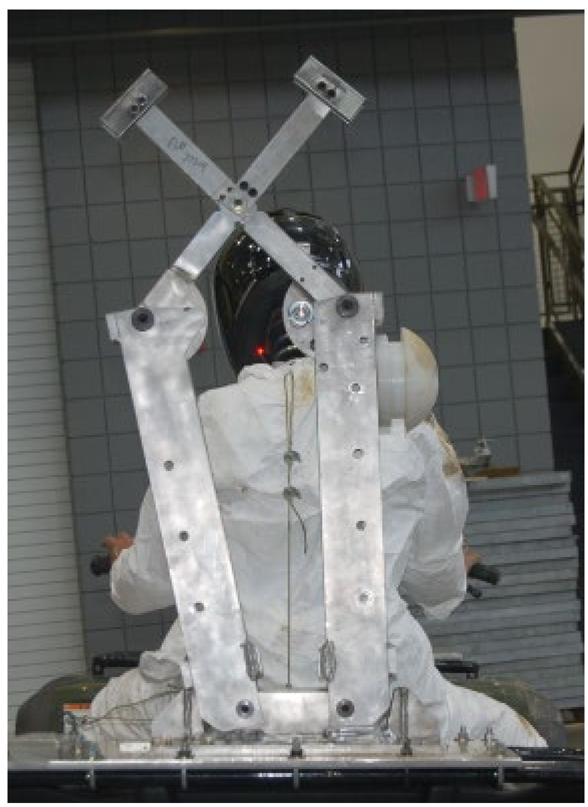


Table 12: POC #5 – Extended Span OPD with Scissors Extensions with Feet







3. SLED TESTING AND RESULTS FOR VEHICLES OUTFITTED WITH POC OPDs

This section describes the sled rollover tests conducted on numerous dates between May 12, 2020 and December 1, 2020. All the vehicles were tested at SEA in Columbus, Ohio, on a laboratory sled that was configured for ATV rollover testing. Tests categorized as Moderate Energy Rollovers were performed using Vehicles A, C, E, F, G, and J. Various sled configuration parameters were tuned to generate sled rollover events that were representative of the dynamic rollover events for a moderate energy rollover. The sled configuration parameters used for these Moderate Energy Rollover tests were the same as those used for previous sled tests with vehicles tested without an OPD and tested with aftermarket OPDs. Appendix B contains a description of the ATV rollover simulator, and it provides discussion on how features and components on the sled facility were adjusted to generate sled rollovers to represent moderate energy rollovers. The moderate energy sled tests are representative of the moderate energy dynamic rollover tests conducted on a groomed dirt surface using autonomously driven ATVs with an ATD. The dynamic rollover maneuvers consisted of applying rapid steering inputs when the test vehicles were traveling between 22 and 25 mph. For vehicles without an OPD, these dynamic moderate energy tests resulted in rollovers of 180° of roll angle or more, and roll rates of 200 deg/s or more. [17]

3.1 Vehicle Loading Condition

The loading condition used for all the sled rollover testing included an instrumented Hybrid III 50th percentile male anthropometric test device (ATD) with a standing pelvis, an ATD secure and release system, vehicle data sensors and a data collection system. Page 1 of Appendix C contains side and front view photographs of an ATV prepared for sled testing and 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 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.

For the sled tests, the ATVs were equipped with a GPS/IMU (OxTS RT4002), a National Instruments (NI) CompactRIO (the on-vehicle computer with the motor and valve controllers and data acquisition software), and a 12V lithium battery. The battery can be seen on Page 1 of Appendix C, under the right side footwell of the vehicle. Page 2 of Appendix C shows the NI CompactRIO, the GPS/IMU, and the supplemental roll rate sensor used for the sled tests.

The same ATD used in previous ATV sled studies, with internal (head, neck, and chest) sensors and onboard wireless data acquisition system, was used in this study. The previously developed ATD "secure and release" system (consisting of pneumatic actuators, cables extending to the ATD's hip, neck, and right hand; and a cable tie securing the ATD's left hand to the handlebars) was used for this testing. Page 3 of Appendix C shows the pneumatic valves and pump used to control and pressurize the ATD secure and release system. The pneumatic actuator and cables used for the ATD body portion of the secure and release system (the neck and hip supports) is shown on Page 4 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

[17] *ATV Rollover Tests and Verification of a Physical Rollover Simulator – Results from Tests on Six 2014-2015 Model Year Vehicles*, HHS Contract HHSP233201400030I, SEA, Ltd. Report to CPSC, October 2019. **https://www.cpsc.gov/s3fs-public/SEA%20Report%20to%20CPSC%20-%20ATV%20Rollover%20Simulator%20%286b%20cleared%29_Redacted.pdf?mlCsq67xfdq8x94QejoFtK37zwXdLLJV**

releasing the hip and neck cable holds to the vehicle. Page 5 of Appendix C shows the cable tie arrangement used to secure the ATD's left hand to the handlebar grips. The handhold (pull away) strength of the cable ties used withstands close to 80 pounds of pull away force before they break. Page 5 also shows the pneumatic actuator and cable used as the handhold for the ATD's right hand. Details regarding the ATD and the ATD secure and release system are contained in Appendix D. The ATD secure and release system is designed to duplicate the capabilities of an actual rider, and it represents an event where the driver is lifted off of the seat between 30 and 45 degrees of roll angle and then remains holding onto the handlebar grips with about 80 pounds of grip force.

Table 13 lists the nominal weights of the components added to the curb weights of the ATVs in their sled rollover loading conditions when outfitted with the POC OPDs.

Table 13: Sled Rollover Vehicle Loading

Component	Nominal Weight (lb)
ATD as Tested	174.0
RT Unit and Roll Rate Sensor with Mounts	10.1
Compact RIO	5.9
Pneumatic Pump and Valves	5.1
Pneumatic Cylinder and Mounts	8.0
Cables	5.0
12V Lithium Battery	6.6
Nominal Weight Added for Sled Tests Without OPD	**214.7**
OPD Weight and Total Weight for Tests with POC #1	93.5 / **308.2**
OPD Weight and Total Weight for Tests with POC #2	71.5 / **286.2**
OPD Weight and Total Weight for Tests with POC #3	78.0 / **292.7**
OPD Weight and Total Weight for Tests with POC #4	44.2 / **258.9**
OPD Weight and Total Weight for Tests with POC #5	37.0 / **251.7**

3.2 On-Vehicle Test Instrumentation

The instrumentation used during the sled rollover testing is listed in Table 14. 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. The RT4002 has a rated range for rate measurements of ±300 deg/s. During some of the previous moderate energy sled rollover events, the RT4002 roll rate signal became "clipped" when vehicle roll rates exceed 300 deg/s. When this happens, the RT4002 internal calculations used to compute roll angle become corrupted because of the clipped roll rate. To get full range roll rate measurements and accurate roll angle measurements during all the rollover tests, a supplemental roll rate sensor was added to the vehicles for the dynamic (and sled) rollover tests. This rate sensor (Silicon Sensing CRH02-400) has a rated range of ±400 deg/s, and it was 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. Furthermore, the roll, pitch and yaw (heading change) angles from the dynamic (and sled) rollover tests were computed from the supplemental roll rate sensor and the RT4002's pitch rate and yaw rate. The angle (orientation) calculations require integrating rates in the appropriate three-dimensional coordinate reference frame. The Euler angle method was used to compute the rates in the desired vehicle fixed coordinate system so they could be integrated to compute the roll, pitch, and yaw angles about the vehicle-fixed coordinate system.[18]

Table 14: 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
Silicon Sensing CRH02-400	(Supplemental) Roll Rate	± 400 deg/s	0.5%

3.3 Sled Rollover Results

Results from the sled tests are contained in Appendix A. Results for sled tests using vehicles with energy absorbing concept OPDs are presented first in Appendix A, followed by the results for tests conducted with the extended span concept OPDs. Table 15 contains details on the arrangement of the POC OPD types and vehicles used for each of the two main concepts, and provides a list of pages of results for each sled run contained in Appendix A.

For each sled run, the first 7 to 10 pages (depending on the amount of roll angle achieved during the test) of results contain images taken from five different video cameras. The pages of camera images are followed by five pages of graphs containing data from the ATD: ATD Head Accelerations, ATD Head Angular Rates, ATD Chest Accelerations, ATD Neck Forces, and ATD Neck Moments. These are followed by three pages of graphs containing data from the vehicle: Vehicle Body Fixed Accelerations, Vehicle Angular Rates and Vehicle Angles. Note that there are no vehicle global (earth fixed) acceleration graphs from the sled tests because GPS signals

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

were not available for the predominately indoor portion of sled tests, and no earth fixed (i.e., no ground plane) accelerations were available from the RT4002.

The vehicle body fixed coordinate system is an orthogonal coordinate system with its origin at the center of gravity of the vehicle. For this 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.

The ATD head, chest, and upper neck coordinate systems are orthogonal coordinate systems with their origins near the center of the head, chest, and upper neck, respectively. These are 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. The polarities of the head and chest accelerations, the head rotational rates, and the upper neck forces and moments are consistent with SAE standard sign conventions for ATD measurements.[19]

Table 15: Arrangement and Pagination of Appendix A

OPD Concept	POC OPD Type	Vehicle	Pages
Energy Absorbing	**POC #2** Energy Absorbing OPD	A	1 - 18
		E	19 - 36
		F	37 - 53
	POC #4 Energy Absorbing OPD with Energy Deflecting Feature	C	54 - 71
Extended Span	**POC #1** Extended Span OPD with Fixed Geometry	A	72 - 86
		G	87 - 103
		J	104 - 118
	POC #3 Extended Span OPD with Telescoping Extensions	C	119 - 133
		F	134 - 148
		G	149 - 163
	POC #3 Extra POC #3 with Downside Extension Undeployed	C	164 - 180
	POC #5 Extended Span OPD with Scissors Extensions	E	181 - 195
		J	196 - 210

[19] *Sign Convention for Vehicle Crash Testing*, SAE Surface Vehicle Information Report, SAE J1733, November 2018.

3.3.1 Video Image Results

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

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

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 cameras were synchronized to the sled DAQ (and therefore the vehicle DAQ) using a pressure sensitive ribbon switch that was triggered by one of the pneumatic tires on the sled. The ribbon switch was positioned on the lab floor at the precise location when the sled electromagnetic particle brake was activated to generate the onset of sled deceleration. For the sled tests, time zero for the cameras and for the vehicle data is the time when sled deceleration is initiated. The times listed on the titles of the camera images in Appendix A are the times from the start of the sled deceleration.

3.3.2 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 D.

As mentioned earlier, each section in Appendix A for a specific vehicle contains five pages of ATD results. The first page contains Head Accelerations in the head fixed X, Y, and Z directions; the second page contains Head Angular Rates about the head roll, pitch, and yaw axes; the third page contains Chest Accelerations in the chest fixed X, Y, and Z directions; the fourth page contains Upper Neck Forces in the neck fixed X, Y, and Z directions; and the fifth page contains Upper Neck Moments about the roll, pitch, and yaw axes. All the ATD data was zeroed prior to the time the vehicle started moving, so the data presented shows the changes in accelerations, rates, forces, and moments that occurred throughout the rollover event. All the ATD data shown has been filtered using a 1,000 Hz low pass, Butterworth filter.

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

3.3.3 Vehicle Results

The pages of ATD results in each vehicle section in Appendix A are followed by three pages of vehicle results. The first page contains Vehicle Body Fixed Accelerations in the vehicle body fixed X, Y, and Z directions; the second page contains Vehicle Angular Rates about the vehicle's roll, pitch, and yaw axes; and the third page contains Vehicle Angles about the vehicle's 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 moderate energy sled rollovers, with the sled yaw platform edge rotated 10° from perpendicular to the direction of sled travel, the initial heading angle is -80°. All the vehicle data from the sled tests is unfiltered.

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 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 because 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. For these moderate energy sled runs, the first peaks in the acceleration traces occur at roll angles between 100° and 120° of roll angle, when the side of the ATV or OPD first strikes the ground. These results regarding the roll angle ranges when the first peaks in vehicle accelerations occur are similar to the ranges observed during sled rollover tests conducted without an OPD and with aftermarket OPDs. Other peaks in the body fixed acceleration traces occur during rollover events that have other abrupt vehicle impacts with the ground. The body fixed accelerations at the end of the rollover events are a function of the final orientation of the vehicle at the end of the run.

In all the sled rollovers, the vehicle reached 90° 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 exhibit their first spikes when the roll angle is between 100° to 120° for the moderate energy runs. The acceleration plots show that these acceleration spikes occur within the vertical band indicating the head strike.

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.

3.4 Discussion of Test Outcomes for ATVs Outfitted with Energy Absorbing POC OPDs

Pages 1 through 71 of Appendix A contain results for the tests conducted using the energy absorbing POC OPDs, POC #2 and POC #4. Figure 1 provides maximum and final roll angle results for vehicles outfitted with POC #2, and Figure 2 for the vehicle outfitted with POC #4. These figures include results from previous tests on vehicles with no OPD and when outfitted with AM #1 and AM #2 OPDs.

When used on Vehicles A and E, the first-round design energy absorbing POC OPD, POC #2, did not prevent the ATV from rolling above the ATD and landing at a final roll angle near 270°. The results shown in Appendix A for Vehicles A and E using POC #2 are for tests conducted using 1/2" bendable bars as the energy absorbing elements. Bars of other sizes were used in POC #2 for these two vehicles, but the rollovers were more severe than those using 1/2" bendable bars. Figure 3 shows the trends in Vehicle E responses when bendable bars of different size are used in POC #2. POC #2 had very little deflection when the thickest 3/4" (1/2"+1/4") bars were used, so little energy was absorbed. Using the 1/2" bars absorbed more energy, and the graphs on Figure 3 show that the roll response is somewhat retarded using the 1/2" bars. The bottom graph on Figure 3 shows the roll rate decreased using the 1/2" bars in the range of about 130° to 220° of roll angle. However, the reduction in roll rate caused by bar deflection was not enough to prevent full rollover to 270°. The bars deflected (and the frame rotated) less than half of the available deflection designed into POC #2. Page 23 of Appendix A shows Vehicle E rolled to 180°, and the POC #2 frame is rotated less than 10°. Using thinner bars (3/8") did not reduce the roll motion. The 3/8" bars bent more (and the frame rotated more) but the roll rate increased in the range of 110° to 140° of roll angle as the thinner bars deflected more while absorbing less energy than the 1/2" bars did. Similar trends were observed for Vehicle A using POC #2, as the 1/2" bars provided the least severe roll motion but they did not prevent full rollover to 270°.

When used on Vehicle F, POC #2 with 1/2" bars did prevent the ATV from rolling to a final roll angle near 270°. Page 43 of Appendix A shows Vehicle F at its final roll angle near 180° when the 1/2" bars were used. Figure 4 also shows that with the 3/8" bars installed, the roll rate increased in the range of 110° to 140° of roll angle, as these thinner bars deflected more while not absorbing as much energy as the 1/2" bars did.

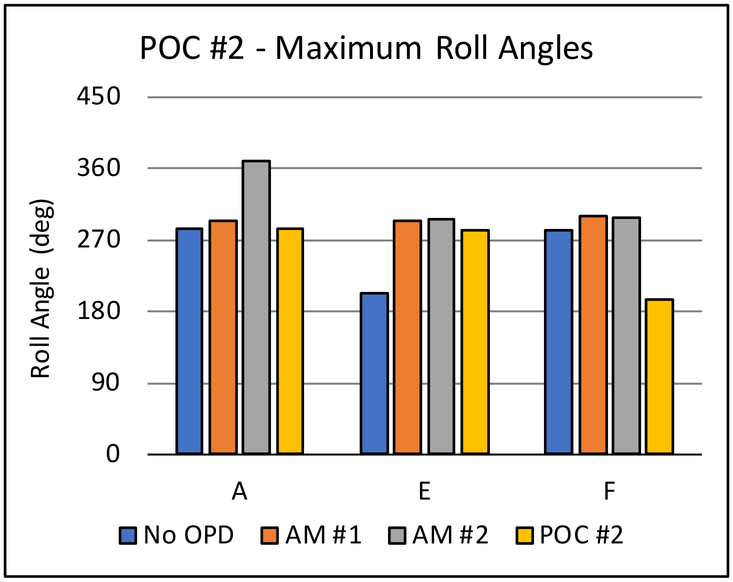
The second-round energy absorbing POC OPD, POC #4, was designed to add an energy restoring feature to POC #2, to "push back" some energy stored in the OPD to further retard roll motion. Designs using metal spring elements (coil springs or linear springs) did not fit well into the OPD deflection space available, so the rubber spring element was developed and tested in POC #4. Appendix A contains results from tests on Vehicle C with only the rubber spring installed in POC #4. POC #4 with only the rubber spring did not prevent the ATV from rolling above the ATD and landing at a final roll angle near 270°. The cable ties holding the swinging arms broke when POC #4 hit the ground and the swinging arms opened as intended, but this added span did not prevent the full rollover.

The side members of POC #4 were angled outward to increase the deflection space available for energy absorbing and energy restoring elements. The rubber spring element did not deflect as much as intended, and this reduced its energy absorbing and restoring capacity. To achieve greater deflection in the rubber spring, an approximately 12" long piece of steel angle iron was bolted, at about 45° relative to the lateral direction of the vehicle, to the downside vertical arm of POC #4. Tests with this angle iron extension did not roll past 180°, not because the rubber spring deflected more but because the angle iron extension dug onto the ground which greatly retarded the roll motion. Subsequent tests using bendable bars without the rubber spring resulted in events that were at least as severe as the test using only the rubber spring.

The fact that the deflection of POC #4 was less than expected indicated that the forces directed laterally at the top of POC #4 were less than expected. To study the direction of the acceleration force vector during a sled rollover event, an approximately 12" long thin piece of aluminum was attached to the downward vertical side of POC #4. The attachment was a simple pivot (bolt through a loose hole in the aluminum) that allowed the aluminum pointer to rotate freely in the direction of the resultant gravity and centrifugal acceleration (force) vector. Figure 5 contains a collection of images taken from the test conducted with the aluminum pointer, which can be seen inside the yellow ovals imposed on the images. The top left image on Figure 5 shows that the acceleration vector is nearly lateral to the vehicle at the early stages of the rollover event, when the vehicle is near 30° of roll angle. However, the lower right image shows that acceleration vector is directed at an angle of about 45° relative to the lateral direction of the vehicle. (Note: The black angle iron piece fixed near the top of the downward side can also be seen in the images in Figure

5.) This simple study revealed that the direction of the force acting on the vehicle was not lateral to the vehicle, and therefore forces acting in the lateral direction during this type of rollover event are indeed less than those expected when POC #4 (and POC #2) were designed. With this better knowledge of the direction of the impact forces, an OPD with better energy absorbing and restoring capacity than POC #4 (and POC #2) could be designed by modifying the geometry of the OPD structural members, pivot locations, and spring elements.

Maximum Roll Angles (deg)				
Vehicle Letter	No OPD	AM #1	AM #2	POC #2
A	284	295	369	283
E	202	295	297	282
F	282	300	297	195



Final Roll Angles (deg)				
Vehicle Letter	No OPD	AM #1	AM #2	POC #2
A	168	274	356	272
E	139	286	277	275
F	253	280	273	178

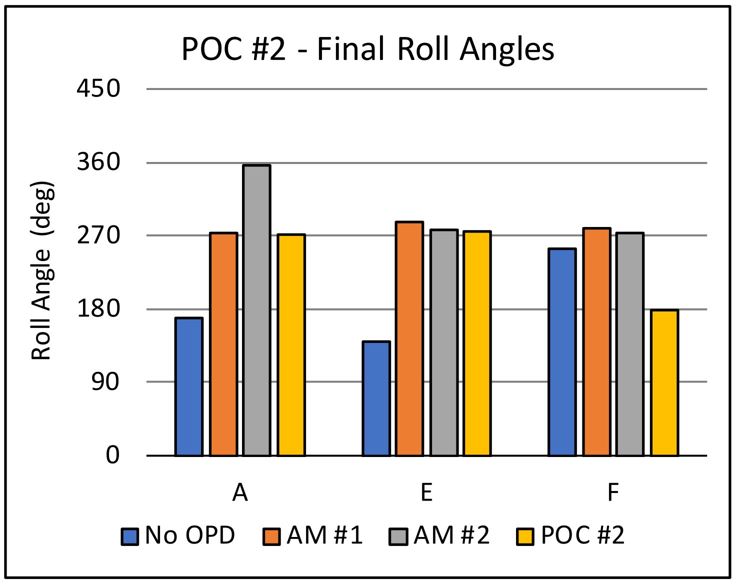
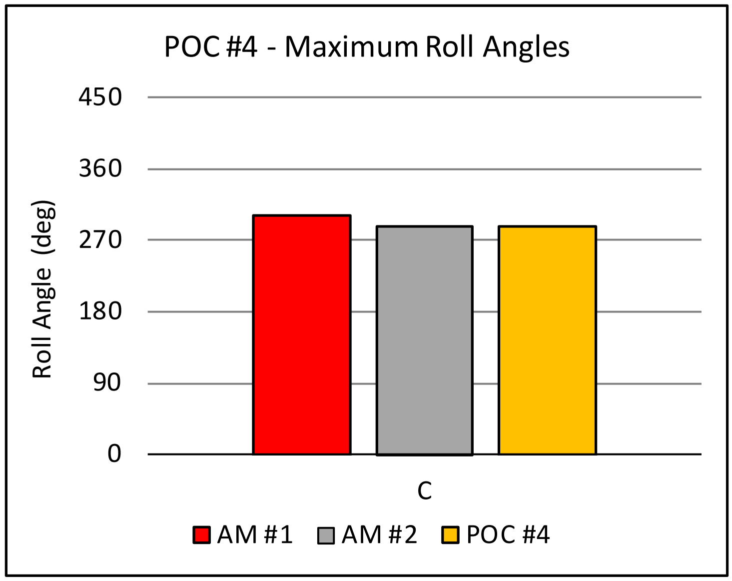


Figure 1: Maximum and Final Roll Angles for Vehicles Outfitted with POC #2

Maximum Roll Angles (deg)				
Vehicle Letter	No OPD	AM #1	AM #2	POC #4
C	NA	301	288	287



Final Roll Angles (deg)				
Vehicle Letter	No OPD	AM #1	AM #2	POC #4
C	NA	272	277	269

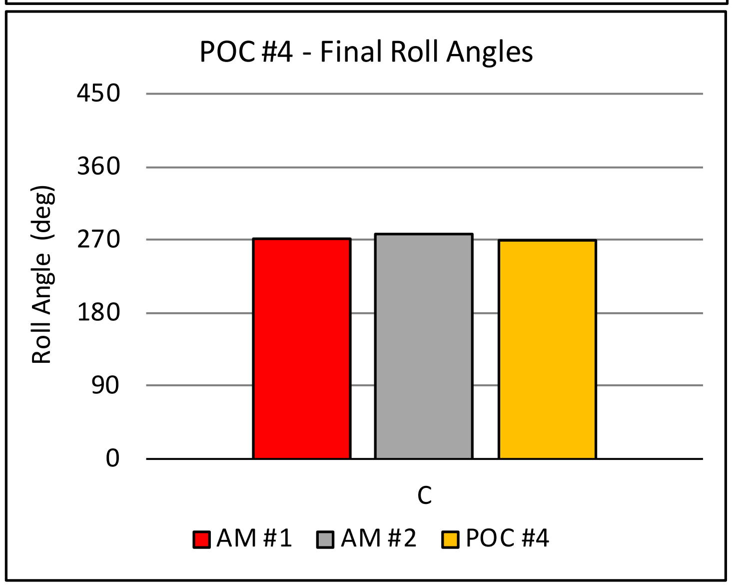


Figure 2: Maximum and Final Roll Angles for Vehicle Outfitted with POC #4

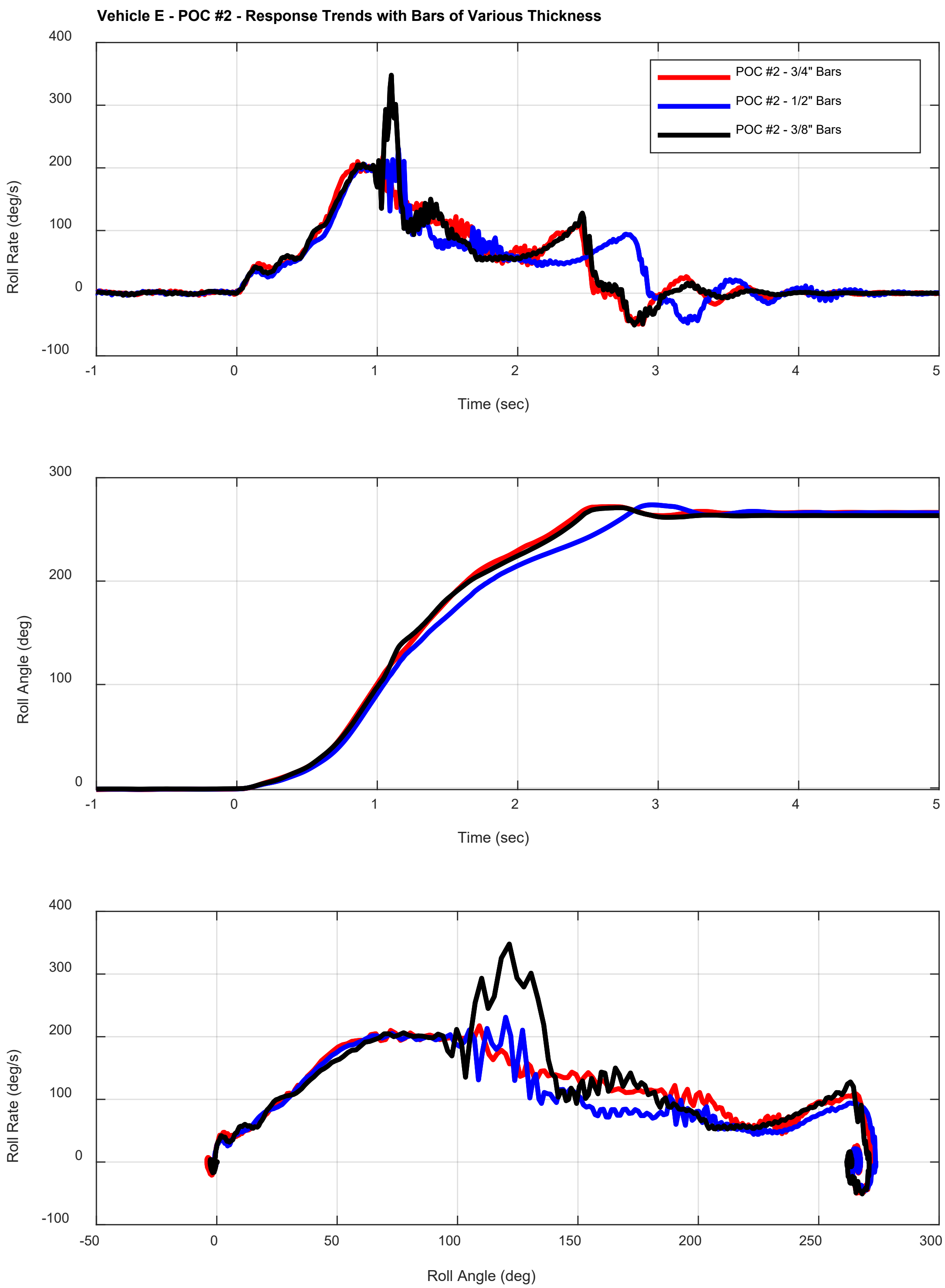


Figure 3: Vehicle E – POC #2 – Roll Motion Response Trends using Bendable Bars of Different Thickness

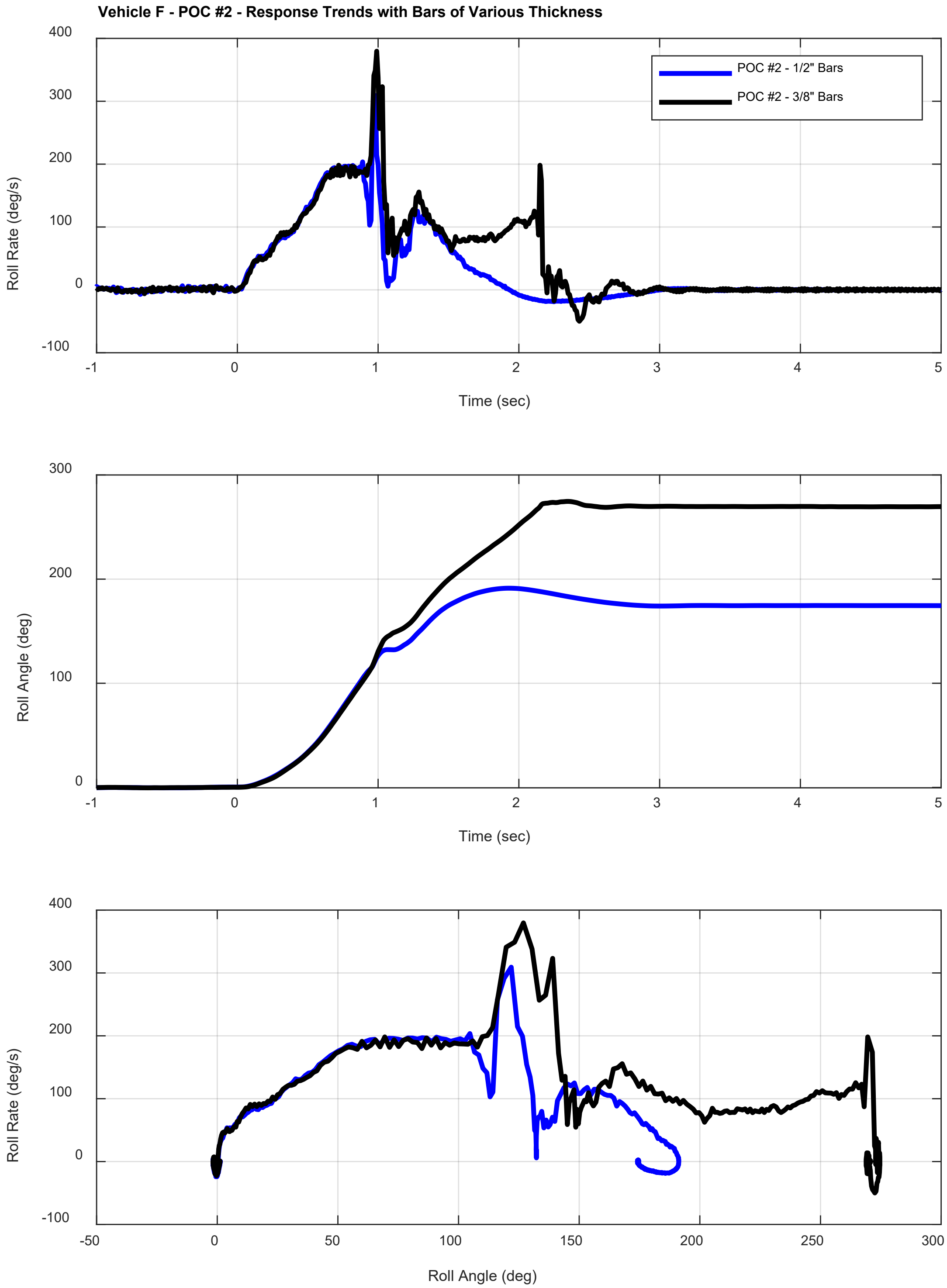


Figure 4: Vehicle F – POC #2 – Roll Motion Response Trends using Bendable Bars of Different Thickness

Figure 5: Free Swinging Aluminum Bar (Pointer) Attached to POC #4 to Demonstrate Acceleration Line of Action

3.5 Discussion of Test Outcomes for ATVs Outfitted with Extended Span POC OPDs

Pages 72 through 210 of Appendix A contain results for the tests conducted using the extended span POC OPDs, POC #1, POC #3, and POC #5. Figures 6, 7, and 8 provide maximum and final roll angle results for vehicles outfitted with POC #1, POC #3, and POC #5, respectively. These figures also include results from previous tests on vehicles with no OPD and when outfitted with AM #1 and AM #2 OPDs.

For all three ATVs outfitted with POC #1, the extended span with fixed geometry, full rollovers (rollovers that did not result in final roll angles of 270° or more) were prevented during the moderate energy sled tests. Images of Vehicles A, G, and J at the maximum roll angle positions are shown on Pages 76, 92 and 108 of Appendix A. During the tests on all three vehicles, the downside extension of POC #1 dug into the dirt landing pit, and then as the vehicles rolled to their maximum positions the other extension contacted the ground. Vehicle A rolled back onto its left side at the end of the run, while vehicles G and J remained nearly upside down with POC #1 providing clearance (protective space) for the ATD. During tests of all three vehicles, the top of POC #1 was in contact with the ground before the ATD rolled with its buttocks near or slightly touching the OPD.

If OPD #1 was used on a surface that was harder than the dirt surface of the sled landing pit, the downside extension would not penetrate the ground as much as it did during the sled tests. Nonetheless, the roll motion would still be significantly retarded by the fact that the body of the ATV would need to rise higher during the roll sequence. Also, if the ATV rolled to an angle near 180° the other extension (opposite the downside extension) would slow or stop the roll motion. We believe the extended span OPDs would be similarly effective whether or not they dig into the soil, that is, digging into the soil is not necessary for the OPD to be effective.

Using a fixed geometry for an OPD, like the one used for POC #1, is not practical because of the potential for impacts with overhead branches and branches (and other objects) near the side of the ATV. However, it demonstrates that extending the span of a rear mounted OPD can be effective in reducing ATV roll motions and minimizing potential for ATV/OPD impact with the driver in rollover events with roll angles of 180° or less. Extended span OPDs are also potentially more effective than shorter, narrower rear mounted OPDs in providing clearance between the driver and ATV/OPD after overturn events with a roll angle of 270° or more.

POC #3, the extended span OPD with telescoping extensions also prevented full rollovers during the moderate energy sled tests. With the extensions deployed, POC #3 is taller and wider than POC #1. This extra span provided further roll motion suppression, as all three vehicles tested using POC #3 (Vehicles C, F, and G) had maximin roll angles of 130° or less and final roll angles of less than 100° in the moderate energy sled tests. Images of Vehicles C, F, and G at the maximum roll angle positions are shown on Pages 123, 138, and 153 of Appendix A. During the tests on all three vehicles, contact of the downside extension of POC #3 with the ground prevented roll motion to the extent that the opposite side extension of POC #3 did not contact the ground.

During rollover events more severe than the moderate energy sled tests, POC #3 would likely provide substantial protective space for the driver when the ATV is nearly upside down and over the driver, and it would also likely provide substantial clearance between the driver and ATV/OPD after overturn events with a roll angle of 270° or more.

The design of POC #3 included an electronics-based feature (algorithm for sensing vehicle roll angle) for monitoring the onset of a rollover event and features (electronic solenoids for releasing the extensions and coil spring energy sources for extending them) for rapidly deploying the telescoping extensions in the event of an imminent rollover. These sensing and deploying features add complexity and cost to the OPD. Sensing the need to deploy a telescoping OPD could be accomplished by means other than electronically monitoring the motion state of the vehicle. A mechanical or electronic contact switch could be attached to the sides of the OPD or vehicle for sensing contact with the ground for use as a trigger signal to deploy a telescoping extension. An additional test using a modified version of POC #3 on Vehicle C was used to demonstrate this concept. The modified version of POC #3 used for this test is called POC #3 Extra.

Full rollover was prevented during the test using POC #3 Extra, the test representing an extended span OPD with a telescoping extension trigger by a (virtual) contact switch mounted on the OPD. The maximum vehicle roll angle during the test was 197.3° and the final roll angle was 100.5° (see Pages 169 and 170 of Appendix A).

The test using POC #3 Extra represents a condition where a contact switch mounted to the outside top locations of the OPD would trigger deployment of the extensions. In actual implementation, when the outside top of the downside portion of the OPD first contacts the ground, the contact switch would send a signal to deploy the upside extension (the extension opposite the downside extension). The image shown on Page 167 of Appendix A shows the approximate position of the vehicle when this first contact would occur. This image shows the upside extension already deployed for this demonstration. For POC #3 Extra, the solenoid used to unlock the downside extension was disabled (so that the downside extension would remain retracted throughout the test) and the upside extension was deployed at 30° of vehicle roll angle. In actual implementation, the deployment of the upside extension would need to be rapid enough to fully deploy it before it contacts the ground, at approximately the position shown on Page 168 of Appendix A. The time between first contact of a suitably positioned switch and the need for full upper extension deployment is greater than 0.3 seconds in the moderate energy sled test, and this time is greater than the time needed to fully deploy the POC #3 extensions (which demonstrates the feasibility of POC #3 Extra concept).

For the POC #3 Extra test, the downside extension was completely disabled for the sake of demonstrating the POC #3 Extra concept using the available features of POC #3. Since the downside extension would not begin to deploy until it was essentially in contact with the ground, the downside extension would probably not be able to extend much, if at all. However, it would likely be beneficial to also deploy the downside extension in this concept at the instance of switch contact with the ground, as this would help resist roll motions. The upside extension by itself would usually be enough to prevent full rollovers.

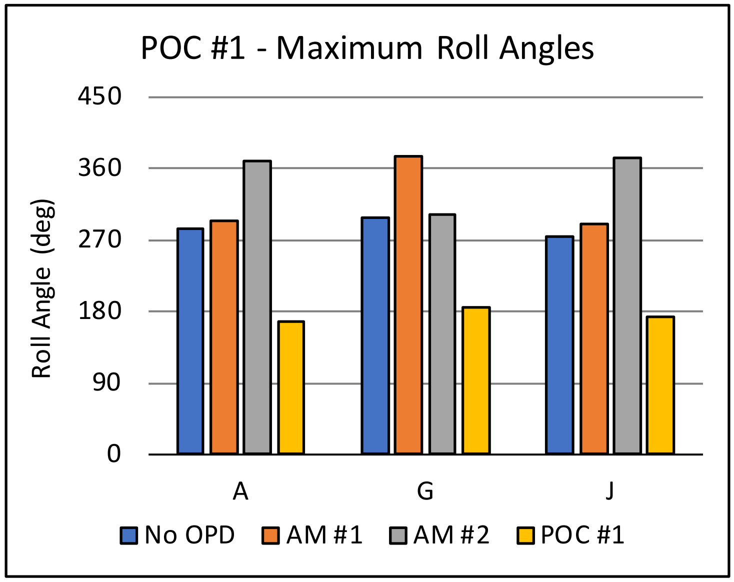
POC #5, the extended span OPD with scissors extensions, was added to the study to demonstrate the feasibility of developing an OPD with a passive (i.e., completely mechanical) extension deployment feature. POC #5 was tested on two vehicles (Vehicles E and J). For both ATVs outfitted with POC #5, full rollovers were prevented during the moderate energy sled tests. Images of Vehicles E and J at the maximum roll angle positions are shown on Pages 185 and 200 of Appendix A. As mentioned in Section 2.7, during the first test with POC #5 on Vehicle J, the downside extension arm penetrated completely into the ground and this reduced the effectiveness of the extended span. The vehicle rolled to a final roll angle near 270°. To lessen ground penetration of the arms, 4" long steel feet were added to the ends of the arms. These feet worked to lessen ground penetration for the test connected on Vehicle J, and results from this test are included in this report.

During the moderate energy sled rollover events, the centrifugal force exerted on the scissors mechanism because of the roll motion causes the scissors to begin to open by about 45° of roll motion. By 90° of vehicle roll motion, the scissors mechanism can clearly be seen opening as shown on Page 183 (Vehicle E) and Page 198 (Vehicle J) of Appendix A. Prior to the time the downside extension first contacted the ground, the scissors mechanism opened enough for the locking pins to lock the scissors in its open position, making it essentially rigid.

The extended span of POC #5 is much narrower and not as tall as the extended span of POC #3. The extended height of POC #5 alone proved to significantly retard roll motion. A taller OPD means the vehicle must rise higher above the roll pivot point during the roll sequence, and more roll energy is dissipated using a taller OPD.

The main structural components of POC #4 were used for POC #5, so the geometry of the POC #5 scissors mechanism was constrained by the space and motion ranges available in the existing structural components. Improvements to the performance of POC #5 could be achieved with a ground up redesign of a passive, scissors-type extended span OPD. The motion range, frame pivot locations, and scissors extension geometry could be redesigned to create an even taller and wider passive extended span OPD.

Maximum Roll Angles (deg)				
Vehicle Letter	No OPD	AM #1	AM #2	POC #1
A	284	295	369	168
G	298	374	302	186
J	275	290	373	174



Final Roll Angles (deg)				
Vehicle Letter	No OPD	AM #1	AM #2	POC #1
A	168	274	356	99
G	277	363	272	164
J	241	265	361	164

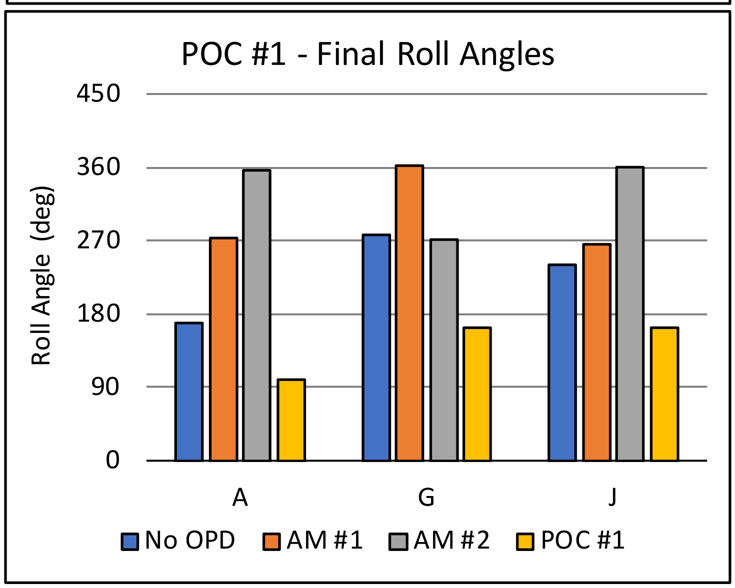
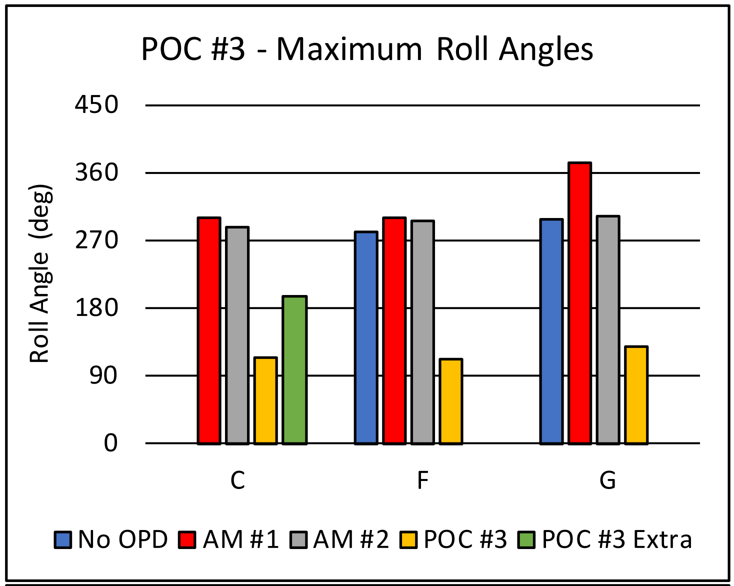


Figure 6: Maximum and Final Roll Angles for Vehicles Outfitted with POC #1

Maximum Roll Angles (deg)					
Vehicle Letter	No OPD	AM #1	AM #2	POC #3	POC #3 Extra
C	NA	301	288	115	197
F	282	300	297	113	NA
G	298	374	302	130	NA



Final Roll Angles (deg)					
Vehicle Letter	No OPD	AM #1	AM #2	POC #3	POC #3 Extra
C	NA	272	269	97	101
F	253	280	273	98	NA
G	277	363	272	99	NA

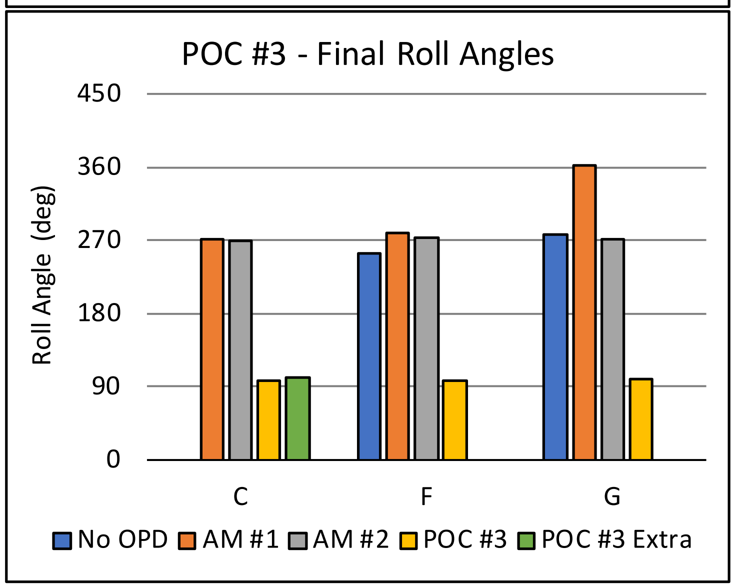
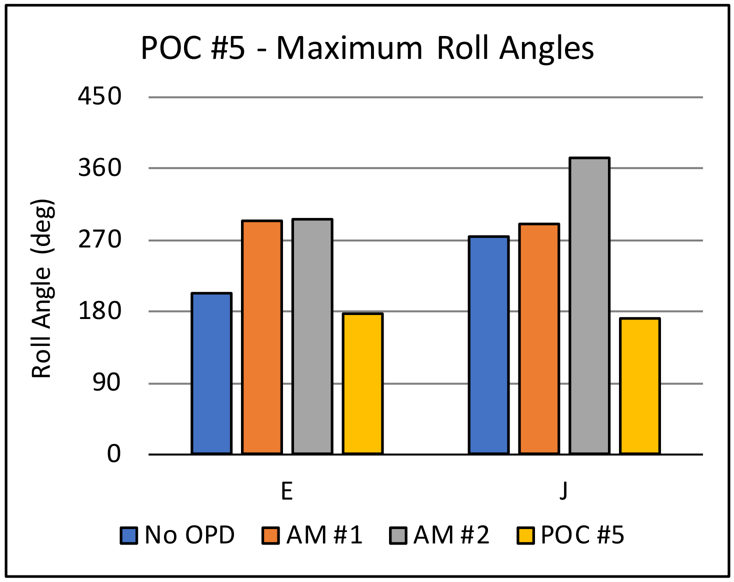


Figure 7: Maximum and Final Roll Angles for Vehicles Outfitted with POC #3

Maximum Roll Angles (deg)				
Vehicle Letter	No OPD	AM #1	AM #2	POC #5
E	202	295	297	178
J	275	290	373	172



Final Roll Angles (deg)				
Vehicle Letter	No OPD	AM #1	AM #2	POC #5
E	139	286	277	107
J	241	265	361	118

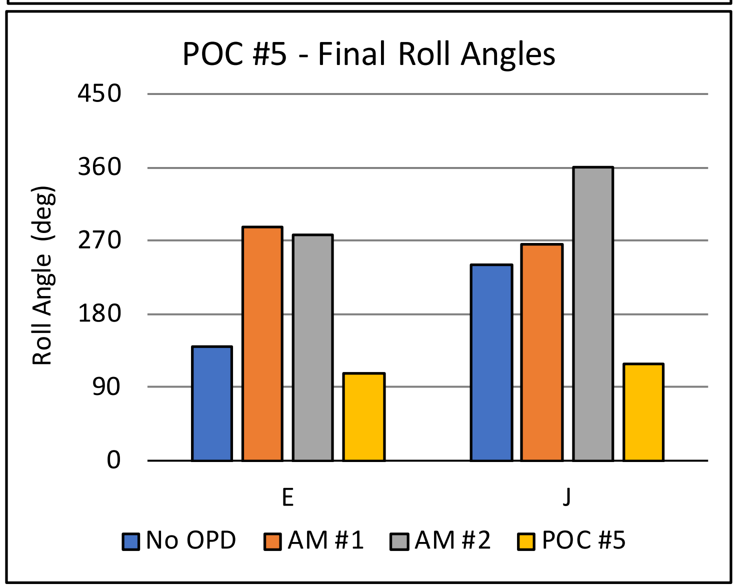


Figure 8: Maximum and Final Roll Angles for Vehicles Outfitted with POC #5

4. COMPARISON OF ROLLOVER EVENTS OF ATVs WITHOUT AN OPD AND OUTFITTED WITH AFTERMARKET AND POC OPDs

This section contains results comparing ATV and ATD responses during moderate energy sled rollover events of ATVs without an occupant protection device (OPD) and outfitted with aftermarket (AM) and proof-of-concept (POC) OPDs. All results from tests conducted on ATVs without an OPD are from a previous study conducted in 2018[20] and results from tests conducted on vehicles outfitted with AM OPDs are from a previous study conducted in 2019. [21]

For the current study, each vehicle was tested using two different POC OPDs. After the sled rollover tests were completed with the first POC OPD, each vehicle was repaired to its original condition prior to conducting tests using the second POC OPD. Repairs included replacing any components (e.g., fenders, racks, and lights) that were damaged during the tests.

The same ATD, and the ATD secure and release system, was used for all the tests. The ATD was inspected after each sled rollover, and it was repaired to its original condition by replacing any damaged components. Also, the pants and shirt on the ATD were replaced when changing to a different vehicle, or as needed if they became moderately torn or dirty.

Both the AM OPDs and all the POC OPDs retained their structural integrity during the sled rollover tests conducted.

4.1 Discussion of Vehicle Responses During Rollover Tests on ATVs with No OPD and Outfitted with Aftermarket and POC OPDs

Table 16 contains values for maximum roll rate, maximum roll angle and final roll angle from all moderate energy sled rollover tests conducted using Vehicles A, C, E, F, G, and J. The table includes results from 30 tests: five tests conducted without an OPD (Vehicle C was not tested without an OPD), six tests conducted using AM OPD #1, six tests conducted using AM OPD #2, and 13 tests conducted using POC OPDs (including the extra test conducted using POC #3, POC #3 Extra).

The information on Table 16 is easier to interpret by looking at the bar charts of maximum roll rates, maximum roll angles, and final roll angles shown on Figure 9. The POC OPD results are organized by POC type. The energy absorbing POC OPDs (POC #2 and POC #4) are side-by-side on the bar charts and indicated by the labeled bracket. Likewise, the extended span POC OPDs (POC #1, POC #3, and POC #5) are together and under a labeled bracket.

The maximum roll rates during all tests with OPDs are less than tests without on OPD. The maximum roll rates occur when the side of the ATV and/or the OPD first contacts the ground and causes a tripping (roll inducing) disturbance to the vehicle which generates a peak in the rate roll.

---

[20] *ATV Rollover Tests and Verification of a Physical Rollover Simulator – Results from Tests on Six 2014-2015 Model Year Vehicles*, HHS Contract HHSP233201400030I, SEA, Ltd. Report to CPSC, October 2019. https://www.cpsc.gov/s3fs-public/SEA%20Report%20to%20CPSC%20-%20ATV%20Rollover%20Simulator%20%286b%20cleared%29_Redacted.pdf?mlCsq67xfdq8x94QejoFtK37zwXdLLJV

[21] *Rollover Tests of ATVs Outfitted with Occupant Protection Devices (OPDs) – Results from Tests on Six 2014-2015 Model Year Vehicles,* CPSC Contract 61320618D0003, SEA, Ltd. Report to CPSC, January 2020. https://www.cpsc.gov/s3fs-public/SEA-Report-to-CPSC-ATVs-OPDs-final-redacted_0.pdf?VRu656v4QtP5rKIiw0kuSQP_hW49TVDK

When an OPD is present, the maximum roll rates are lessened by the impact of the OPD with the ground. The maximum roll rate peaks are generally short lived. An event with a short duration high maximum (peak) roll rate might not result into a full rollover outcome.

In all the tests without an OPD, the ATV rolled on to the ATD with major interaction between the ATV and ATD (this is explained in more detail in Section 4.3). In tests of Vehicles A and E without an OPD, the final roll angles are less than 180°. In these tests, after making major contact with the ATD, the ATV rolled back off the ATD.

The maximum and final roll angles for all tests conducted using the AM OPDs show that the tests resulted in full rollovers with final angles of near 270° or more. However, in most of these rollover events there was not major or any interaction between the ATV and ATD. In these cases, the OPD provided protective space when the ATV was above the ATD and clearance between the ATV and ATD when the ATV rolled completely over (detailed summary provided in Section 4.3).

POC #2 when used with Vehicle F resulted in lower maximum or final roll angles than the tests conducted with either AM OPD. However, when POC #2 was used on Vehicles A and E, the tests did not result in lower maximum or final roll angles than tests conducted using the AM OPDs. POC #4, tested on Vehicle C, also did not result in lower maximum or final roll angles than tests conducted on Vehicle C with either AM OPD. Both energy absorbing POC OPDs provided protective space when the ATV was above the ATD and clearance between the ATV and ATD when the ATV rolled completely over.

All tests using the extended span OPDs resulted in smaller maximum roll angles and smaller final angles than all tests conducted using the AM OPDs. None of the tests using extended span OPDs resulted in full rollover near 270° or more. Two of the three vehicles outfitted with POC #1 (Vehicles G and J) had final roll angles near 164°, with the vehicle balanced by the OPD above the ATD. All other tests using the extended span OPDs resulted in test outcomes where the vehicle rolled back to roll angles of less than 110°, essentially with the vehicle on its downward (right) side.

4.2 Discussion of ATD Responses During Rollover Tests on ATVs with No OPD and Outfitted with Aftermarket and POC OPDs

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

The overall motion of the ATD as it detached from the ATV was consistent for all the sled tests, whether no OPD was used or one of the AM or POC OPDs was used. During all tests, the ATD detached with a head-leading posture, with the right shoulder and/or head making first contact with the ground. By the time the ATD's head first strikes the ground, the buttocks of the ATD are already off the seat by several inches (as can be seen in the ATD Head Strike images in Appendix A).

As described in Appendix D, 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); with a six-axis upper neck load cell to measure three forces and three moments between the ATD's head and upper neck; 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 sled rollover tests using the POC OPDs. For all the sled tests, the maximum peaks in the head accelerations and rates occurred when the ATD head first impacted the ground. Likewise, the maximum peaks in the chest accelerations as well as in the upper neck forces and moments generally occurred when the ATD head first impacted the ground.

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

For each rollover event, HIC values were computed as a measure of head impact severity using time duration ranges of 15 milliseconds and 36 milliseconds. These time duration ranges are commonly used, and they are denoted as HIC_{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 the sled tests conducted, the peak HIC values occurred around the time when the ATD's head first struck the ground. The ATD's head in all tests was wearing a DOT approved large HJC model CL-33 open face helmet with a full-face shield.

Figure 10 contains bar charts showing the HIC_{15} and HIC_{36} values for all the moderate energy sled tests. The HIC values computed in this study are all from tests conducted with the ATD wearing a helmet. The HIC values would likely be somewhat different if the tests were conducted with the ATD not wearing a helmet.

The HIC_{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. The National Highway Traffic Safety Administration (NHTSA) standard for performance requirements for the protection of vehicle occupants in frontal crashes (Federal Motor Vehicle Safety Standard 208[22]) specifies that maximum calculated HIC_{15} values shall not exceed 700 and that the HIC_{36} values shall not exceed 1,000. A review of technical literature indicates that HIC values of 1,000 have over a 50% probability of serious head injury and 90% probability of moderate head injury. In a study involving professional athletes, HIC values of 250 were likely to result in concussions.[23]

The highest HIC_{15} value occurred during the test with POC #4 on Vehicle C. This is likely just a data anomaly, as based on the test videos there appears to be nothing unusual about the ATD head strike event for this test. Also, for this test the HIC_{36} value and the measurements from the other ATD sensors are all within the ranges of measurements from the other moderate energy sled tests.

The HIC_{15}values averaged 217 and the HIC_{36} values averaged 119 for all the moderate energy sled

[22] *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

[23] 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.

tests conducted. The average HIC values are at levels that would suggest that moderate or severe head injuries are not likely to occur during rollover events like those conducted in the study. However, some of the tests with no OPD and some tests with OPDs had HIC_{15} values near or above 250, suggesting that concussions could have occurred during these rollover events. As stated before, all tests were conducted with a helmet on the ATD.

As mentioned, the HIC values indicating the time when the resultant head accelerations were the largest all occurred when the ATD's head first struck the ground. All AM and POC OPDs evaluated in this study feature rear mounted structures that extend upward from the vehicle to provide an occupant space when the vehicle overturns. For the lateral sled rollover tests, adding OPDs to the ATVs does not measurably influence how the ATD releases laterally from the vehicle. Accordingly, the ranges of HIC values measured during tests with the AM OPDs and with the POC OPDs are generally in the range of HIC values measured with no OPD.

4.3 Discussion of ATV Interactions with ATD During Rollover Tests on ATVs with No OPD and Outfitted with Aftermarket and POC OPDs

Tables 17 through 22 (for Vehicles A, C, E, F, G, and J, respectively) contain brief descriptive summaries of the major contact events between the ATV and ATD during the moderate energy sled rollovers. Collectively, these tables contain results from 30 tests: five tests conducted without an OPD (Vehicle C was not tested without an OPD), six tests conducted using AM OPD #1, six tests conducted using AM OPD #2, and 13 tests conducted using POC OPDs (including the extra test conducted using POC #3, POC #3 Extra). The summary descriptions include comments on ATV to ATD interactions that occurred during the rollover events, as well as comments on the final rest position of the ATV relative to the ATD at the end of each run. In addition to the descriptive summaries, Tables 17 through 22 list the maximum and final roll angles during the rollover events and show a photograph of the final rest position for each test.

Table 23 contains yes (X) or no (O) indicators of two items based on the summary descriptions in Tables 17 through 22:

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

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

Certainly, ATV impacts to a rider's upper and/or lower limbs could result in severe injuries. However, potentially more serious injuries could occur to impacts with the pelvis, abdomen, thorax, or head. Likewise, having an ATV come to rest on top of the pelvis, abdomen, thorax, or head likely presents a greater potential for a rider to be pinned by the ATV and unable to free themselves, and in the case of the ATV resting on the thorax could potentially lead to suffocation (when the air supply to the body is blocked from entering the body). ATVs are sometimes driven through deep mud or water, in which case having the ATV on any part of the body could lead to drowning. Also, ATVs sometimes leak fuel when overturned, which could ignite and injure or kill a rider who was trapped under the vehicle.

Table 23 contains a summary of occurrences of major ATV and ATD interactions during rollovers and at final rest position. For all five vehicles tested without an OPD, there was major interaction between the ATV and ATD during the moderate energy sled tests. In one of the five tests without an OPD, there was also major interaction between the ATV and ATD at the end of the rollover event. For tests using AM #1, there was major interaction during the rollover event in two of the six tests, and major interaction at the end of the test in one of the six tests. There were no major interactions between the ATV and ATD during or at the end of any moderate energy sled tests conducted using AM #2 or using any of the POC OPDs. These results show that rear mounted OPDs may be effective in reducing the potential for injury in lateral rollover events like the moderate energy sled rollover events.

All of the tests using the AM OPDs and three of the four tests using energy absorbing POC OPDs resulted in full rollover events, with the final roll angles in the range of 270° or more. As mentioned, in most of these tests were was no major interaction between the ATV and ATD during or at the end of the rollover event. This is because the OPD provides protective clearance as the ATV rolls above the ATD and clearance distance after the ATV rolls past the ATD. This is considered a better outcome than the tests using no OPD. However, tests using the extended span OPDs provided additional safety to the driver by completely preventing full rollovers to 270°.

Table 24 is a summary of the incidences when the ATV rolling on top of of the ATD (during tests without an OPD) and the incidences when the ATV's final roll angle exceeded 180° (during tests with an OPD). As shown in Table 24, the extended span POC OPDs reduced the final roll angles to less than 180° in all tests. Preventing an ATV with a rear mounted OPD from rolling past 180° reduces the potential for the ATV or OPD from impacting or interacting with the driver.

4.4 Summary

This current rollover study of ATV's outfitted with proof-of-concept (POC) OPDs, and the previous rollover studies of ATV's without OPDs and outfitted with aftermarket (AM) OPDs, involved conducting moderate energy lateral rollover events using an ATV rollover sled. In all the studies, the same ATD secure and release system was used, and the release of the ATD's body from the ATV was initiated when the vehicle roll angle achieved 30°. The sled rollover tests conducted are representative of ATV and ATD motions during a subset of potential ATV rollovers, and they are useful for evaluating the feasibility and effectiveness of using OPD devices on ATVs.

Results from 30 rollover tests were analyzed and presented in this report, including five rollovers with no OPD, six with AM #1, six with AM #2, and 13 rollovers with POC OPDs: three with POC #1, three with POC #2, four POC #3 (including POC #3 Extra), one with POC #4 and two with POC #5. POC #2 and POC #4 are energy absorbing OPD concepts; and POC #1, POC #3, and POC #5 are extended span OPD concepts. In all the sled rollover tests conducted, all the OPDs retained their structural integrity, and their general position and orientation on the ATVs tested was not compromised during any of the tests.

Tables and graphs of ATV maximum roll rates, maximum roll angles and final roll angles during each rollover have been presented. The energy absorbing POC OPDs performed as well as or better than the AM OPDs. The energy absorbing POC OPDs did absorb some of ATVs rolling energy, but nonetheless, in three of the four tests conducted using energy absorbing OPDs, the ATV rolled over to near 270° of final roll angle. The deforming, energy absorbing components of

POC #2 and POC #4 were designed assuming that the force directed laterally near the top of OPD was larger than it actually was during the rollover events. A simple device (an aluminum pointer attached near the top of POC #4) was devised and used to evaluate the direction of the impact force at the time the OPD first contacts the ground. This demonstrated that the direction of the force was about 45° relative to the lateral direction, and not as close to 90° as assumed. This explained why the energy absorbing POC OPDs did not work as well as intended, and this information is useful for efforts to re-design an energy absorbing OPD.

The extended span POC OPDs performed better than the AM OPDs and the energy absorbing OPDs. All tests conducted using the extended span OPDs resulted in final ATV roll angles of less than 180°.

A fixed geometry extended span OPD, POC #1, was used to demonstrate the benefits of the extended span concept. Two second-phase extended span POC OPDs, POC #3 and POC #5, were subsequently designed and tested.

POC #3, an OPD with telescoping extensions, can be classified as an active OPD given that electronics were used to sense vehicle roll motion and trigger the telescoping extensions and given that energy sources (in this case coil springs) were needed to deploy the extensions. A modifed version of POC #3, POC #3 Extra, was developed to test and confirm the feasability of a concept using a contact switch mounted to the outside of the OPD to trigger the extensions, thus eliminating the need to sense vehicle roll motion to trigger extension deployment.

POC #5, an OPD with scissors extensions, can be classified as a passive OPD given that no sensors or energy sources are required for its use. Tests conducted using POC #5 confirmed the concept of creating a purely mechanical extending span OPD that would deploy and lock into an extended position during a lateral rollover event.

For the lateral rollover tests used in this and the previous studies without OPDs and with AM OPDs, adding OPDs to the ATVs did not measurably influence how the ATD releases laterally from the vehicle. Accordingly, the ranges of HIC values measured during tests with OPDs were found to be generally in the range of HIC values measured with no OPD. Also, during lateral rollover events like the moderate energy rollovers simulated using the sled, the rear mounted OPDs contacted the ground before the ATD's body had a chance to roll into a position that would allow it to be impacted by the OPD.

For tests using AM #1, there was major interaction between the ATV and ATD during the rollover event in two of the six tests conducted. There were no major interactions between the ATV and ATD during tests conducted using AM #2 or any of the POC OPDs. These results show that rear mounted OPDs can reduce the potential for injury in lateral rollover events like the moderate energy sled rollover events.

All of the tests using the AM OPDs and three of the four tests using energy absorbing POC OPDs resulted in full rollover events, with the final roll angles in the range of 270° or more. In most of these tests were was no major interaction between the ATV and ATD during or at the end of the rollover event. This was because the OPDs provided protective clearance when the ATV rolled above the ATD and provided clearance distance after the ATV rolled past the ATD. This is considered a better outcome than the tests using no OPD. However, tests using the extended span

OPDs provided additional safety to the driver by completely preventing full rollovers to 270°. The extended span POC OPDs reduced the final roll angles to less than 180° in all tests. Preventing an ATV with a rear mounted OPD from rolling past 180° greatly diminishes the possibility of the ATV or OPD impacting or interacting with the driver.

The designs of the POC OPDs used in this study could be improved. The energy absorbing POC OPD designs could be improved by better accounting for the direction of the impact force of the OPD striking the ground, so that the energy absorbing features would absorb more of the ATV's rollover energy. The overall retracted and extended geometries of the POC #3 and POC #5 could be adjusted to minimize the retracted span and optimize desired extended span. The geometry and configuration of the scissors mechanism and of the side structures and their pivots of POC #5 could be modified to provide a taller and wider extended span. The POC OPDs were designed to withstand multiple rollover events, so they weigh more than a final design OPD would need to weigh. Lighter weight OPDs based off any of the POC OPD designs could be created and reducing the OPD weight would improve the rollover resistance of the ATV.

Table 16: Maximum Roll Rate, Maximum Roll Angle and Final Roll Angle for all Moderate Energy Sled Rollovers				
Vehicle Letter	**Condition**	**Max Roll Rate (deg/s)**	**Max Roll Angle (deg)**	**Final Roll Angle (deg)**
A	No OPD	386.3	283.5	168.2
	AM #1	303.2	295.0	274.0
	AM #2	356.5	369.4	355.5
	POC #1	218.9	167.6	98.7
	POC #2	273.8	283.4	272.4
C	No OPD	NA	NA	NA
	AM #1	246.7	301.0	271.7
	AM #2	234.4	288.0	268.7
	POC #3	203.1	115.4	96.7
	POC #3 Extra	224.4	197.3	100.5
	POC #4	311.9	287.3	269.1
E	No OPD	344.9	202.3	139.2
	AM #1	268.7	294.8	286.1
	AM #2	317.0	296.9	277.1
	POC #2	231.0	282.3	274.5
	POC #5	208.1	177.9	107.0
F	No OPD	393.9	281.6	253.1
	AM #1	267.4	300.3	279.6
	AM #2	240.7	297.2	273.2
	POC #2	309.2	195.3	178.4
	POC #3	206.4	113.0	97.8
G	No OPD	284.9	297.7	277.1
	AM #1	264.6	374.3	362.5
	AM #2	250.3	302.2	271.5
	POC #1	277.3	186.0	163.5
	POC #3	216.9	130.0	99.1
J	No OPD	306.4	274.8	241.0
	AM #1	250.5	289.6	265.4
	AM #2	219.7	372.9	360.8
	POC #1	210.3	174.2	163.6
	POC #5	274.6	171.5	118.0

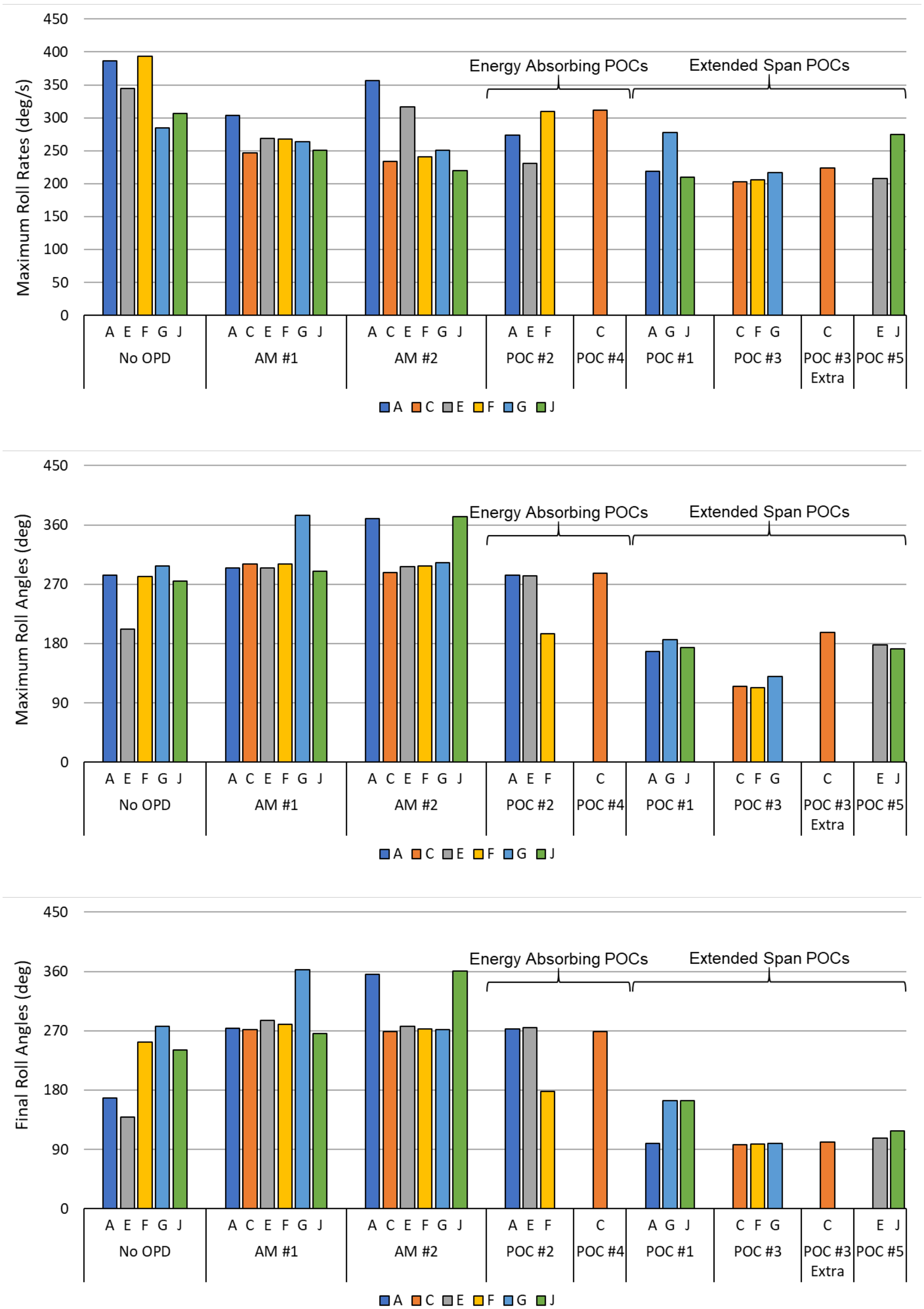


Figure 9: Maximum Roll Rates, Maximum Roll Angles and Final Roll Angles From All Moderate Energy Sled Tests

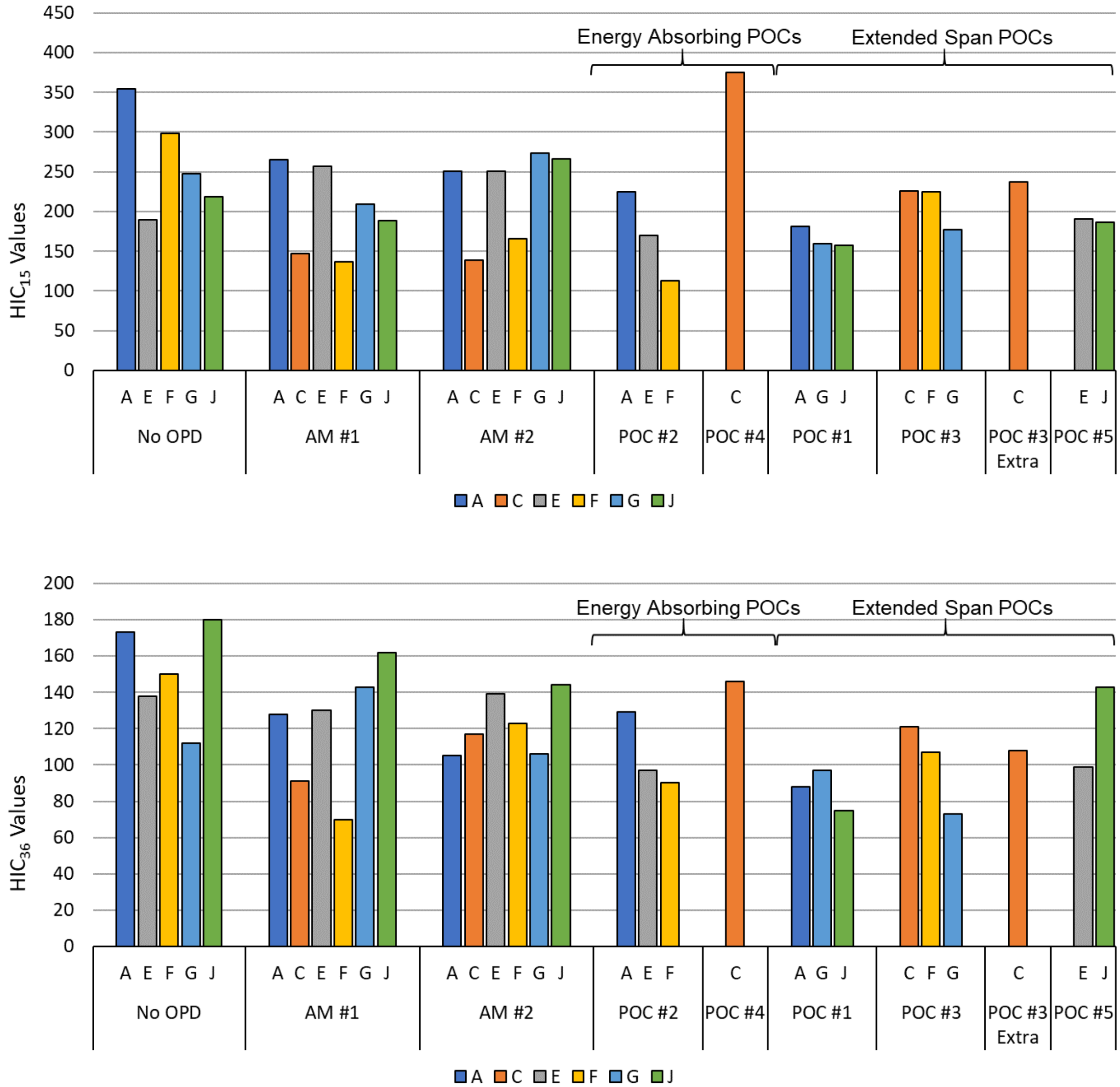


Figure 10: HIC15 and HIC36 Values From All Moderate Energy Sled Tests

Table 17: Vehicle A Sled Moderate Energy Rollovers – Descriptions of ATV and ATD Interactions and Rest Position Photographs		
No OPD	Max Roll 284° – Final Roll 168° The left side of the ATV rolled completely onto ATD as it went from 180° to 284°, and then rolled off the ATD at its final rest position.	
AM #1	Max Roll 295° – Final Roll 274° AM #1 caused the ATV to roll above the ATD until the left side of the ATV landed on the ATD's left leg near 270°. At the final position, AM #1 was resting on the ATD's left arm.	
AM #2	Max Roll 369° – Final Roll 356° AM #2 caused the ATV to roll above the ATD until the left side of the ATV landed on the ATD's left arm near 270°. The ATV continued to roll completely off the ATD to its rest position.	
POC #1	Max Roll 168° – Final Roll 99° POC #1 prevented the ATV from having any contact with the ATD.	
POC #2	Max Roll 283° – Final Roll 272° POC #2 caused the ATV to roll above the ATD. The ATV came to rest without having any contact with the ATD.	

Table 18: Vehicle C Sled Moderate Energy Rollovers – Descriptions of ATV and ATD Interactions and Rest Position Photographs		
No OPD	NA	NA
AM #1	Max Roll 301° – Final Roll 272° AM #1 caused the ATV to roll above the ATD until the left side of the ATV landed on the ATD's left arm near 270°. AM #1 brushed the ATD's helmet as the ATV rolled back to its final rest position, off the ATD.	
AM #2	Max Roll 288° – Final Roll 269° AM #2 caused the ATV to roll above the ATD throughout the entire rollover sequence and the ATV landed clear of the ATD at its rest position	
POC #3	Max Roll 115° – Final Roll 97° POC #3 prevented the ATV from having any contact with the ATD.	
POC #3 Extra	Max Roll 197° – Final Roll 101° POC #3 Extra prevented the ATV from having any contact with the ATD.	
POC #4	Max Roll 287° – Final Roll 269° POC #4 caused the ATV to roll above the ATD. The rear fender/rack of the ATV landed on, and came to rest on, the ATD's left arm and leg.	

Table 19: Vehicle E Sled Moderate Energy Rollovers – Descriptions of ATV and ATD Interactions and Rest Position Photographs		
No OPD	Max Roll 202° – Final Roll 139° The ATV rolled completely onto ATD near its maximum roll angle. The ATV's rear rack came to rest on the ATD's right foot.	
AM #1	Max Roll 295° – Final Roll 286° AM #1 caused the ATV to roll above the ATD until the left side base of AM #1 and left side of the rear rack of the ATV landed on the ATD's head near 270° and came to rest on the ATD's head at final rest position.	
AM #2	Max Roll 297° – Final Roll 277° AM #2 caused the ATV to roll above the ATD until the left side of the ATV landed on the ATD's left leg near 270° and came to rest on ATD's left leg.	
POC #2	Max Roll 282° – Final Roll 275° AM #2 caused the ATV to roll above the ATD until the left rear fender of the ATV landed on the ATD's left heel near 270°. The ATV came to rest off the ATD.	
POC #5	Max Roll 178° – Final Roll 107° POC #5 prevented the ATV from having any contact with the ATD.	

Table 20: Vehicle F Sled Moderate Energy Rollovers – Descriptions of ATV and ATD Interactions and Rest Position Photographs

No OPD	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.	
AM #1	Max Roll 300° – Final Roll 280° The left side of AM #1 landed on the ATD's left arm and the left side of the ATV landed on the ATD's left leg near 270°. The ATV came to rest clear of the ATD.	
AM #2	Max Roll 297° – Final Roll 273° AM #2 caused the ATV to roll above the ATD throughout the entire rollover sequence. AM #2 engaged the ATD's leg arm near 180°. At rest, the ATV landed clear of the ATD.	
POC #2	Max Roll 195° – Final Roll 178° POC #2 caused the ATV to roll above the ATD, and to come to rest in an upside-down position over the ATD. After the top of POC #2 was in contact with the ground, the buttocks of the ATV rolled into contact with, and remained in contact with, POC #2.	
POC #3	Max Roll 113° – Final Roll 97° POC #3 prevented the ATV from having any contact with the ATD.	

Table 21: Vehicle G Sled Moderate Energy Rollovers – Descriptions of ATV and ATD Interactions and Rest Position Photographs

No OPD	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, and back onto, the ATD before coming to rest with its left side resting on the ATD’s left leg and left arm.	
AM #1	Max Roll 374° – Final Roll 363° AM #1 caused the ATV to roll above the ATD until the left side base of AM #1 and left side of the rear rack of the ATV landed on the ATD’s head near 270°. After this contact, the ATV rolled clear of the ATD.	
AM #2	Max Roll 302° – Final Roll 272° AM #2 caused the ATV to roll above the ATD throughout the entire rollover sequence and the ATV landed clear of the ATD at its rest position	
POC #1	Max Roll 186° – Final Roll 164° POC #1 prevented the ATV from having any contact with the ATD.	
POC #3	Max Roll 130° – Final Roll 99° POC #3 prevented the ATV from having any contact with the ATD.	

Table 22: Vehicle J Sled Moderate Energy Rollovers – Descriptions of ATV and ATD Interactions and Rest Position Photographs		
No OPD	Max Roll 275° – Final Roll 241° The ATV landed on the ATD’s pelvis and chest near 270° of roll angle. The rear of the ATV came to rest leaning on ATD's pelvis.	
AM #1	Max Roll 290° – Final Roll 265° AM #1 caused the ATV to roll above the ATD throughout the entire rollover sequence. AM #1 engaged the ATD’s helmet near 225°. At rest, the ATV landed clear of the ATD.	
AM #2	Max Roll 373° – Final Roll 361° AM #2 caused the ATV to roll above the ATD throughout the entire rollover sequence and the ATV landed clear of the ATD at its rest position	
POC #1	Max Roll 174° – Final Roll 164° POC #1 caused the ATV to roll above the ATD, and to come to rest in an upside-down position over the ATD. After the top of POC #1 was in contact with the ground, the buttocks of the ATV rolled into contact with, and remained in contact with, POC #1.	
POC #5	Max Roll 172° – Final Roll 118° POC #5 prevented the ATV from having any contact with the ATD.	

Table 23: Major ATV and ATD Interactions During Moderate Energy Sled Rollovers and at Final Rest Position									
Key: X Means Yes -- O Means No -- Blank Cell Indicates Not Tested					Energy Absorbing POC OPDs		Extended Span POC OPDs		
Vehicle Letter		No OPD	AM #1	AM #2	POC #2	POC #4	POC #1	POC #3	POC #5
A	Major ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	X	O	O	O		O		
	ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	O	O	O	O		O		
C	Major ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head		O	O		O		O	
	ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head		O	O		O		O	
E	Major ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	X	X	O	O				O
	ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	O	X	O	O				O
F	Major ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	X	O	O	O			O	
	ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	X	O	O	O			O	
G	Major ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	X	X	O			O	O	
	ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	O	O	O			O	O	
J	Major ATV Interaction with ATD's Pelvis, Abdomen, Thorax or Head	X	O	O			O		O
	ATV Rest Position on ATD's Pelvis, Abdomen, Thorax or Head	O	O	O			O		O

Table 24: Incidences of ATV Rolling on Top of ATD (if No OPD) and/or ATV Final Roll Angle Exceeding 180° During Moderate Energy Sled Rollovers

Key: X Means Yes -- O Means No -- Blank Cell Indicates Not Tested					Energy Absorbing POC OPDs		Extended Span POC OPDs		
Vehicle Letter		No OPD	AM #1	AM #2	POC #2	POC #4	POC #1	POC #3	POC #5
A	ATV Rolled on Top of ATD (if No OPD) and/or ATV Final Roll Angle Exceeded 180°	X	X	X	X		O		
C	ATV Rolled on Top of ATD (if No OPD) and/or ATV Final Roll Angle Exceeded 180°		X	X		X		O	
E	ATV Rolled on Top of ATD (if No OPD) and/or ATV Final Roll Angle Exceeded 180°	X	X	X	X				O
F	ATV Rolled on Top of ATD (if No OPD) and/or ATV Final Roll Angle Exceeded 180°	X	X	X	O			O	
G	ATV Rolled on Top of ATD (if No OPD) and/or ATV Final Roll Angle Exceeded 180°	X	X	X			O	O	
J	ATV Rolled on Top of ATD (if No OPD) and/or ATV Final Roll Angle Exceeded 180°	X	X	X			O		O

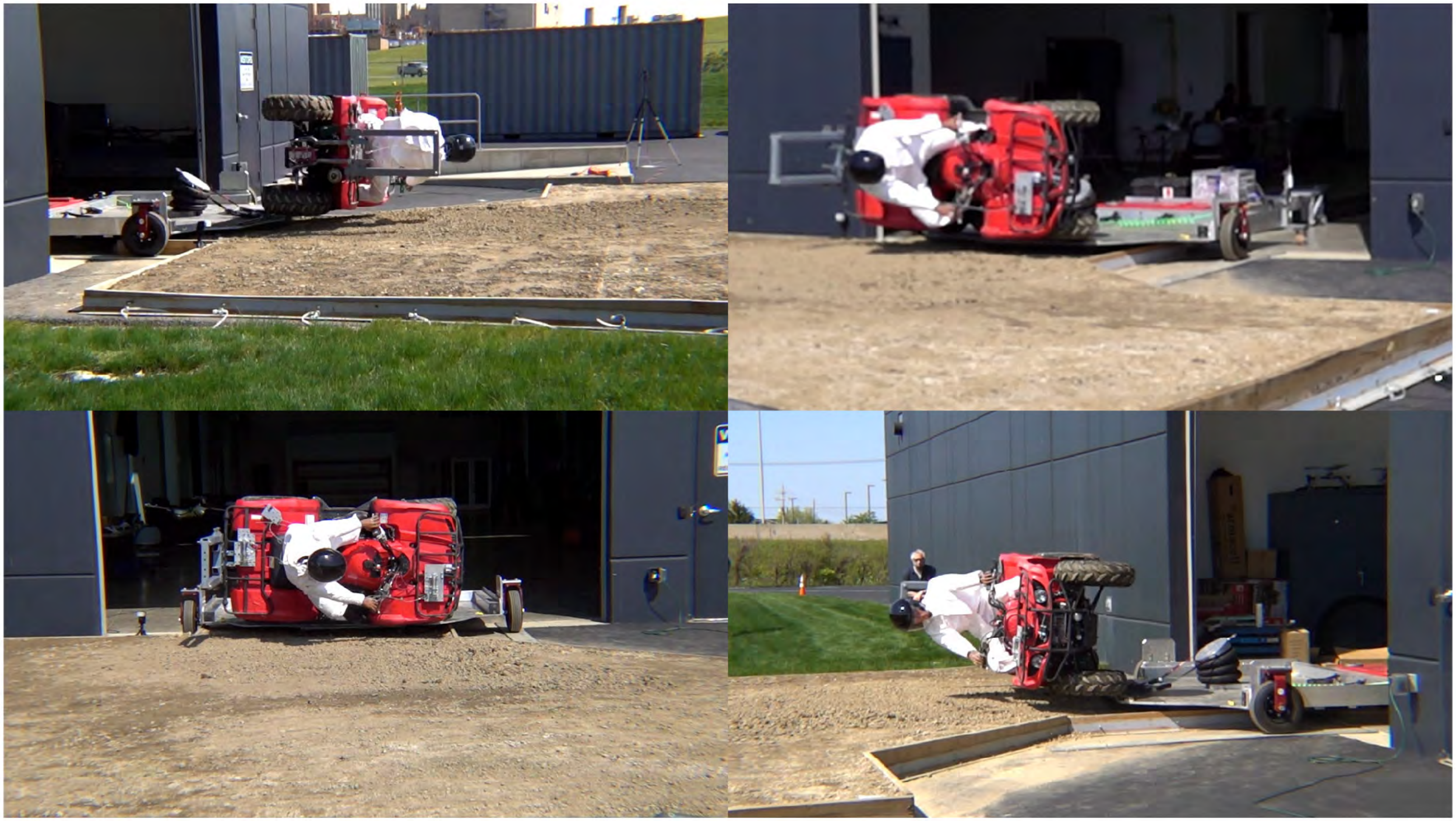
Roll Angle = 30° - Time = 0.45 sec

Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 45° - Time = 0.57 sec

Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 90° - Time = 0.80 sec



Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

ATD Head Strike - Time = 0.94 sec

Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 180° - Time = 1.36 sec

Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 270° - Time = 2.86 sec

Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Max Roll Angle = 283.4° - Time = 3.17 sec

Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

End of Run - Roll Angle = 272.4°

Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

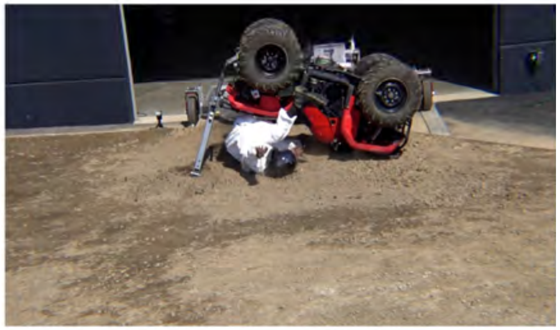
Drone Camera - Roll Angle = 30° - Time = 0.45 sec

Drone Camera - Roll Angle = 45° - Time = 0.57 sec

Drone Camera - Roll Angle = 90° - Time = 0.80 sec

Drone Camera - ATD Head Strike - Time = 0.94 sec

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



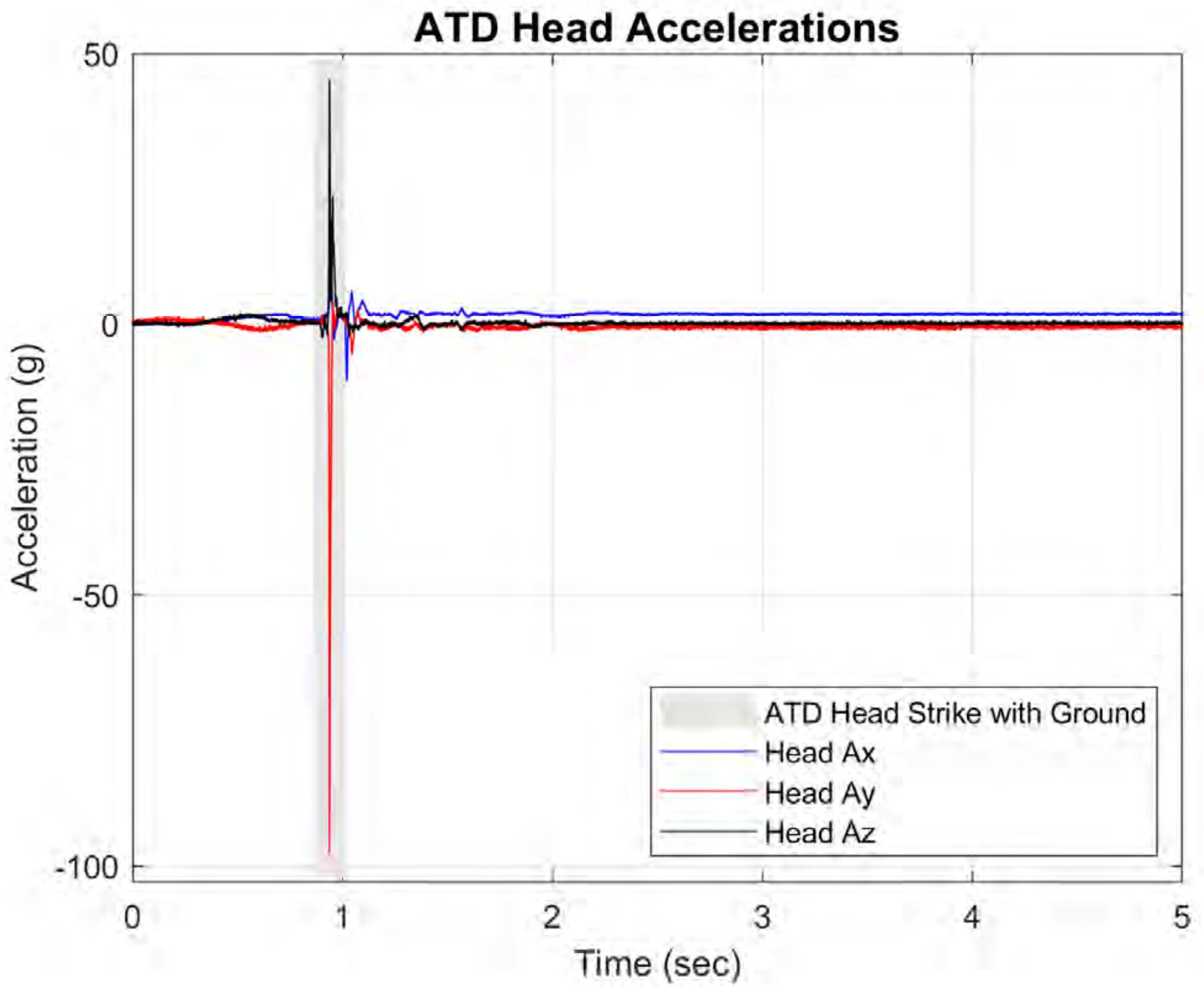
Drone Camera - Roll Angle = 270° - Time = 2.86 sec

Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

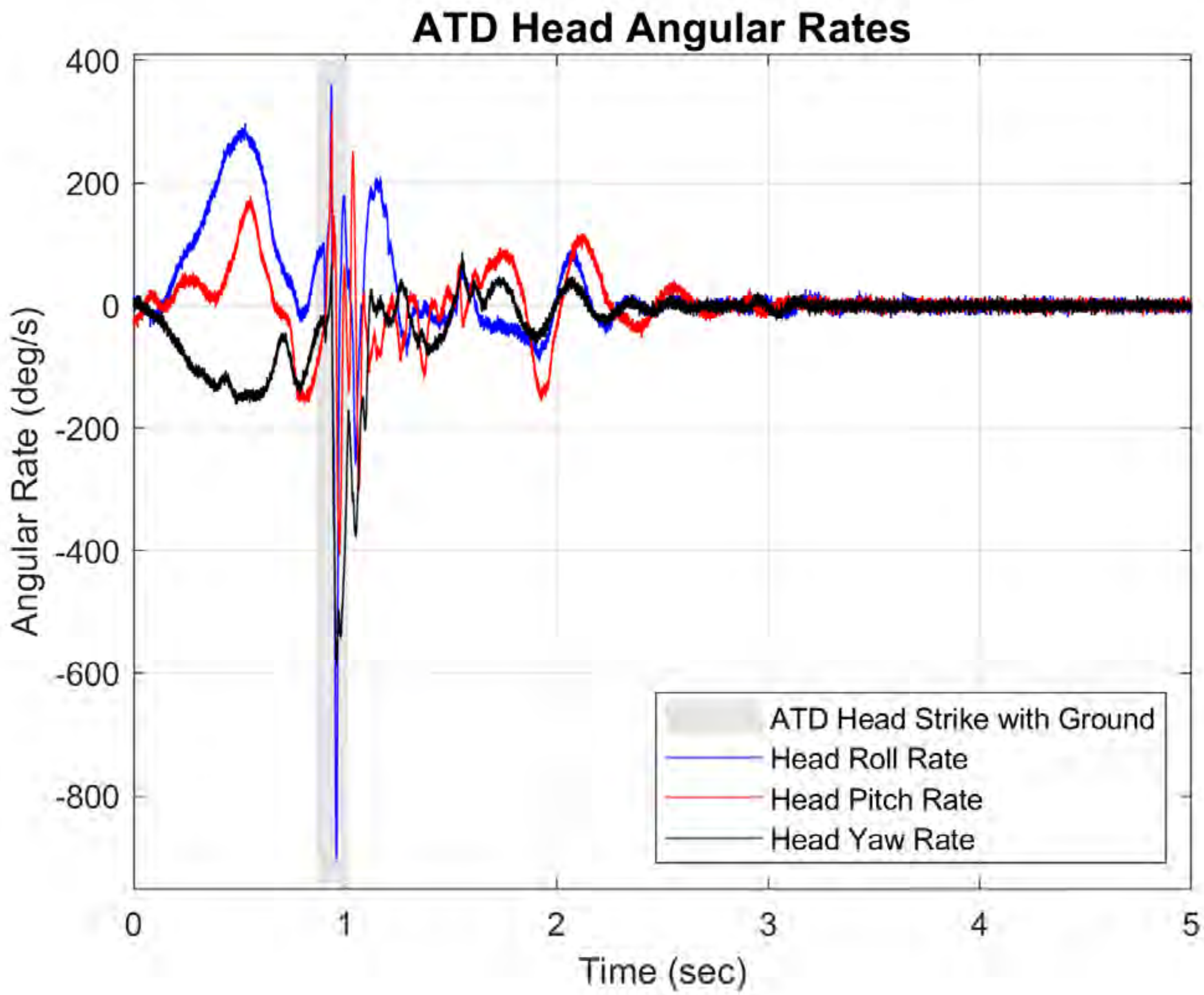
Drone Camera - Max Angle = 283.4° - Time = 3.17 sec

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

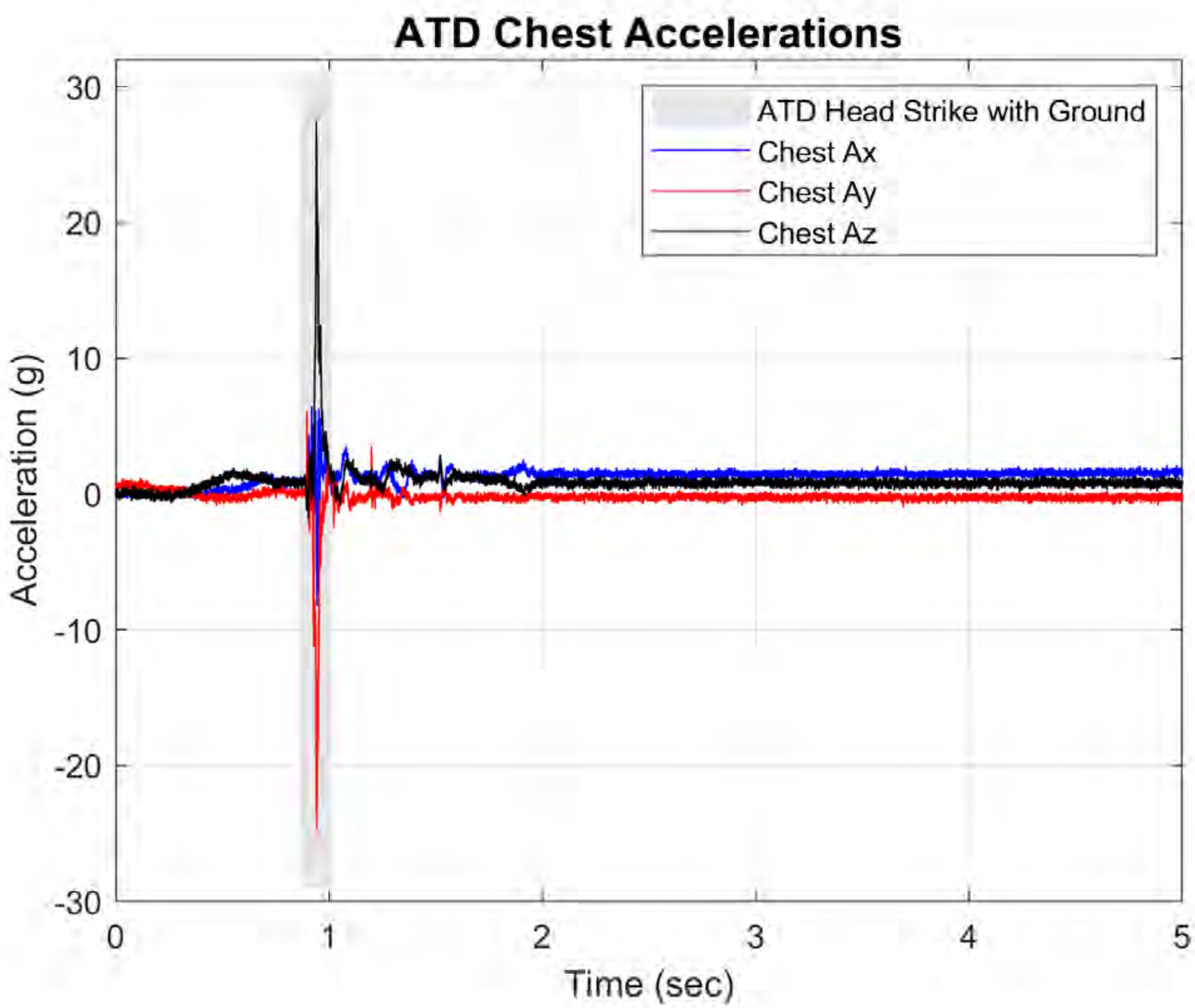
Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



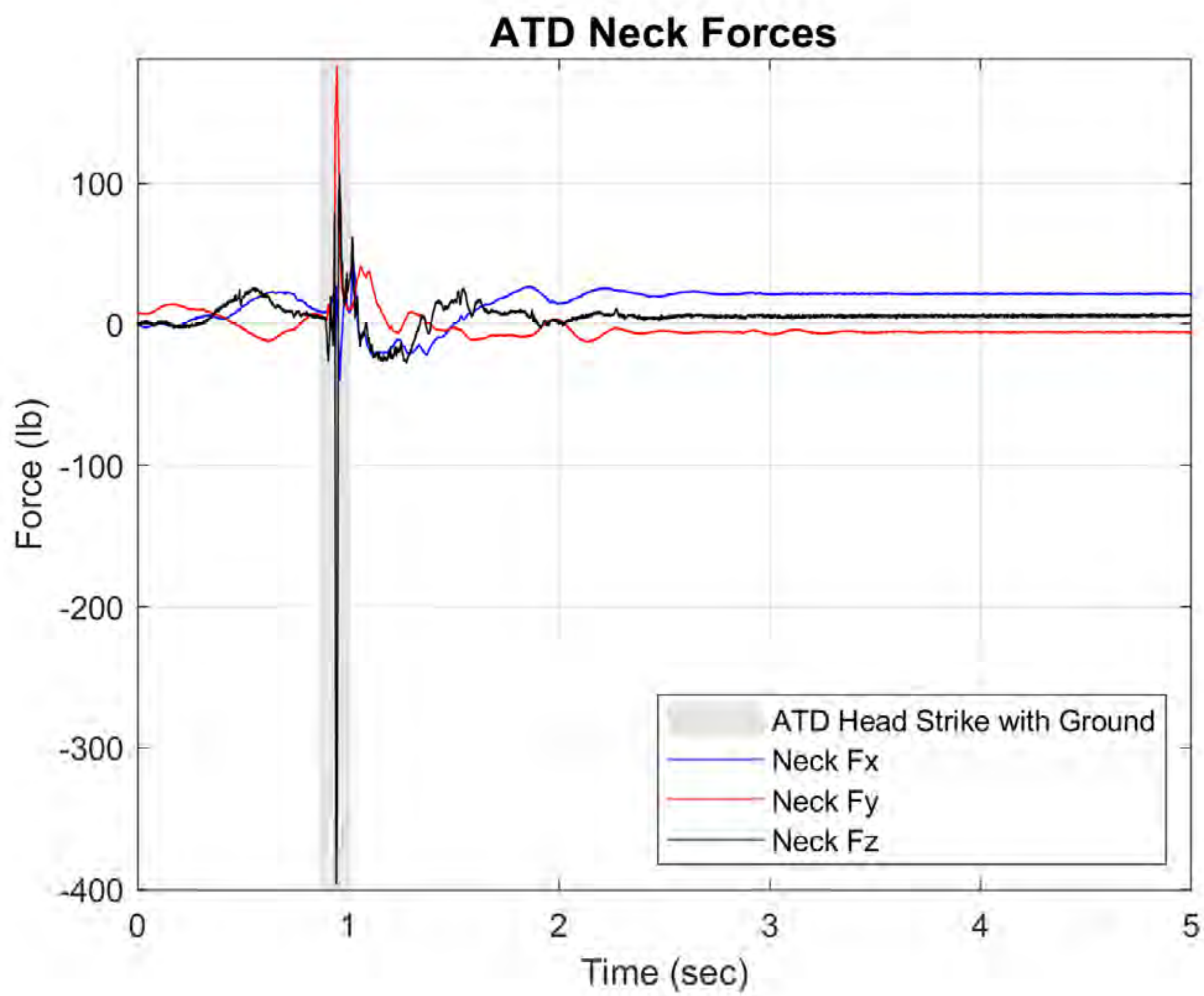
Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



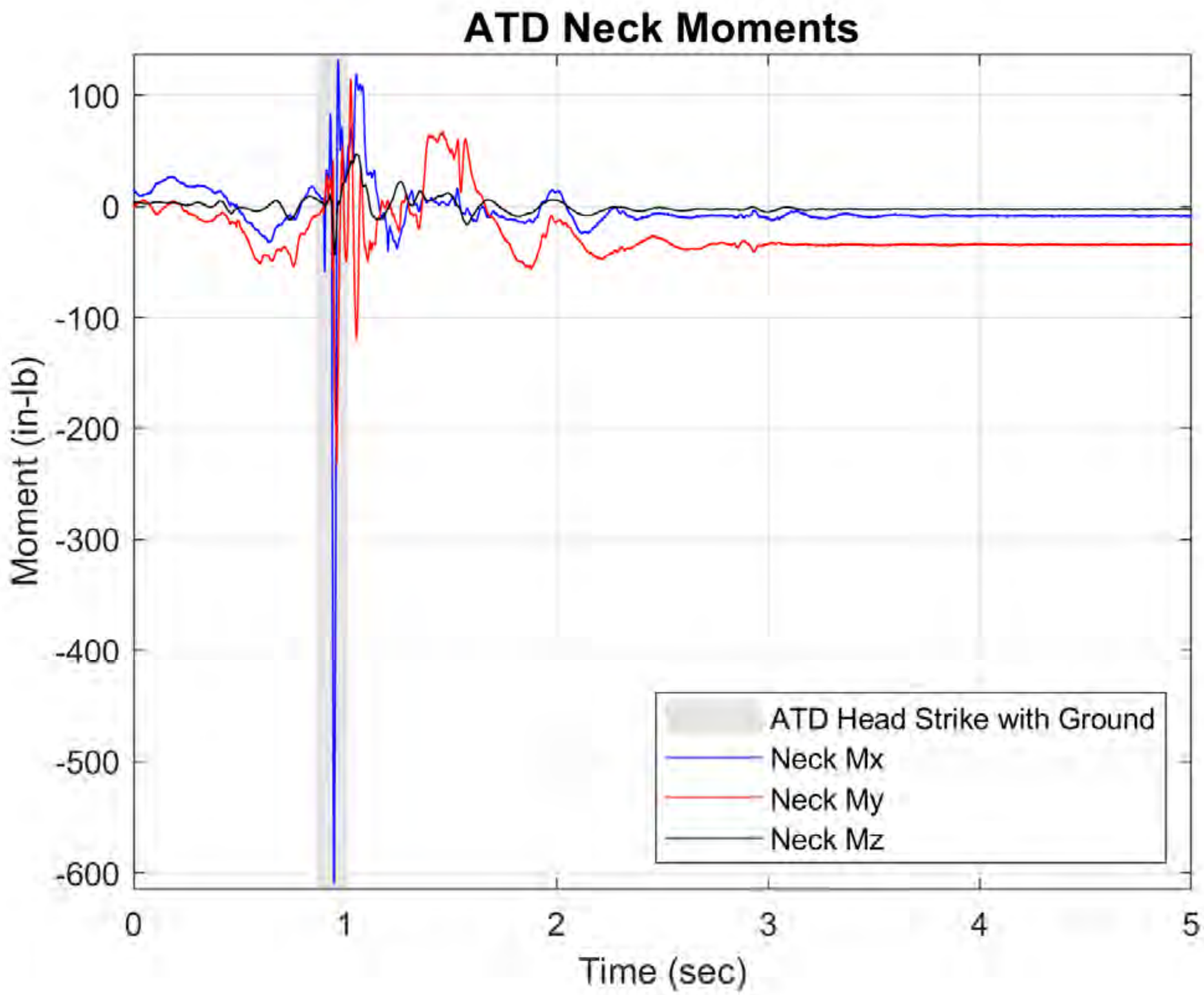
Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



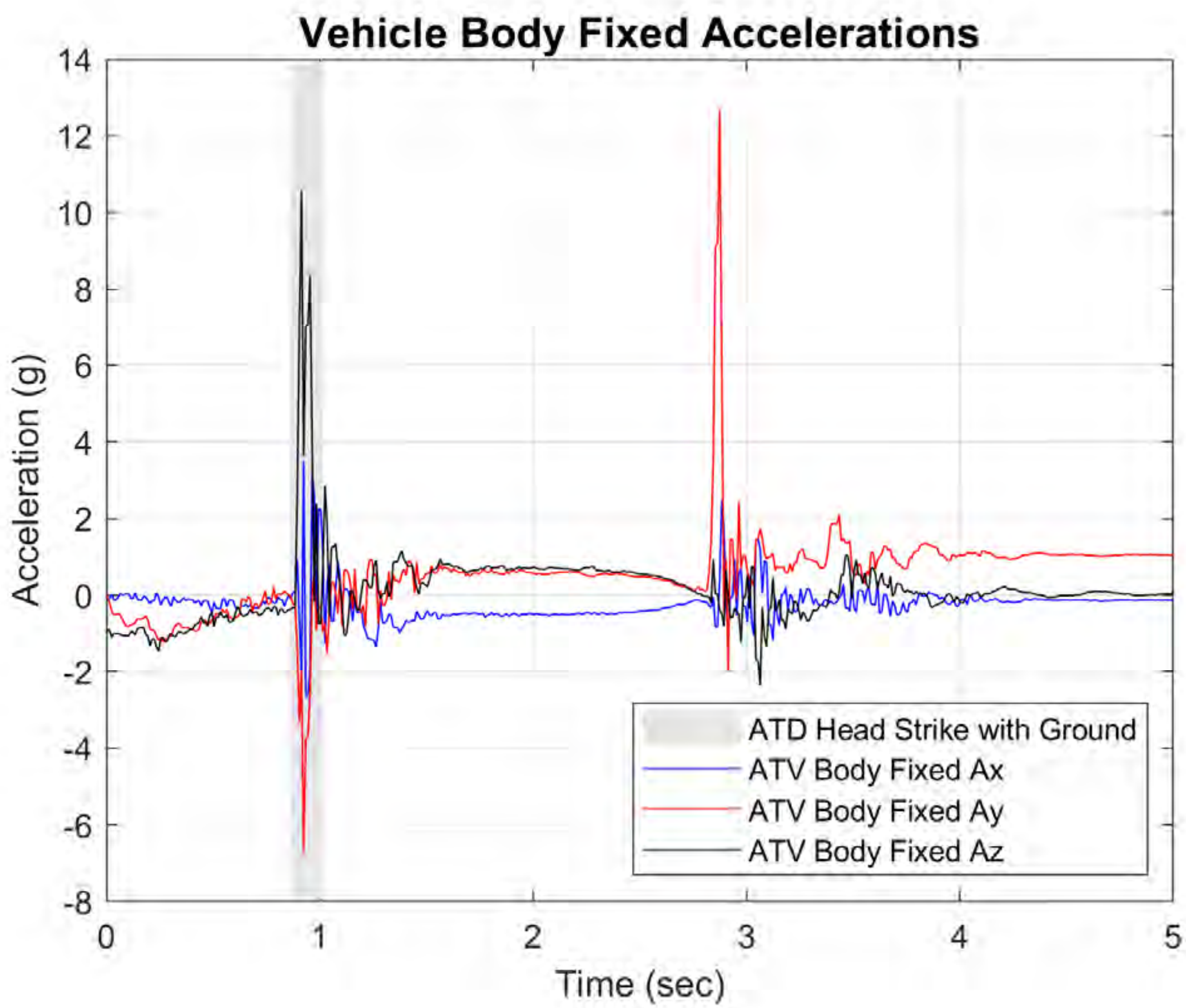
Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



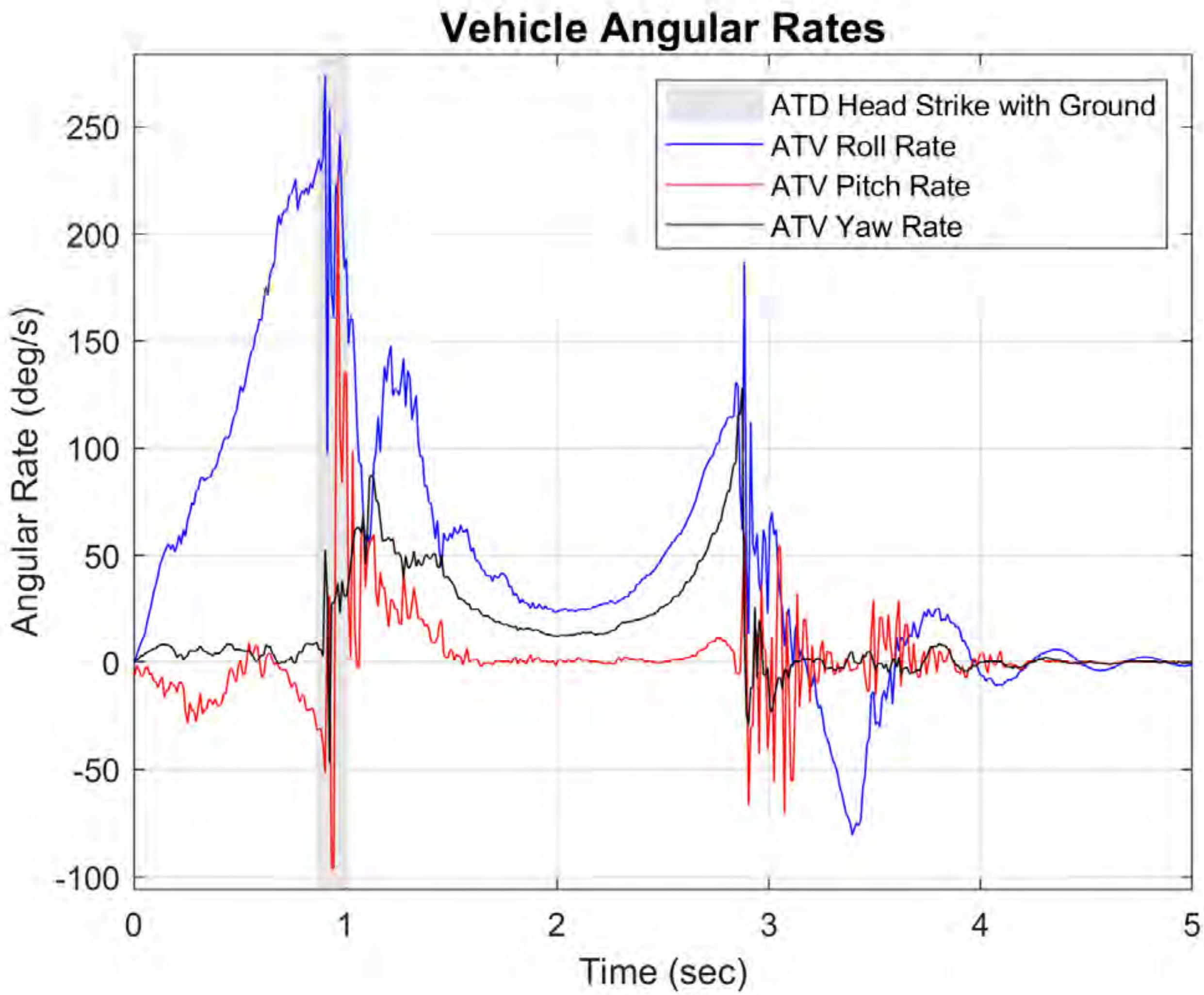
Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



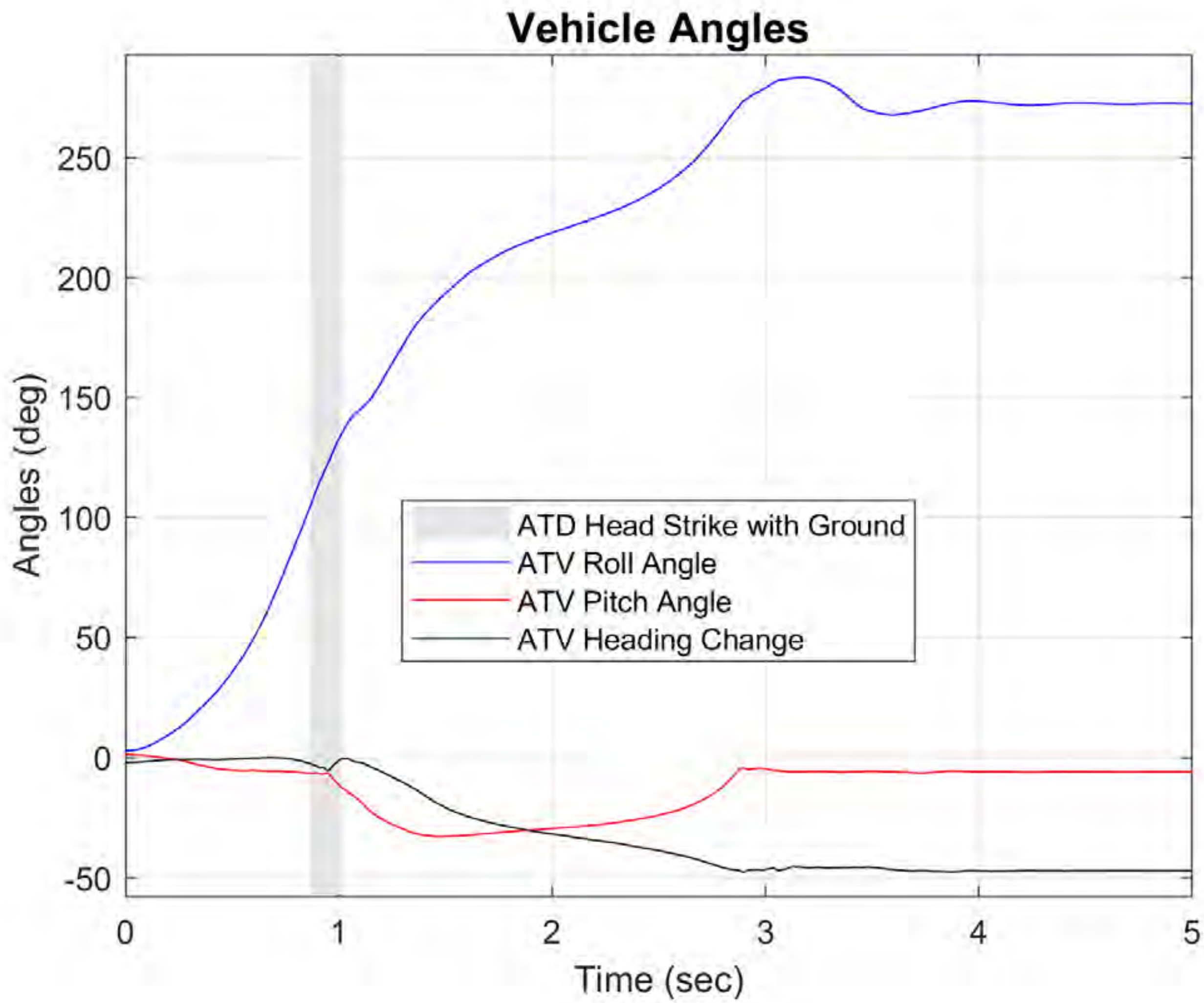
Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

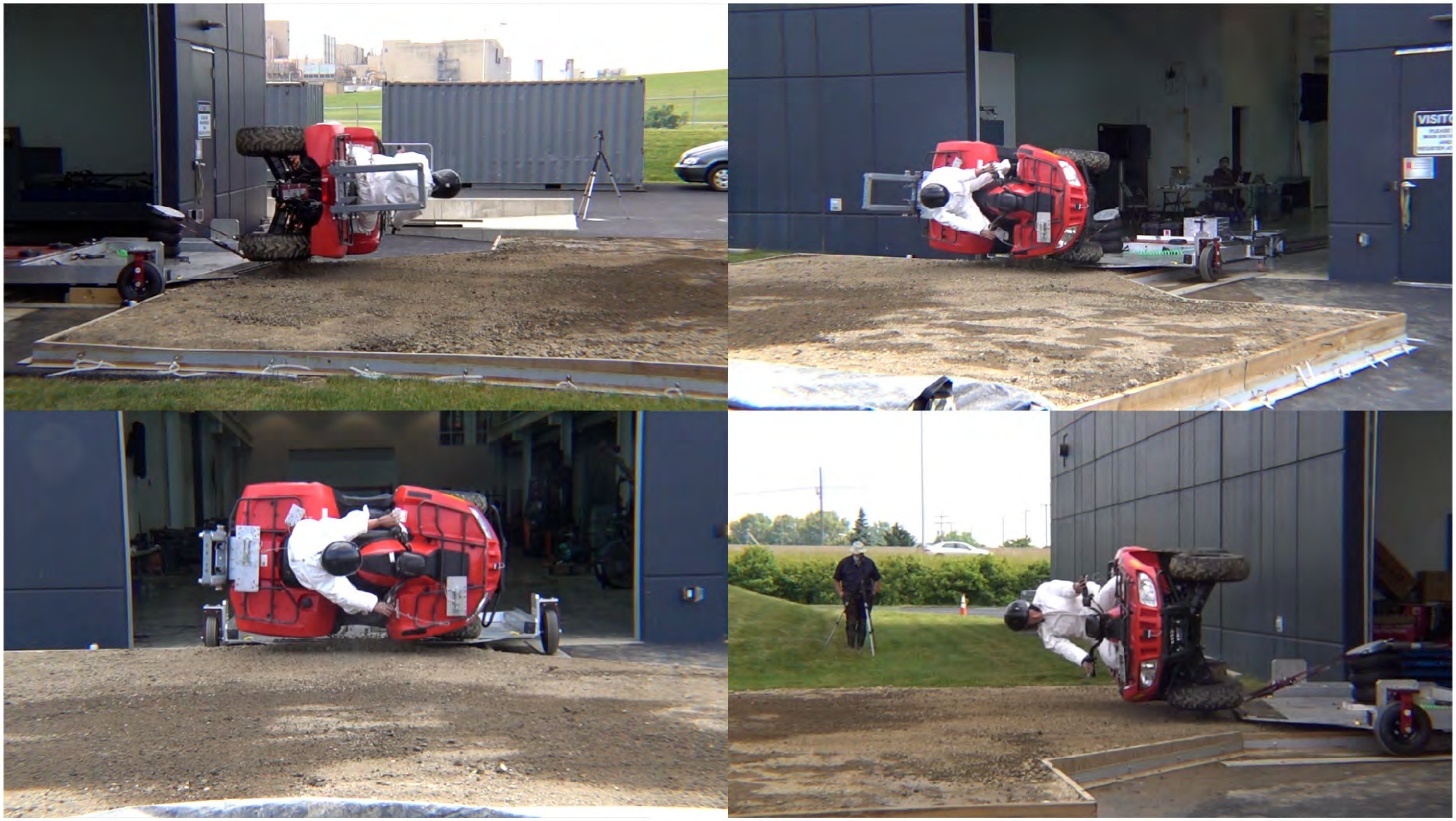
Roll Angle = 30° - Time = 0.53 sec

Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 45° - Time = 0.68 sec

Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 90° - Time = 0.93 sec



Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

ATD Head Strike - Time = 1.11 sec

Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 180° - Time = 1.52 sec

Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 270° - Time = 2.73 sec

Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Max Roll Angle = 282.3° - Time = 2.93 sec

Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

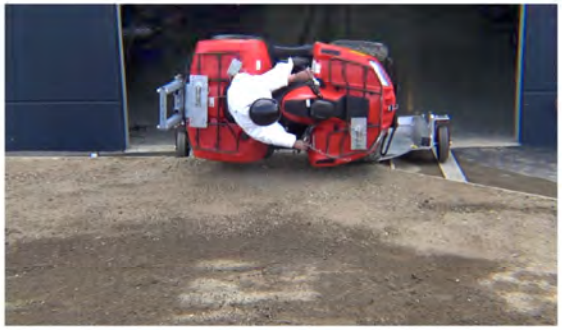
End of Run - Roll Angle = 274.5°

Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

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

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

Drone Camera - Roll Angle = 90° - Time = 0.93 sec



Drone Camera - ATD Head Strike - Time = 1.11 sec

Drone Camera - Roll Angle = 180° - Time = 1.52 sec

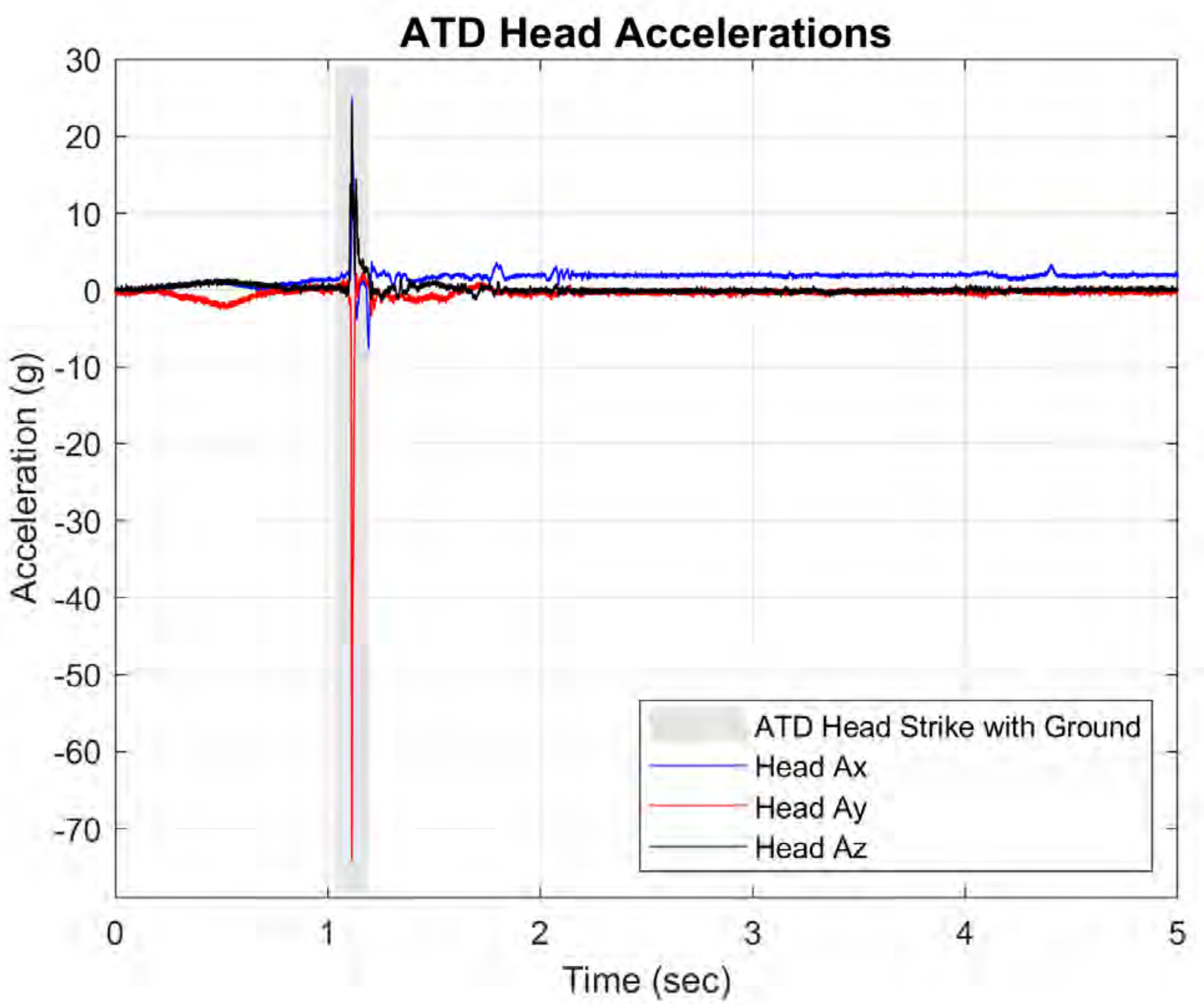
Drone Camera - Roll Angle = 270° - Time = 2.73 sec

Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

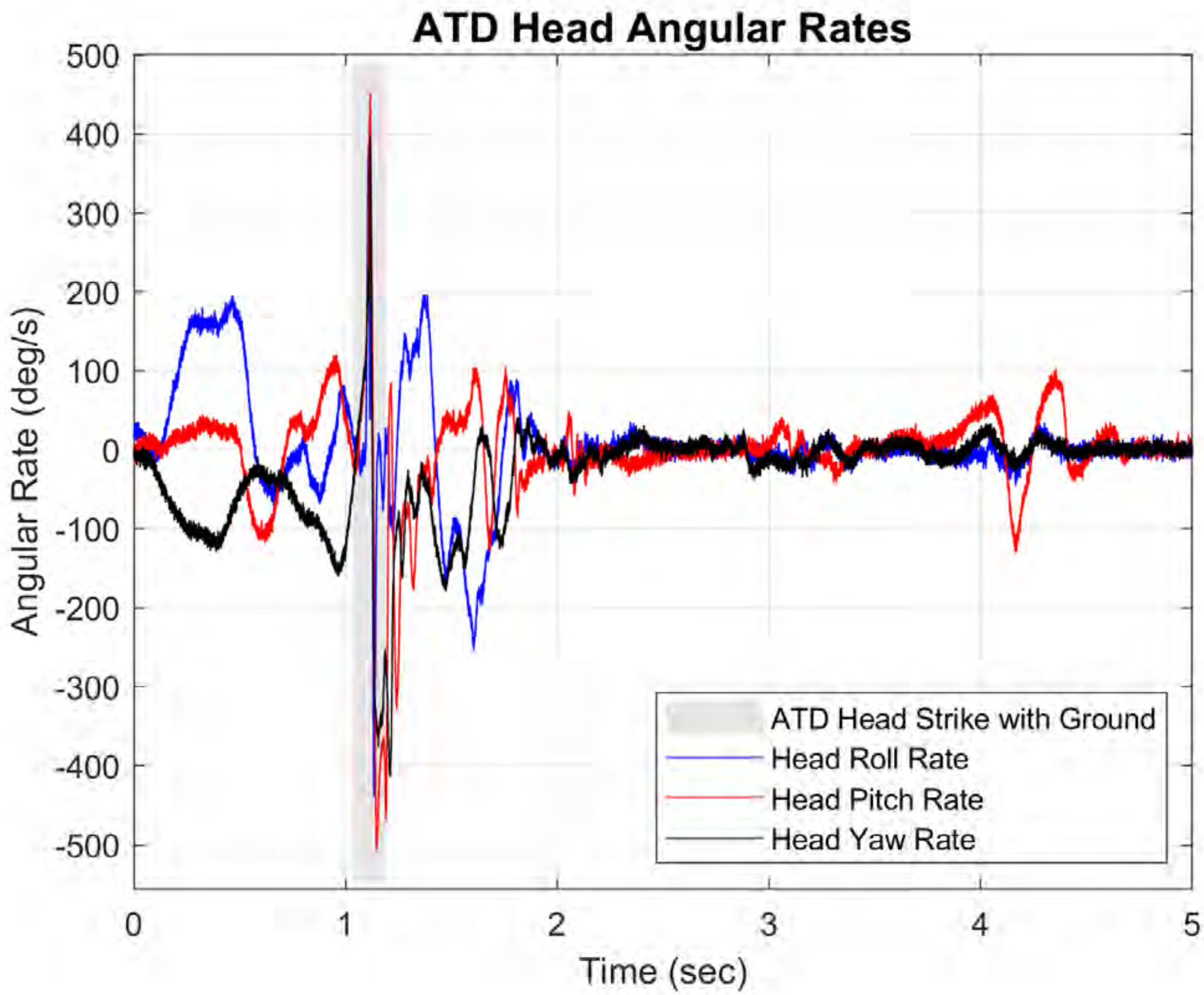
Drone Camera - Max Angle = 282.3° - Time = 2.93 sec

Drone Camera - End of Run - Roll Angle = 274.5°

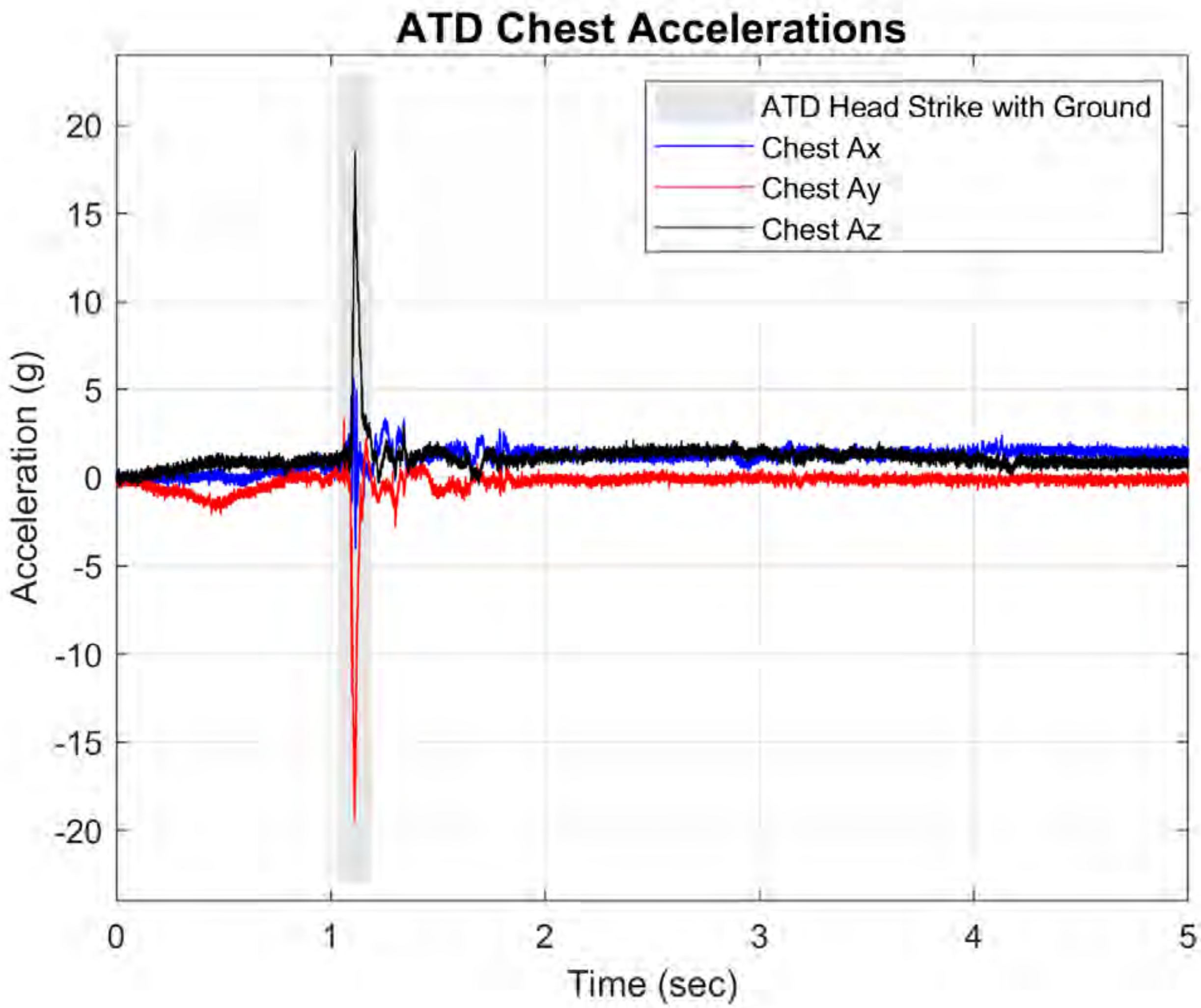
Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



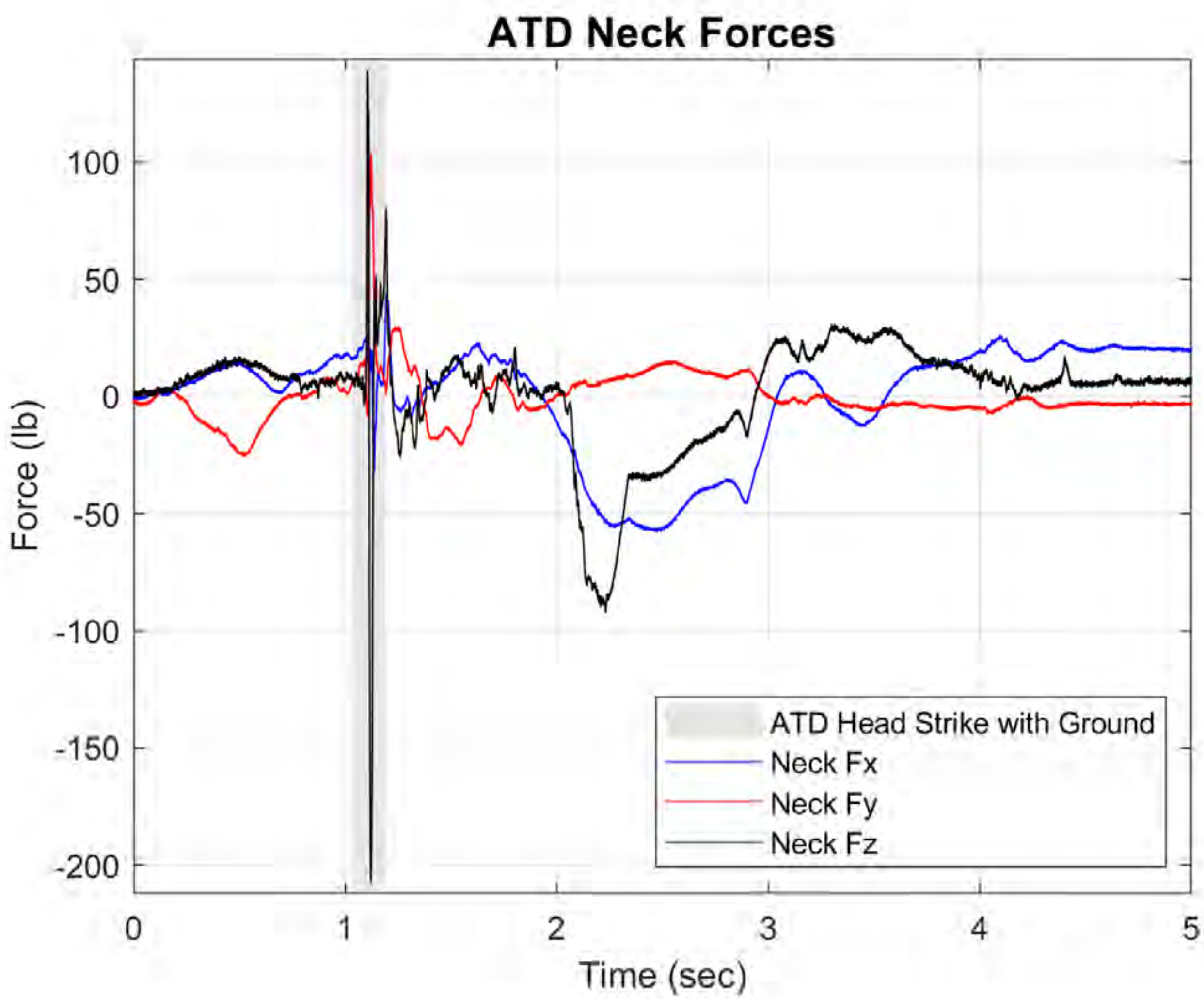
Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



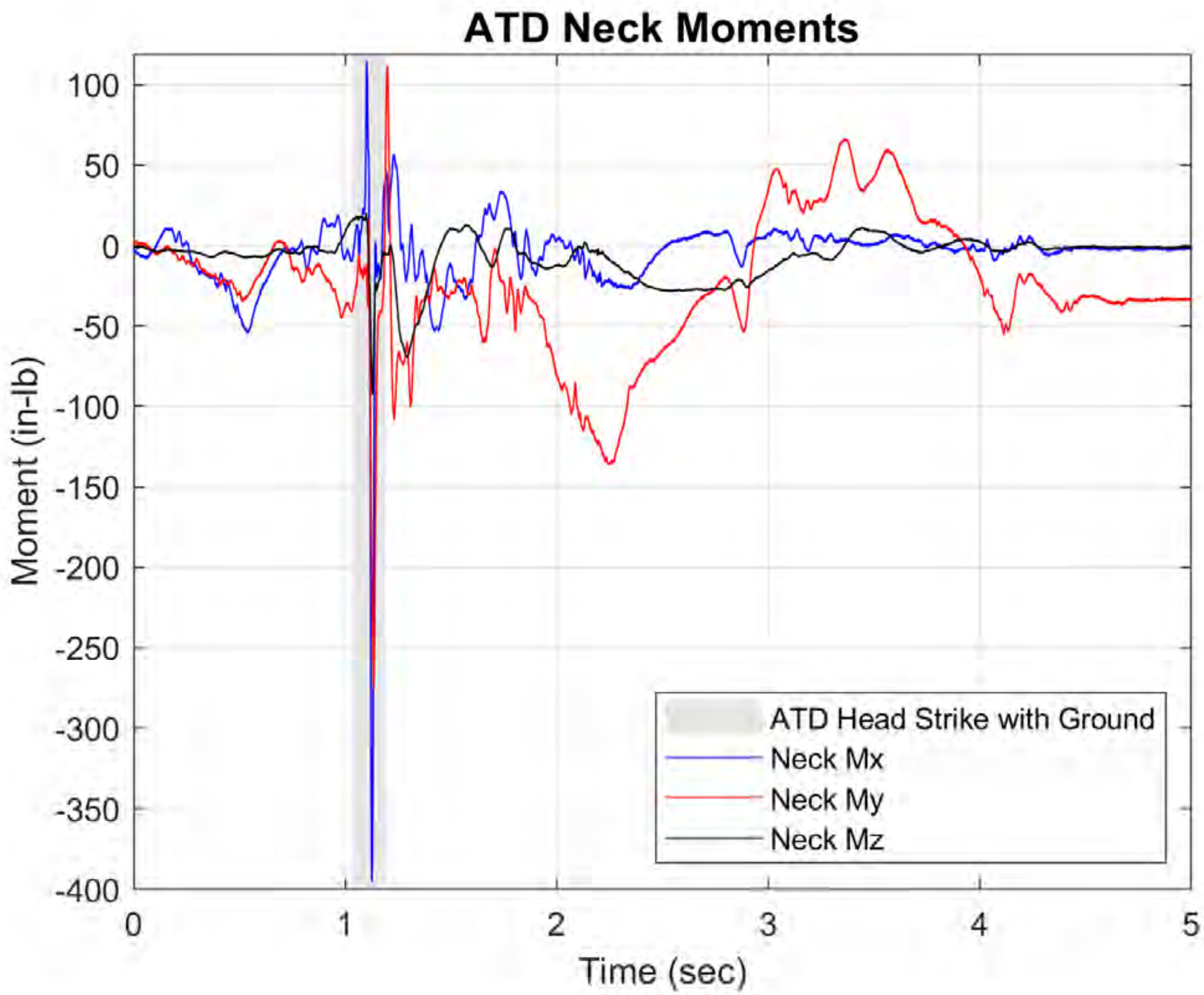
Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



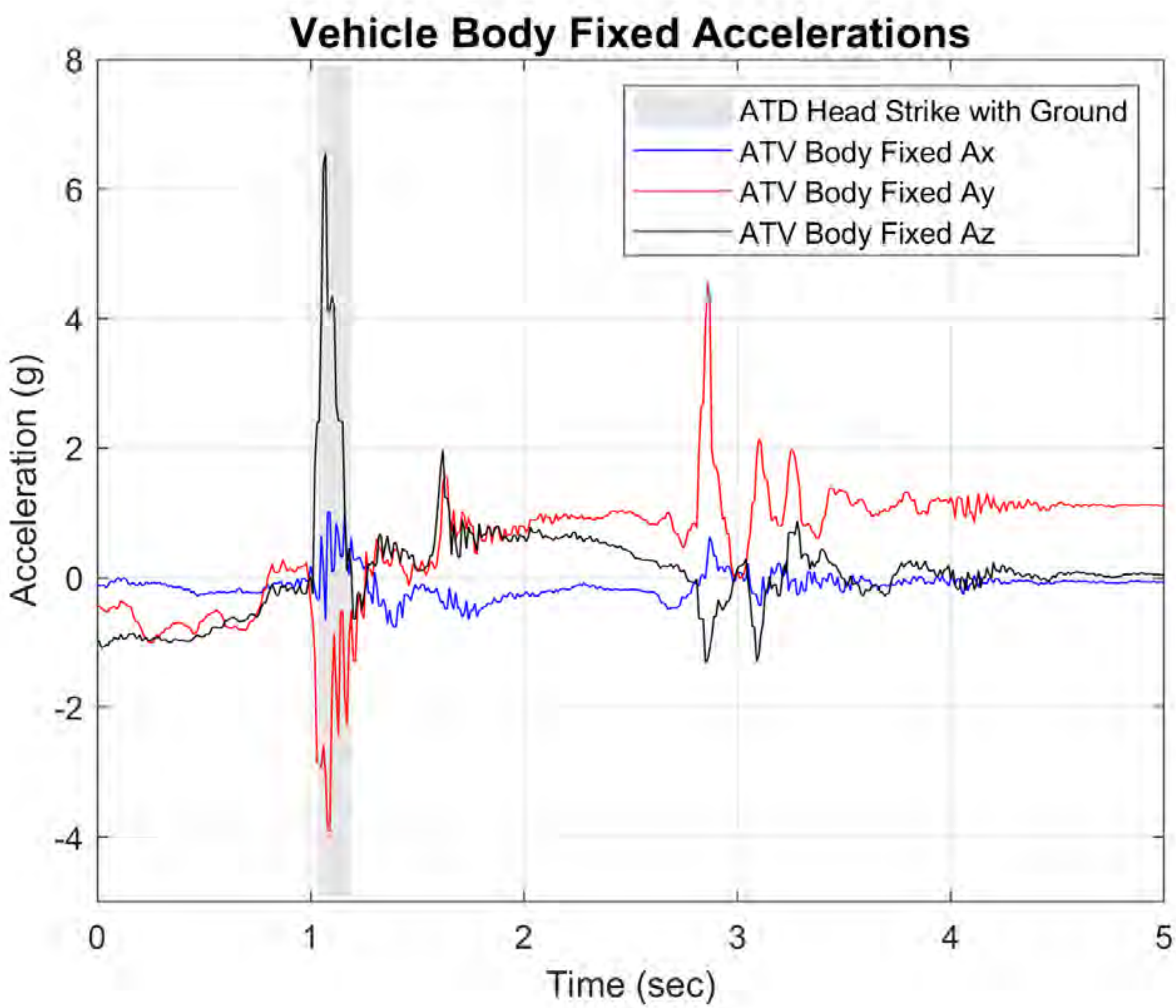
Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



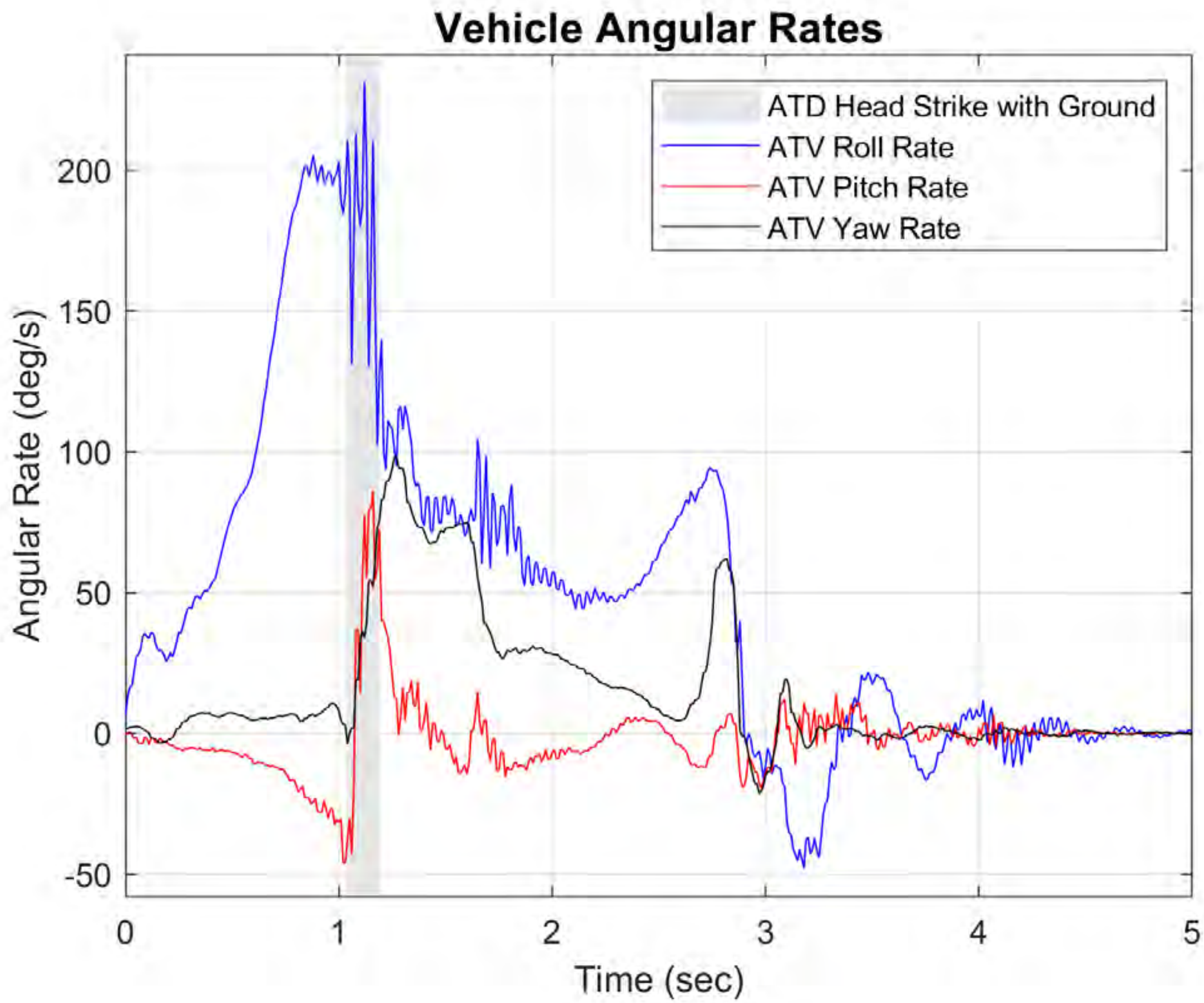
Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



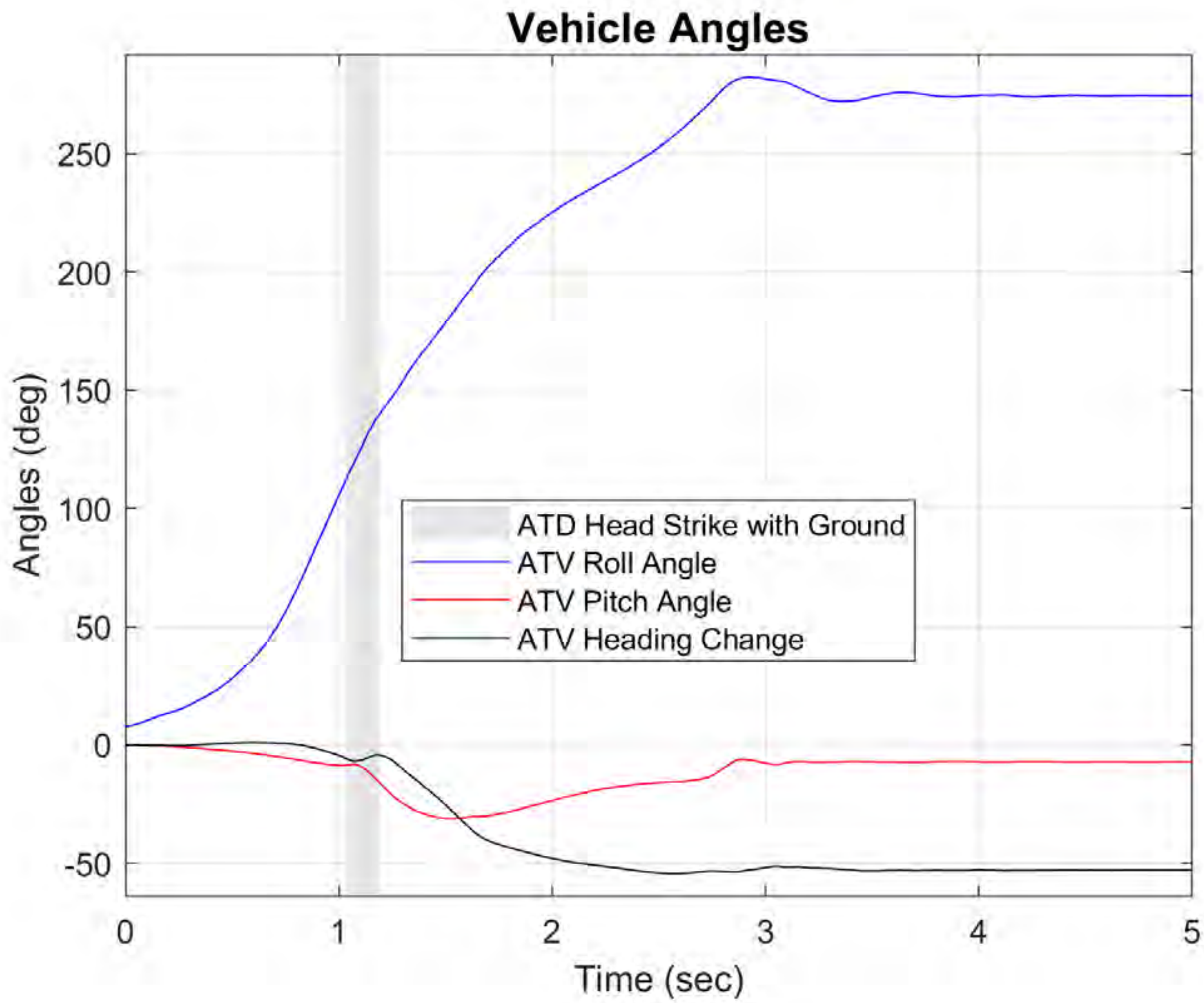
Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 30° - Time = 0.39 sec

Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 45° - Time = 0.51 sec

Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 90° - Time = 0.75 sec

Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

ATD Head Strike - Time = 0.85 sec

Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 180° - Time = 1.47 sec

Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Max Roll Angle = 195.3° - Time = 1.88 sec

Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

End of Run - Roll Angle = 178.4°

Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Drone Camera - Roll Angle = 30° - Time = 0.39 sec

Drone Camera - Roll Angle = 45° - Time = 0.51 sec

Drone Camera - Roll Angle = 90° - Time = 0.75 sec

Drone Camera - ATD Head Strike - Time = 0.85 sec

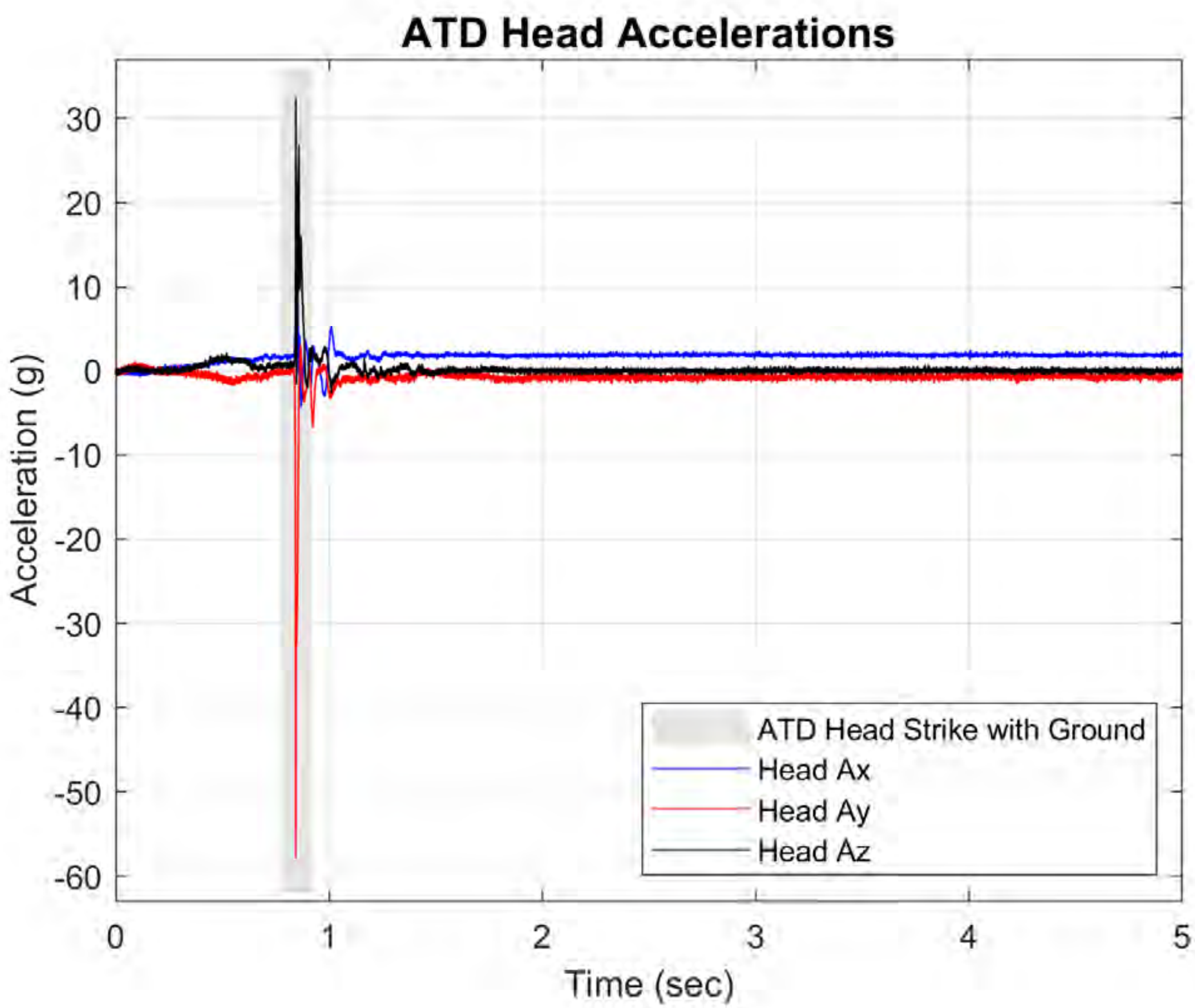
Drone Camera - Roll Angle = 180° - Time = 1.47 sec

Drone Camera - Max Angle = 195.3° - Time = 1.88 sec

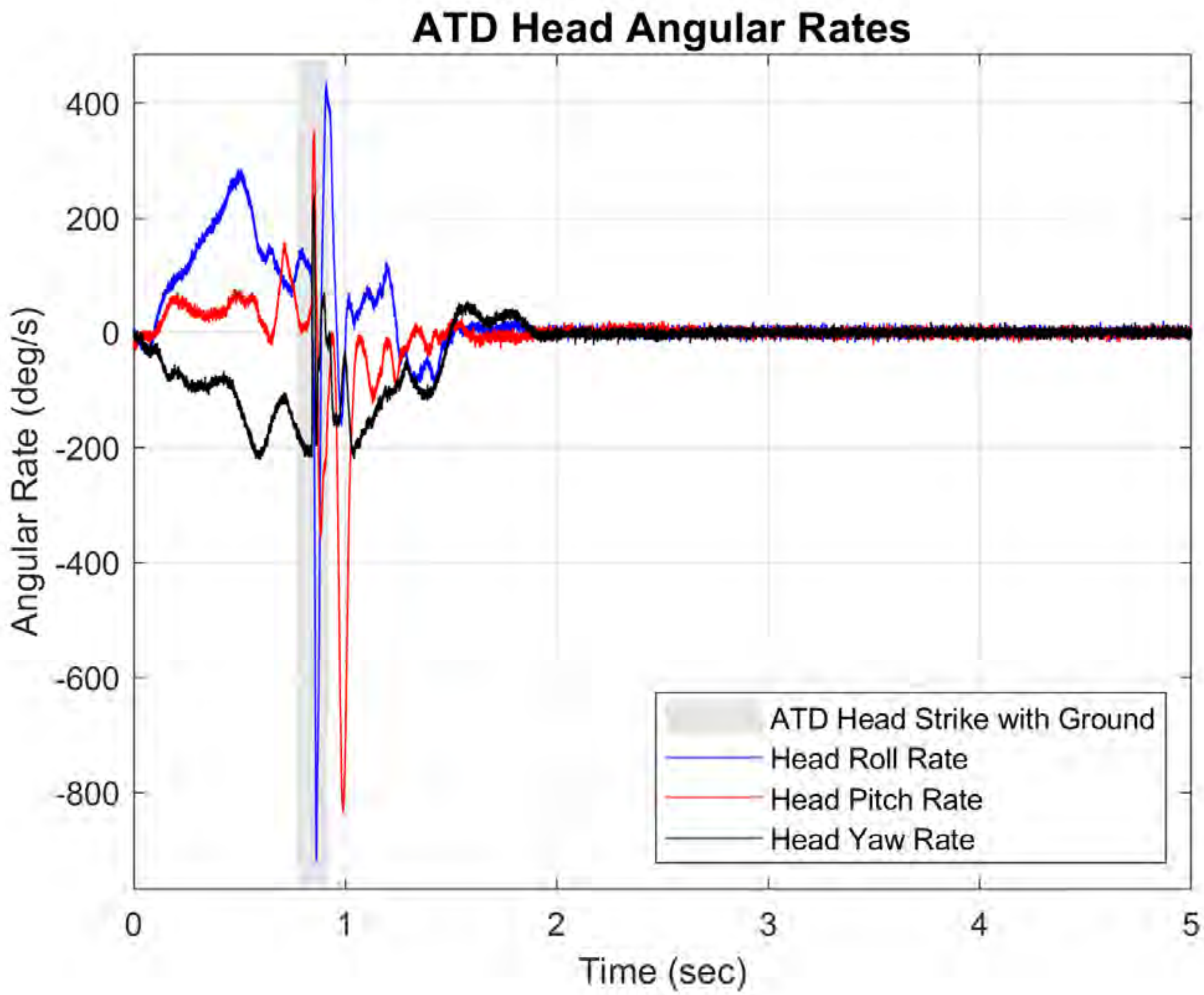
Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Drone Camera - End of Run - Roll Angle = 178.4°

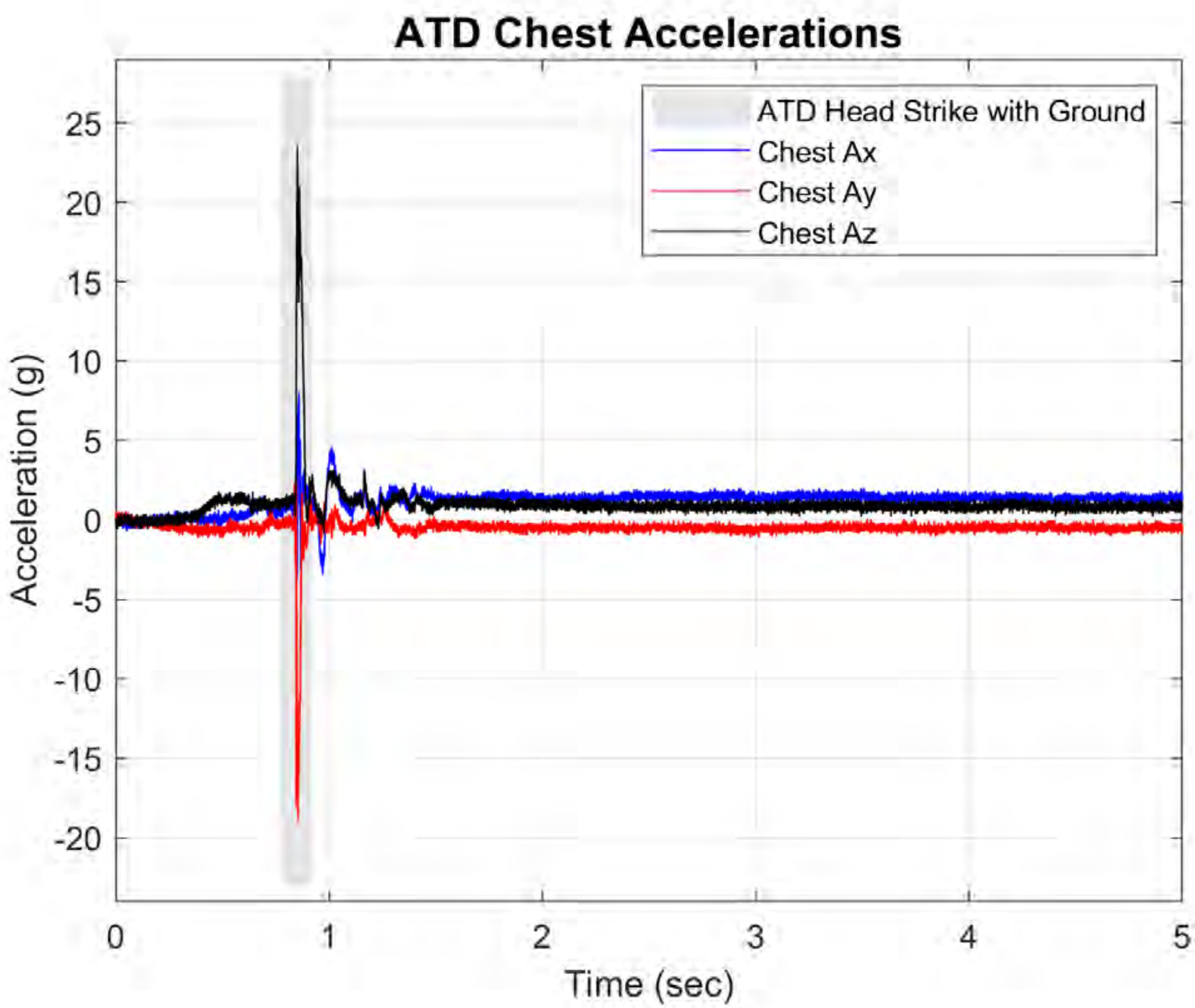
Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



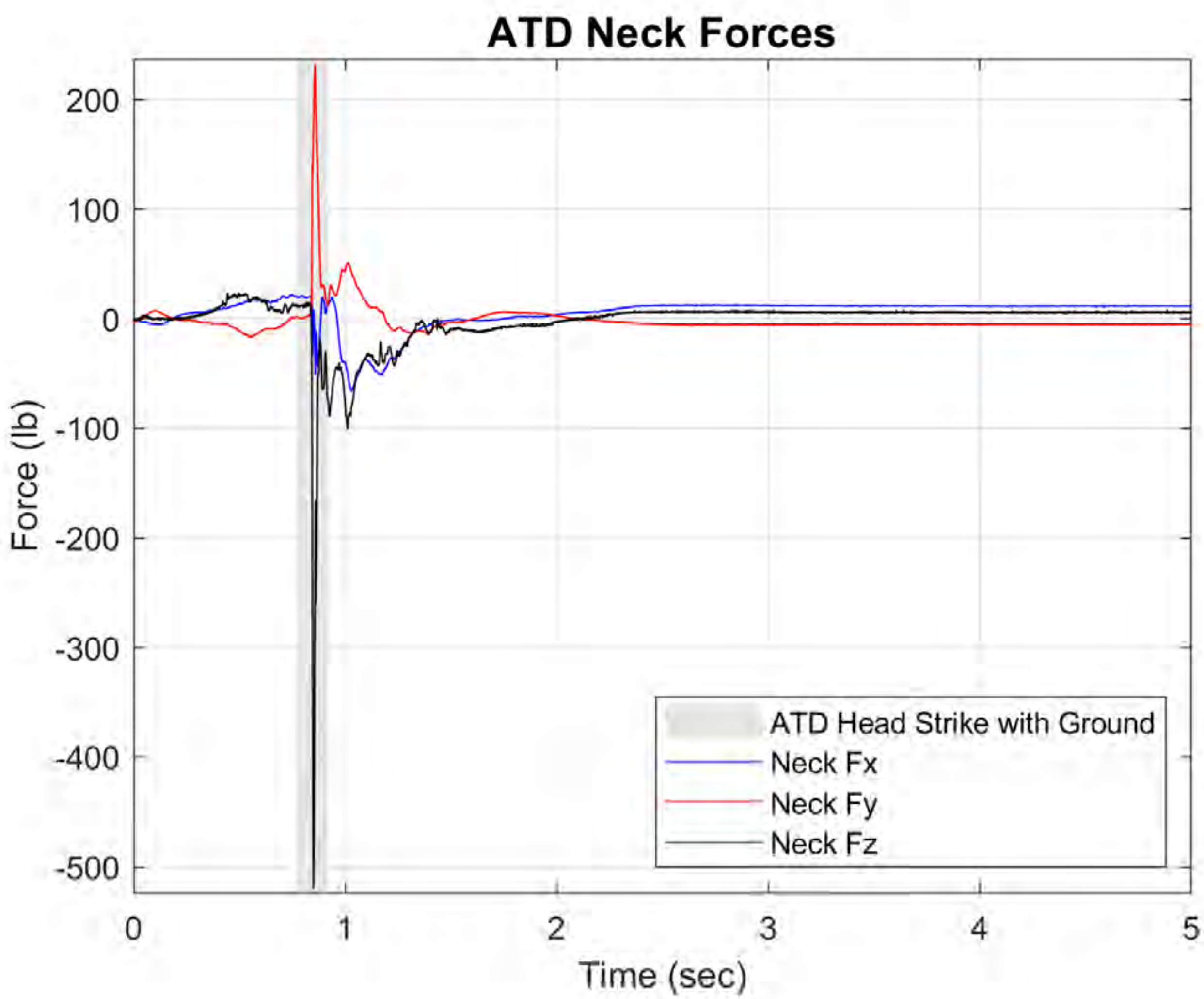
Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



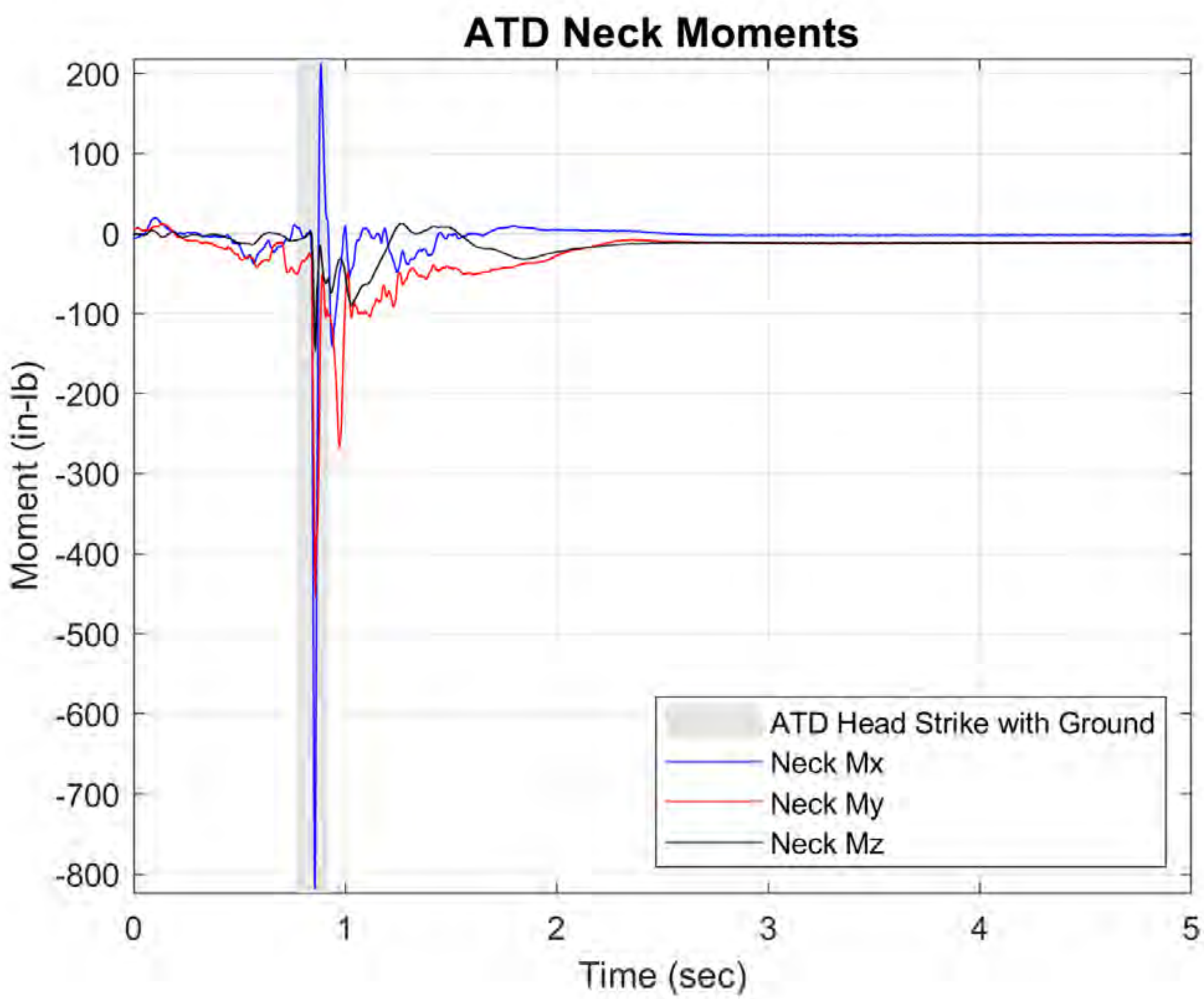
Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



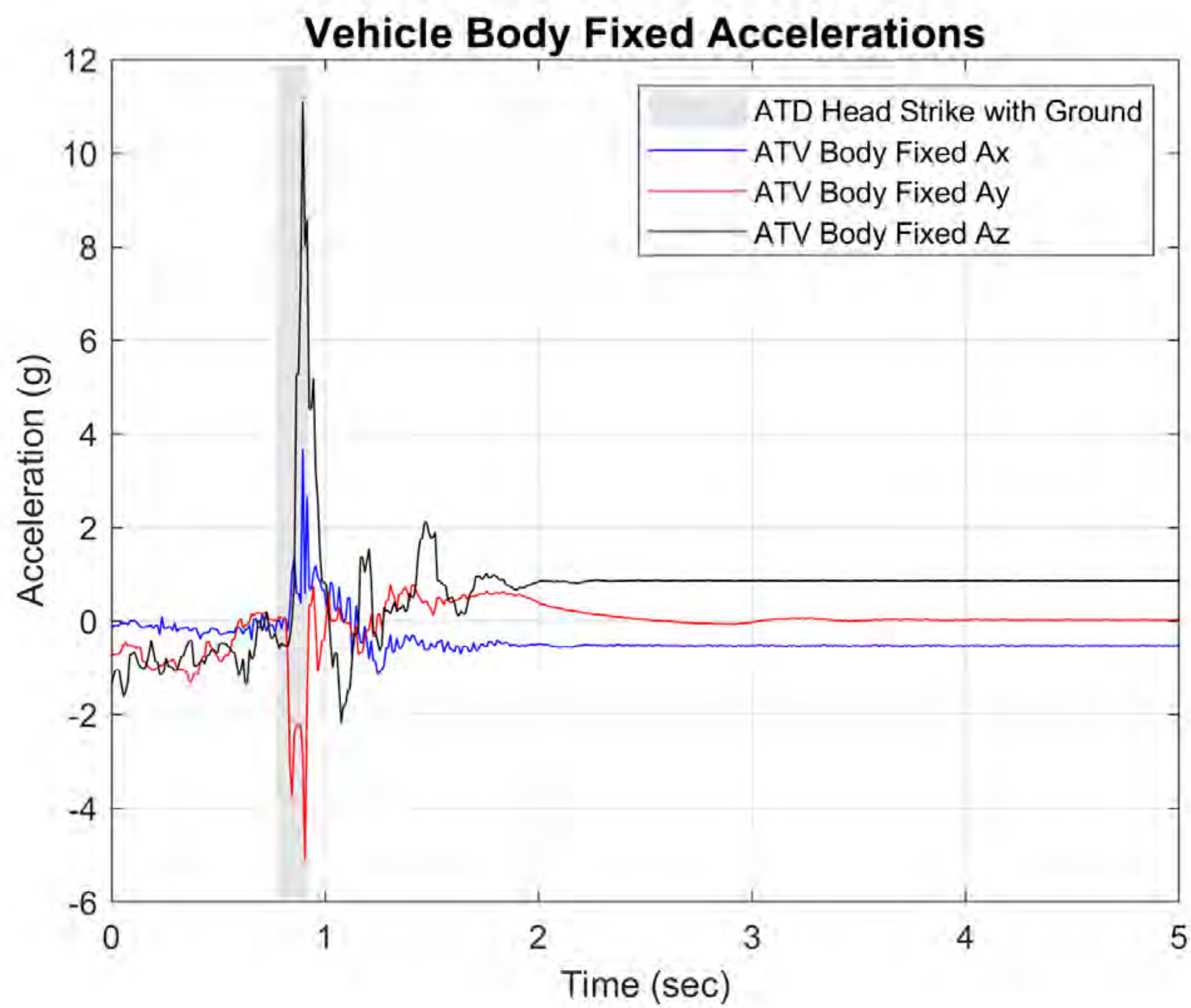
Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



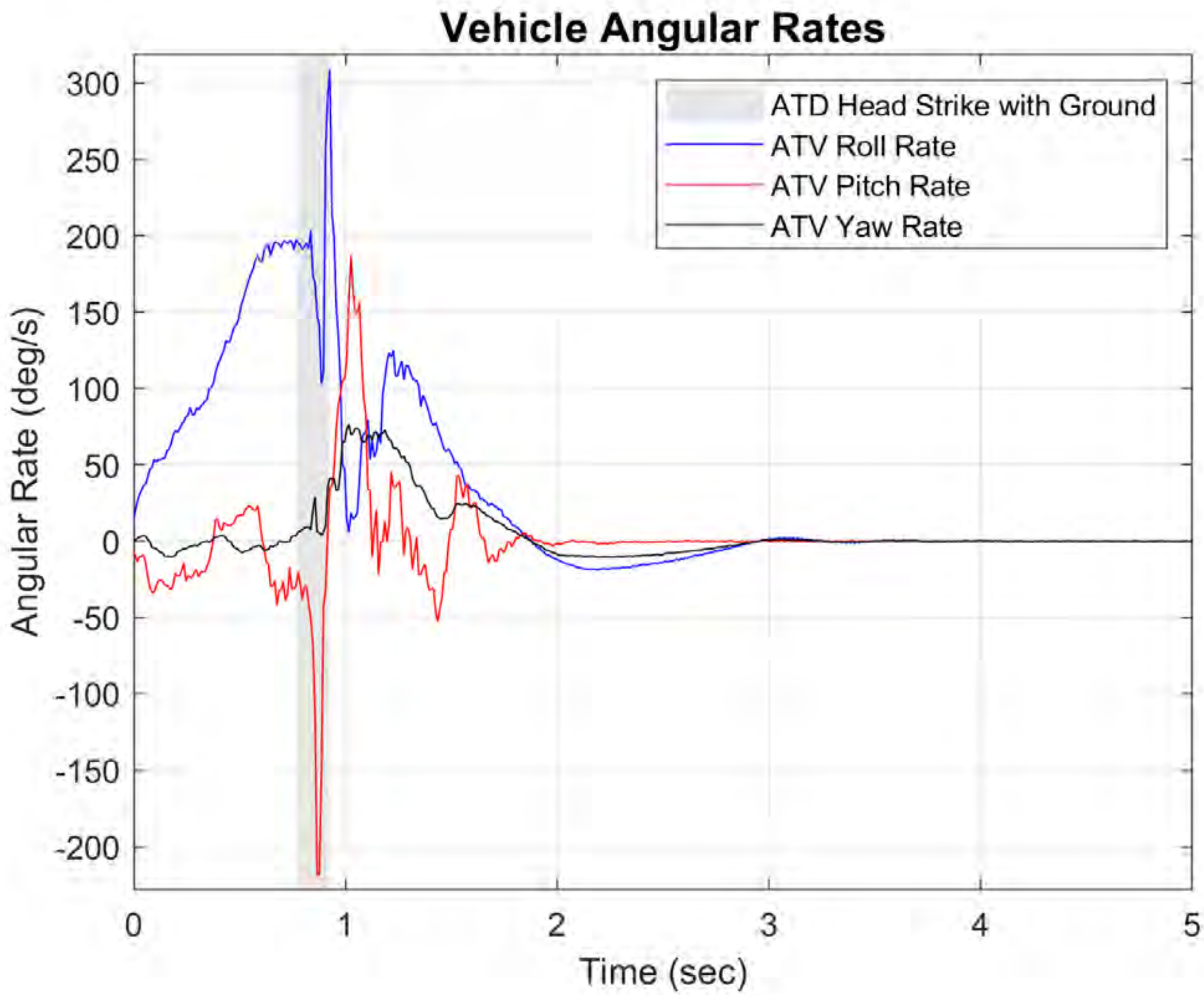
Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



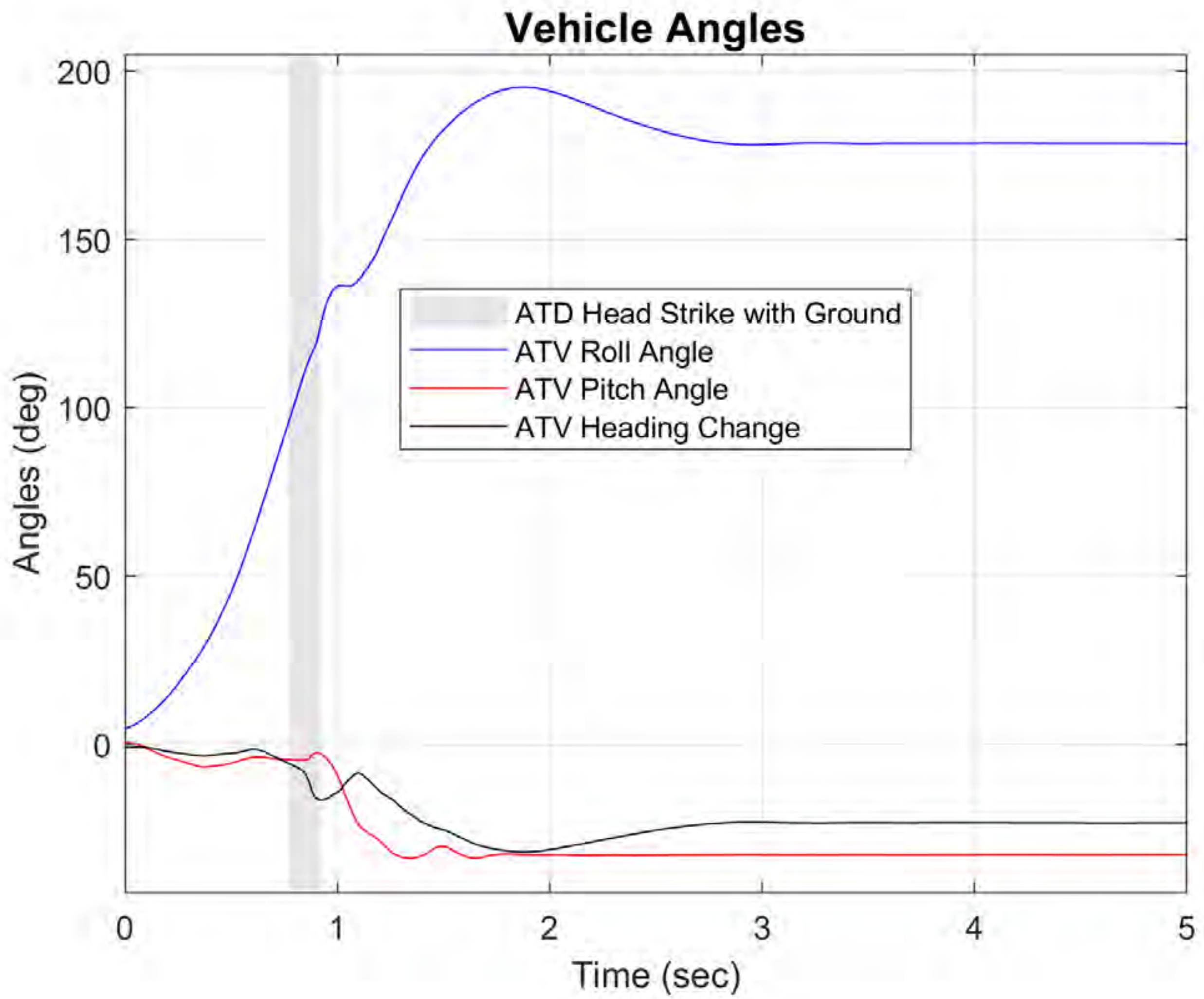
Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 30° - Time = 0.51 sec

Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD

Roll Angle = 45° - Time = 0.64 sec

Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD

Roll Angle = 90° - Time = 0.89 sec

Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD

ATD Head Strike - Time = 1.02 sec

Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD

Roll Angle = 180° - Time = 1.46 sec

Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD

Roll Angle = 270° - Time = 2.19 sec

Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD

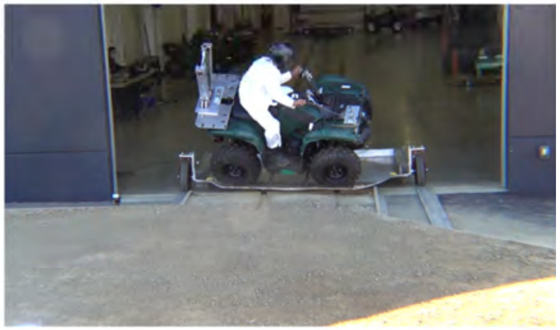
Max Roll Angle = 287.3° - Time = 2.62 sec

Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD

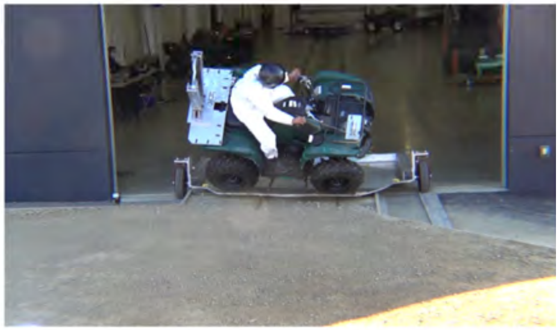
End of Run - Roll Angle = 269.1°

Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD

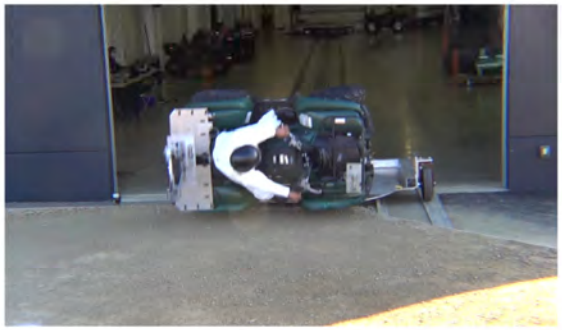
Drone Camera - Roll Angle = 30° - Time = 0.51 sec



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



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



Drone Camera - ATD Head Strike - Time = 1.02 sec

Drone Camera - Roll Angle = 180° - Time = 1.46 sec

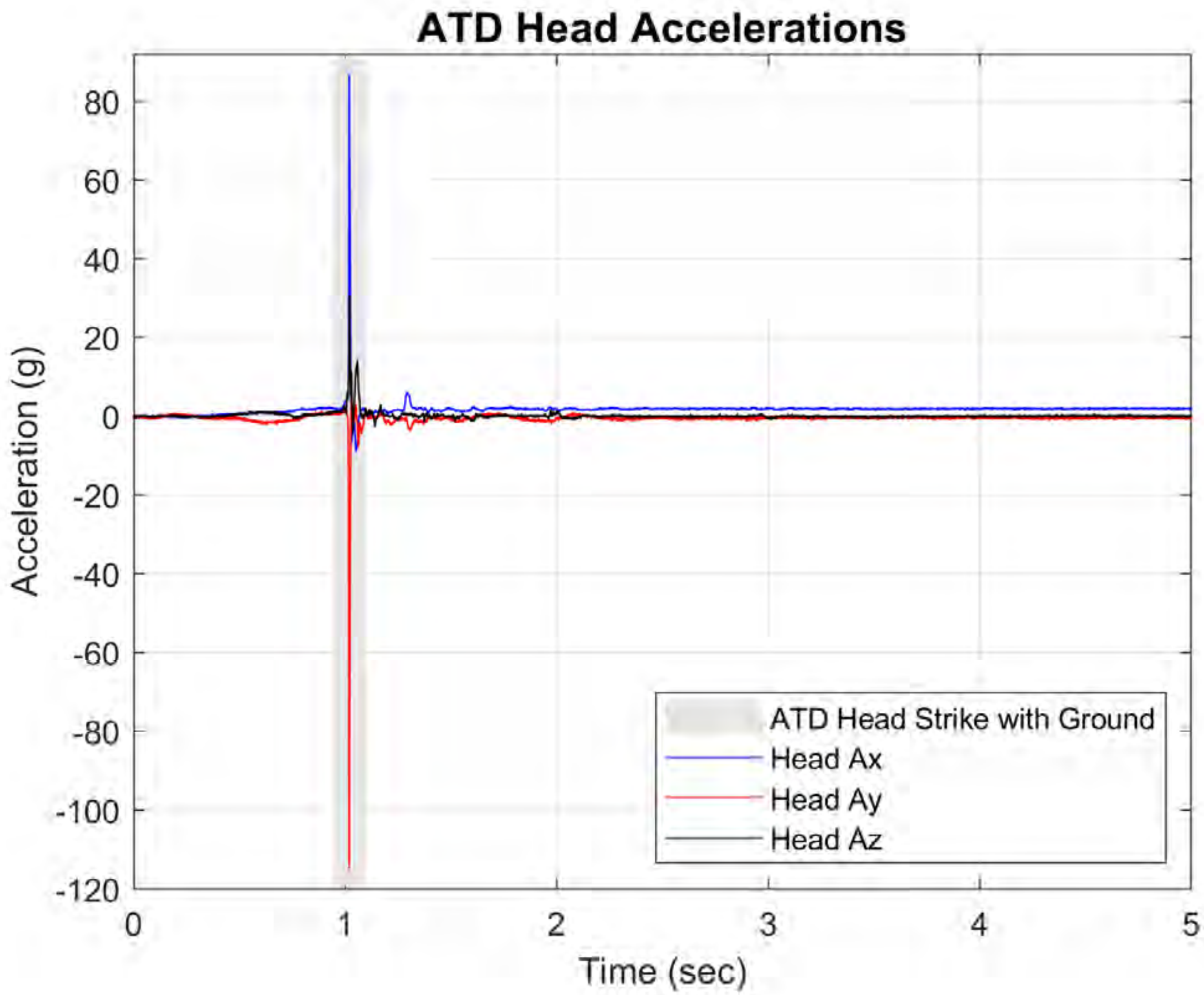
Drone Camera - Roll Angle = 270° - Time = 2.19 sec

Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD

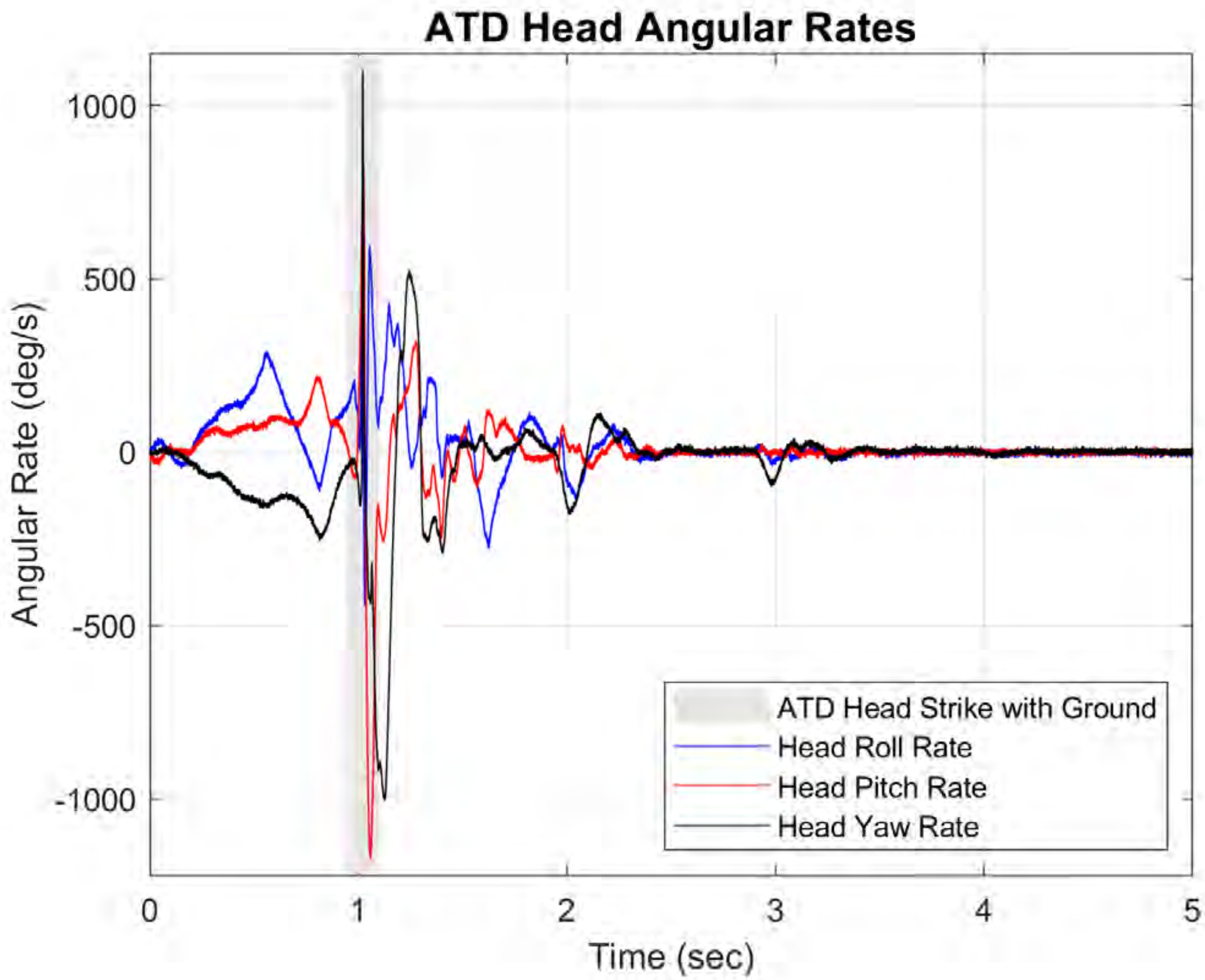
Drone Camera - Max Angle = 287.3° - Time = 2.62 sec

Drone Camera - End of Run - Roll Angle = 269.1°

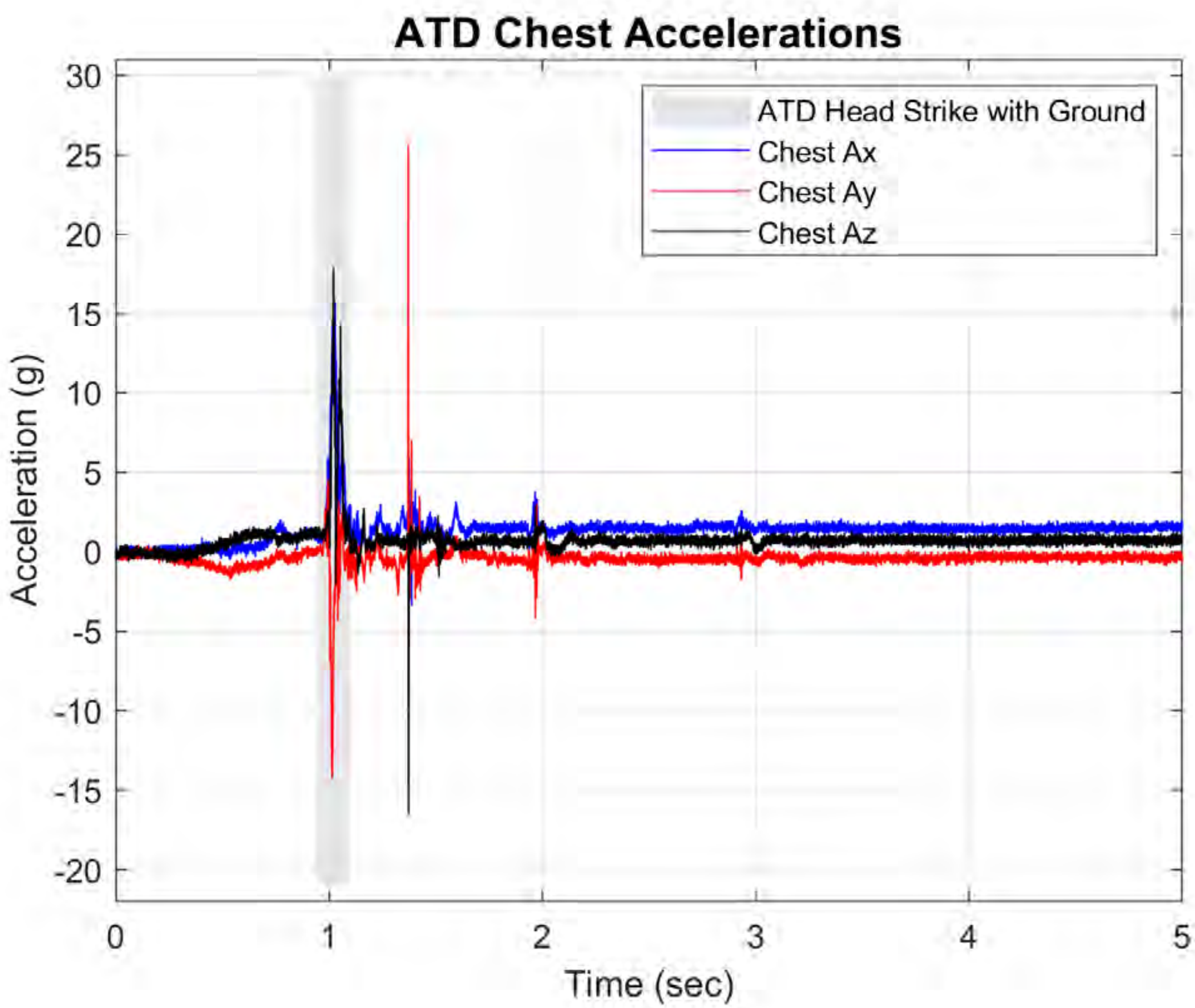
Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD



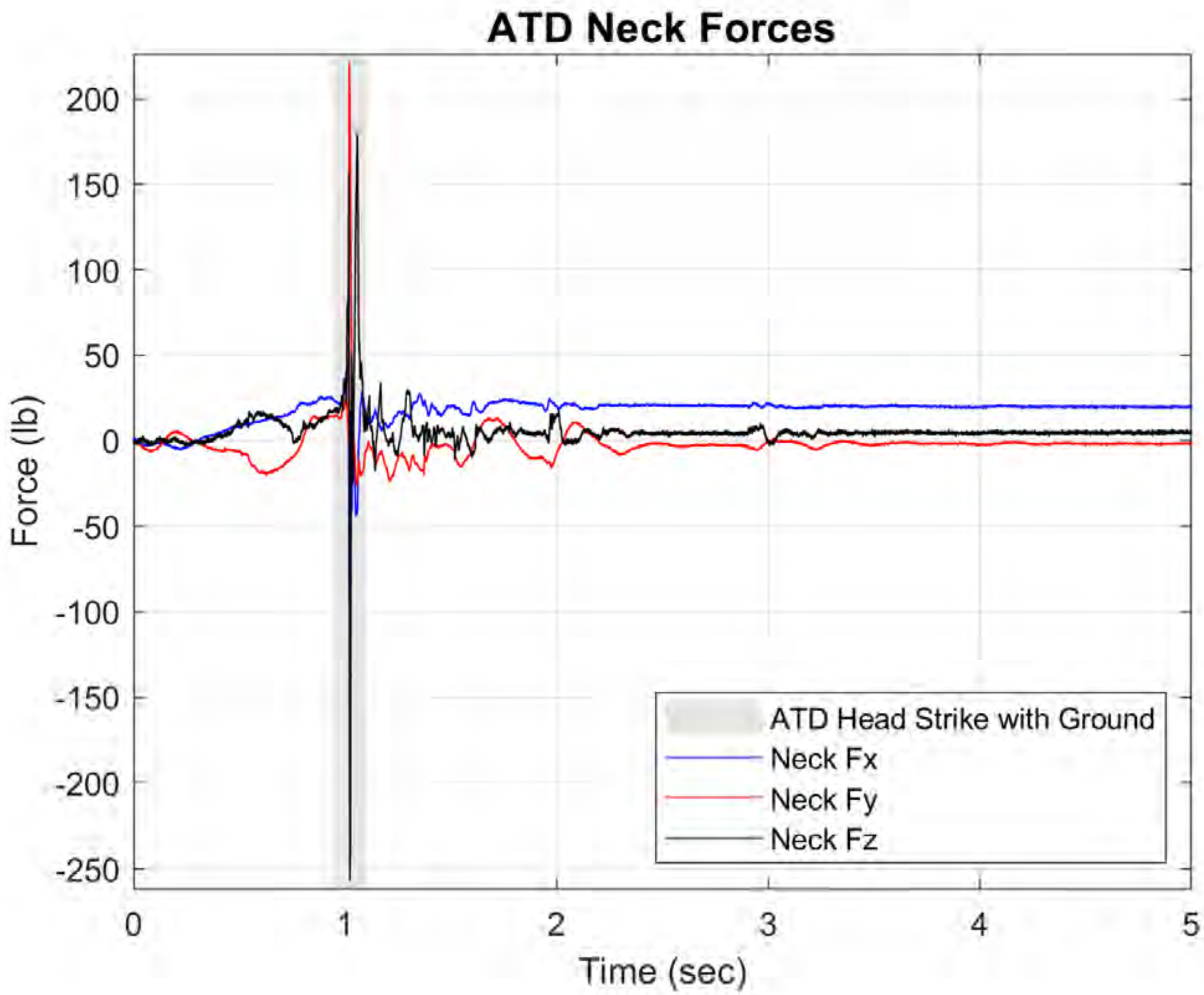
Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD



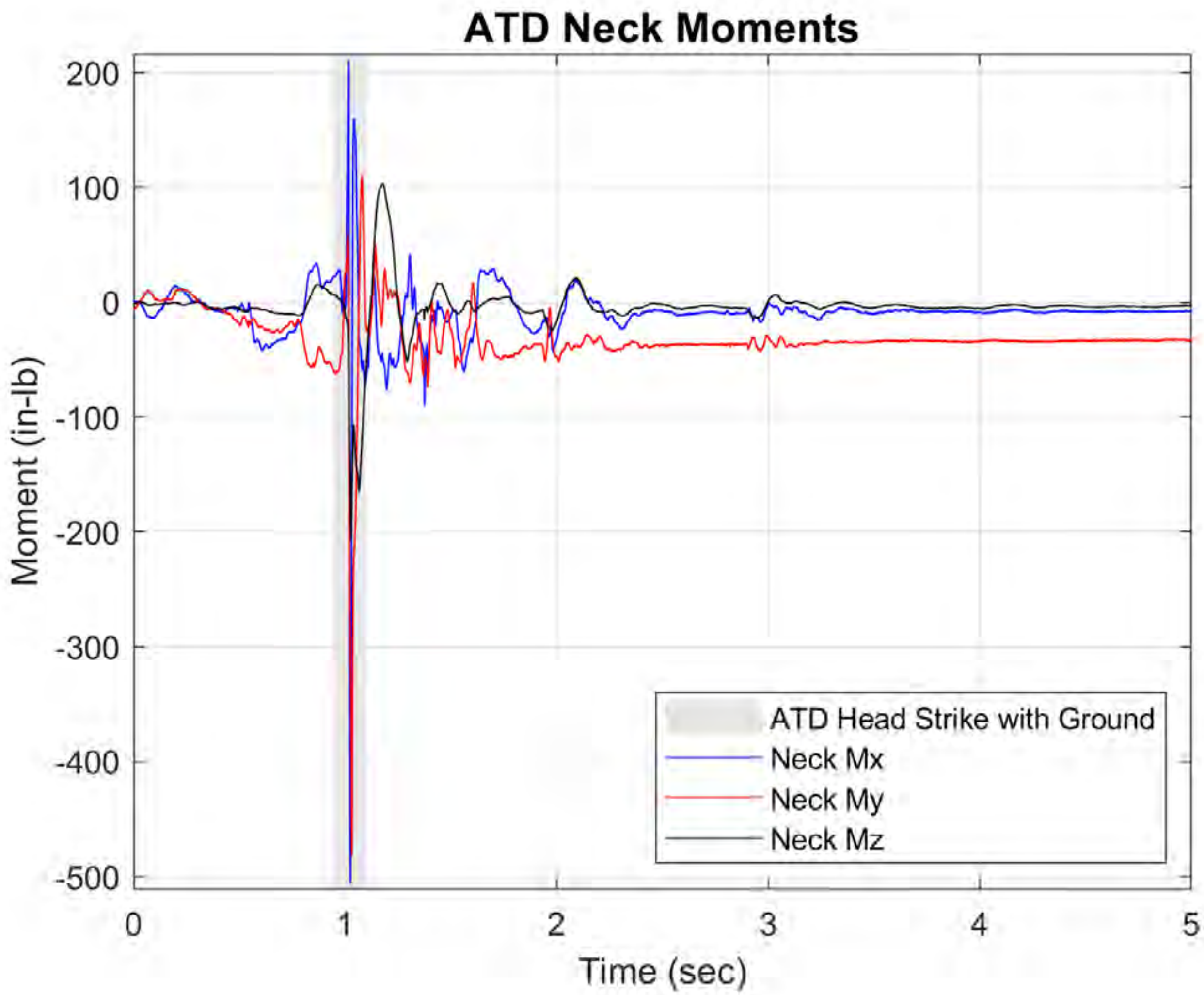
Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD



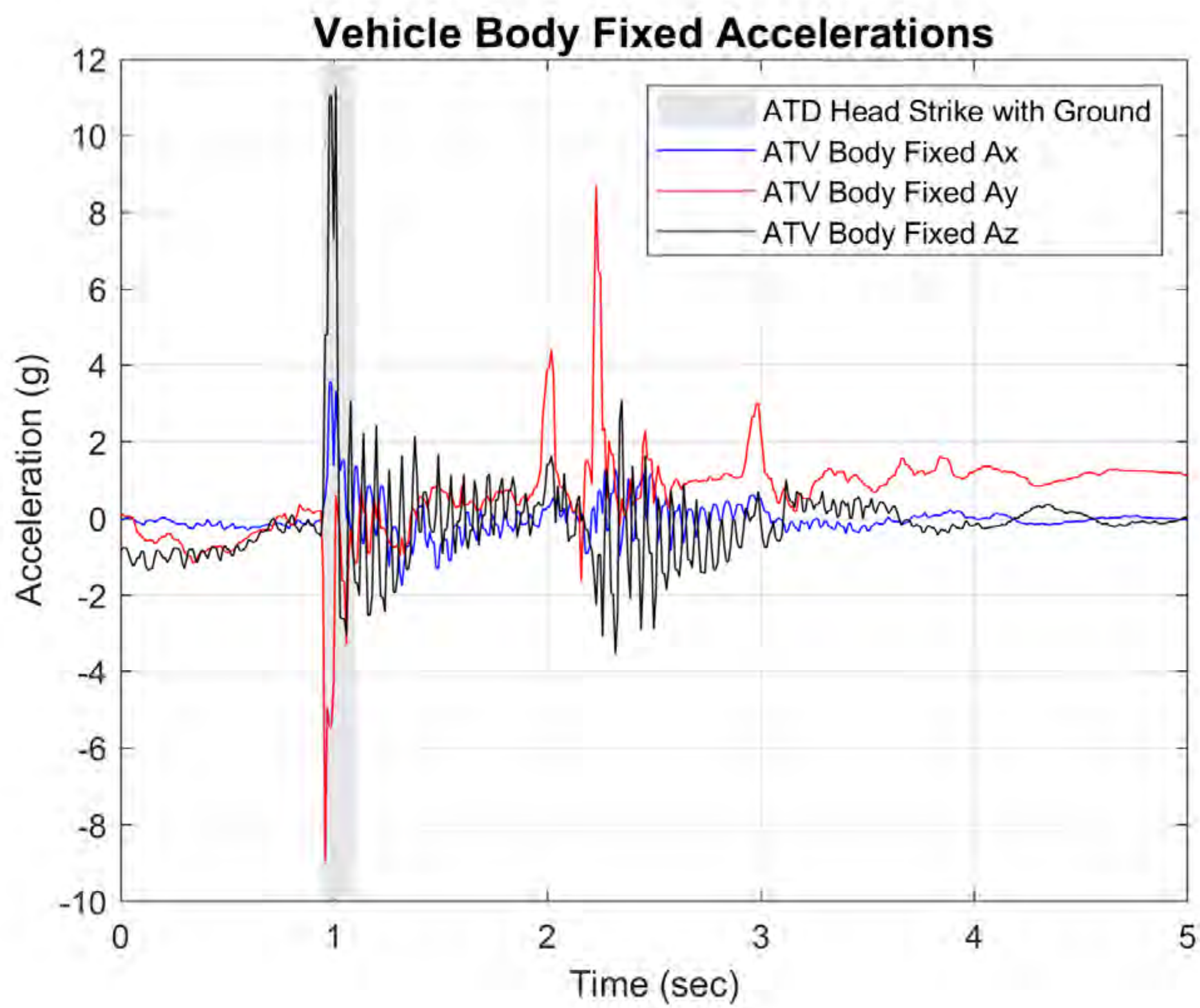
Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD



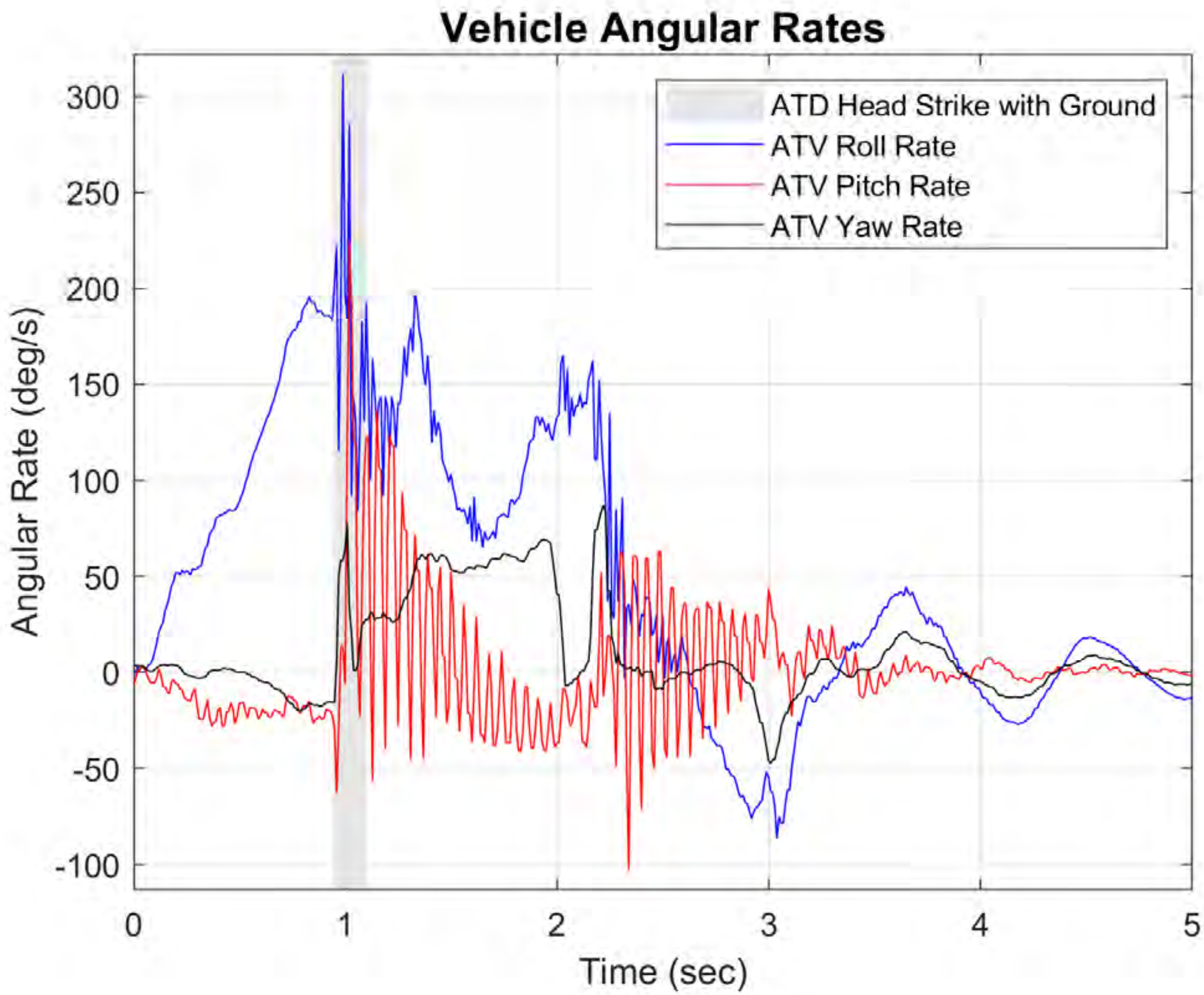
Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD



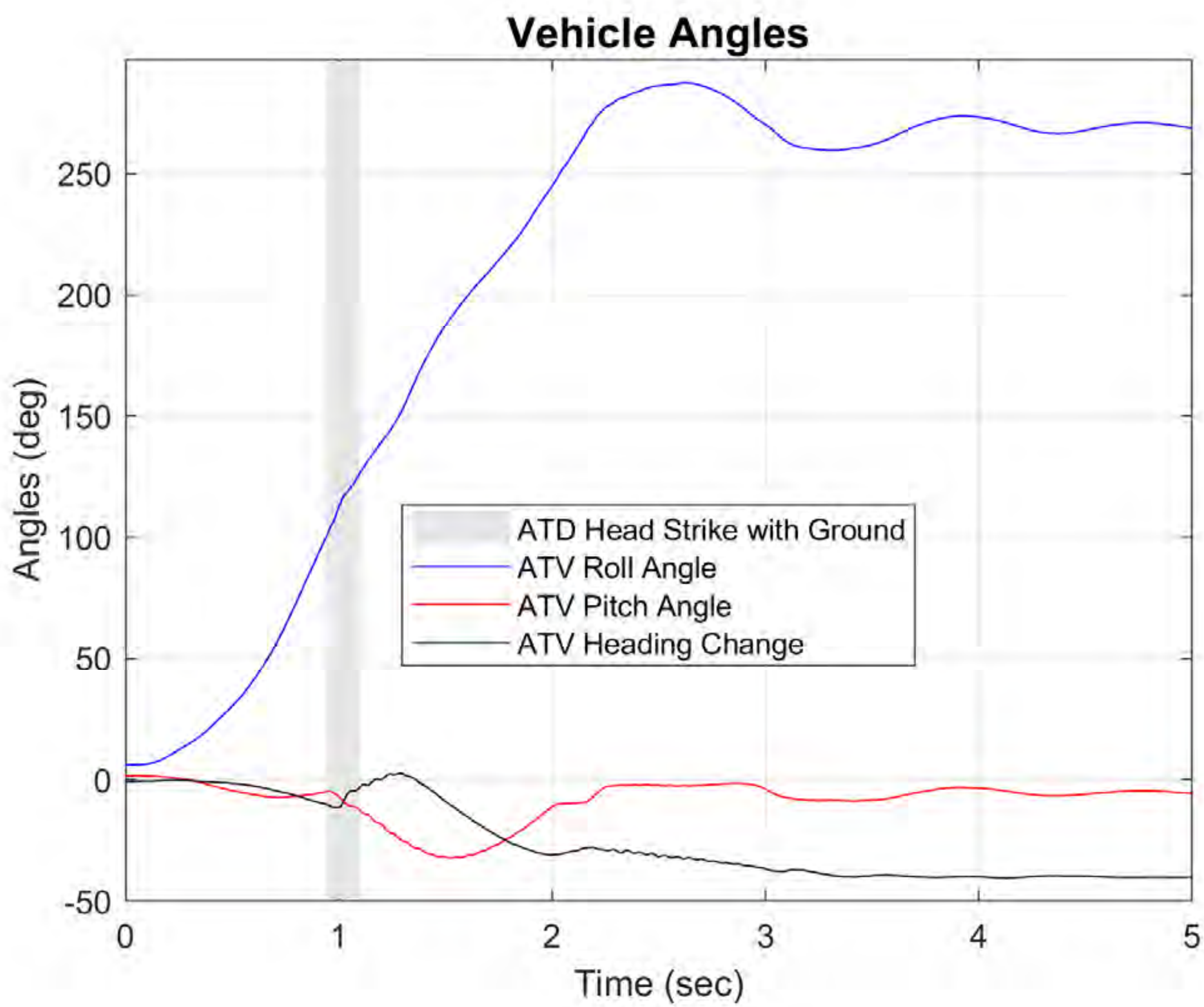
Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD



Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD



Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD



Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD

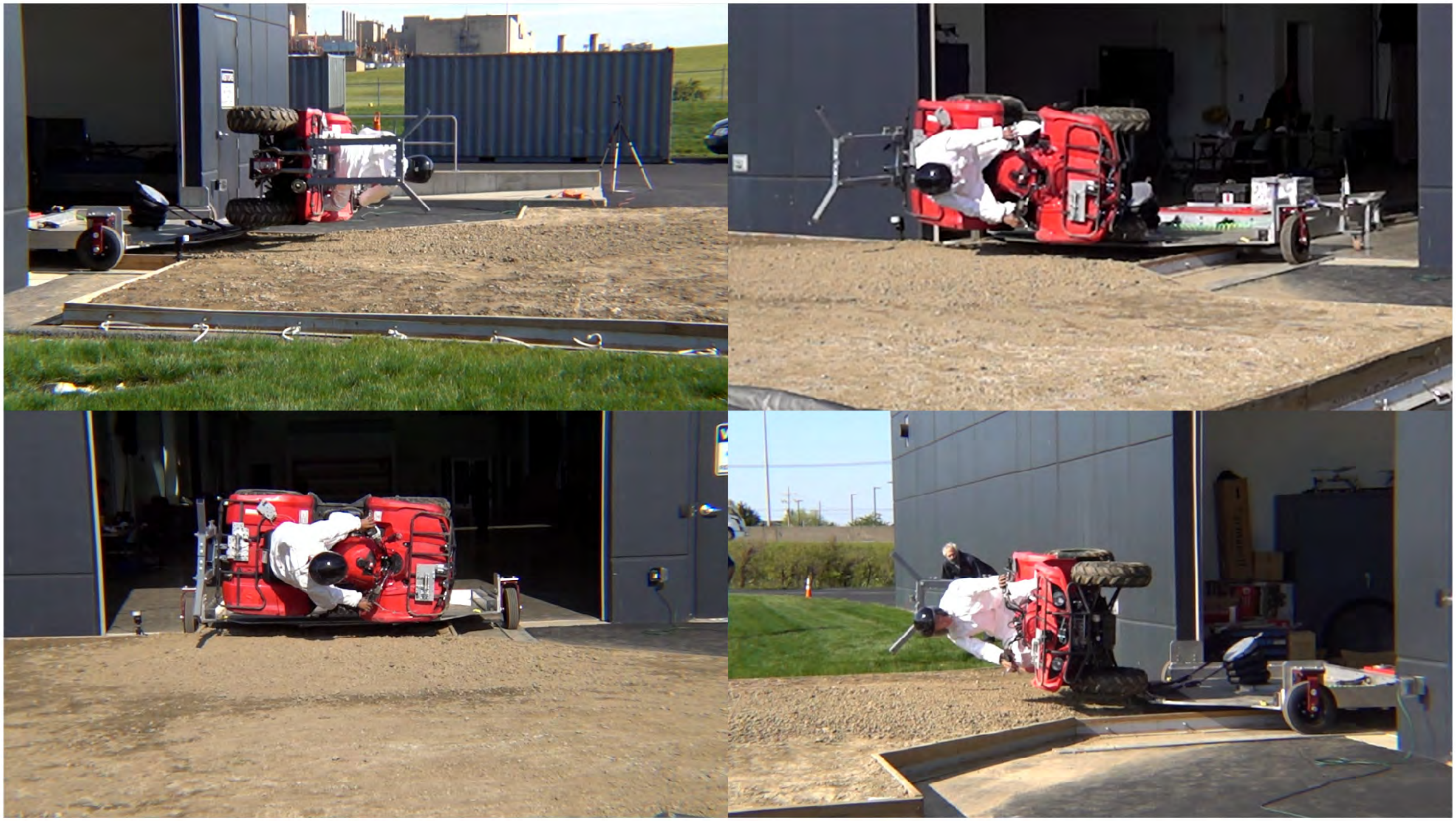
Roll Angle = 30° - Time = 0.41 sec

Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Roll Angle = 45° - Time = 0.52 sec

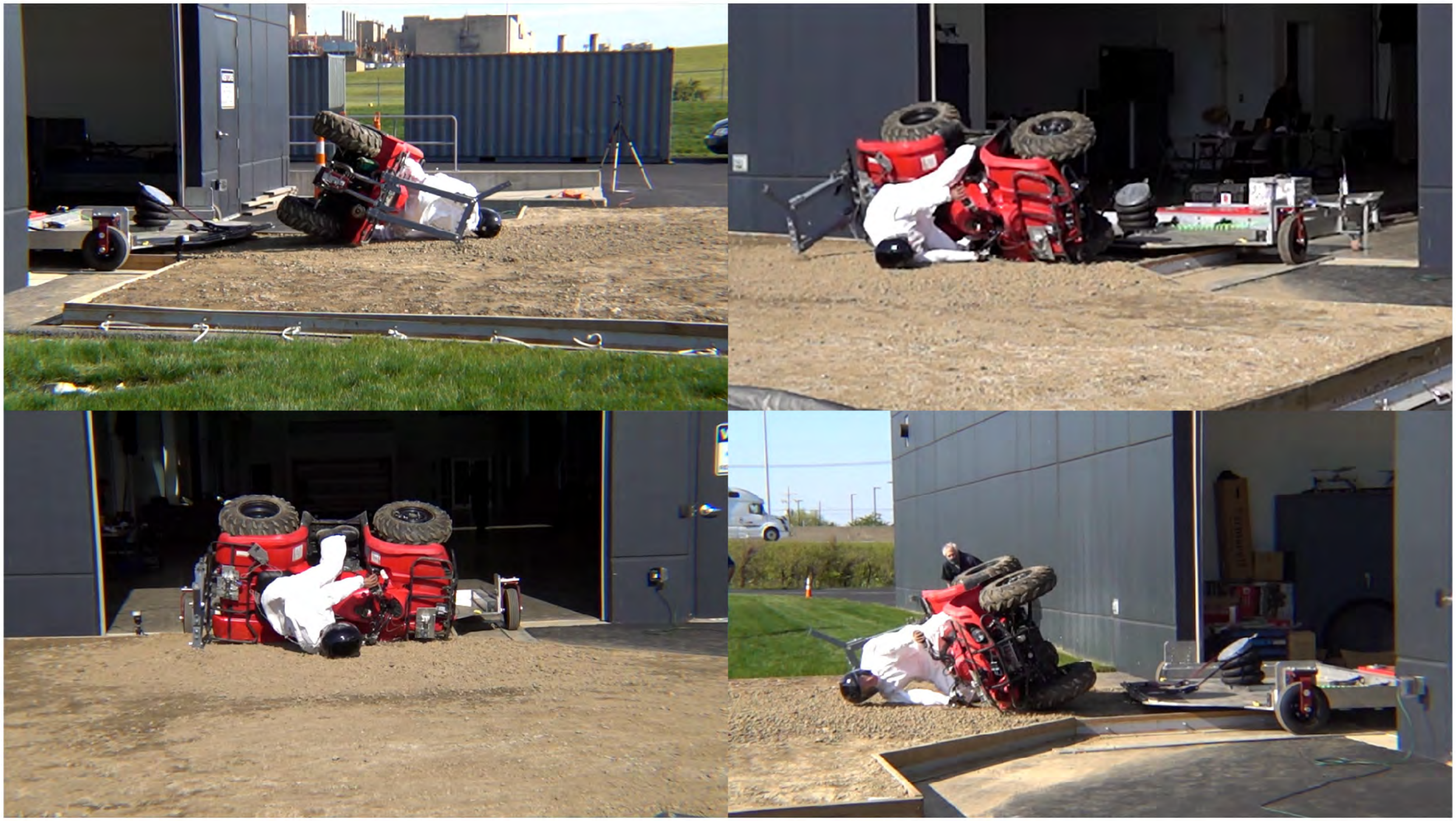
Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Roll Angle = 90° - Time = 0.74 sec



Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

ATD Head Strike - Time = 0.86 sec



Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Max Roll Angle = 167.6° - Time = 1.75 sec

Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

End of Run - Roll Angle = 98.7°

Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

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

Drone Camera - Roll Angle = 45° - Time = 0.52 sec

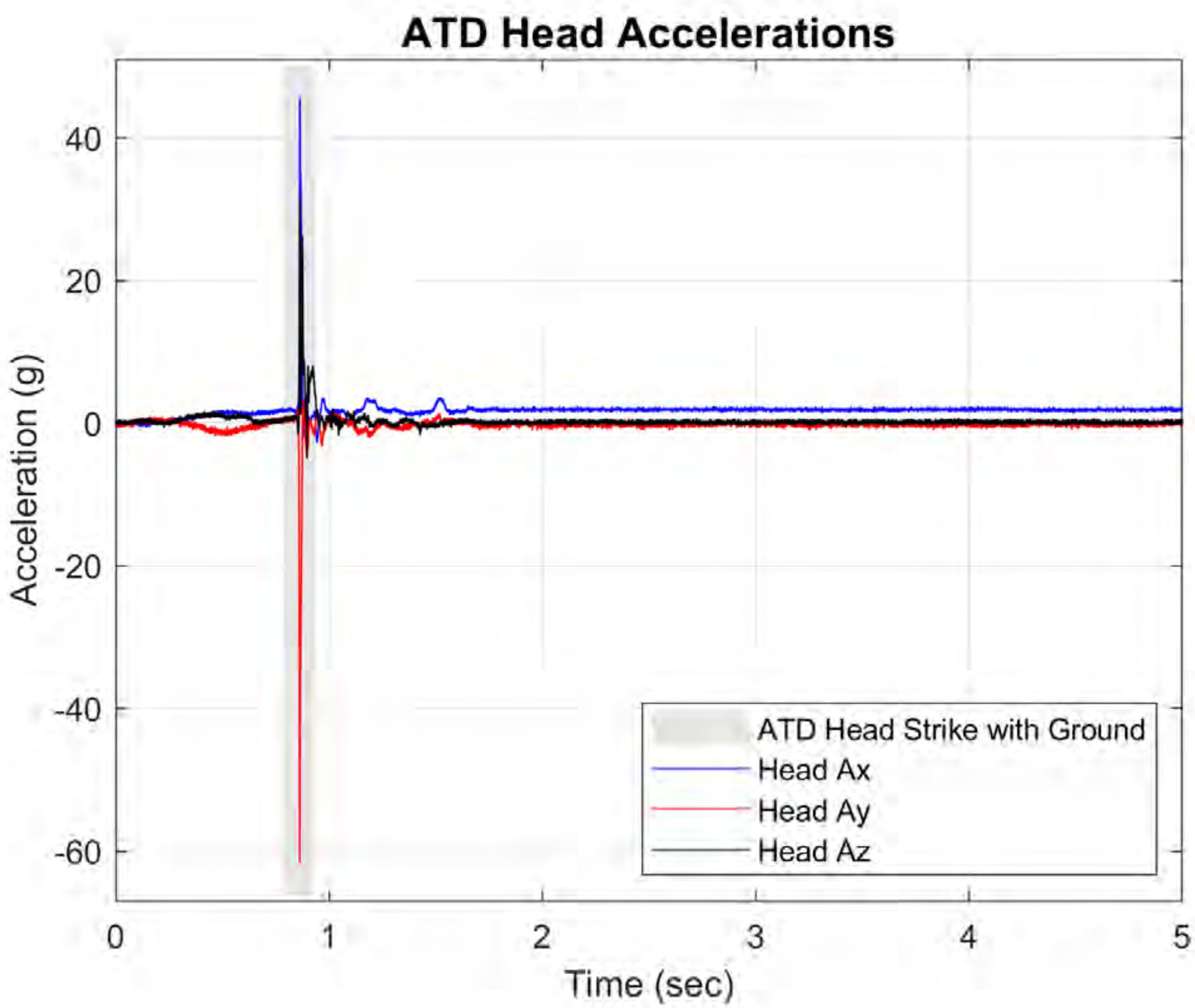
Drone Camera - Roll Angle = 90° - Time = 0.74 sec

Drone Camera - ATD Head Strike - Time = 0.82 sec

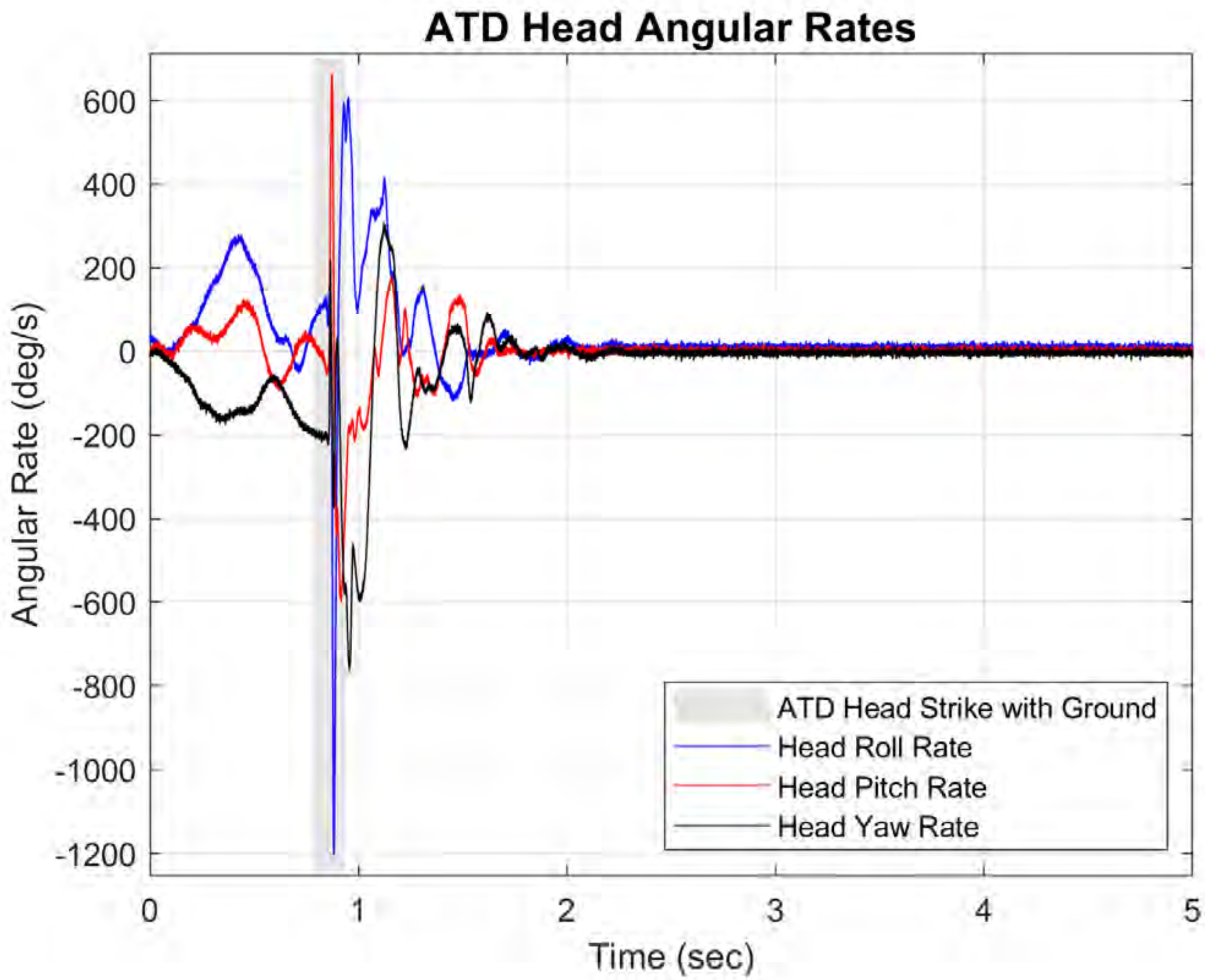
Drone Camera - Max Angle = 167.6° - Time = 1.75 sec

Drone Camera - End of Run - Roll Angle = 98.7°

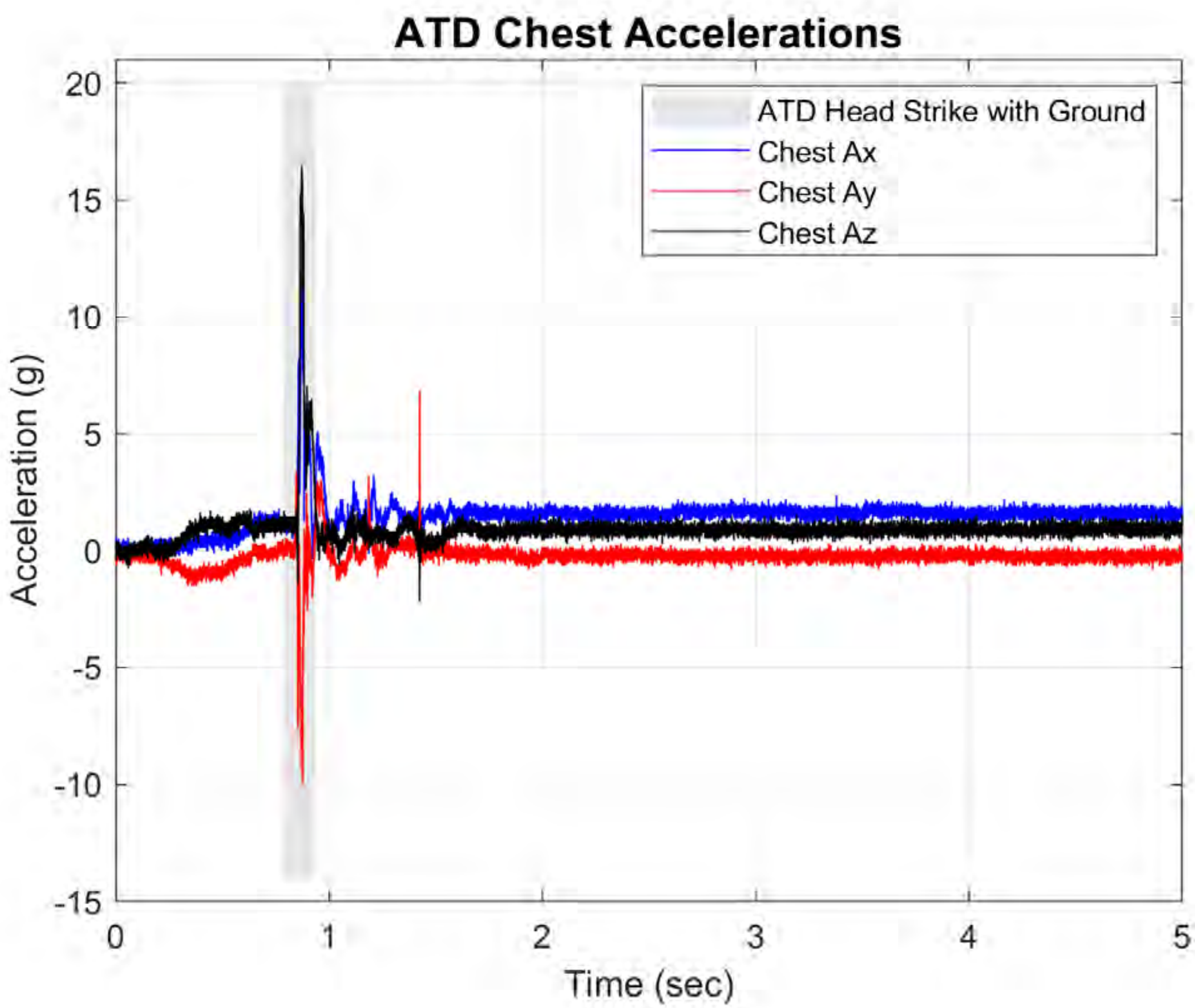
Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



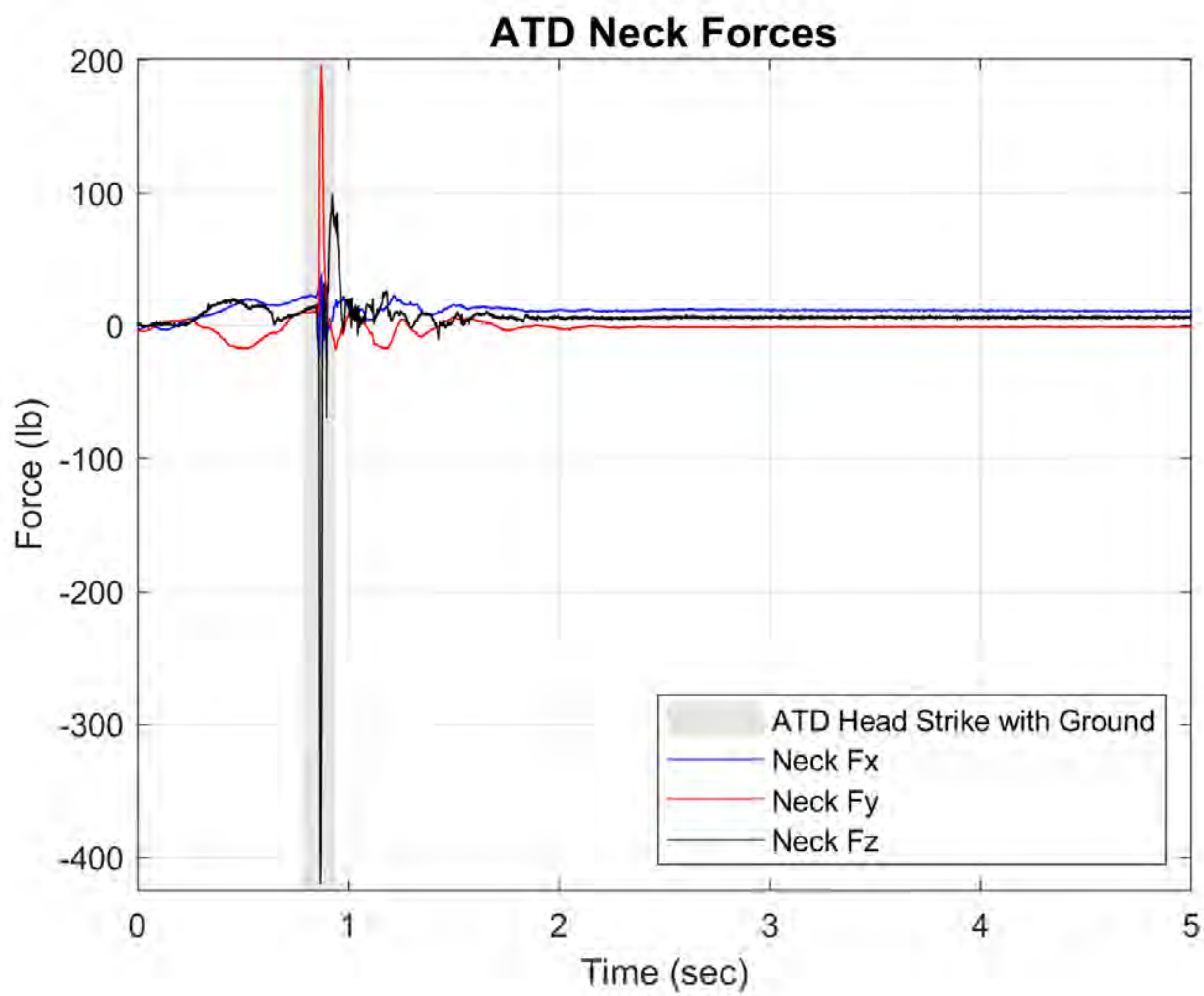
Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



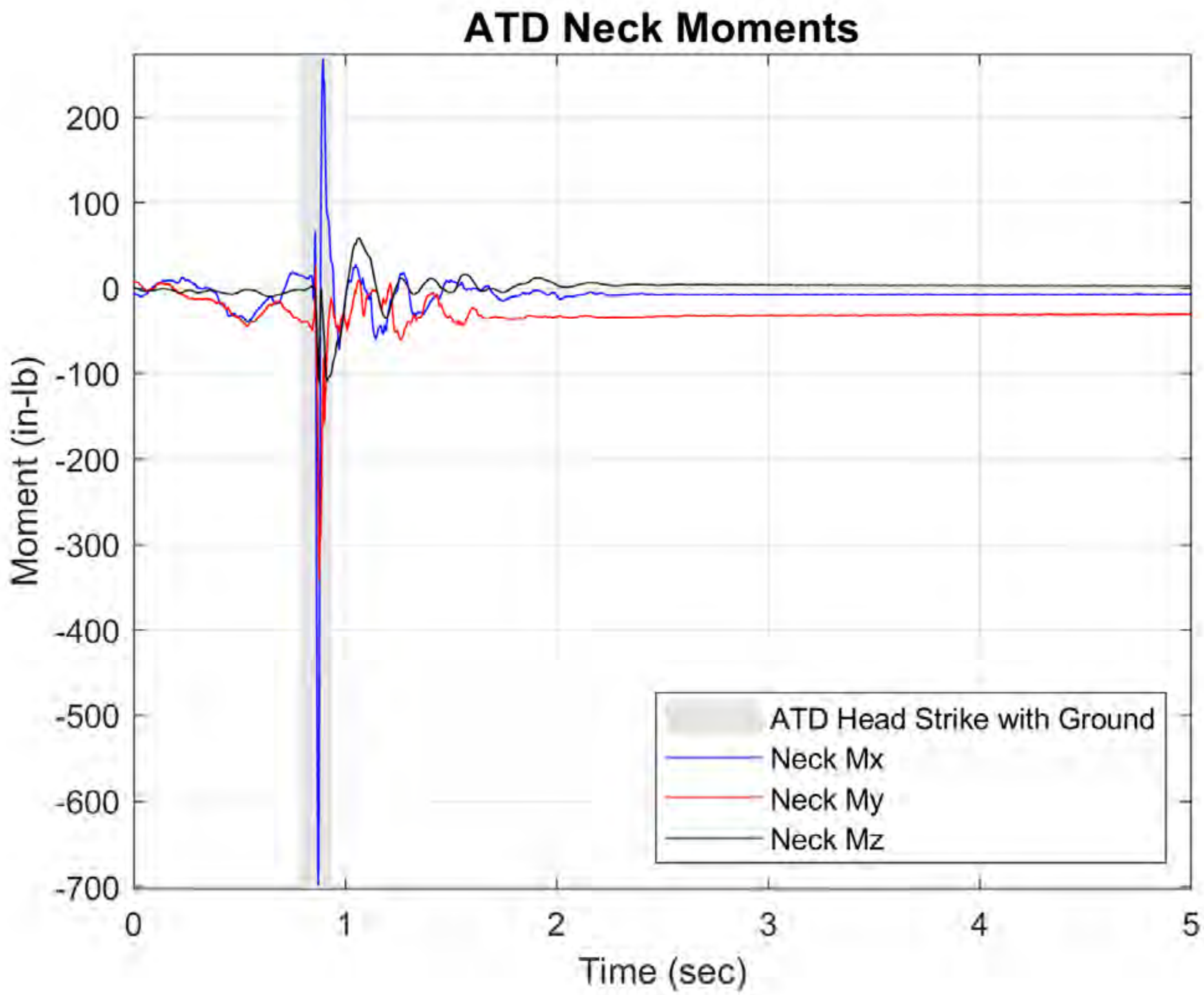
Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



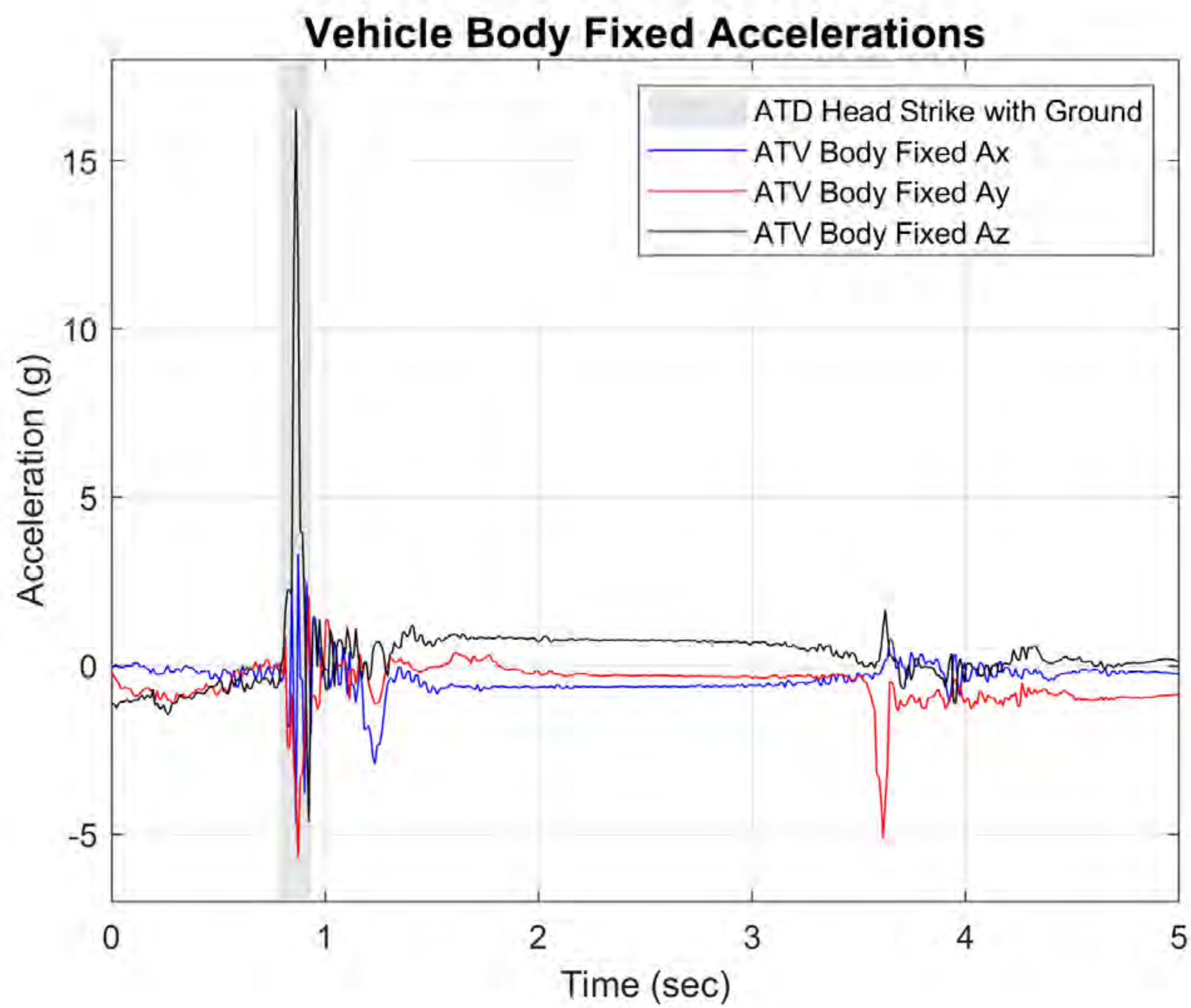
Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



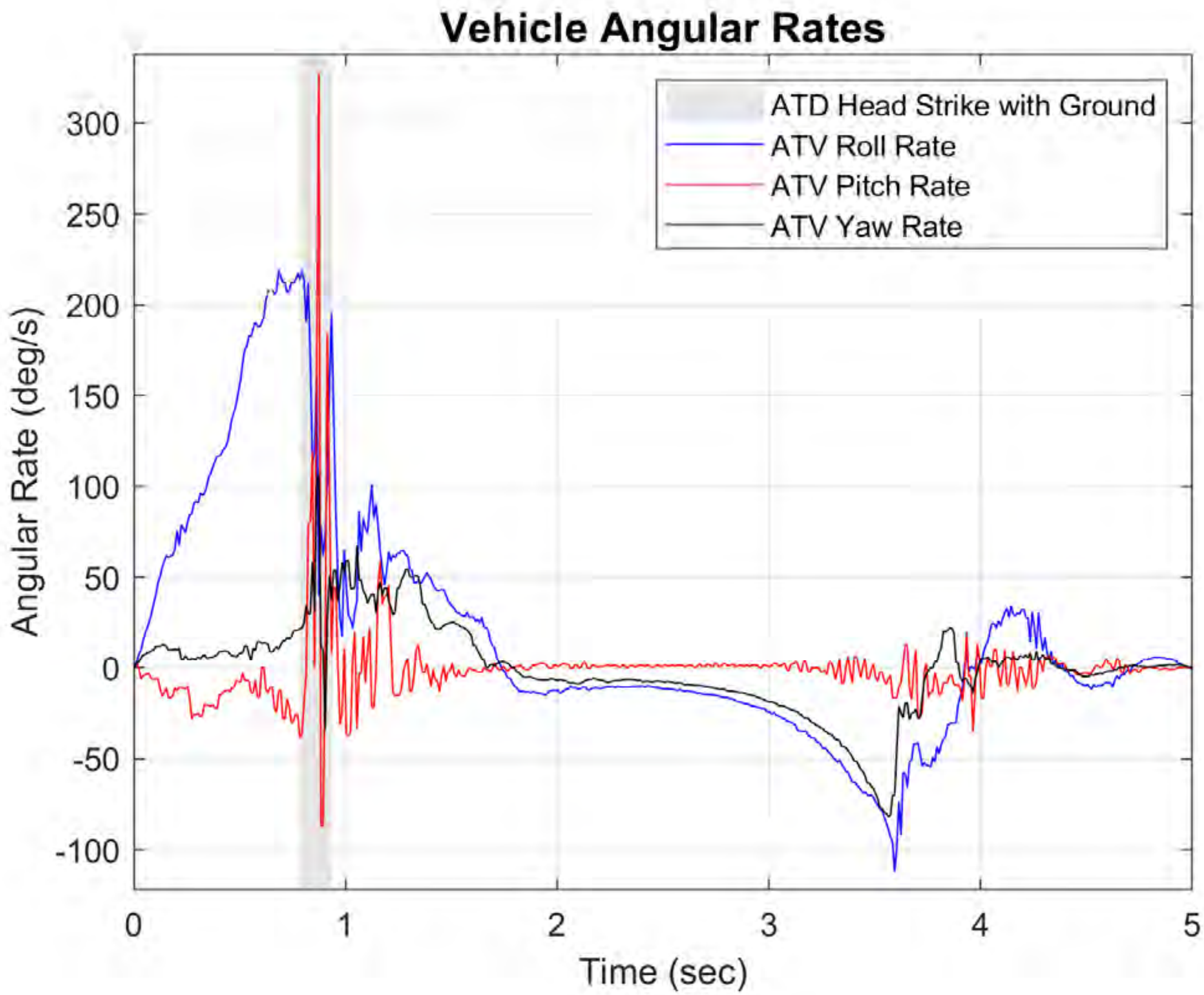
Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



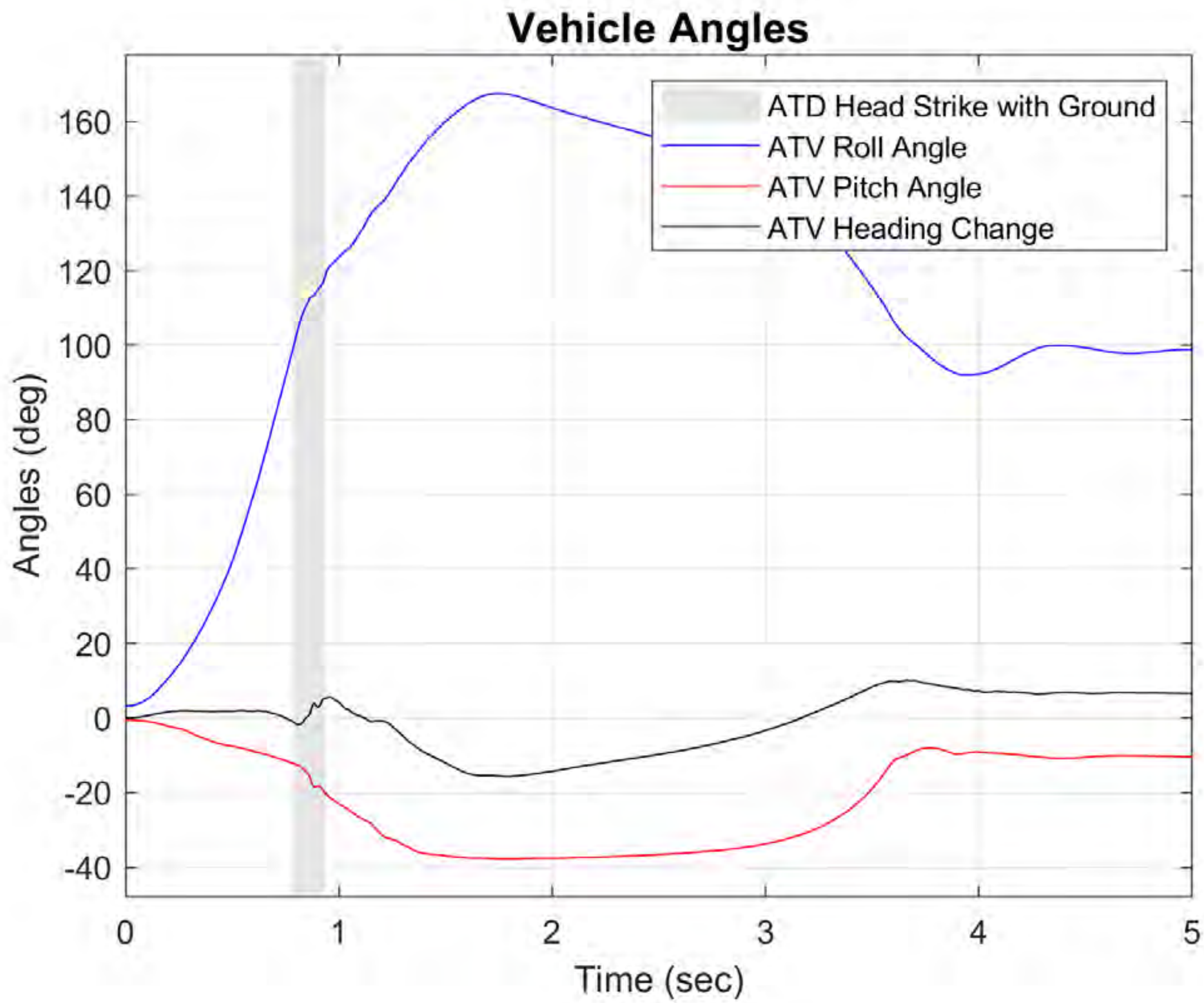
Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

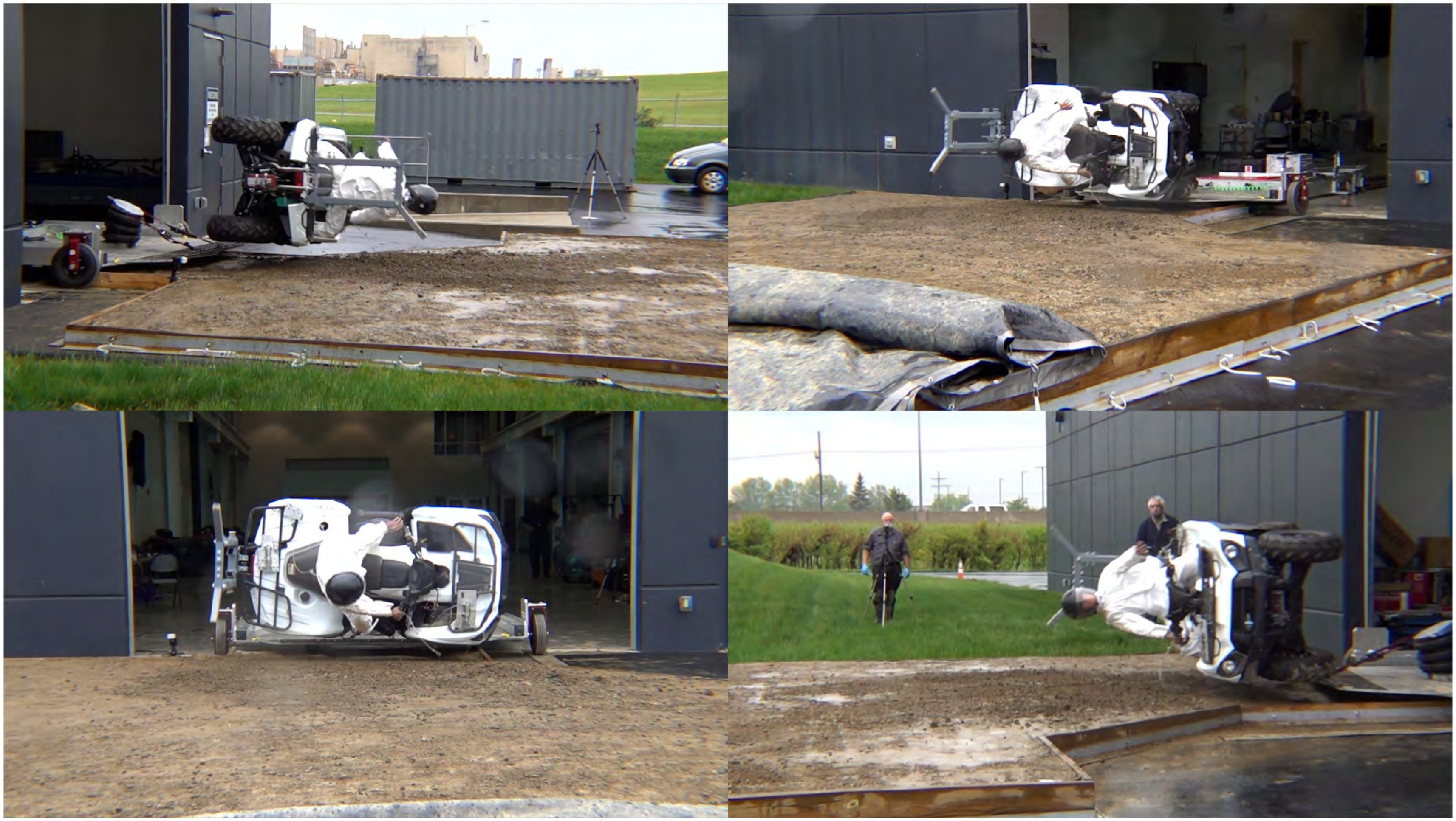
Roll Angle = 30° - Time = 0.36 sec

Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Roll Angle = 45° - Time = 0.48 sec

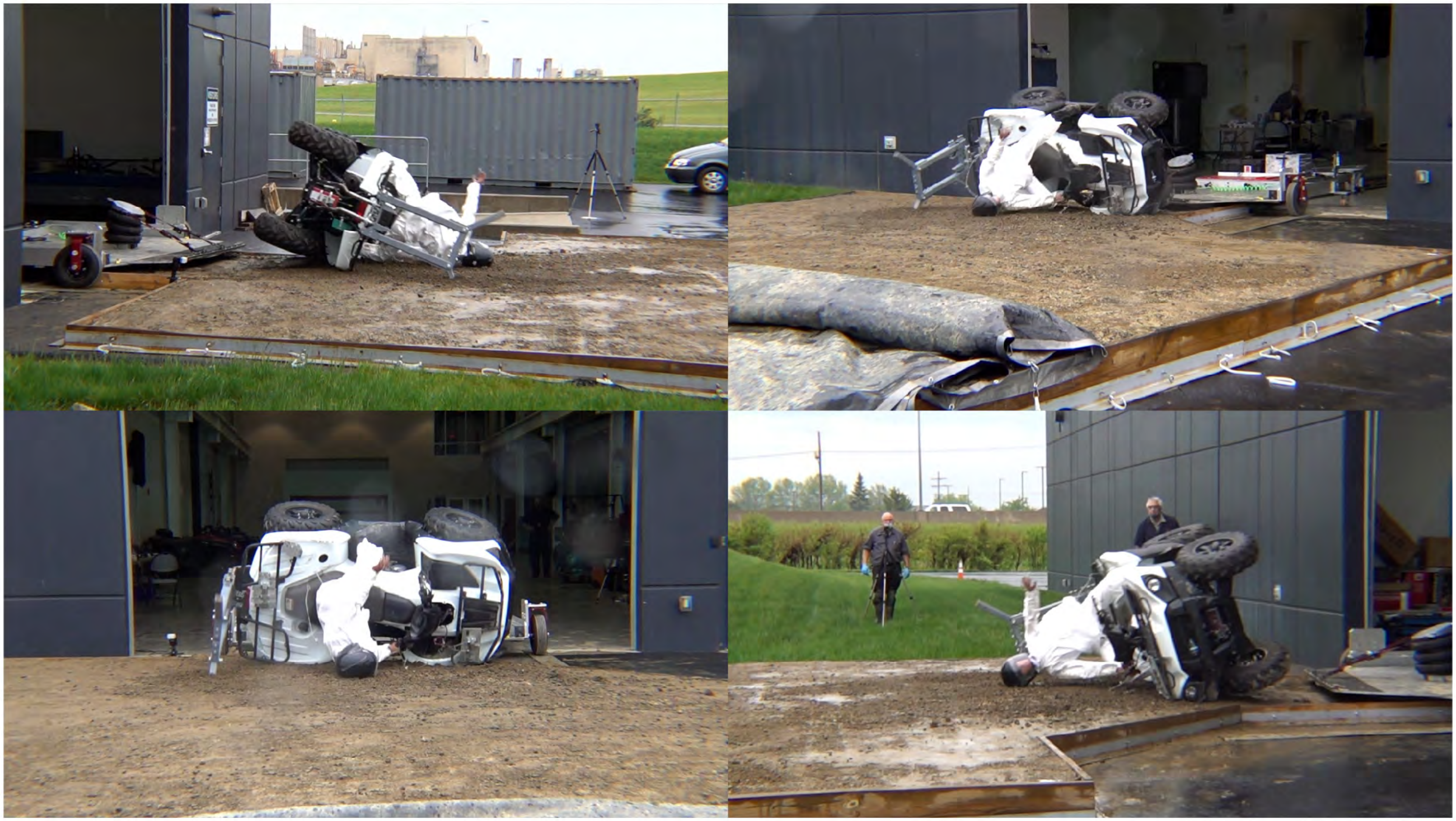
Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Roll Angle = 90° - Time = 0.72 sec



Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

ATD Head Strike - Time = 0.82 sec



Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Roll Angle = 180° - Time = 1.45 sec

Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Max Roll Angle = 186.0° - Time = 1.68 sec

Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

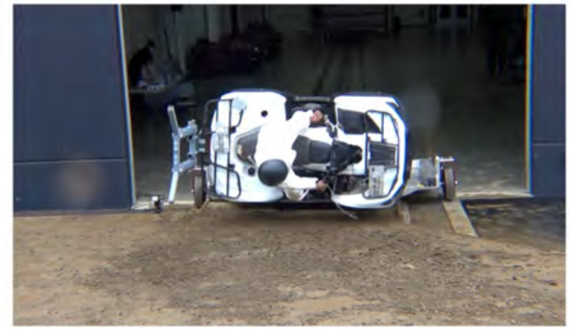
End of Run - Roll Angle = 163.5°

Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Drone Camera - Roll Angle = 30° - Time = 0.36 sec

Drone Camera - Roll Angle = 45° - Time = 0.48 sec

Drone Camera - Roll Angle = 90° - Time = 0.72 sec



Drone Camera - ATD Head Strike - Time = 0.82 sec

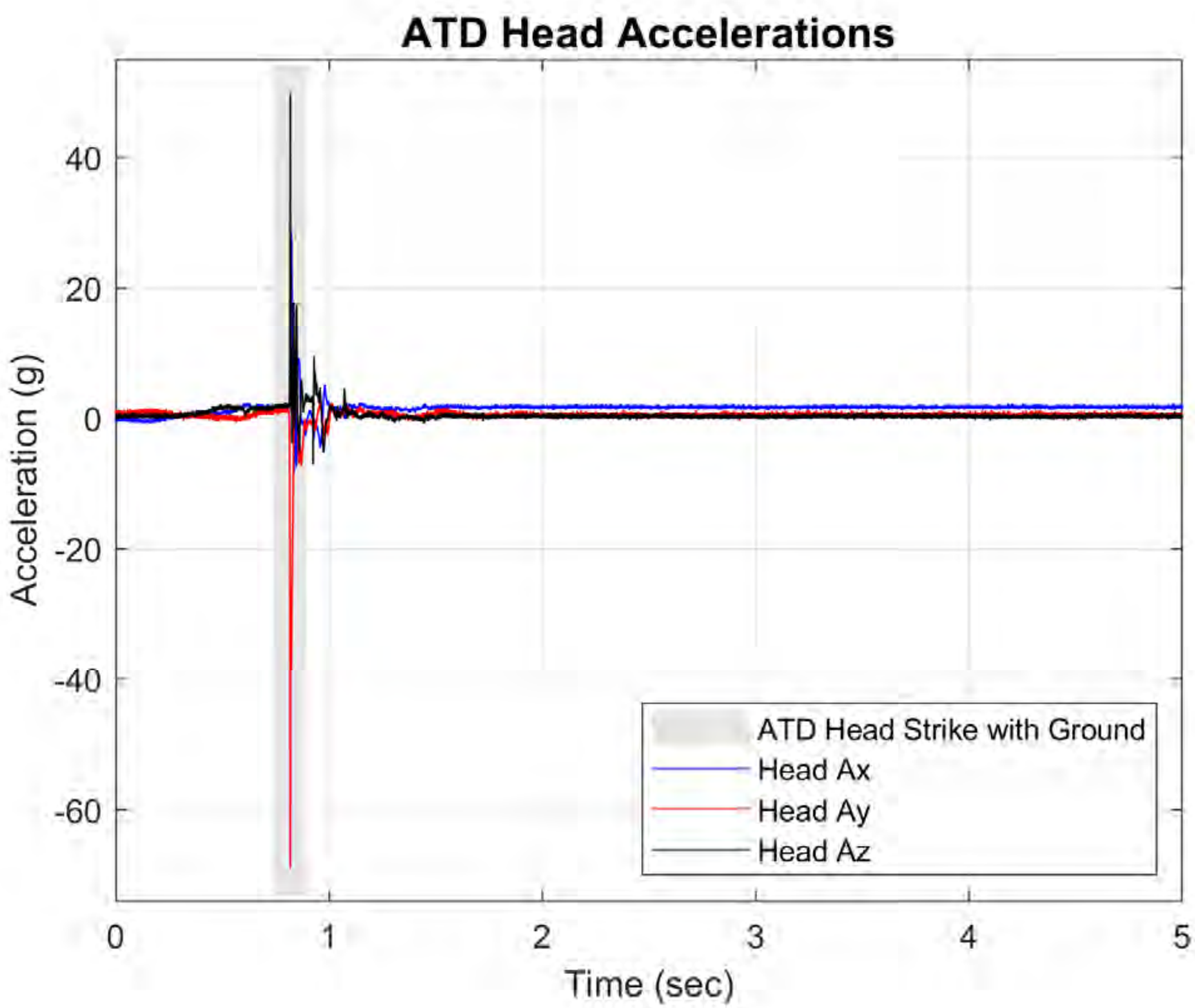
Drone Camera - Roll Angle = 180° - Time = 1.45 sec

Drone Camera - Max Angle = 186.0° - Time = 1.68 sec

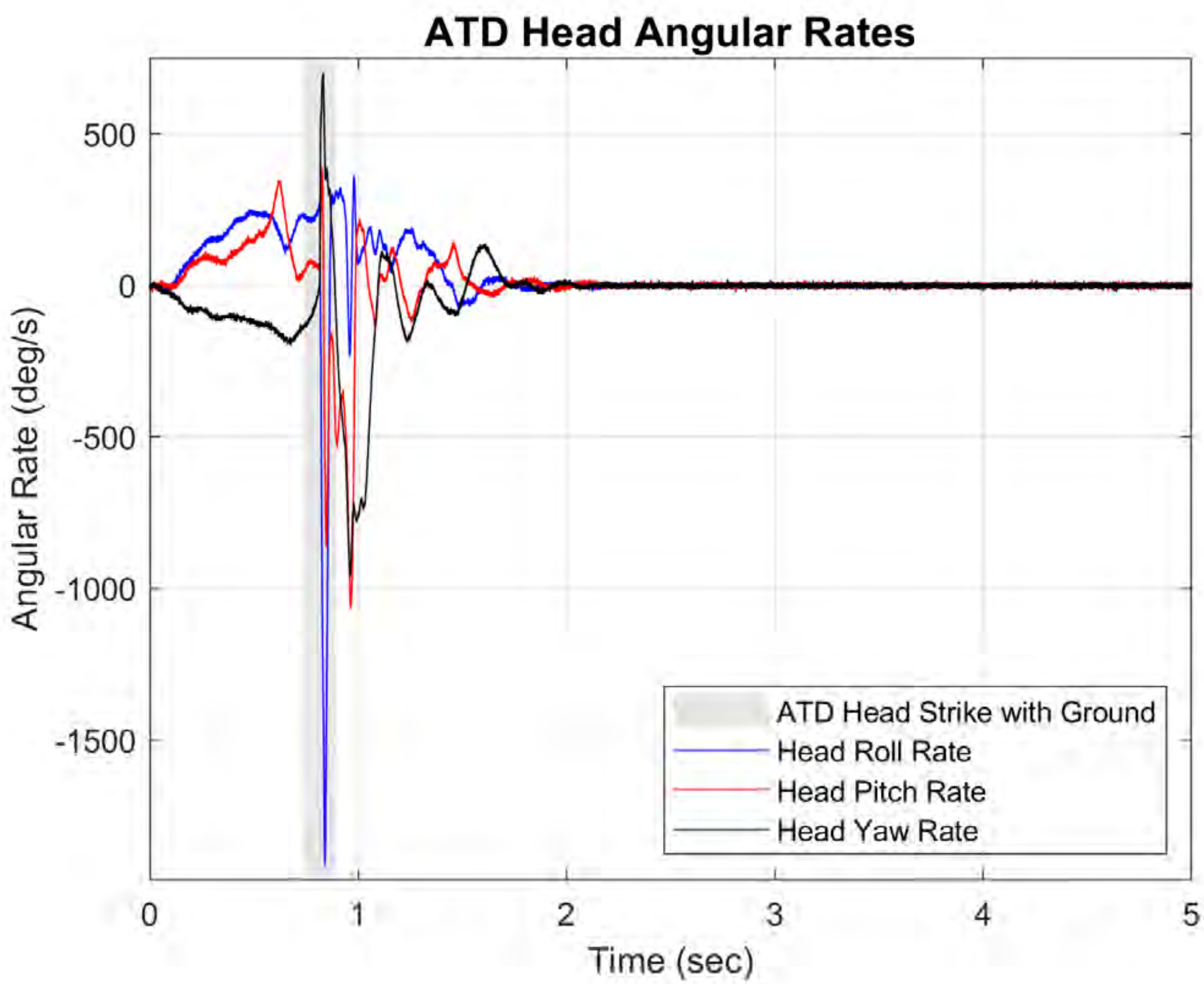
Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Drone Camera - End of Run - Roll Angle = 163.5°

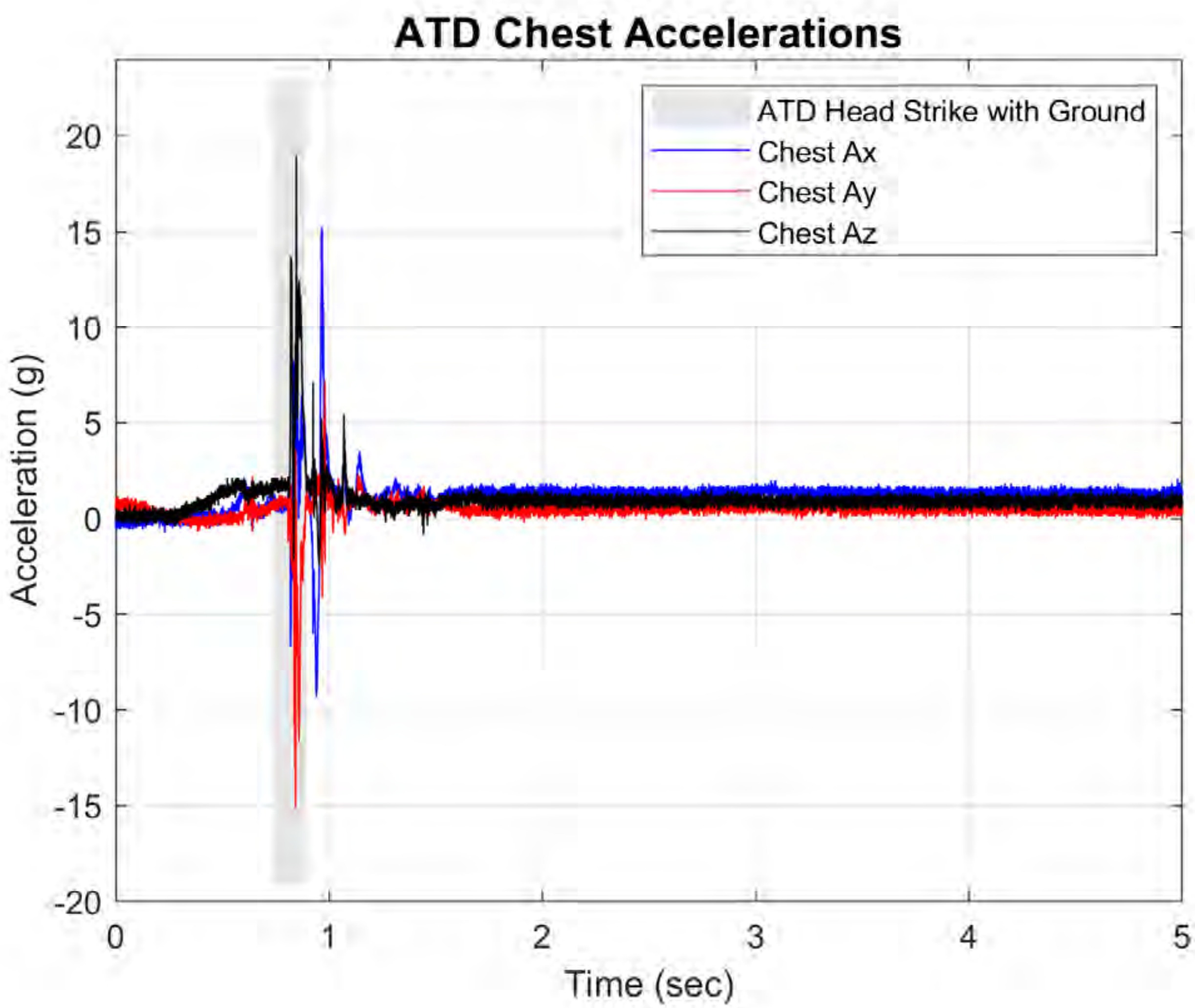
Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



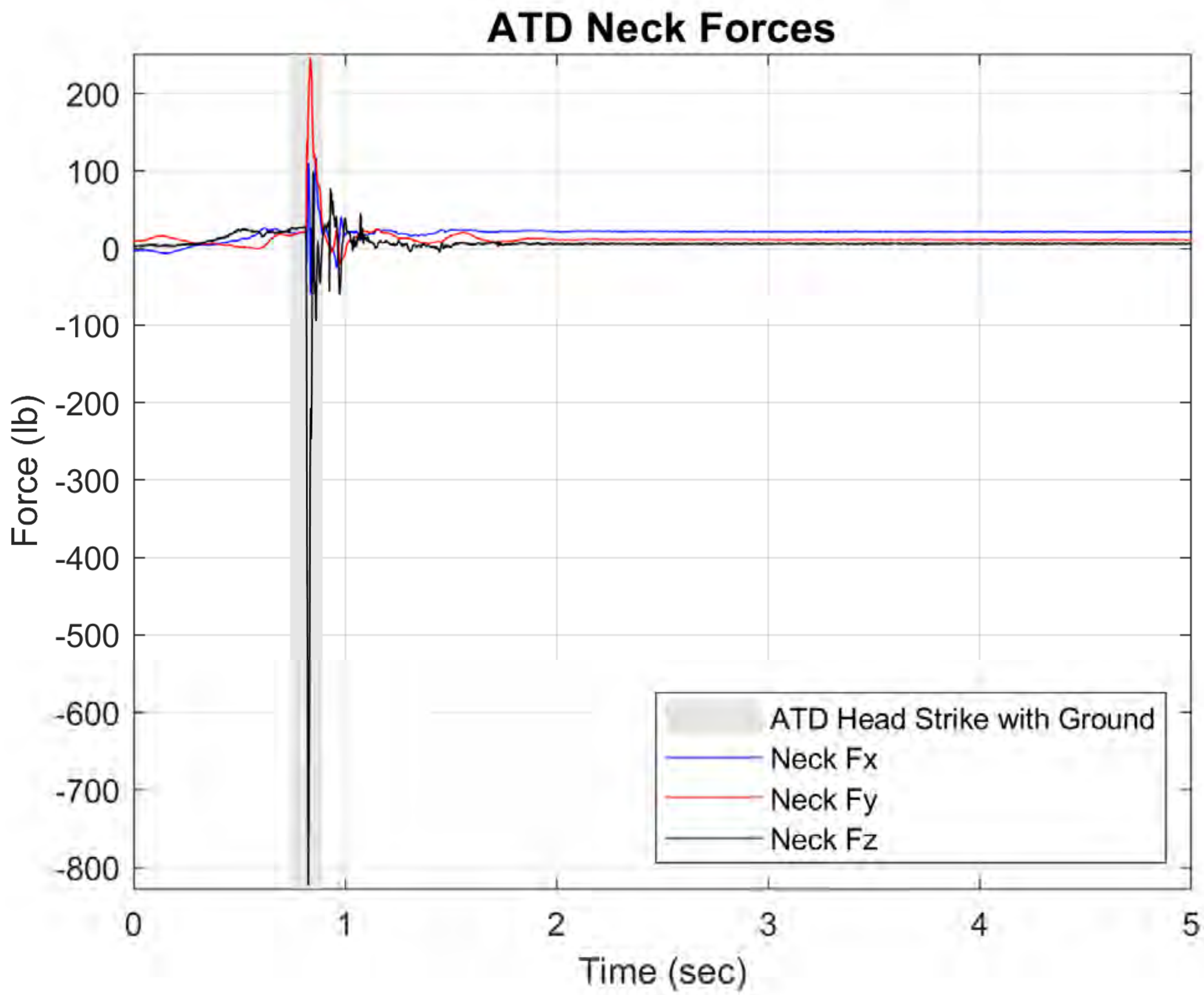
Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



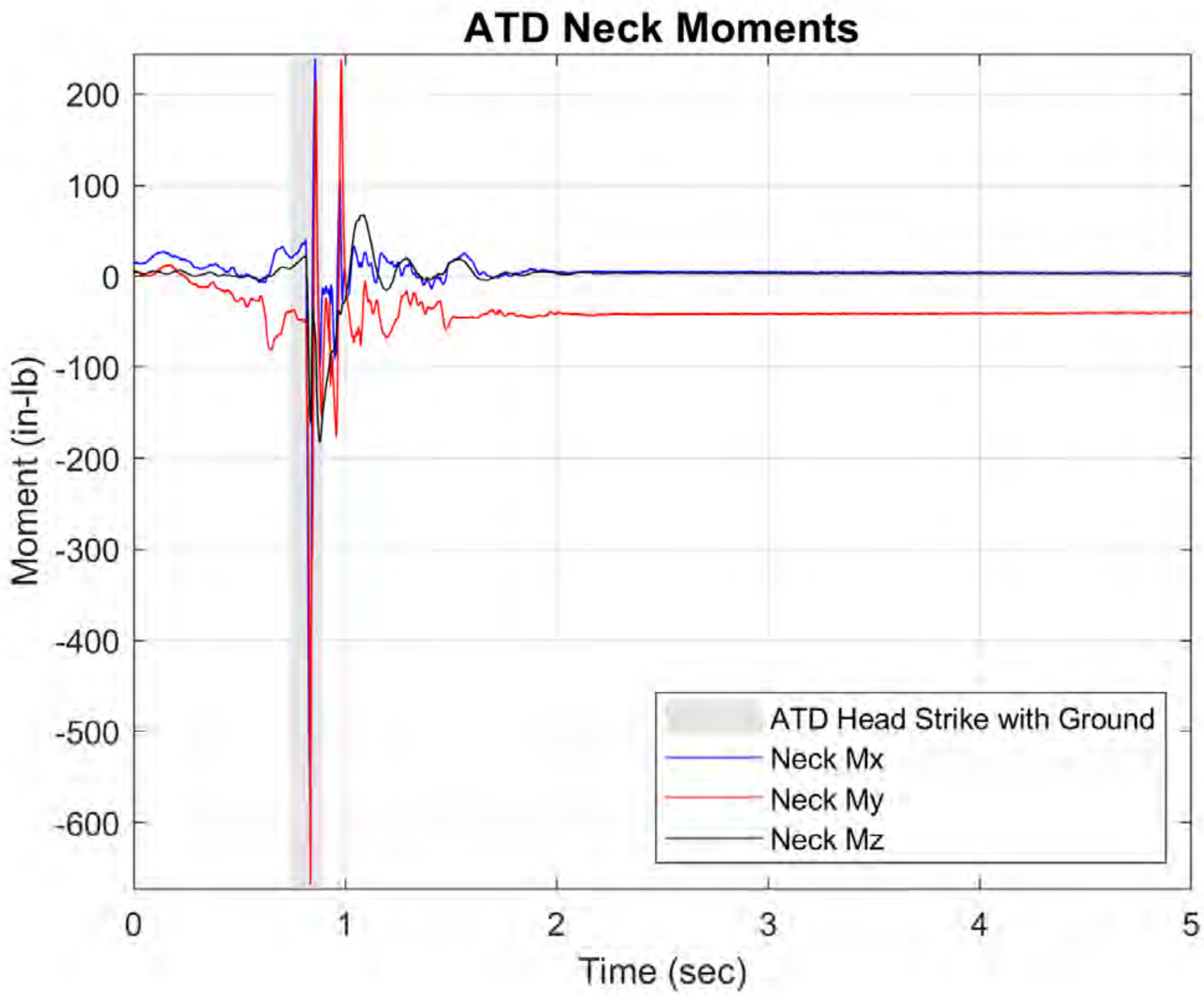
Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



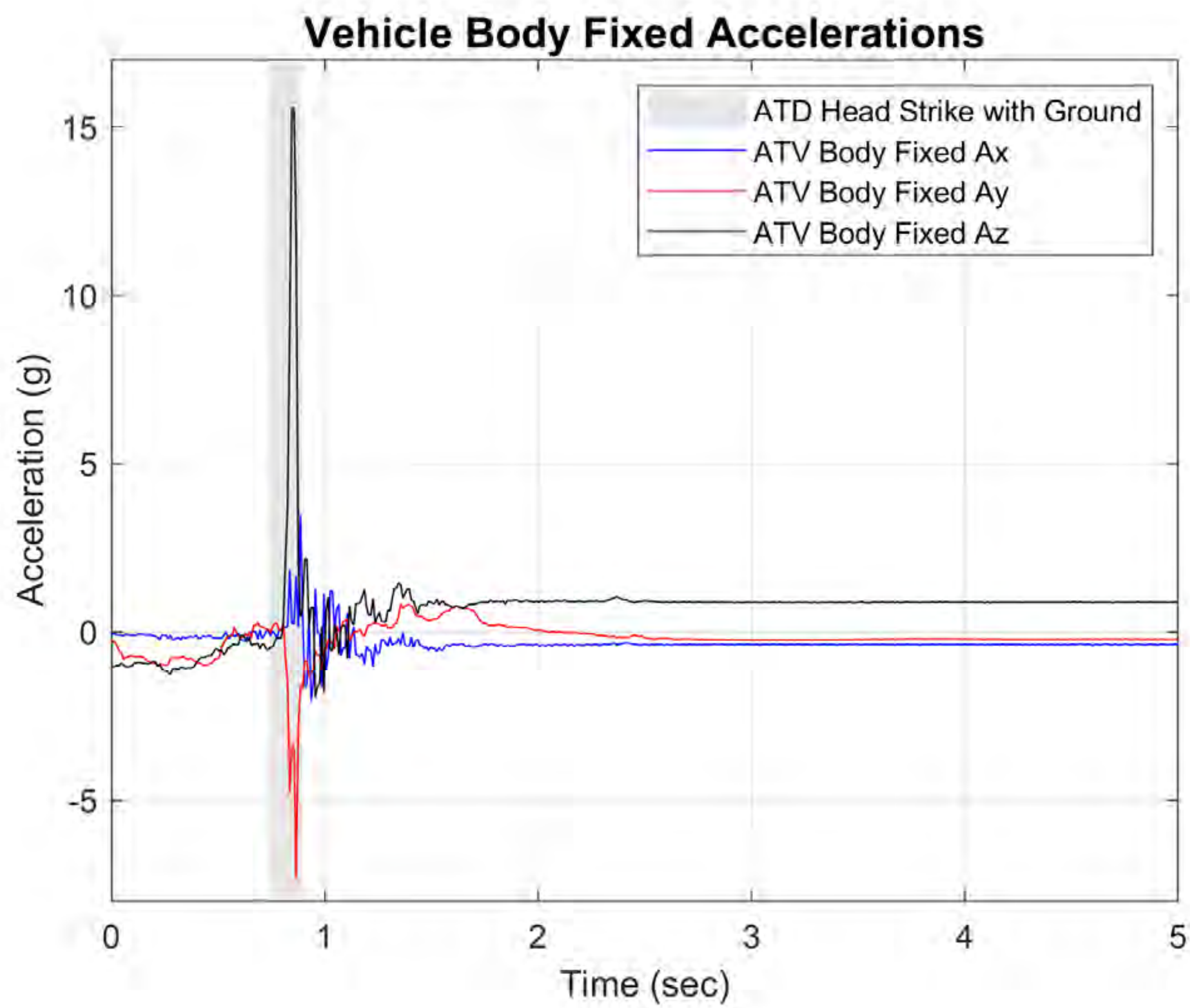
Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



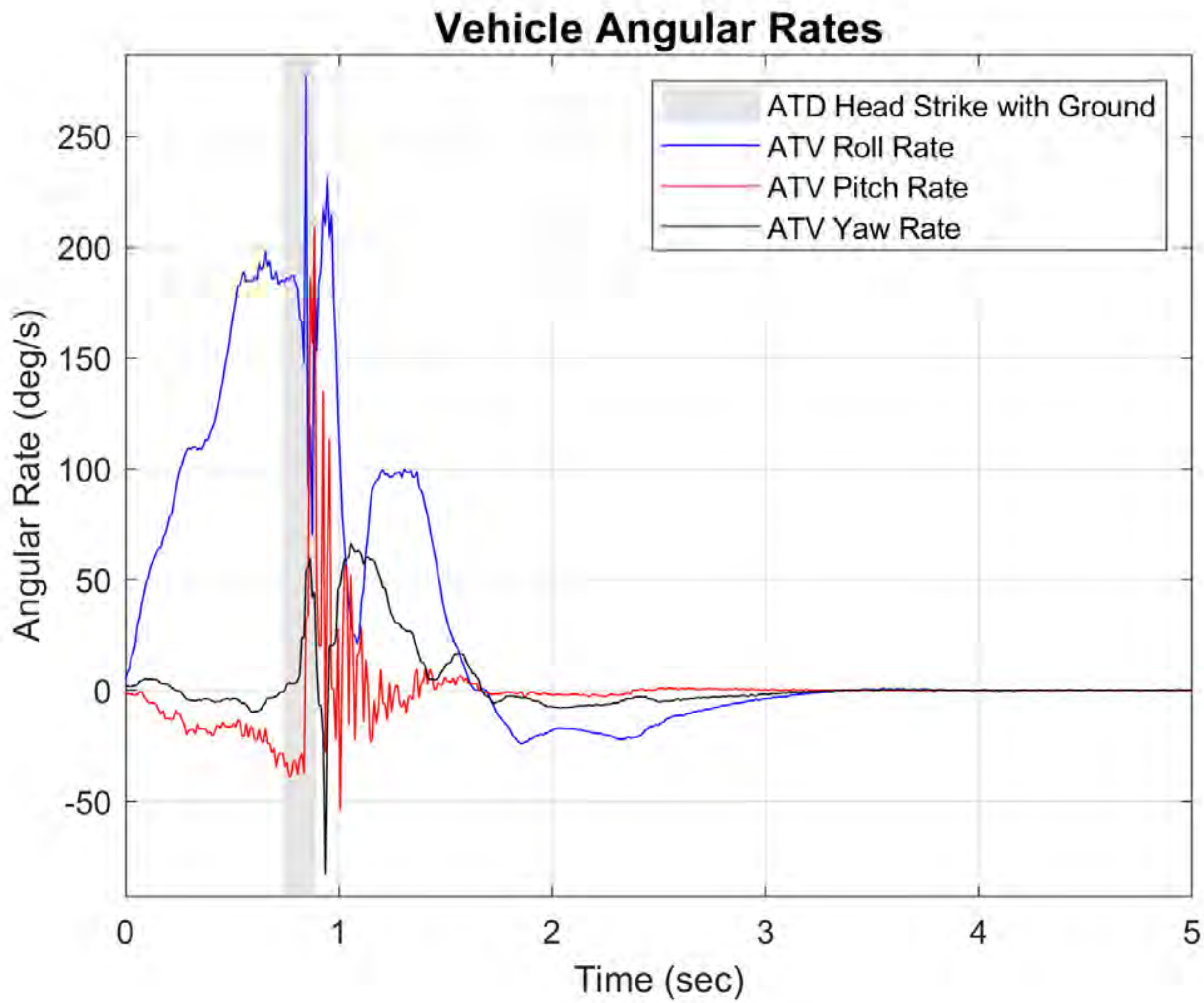
Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



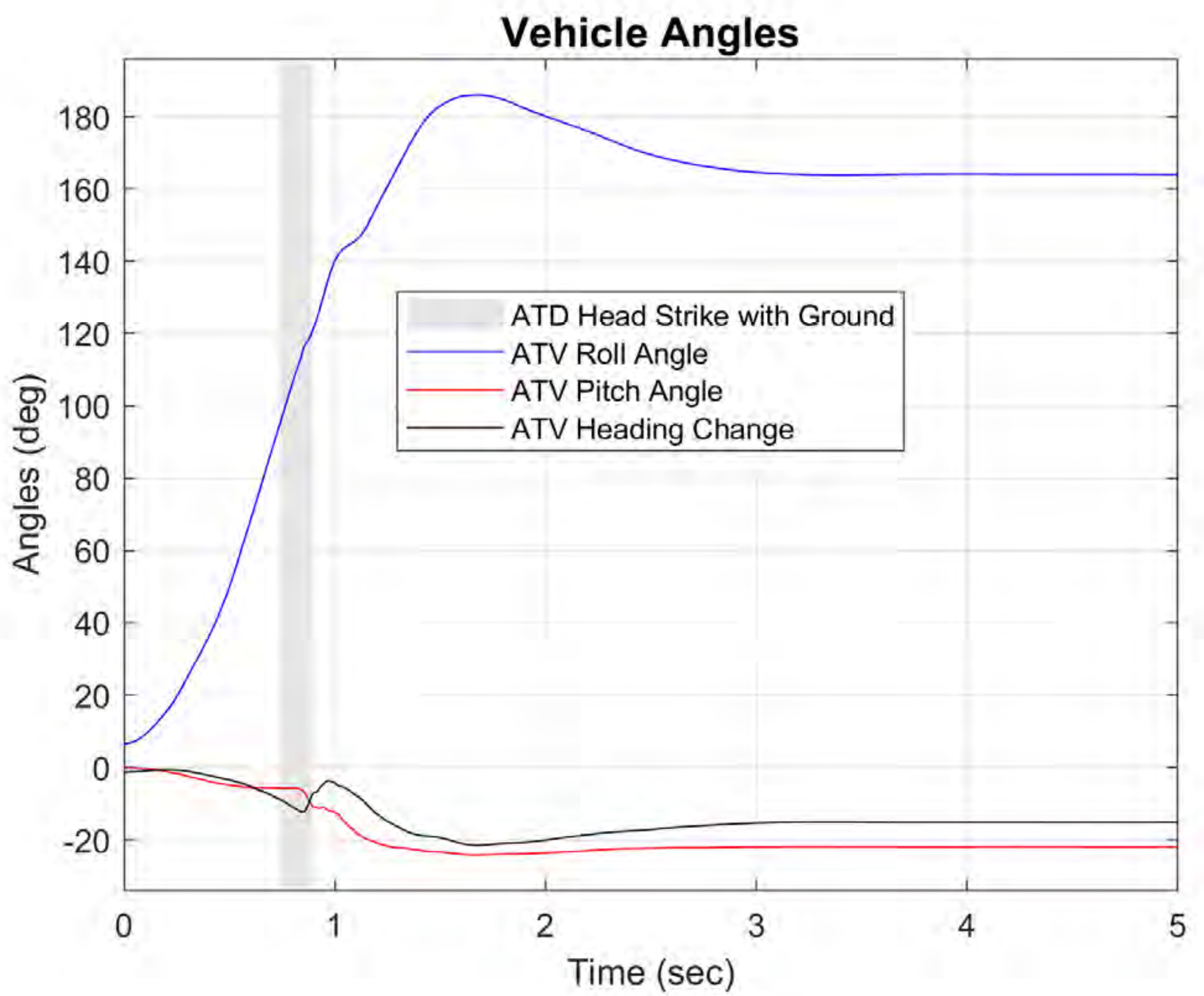
Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

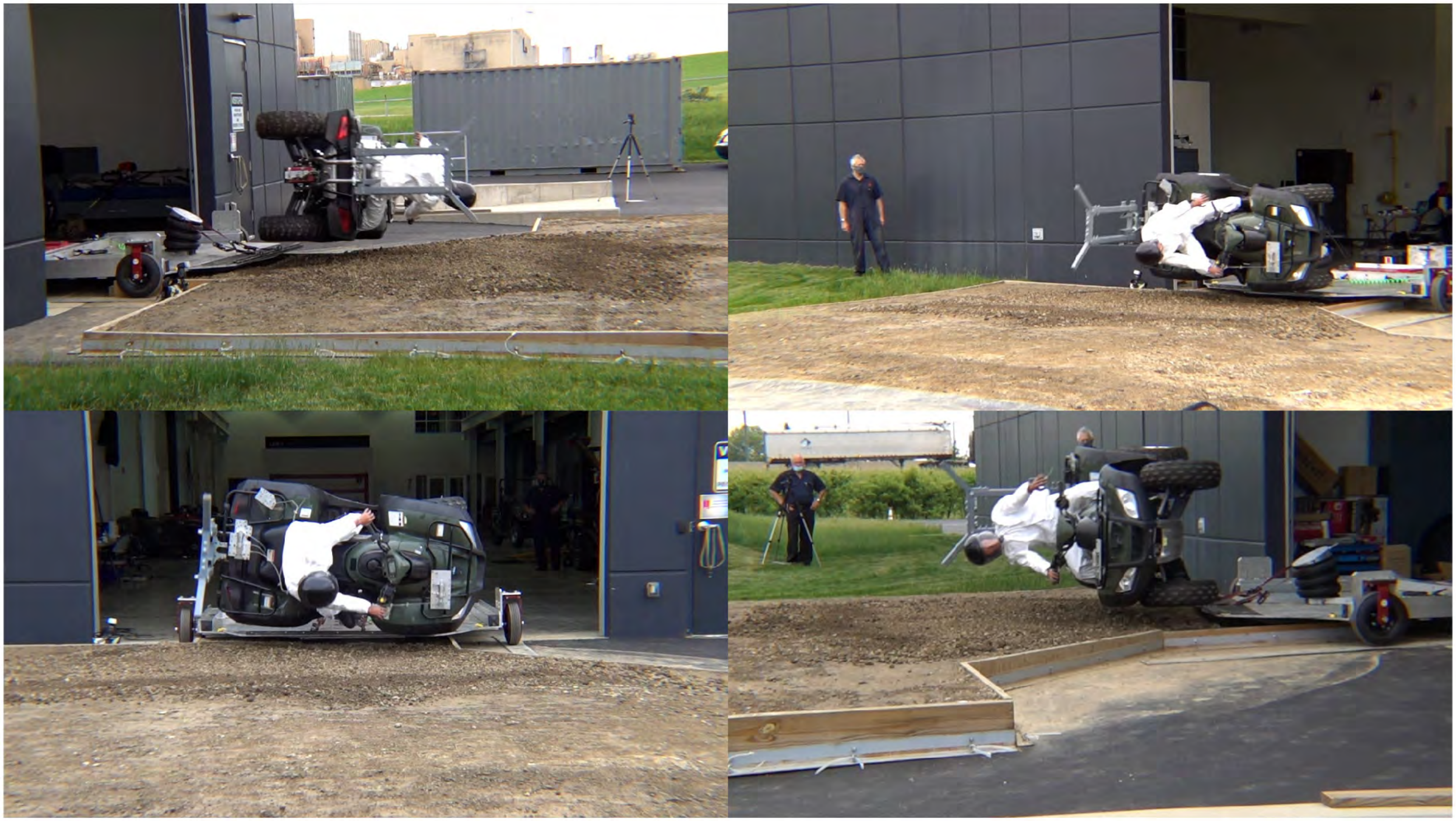
Roll Angle = 30° - Time = 0.41 sec

Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Roll Angle = 45° - Time = 0.53 sec

Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Roll Angle = 90° - Time = 0.76 sec



Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

ATD Head Strike - Time = 0.86 sec

Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Max Roll Angle = 174.2° - Time = 1.62 sec

Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

End of Run - Roll Angle = 163.6°

Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

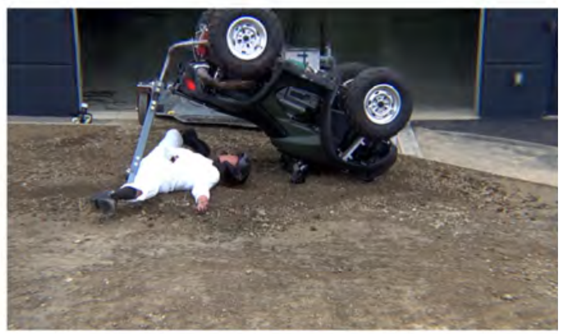
Drone Camera - Roll Angle = 30° - Time = 0.41 sec

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

Drone Camera - Roll Angle = 90° - Time = 0.76 sec

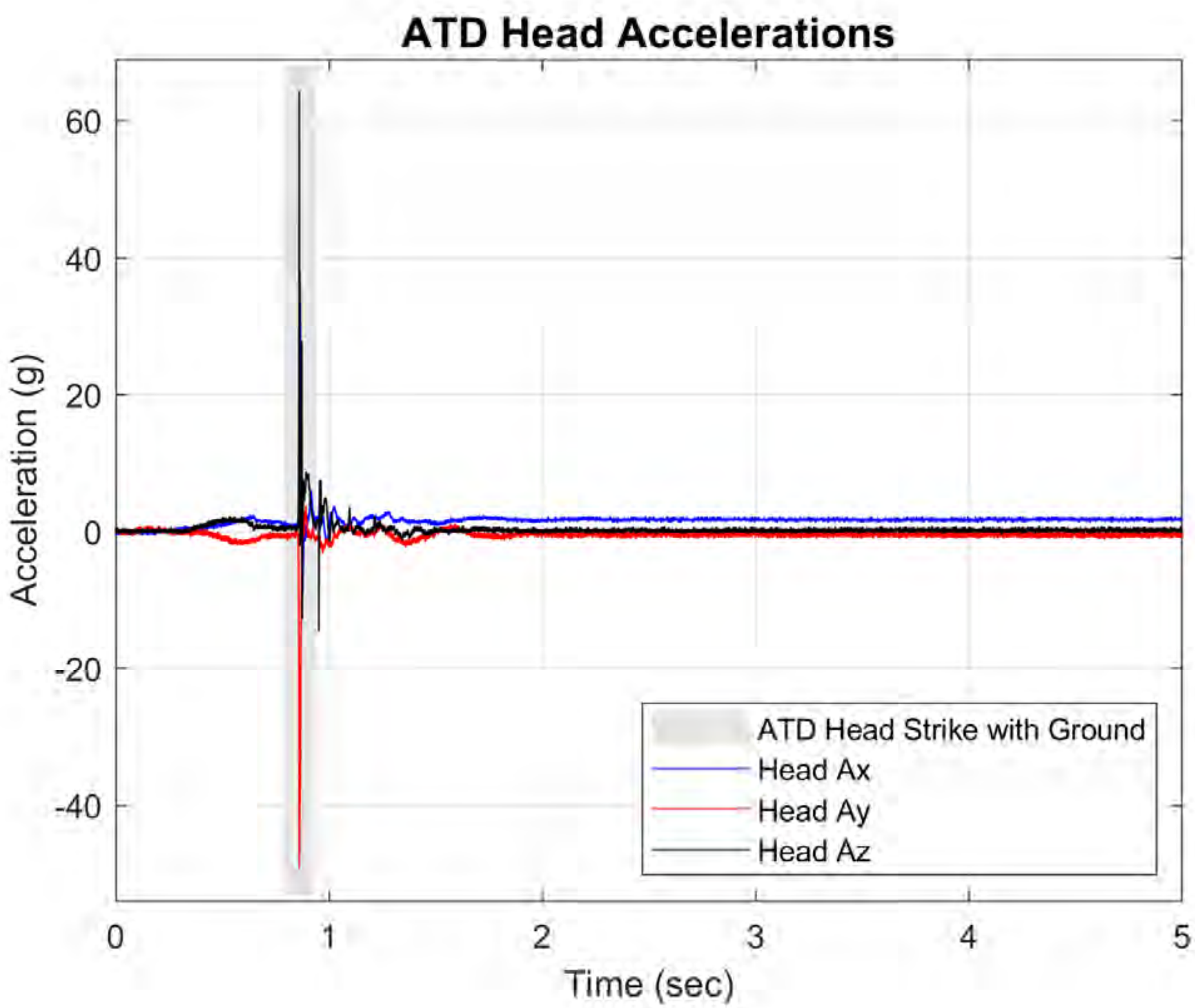
Drone Camera - ATD Head Strike - Time = 0.86 sec

Drone Camera - Max Angle = 174.2° - Time = 1.62 sec

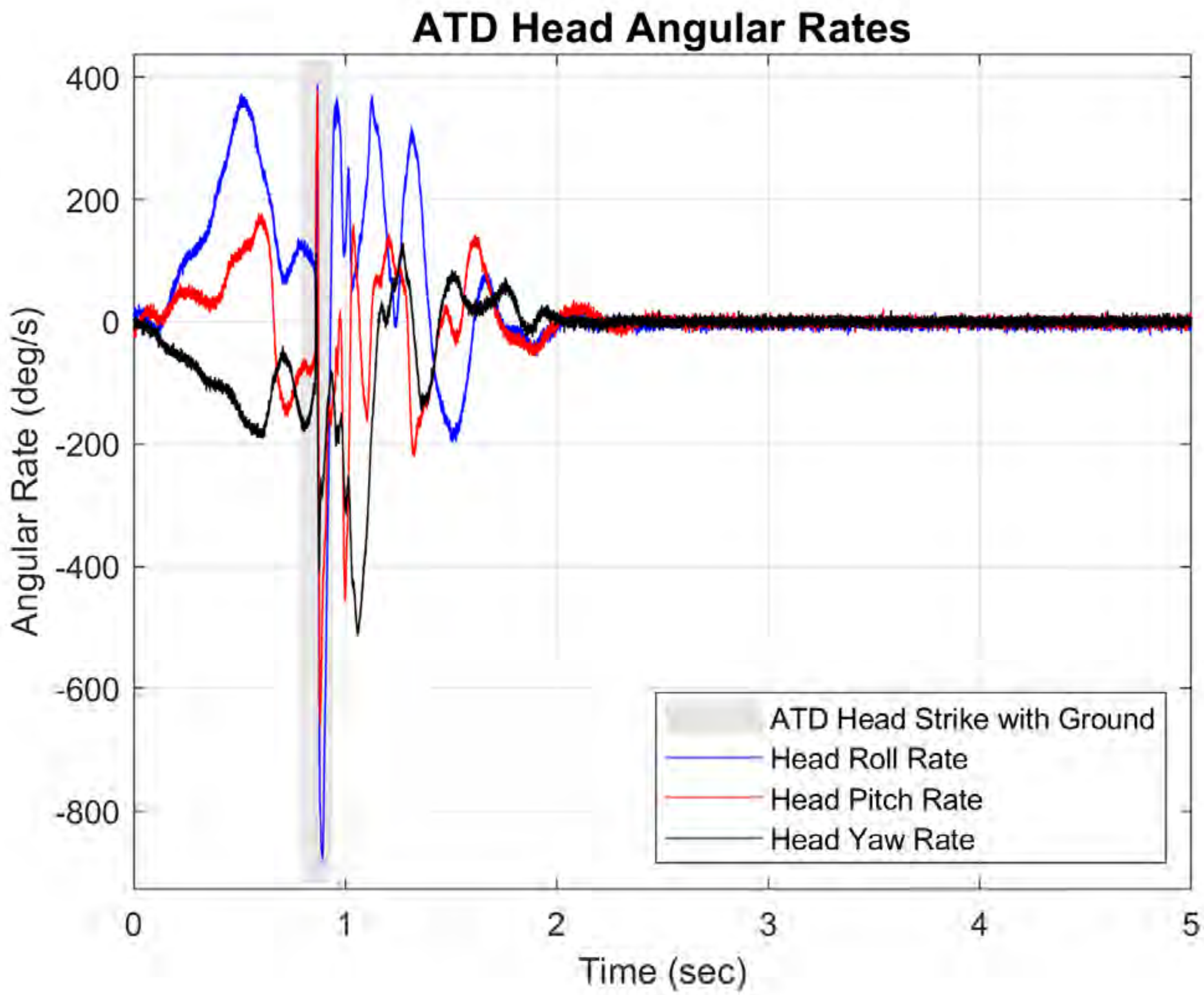


Drone Camera - End of Run - Roll Angle = 163.6°

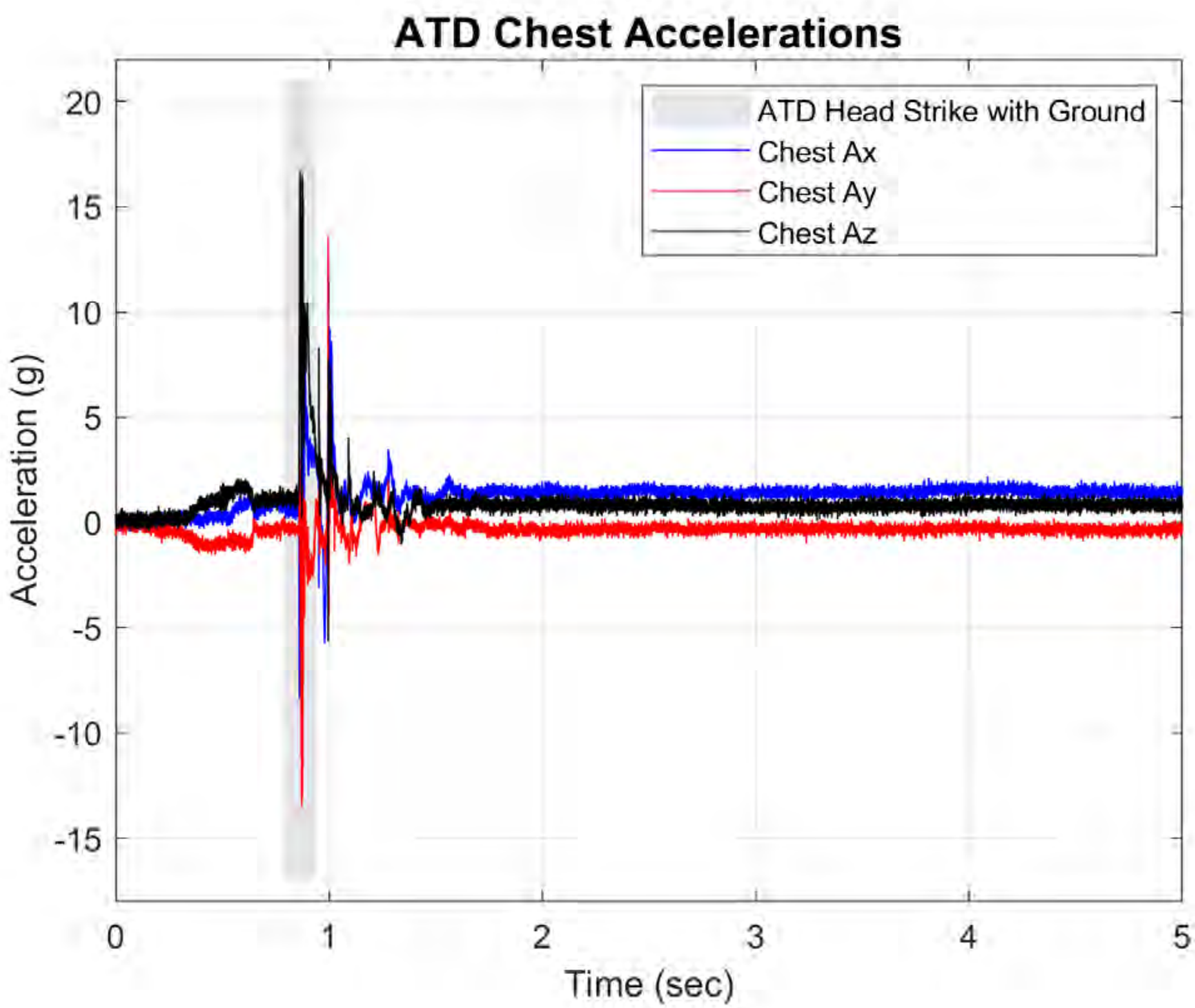
Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



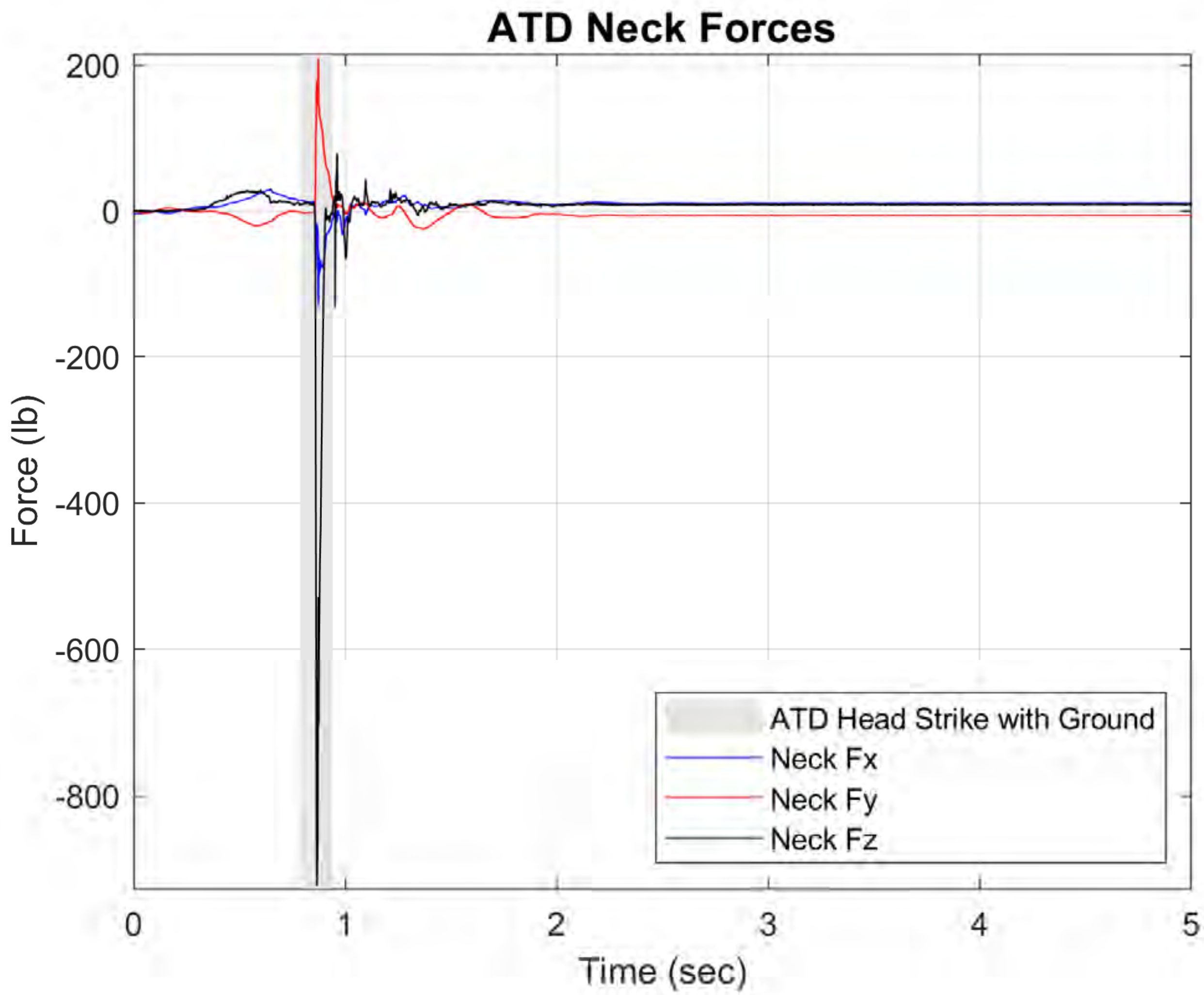
Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



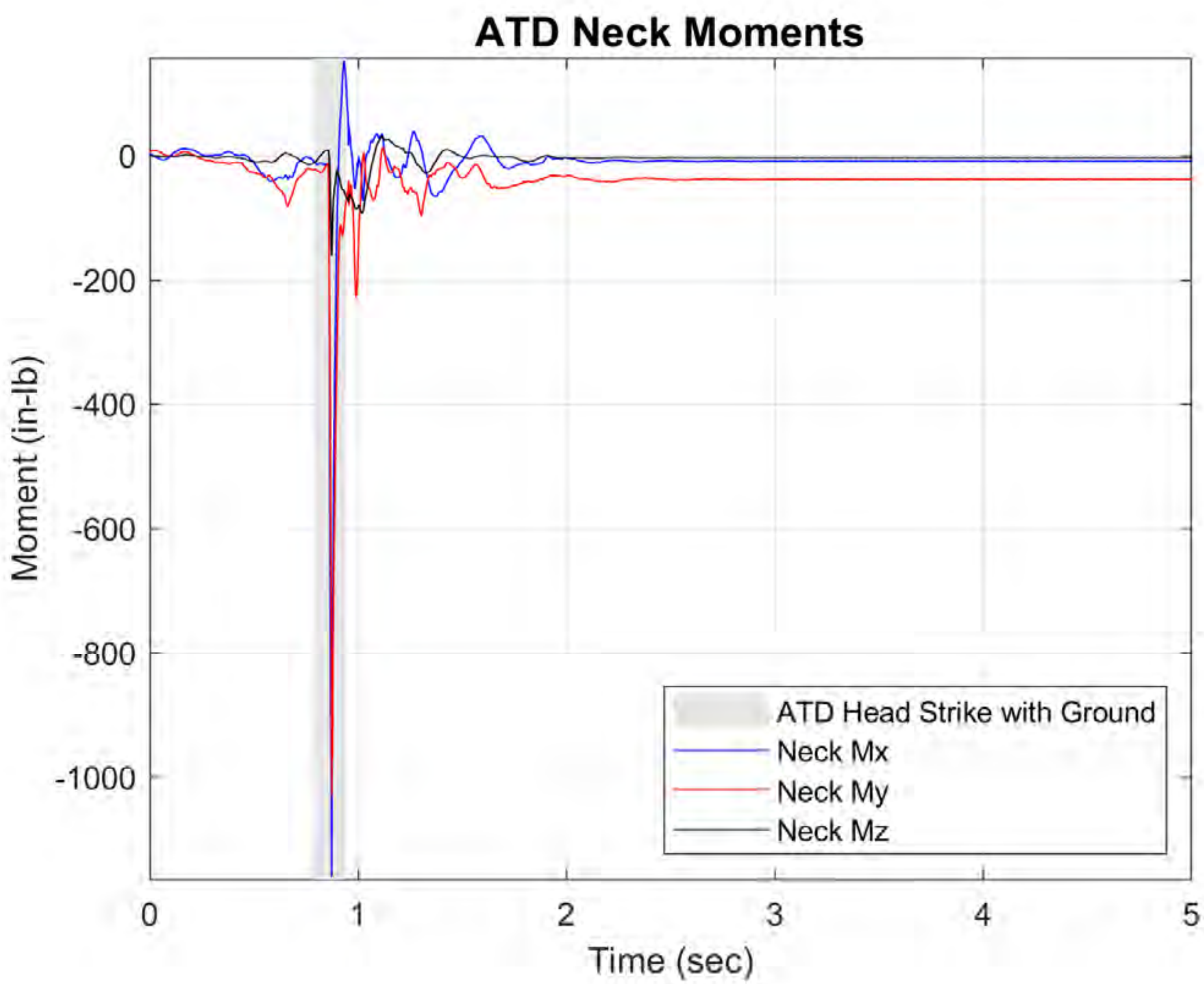
Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



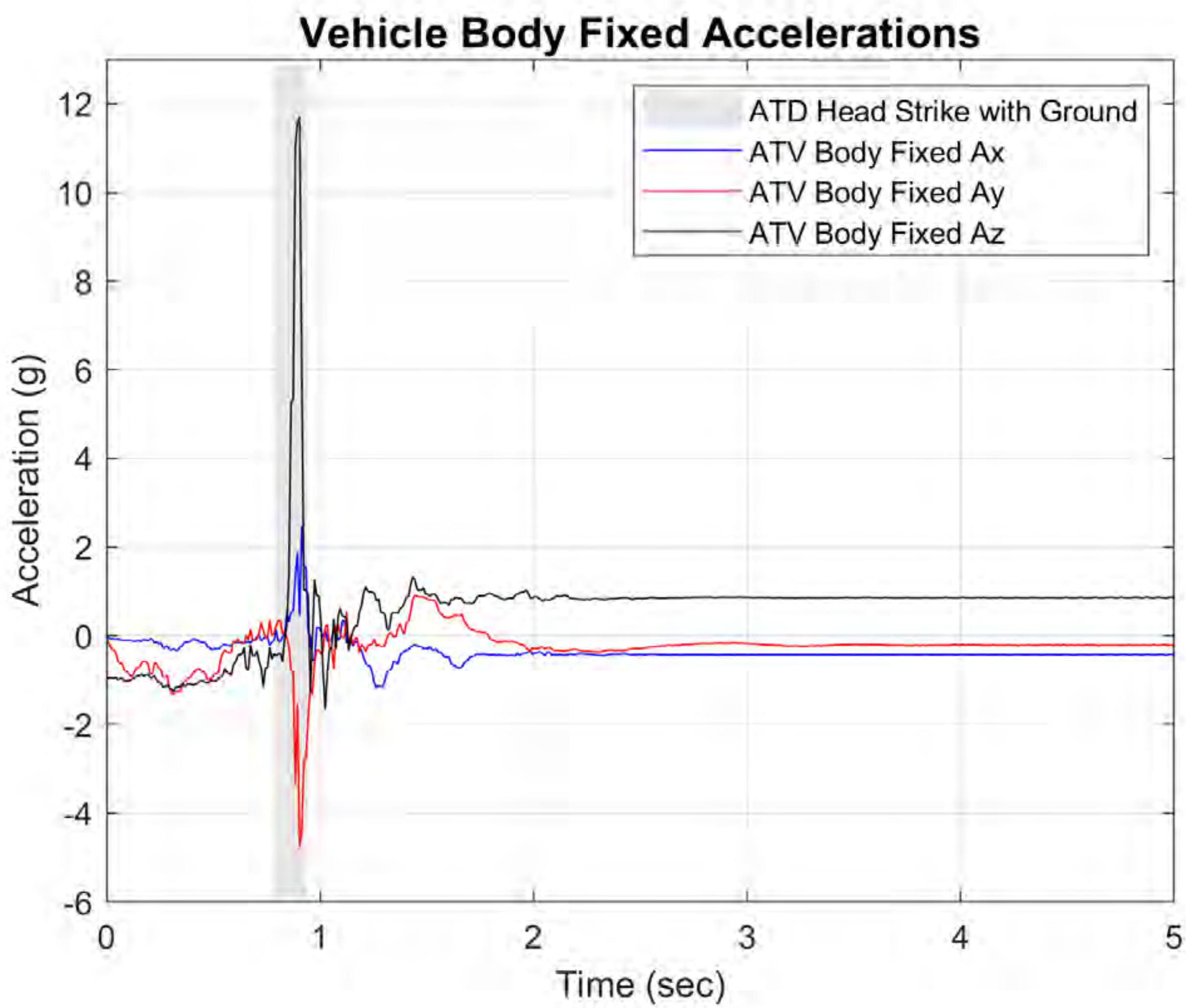
Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



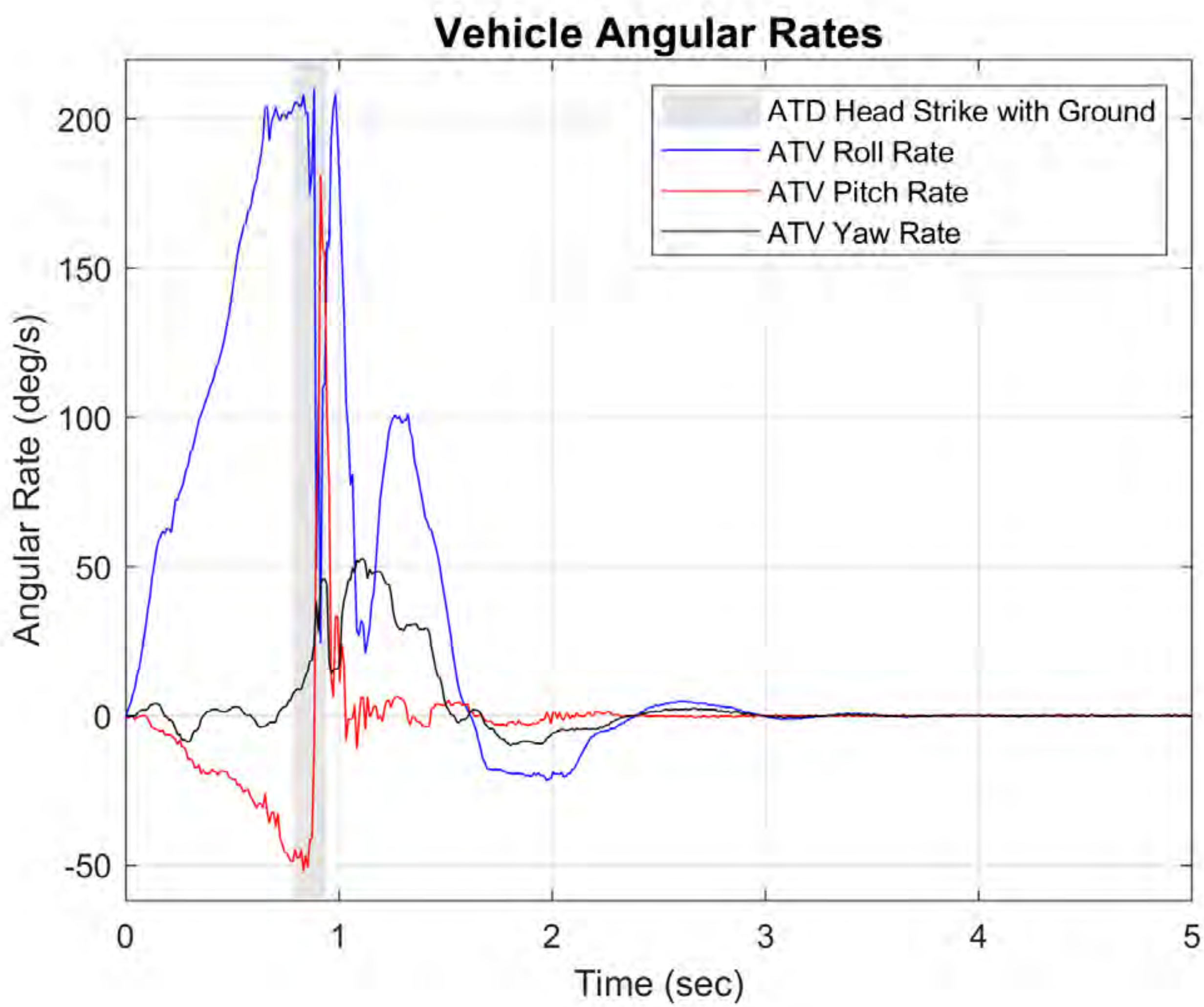
Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



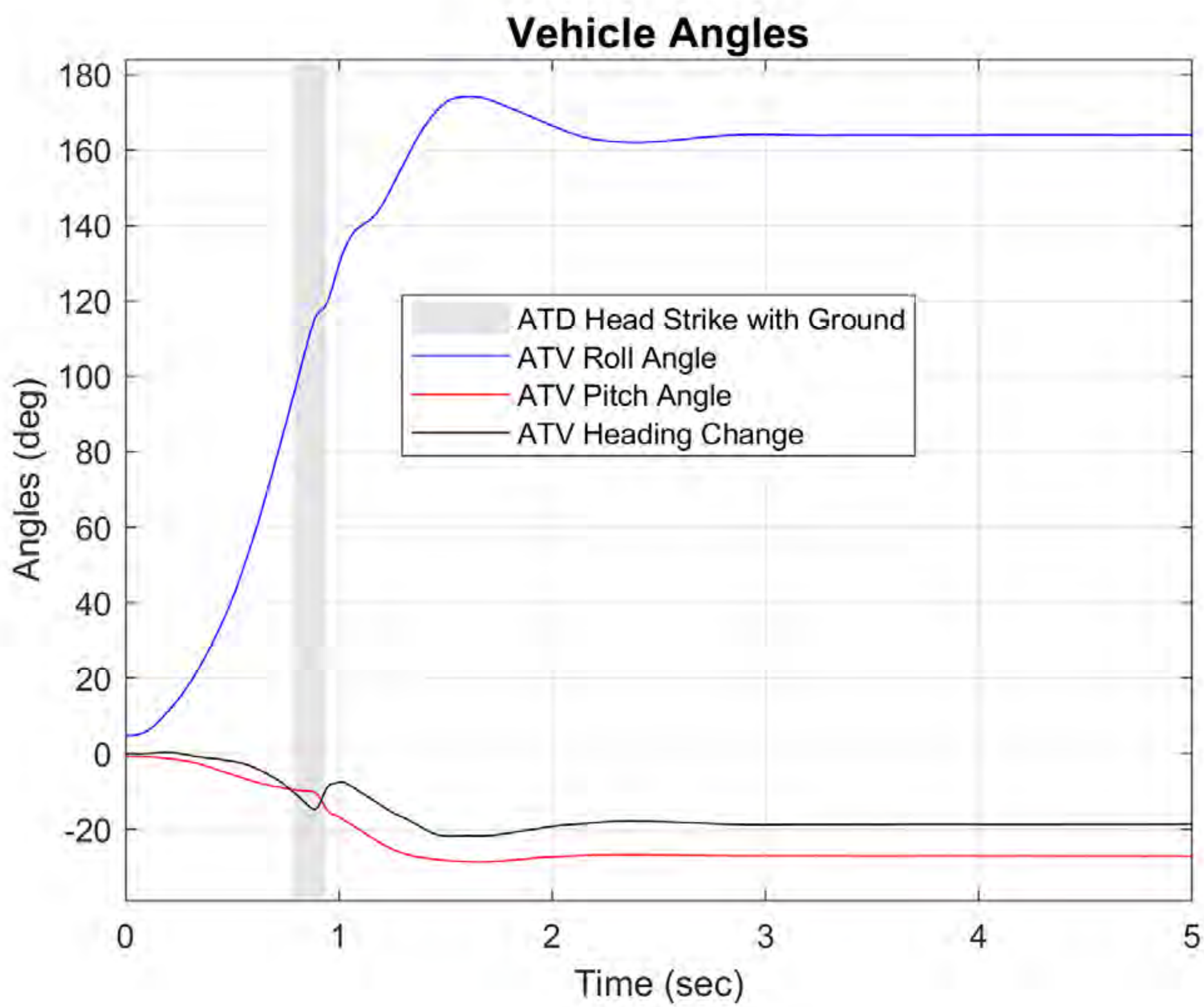
Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Roll Angle = 30° - Time = 0.56 sec

Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Roll Angle = 45° - Time = 0.69 sec

Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Roll Angle = 90° - Time = 0.93 sec

Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

ATD Head Strike - Time = 1.11 sec

Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Max Roll Angle = 115.4° - Time = 1.51 sec

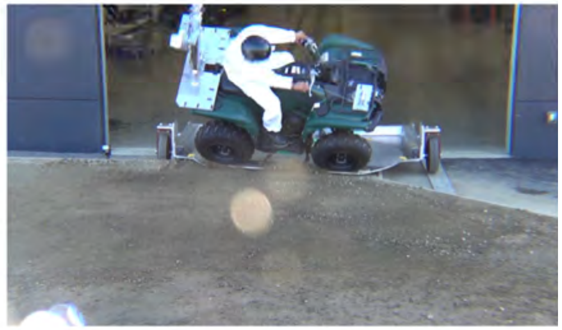
Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

End of Run - Roll Angle = 96.7°

Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Drone Camera - Roll Angle = 30° - Time = 0.56 sec

Drone Camera - Roll Angle = 45° - Time = 0.69 sec



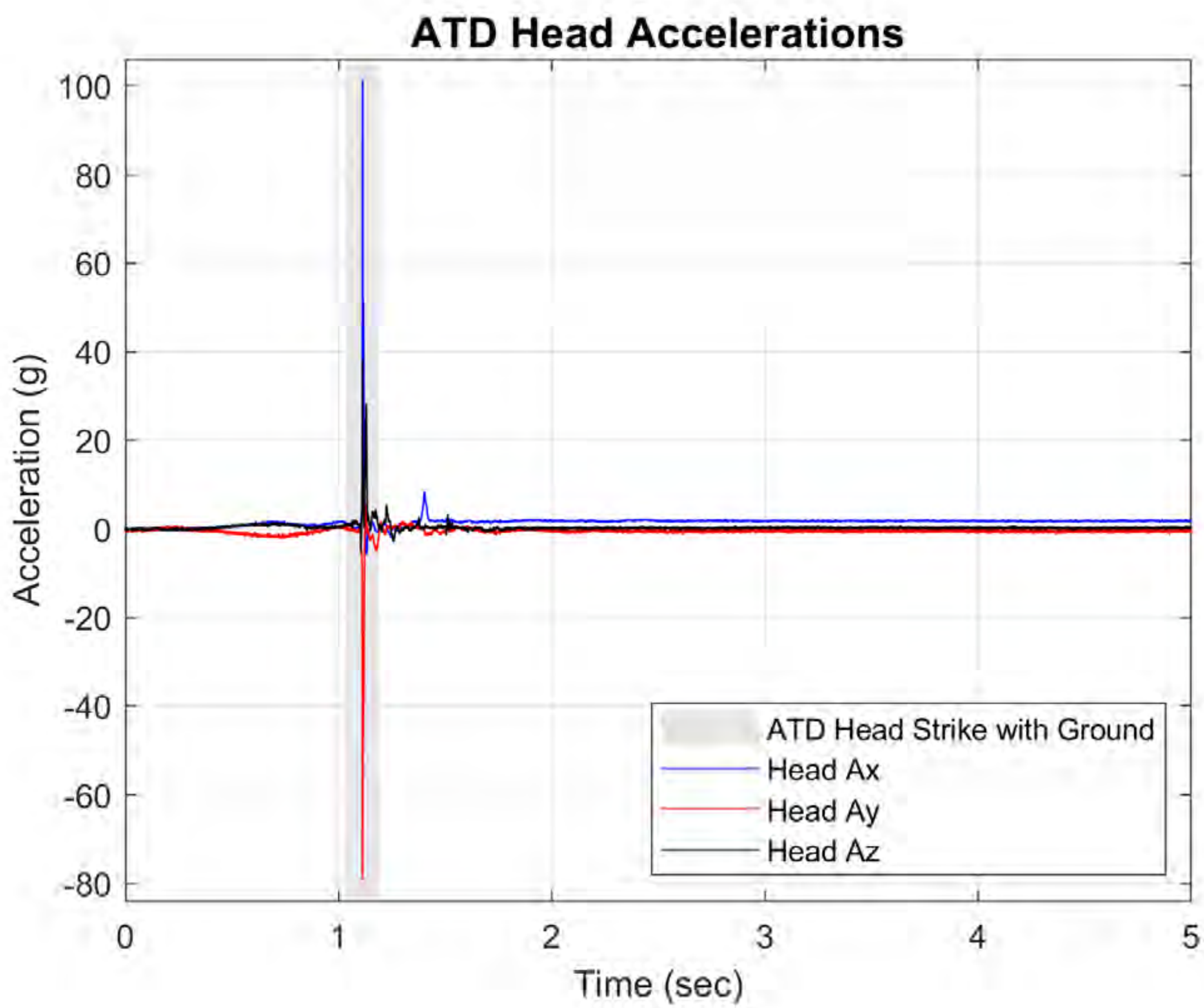
Drone Camera - Roll Angle = 90° - Time = 0.93 sec

Drone Camera - ATD Head Strike - Time = 1.11 sec

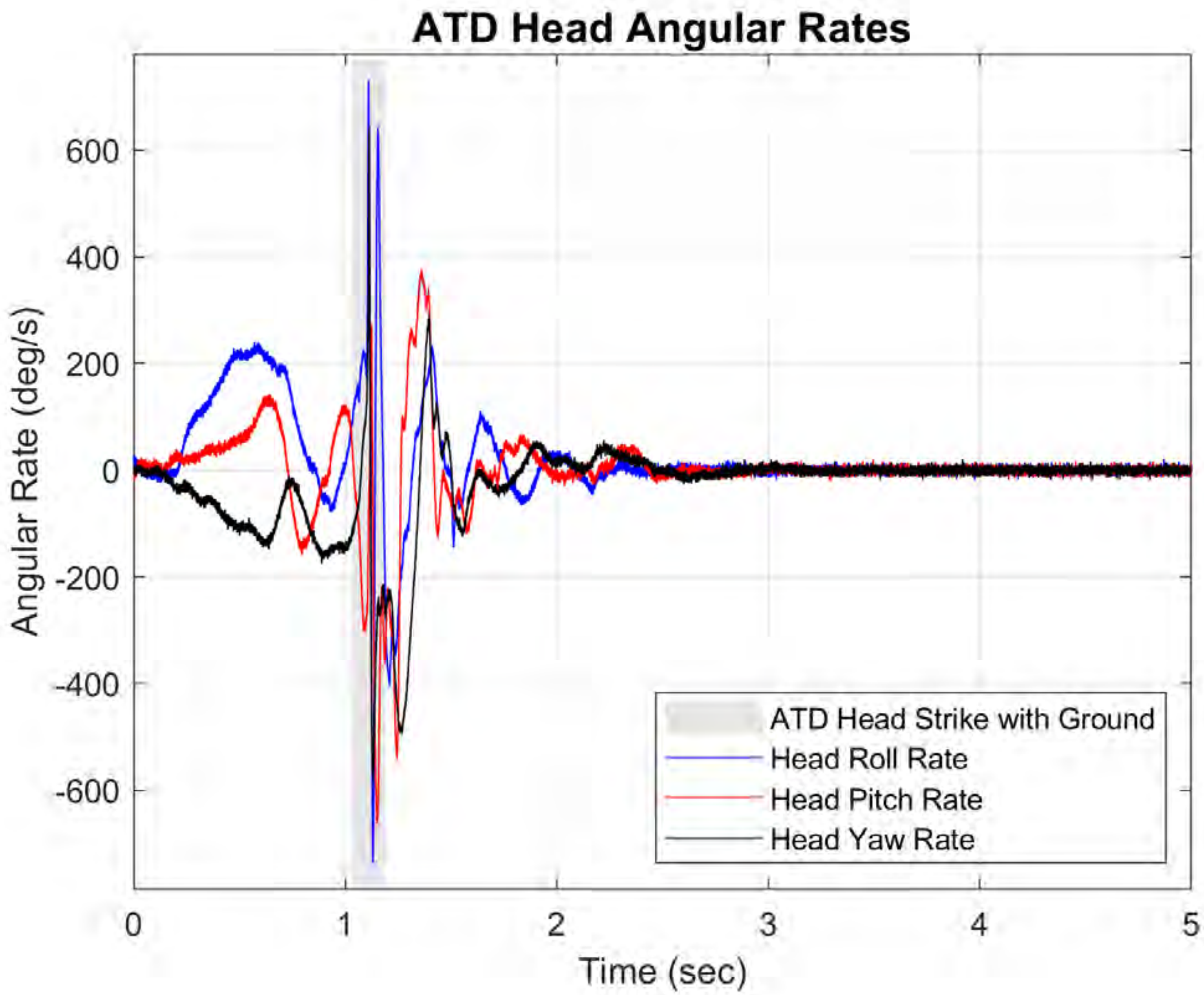
Drone Camera - Max Angle = 115.4° - Time = 1.51 sec

Drone Camera - End of Run - Roll Angle = 96.7°

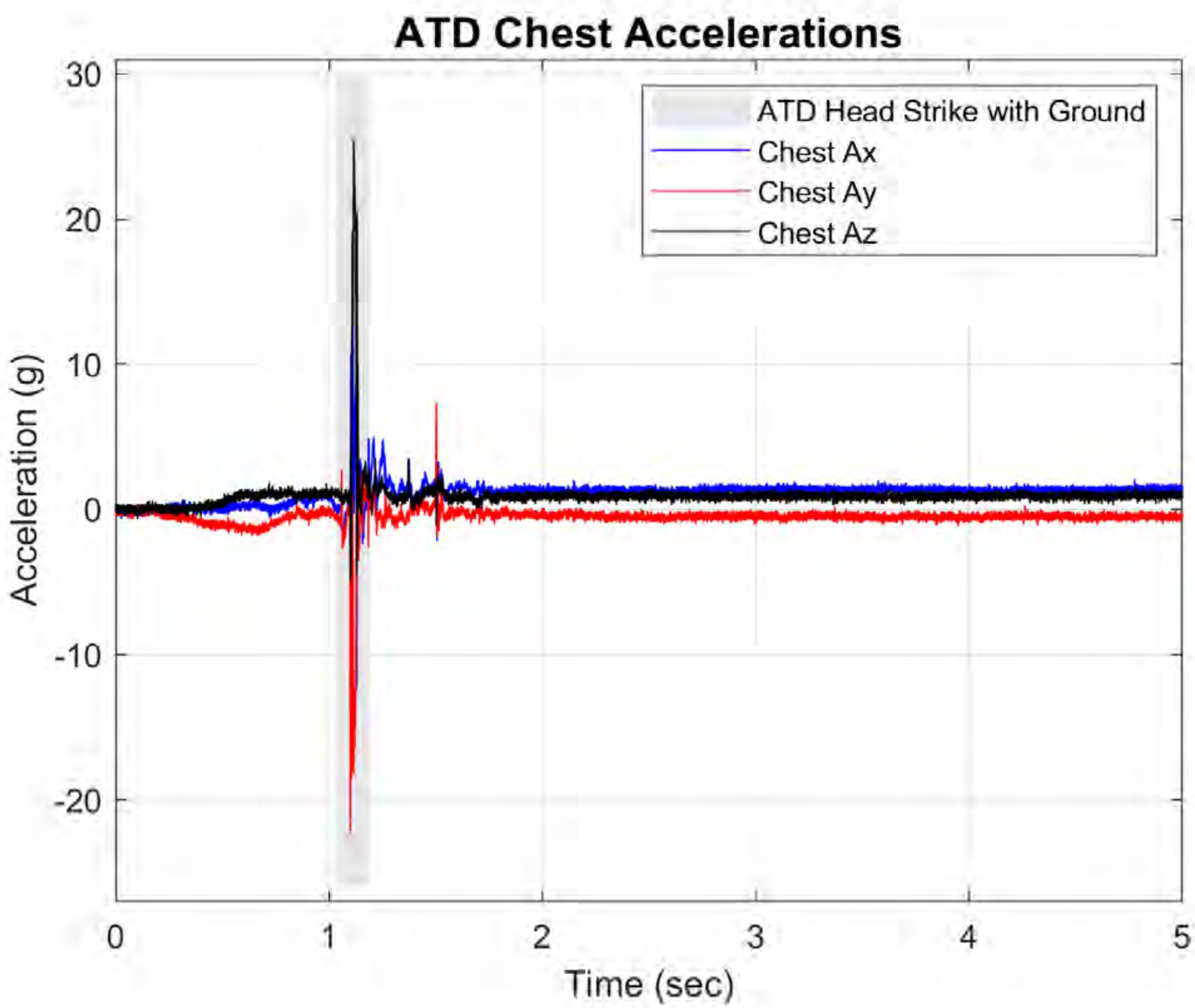
Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



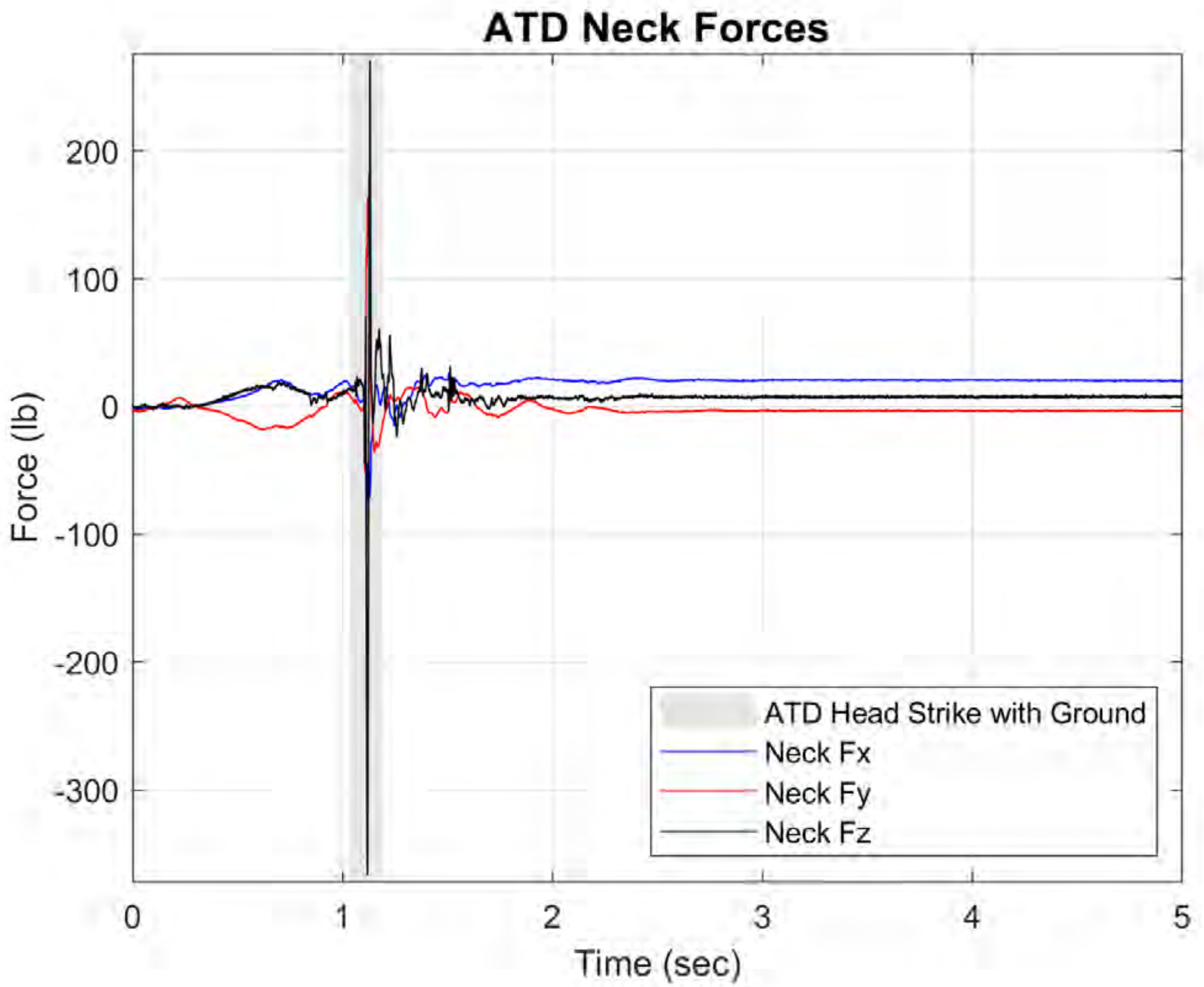
Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



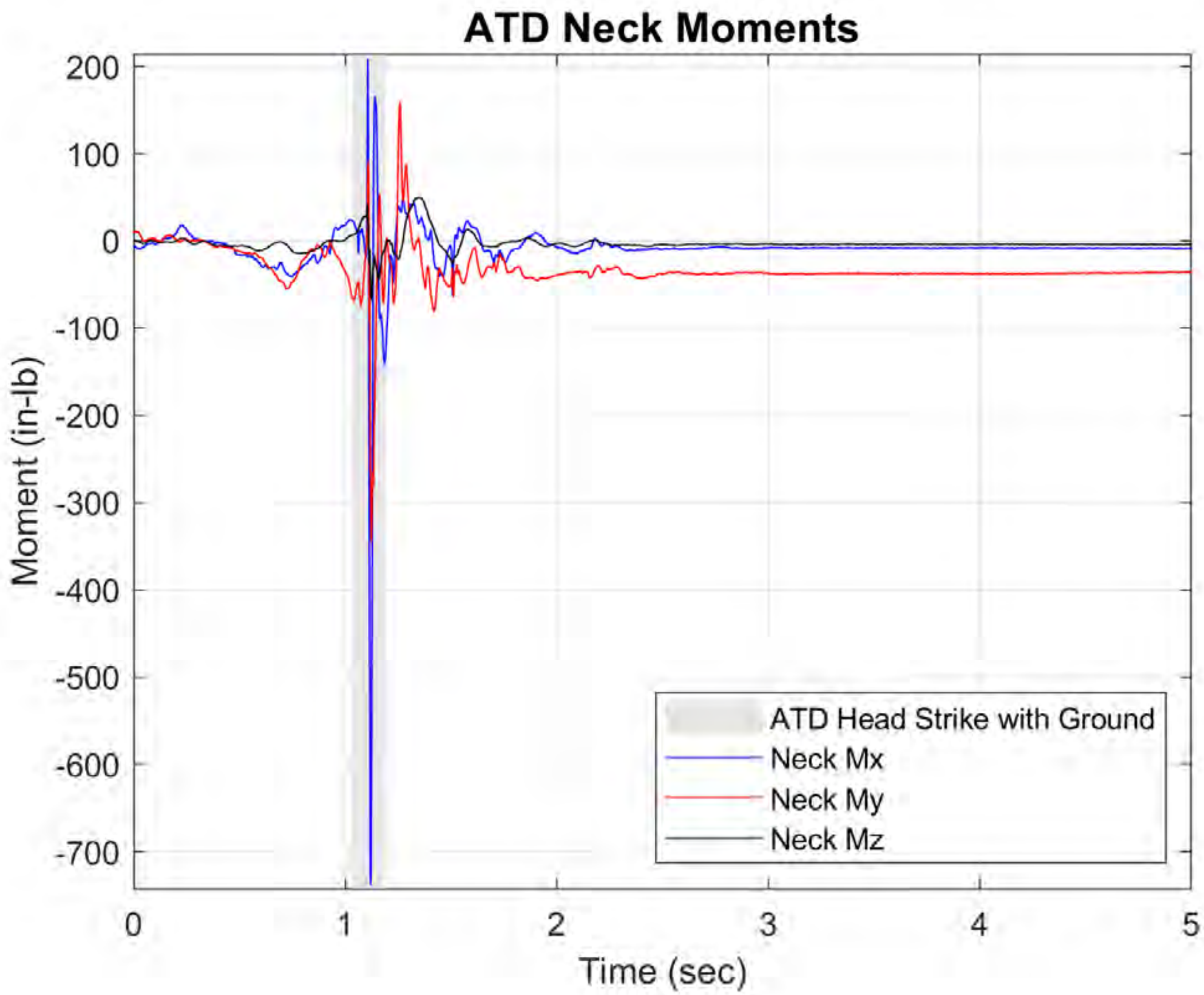
Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



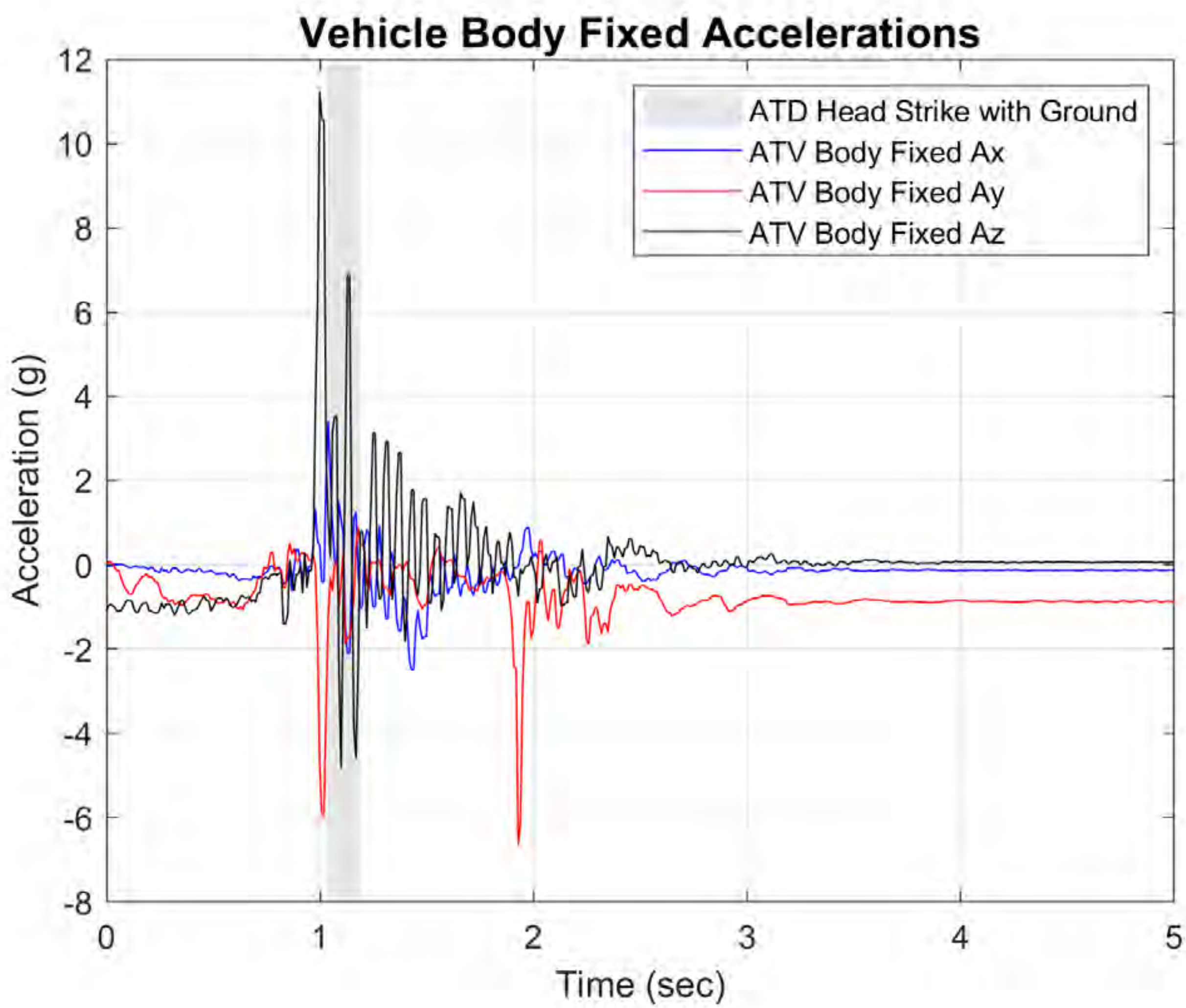
Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



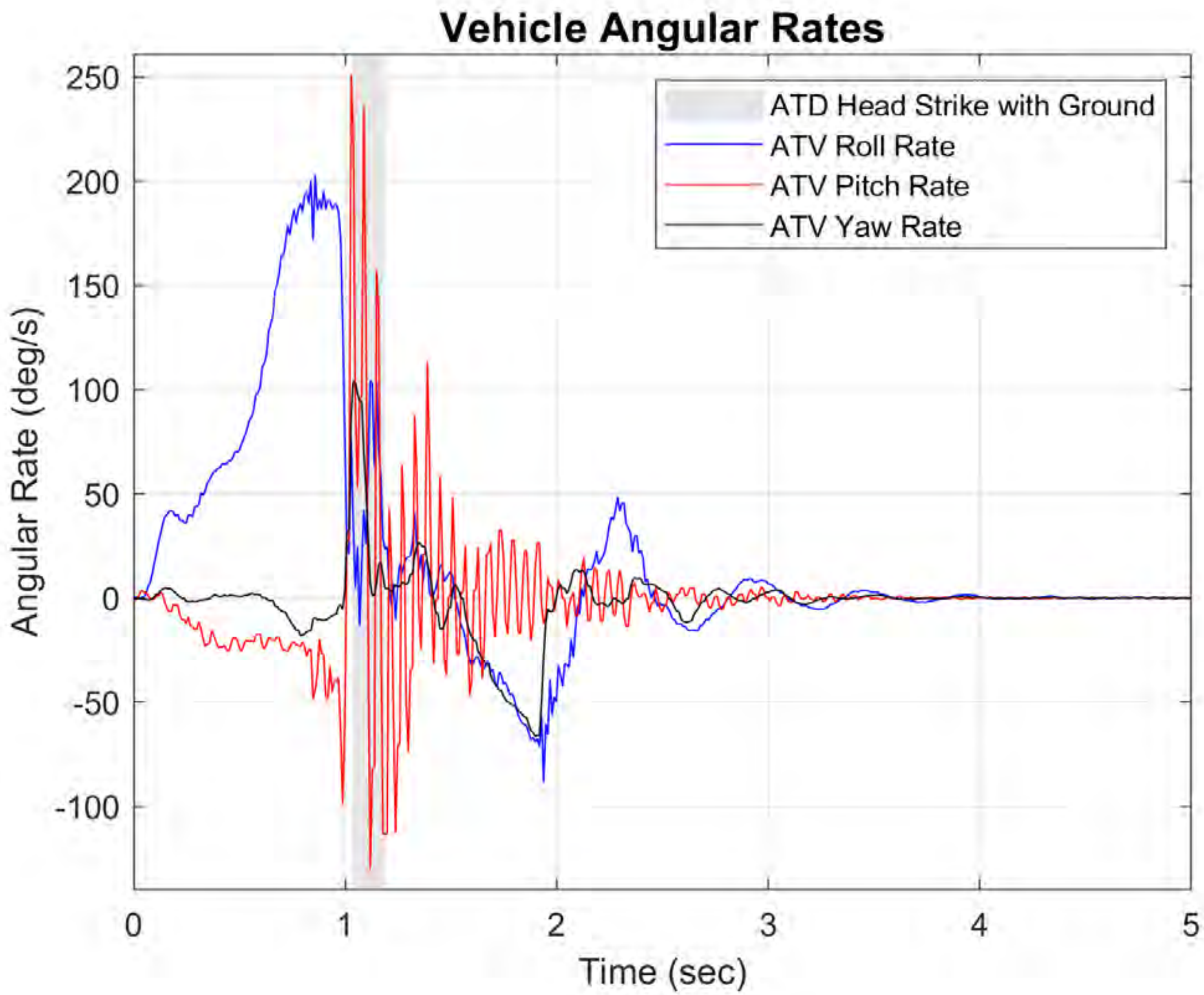
Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



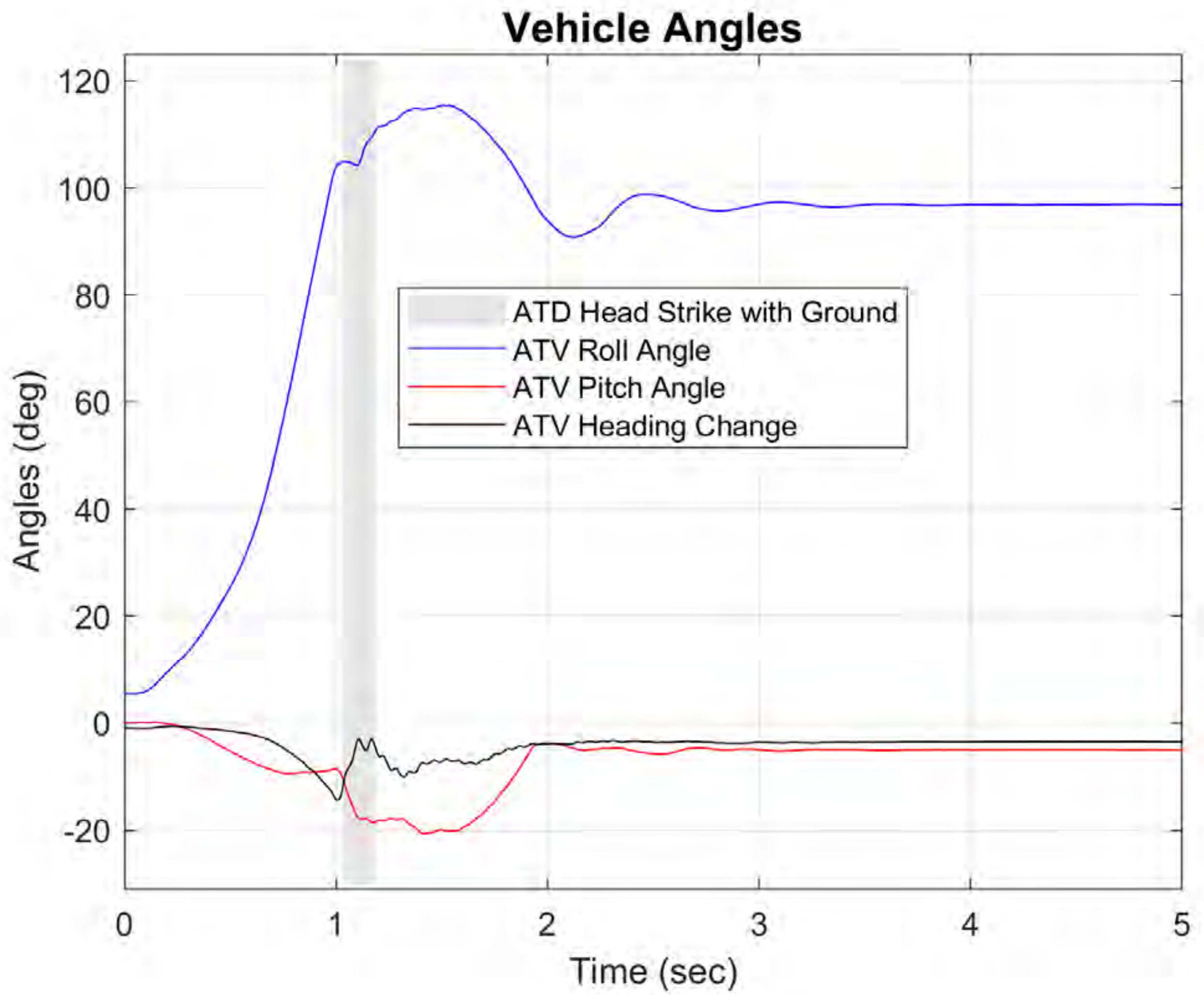
Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

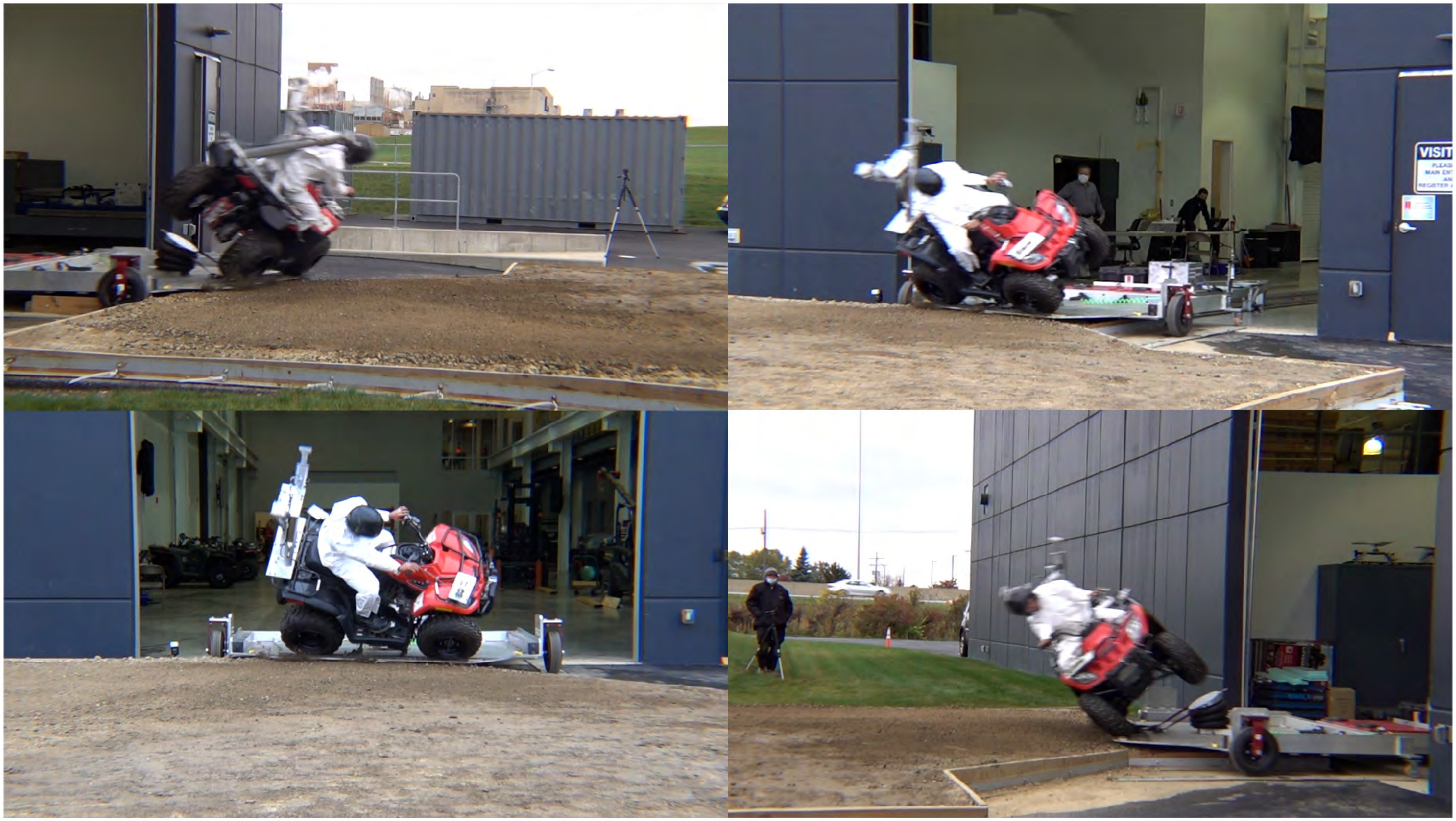


Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Roll Angle = 30° - Time = 0.61 sec

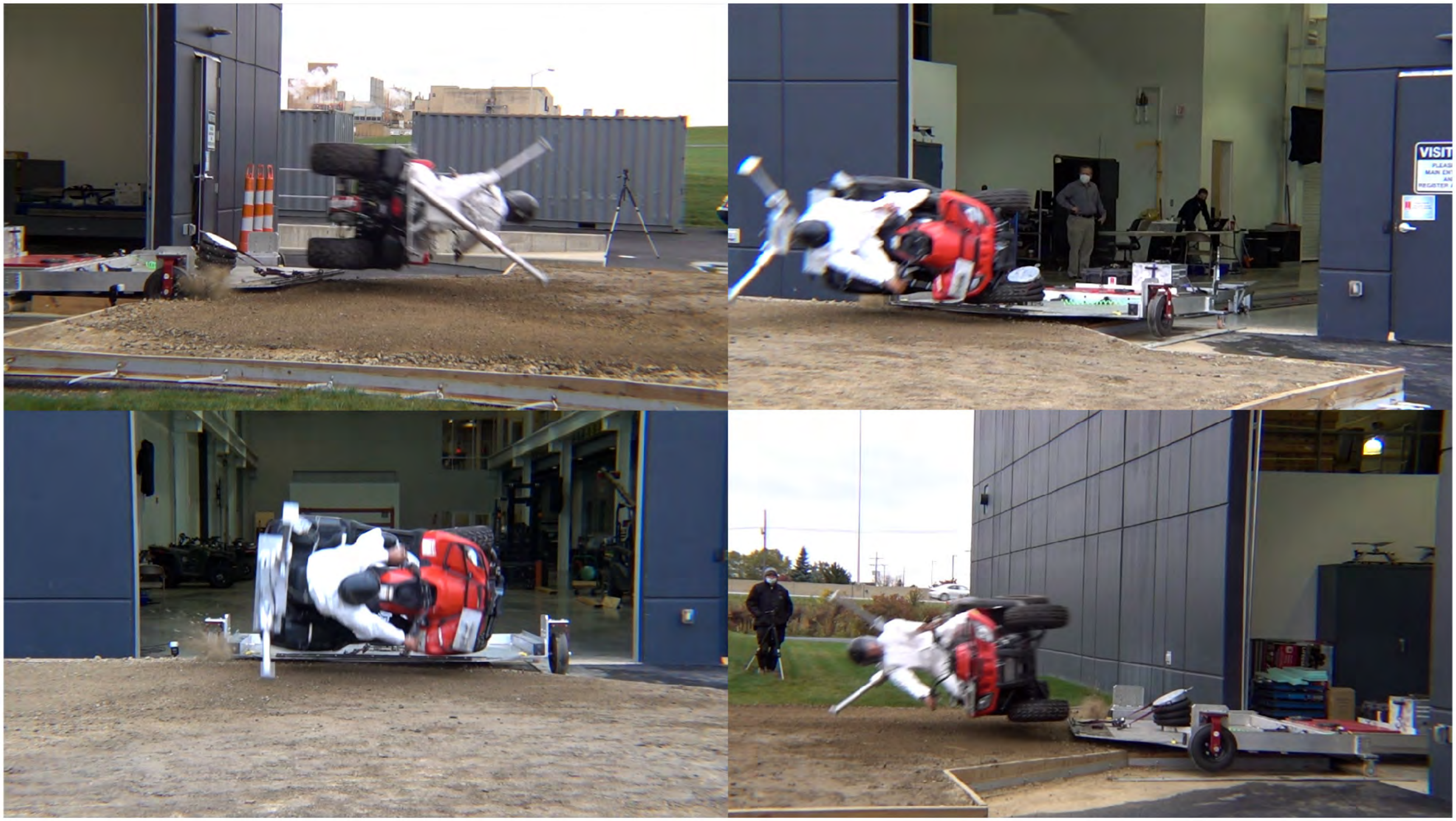
Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Roll Angle = 45° - Time = 0.72 sec



Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Roll Angle = 90° - Time = 0.97 sec



Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

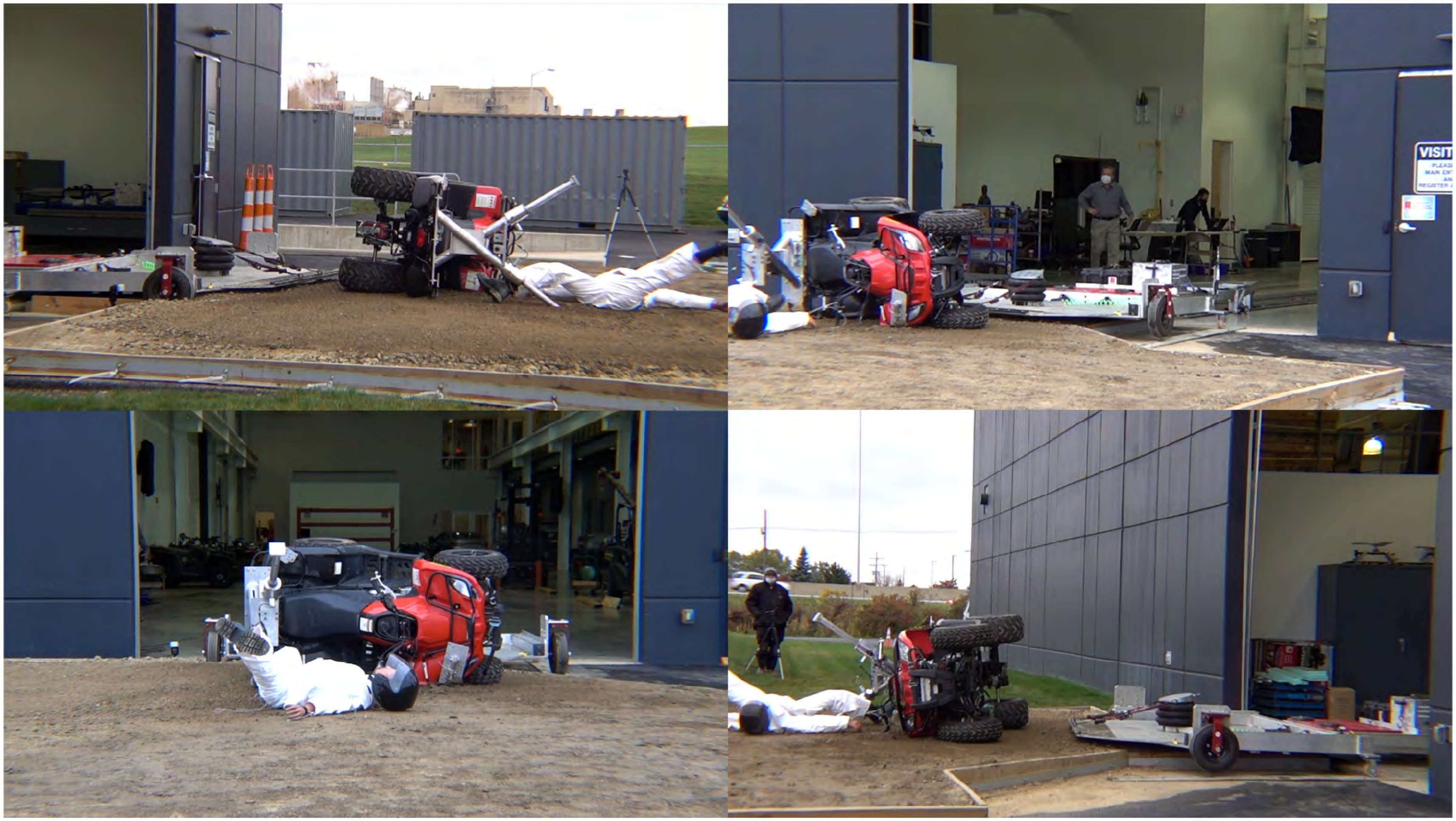
ATD Head Strike - Time = 1.12 sec

Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Max Roll Angle = 113.0° - Time = 1.26 sec

Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

End of Run - Roll Angle = 97.8°



Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Drone Camera - Roll Angle = 30° - Time = 0.61 sec

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

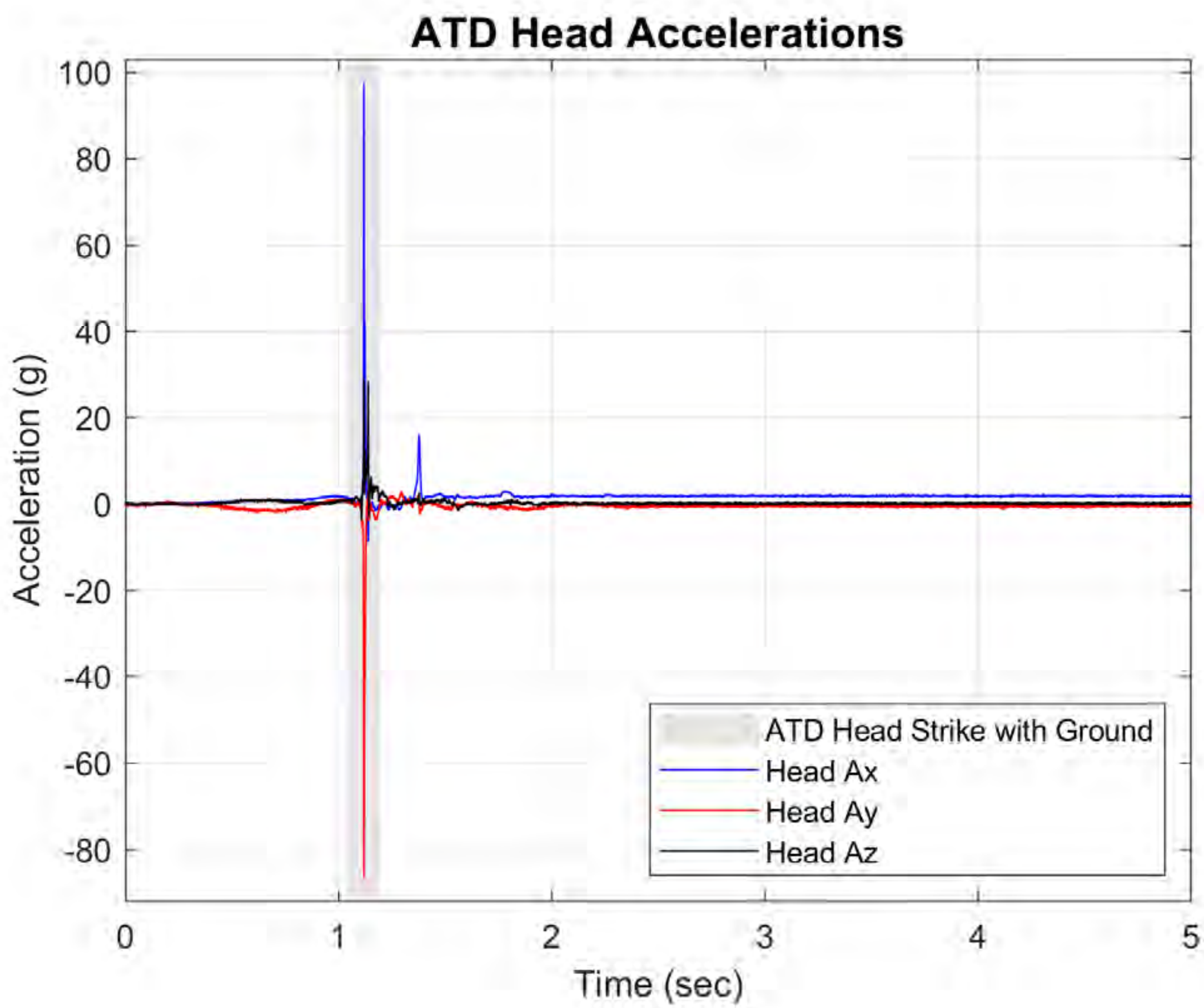
Drone Camera - Roll Angle = 90° - Time = 0.97 sec

Drone Camera - ATD Head Strike - Time = 1.12 sec

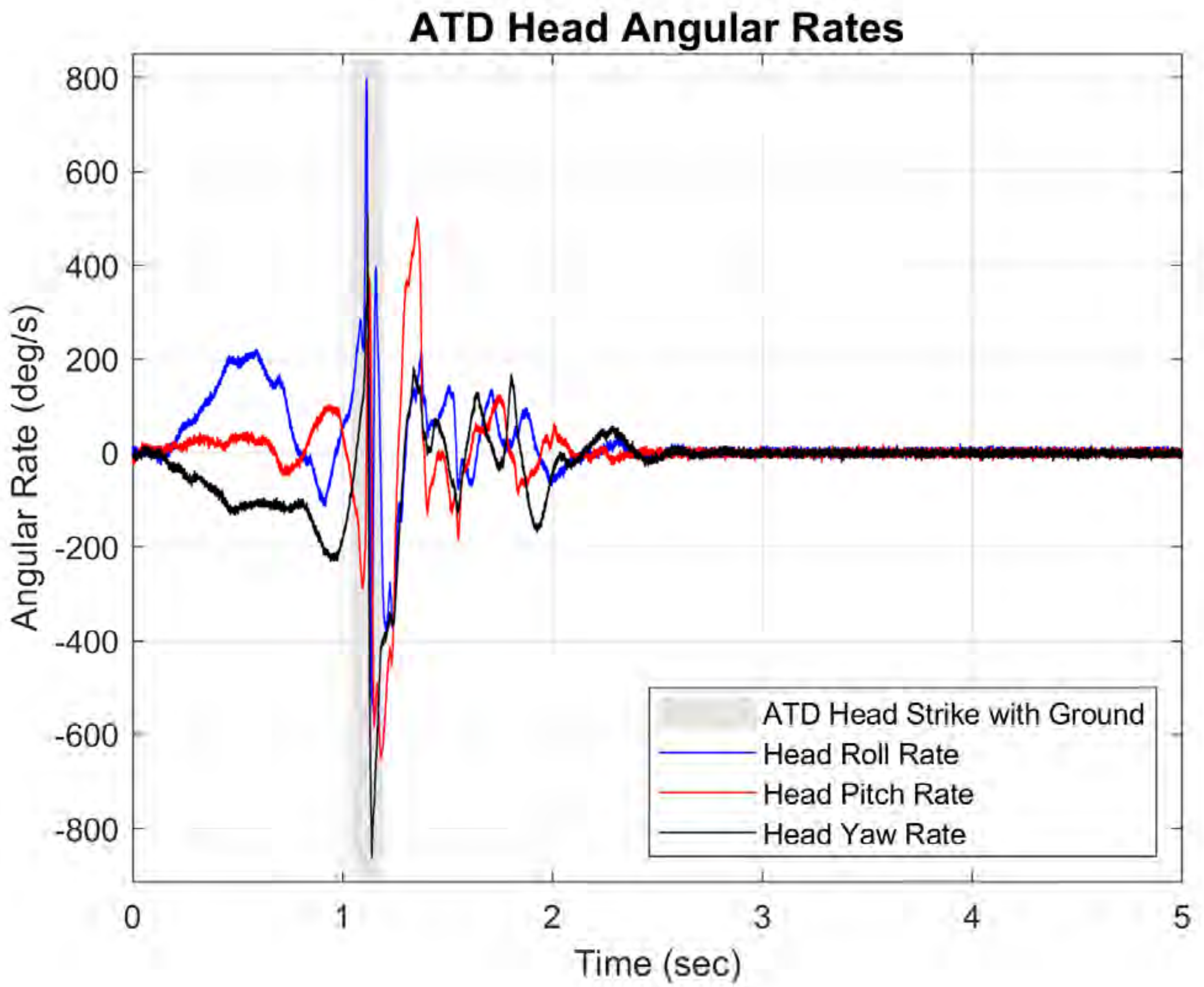
Drone Camera - Max Angle = 113.0° - Time = 1.26 sec

Drone Camera - End of Run - Roll Angle = 97.8°

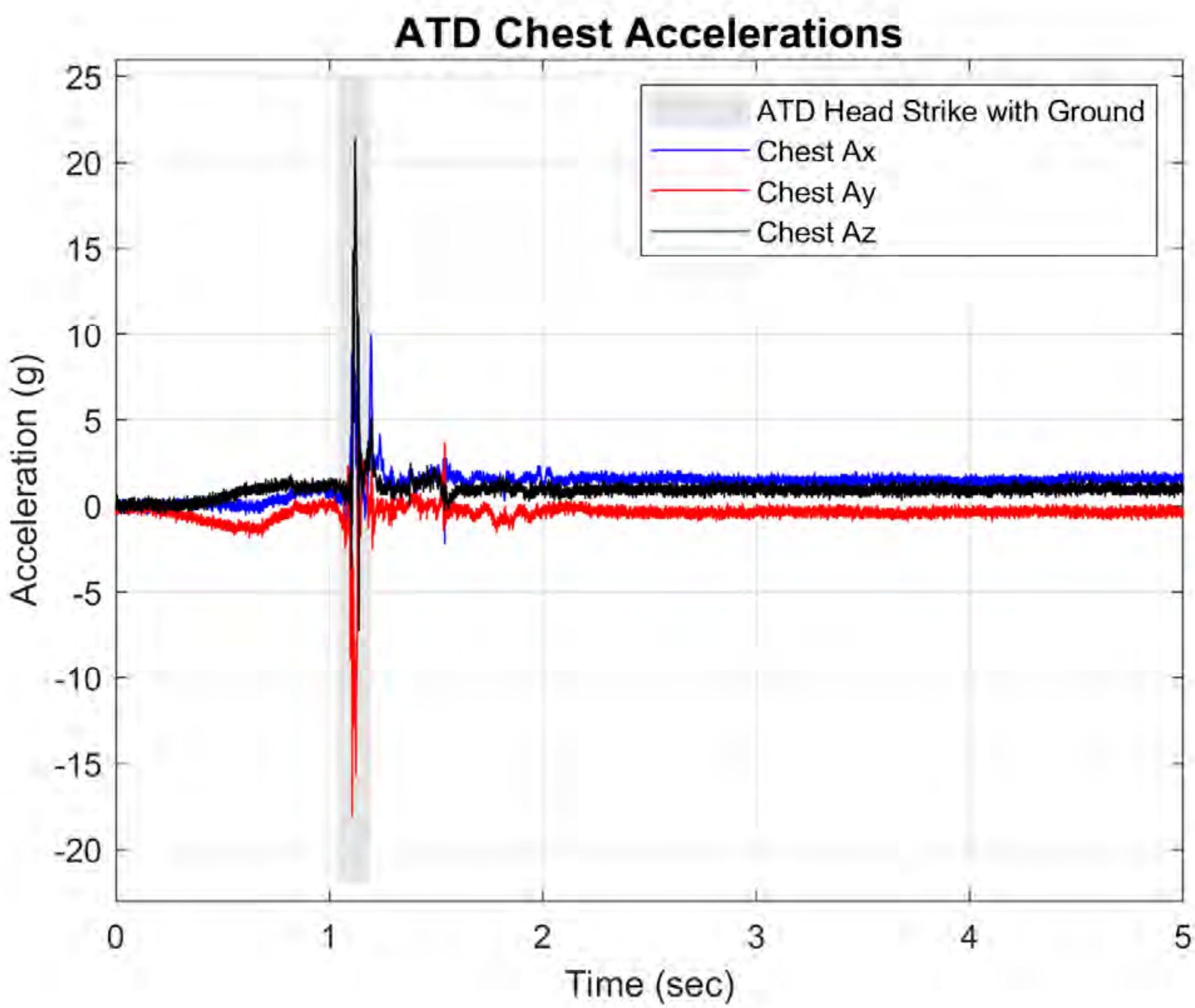
Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



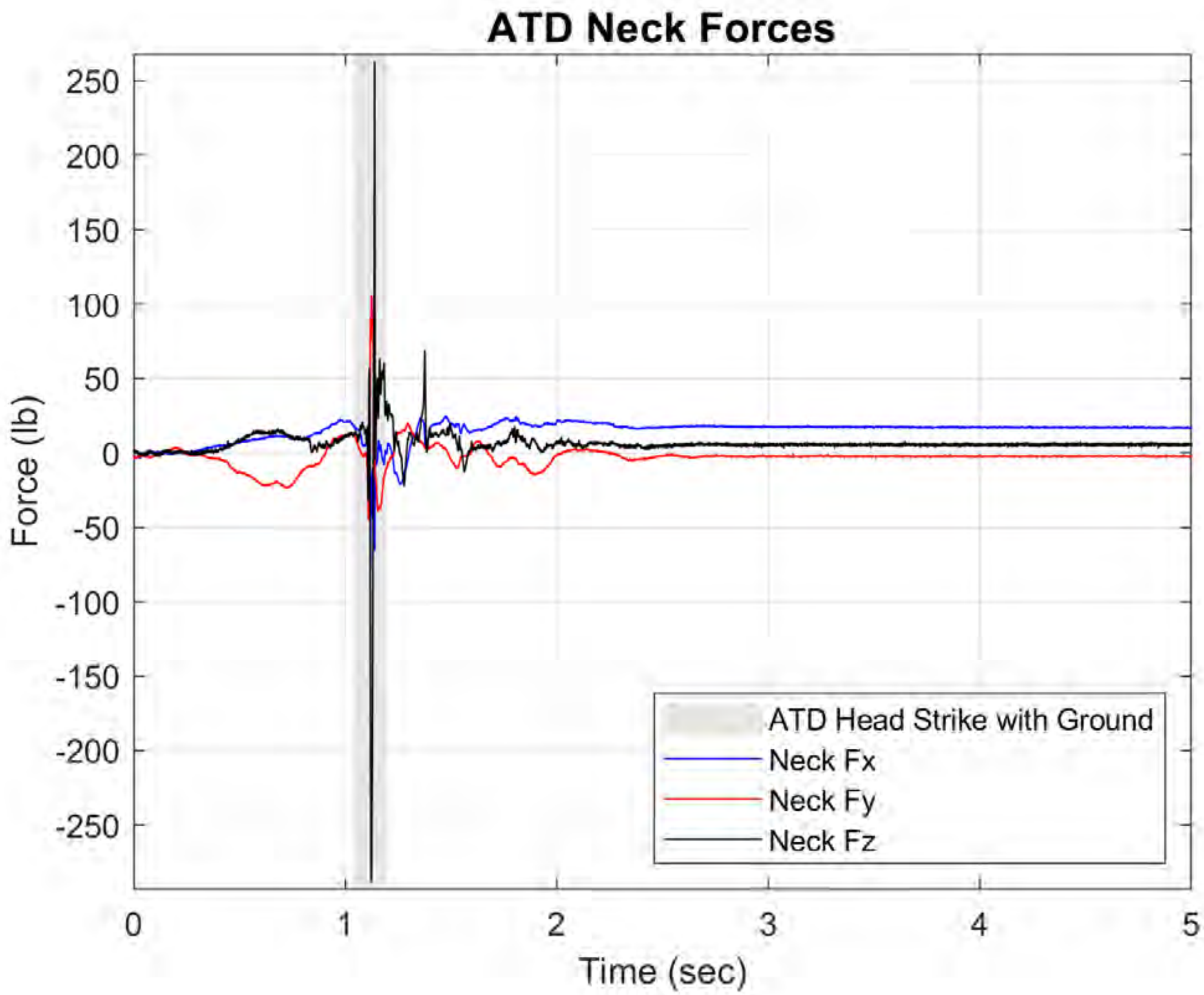
Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



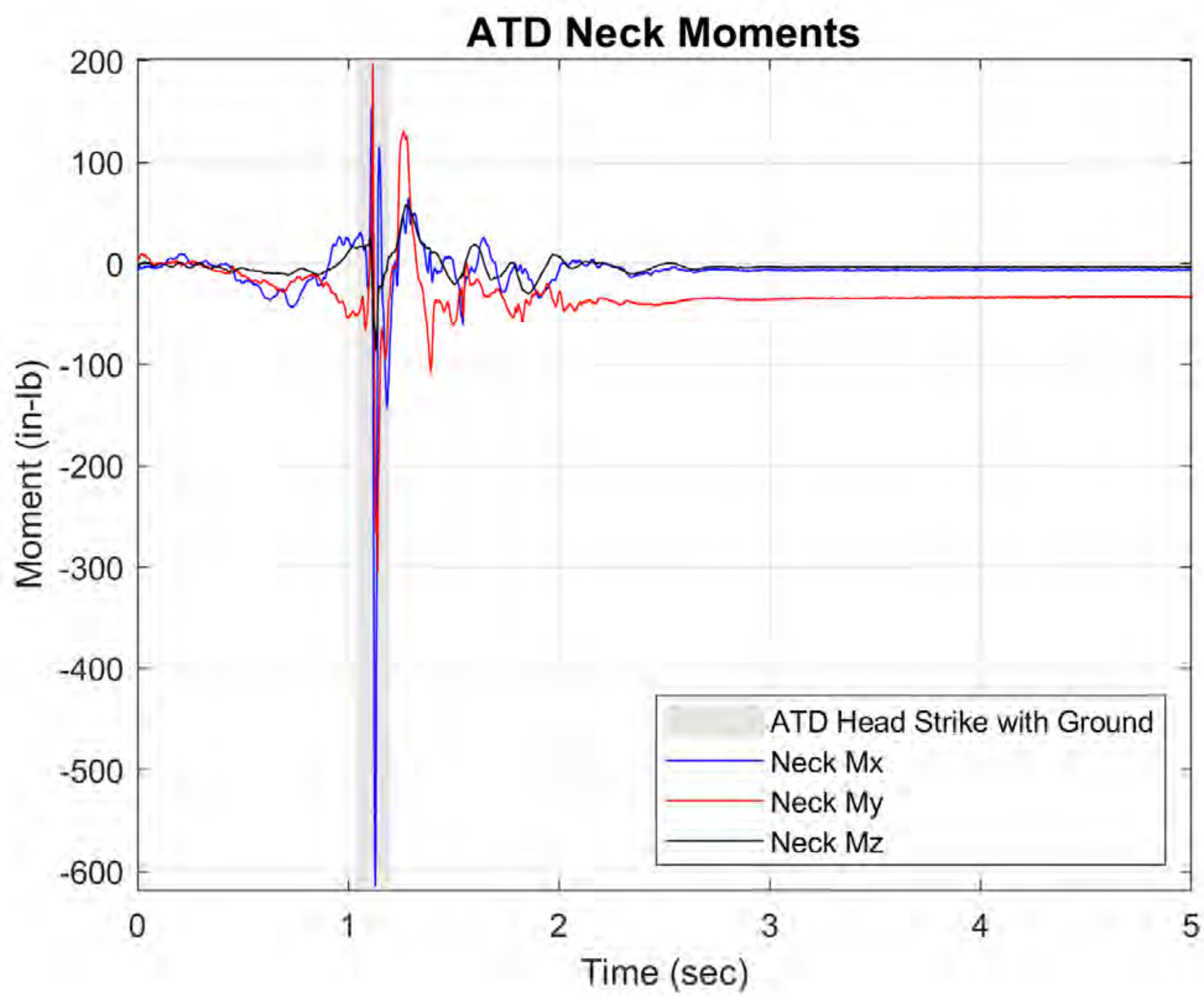
Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



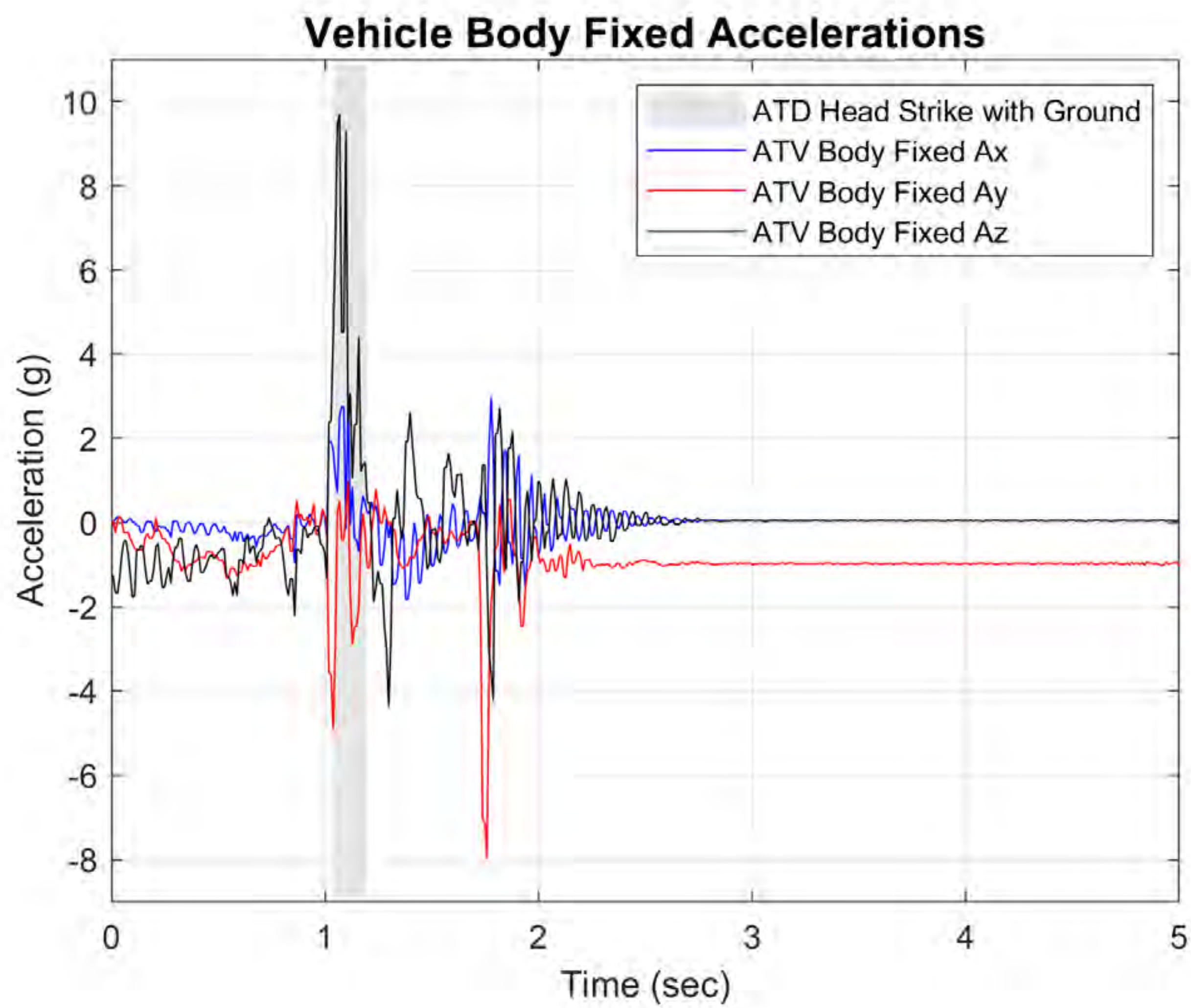
Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



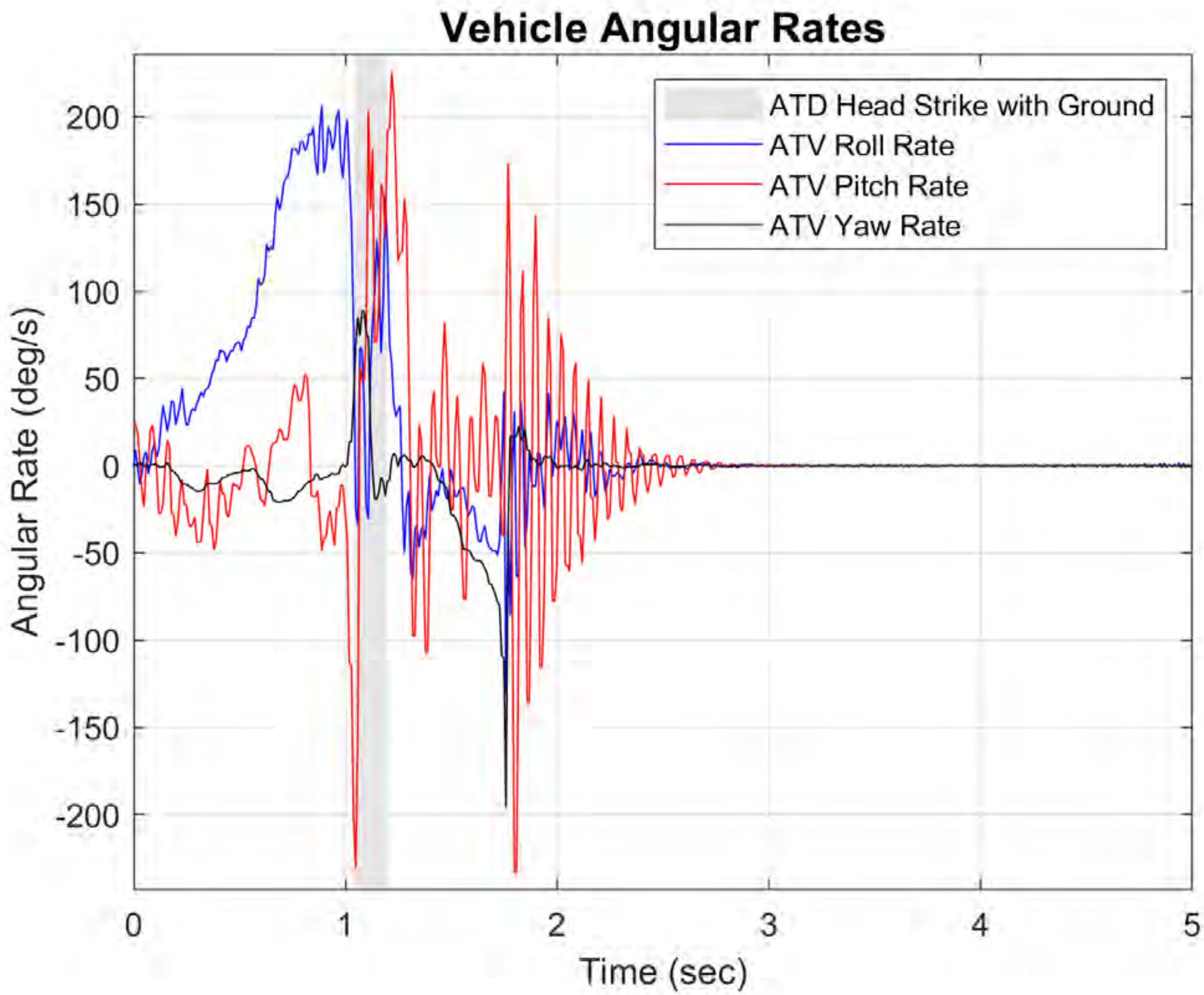
Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



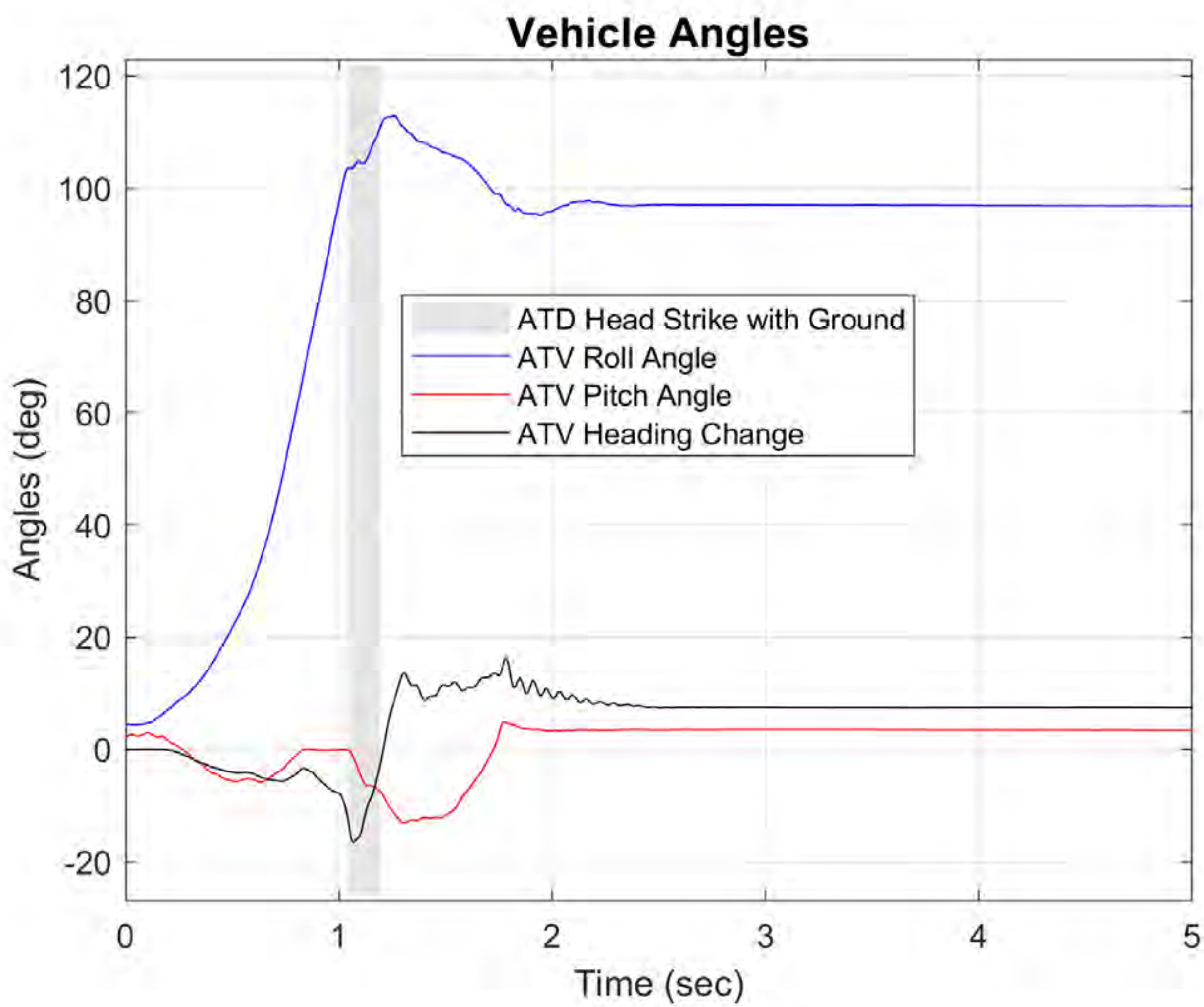
Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Roll Angle = 30° - Time = 0.55 sec

Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Roll Angle = 45° - Time = 0.67 sec

Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Roll Angle = 90° - Time = 0.90 sec

Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

ATD Head Strike - Time = 1.02 sec

Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Max Roll Angle = 130.0° - Time = 1.55 sec

Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

End of Run - Roll Angle = 99.1°

Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

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

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

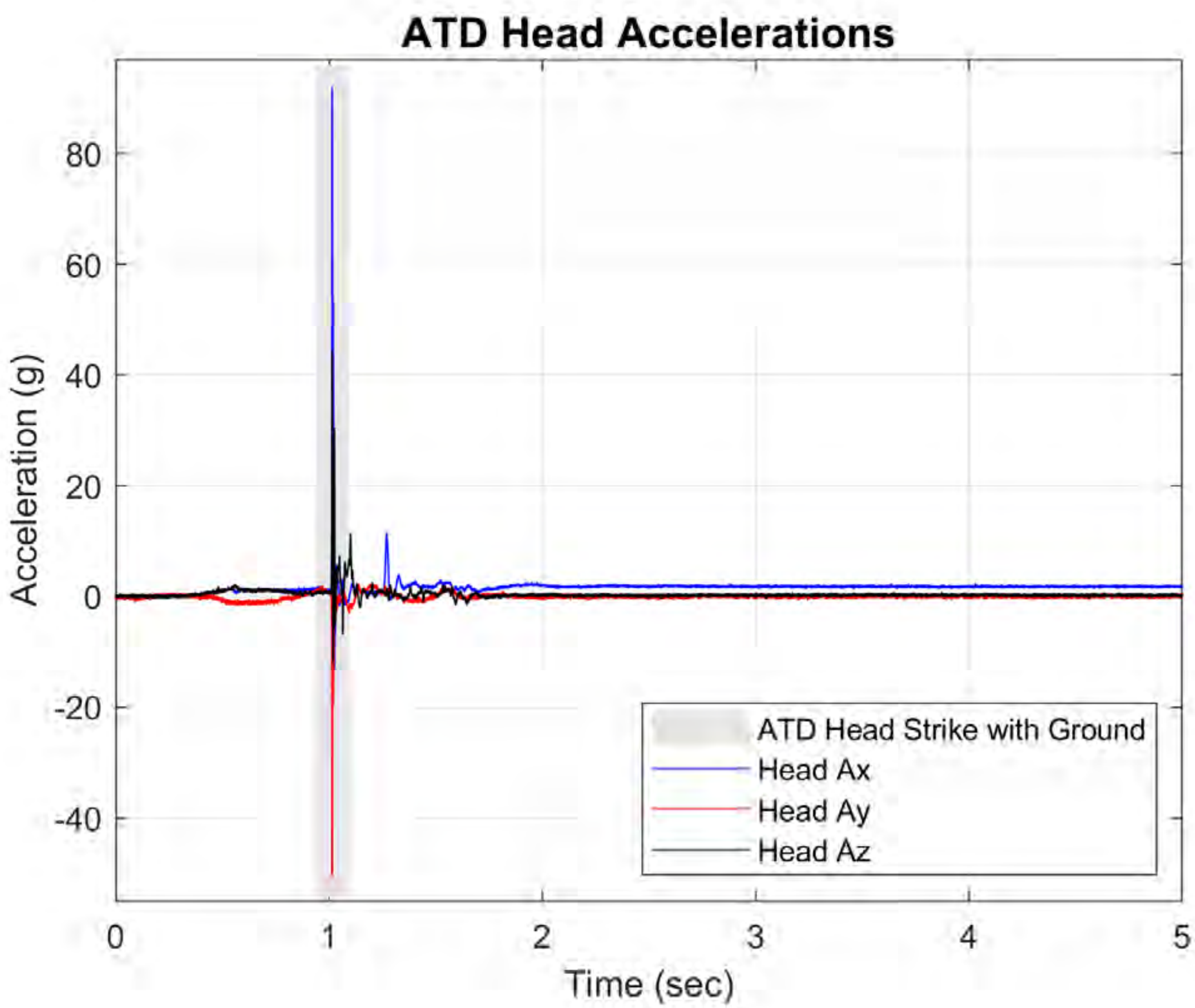
Drone Camera - Roll Angle = 90° - Time = 0.90 sec

Drone Camera - ATD Head Strike - Time = 0.82 sec

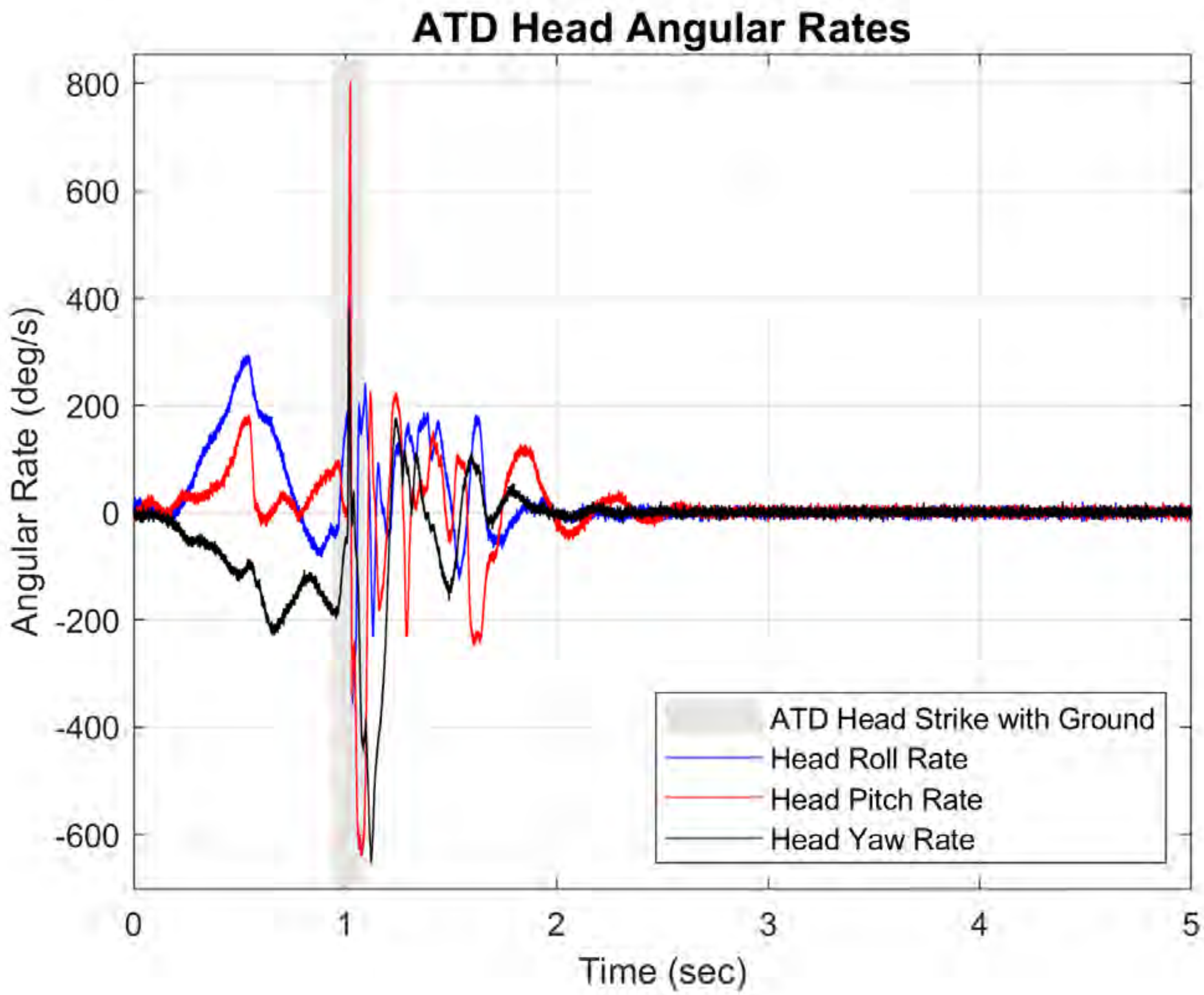
Drone Camera - Max Angle = 130.0° - Time = 1.55 sec

Drone Camera - End of Run - Roll Angle = 99.1°

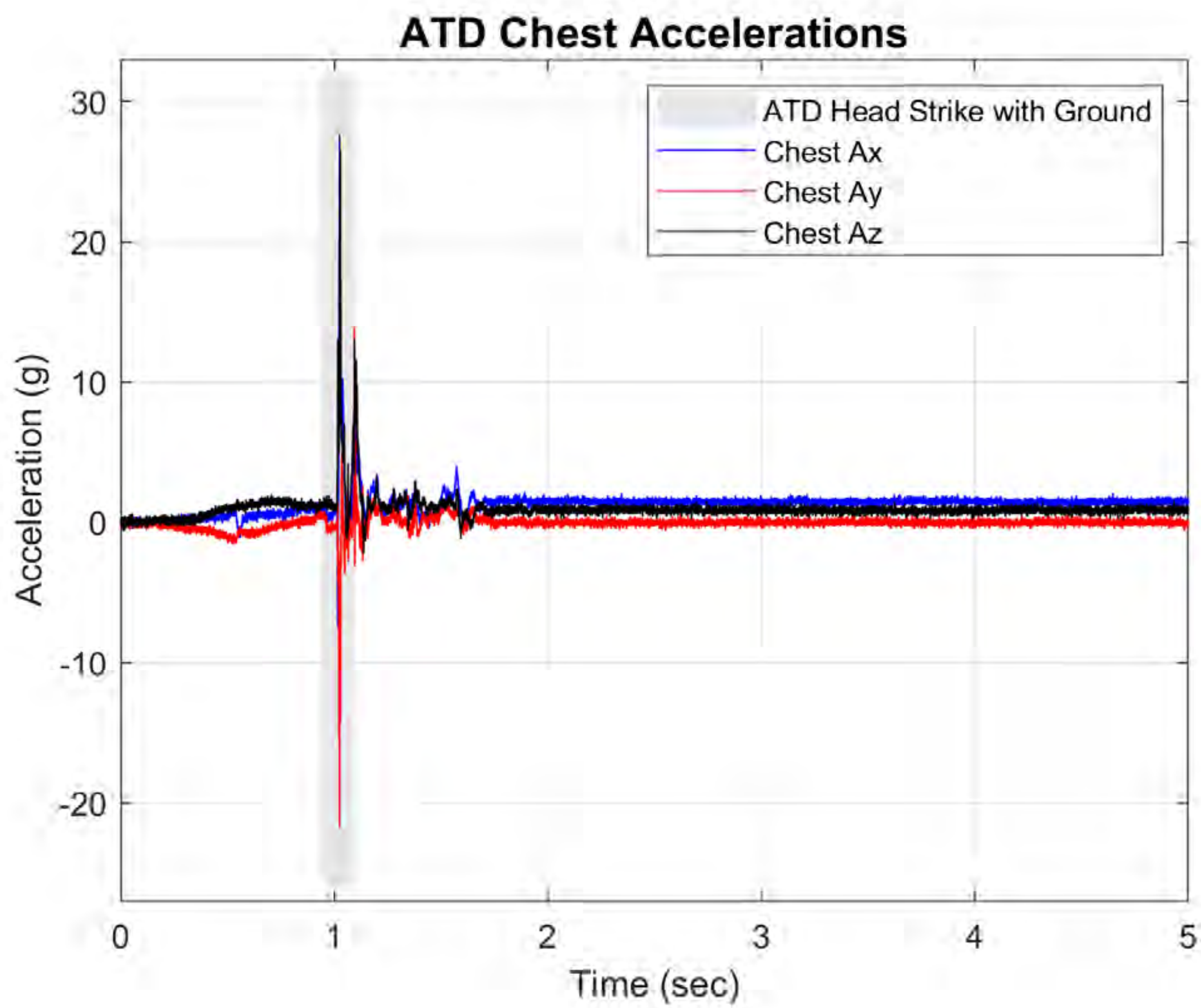
Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



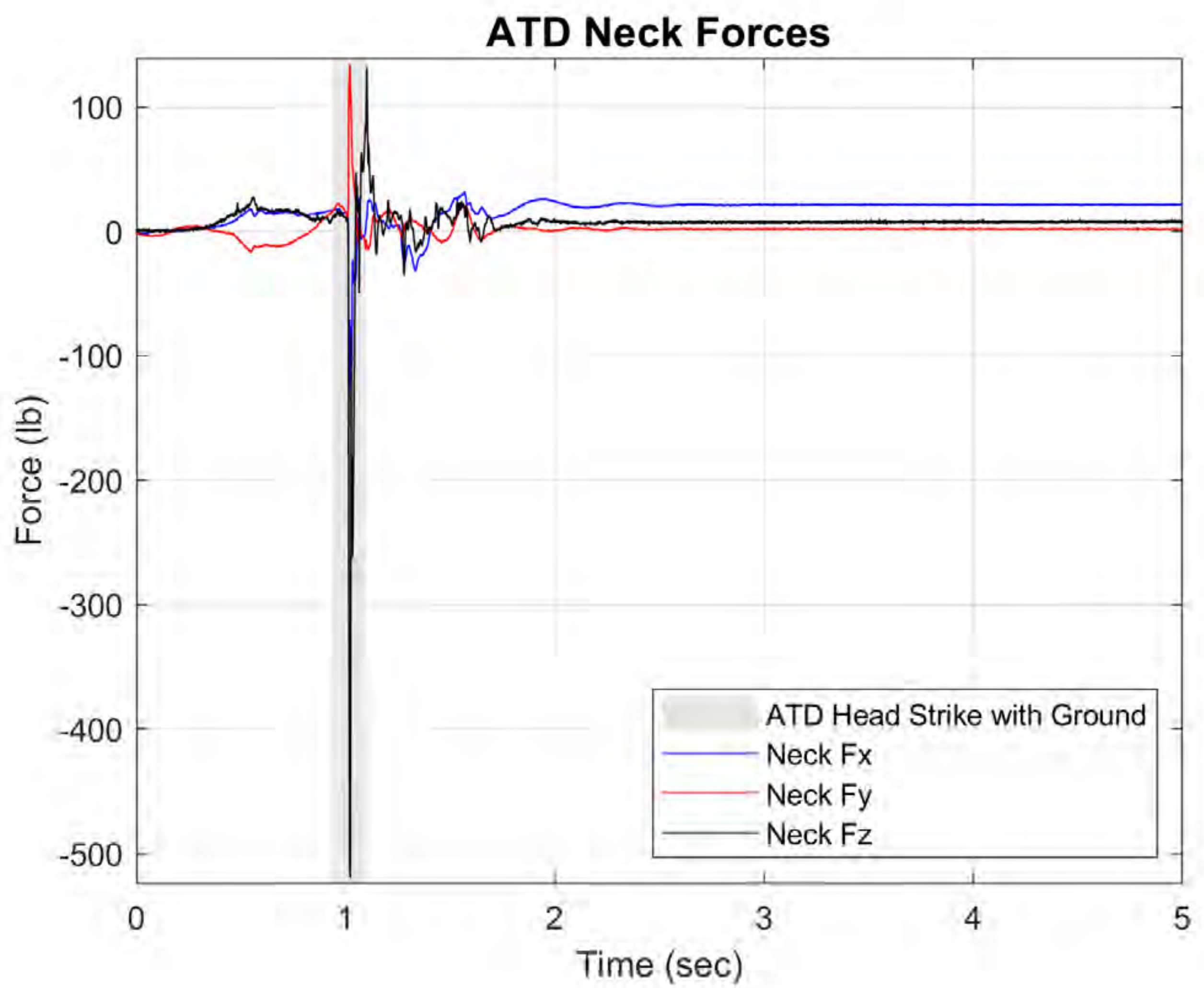
Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



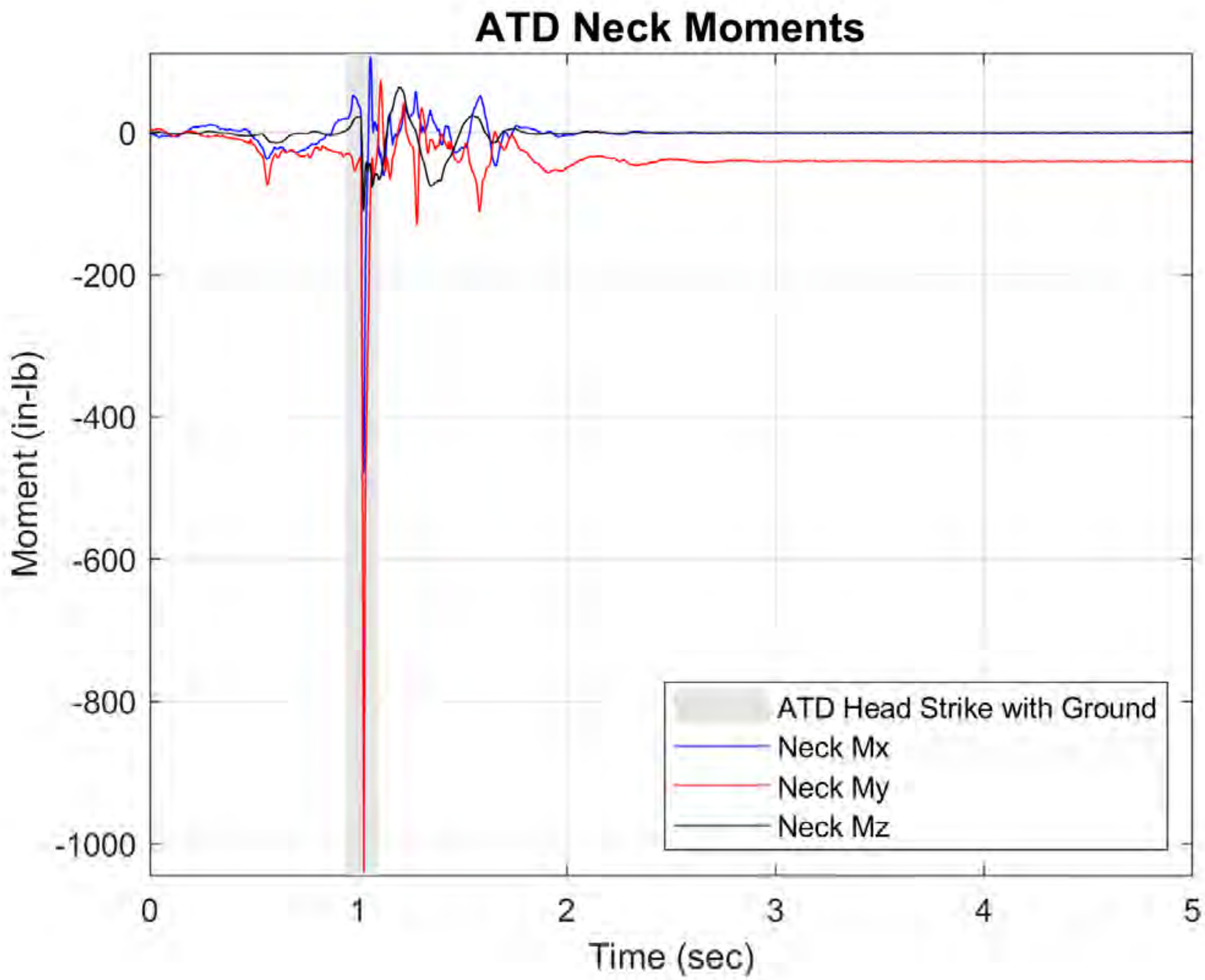
Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



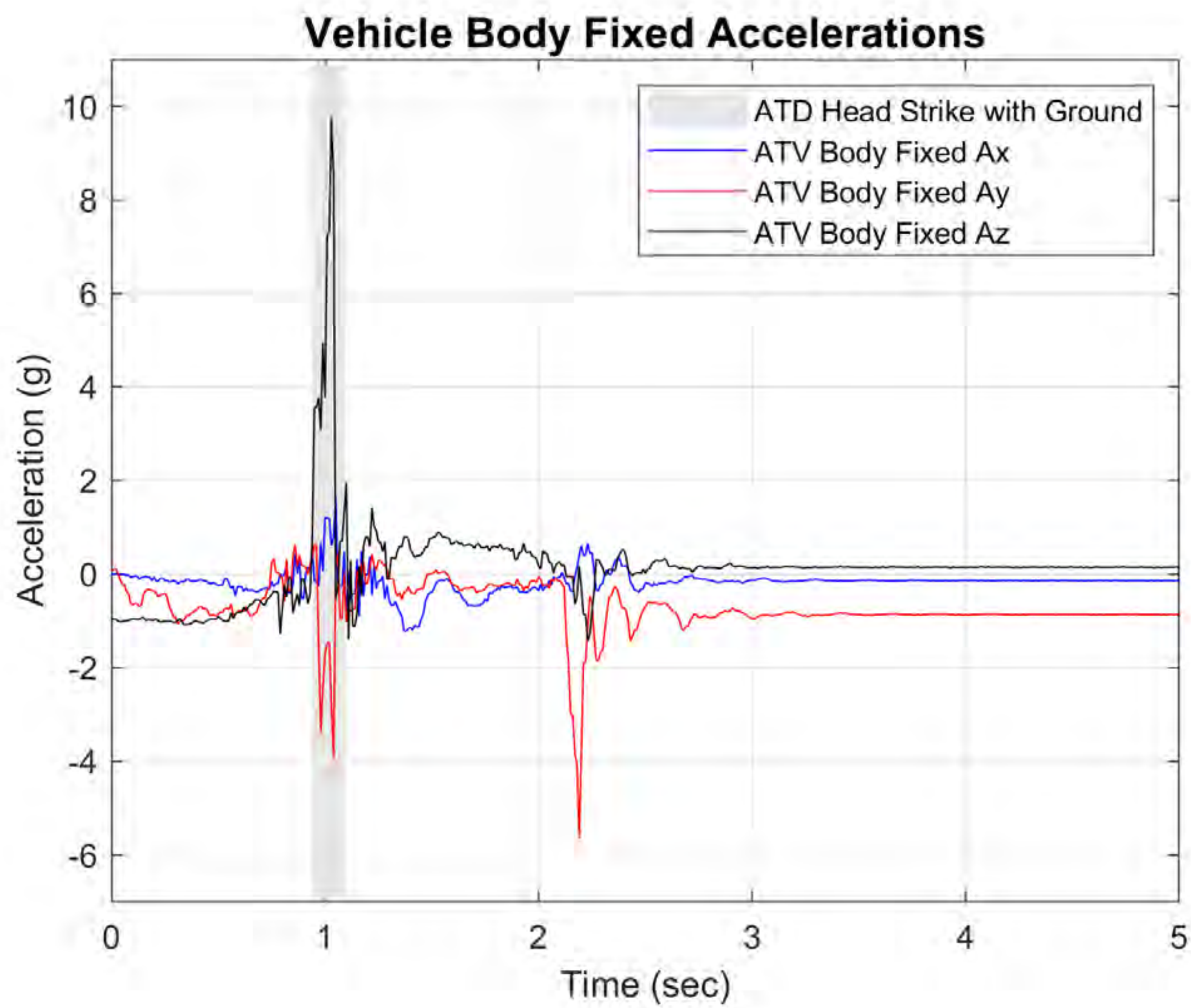
Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



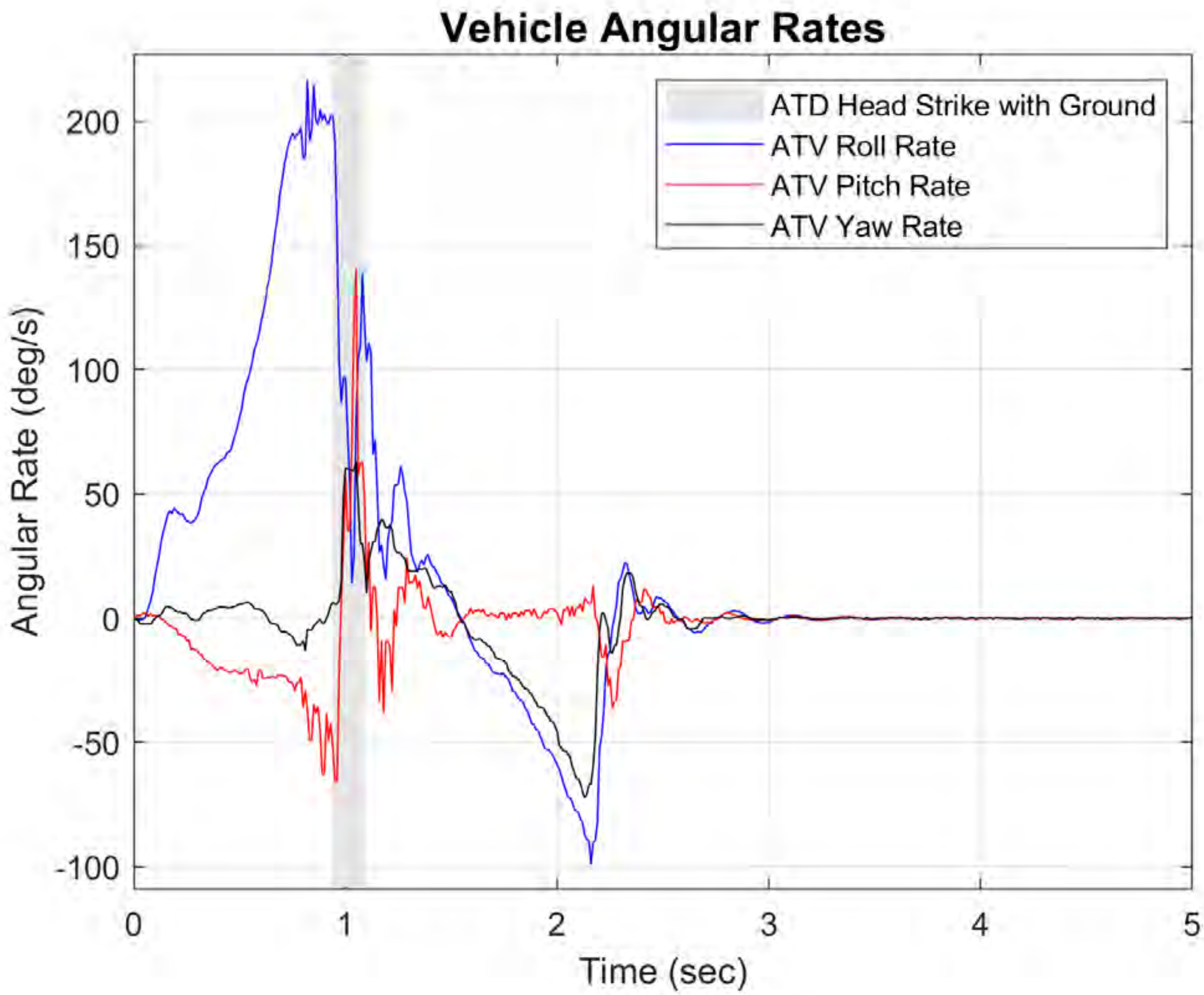
Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



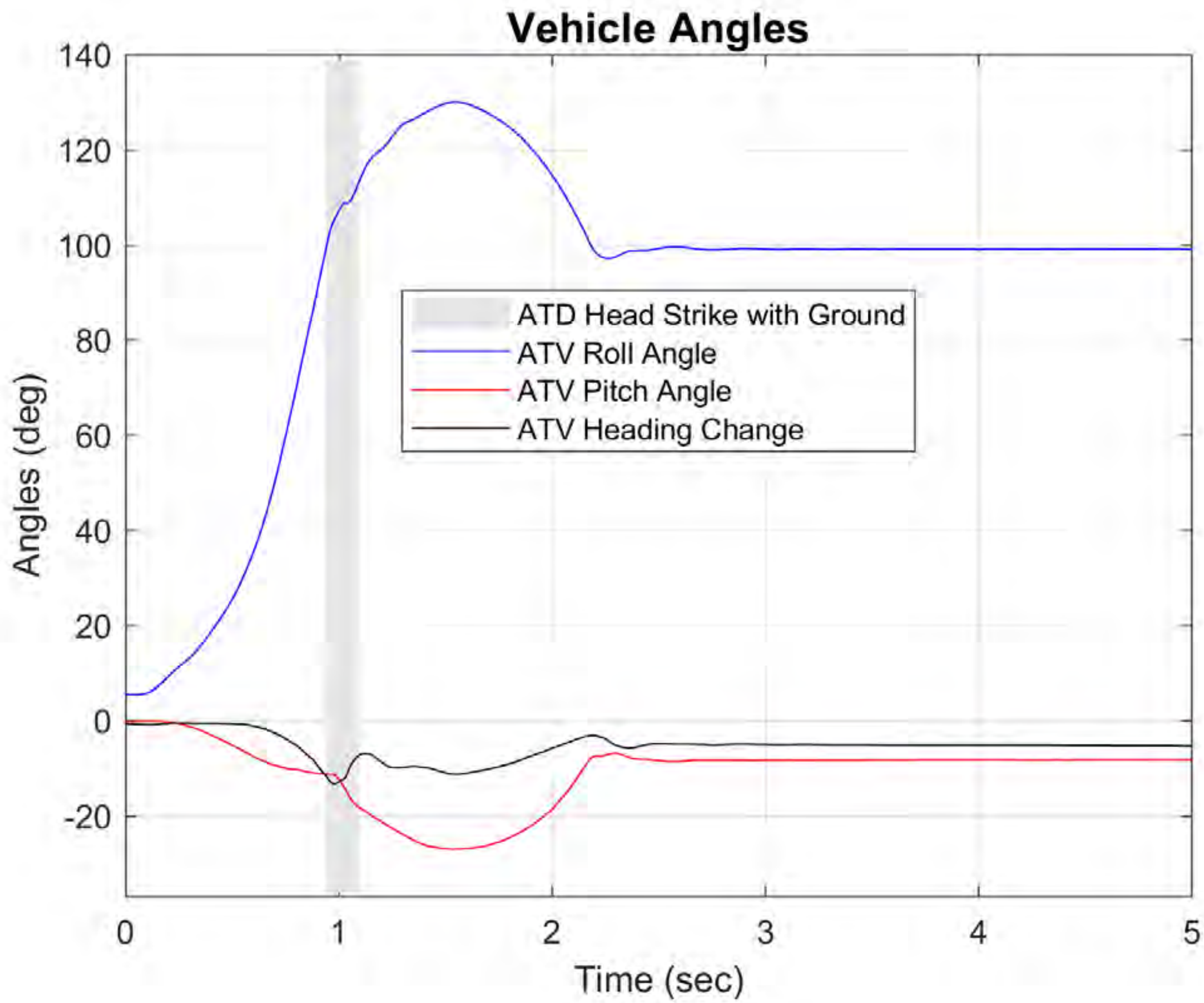
Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Roll Angle = 30° - Time = 0.54 sec

Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD

Roll Angle = 45° - Time = 0.68 sec

Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD

Roll Angle = 90° - Time = 0.95 sec

Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD

ATD Head Strike - Time = 1.10 sec

Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD

Roll Angle = 180° - Time = 1.60 sec

Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD

Max Roll Angle = 197.3° - Time = 2.06 sec

Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD

End of Run - Roll Angle = 100.5°

Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD

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

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

Drone Camera - Roll Angle = 90° - Time = 0.95 sec

Drone Camera - ATD Head Strike - Time = 1.10 sec

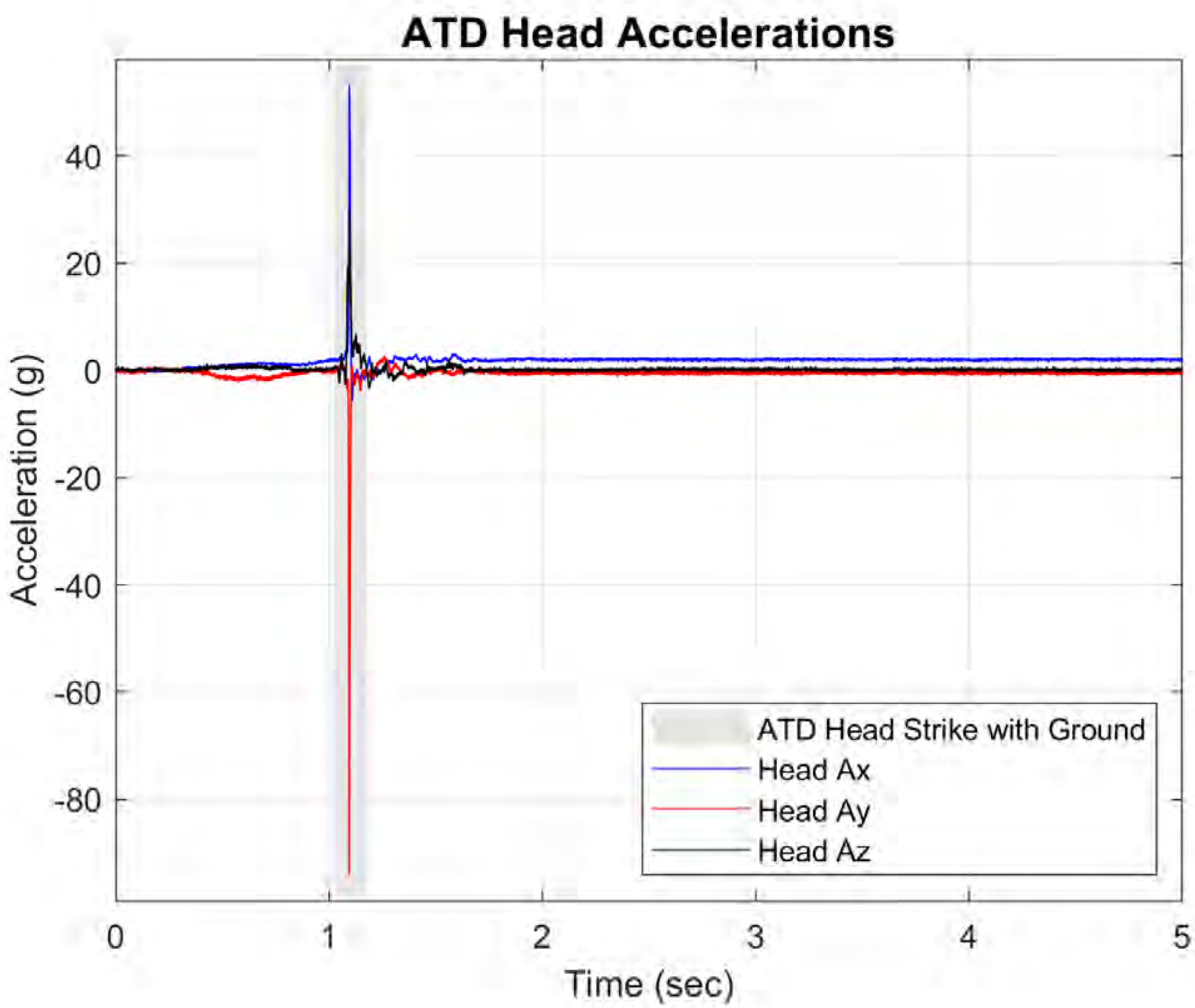
Drone Camera - Roll Angle = 180° - Time = 1.60 sec

Drone Camera - Max Angle = 197.3° - Time = 2.06 sec

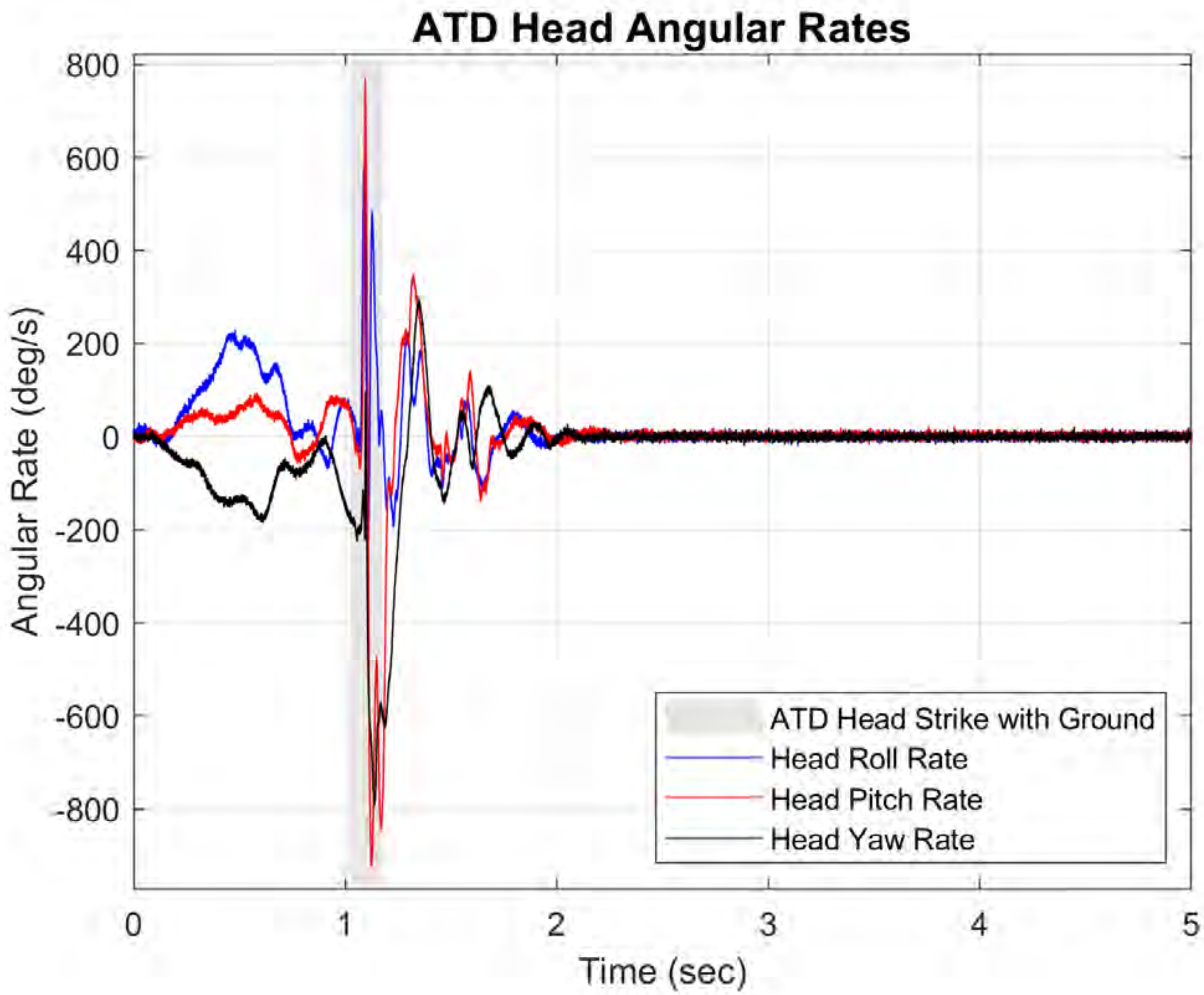
Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD

Drone Camera - End of Run - Roll Angle = 100.5°

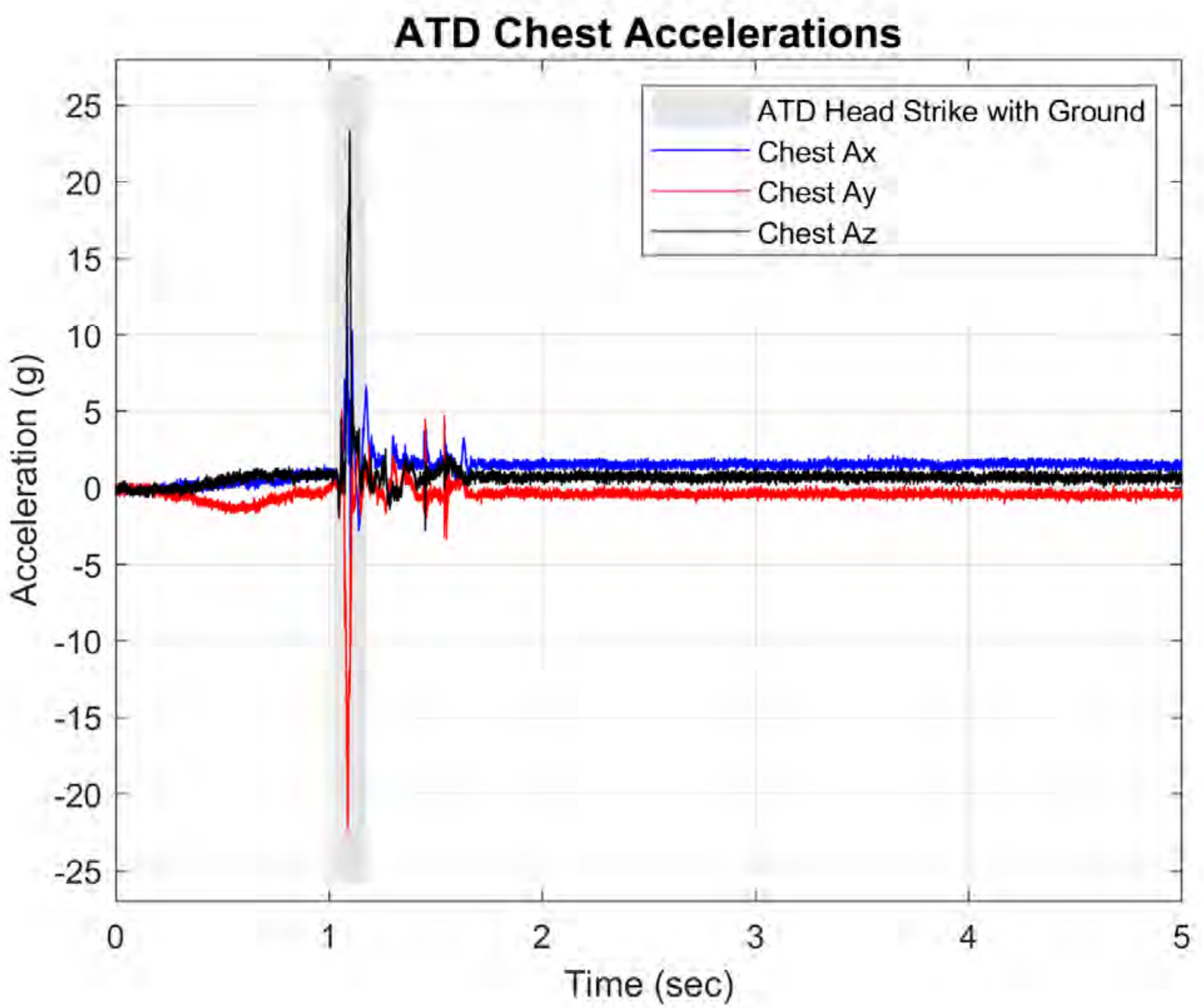
Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD



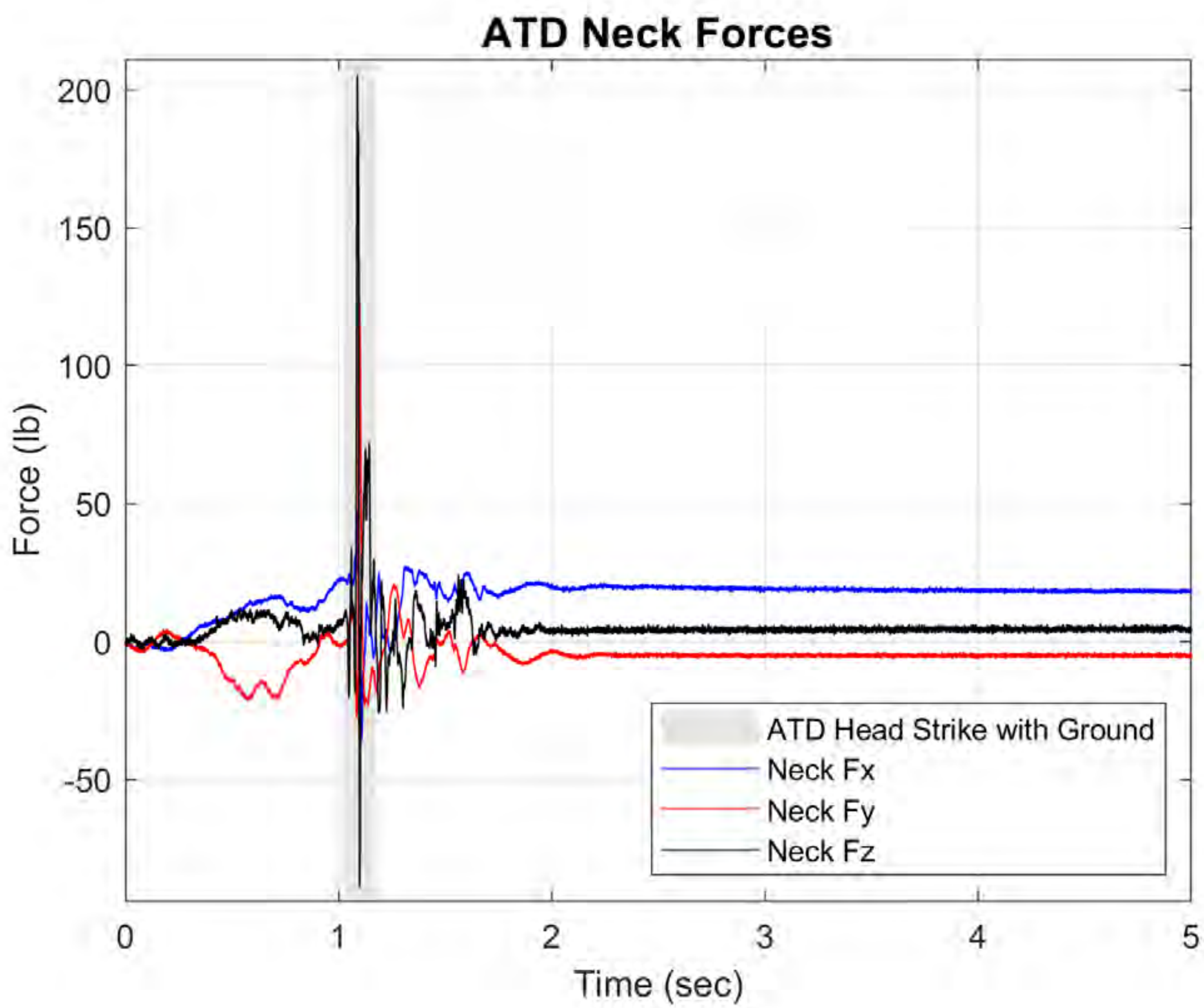
Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD



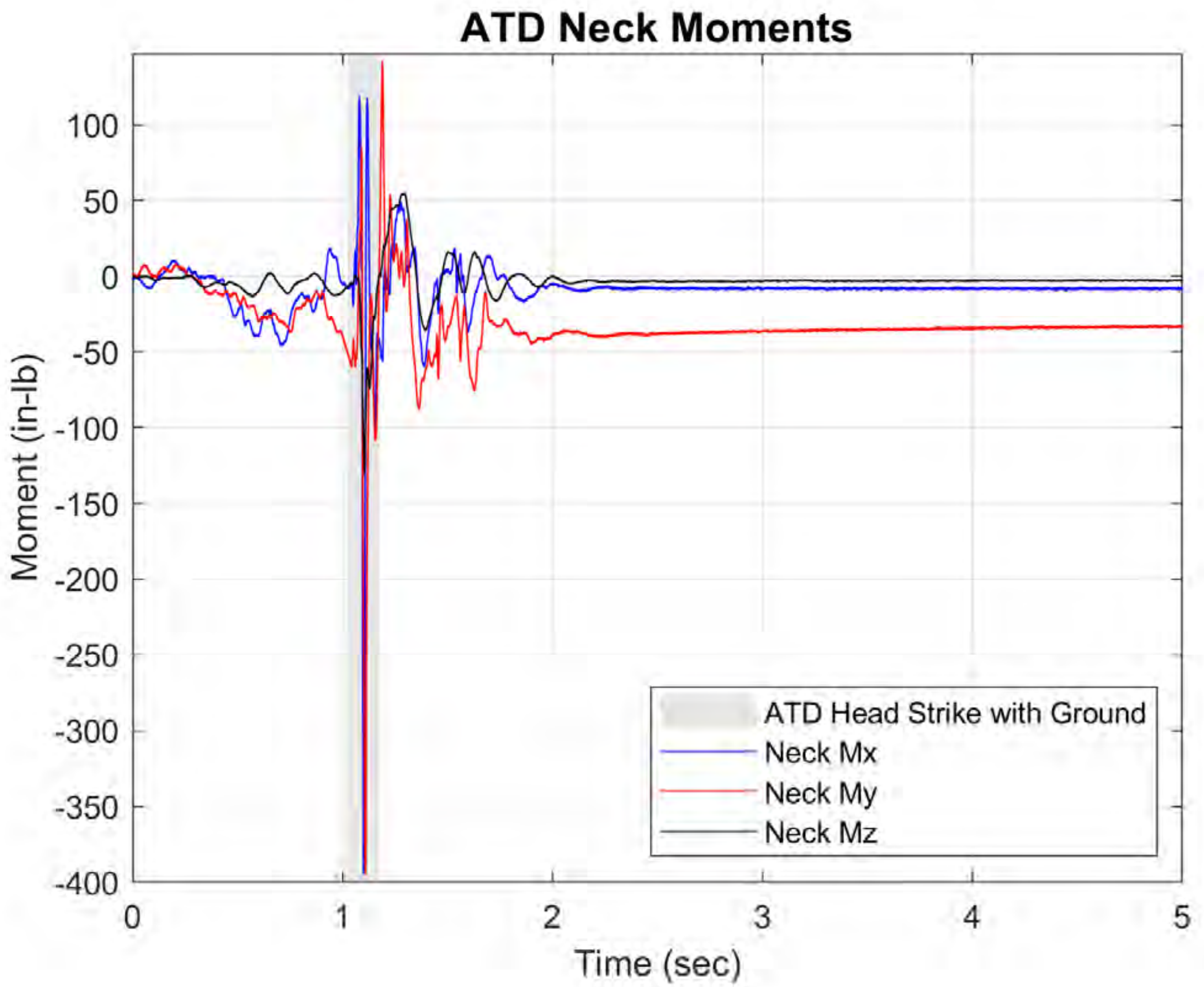
Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD



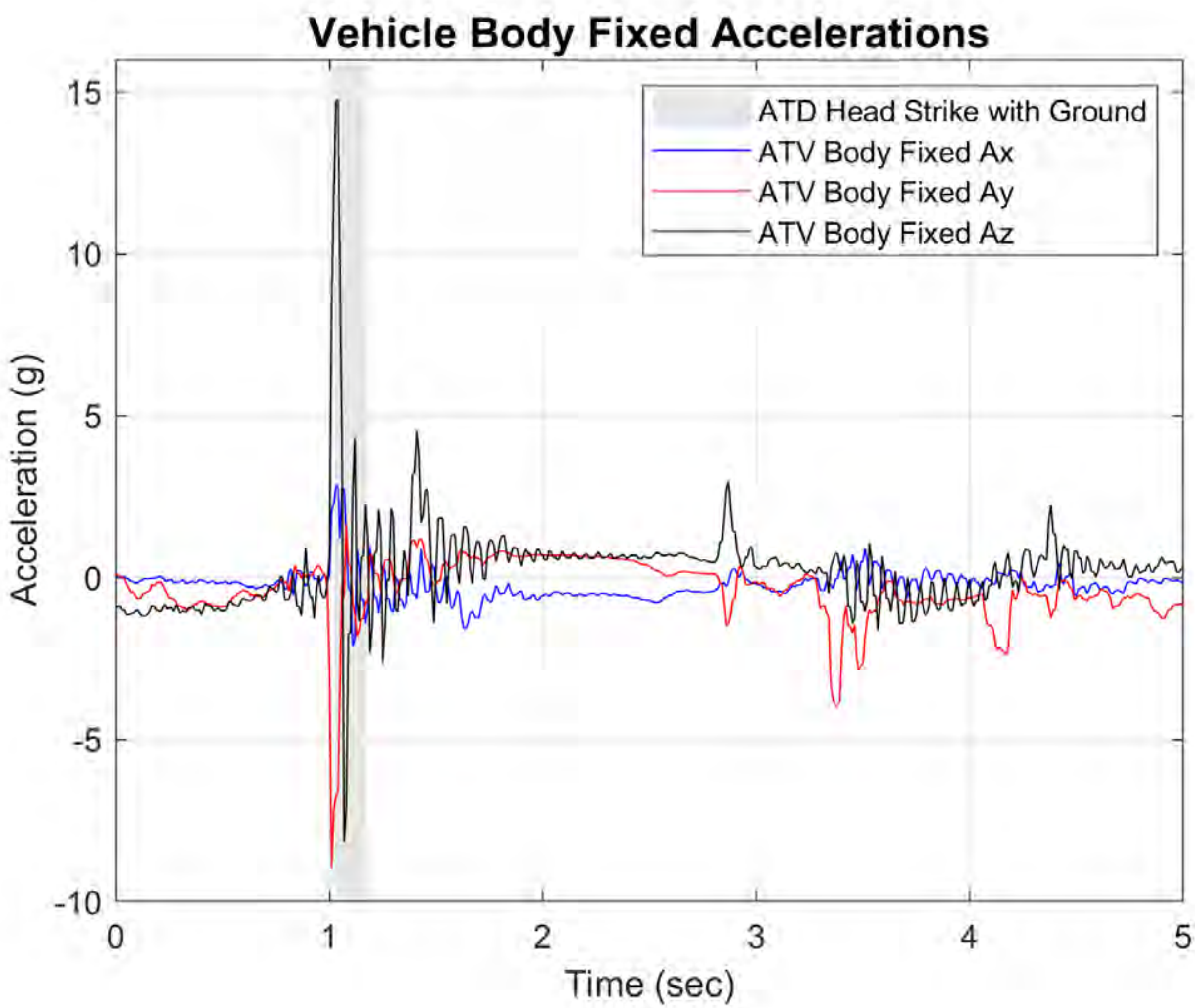
Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD



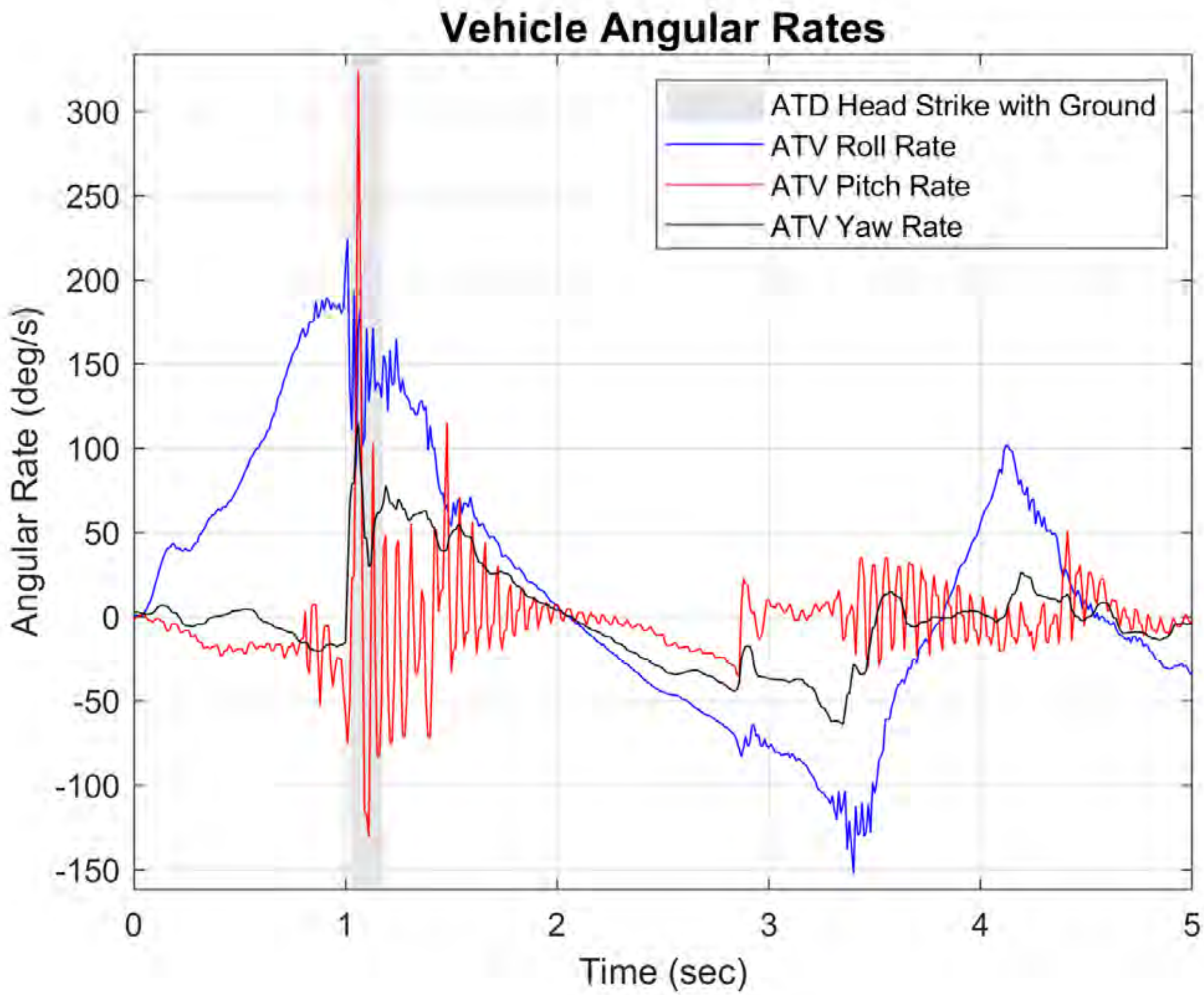
Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD



Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD



Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD



Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD

Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD

Roll Angle = 30° - Time = 0.53 sec

Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

Roll Angle = 45° - Time = 0.67 sec

Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

Roll Angle = 90° - Time = 0.92 sec

Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

ATD Head Strike - Time = 1.05 sec

Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

Max Roll Angle = 177.9° - Time = 1.98 sec

Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

End of Run - Roll Angle = 107.0°

Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

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

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

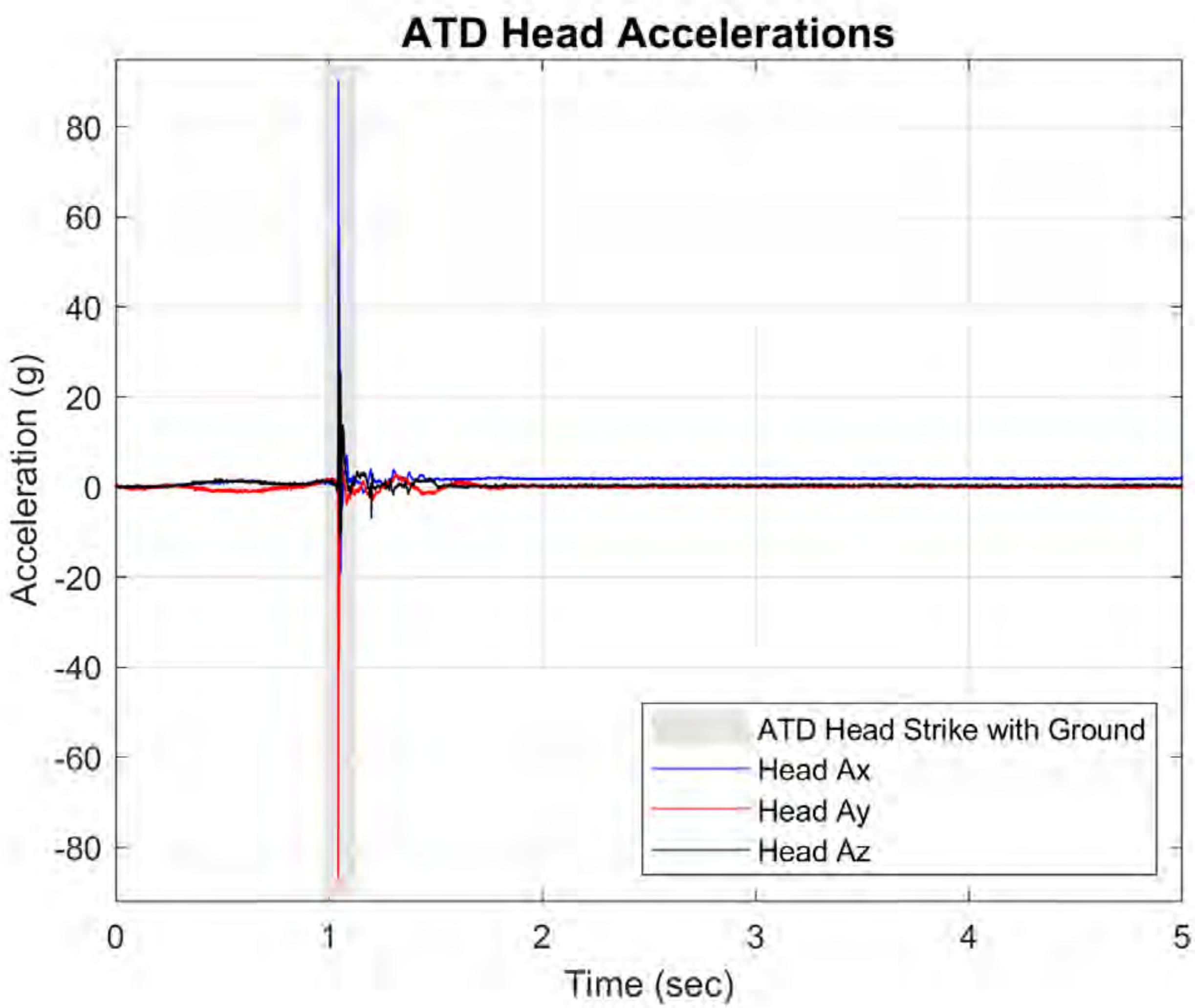
Drone Camera - Roll Angle = 90° - Time = 0.92 sec

Drone Camera - ATD Head Strike - Time = 1.05 sec

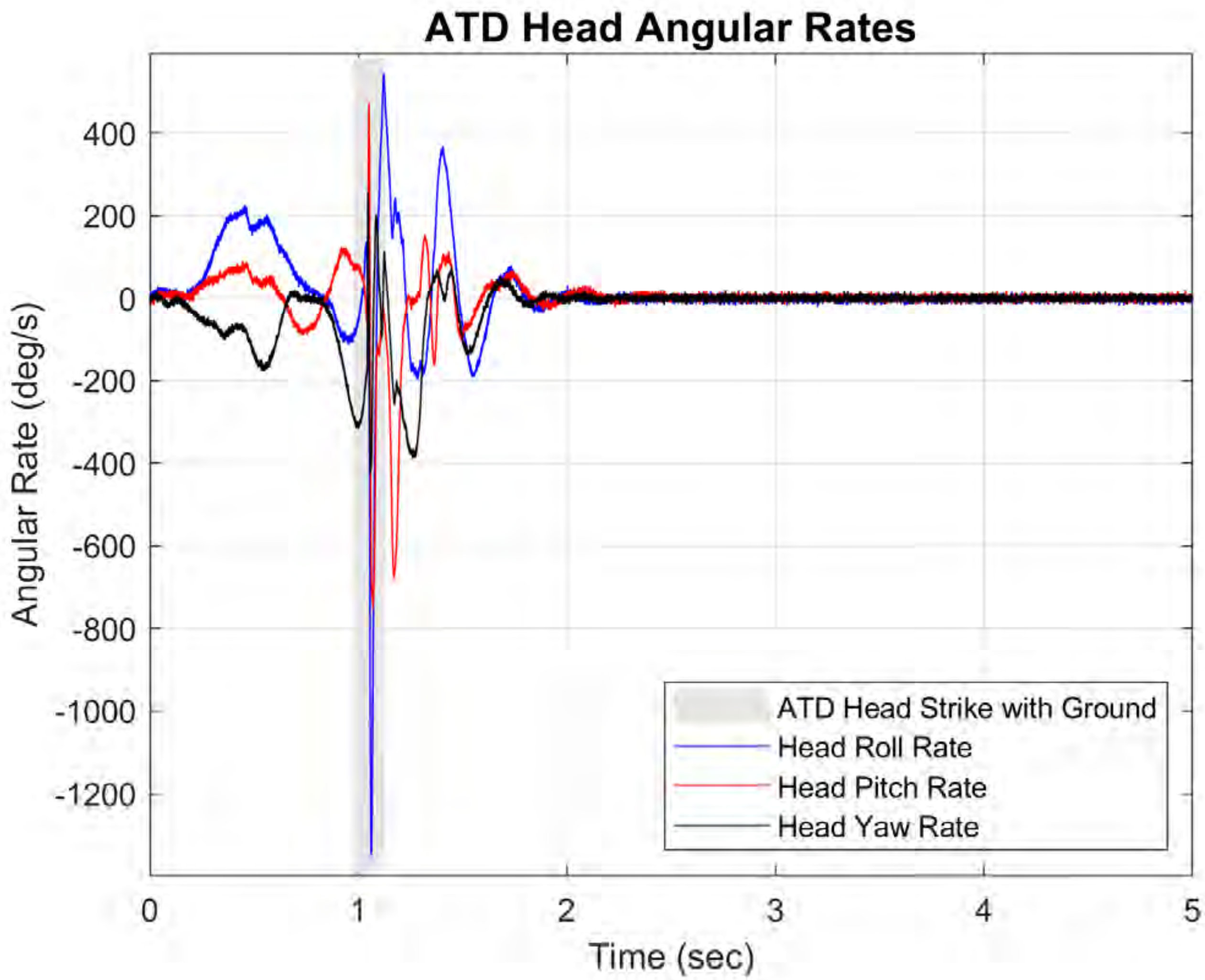
Drone Camera - Max Angle = 177.9° - Time = 1.98 sec

Drone Camera - End of Run - Roll Angle = 107.0°

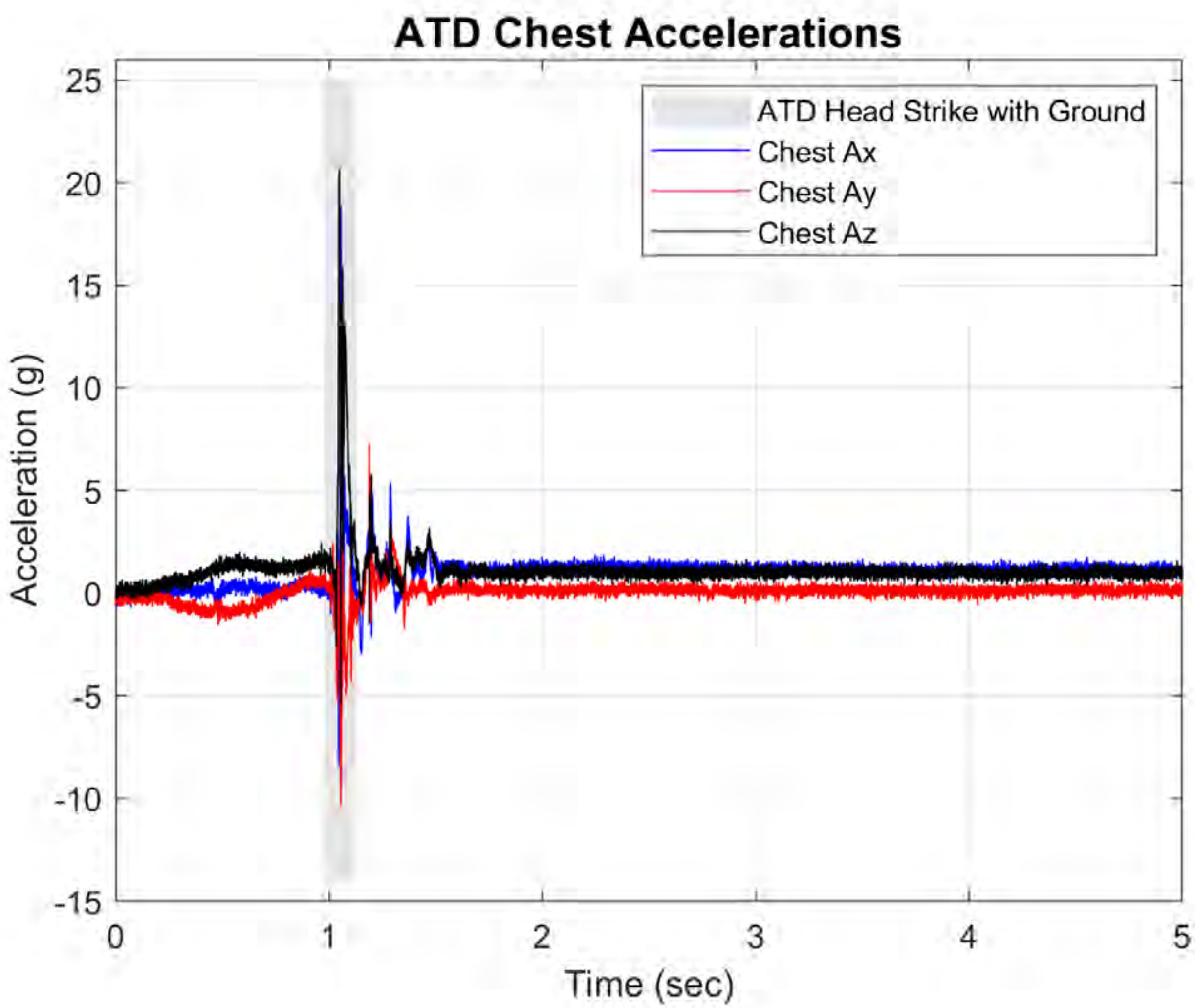
Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



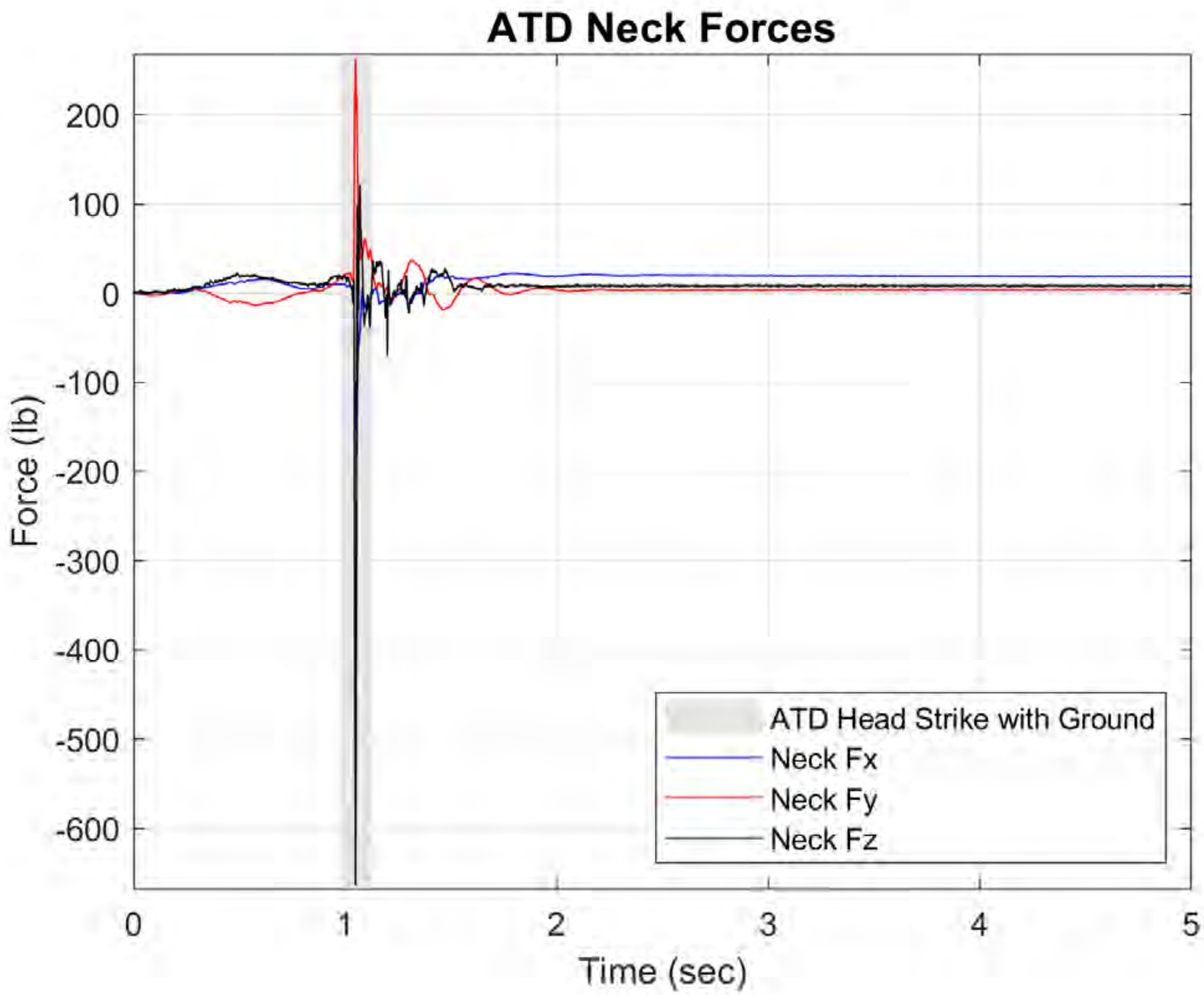
Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



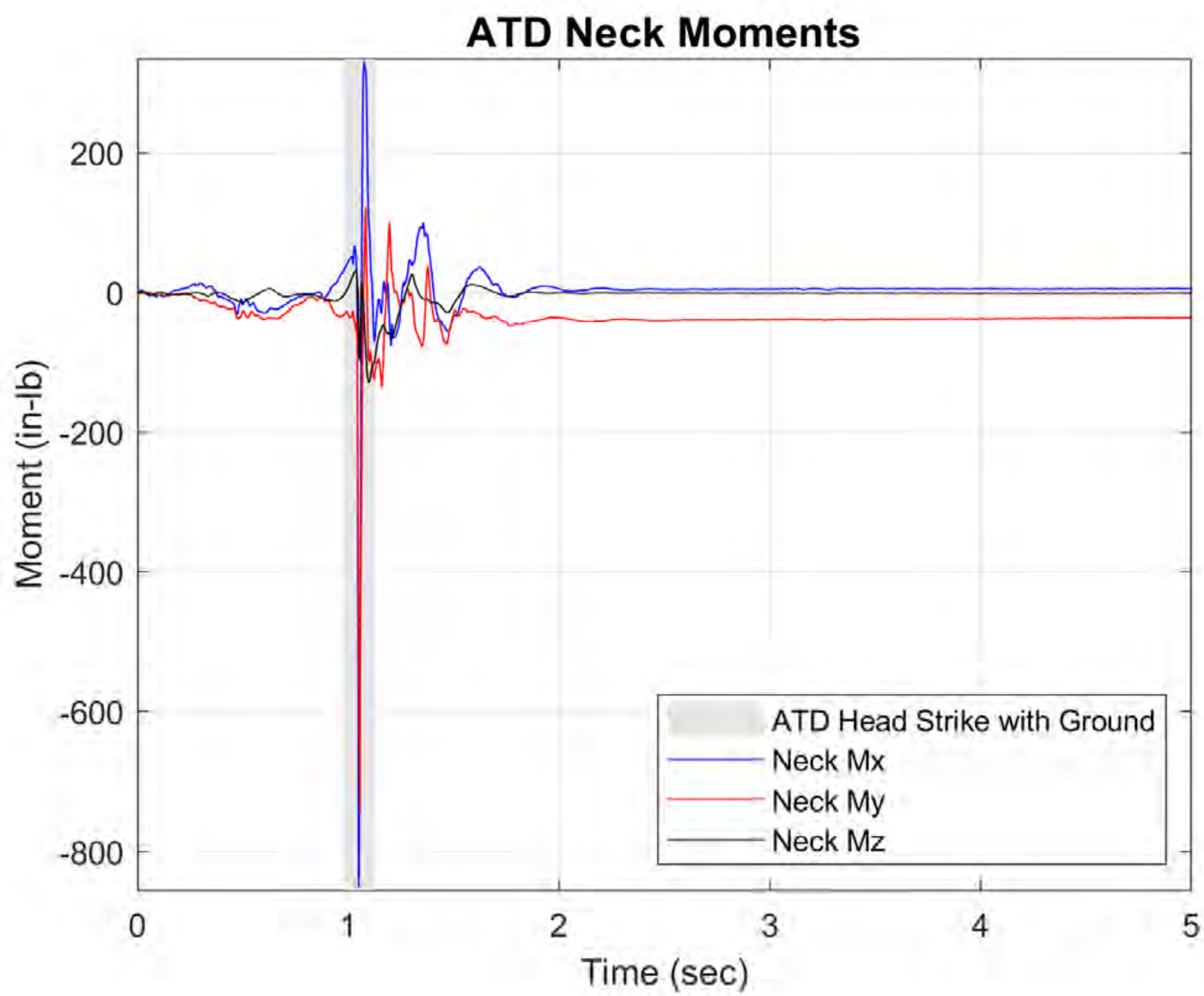
Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



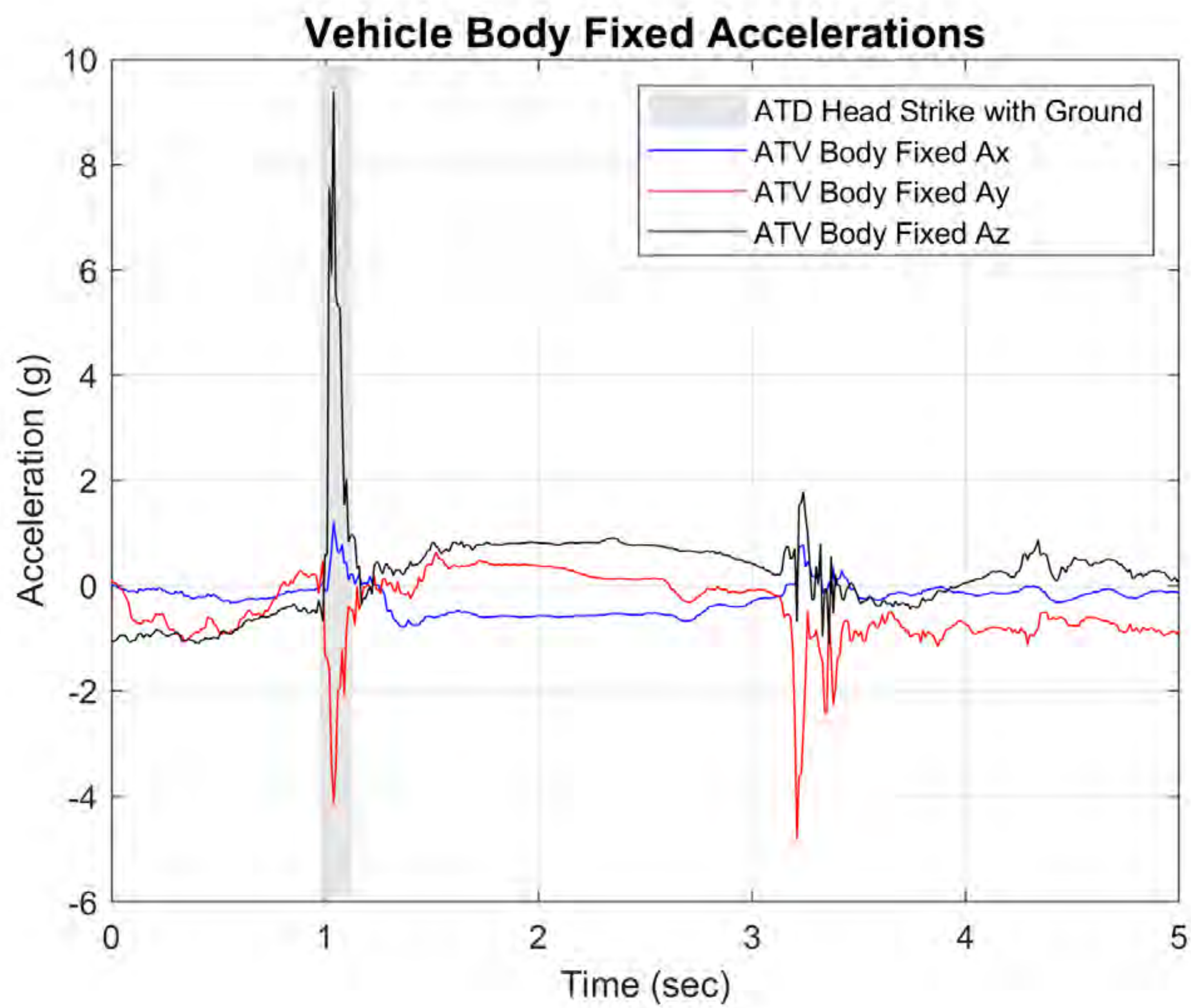
Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



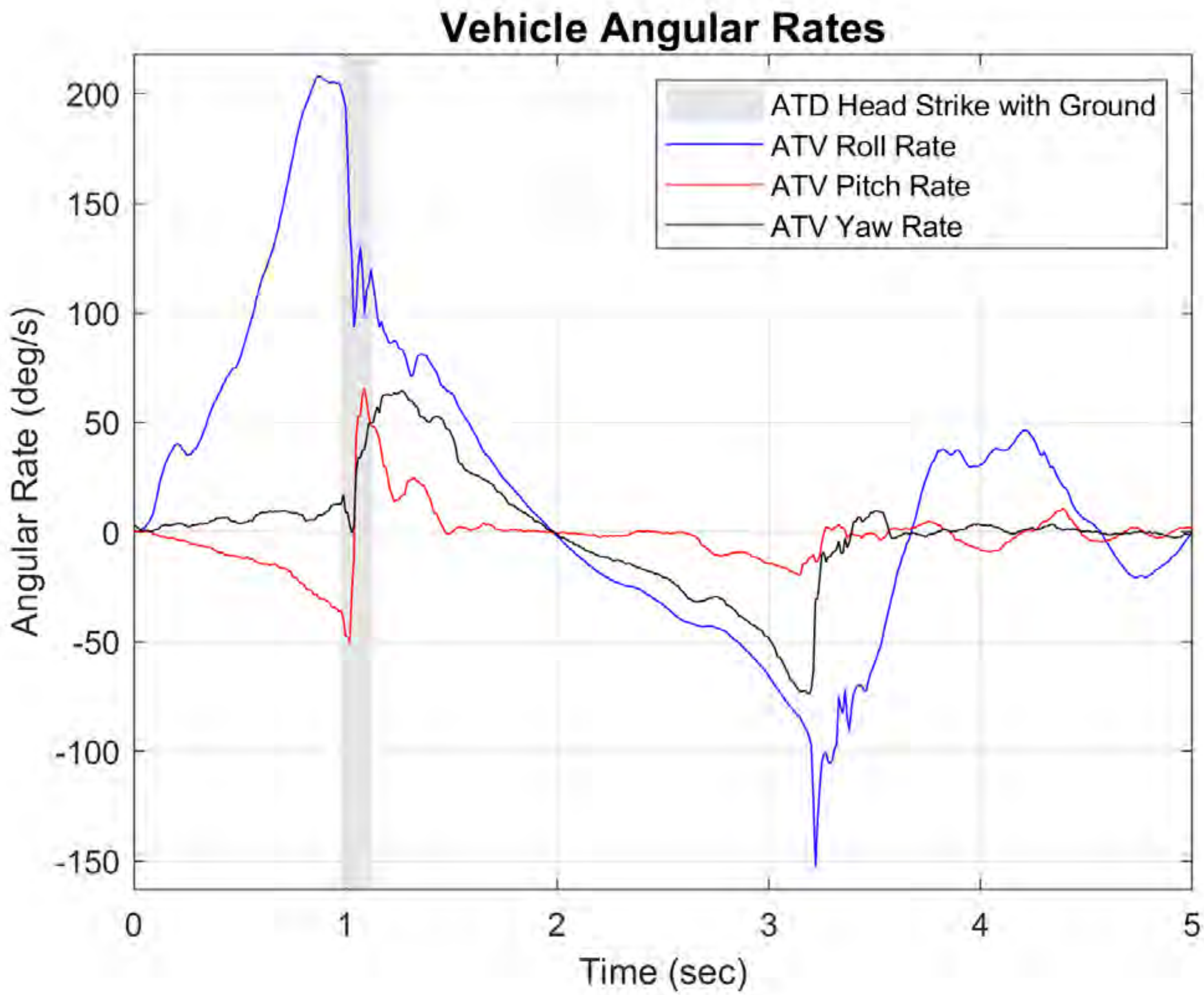
Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



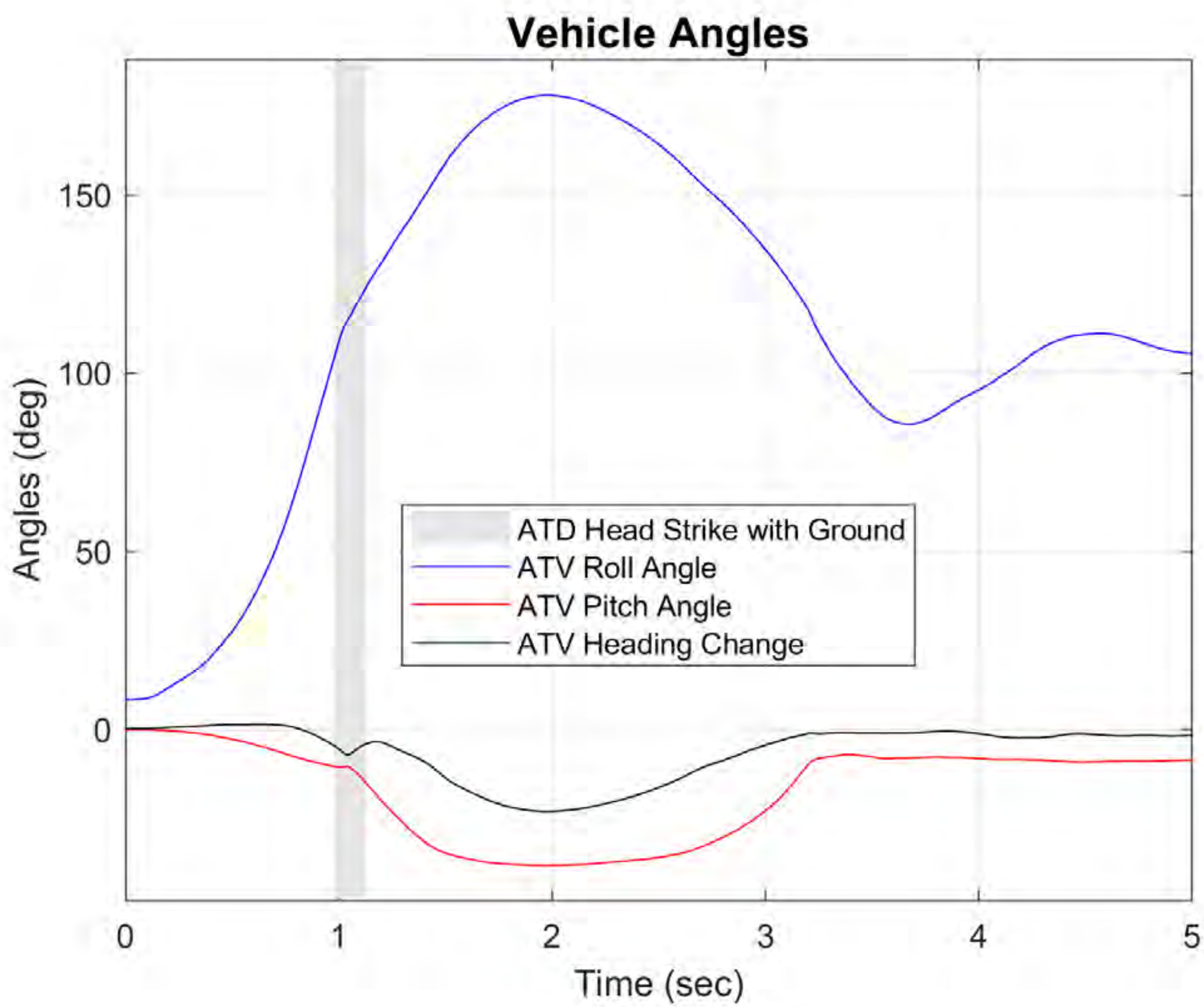
Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

Roll Angle = 30° - Time = 0.52 sec

Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

Roll Angle = 45° - Time = 0.65 sec

Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

Roll Angle = 90° - Time = 0.90 sec

Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

ATD Head Strike - Time = 0.98 sec

Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

Max Roll Angle = 171.5° - Time = 2.08 sec

Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

End of Run - Roll Angle = 118.0°

Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

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

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

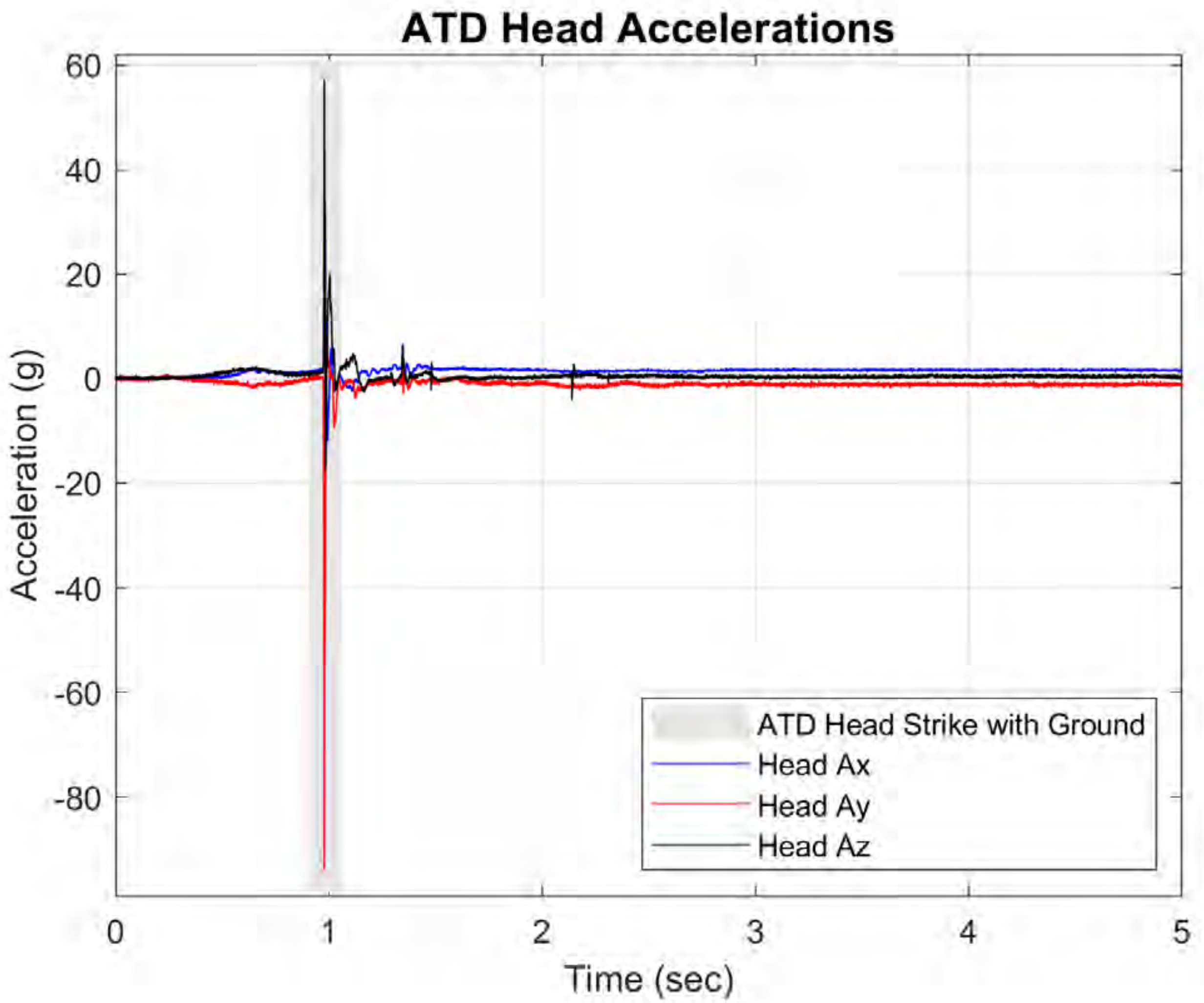
Drone Camera - Roll Angle = 90° - Time = 0.90 sec

Drone Camera - ATD Head Strike - Time = 0.98 sec

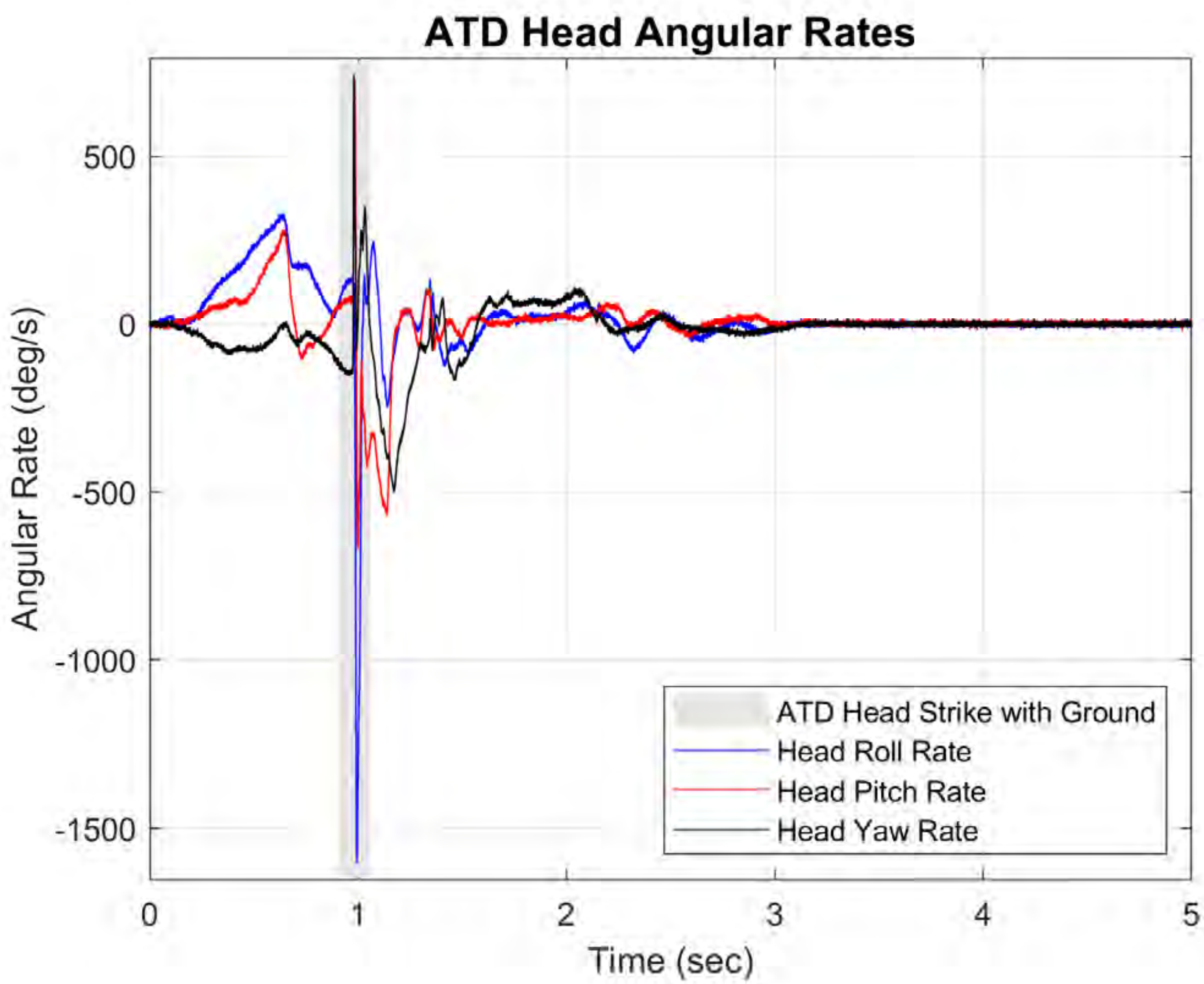
Drone Camera - Max Angle = 171.5° - Time = 2.08 sec

Drone Camera - End of Run - Roll Angle = 118.0°

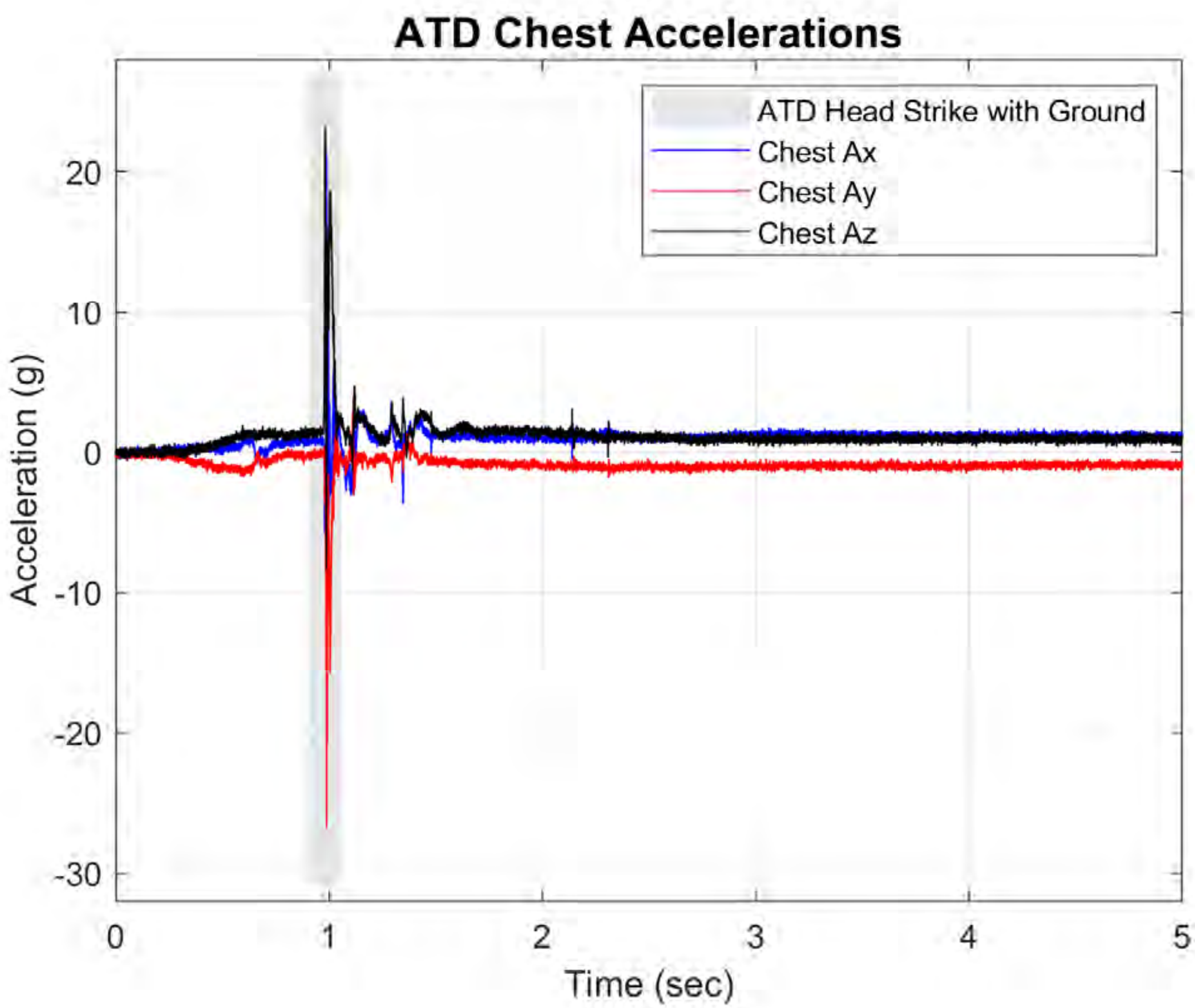
Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



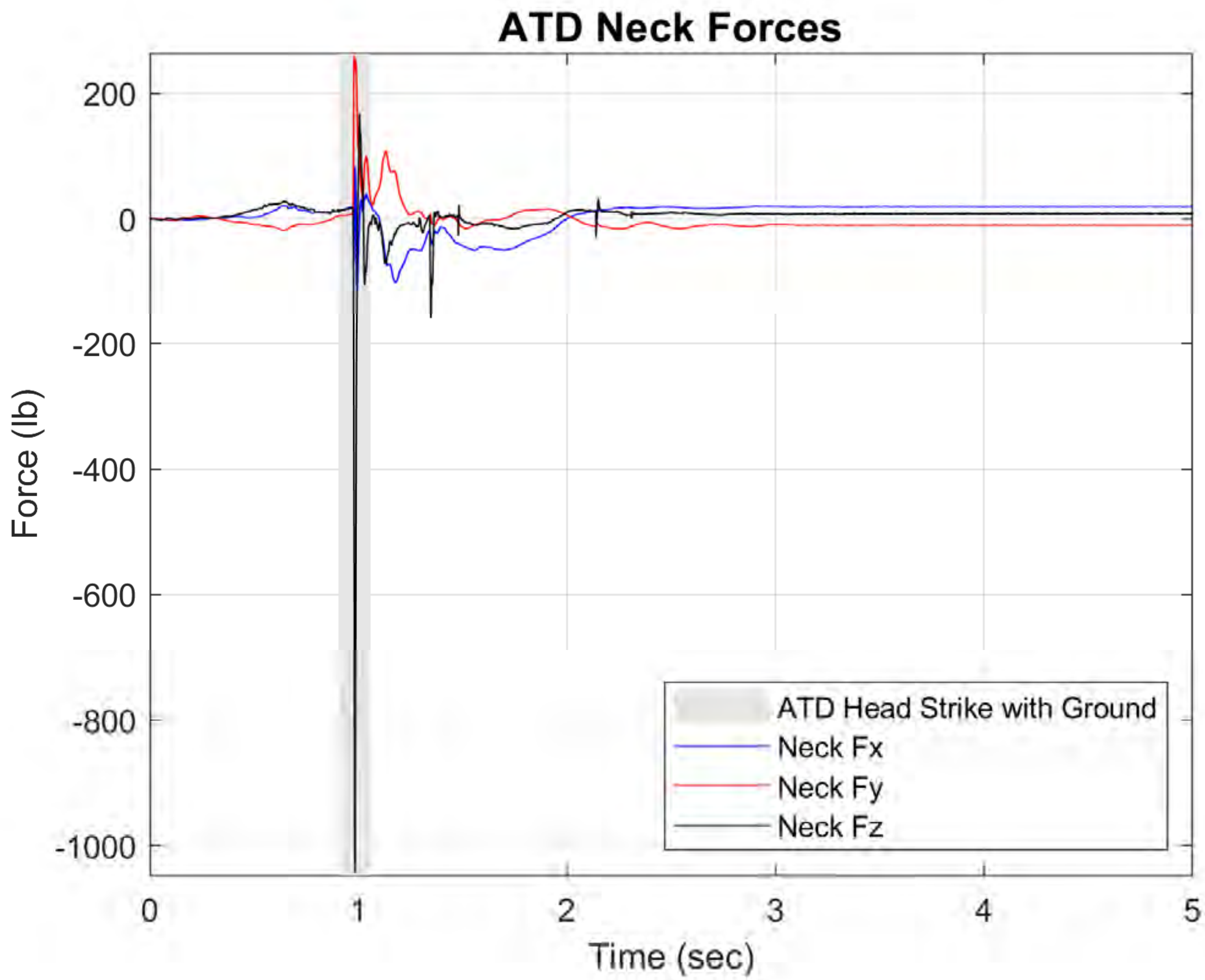
Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



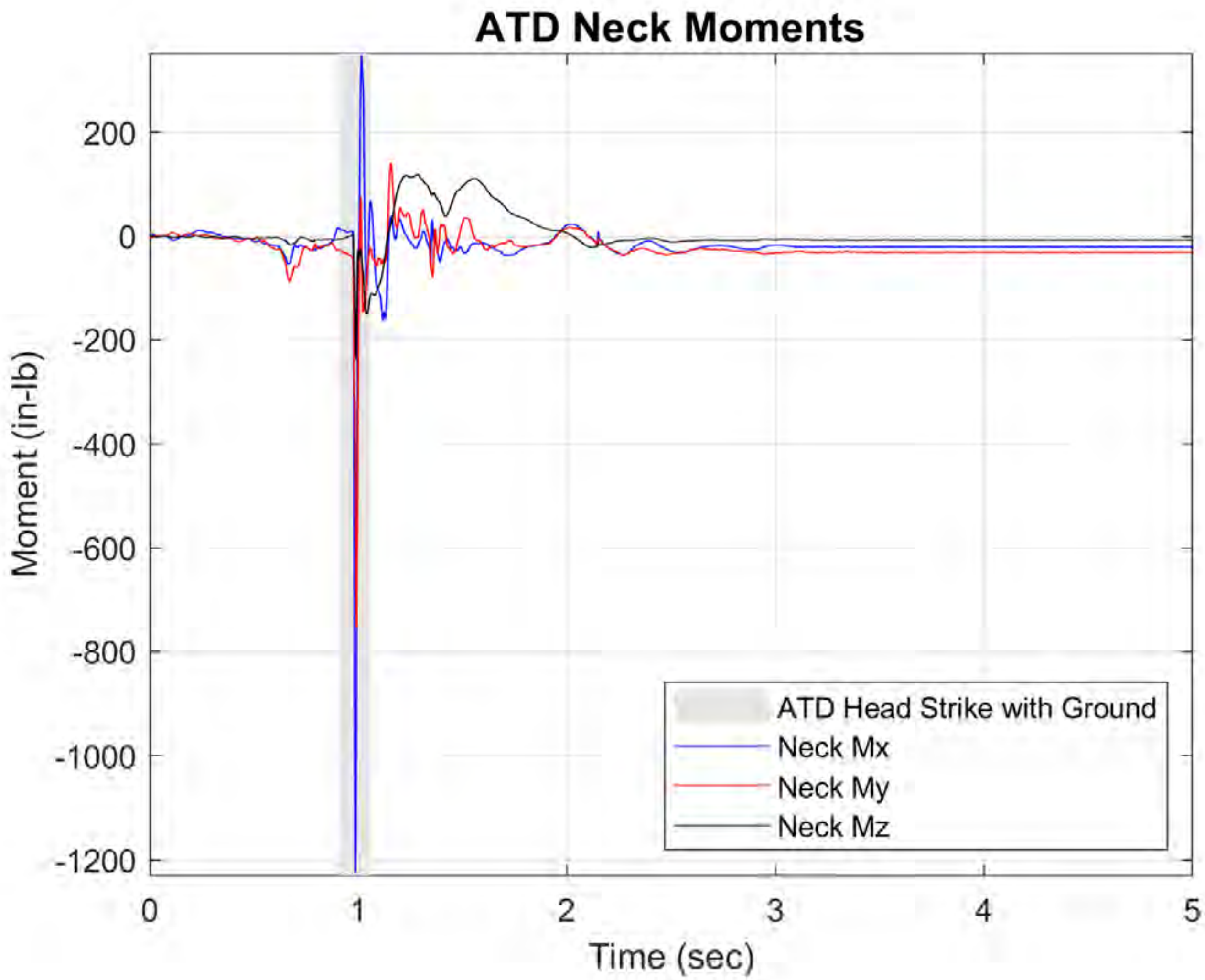
Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



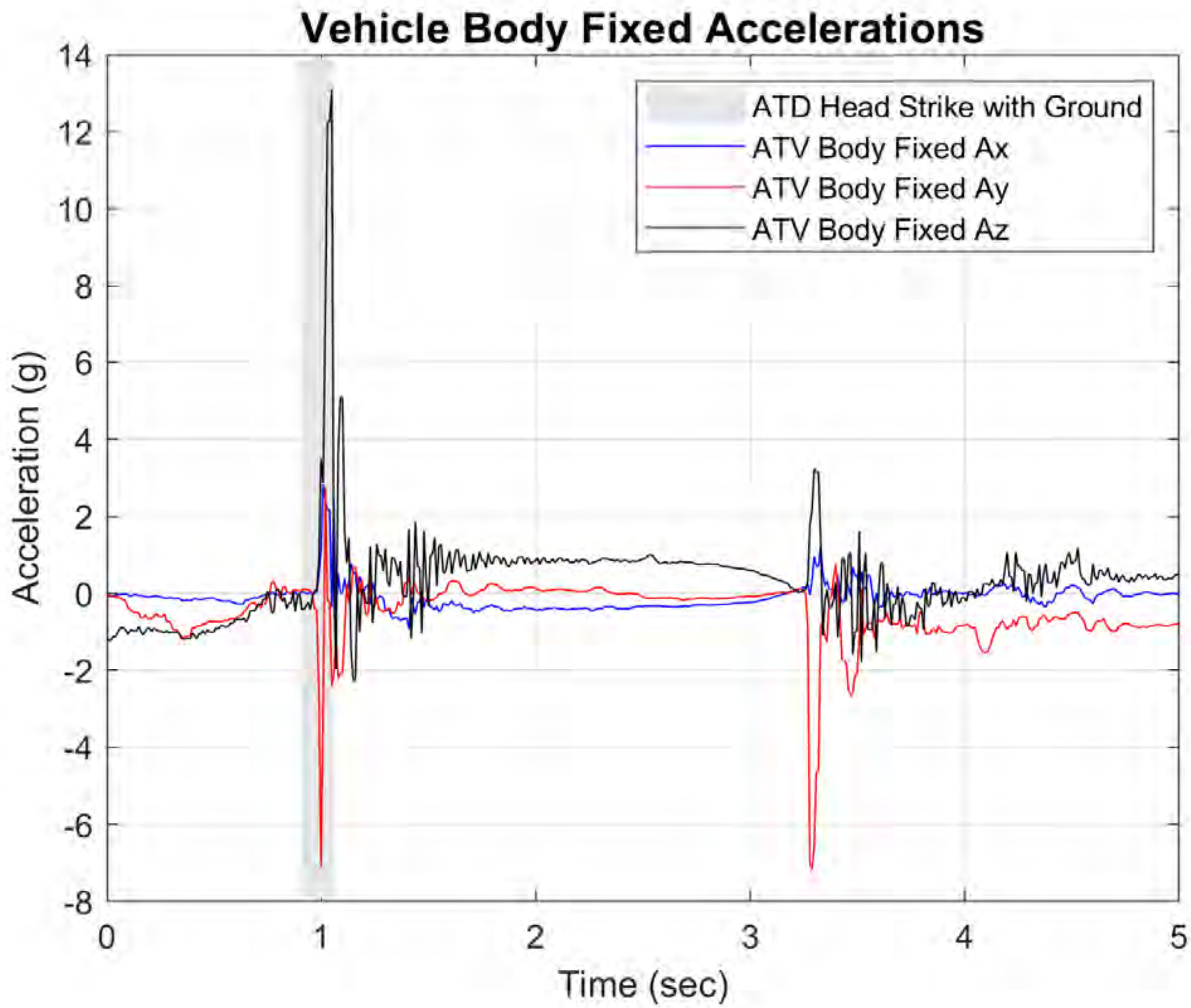
Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



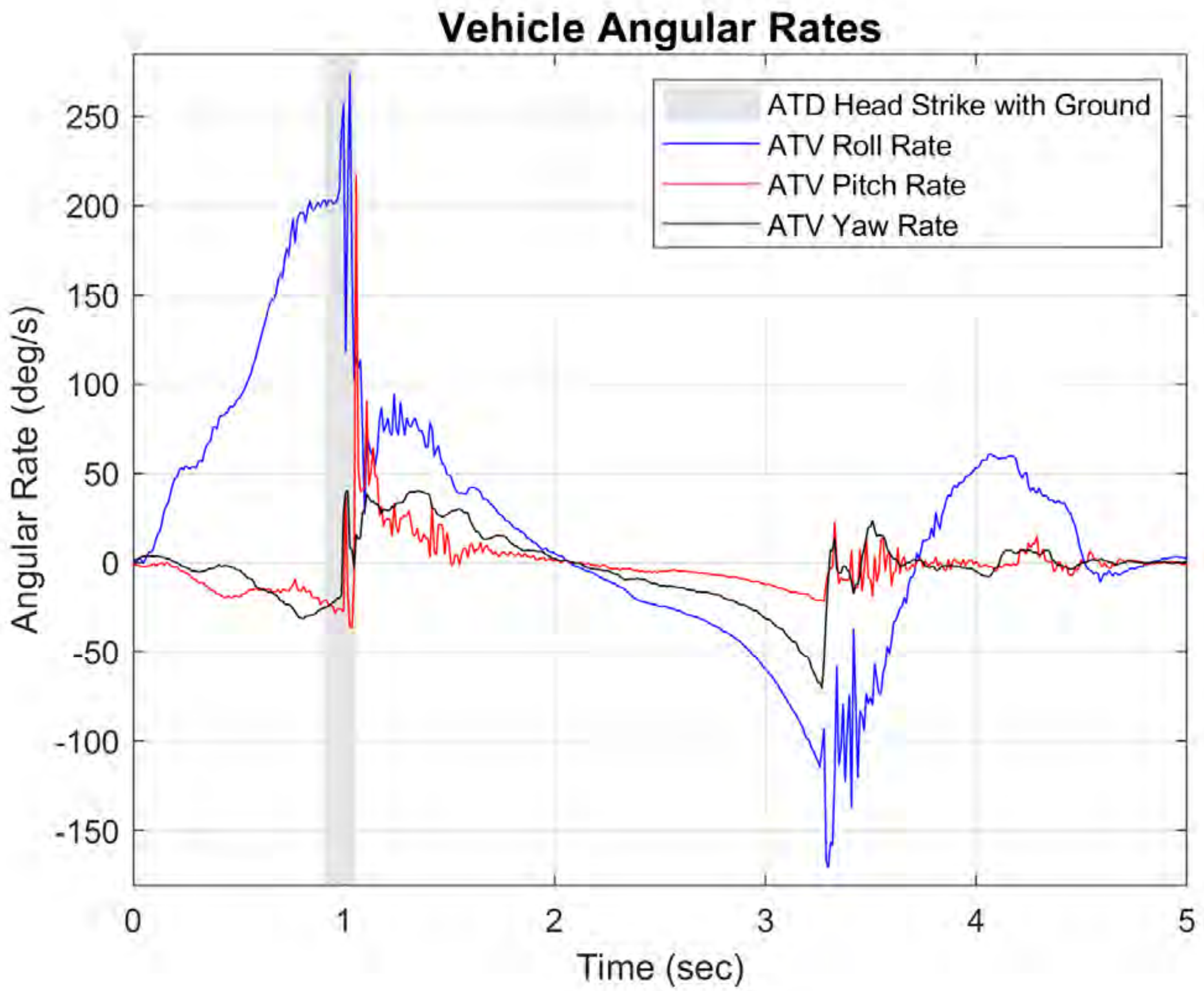
Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



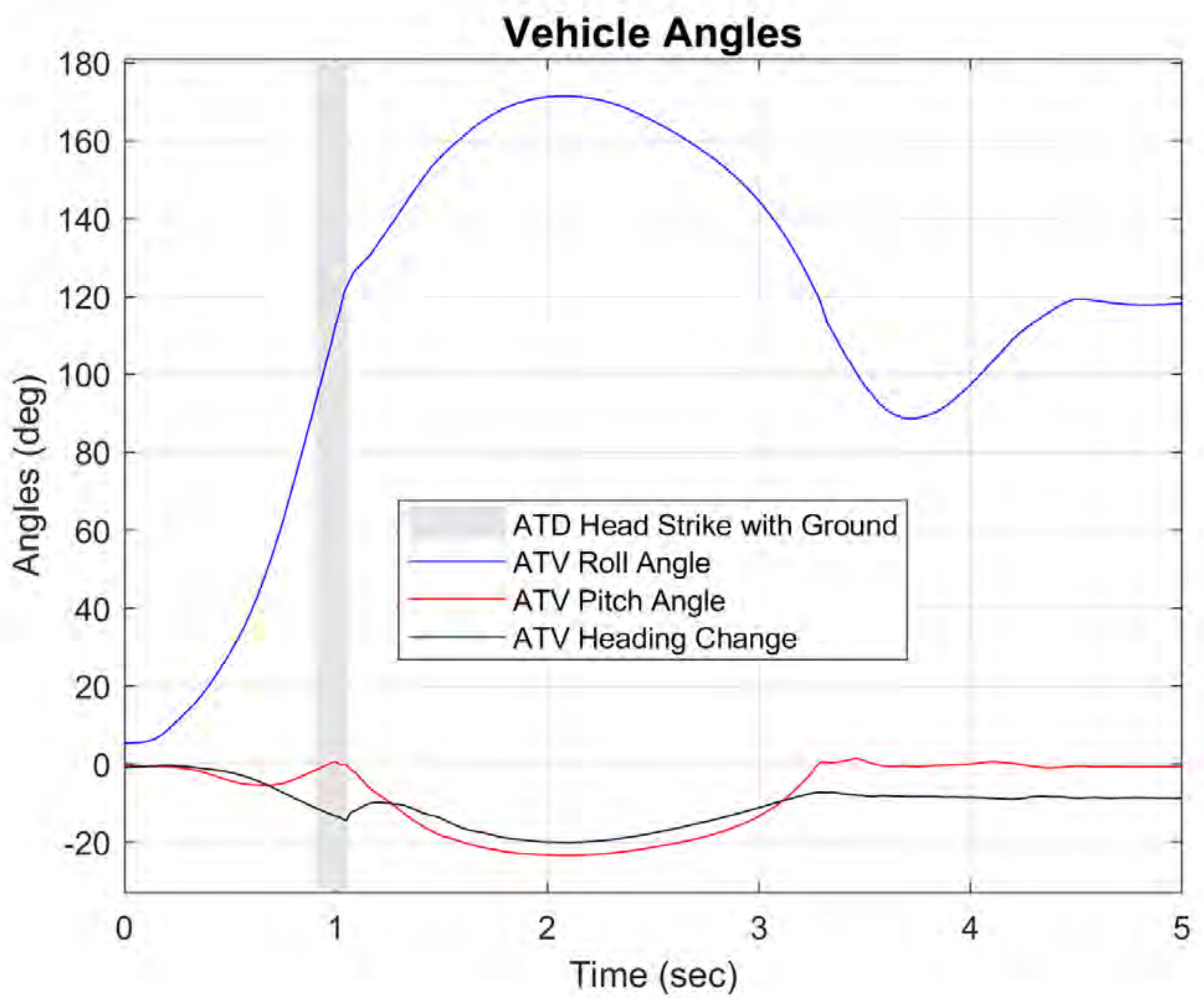
Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

Roll Angle = 30° - Time = 0.45 sec

Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 45° - Time = 0.57 sec

Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 90° - Time = 0.80 sec

Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

ATD Head Strike - Time = 0.94 sec

Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 180° - Time = 1.36 sec

Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 270° - Time = 2.86 sec

Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Max Roll Angle = 283.4° - Time = 3.17 sec

Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

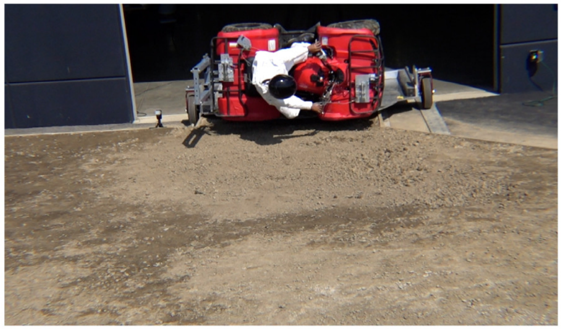
End of Run - Roll Angle = 272.4°

Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Drone Camera - Roll Angle = 30° - Time = 0.45 sec

Drone Camera - Roll Angle = 45° - Time = 0.57 sec

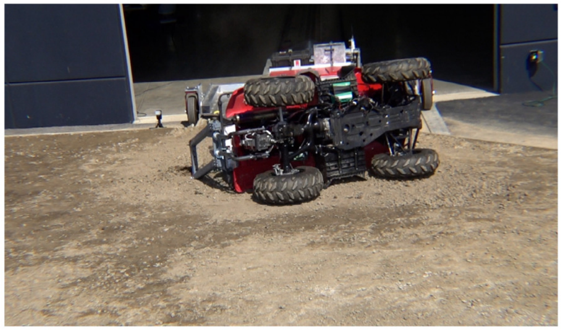
Drone Camera - Roll Angle = 90° - Time = 0.80 sec



Drone Camera - ATD Head Strike - Time = 0.94 sec

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

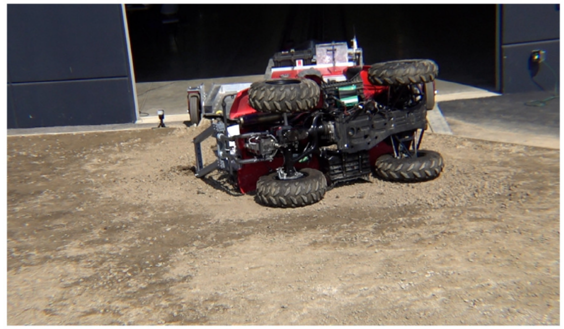
Drone Camera - Roll Angle = 270° - Time = 2.86 sec



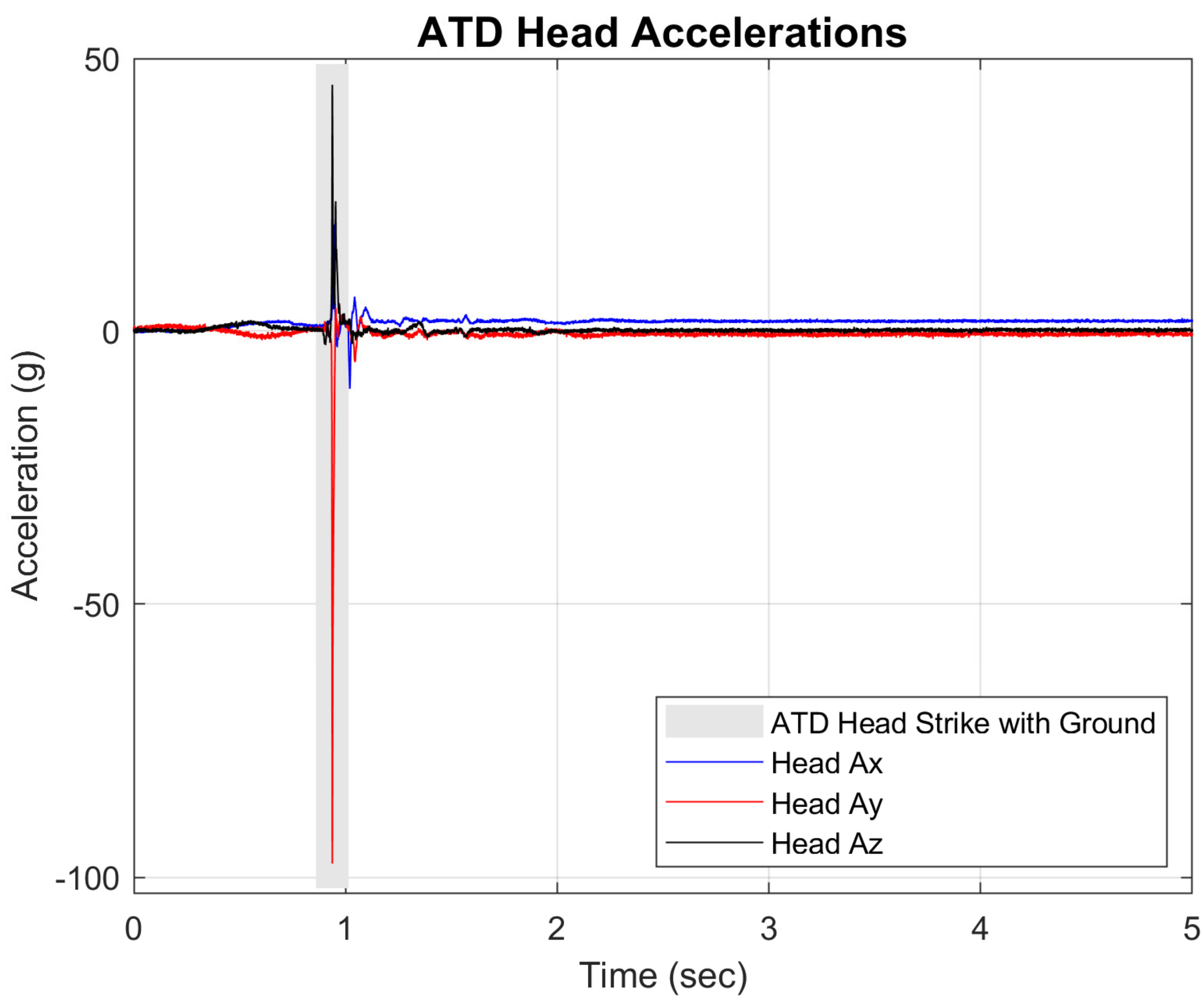
Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Drone Camera - Max Angle = 283.4° - Time = 3.17 sec

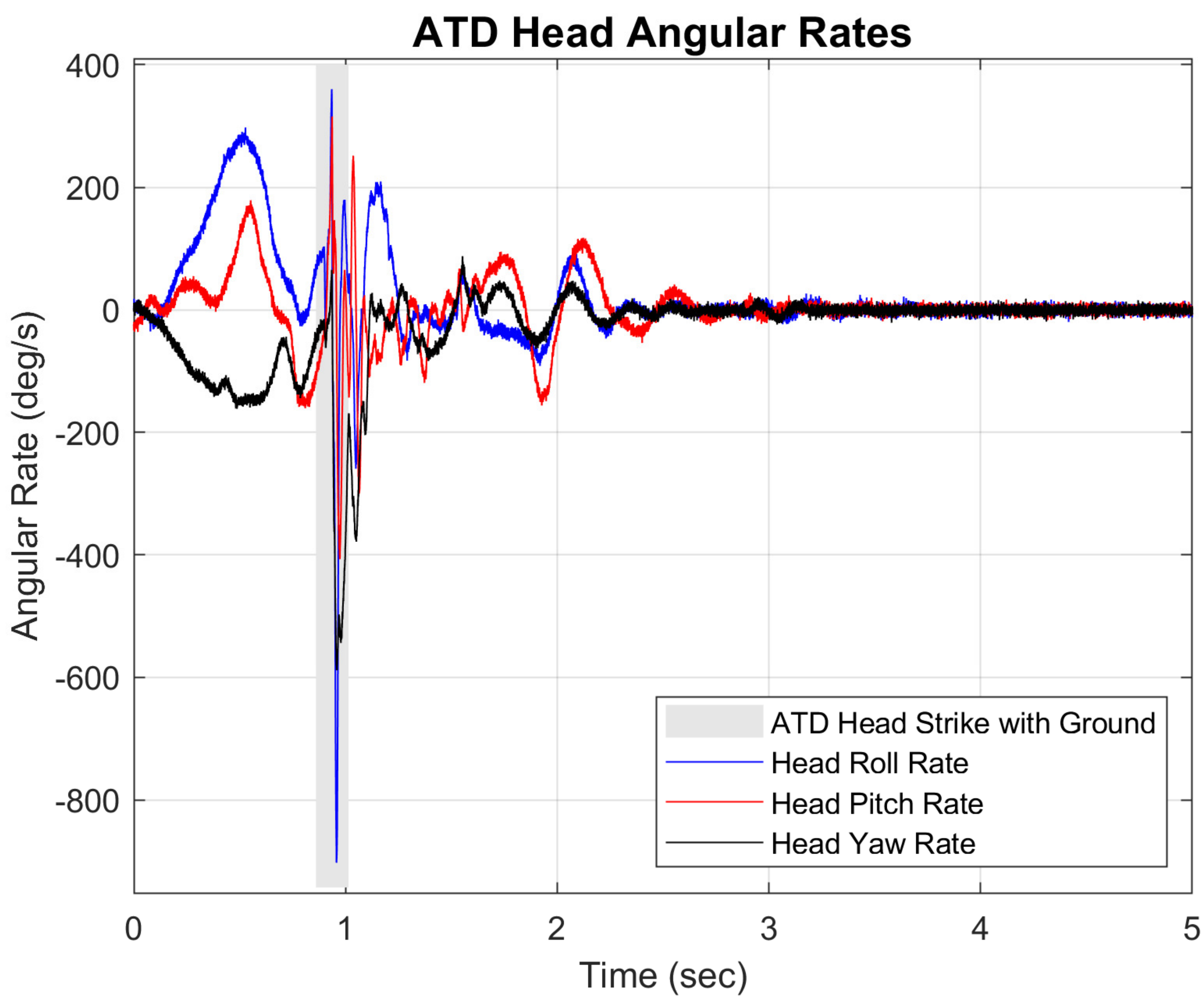
Drone Camera - End of Run - Roll Angle = 272.4°



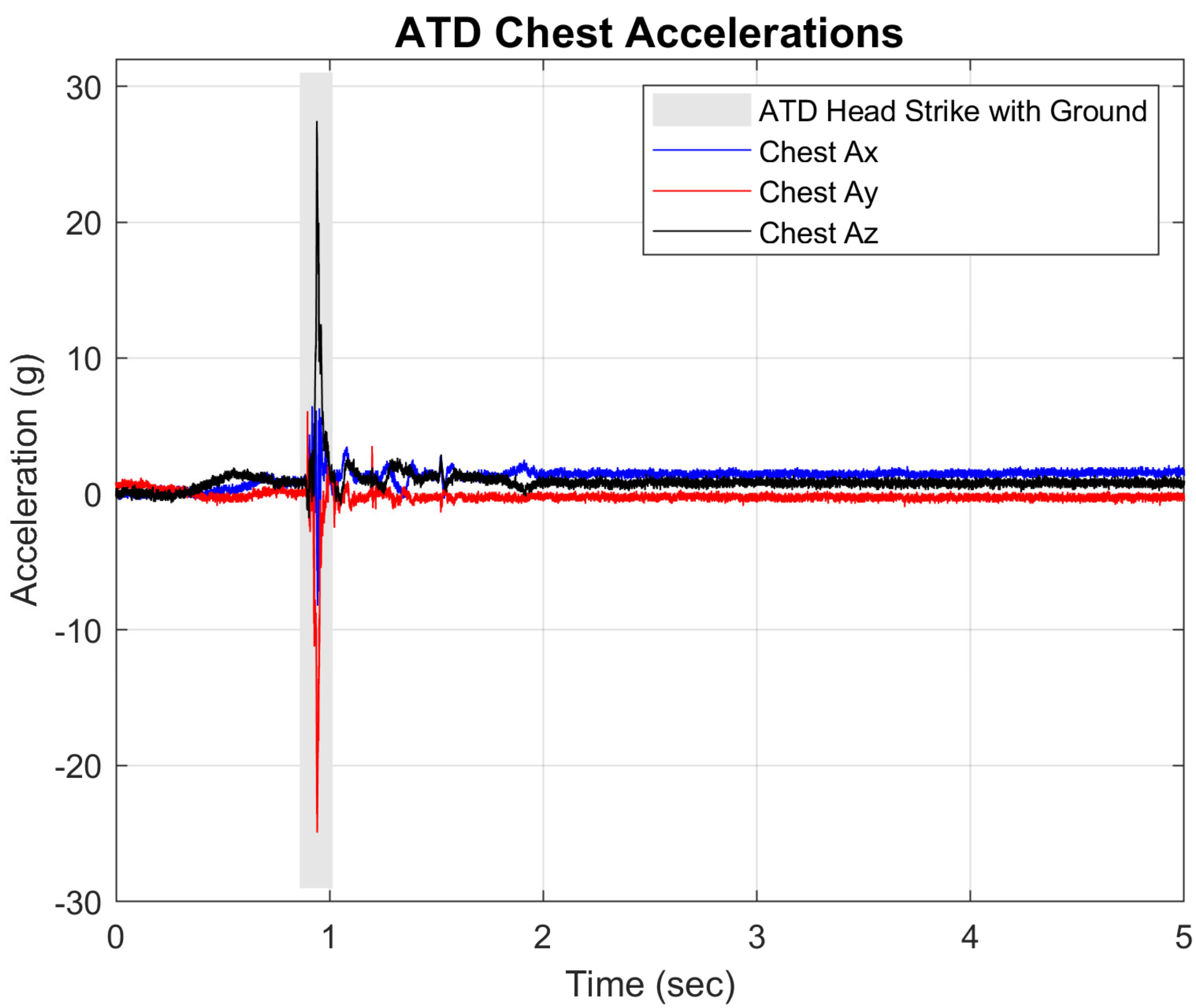
Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



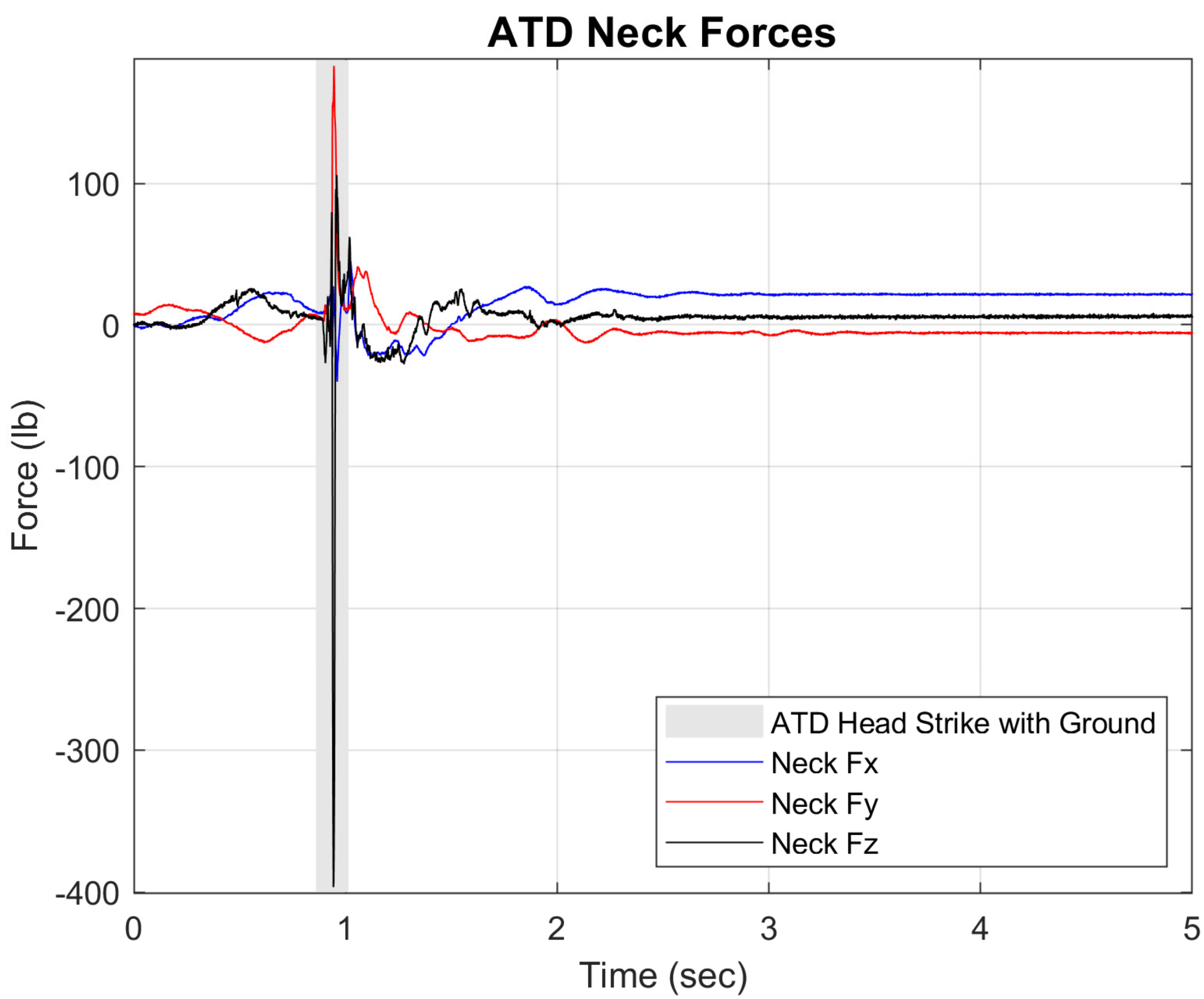
Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



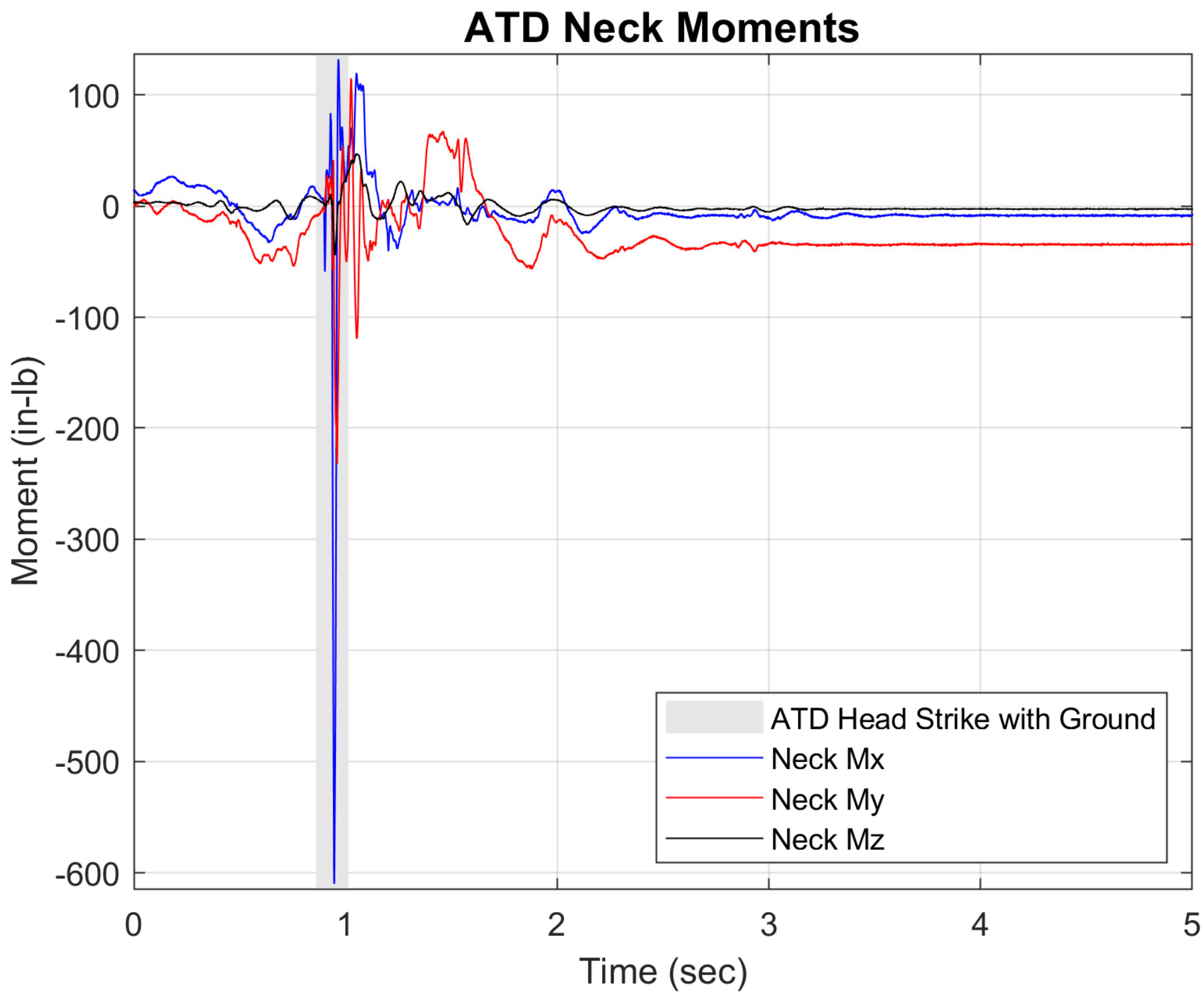
Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



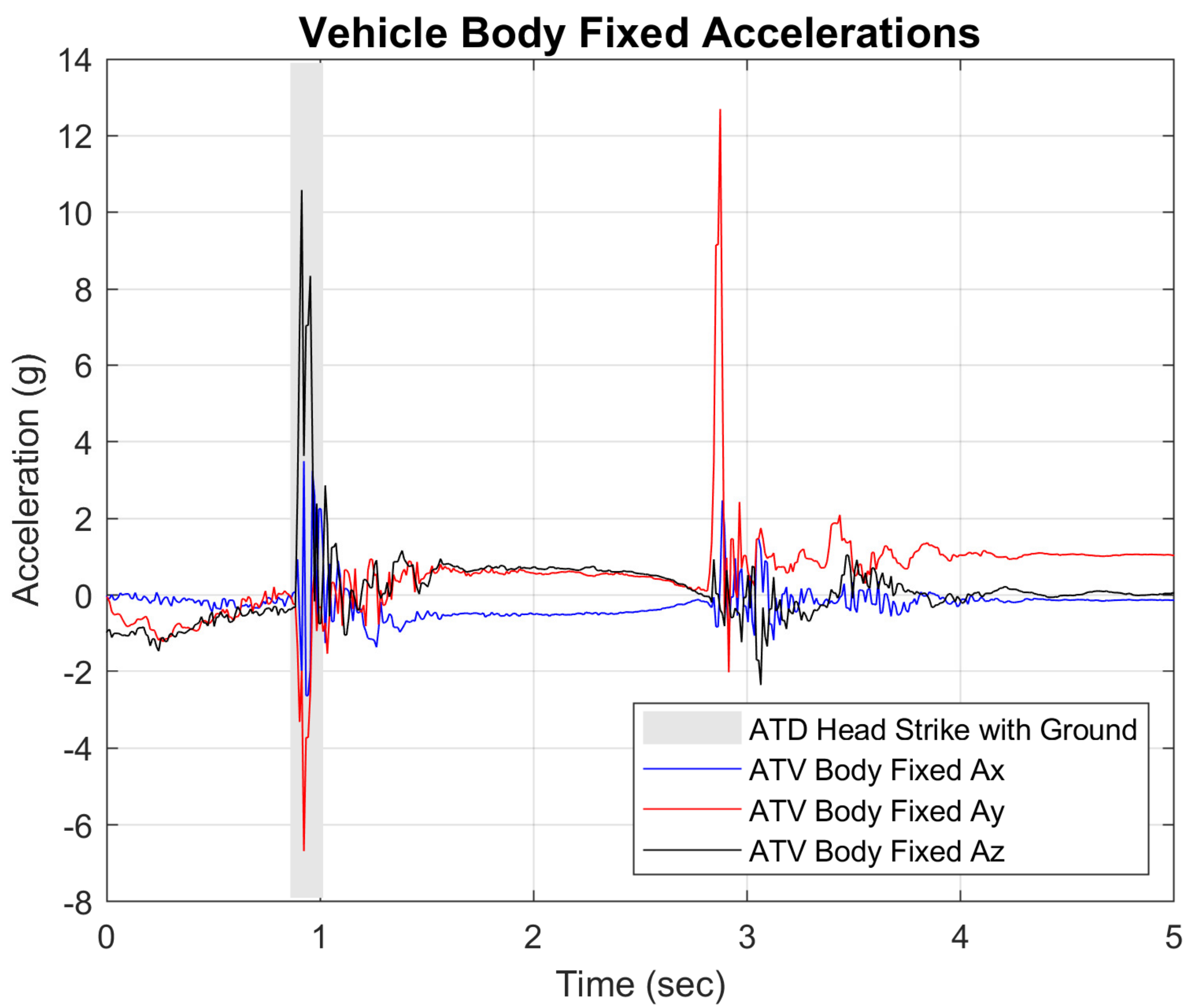
Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



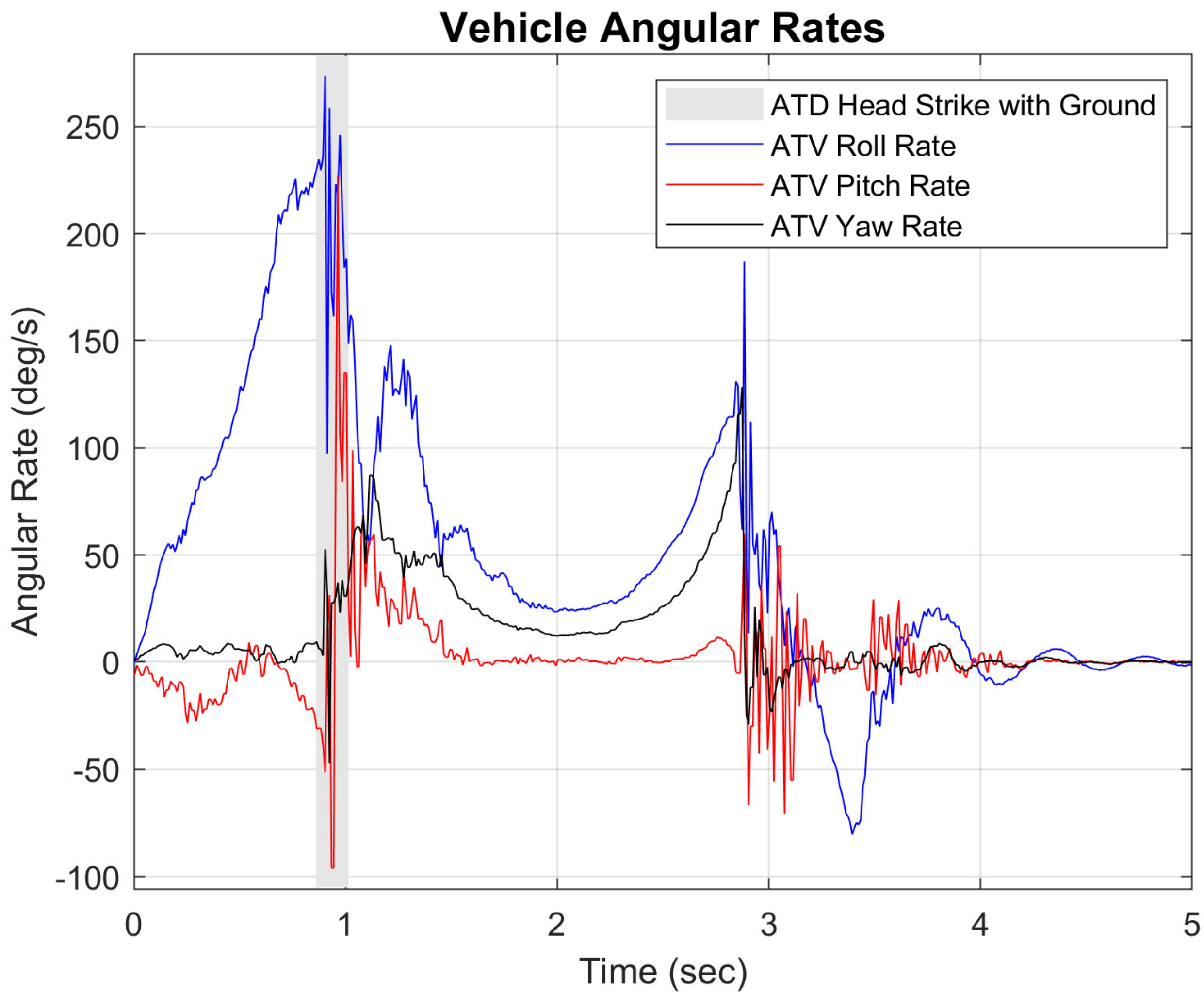
Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



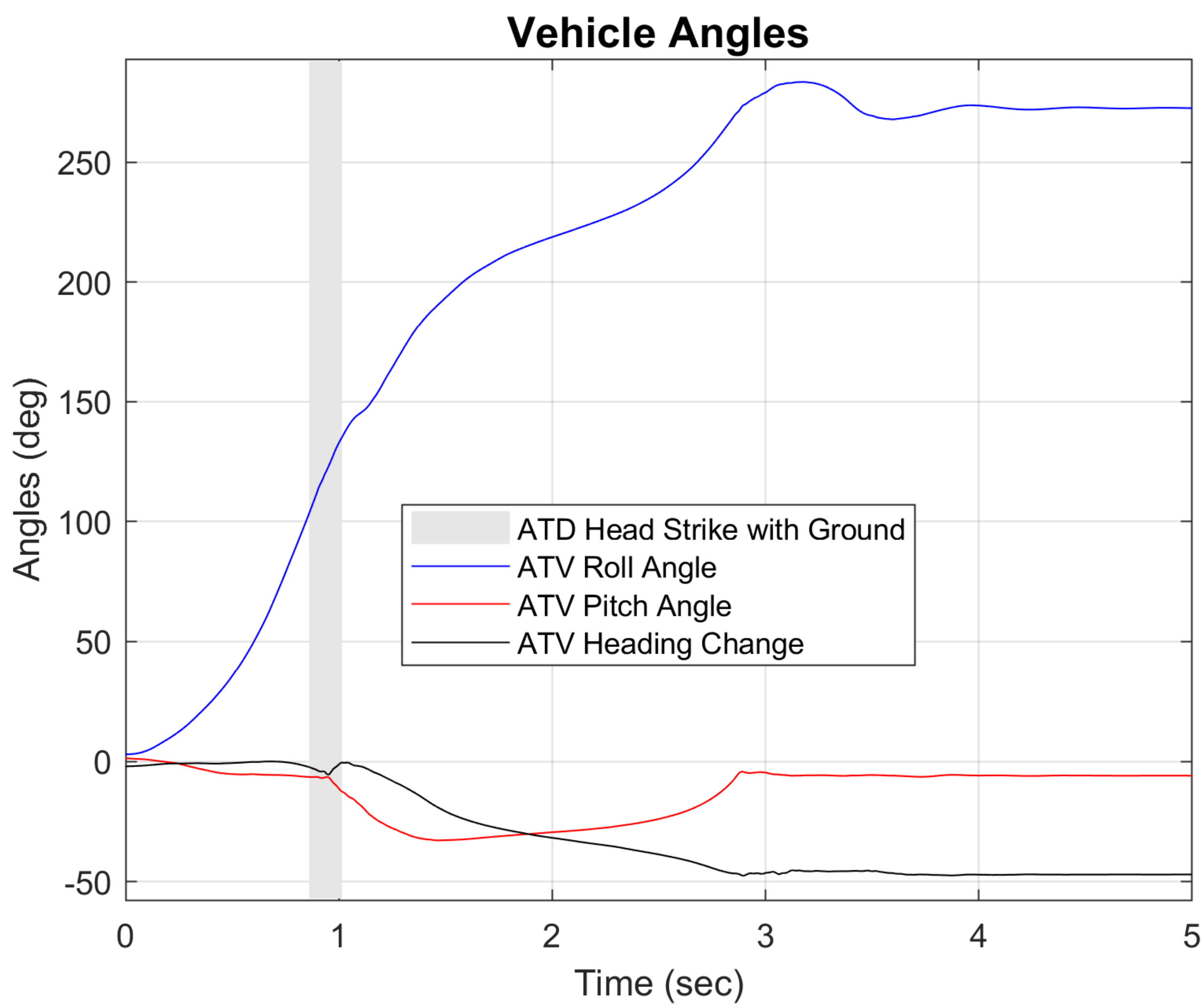
Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



Vehicle A - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 30° - Time = 0.53 sec

Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 45° - Time = 0.68 sec

Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 90° - Time = 0.93 sec

Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

ATD Head Strike - Time = 1.11 sec

Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 180° - Time = 1.52 sec

Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 270° - Time = 2.73 sec

Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Max Roll Angle = 282.3° - Time = 2.93 sec

Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

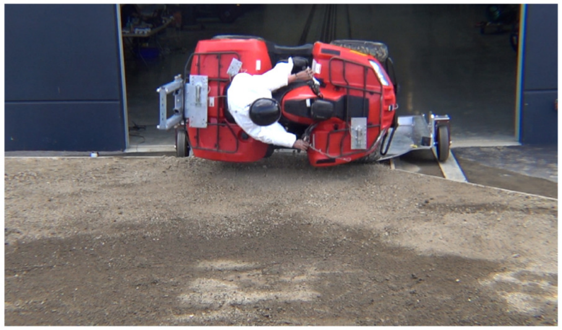
End of Run - Roll Angle = 274.5°

Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

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

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

Drone Camera - Roll Angle = 90° - Time = 0.93 sec



Drone Camera - ATD Head Strike - Time = 1.11 sec

Drone Camera - Roll Angle = 180° - Time = 1.52 sec

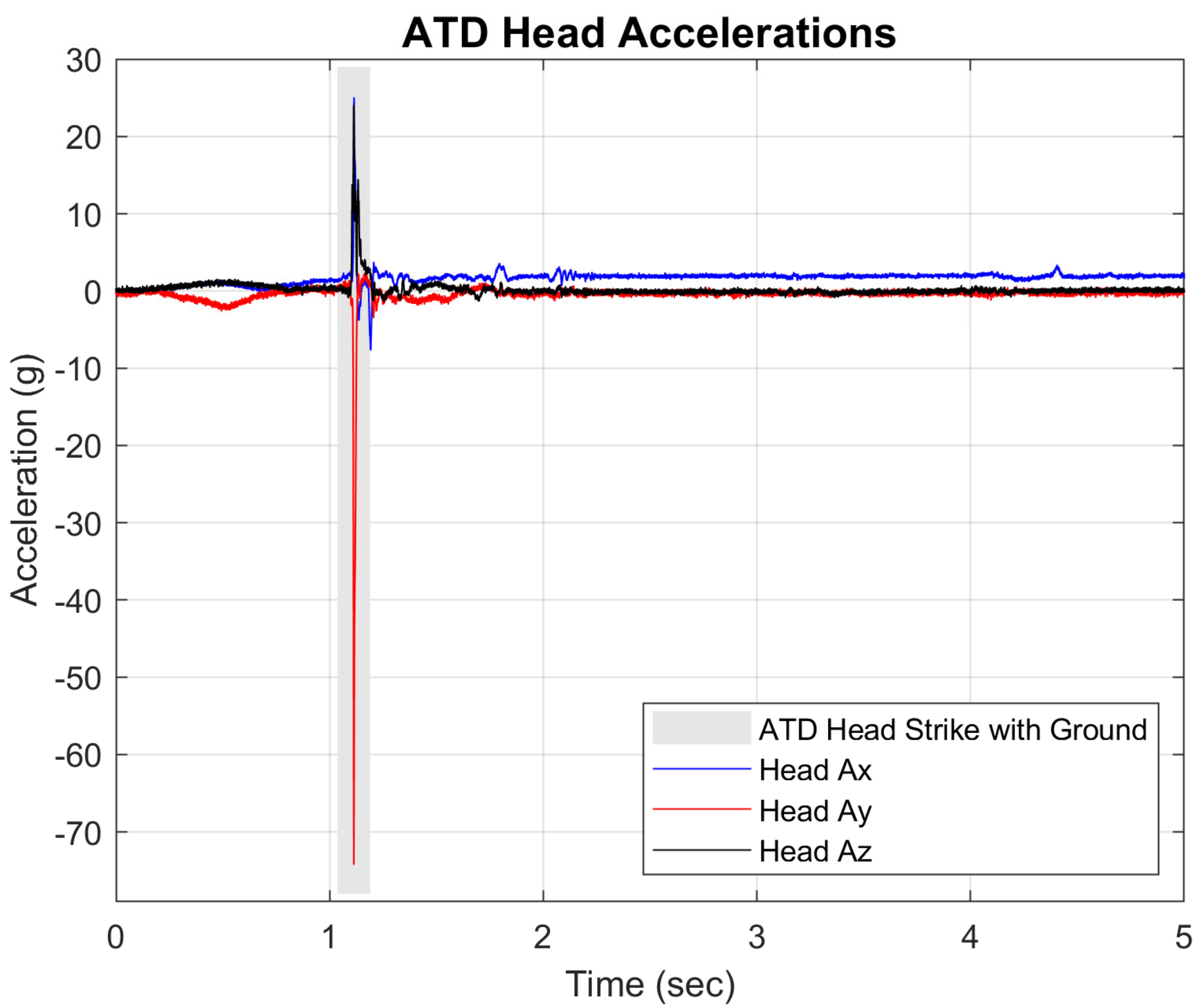
Drone Camera - Roll Angle = 270° - Time = 2.73 sec

Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

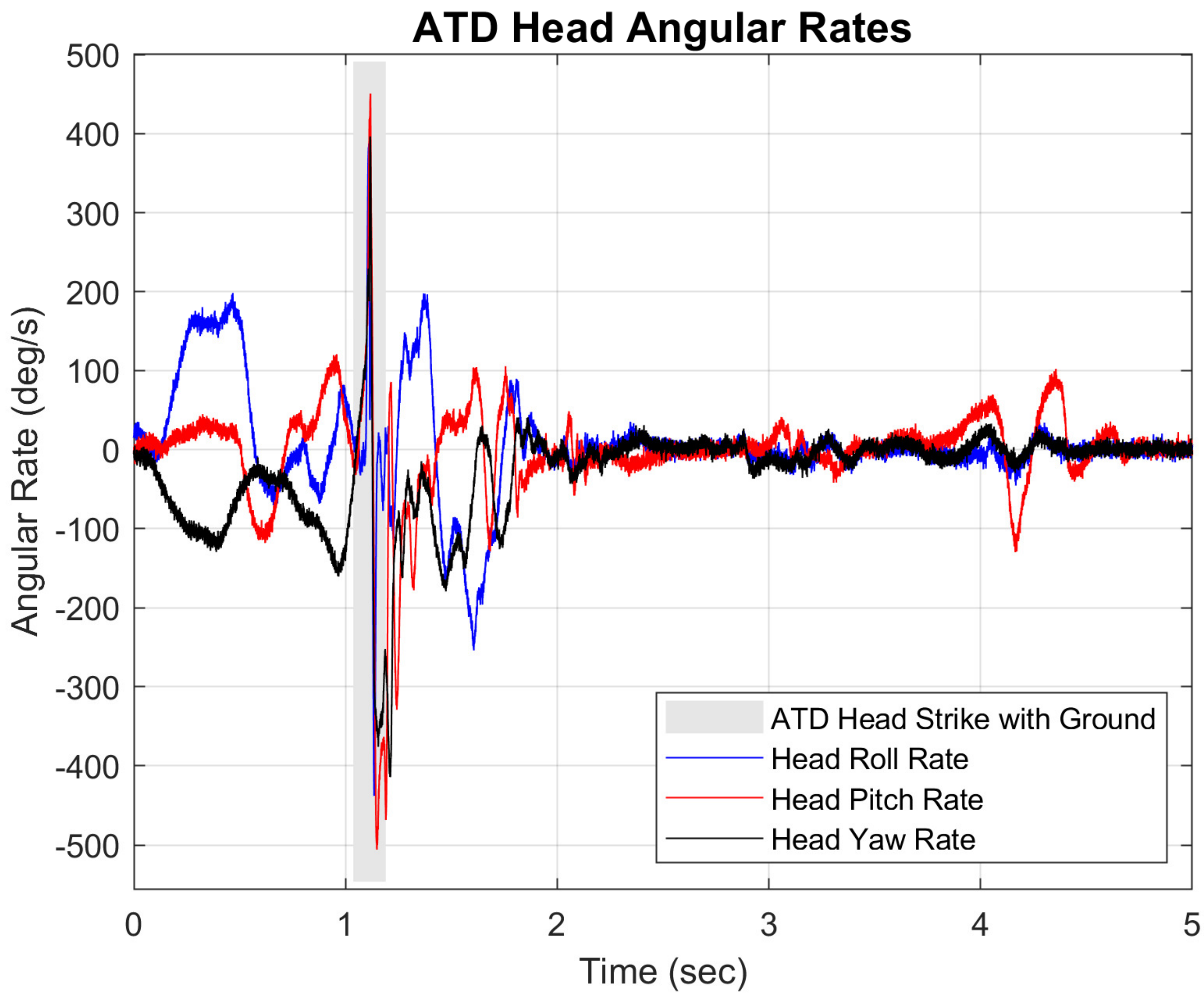
Drone Camera - Max Angle = 282.3° - Time = 2.93 sec

Drone Camera - End of Run - Roll Angle = 274.5°

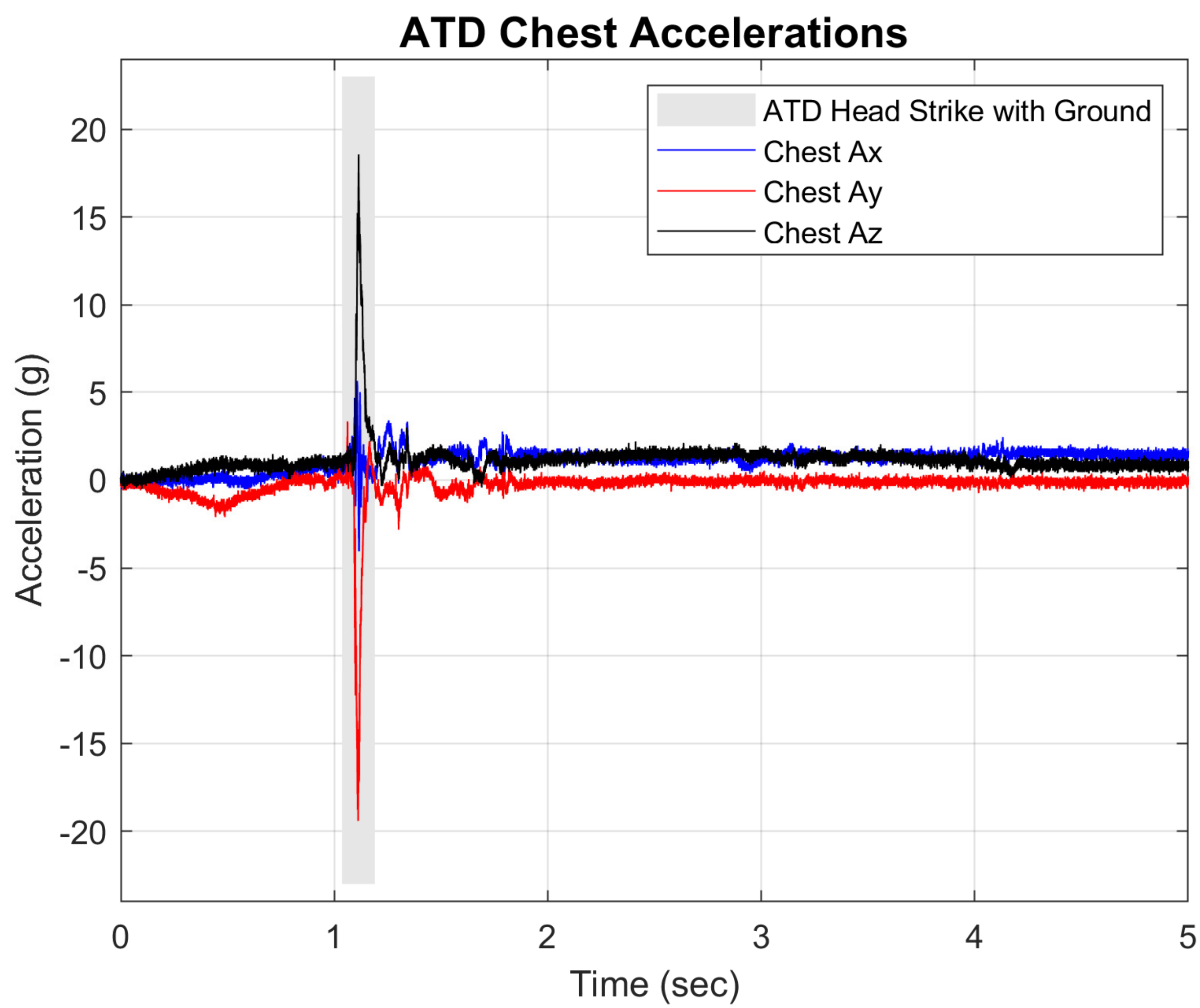
Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



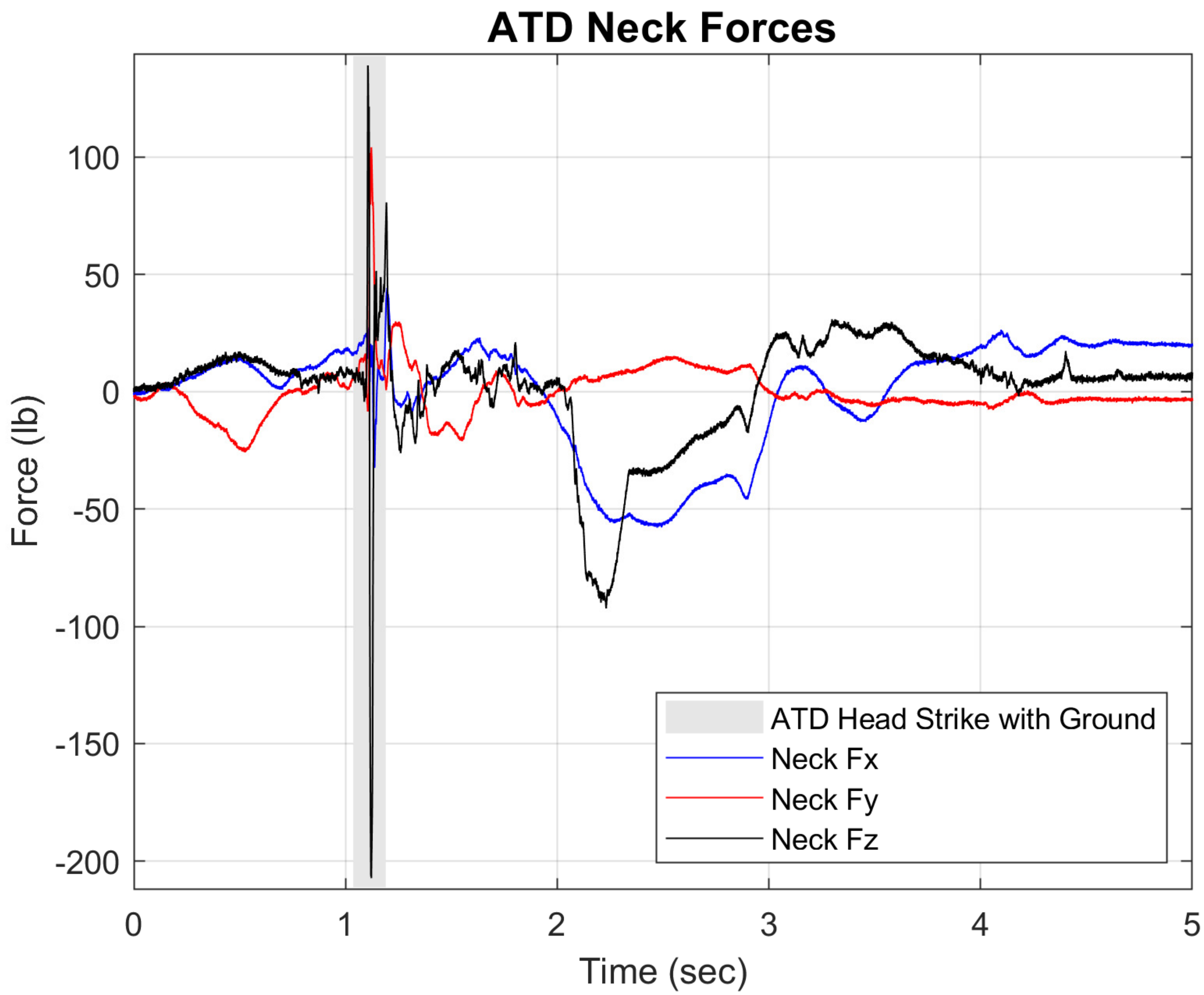
Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



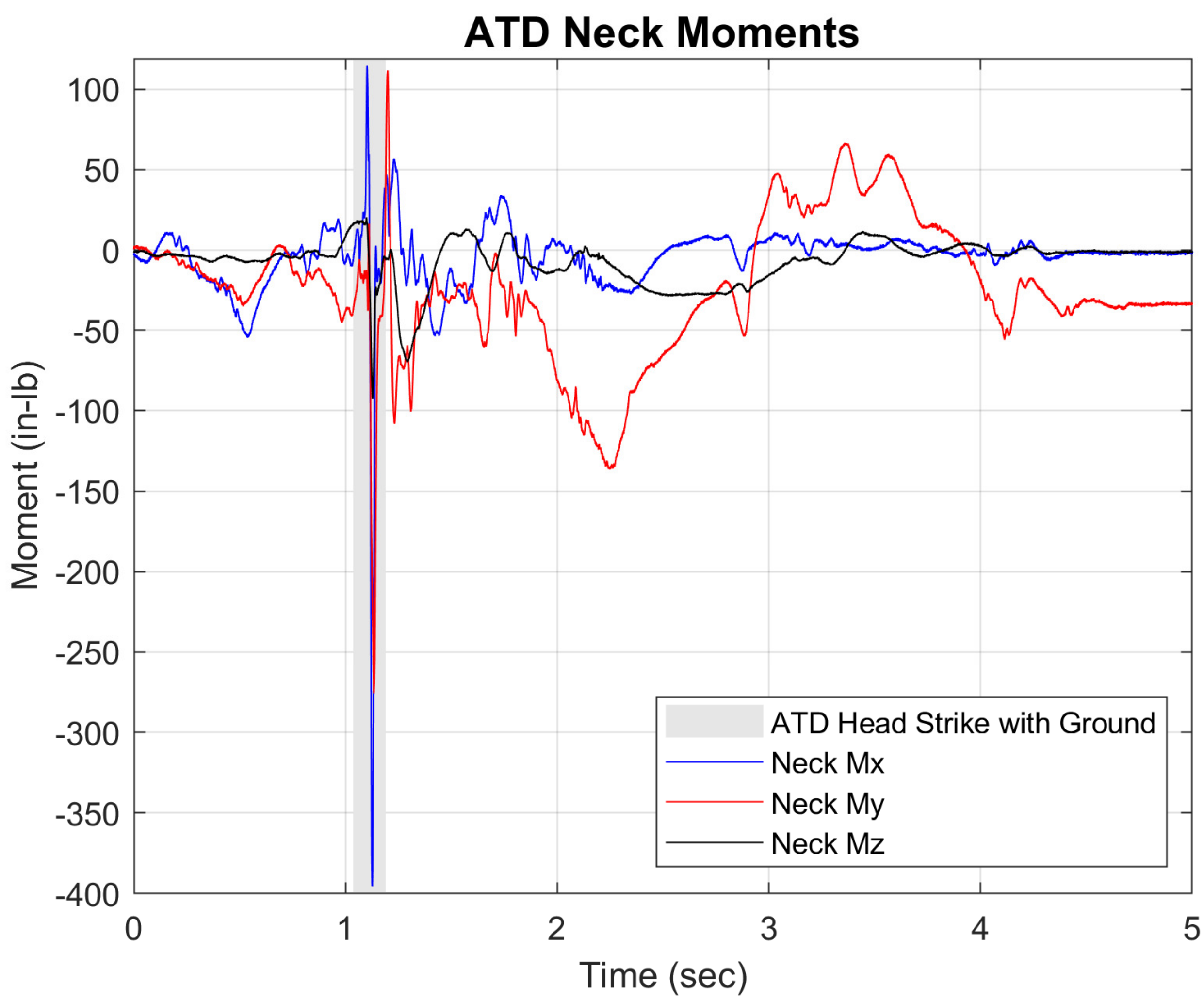
Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



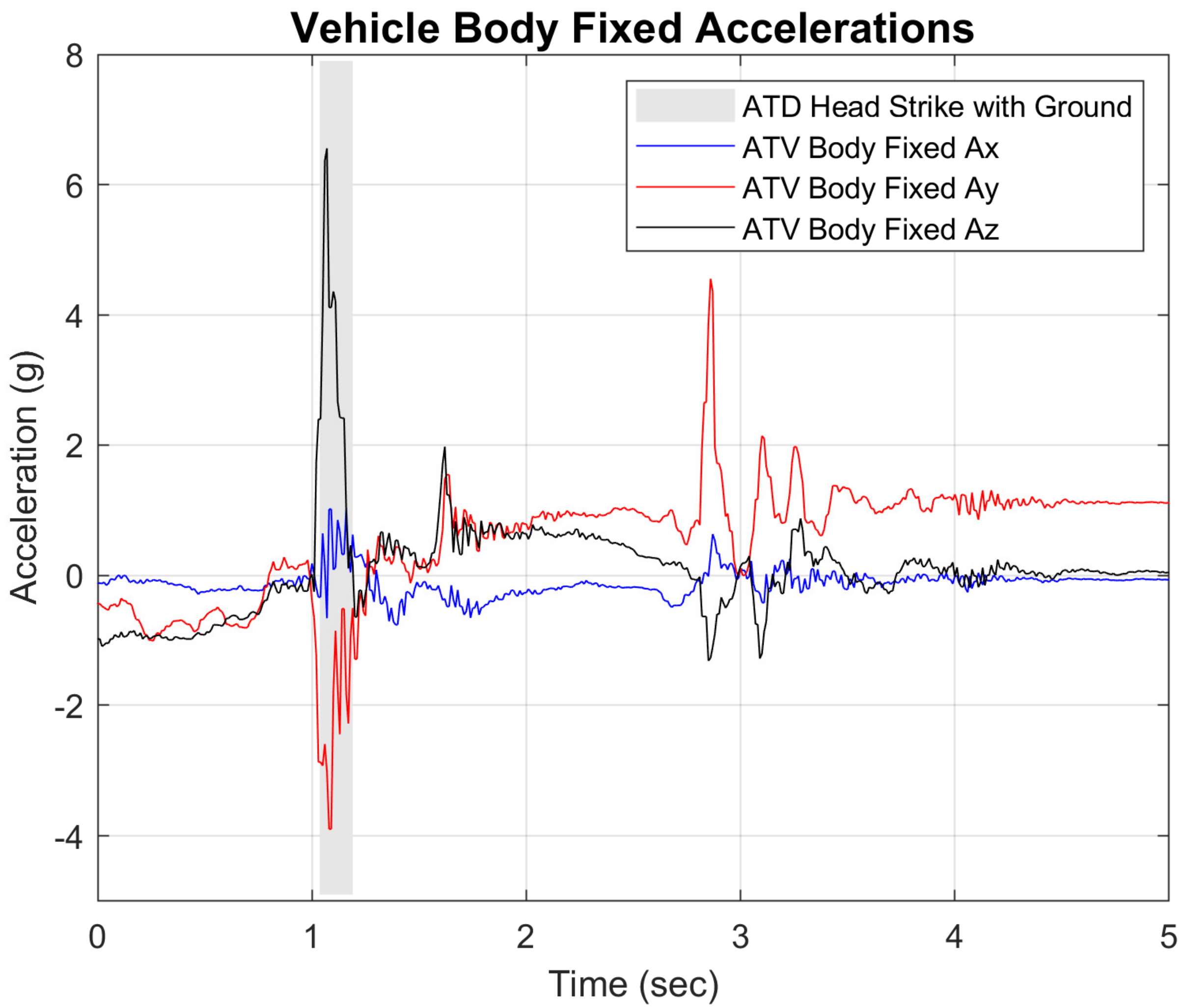
Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



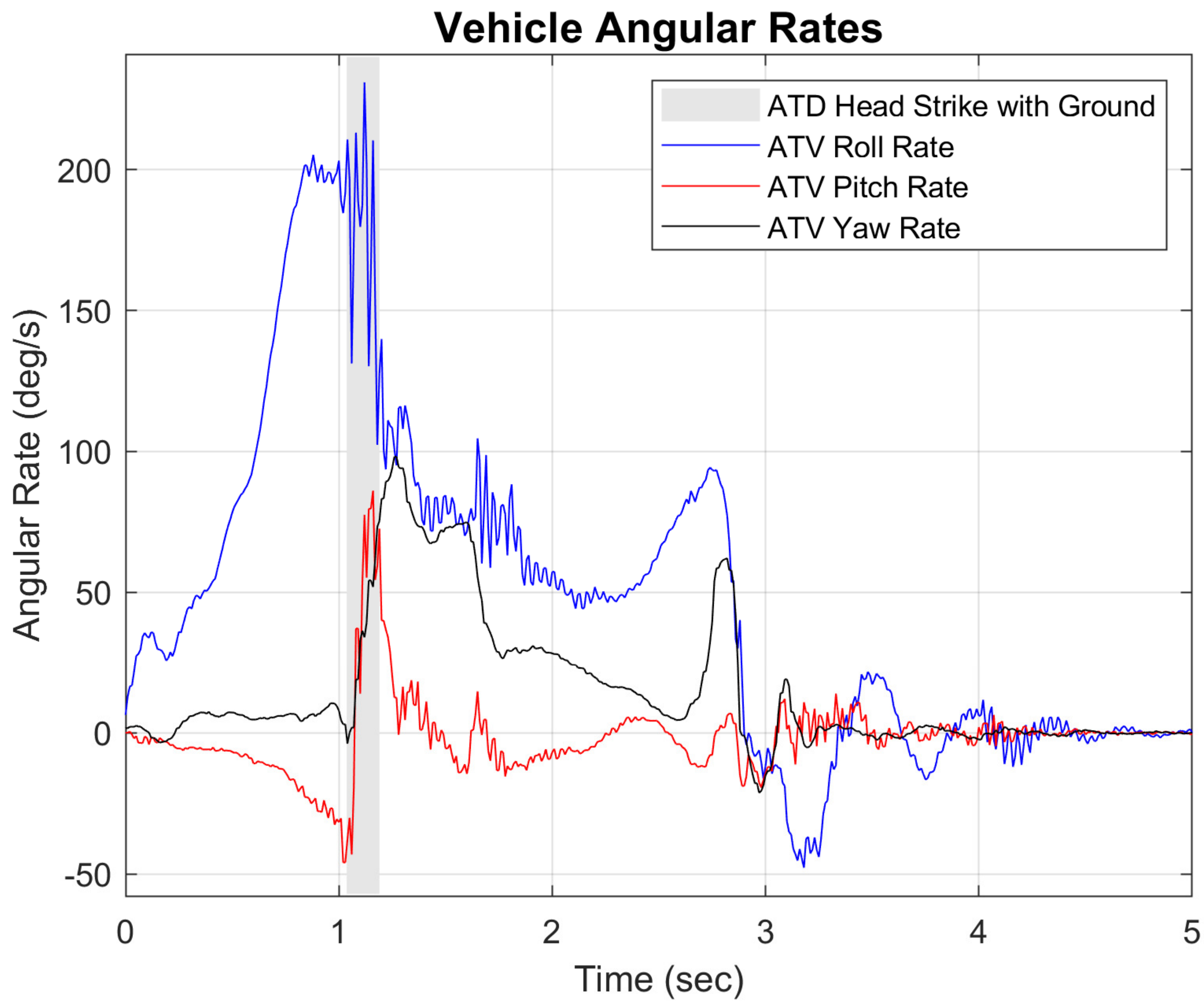
Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



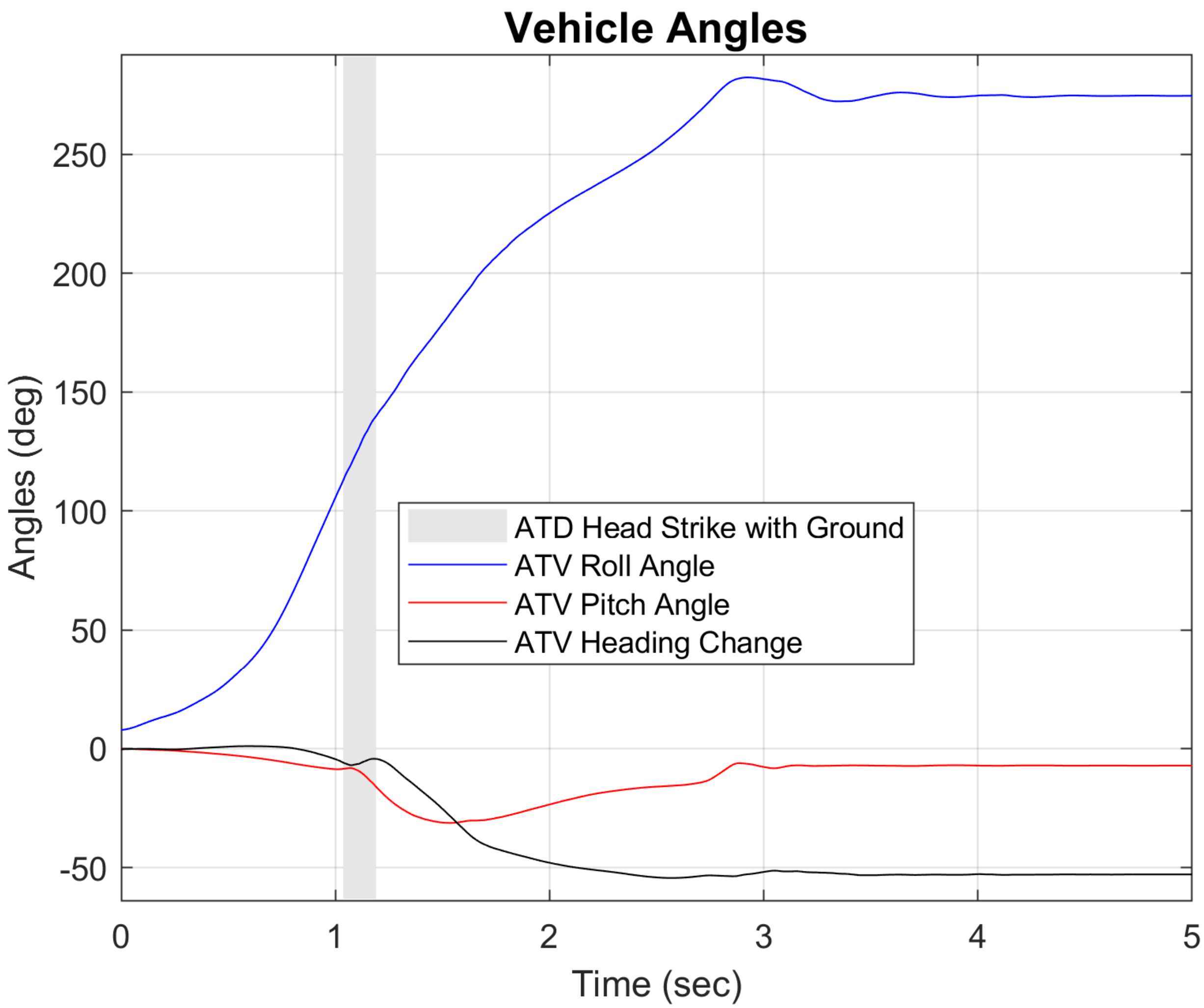
Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



Vehicle E - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 30° - Time = 0.39 sec

Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 45° - Time = 0.51 sec

Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 90° - Time = 0.75 sec

Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

ATD Head Strike - Time = 0.85 sec

Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 180° - Time = 1.47 sec

Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Max Roll Angle = 195.3° - Time = 1.88 sec

Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

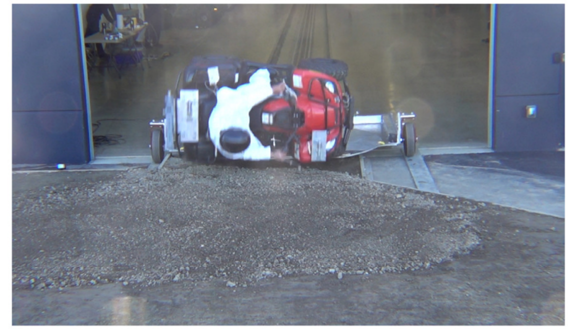
End of Run - Roll Angle = 178.4°

Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Drone Camera - Roll Angle = 30° - Time = 0.39 sec

Drone Camera - Roll Angle = 45° - Time = 0.51 sec

Drone Camera - Roll Angle = 90° - Time = 0.75 sec



Drone Camera - ATD Head Strike - Time = 0.85 sec

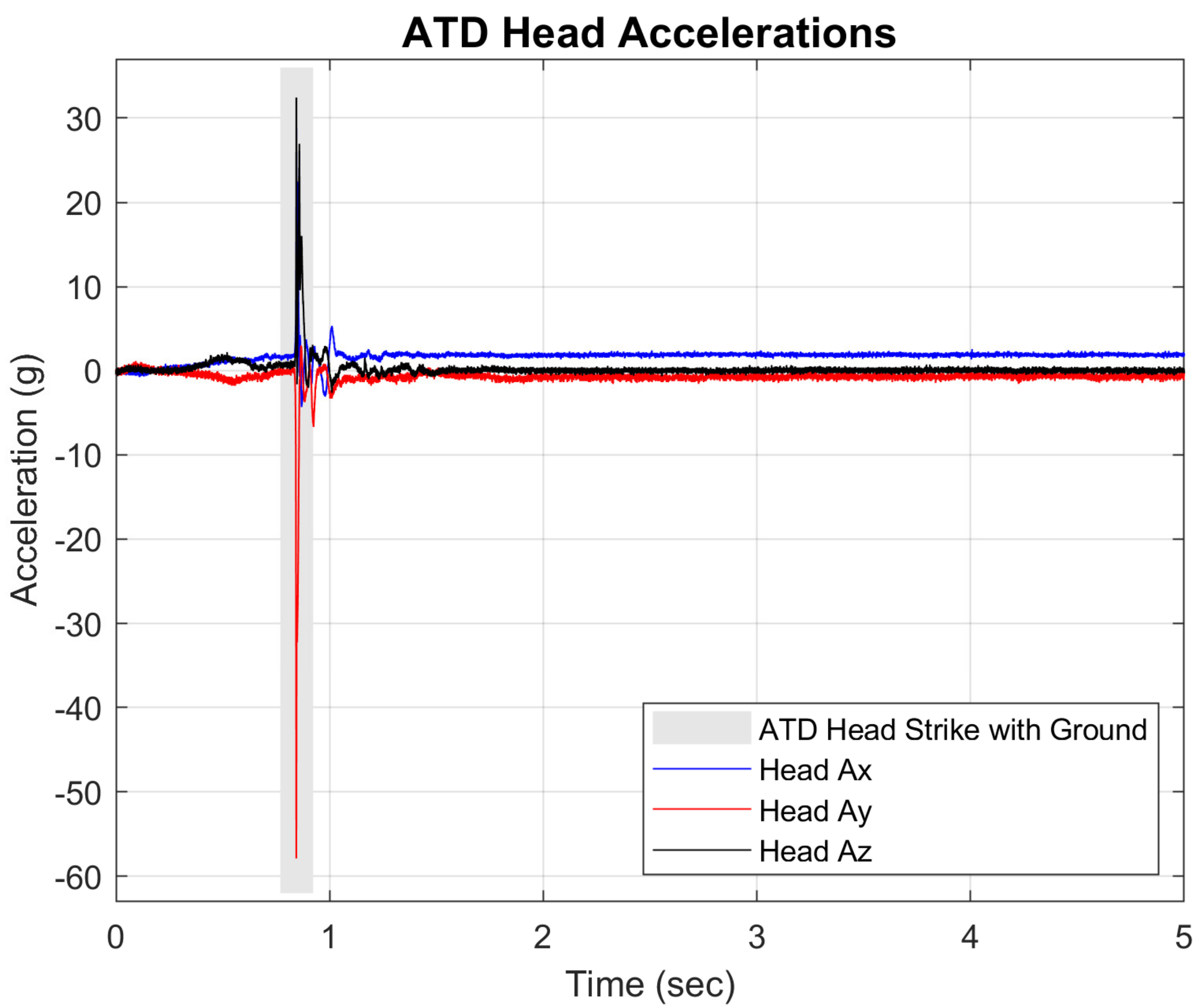
Drone Camera - Roll Angle = 180° - Time = 1.47 sec

Drone Camera - Max Angle = 195.3° - Time = 1.88 sec

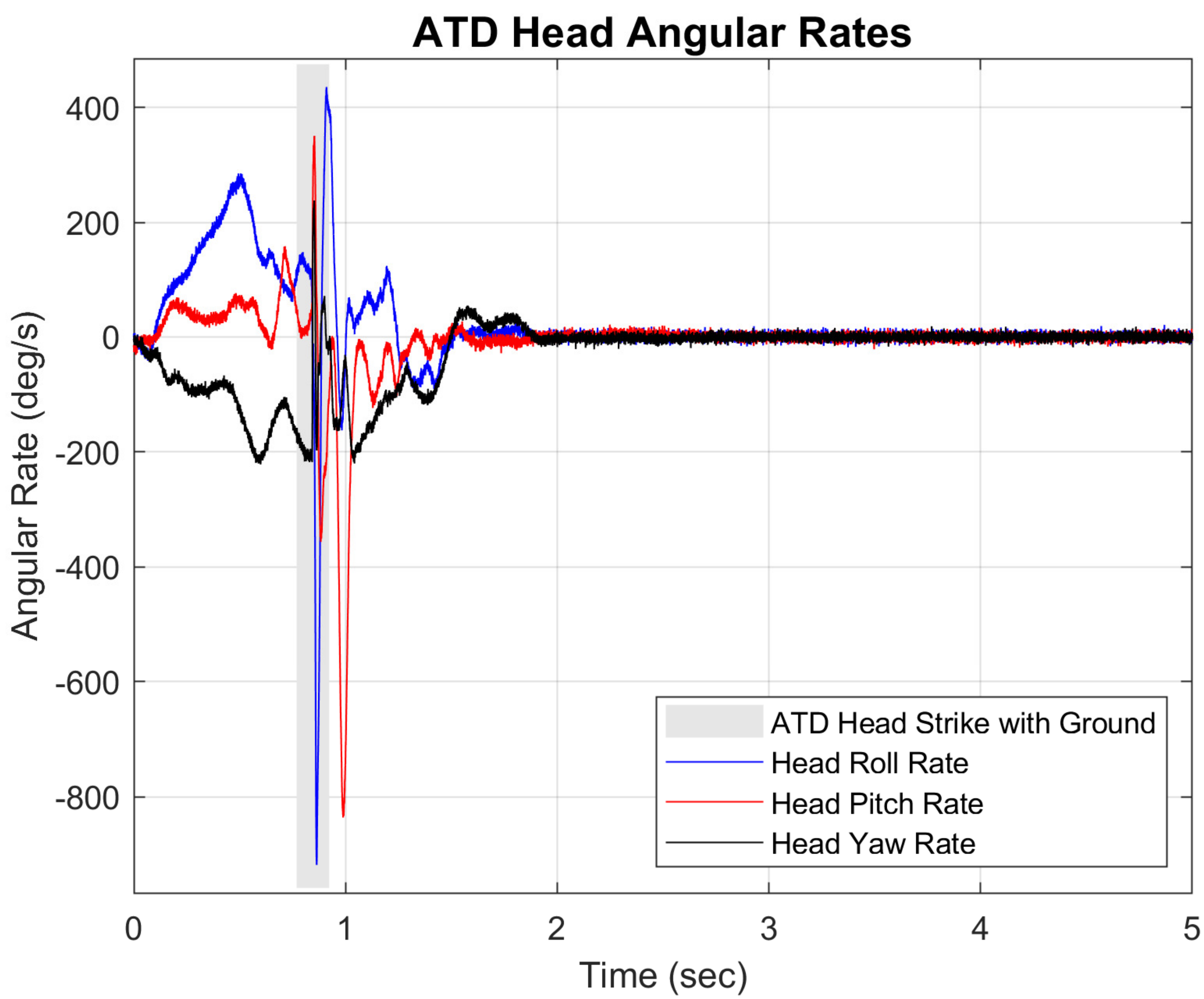
Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Drone Camera - End of Run - Roll Angle = 178.4°

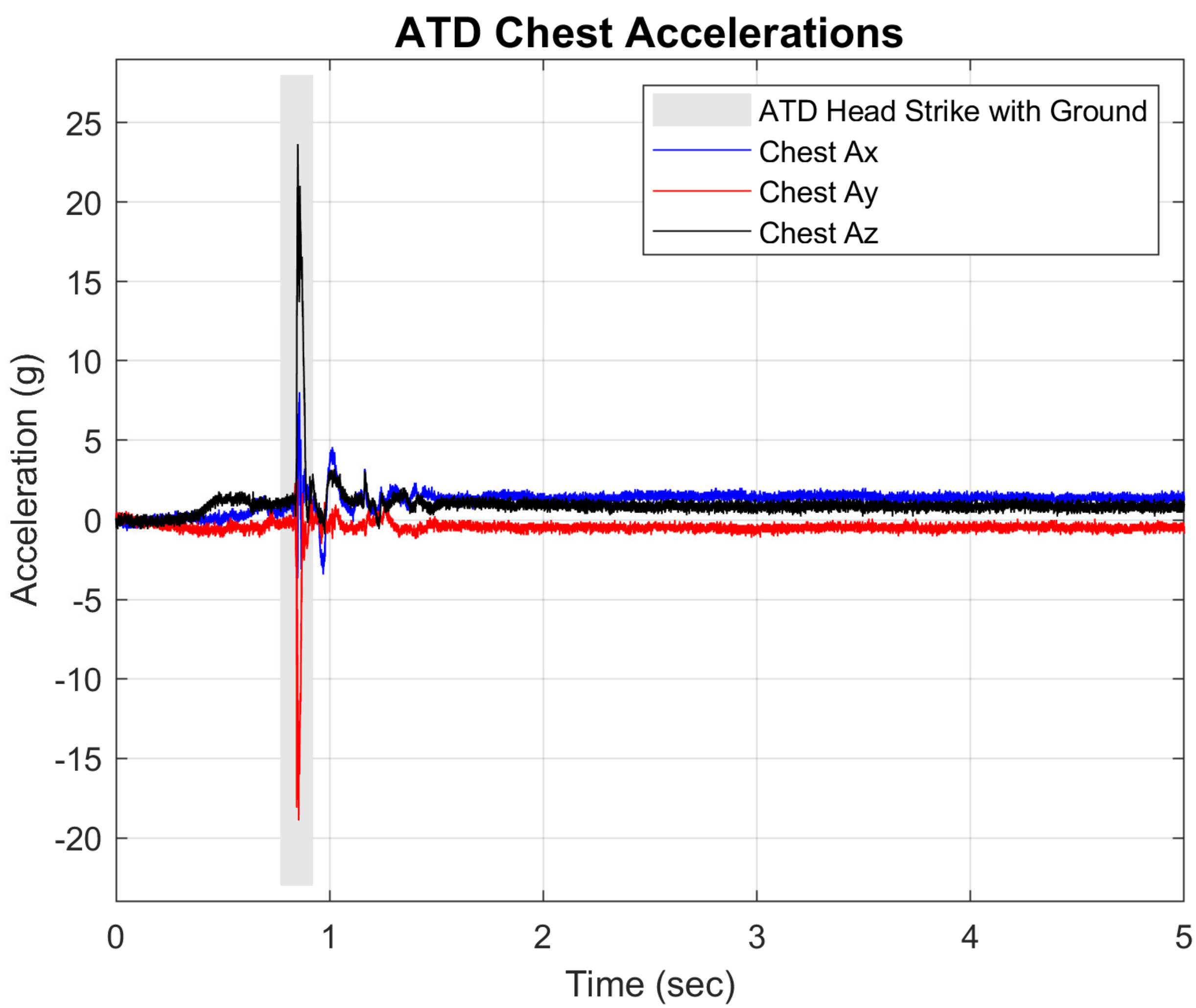
Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



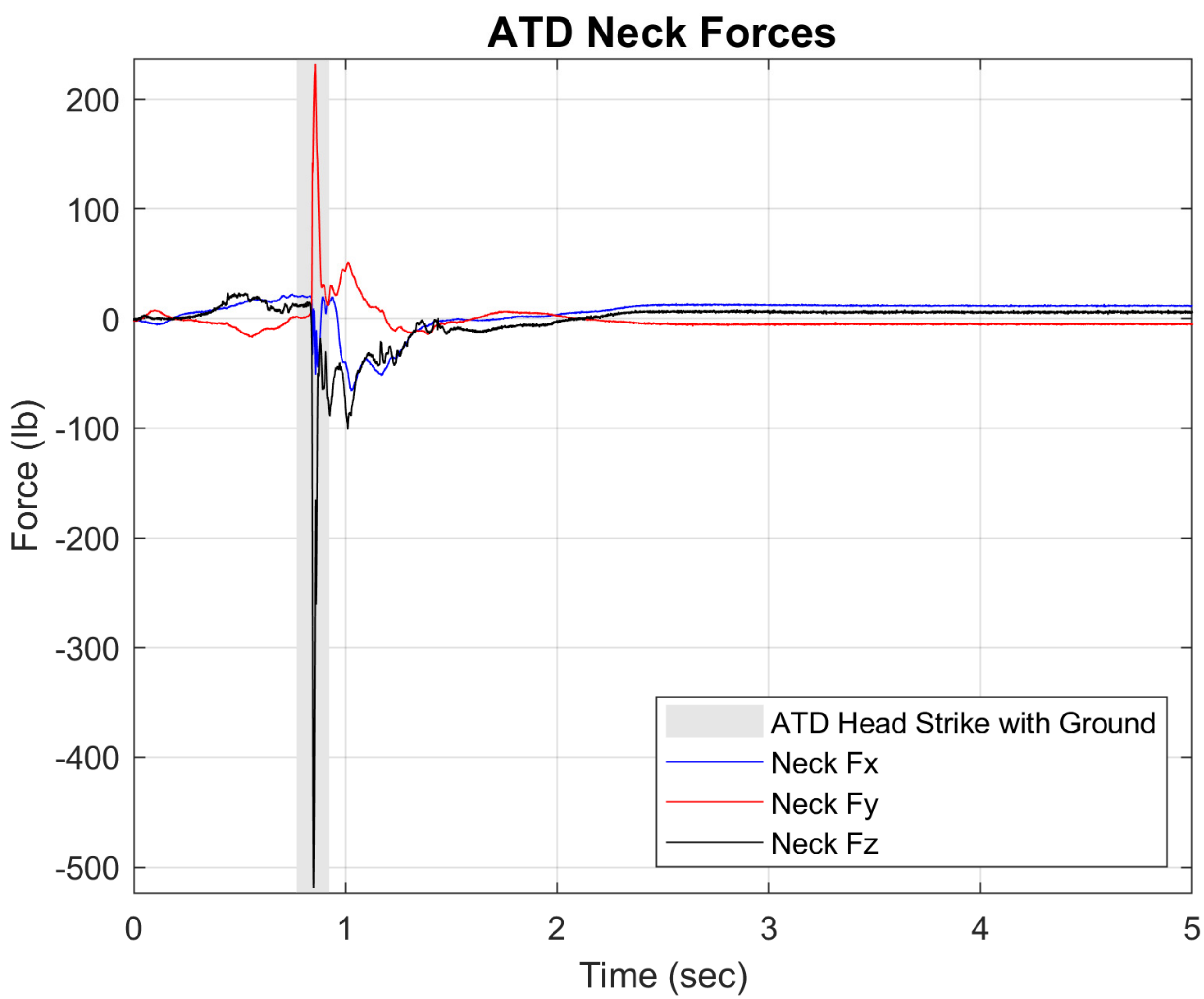
Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



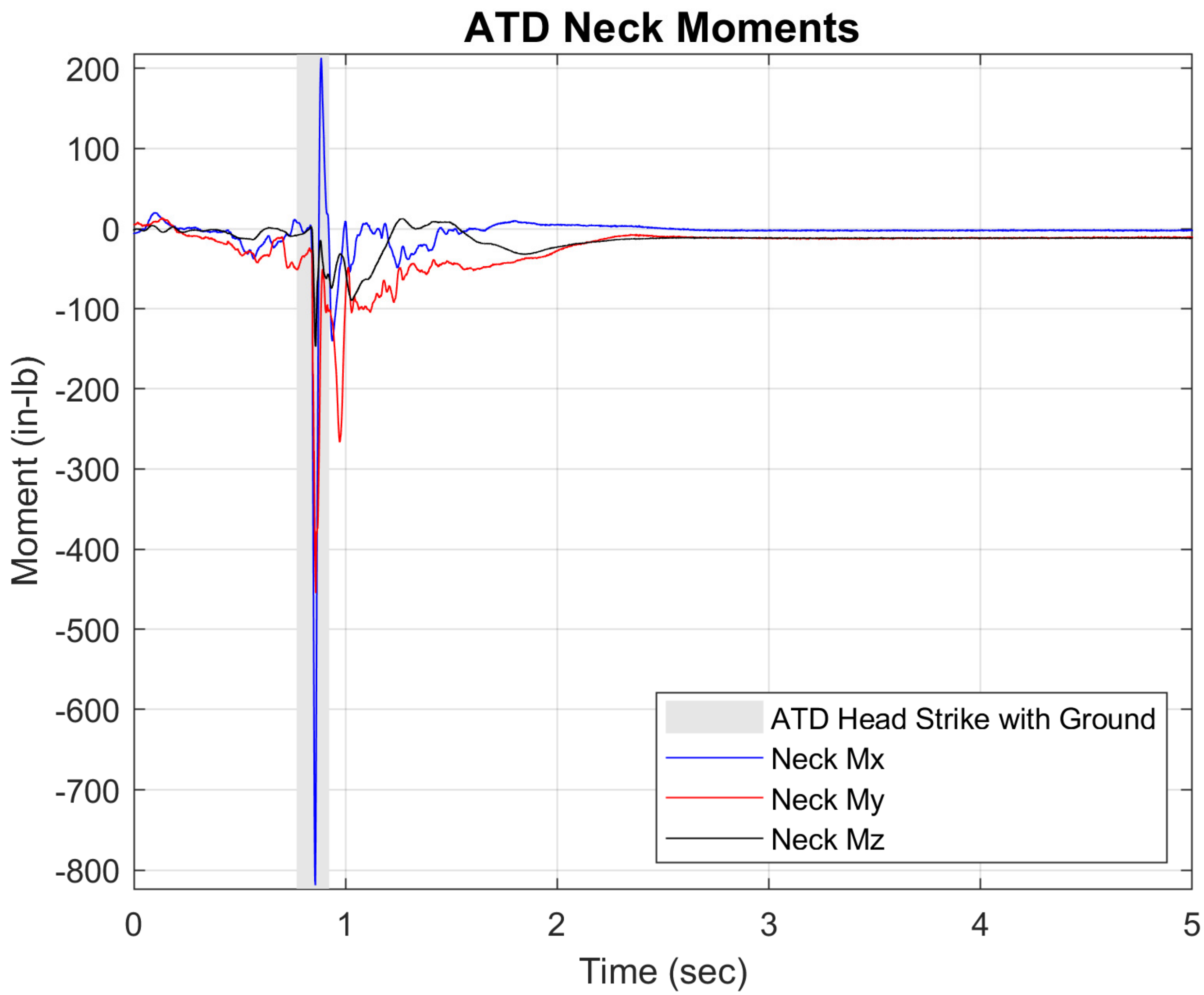
Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



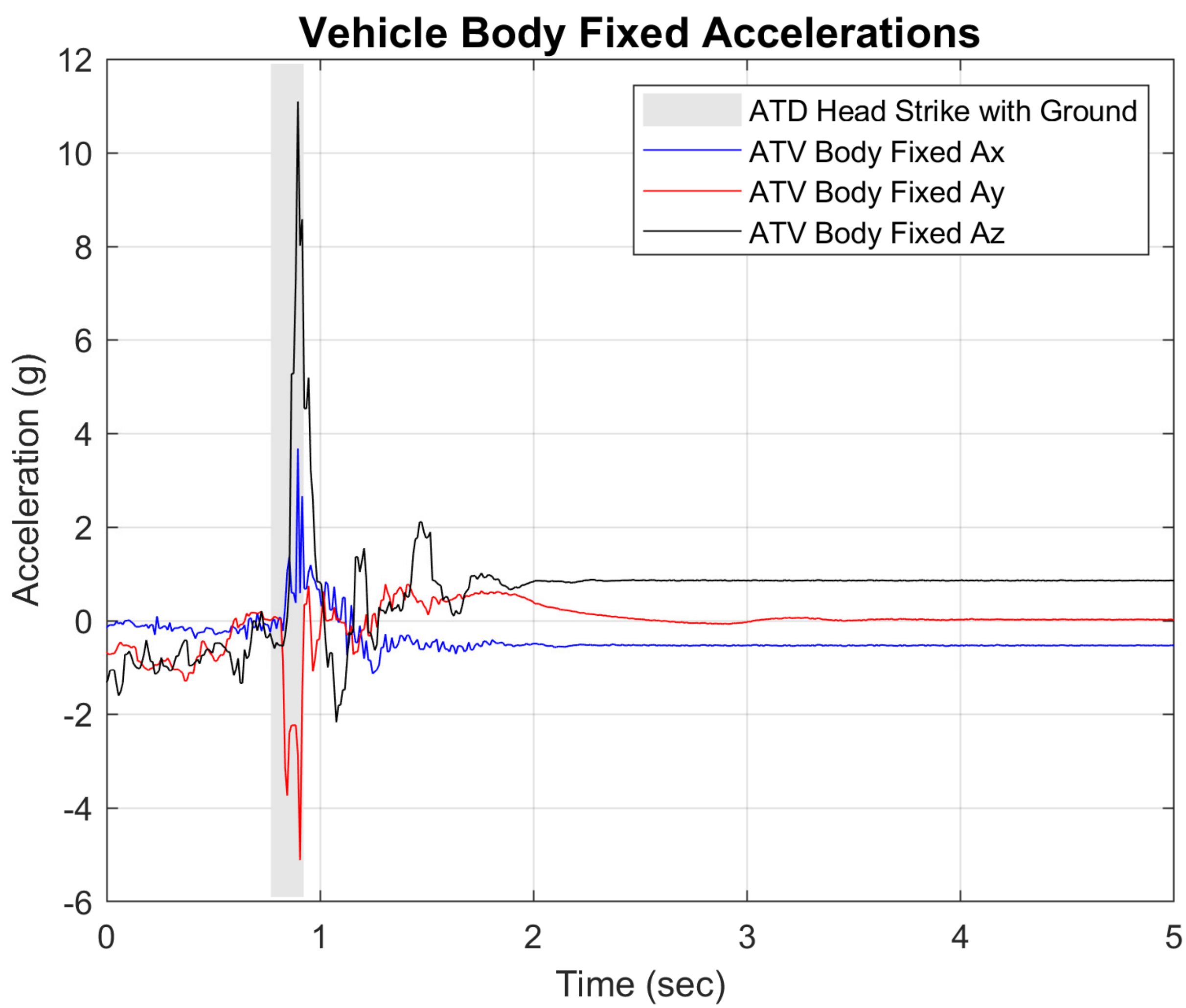
Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



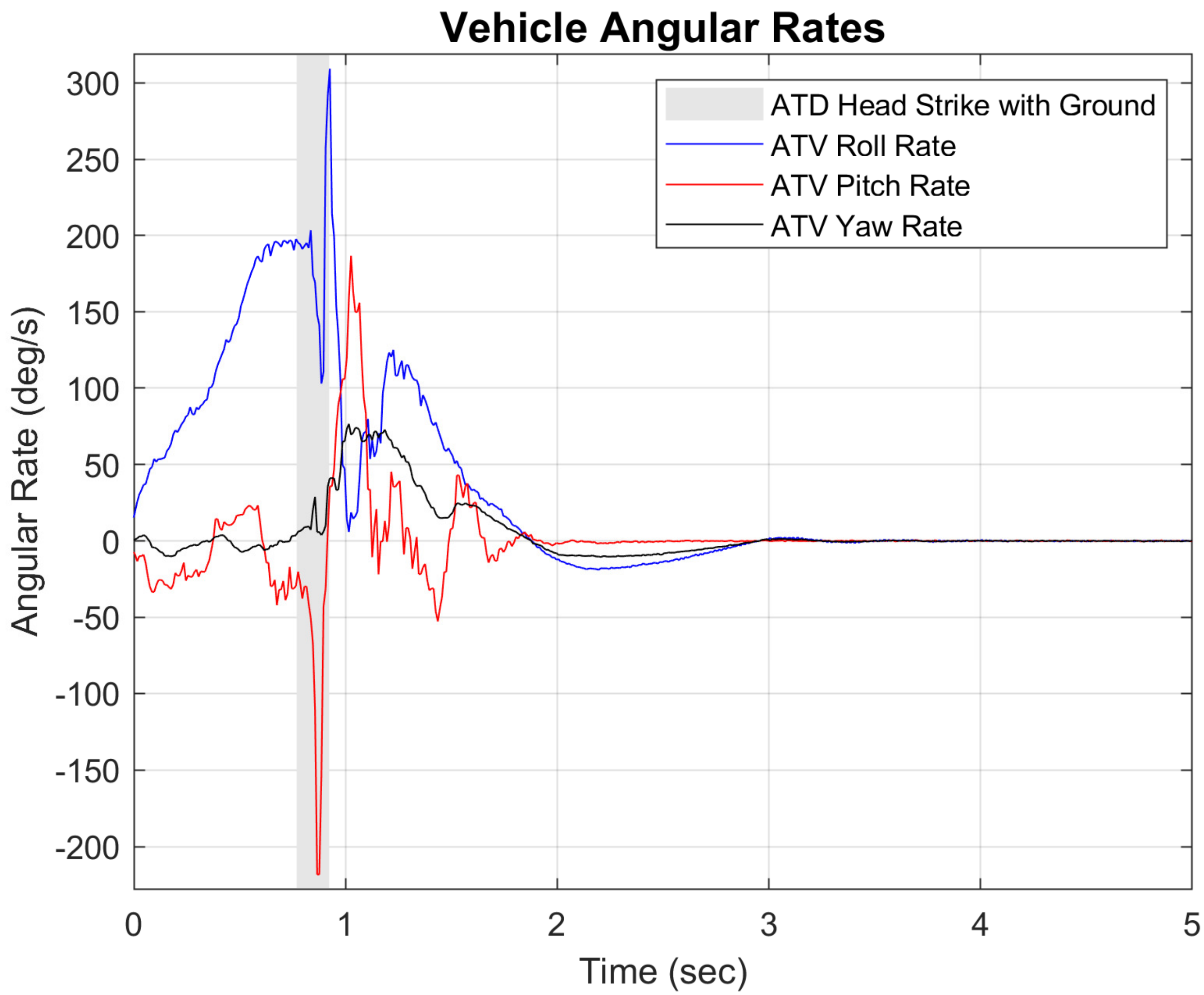
Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



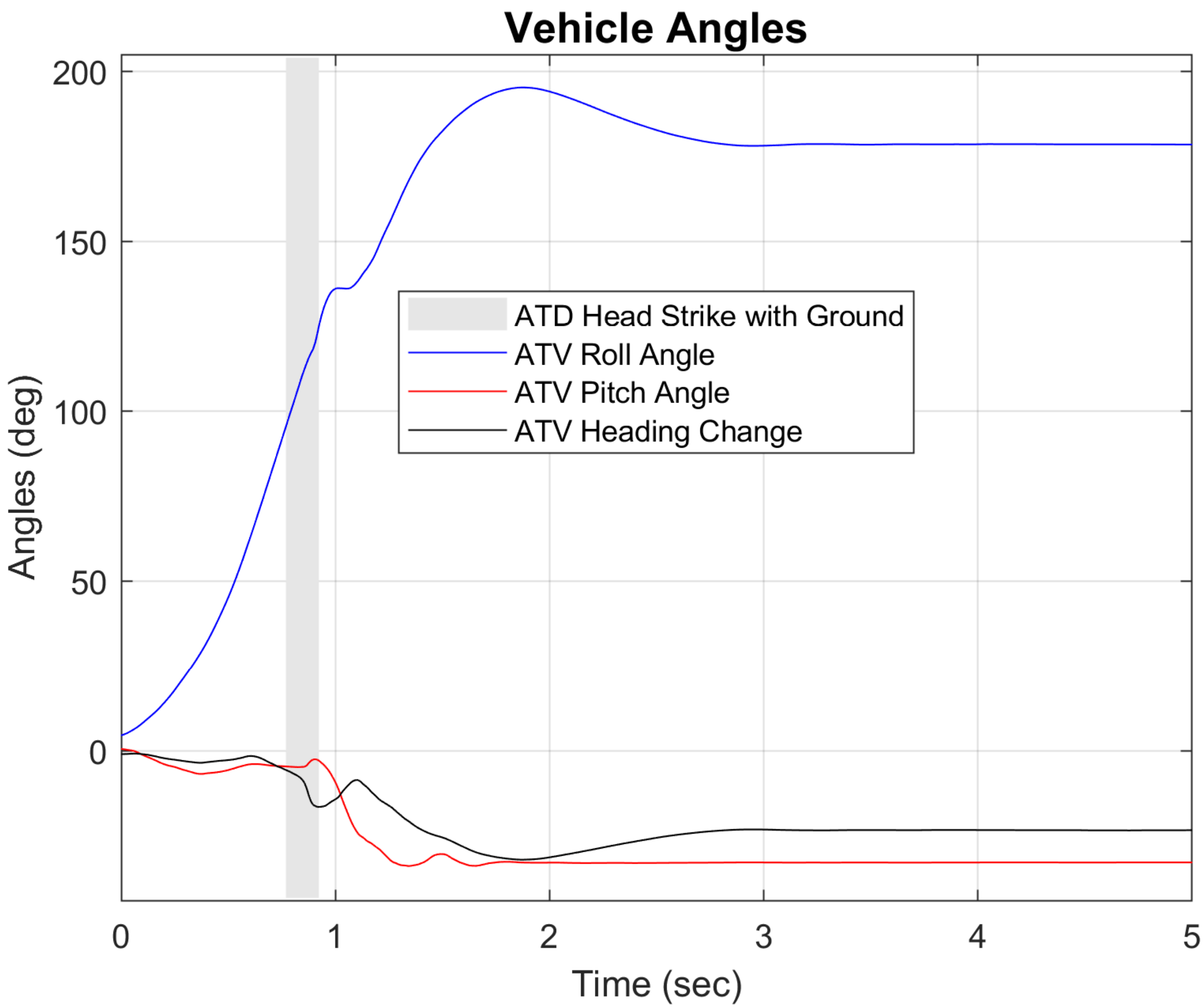
Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD



Vehicle F - Sled Moderate Energy Rollover – POC #2 – Energy Absorbing OPD

Roll Angle = 30° - Time = 0.51 sec

Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD

Roll Angle = 45° - Time = 0.64 sec

Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD

Roll Angle = 90° - Time = 0.89 sec

Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD

ATD Head Strike - Time = 1.02 sec

Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD

Roll Angle = 180° - Time = 1.46 sec

Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD

Roll Angle = 270° - Time = 2.19 sec

Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD

Max Roll Angle = 287.3° - Time = 2.62 sec

Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD

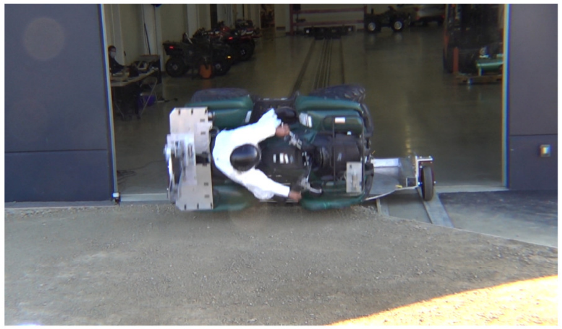
End of Run - Roll Angle = 269.1°

Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD

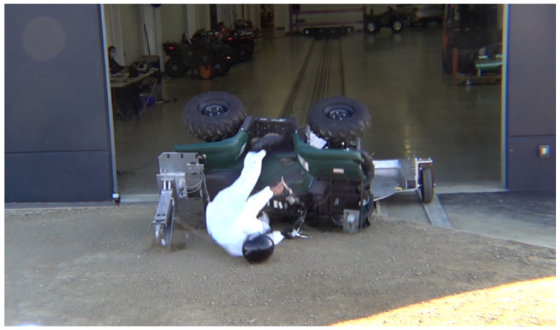
Drone Camera - Roll Angle = 30° - Time = 0.51 sec

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

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



Drone Camera - ATD Head Strike - Time = 1.02 sec



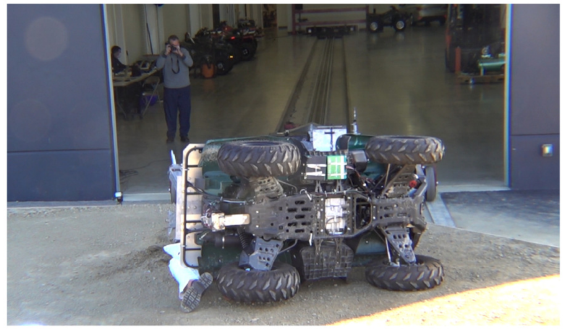
Drone Camera - Roll Angle = 180° - Time = 1.46 sec

Drone Camera - Roll Angle = 270° - Time = 2.19 sec

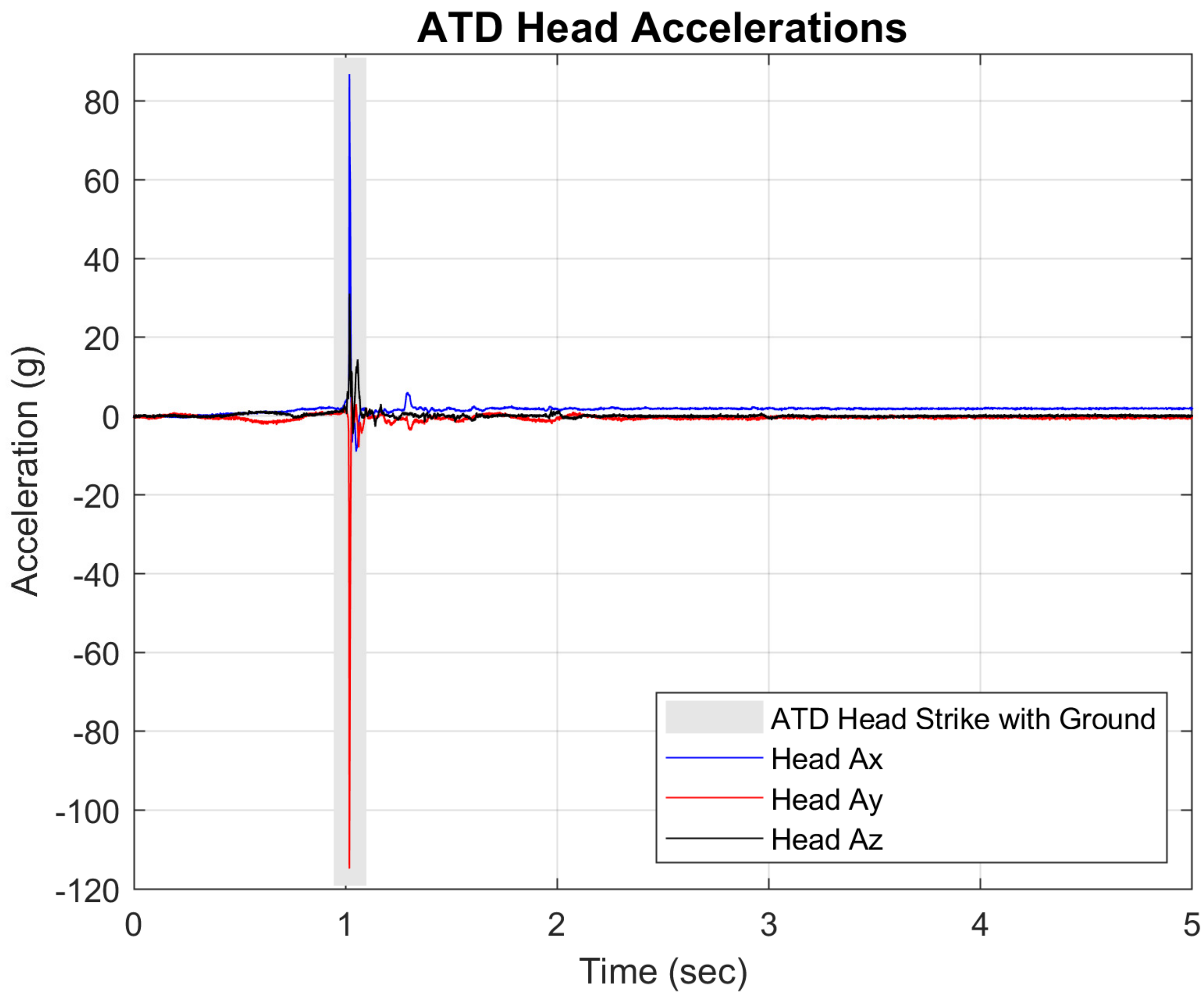
Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD

Drone Camera - Max Angle = 287.3° - Time = 2.62 sec

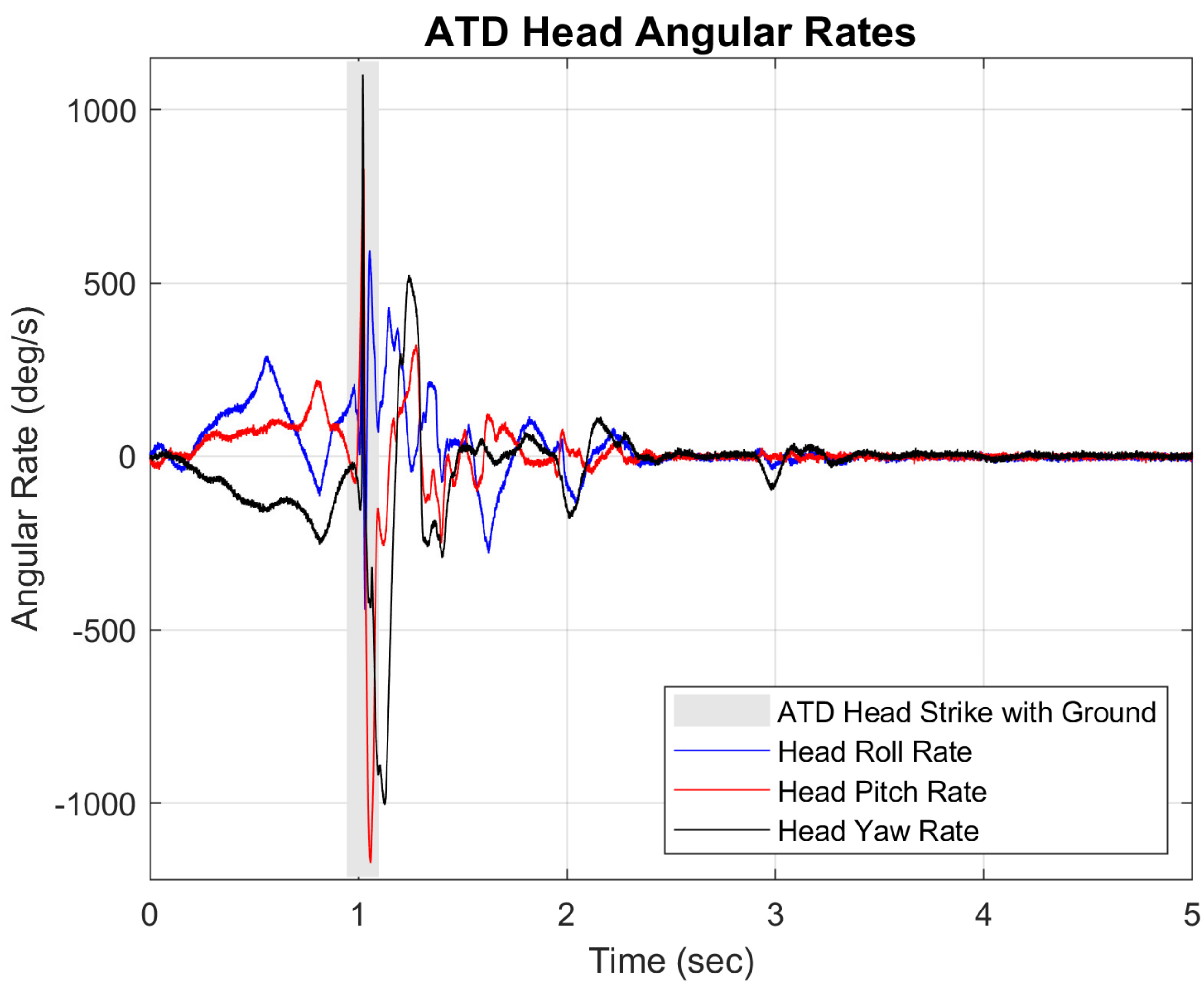
Drone Camera - End of Run - Roll Angle = 269.1°



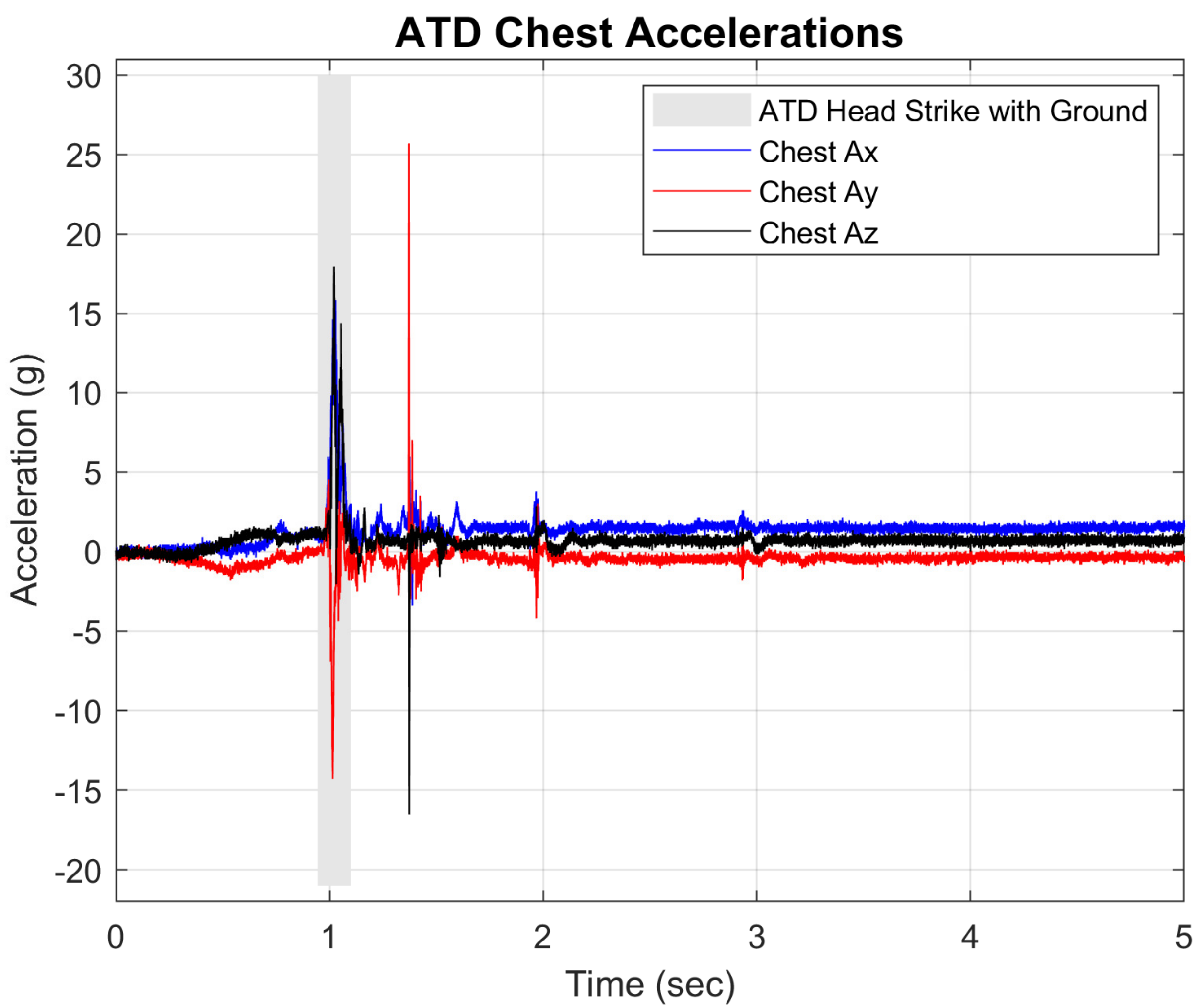
Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD



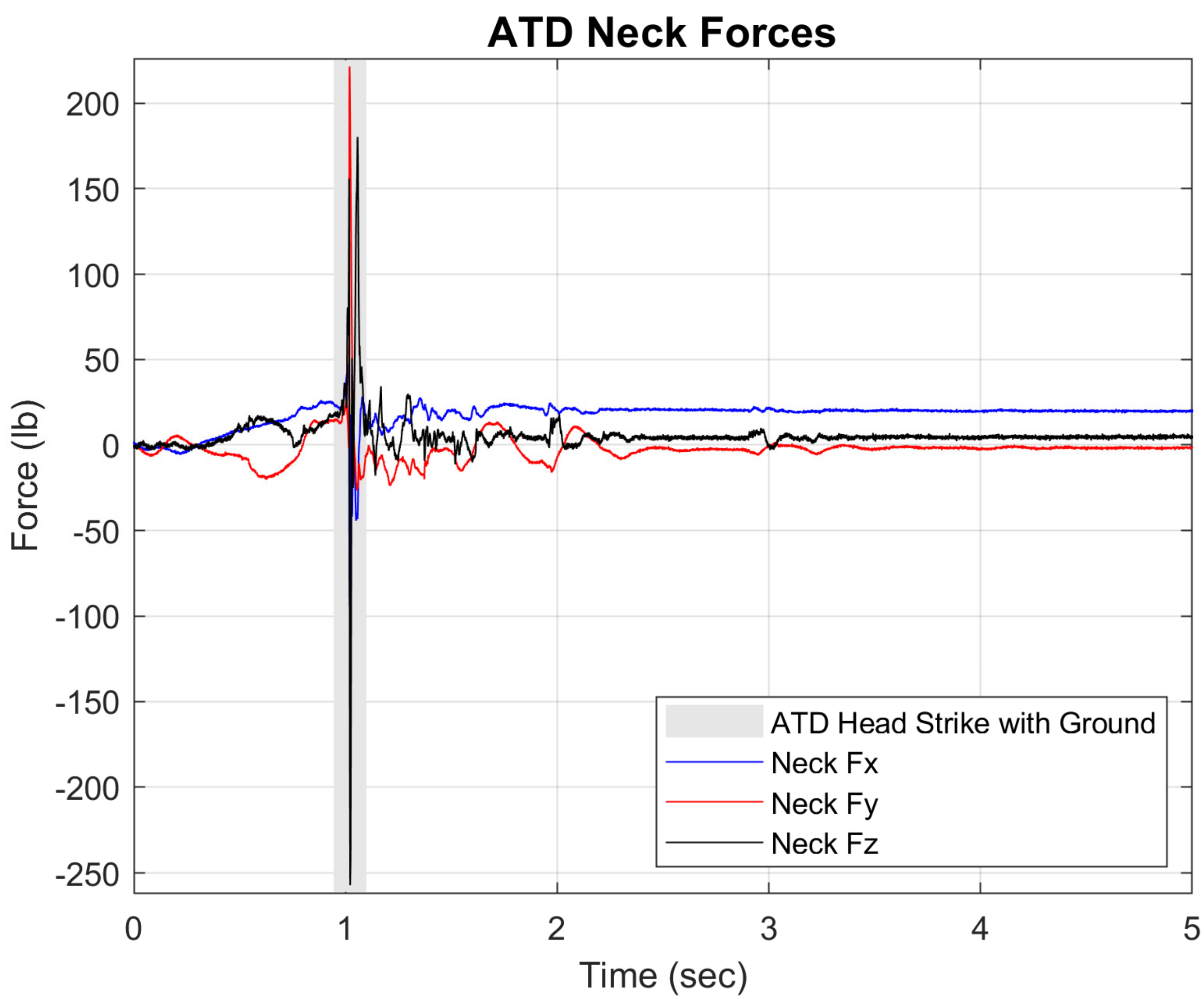
Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD



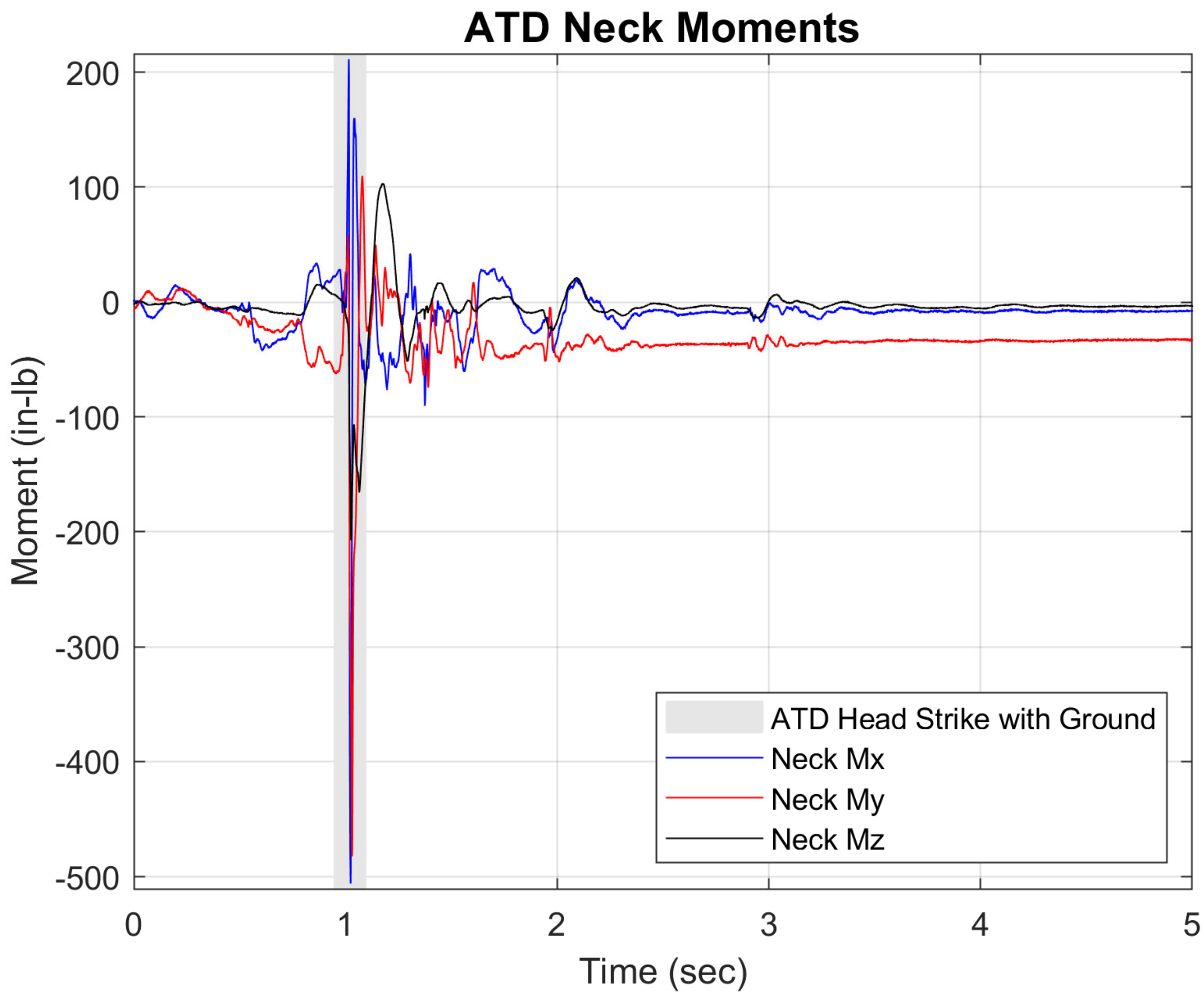
Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD



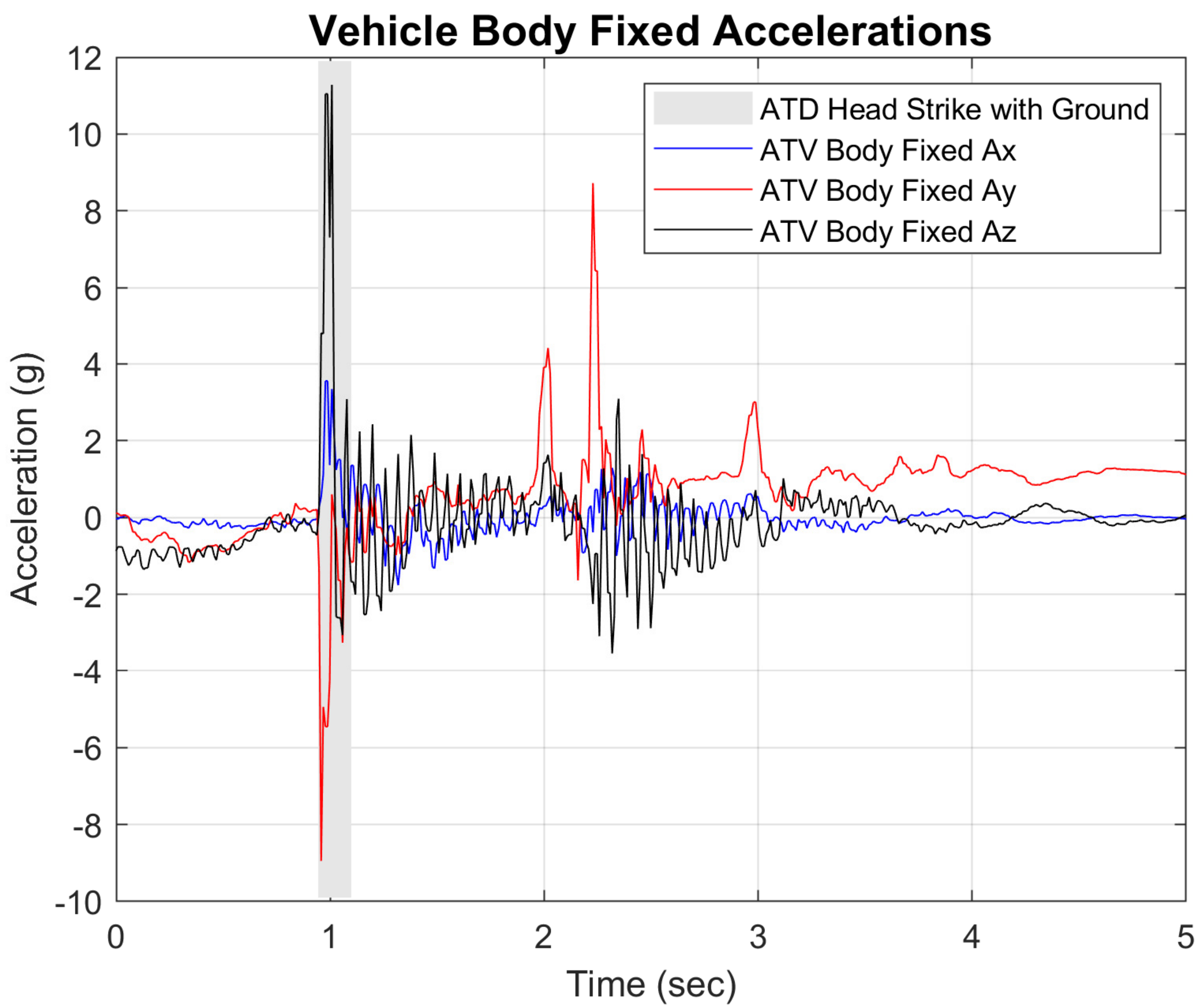
Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD



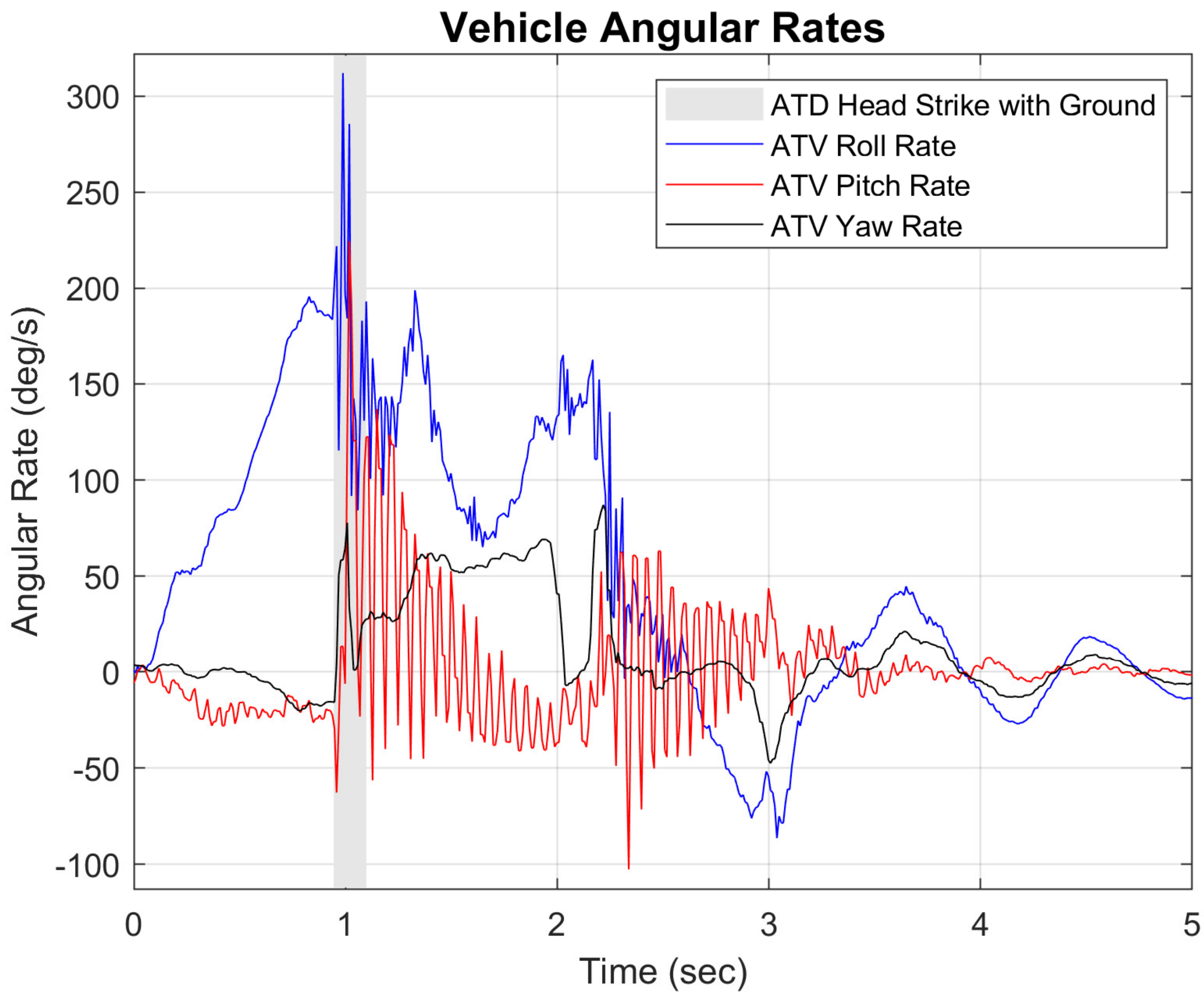
Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD



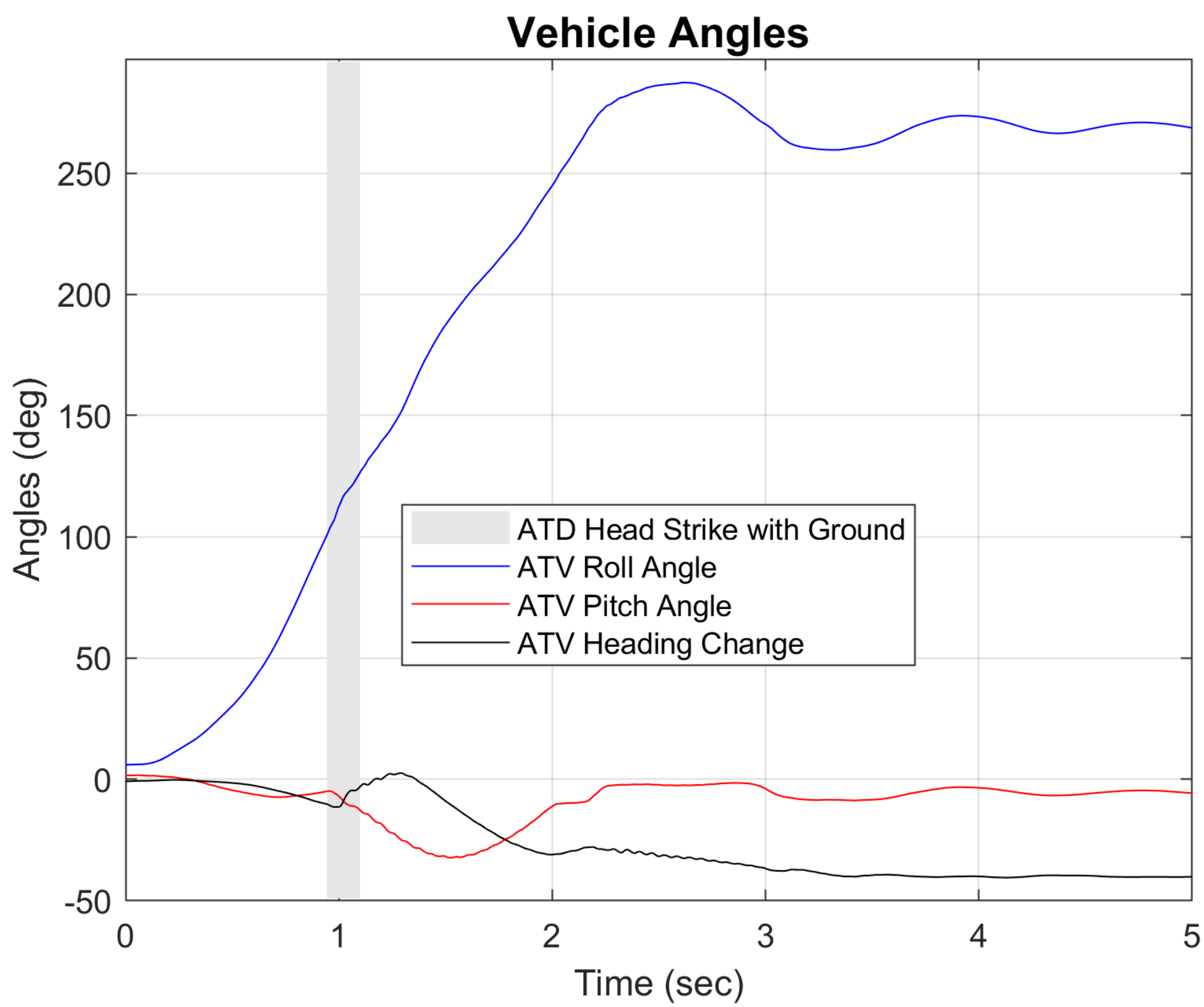
Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD



Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD



Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD



Vehicle C - Sled Moderate Energy Rollover – POC #4 – Energy Absorbing OPD

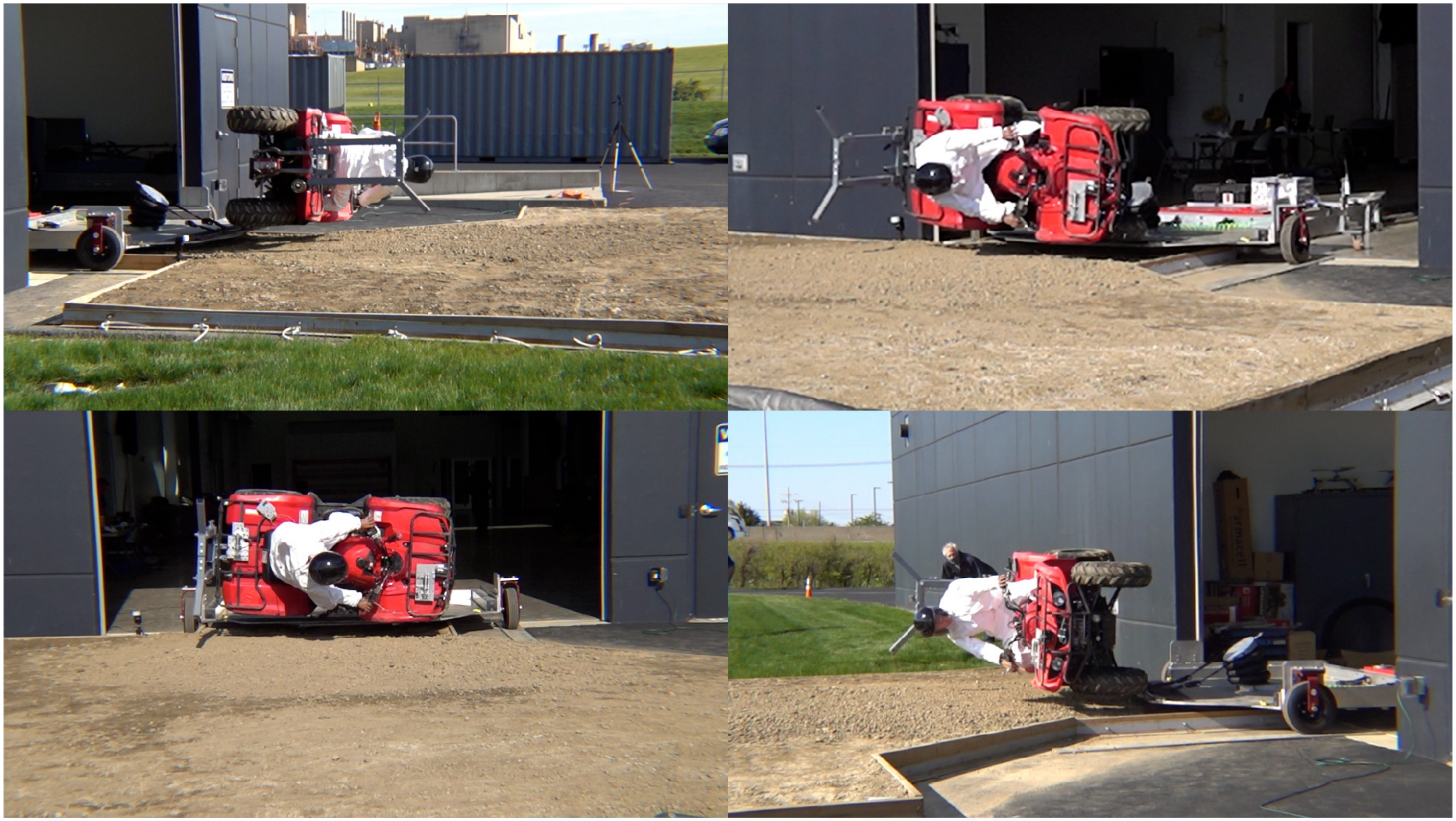
Roll Angle = 30° - Time = 0.41 sec

Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Roll Angle = 45° - Time = 0.52 sec

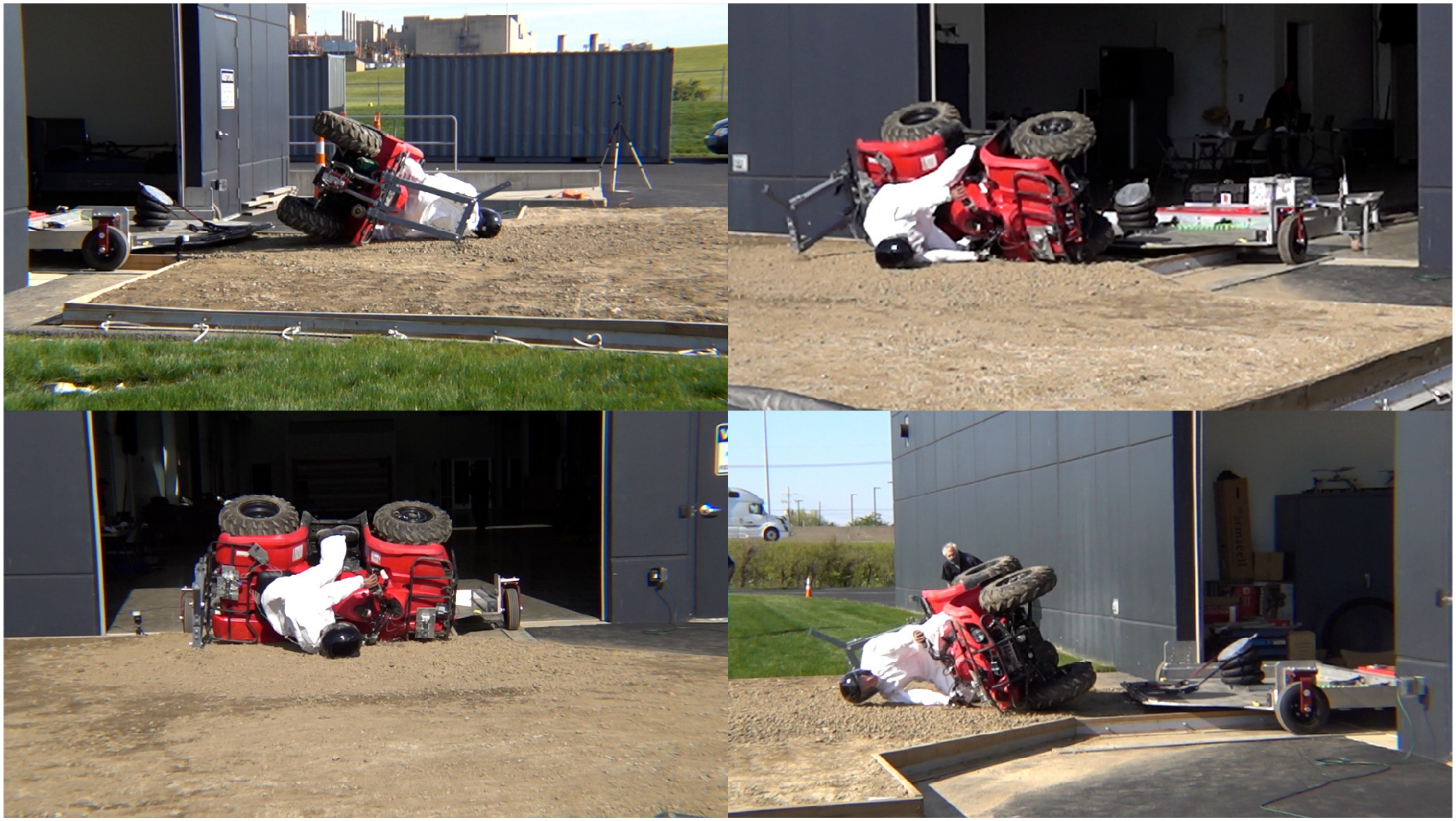
Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Roll Angle = 90° - Time = 0.74 sec



Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

ATD Head Strike - Time = 0.86 sec



Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Max Roll Angle = 167.6° - Time = 1.75 sec

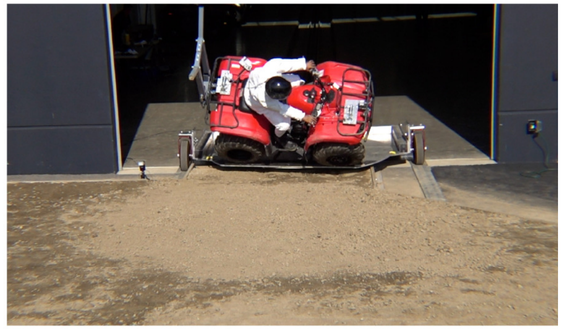
Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

End of Run - Roll Angle = 98.7°

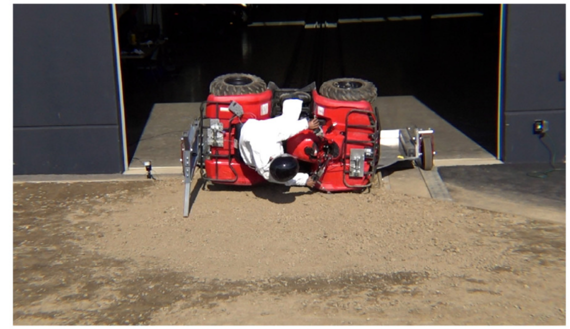
Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

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

Drone Camera - Roll Angle = 45° - Time = 0.52 sec



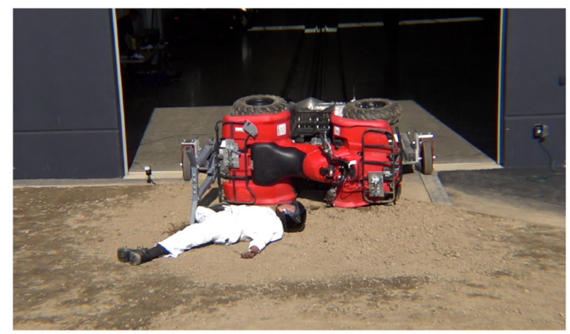
Drone Camera - Roll Angle = 90° - Time = 0.74 sec



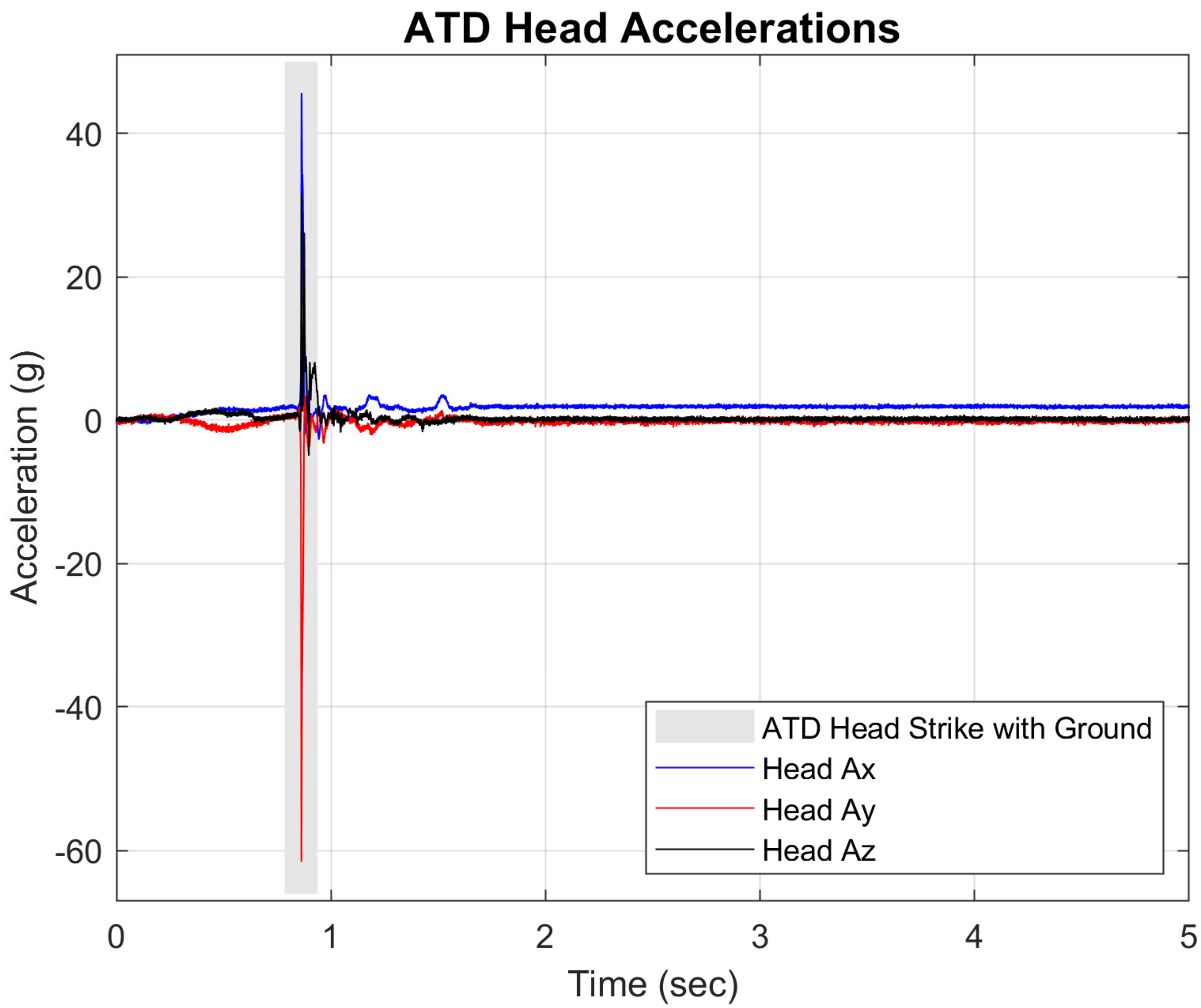
Drone Camera - ATD Head Strike - Time = 0.82 sec

Drone Camera - Max Angle = 167.6° - Time = 1.75 sec

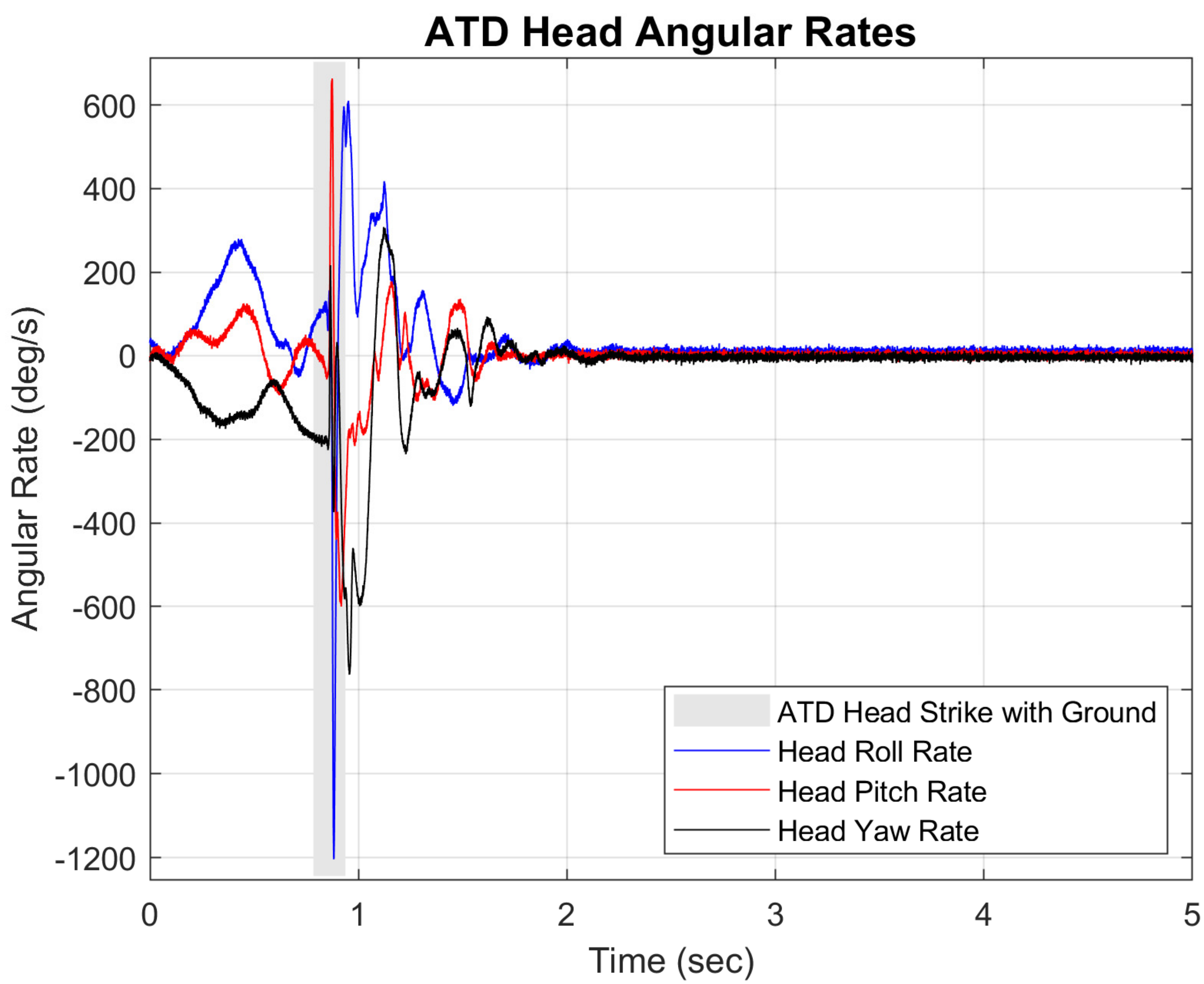
Drone Camera - End of Run - Roll Angle = 98.7°



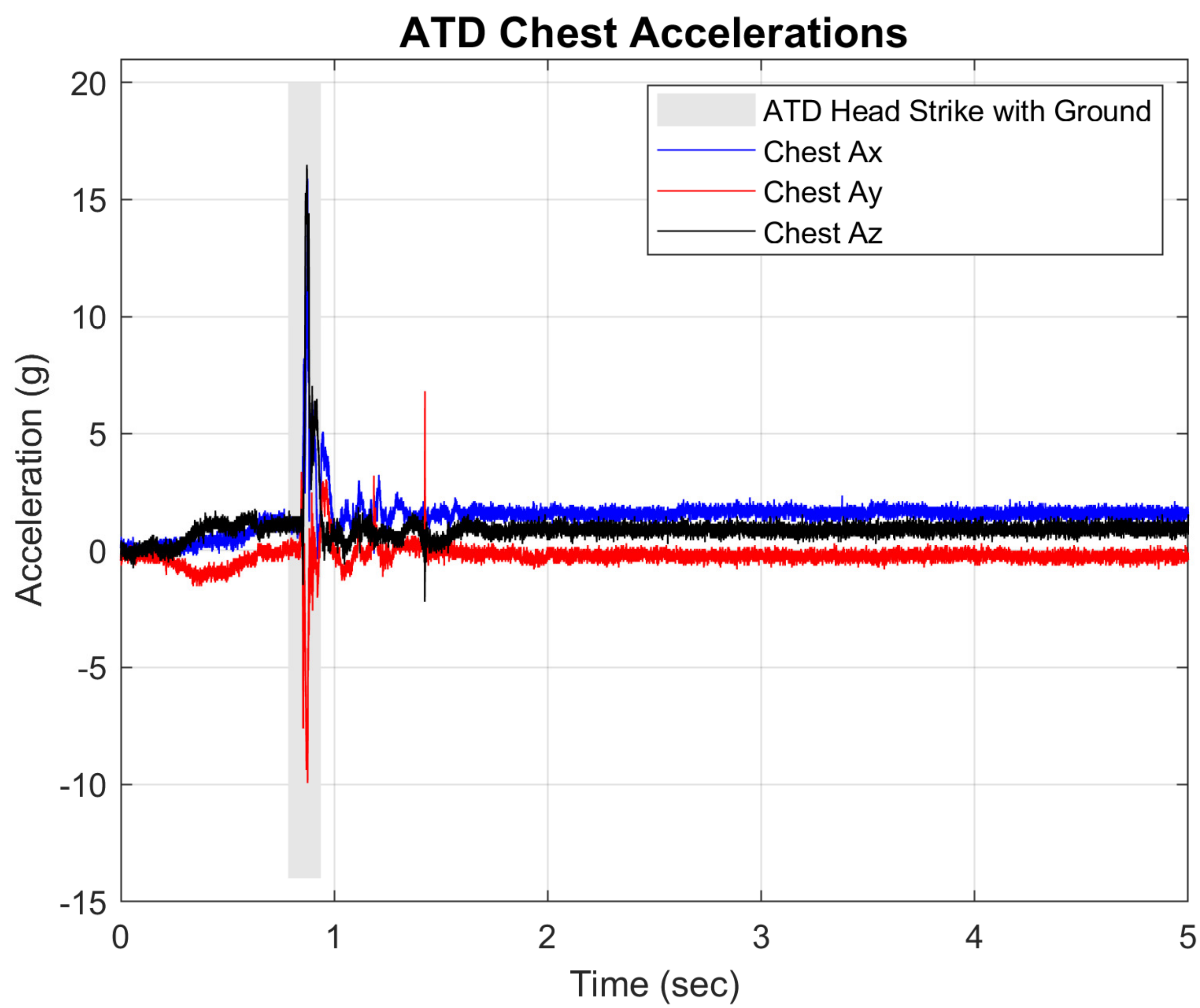
Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



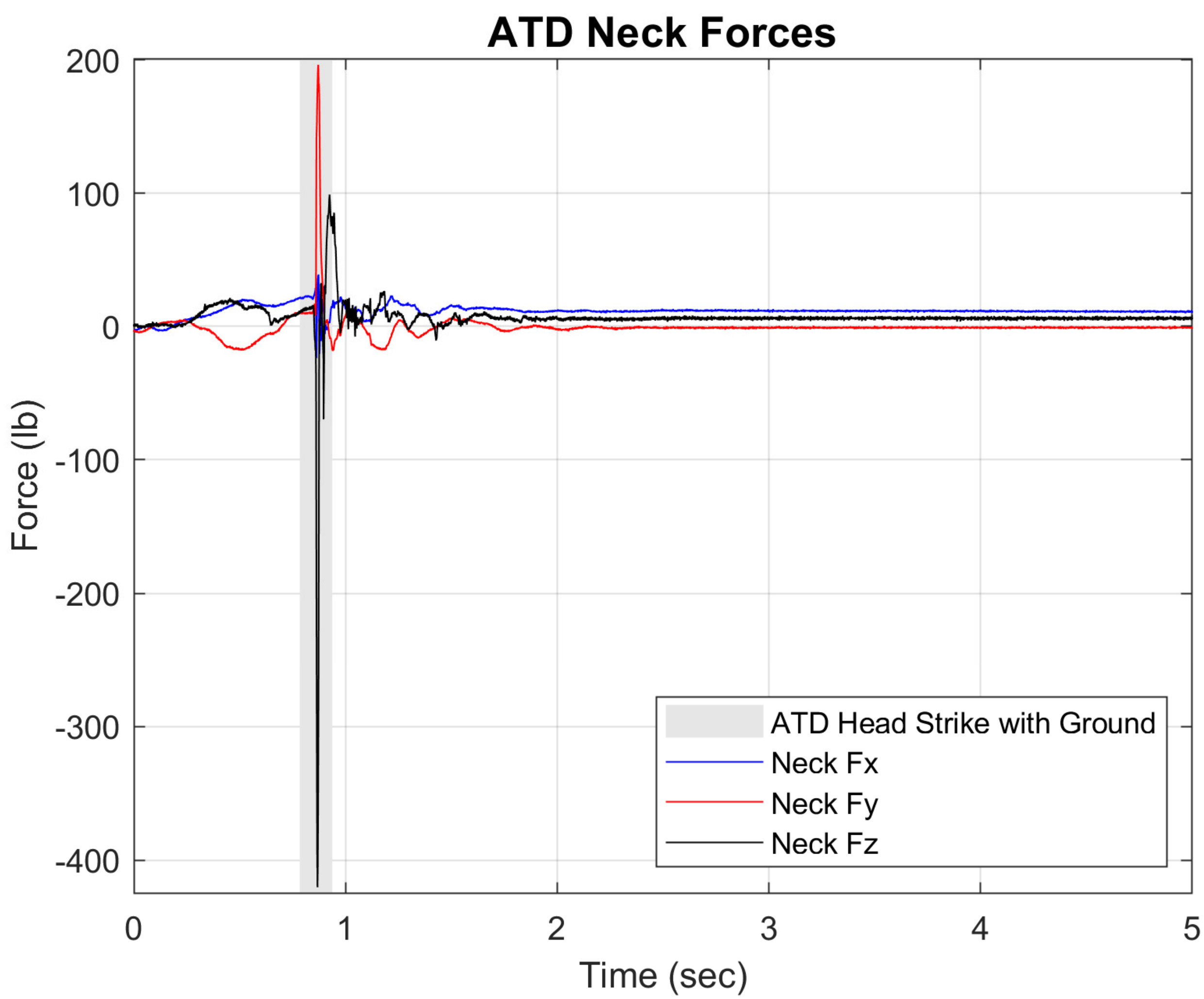
Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



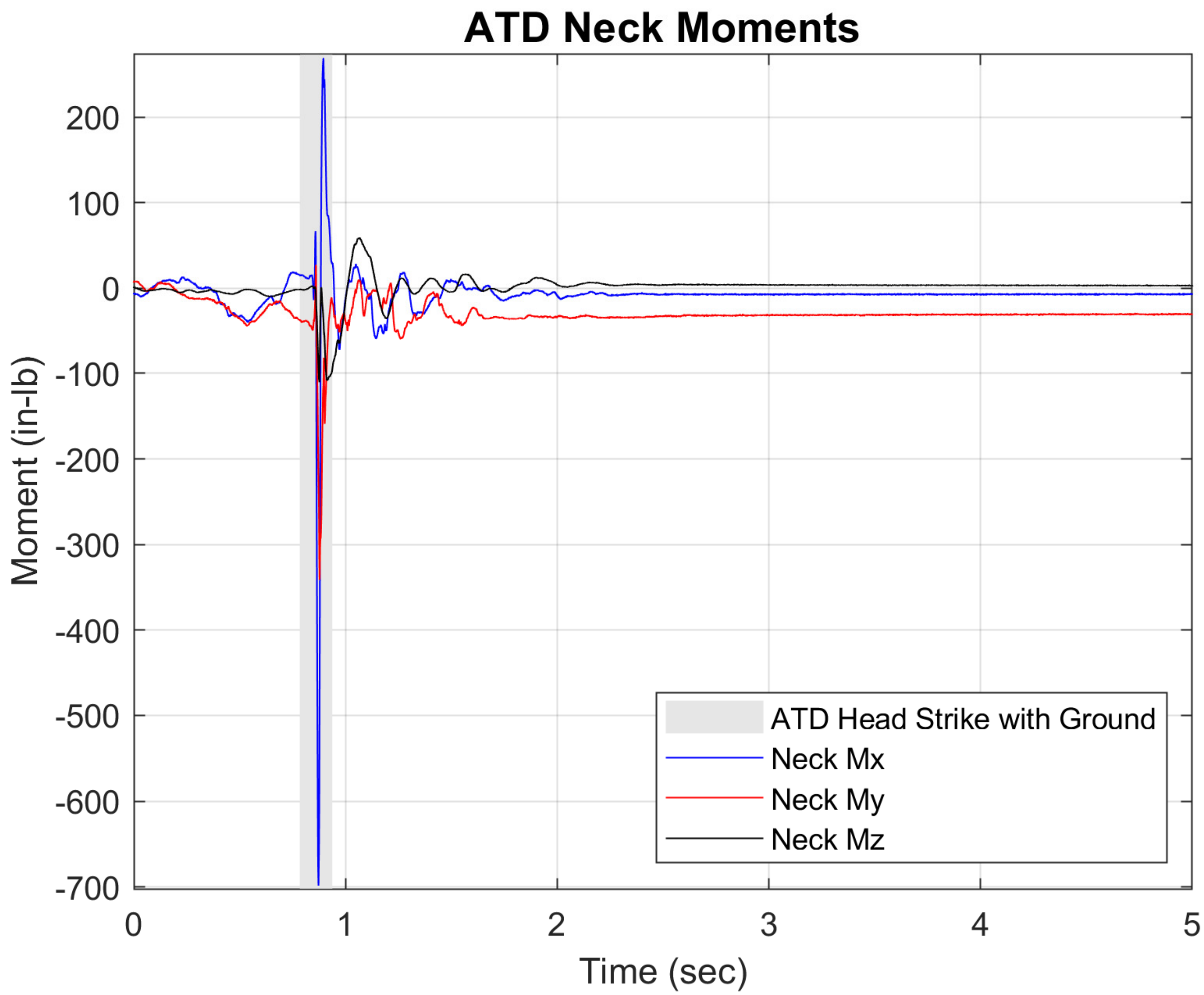
Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



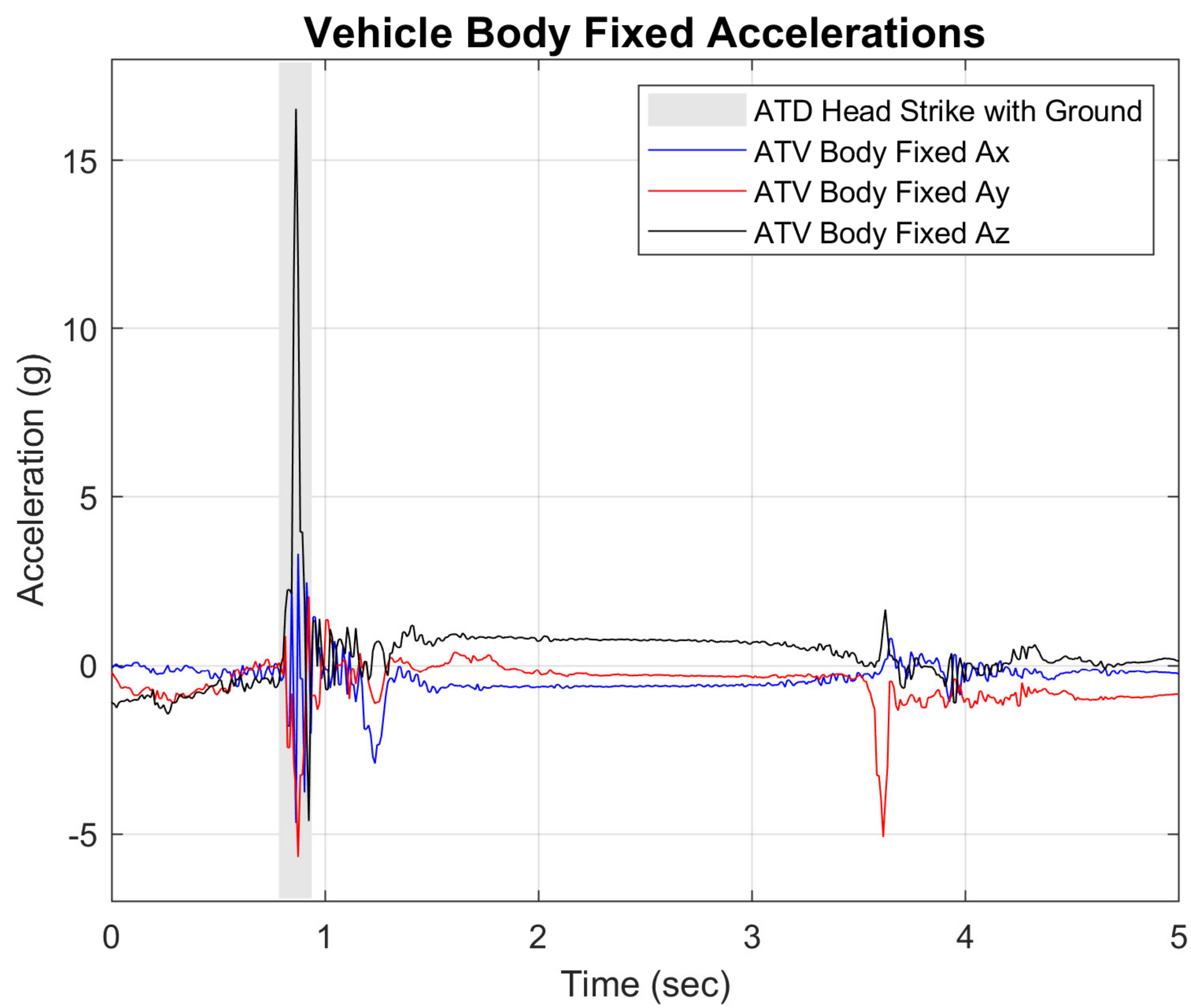
Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



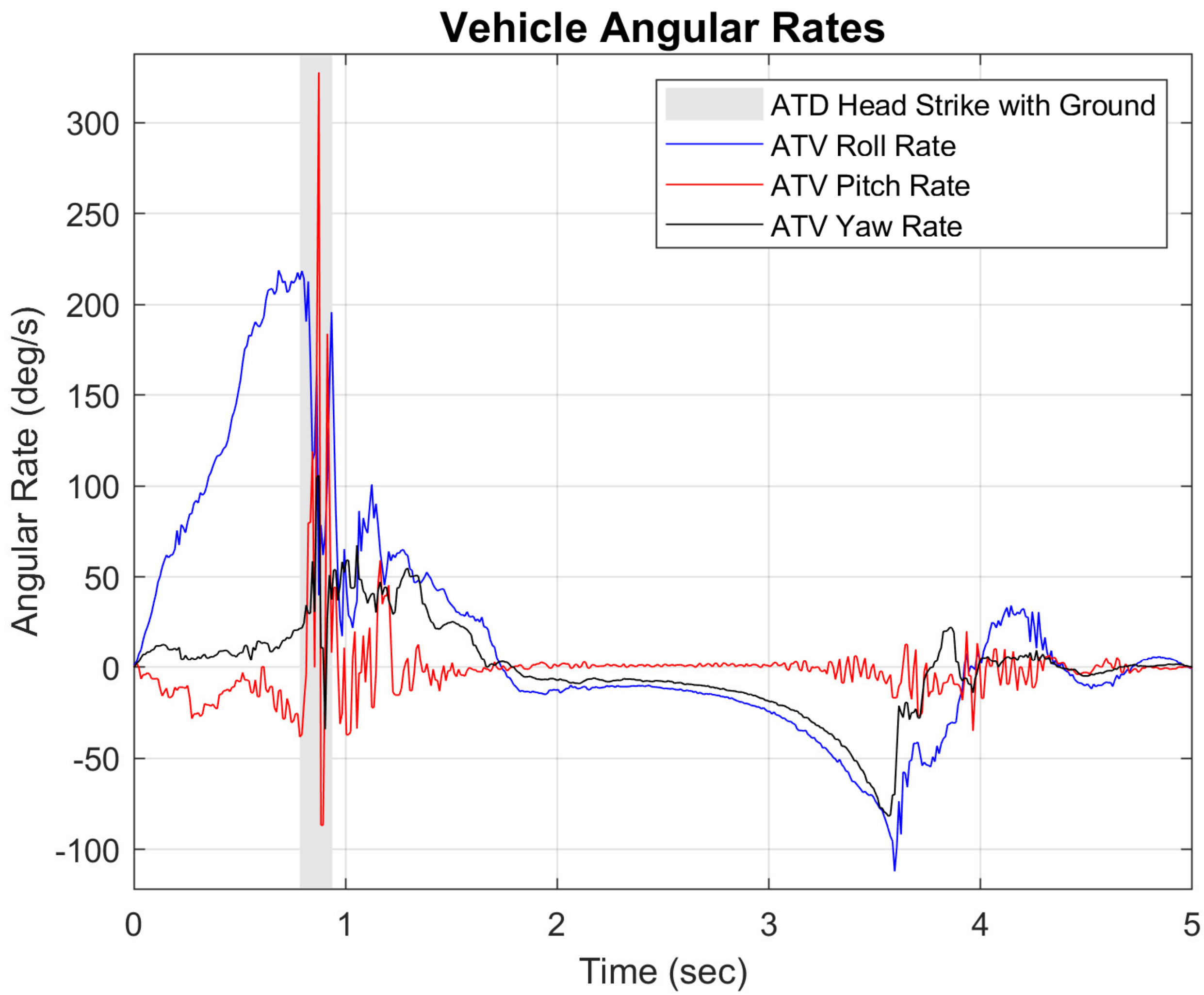
Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



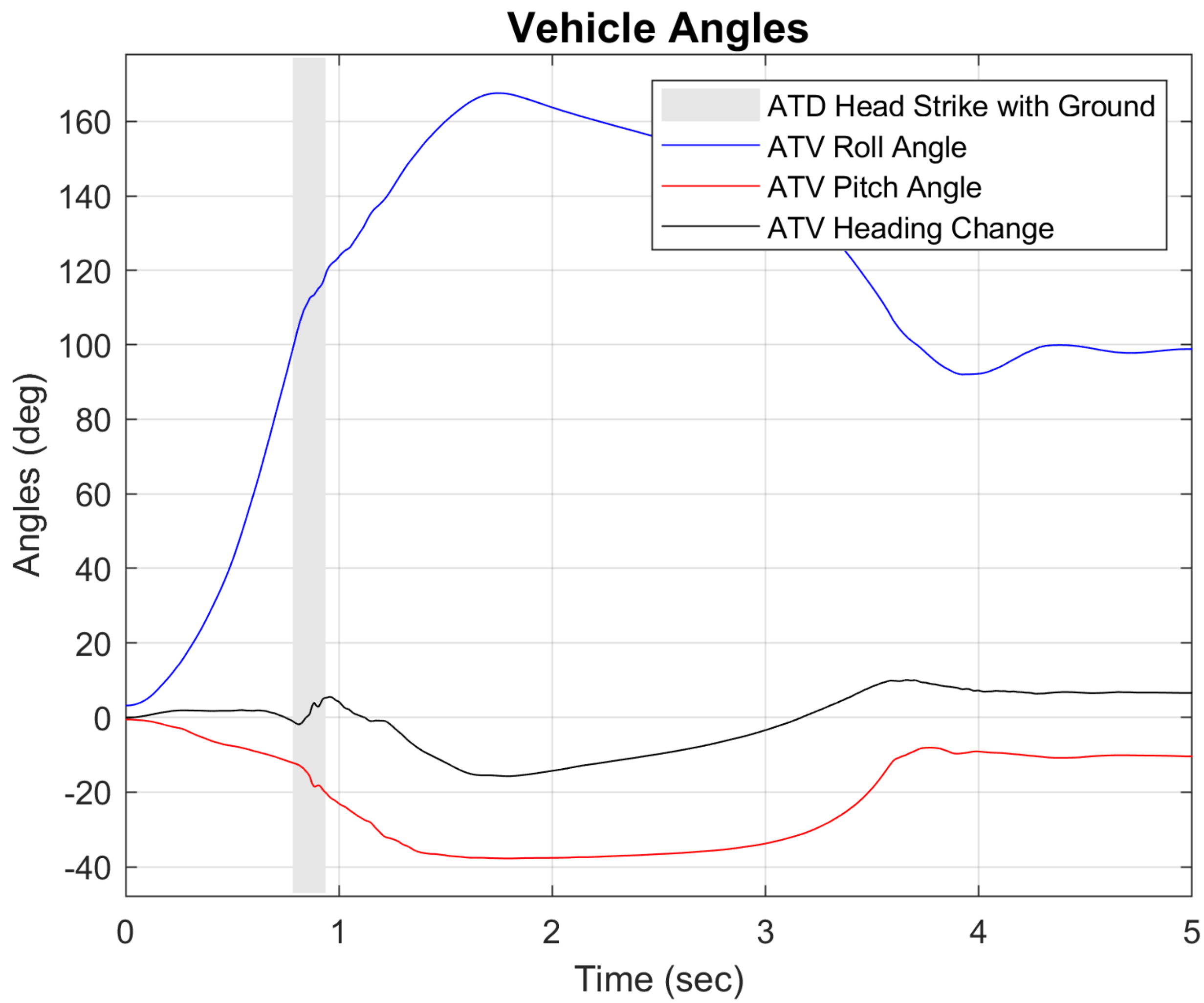
Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



Vehicle A - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

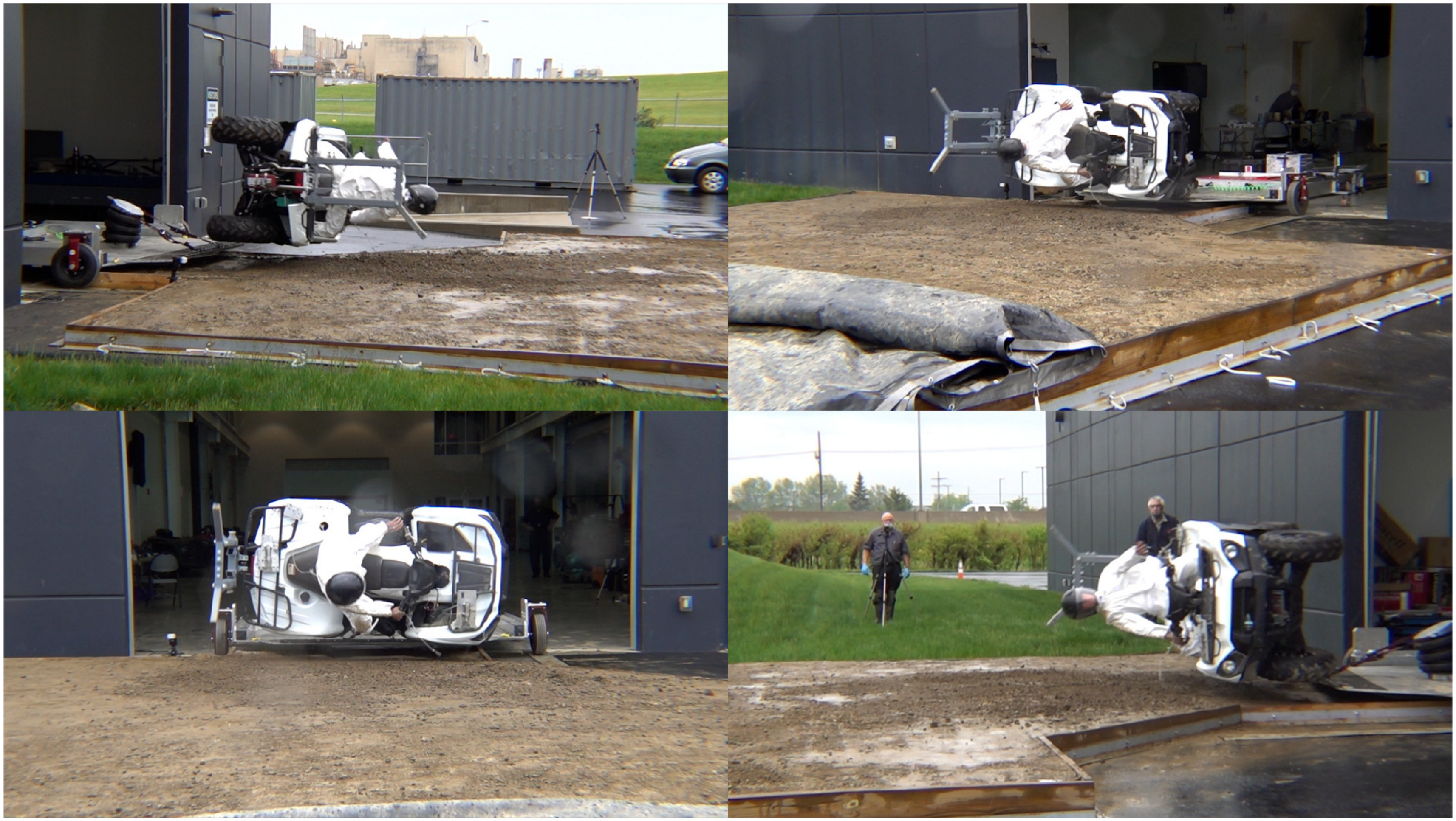
Roll Angle = 30° - Time = 0.36 sec

Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Roll Angle = 45° - Time = 0.48 sec

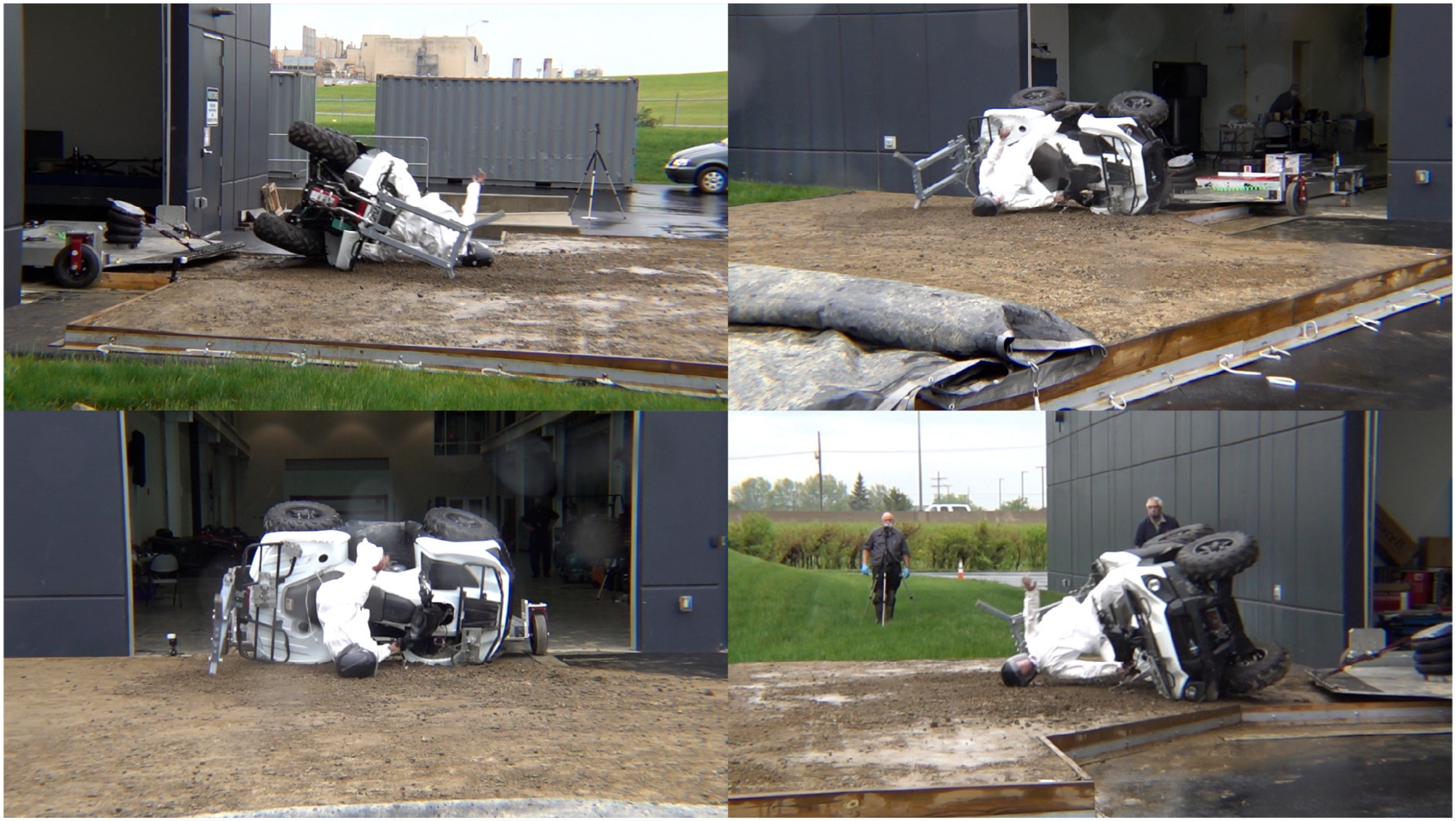
Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Roll Angle = 90° - Time = 0.72 sec



Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

ATD Head Strike - Time = 0.82 sec



Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Roll Angle = 180° - Time = 1.45 sec

Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Max Roll Angle = 186.0° - Time = 1.68 sec

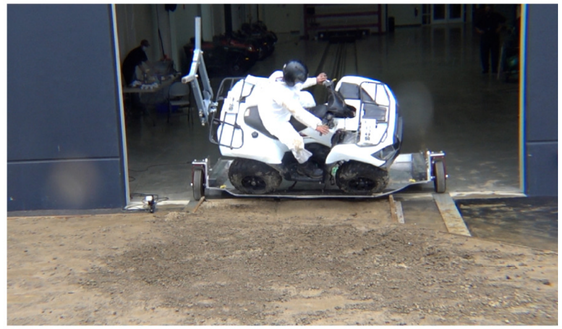
Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

End of Run - Roll Angle = 163.5°

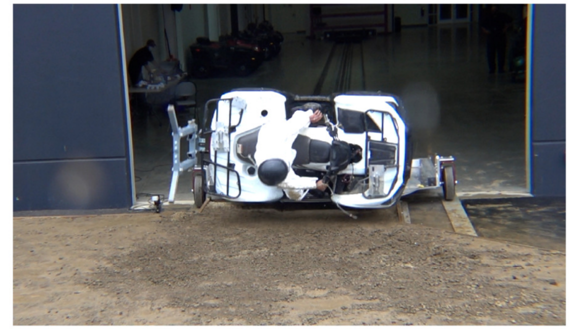
Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Drone Camera - Roll Angle = 30° - Time = 0.36 sec

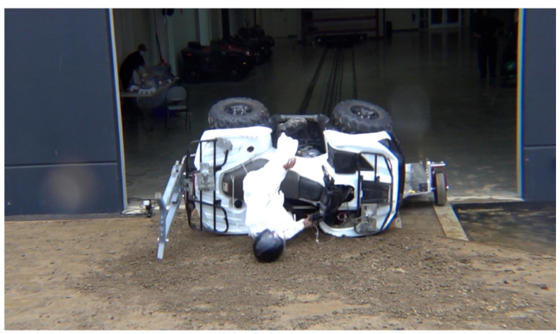
Drone Camera - Roll Angle = 45° - Time = 0.48 sec



Drone Camera - Roll Angle = 90° - Time = 0.72 sec



Drone Camera - ATD Head Strike - Time = 0.82 sec



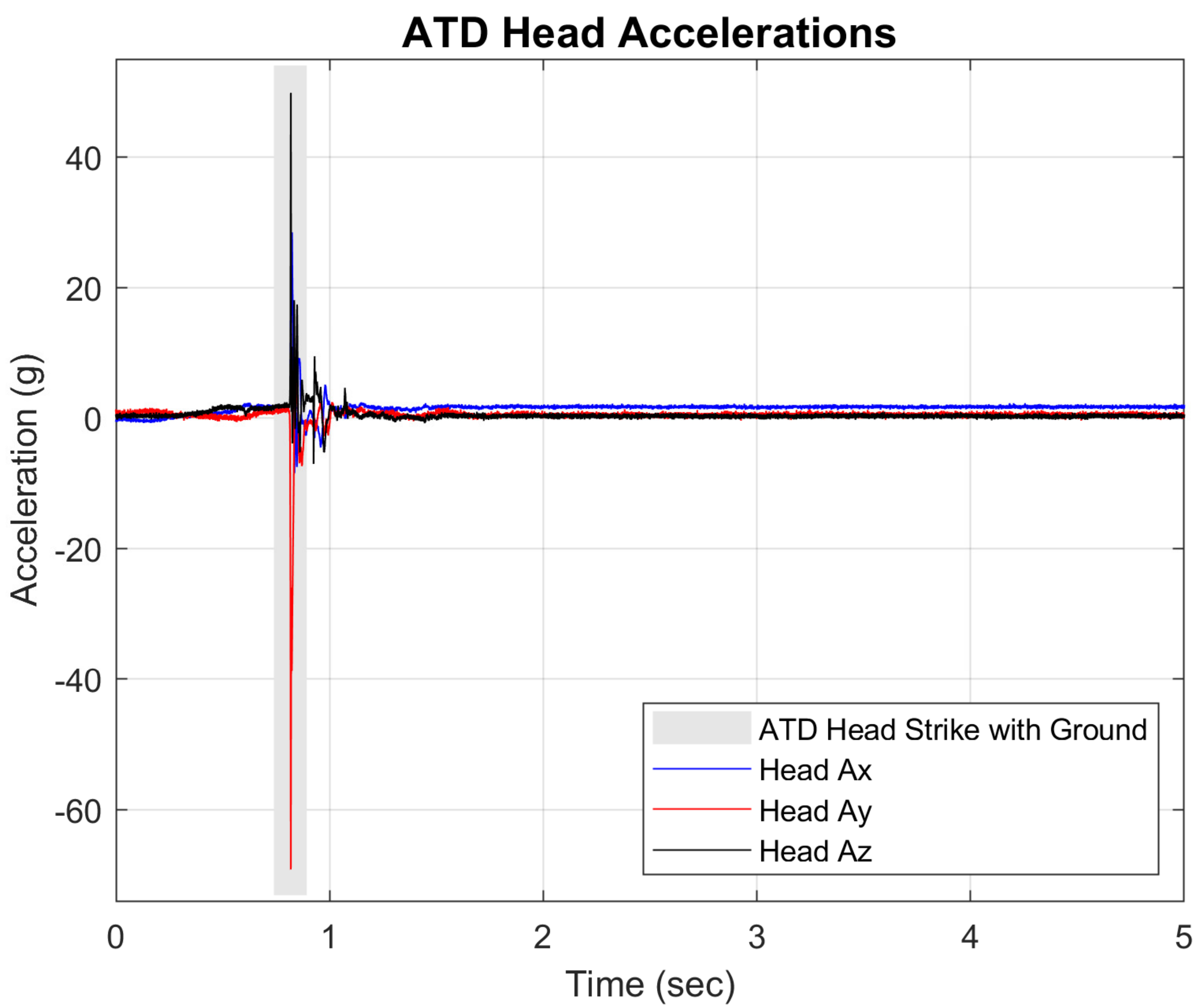
Drone Camera - Roll Angle = 180° - Time = 1.45 sec

Drone Camera - Max Angle = 186.0° - Time = 1.68 sec

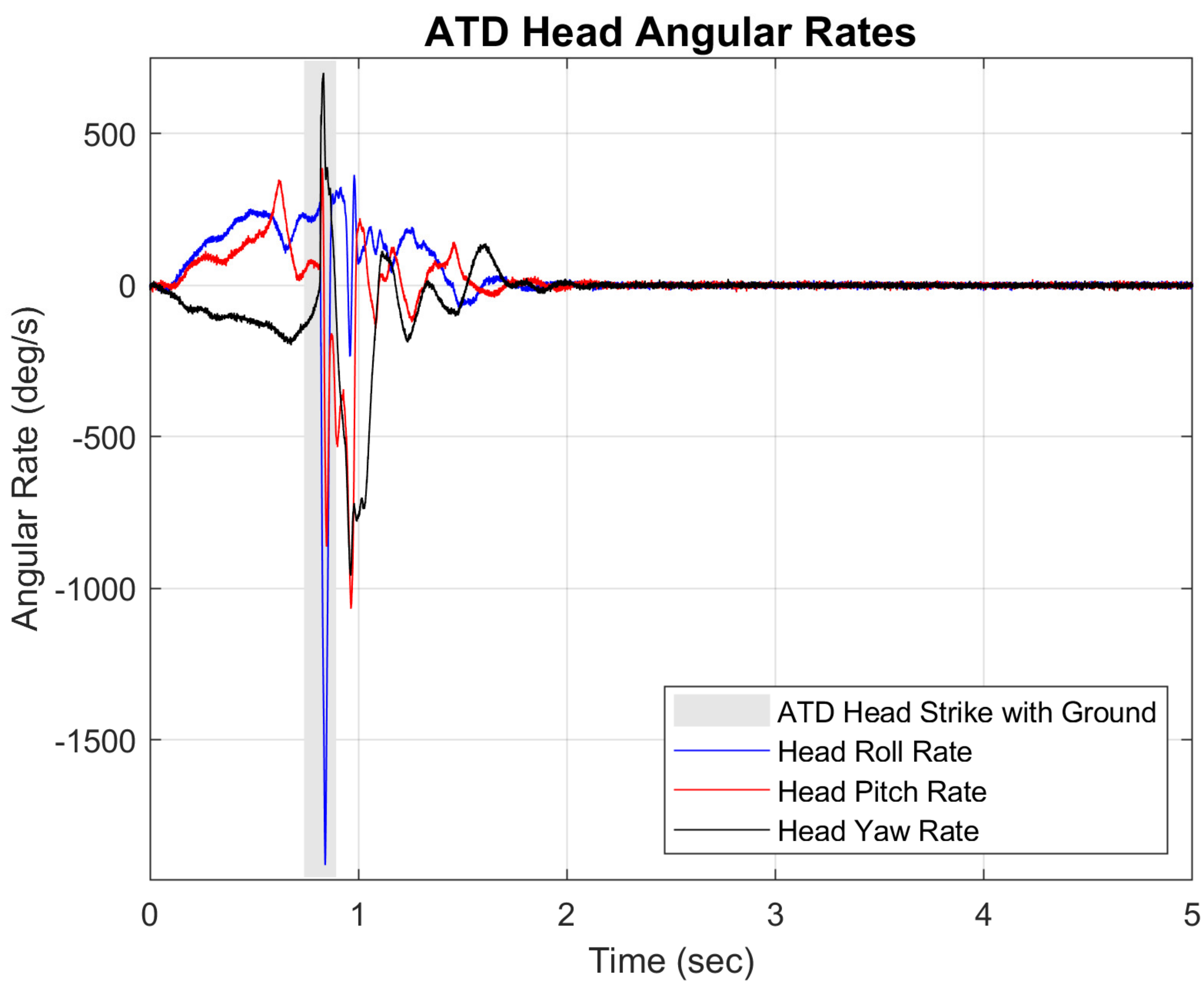
Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Drone Camera - End of Run - Roll Angle = 163.5°

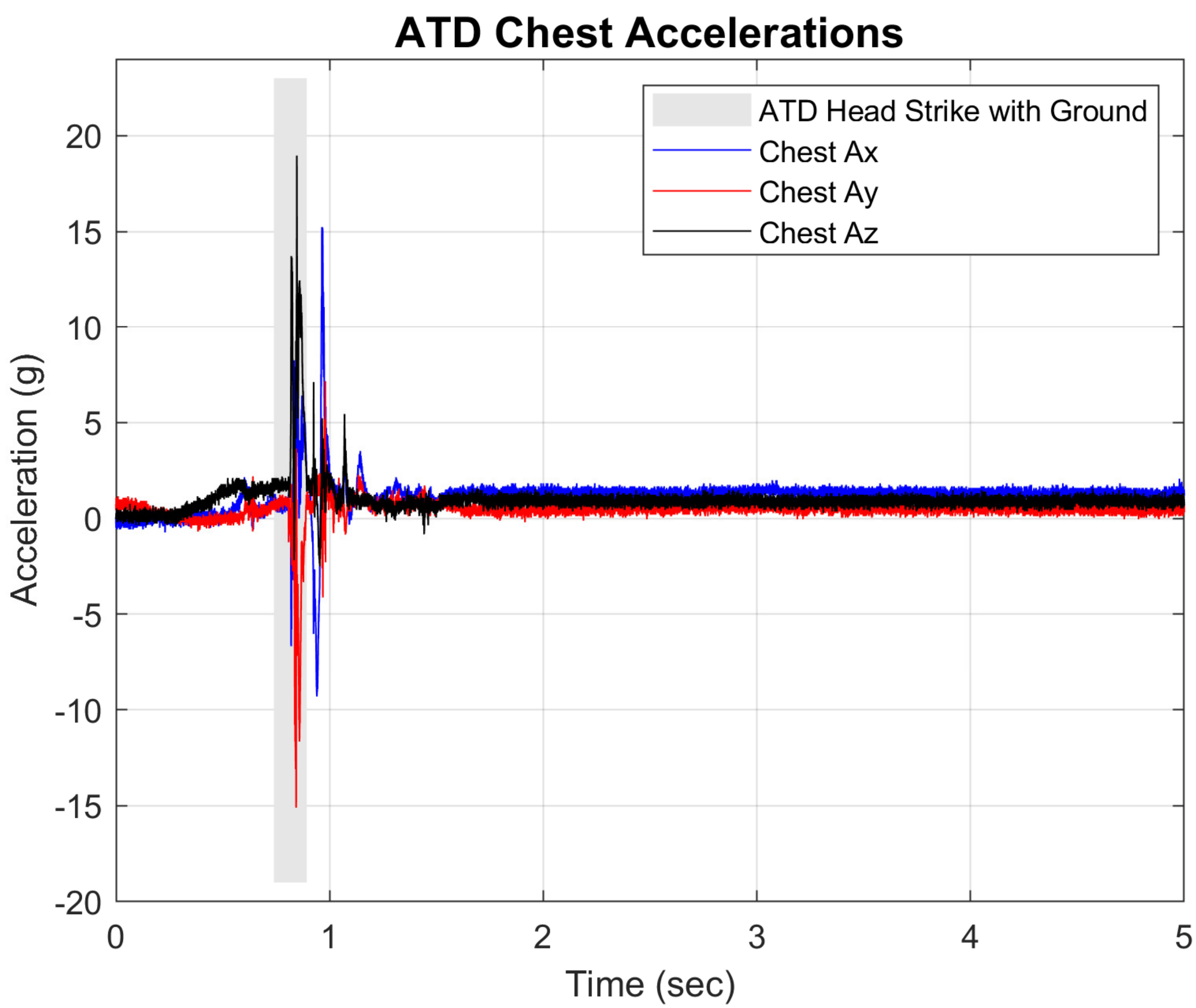
Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



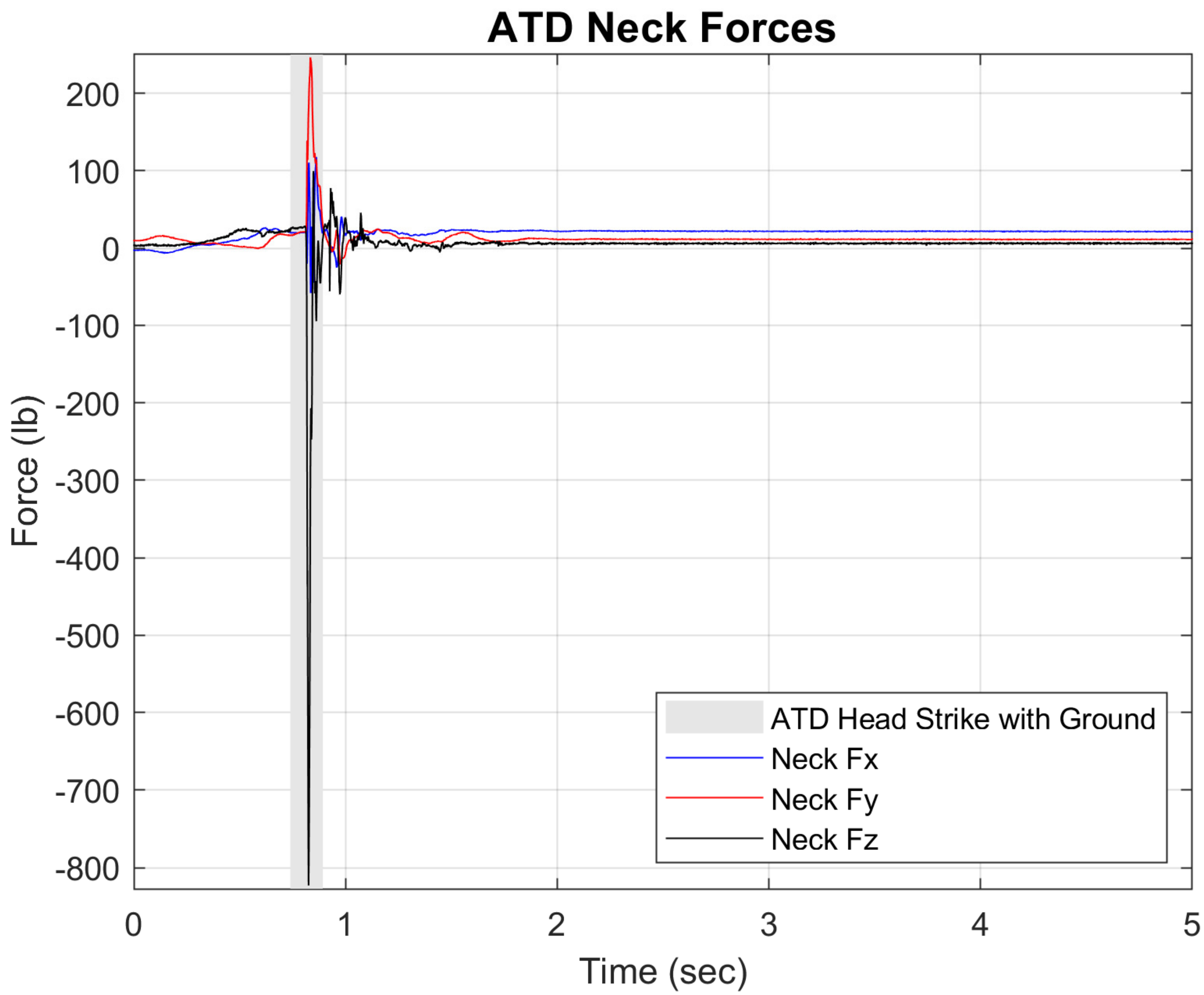
Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



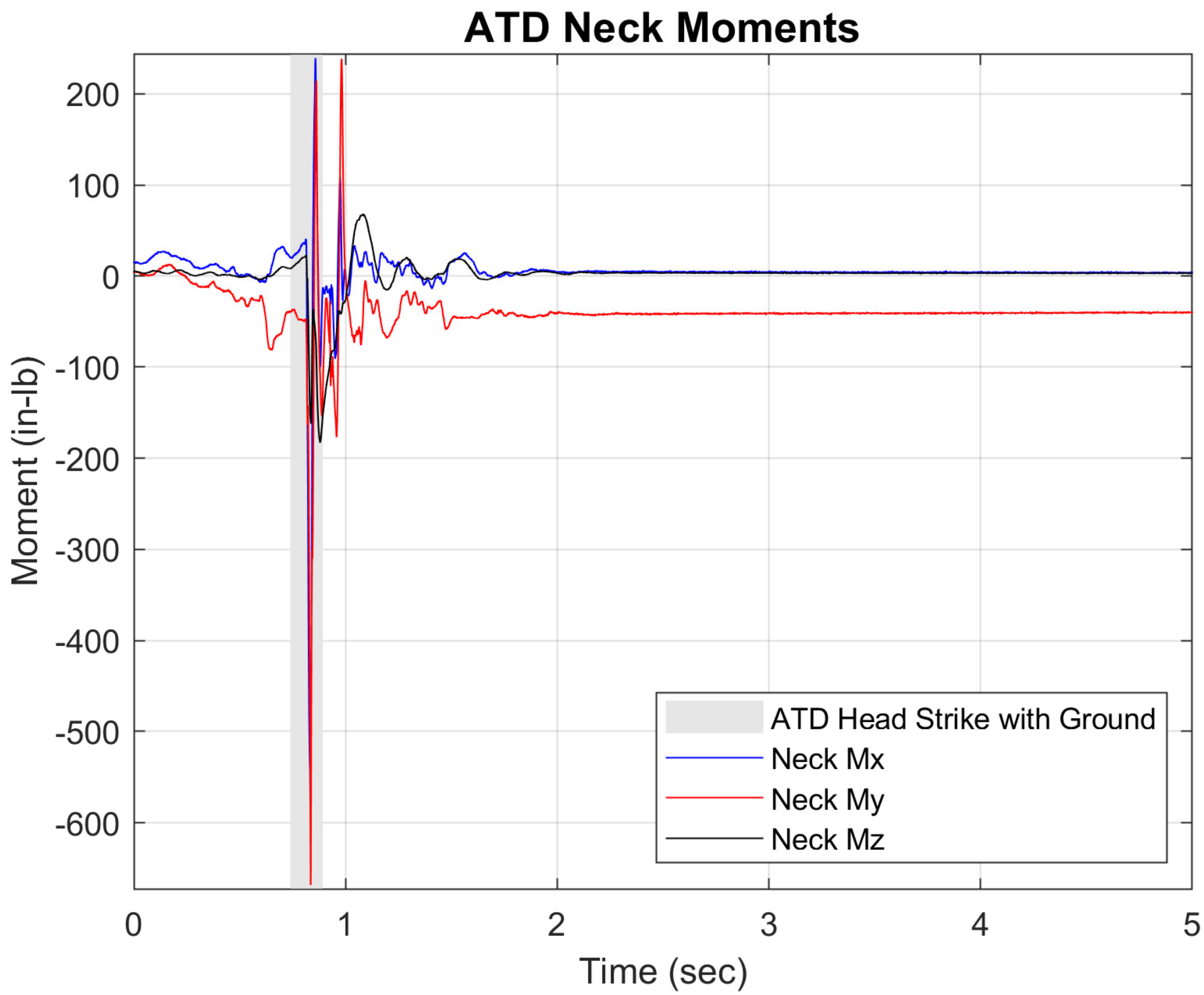
Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



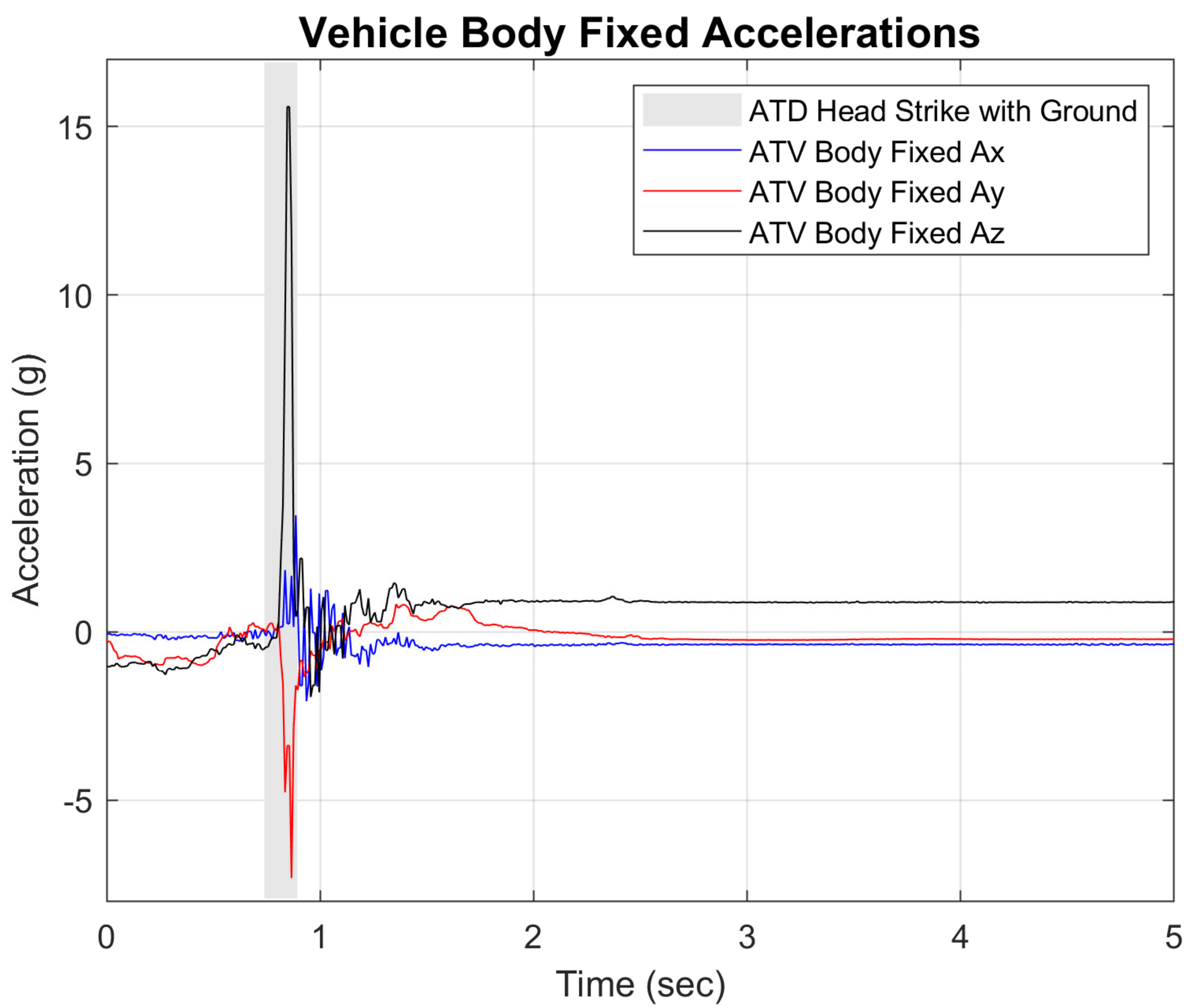
Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



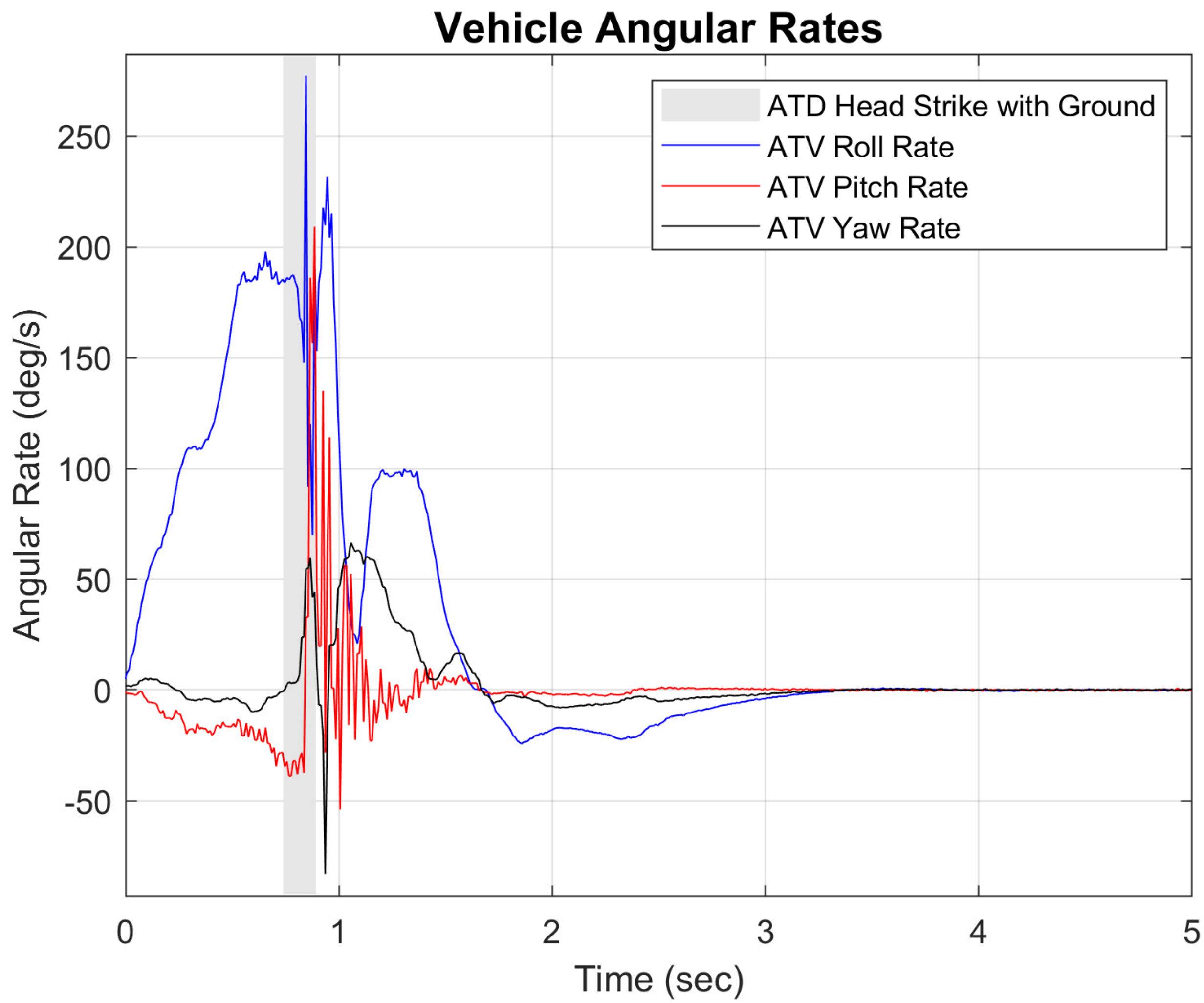
Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



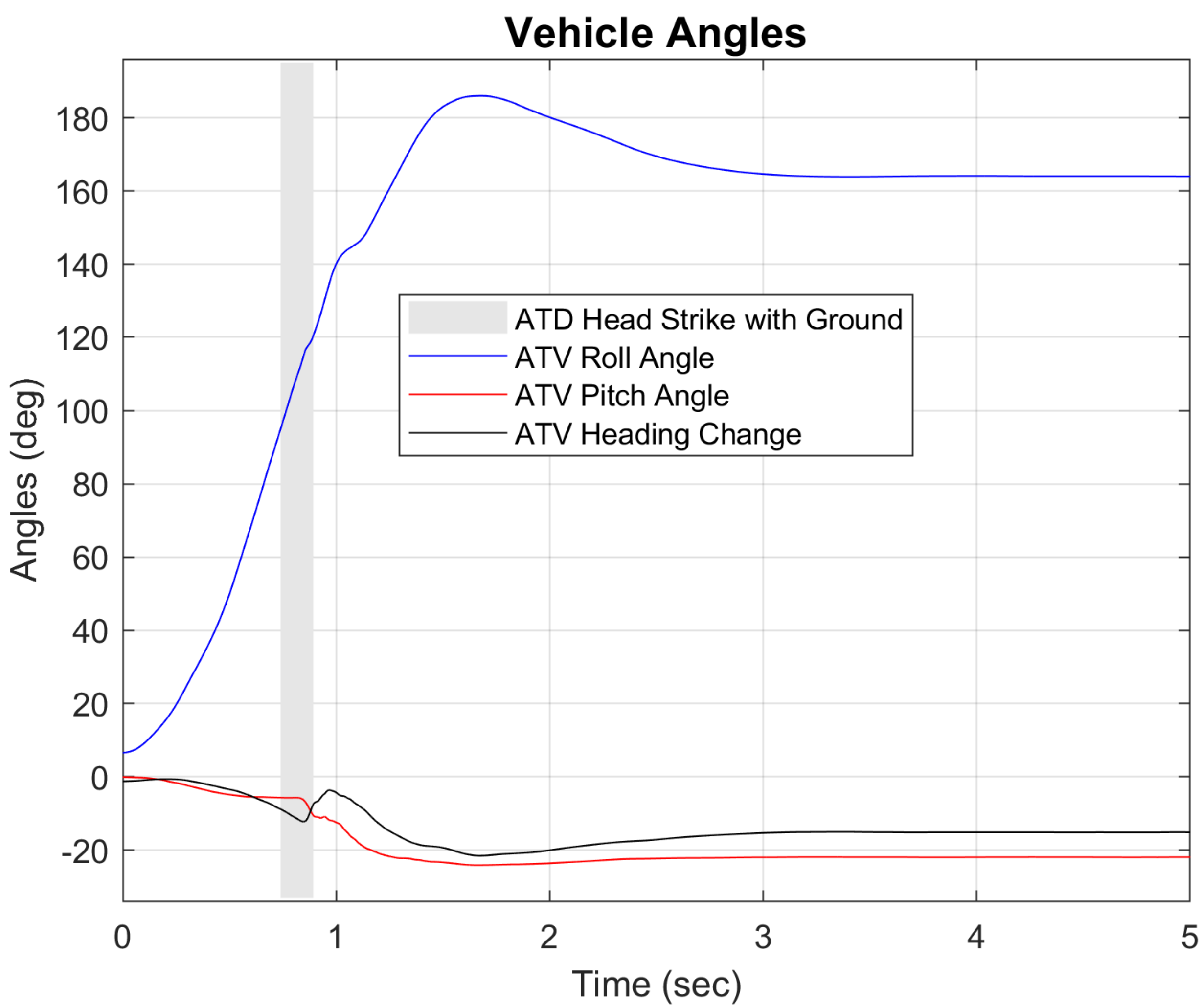
Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



Vehicle G - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

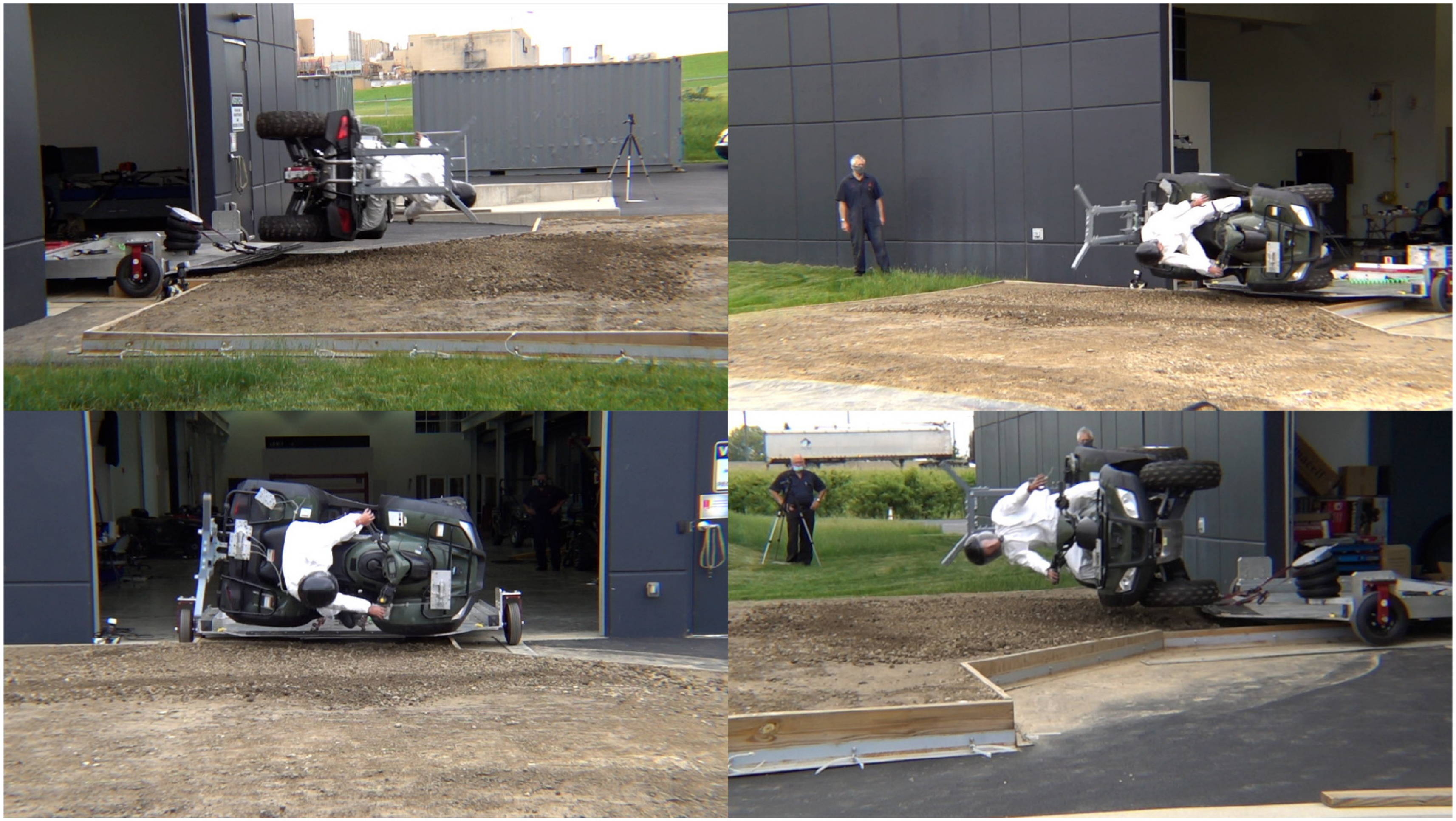
Roll Angle = 30° - Time = 0.41 sec

Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Roll Angle = 45° - Time = 0.53 sec

Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Roll Angle = 90° - Time = 0.76 sec



Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

ATD Head Strike - Time = 0.86 sec

Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Max Roll Angle = 174.2° - Time = 1.62 sec

Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

End of Run - Roll Angle = 163.6°

Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

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

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

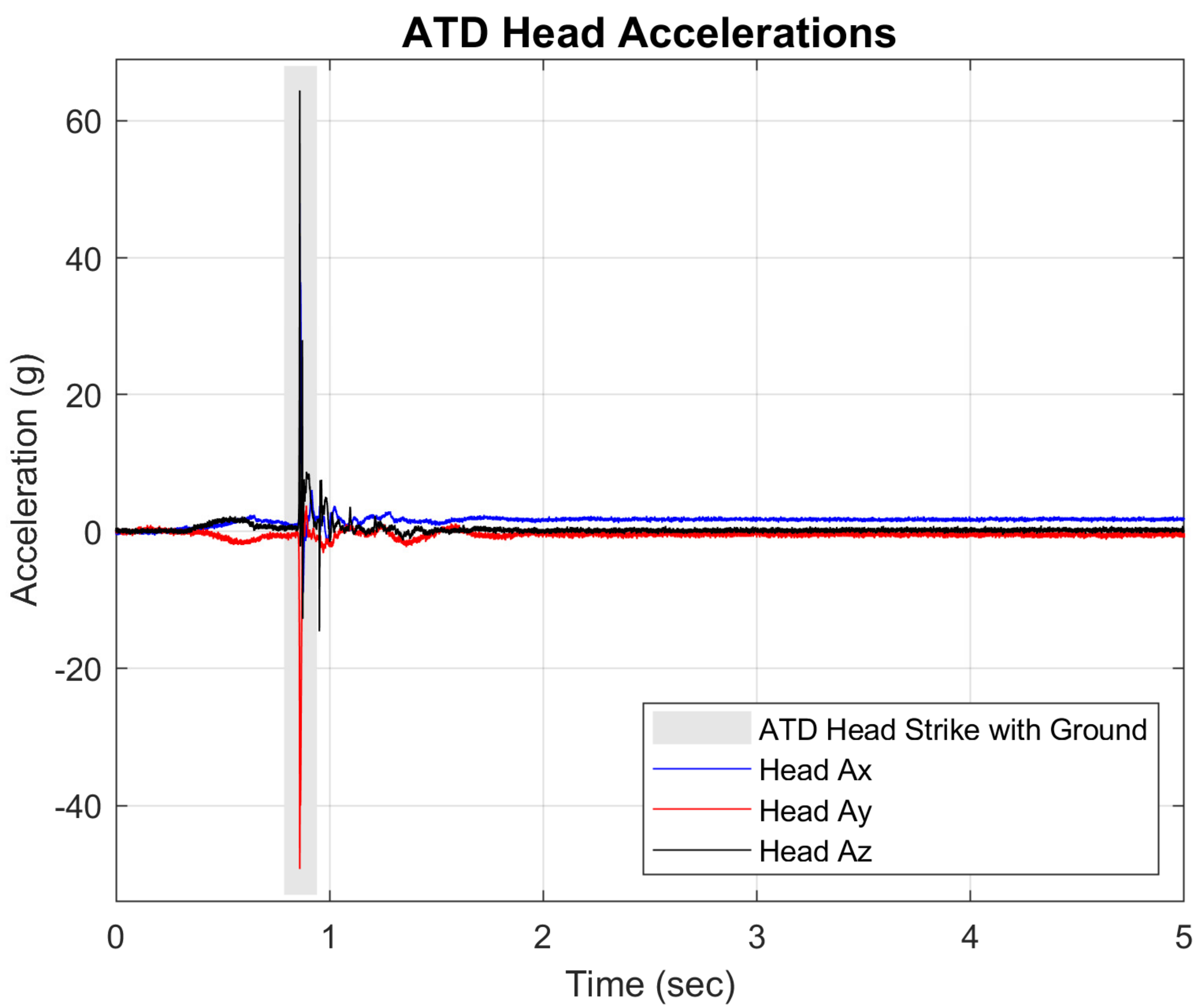
Drone Camera - Roll Angle = 90° - Time = 0.76 sec

Drone Camera - ATD Head Strike - Time = 0.86 sec

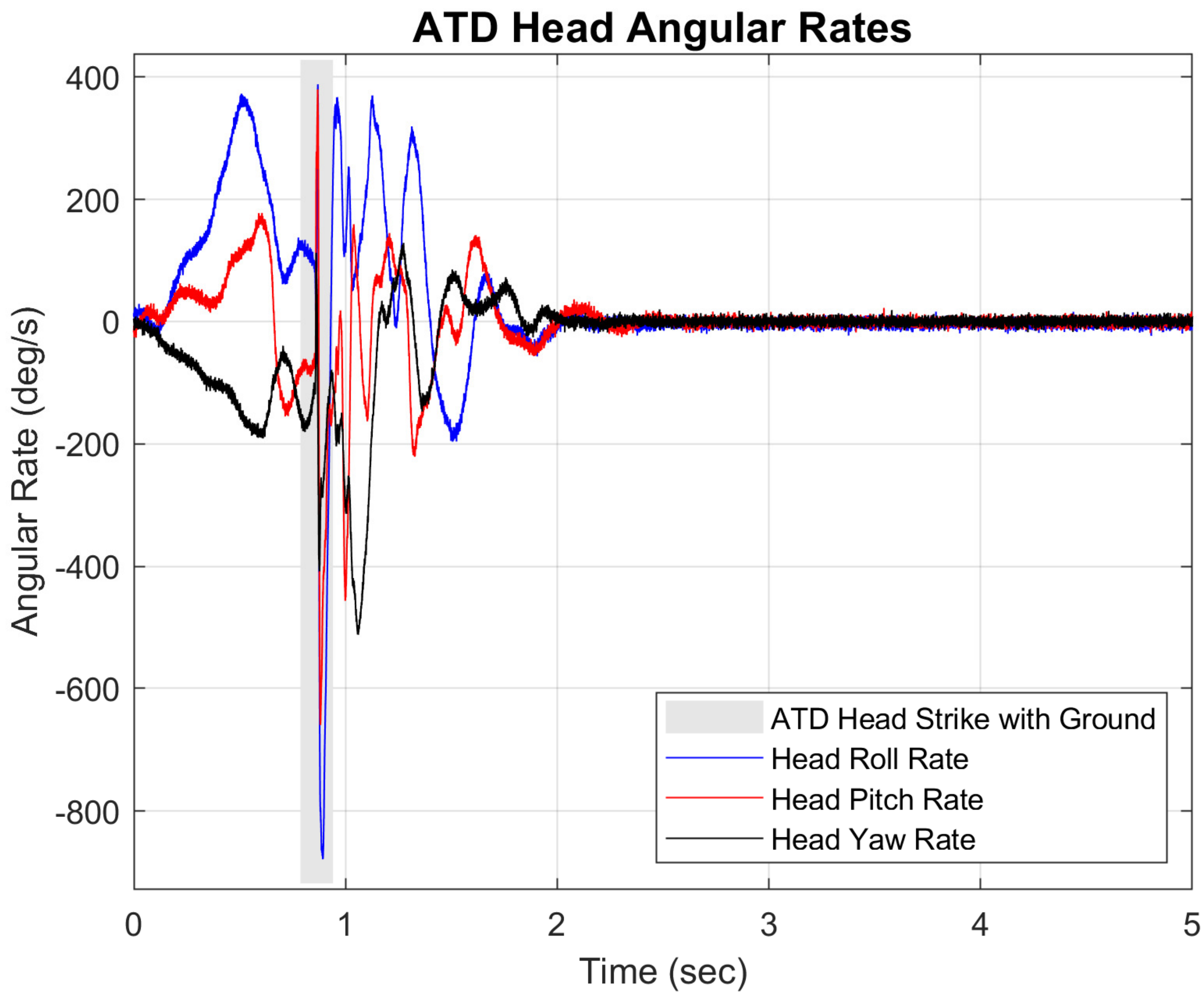
Drone Camera - Max Angle = 174.2° - Time = 1.62 sec

Drone Camera - End of Run - Roll Angle = 163.6°

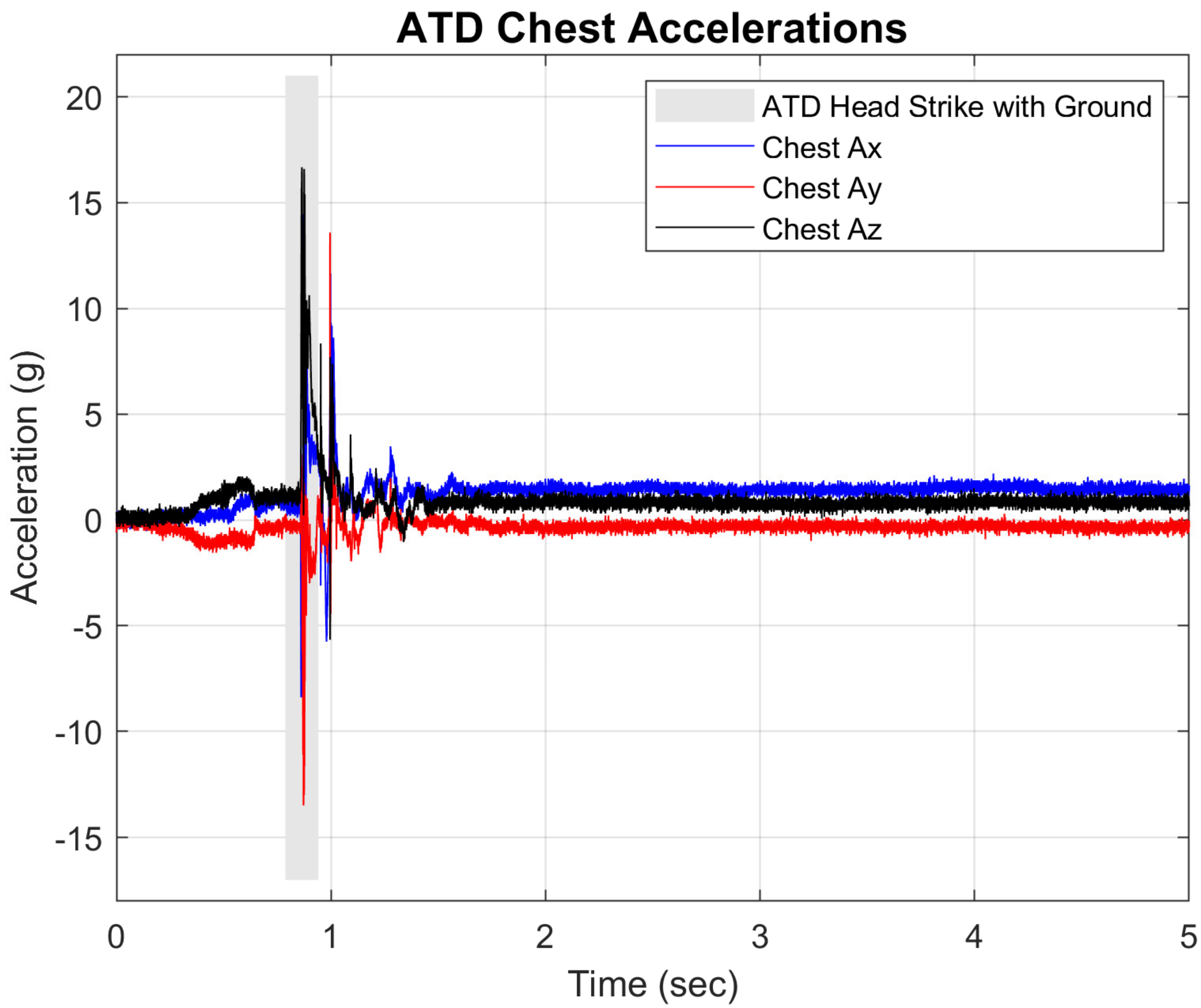
Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



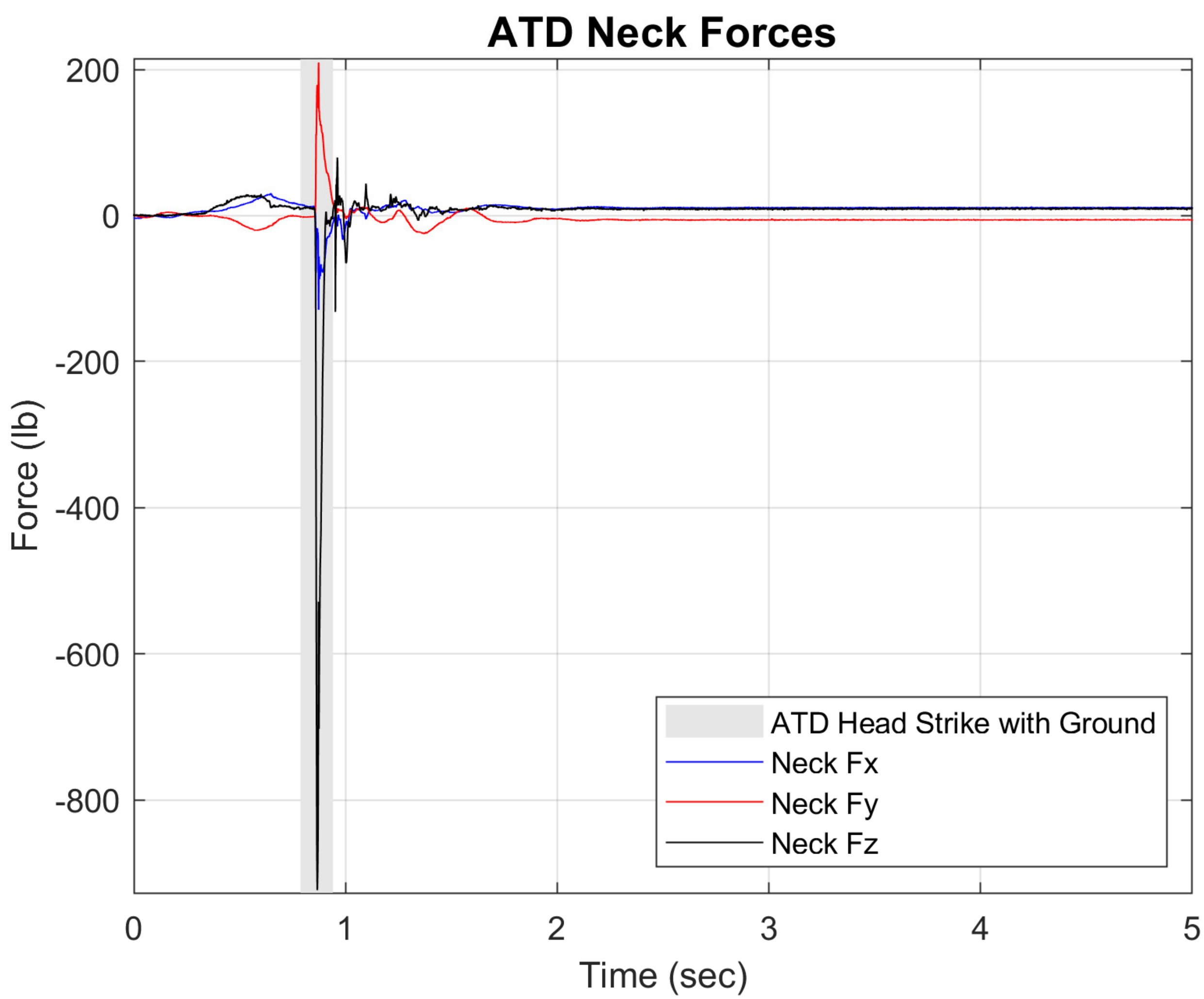
Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



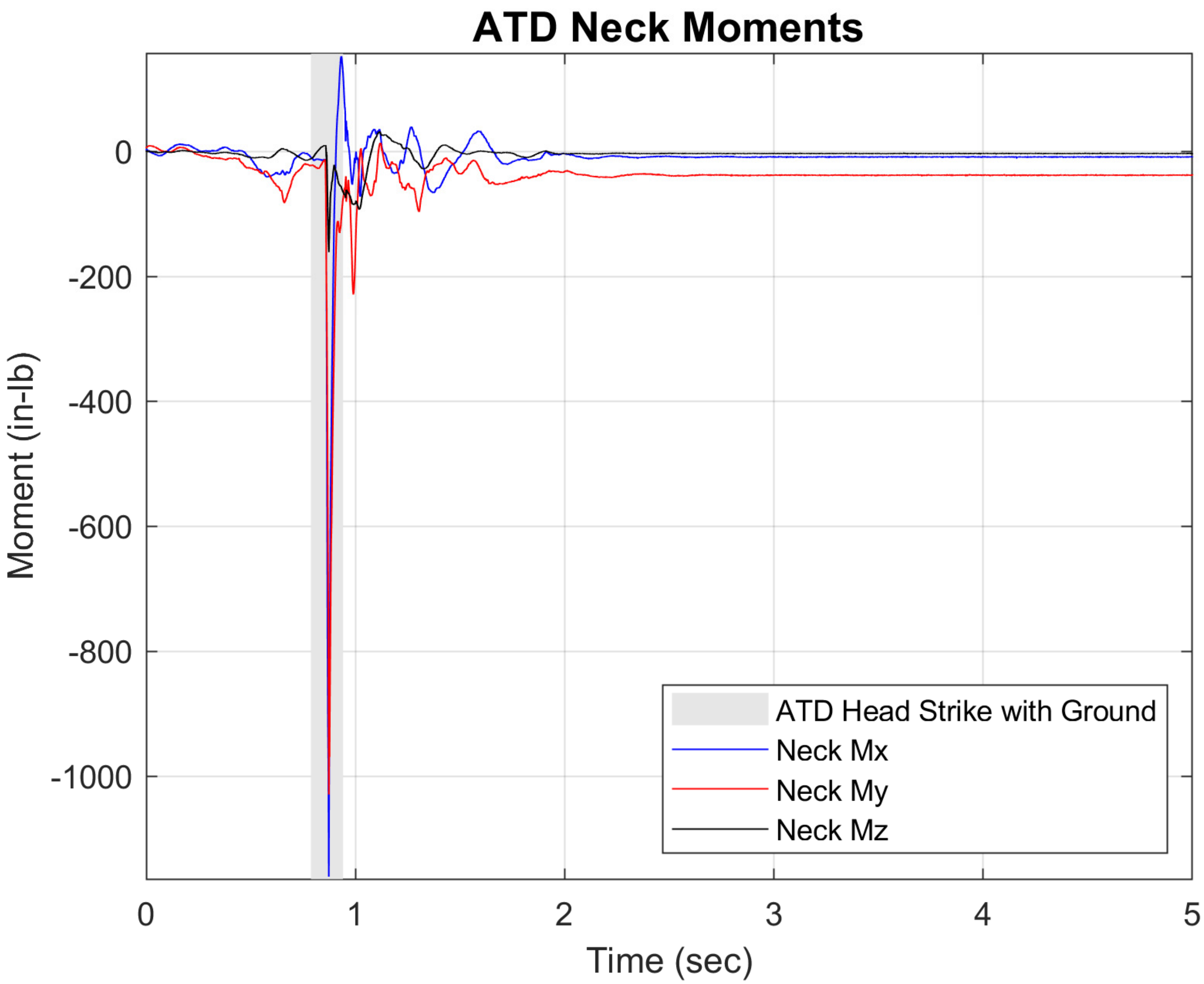
Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



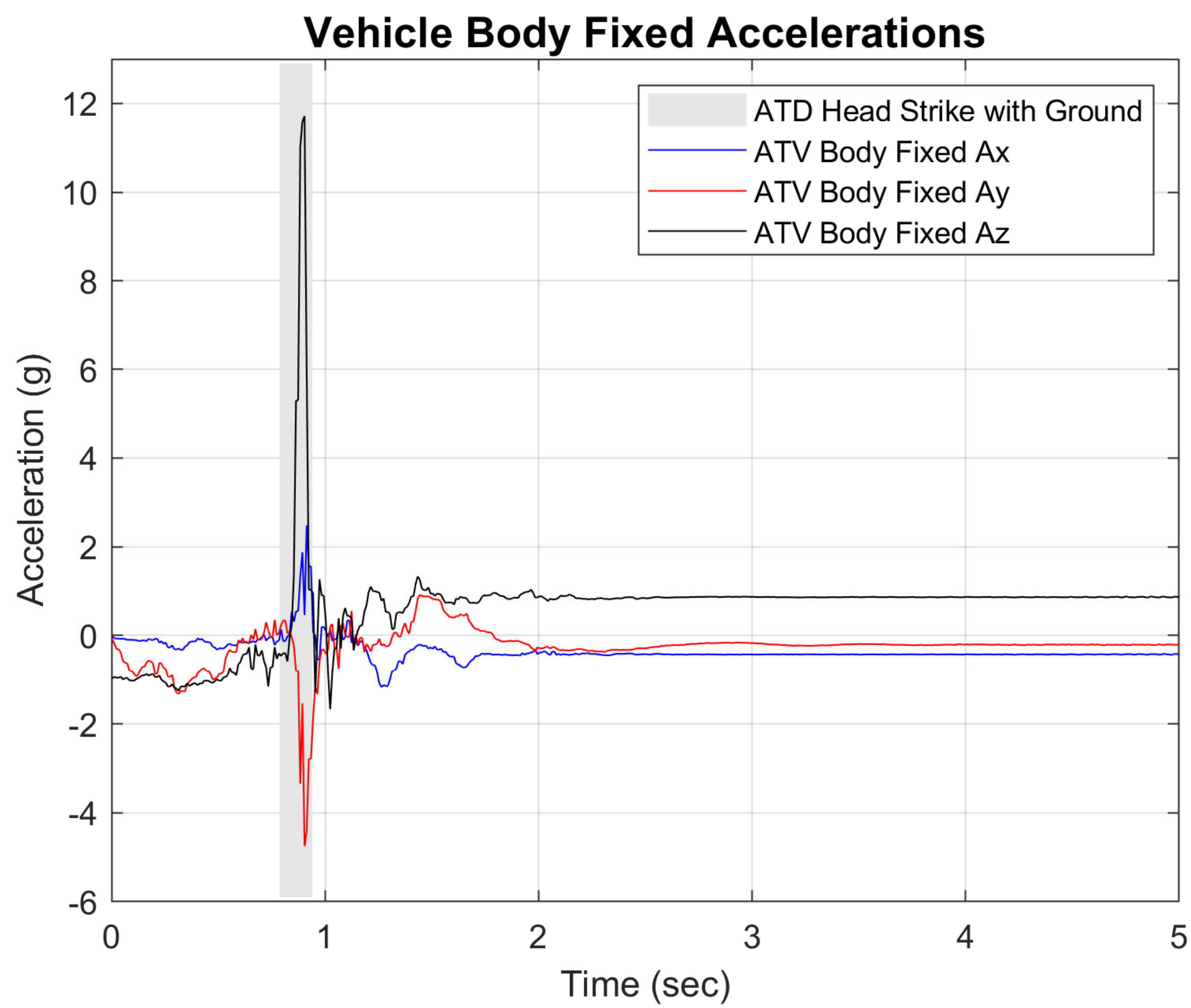
Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



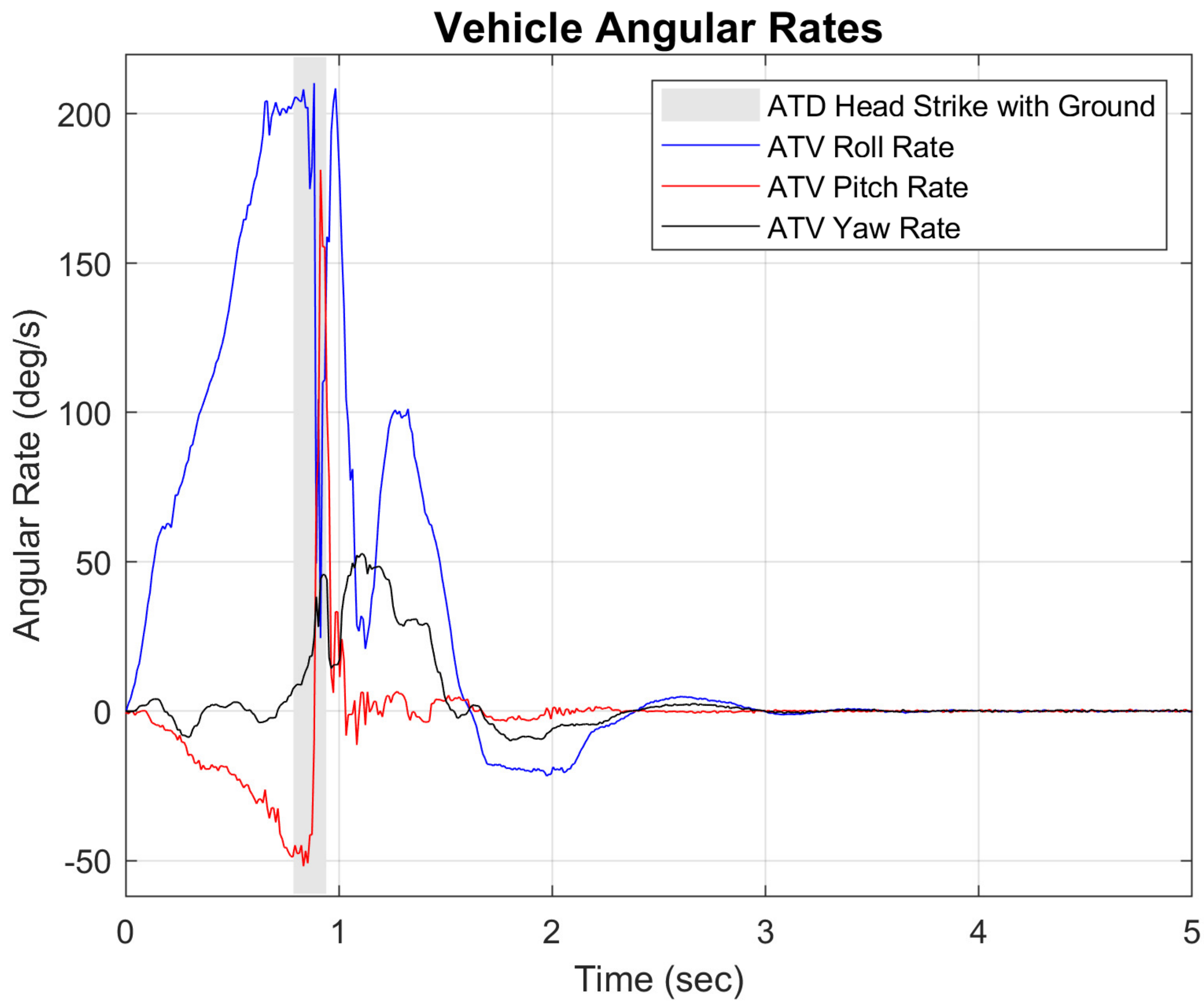
Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



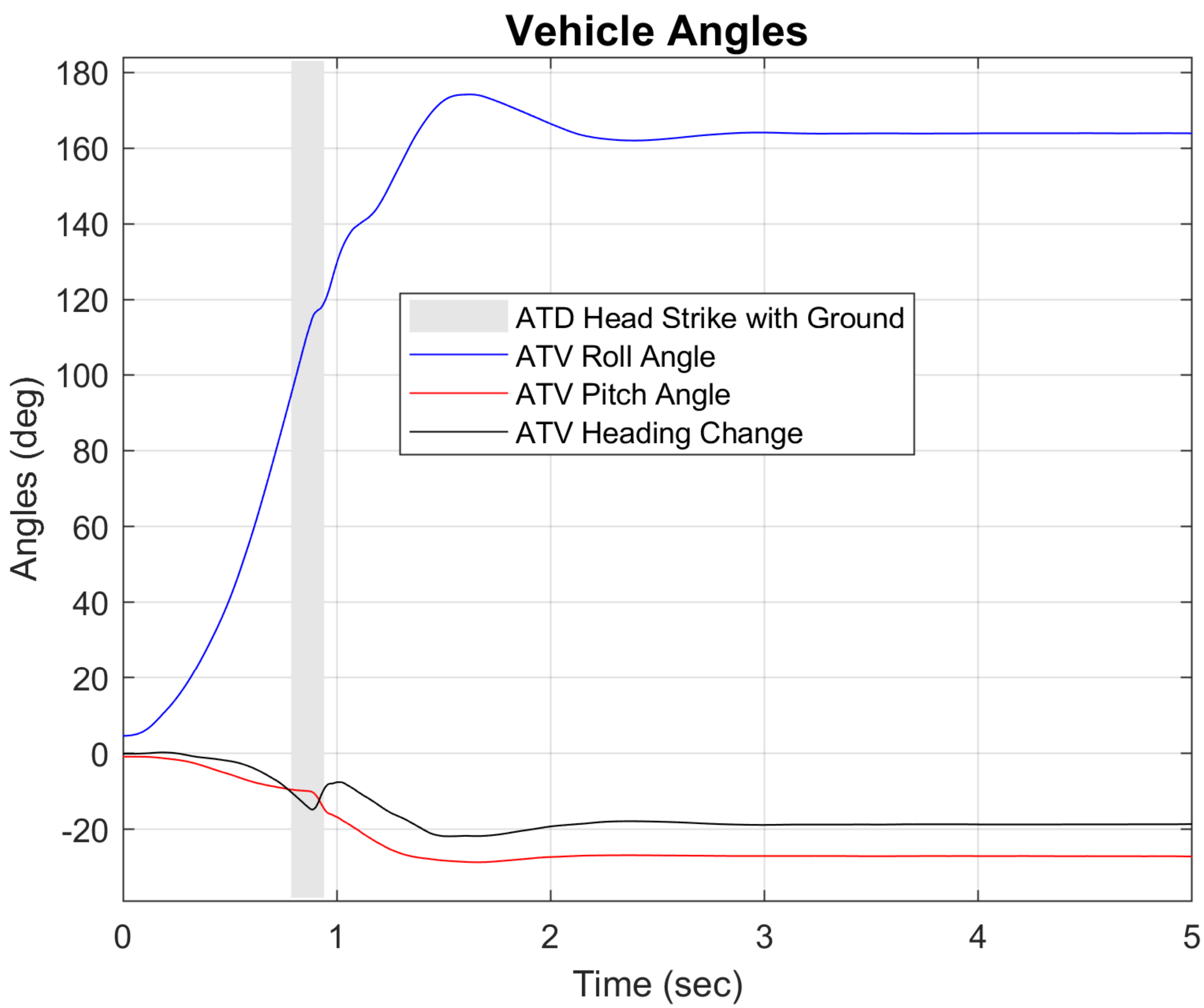
Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD



Vehicle J - Sled Moderate Energy Rollover – POC #1 – Extended Span OPD

Roll Angle = 30° - Time = 0.56 sec

Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Roll Angle = 45° - Time = 0.69 sec

Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Roll Angle = 90° - Time = 0.93 sec

Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

ATD Head Strike - Time = 1.11 sec

Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Max Roll Angle = 115.4° - Time = 1.51 sec

Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

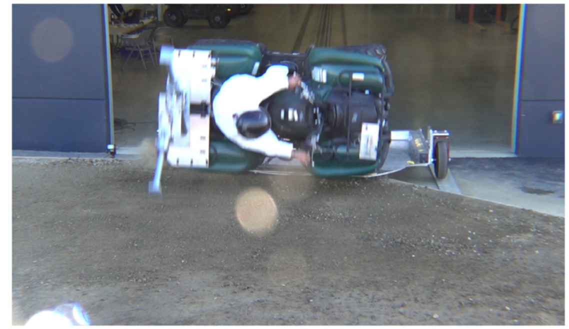
End of Run - Roll Angle = 96.7°

Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Drone Camera - Roll Angle = 30° - Time = 0.56 sec

Drone Camera - Roll Angle = 45° - Time = 0.69 sec

Drone Camera - Roll Angle = 90° - Time = 0.93 sec

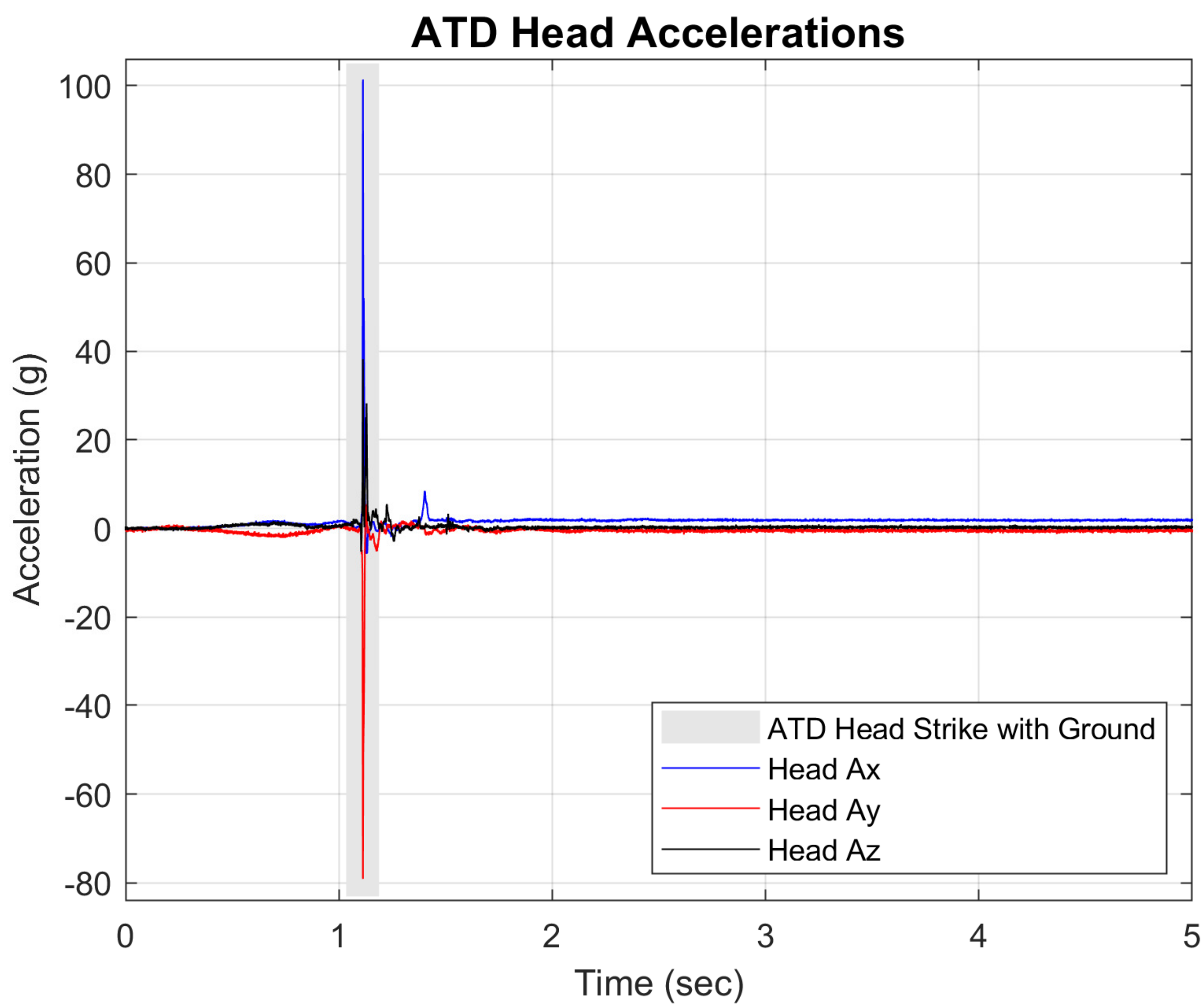


Drone Camera - ATD Head Strike - Time = 1.11 sec

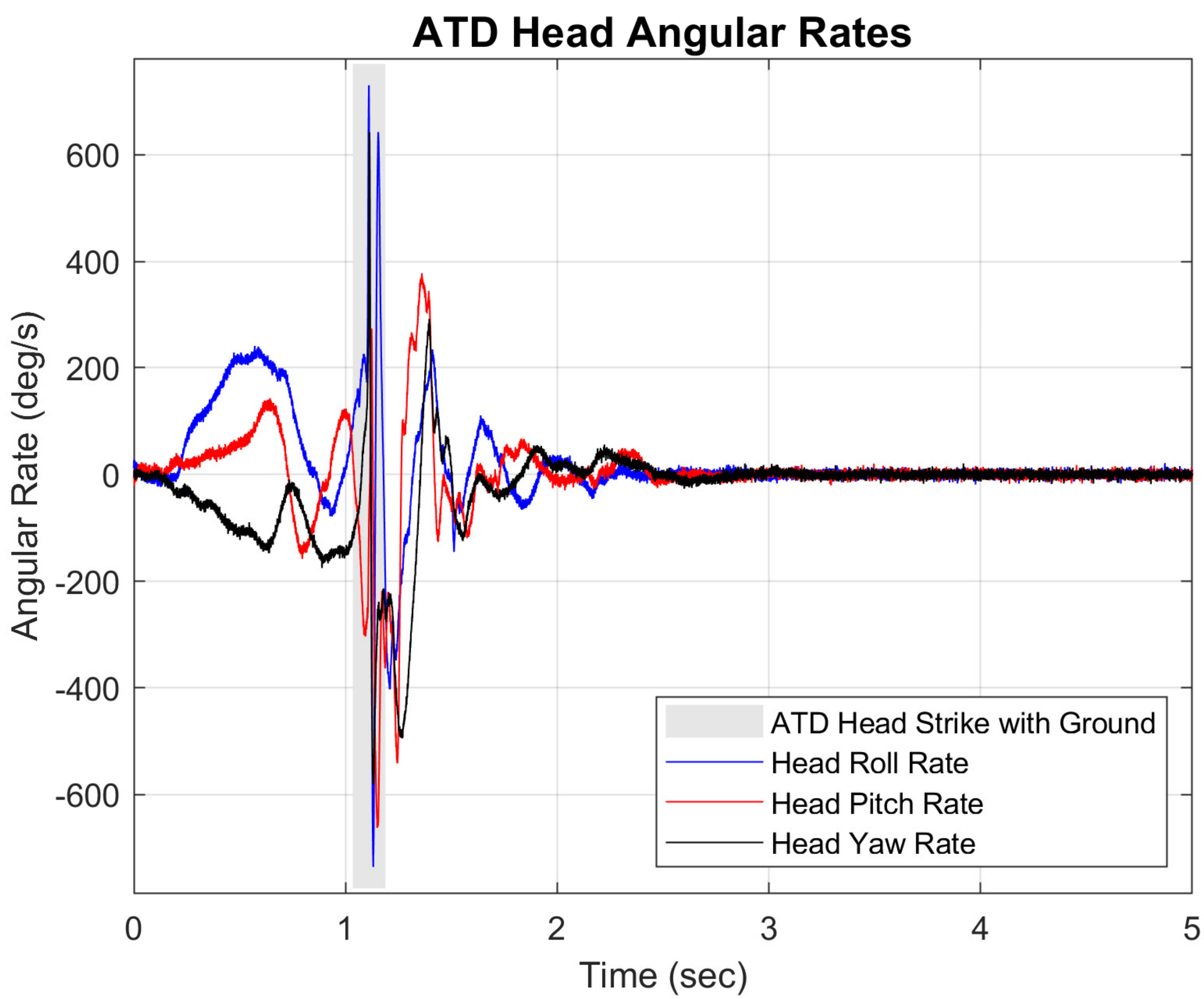
Drone Camera - Max Angle = 115.4° - Time = 1.51 sec

Drone Camera - End of Run - Roll Angle = 96.7°

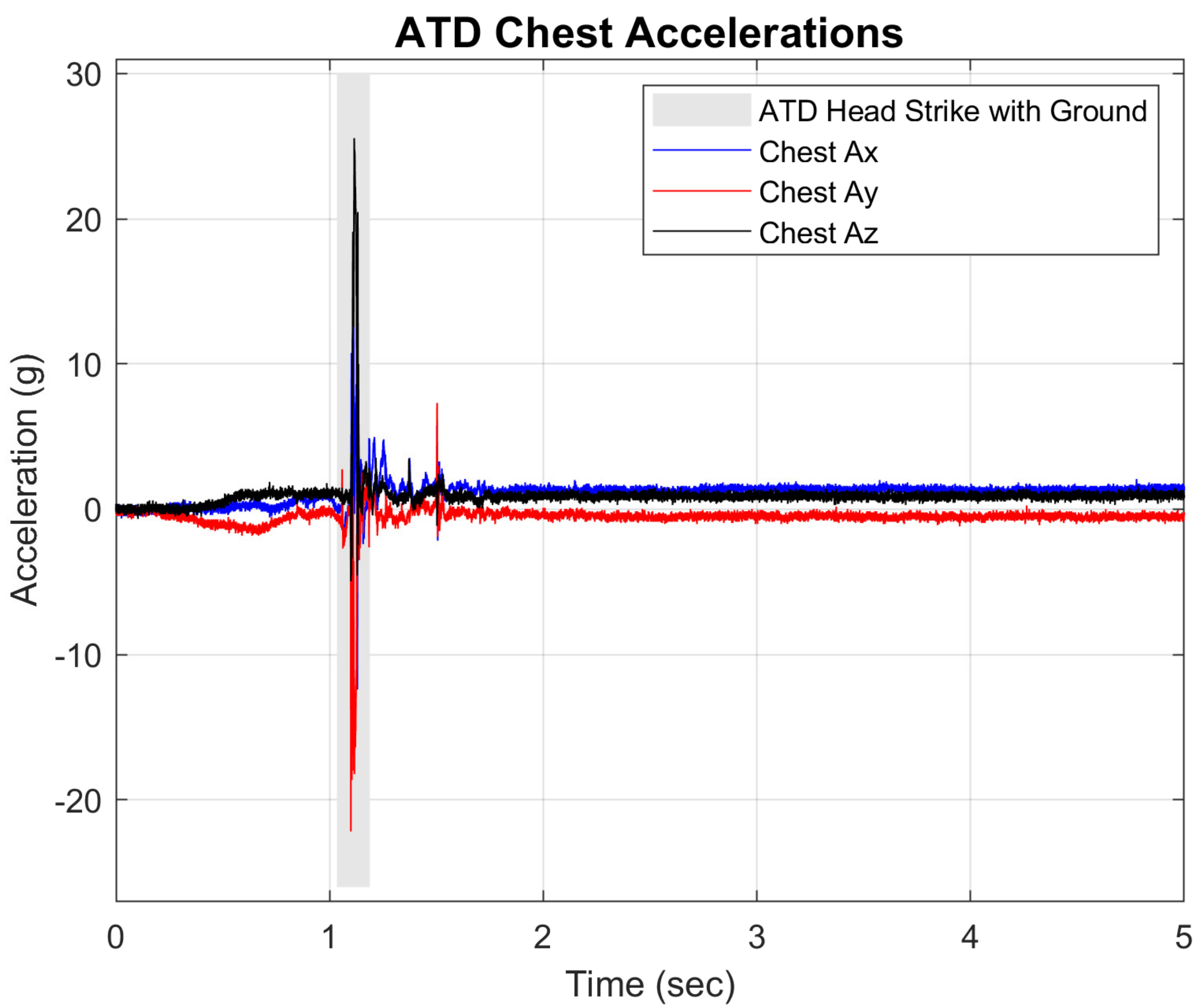
Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



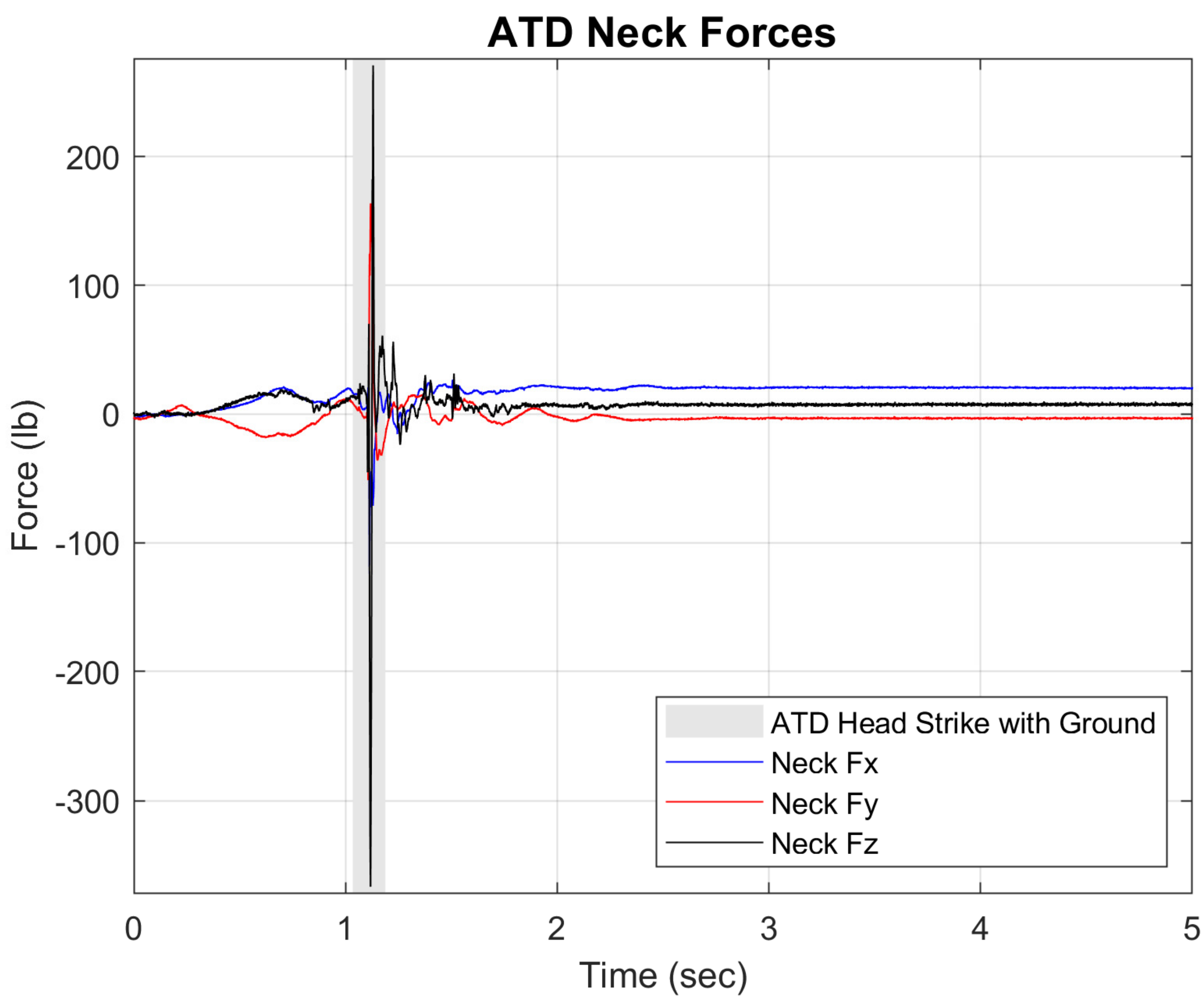
Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



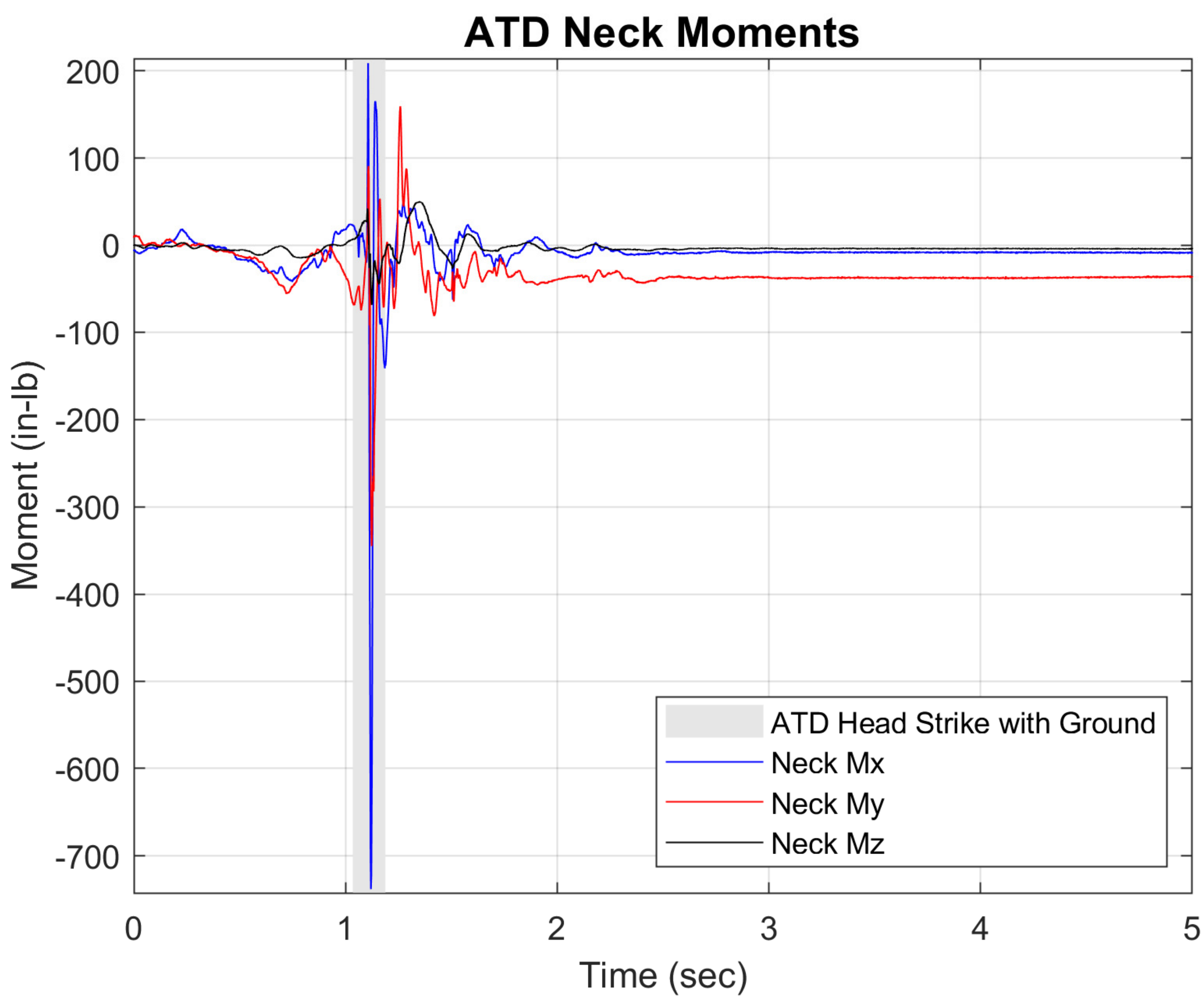
Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



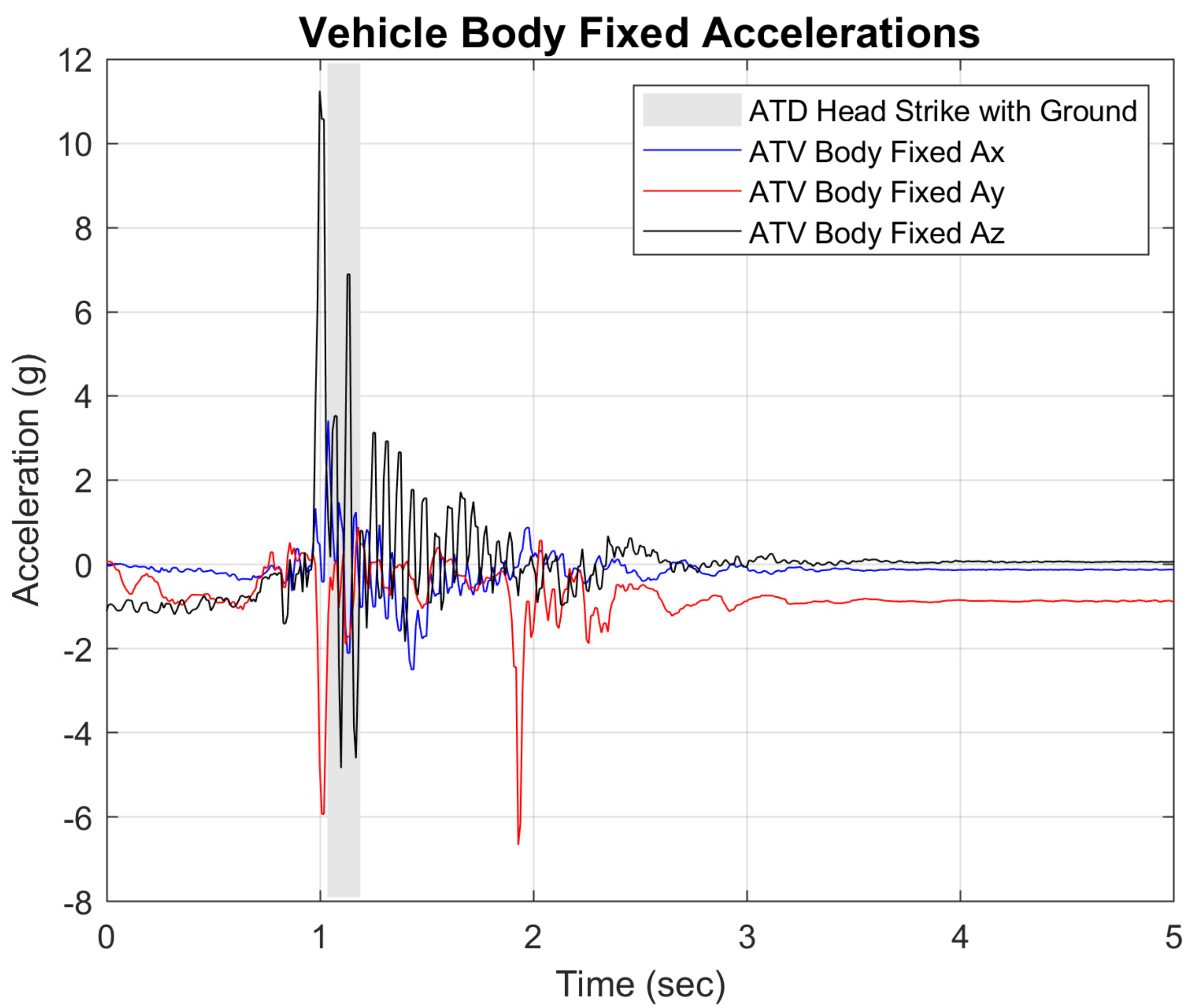
Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



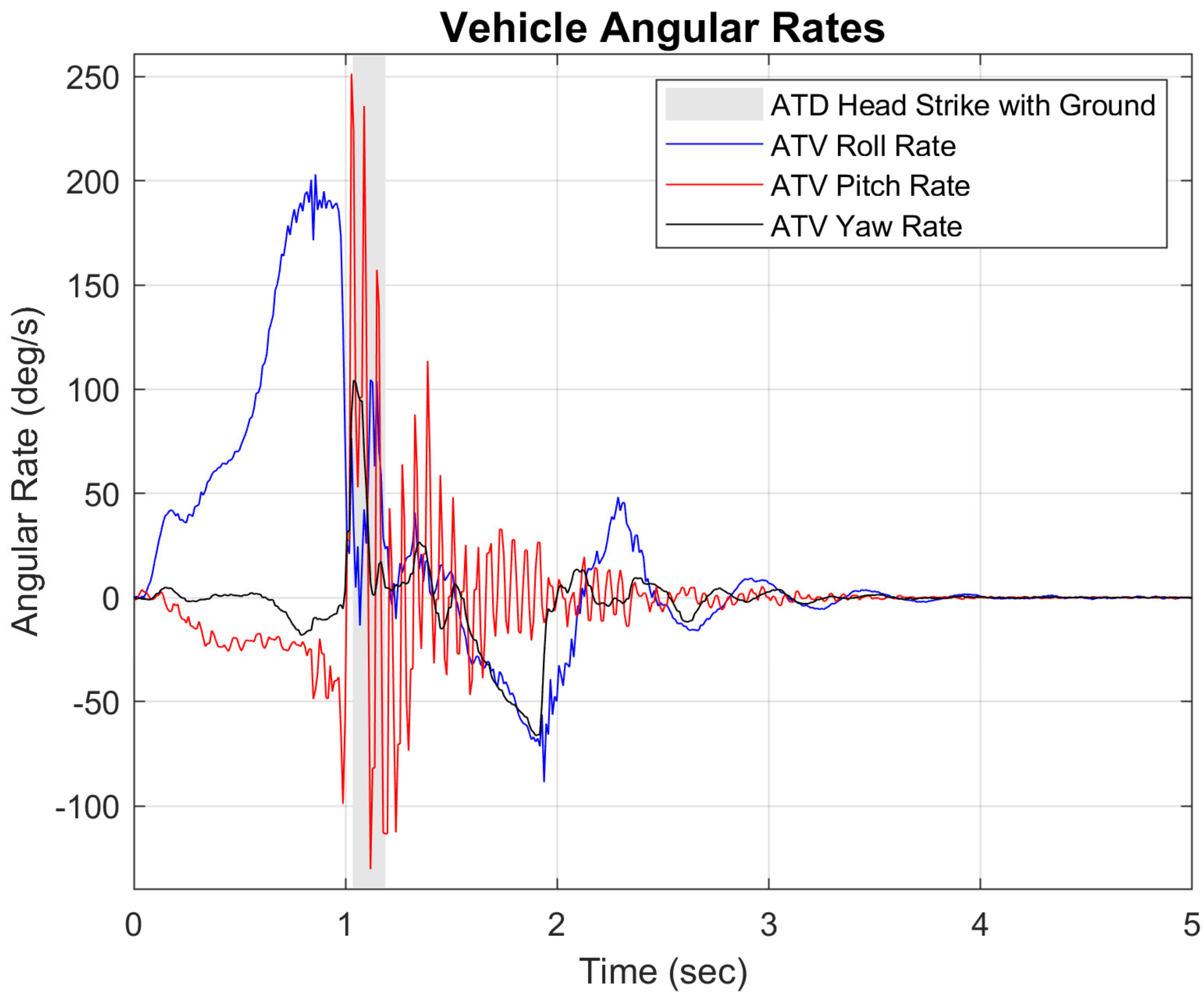
Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



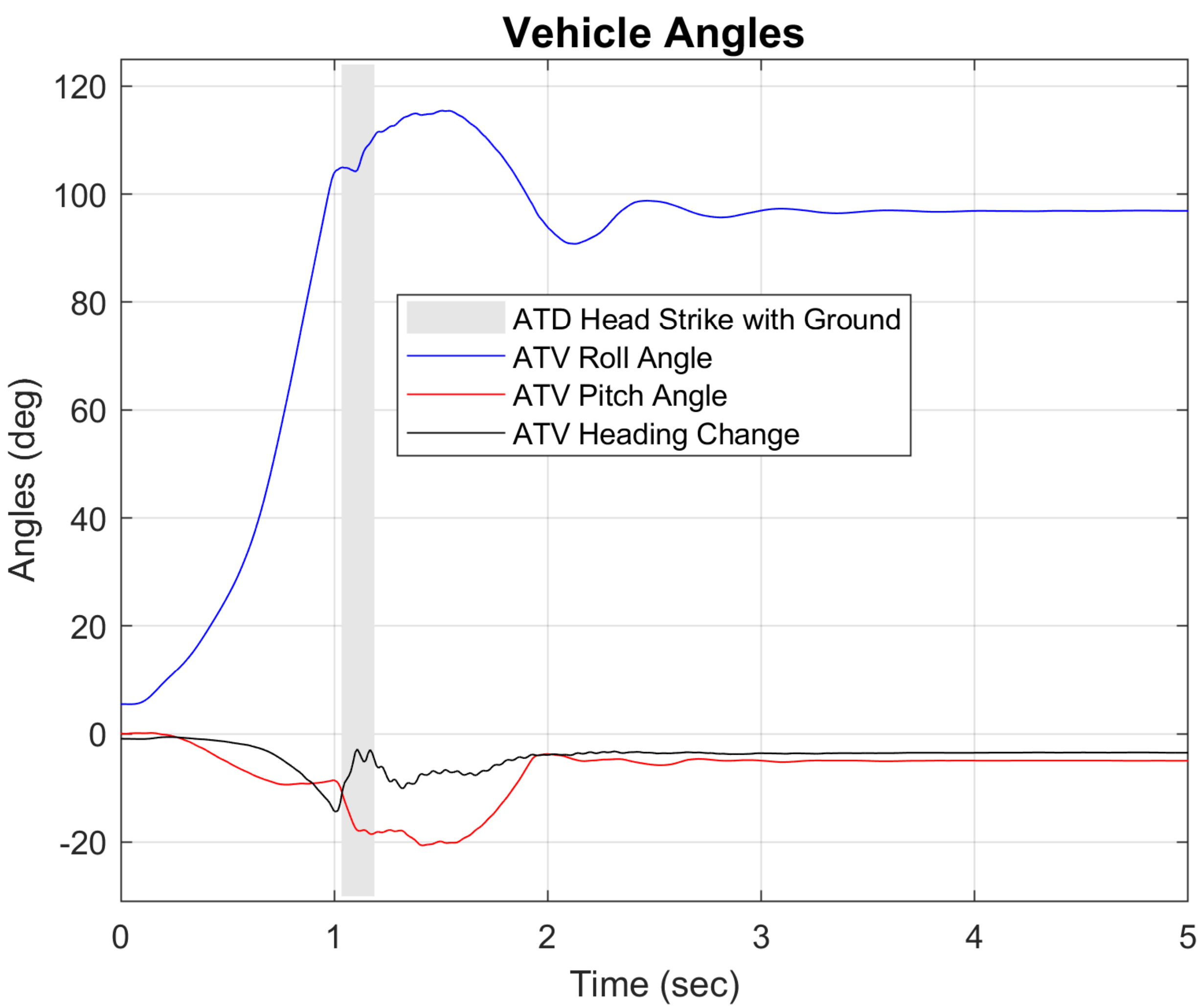
Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

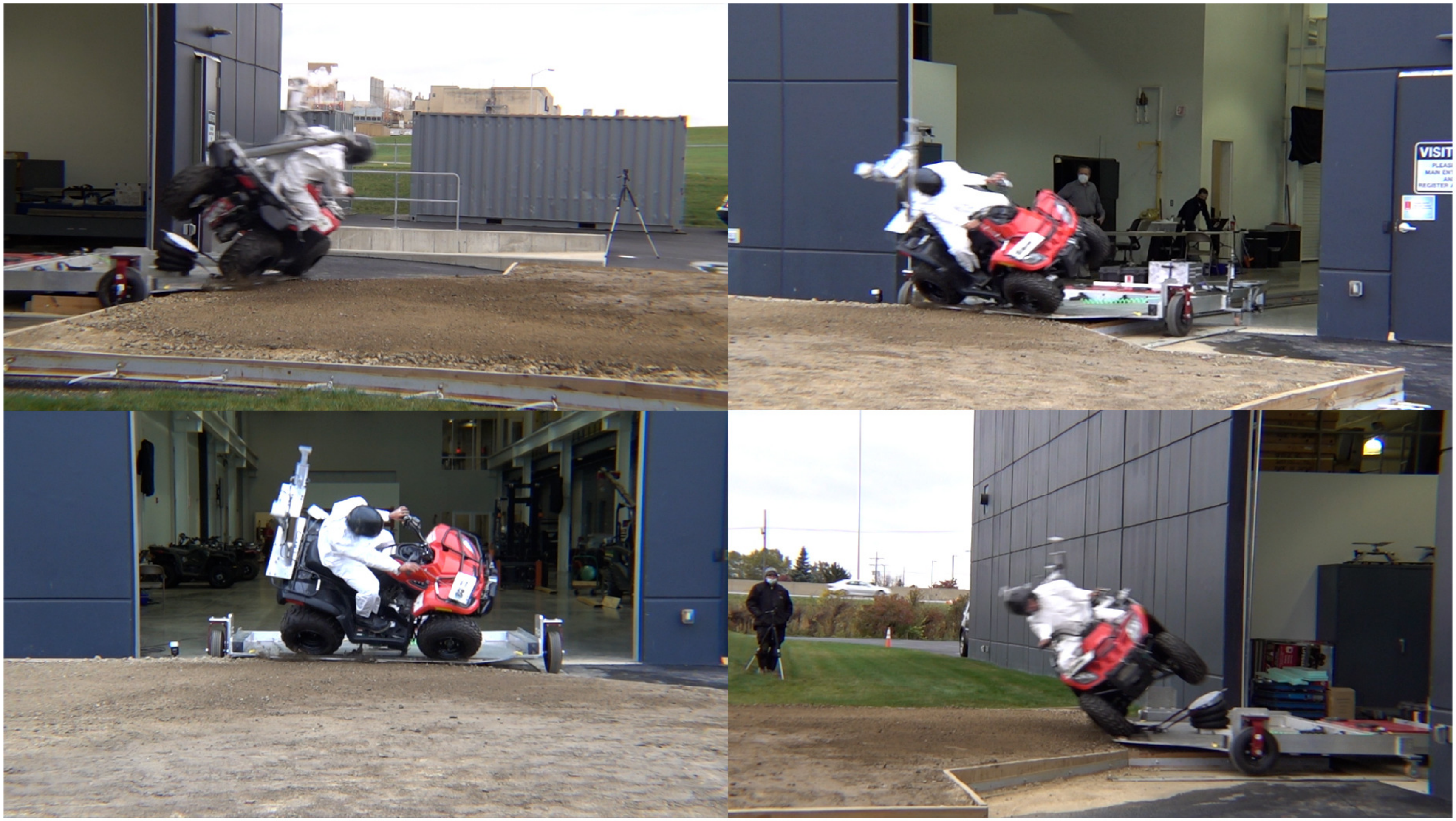


Vehicle C - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Roll Angle = 30° - Time = 0.61 sec

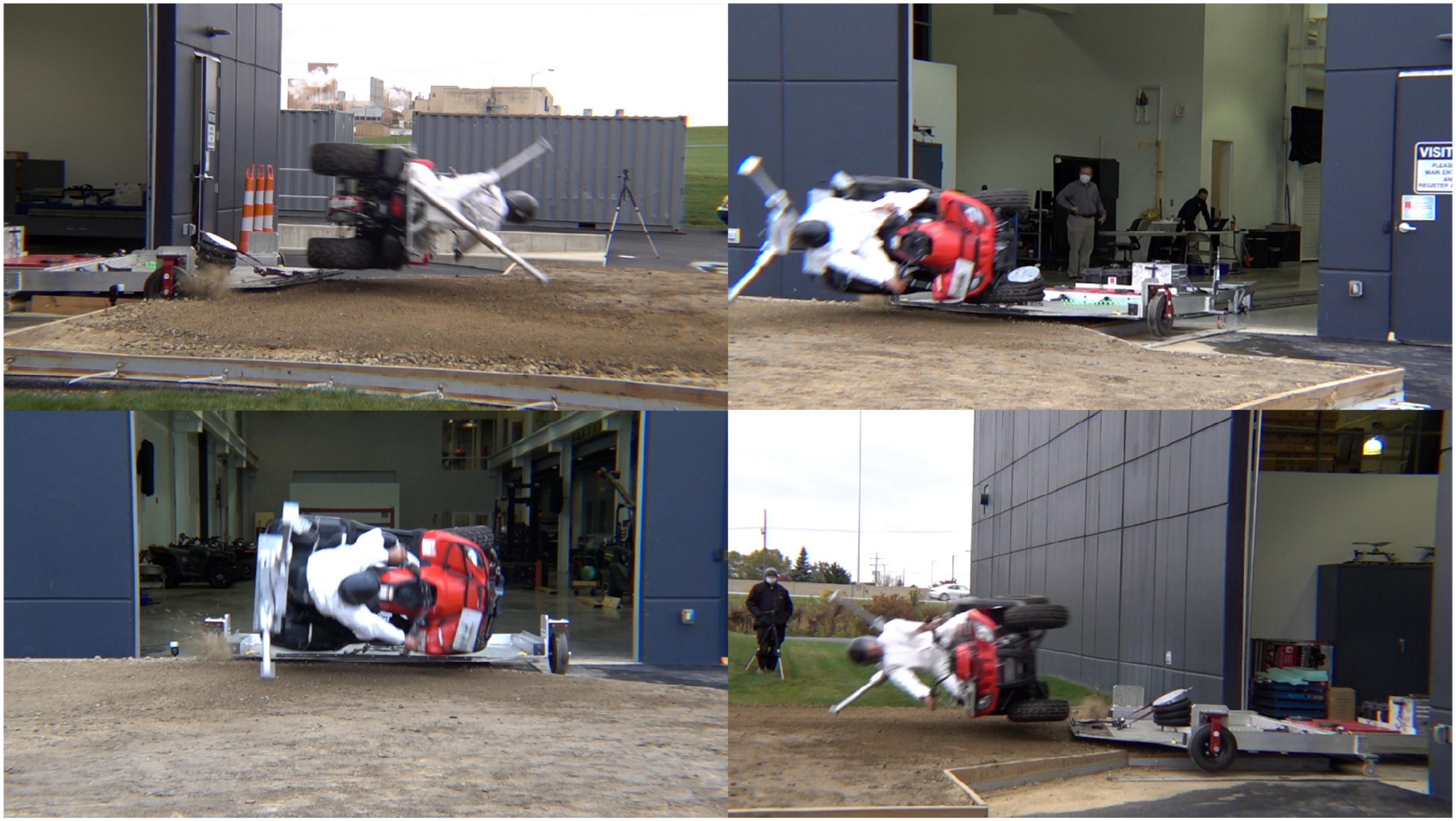
Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Roll Angle = 45° - Time = 0.72 sec



Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Roll Angle = 90° - Time = 0.97 sec



Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

ATD Head Strike - Time = 1.12 sec

Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Max Roll Angle = 113.0° - Time = 1.26 sec

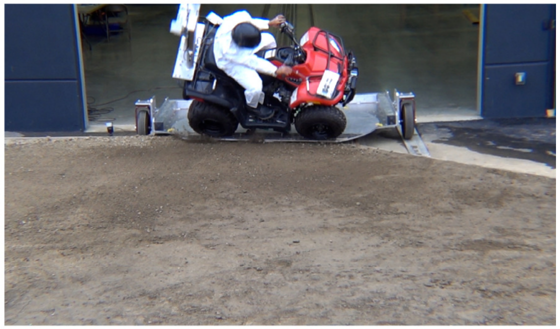
Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

End of Run - Roll Angle = 97.8°

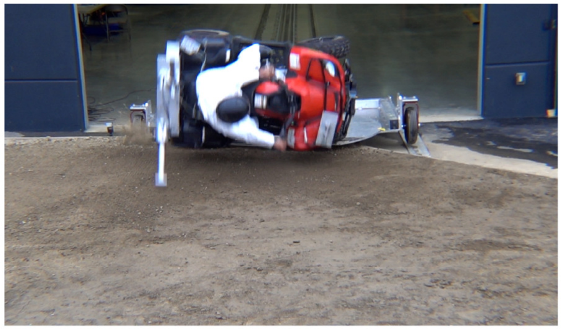
Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Drone Camera - Roll Angle = 30° - Time = 0.61 sec

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



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

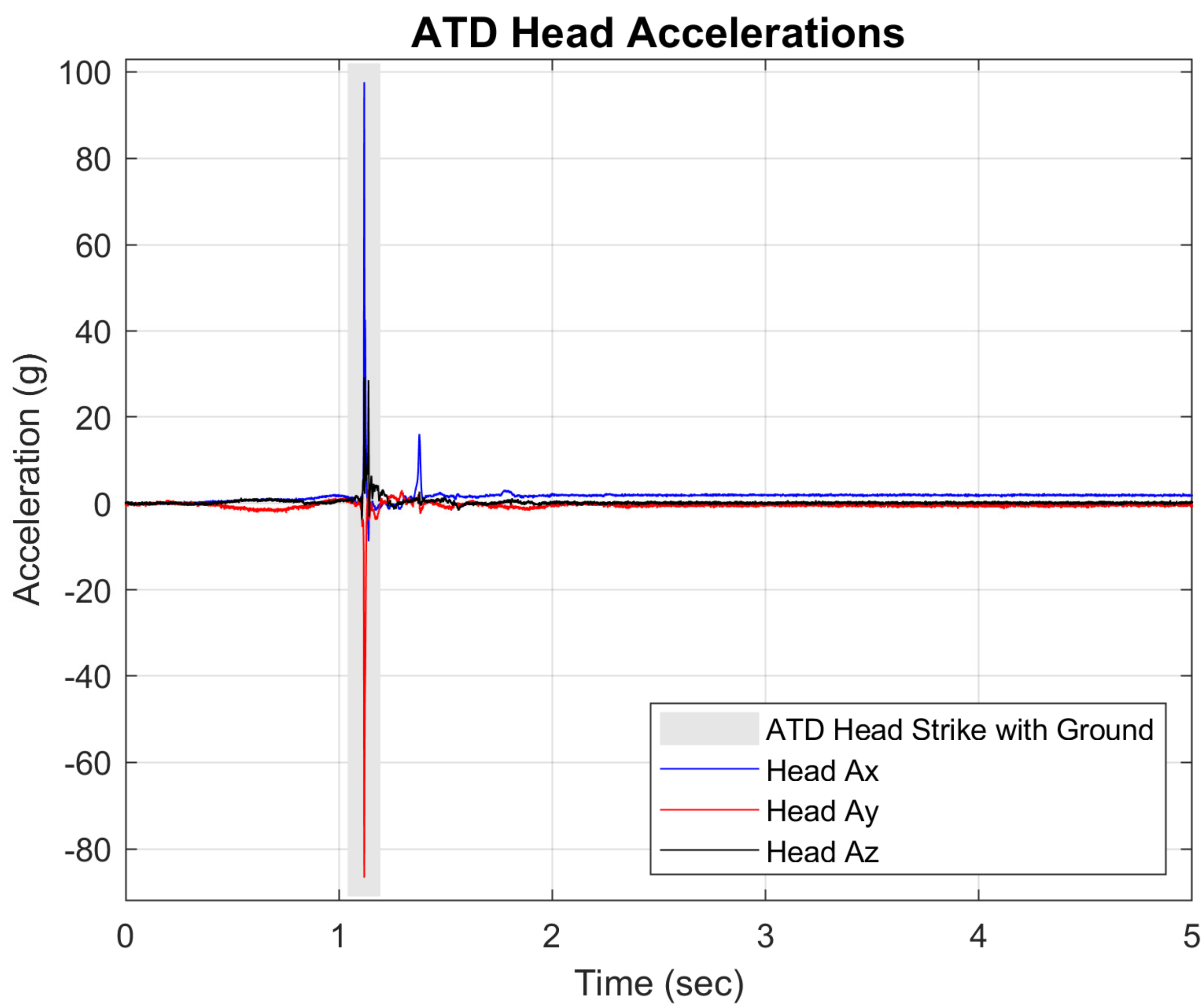


Drone Camera - ATD Head Strike - Time = 1.12 sec

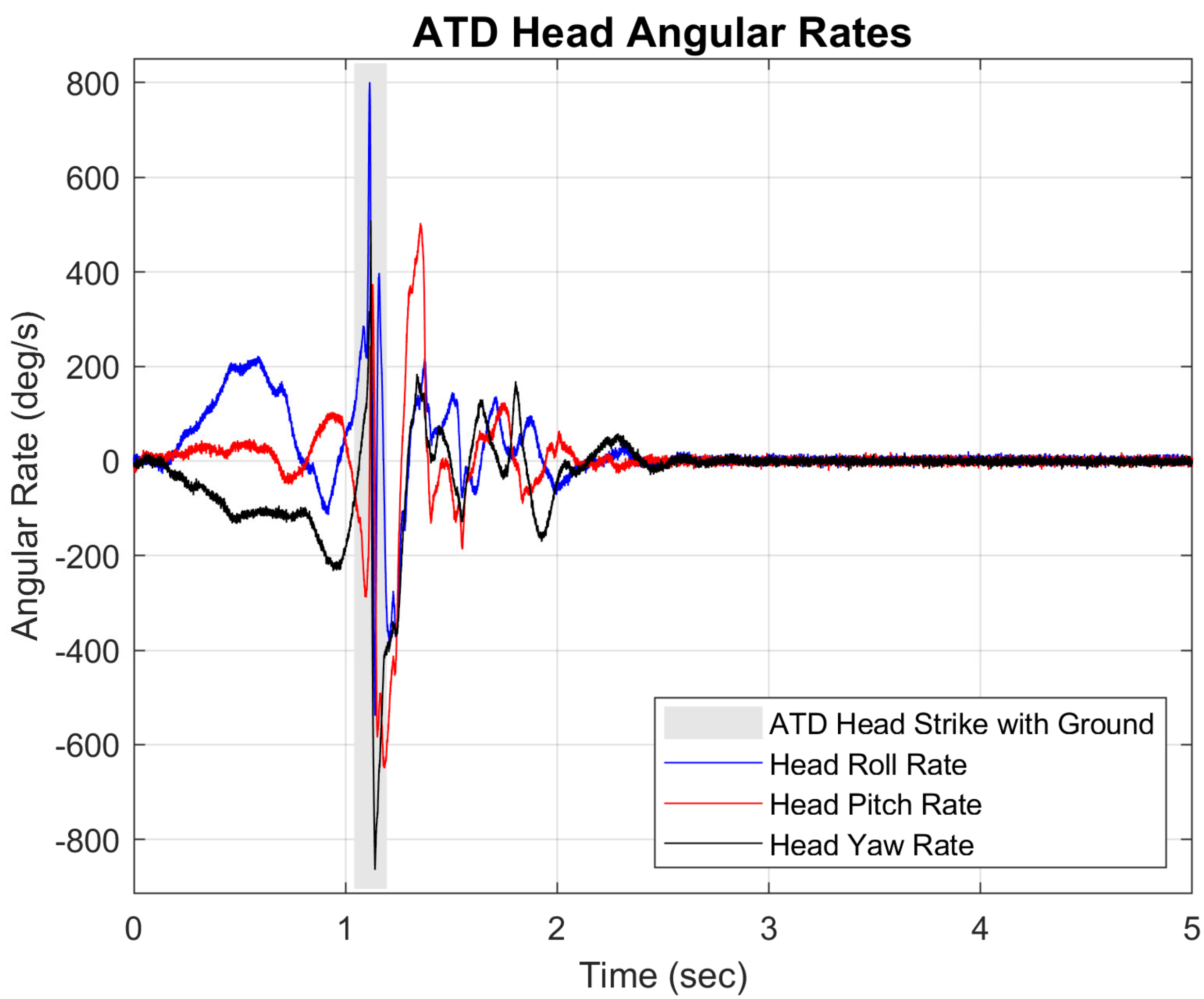
Drone Camera - Max Angle = 113.0° - Time = 1.26 sec

Drone Camera - End of Run - Roll Angle = 97.8°

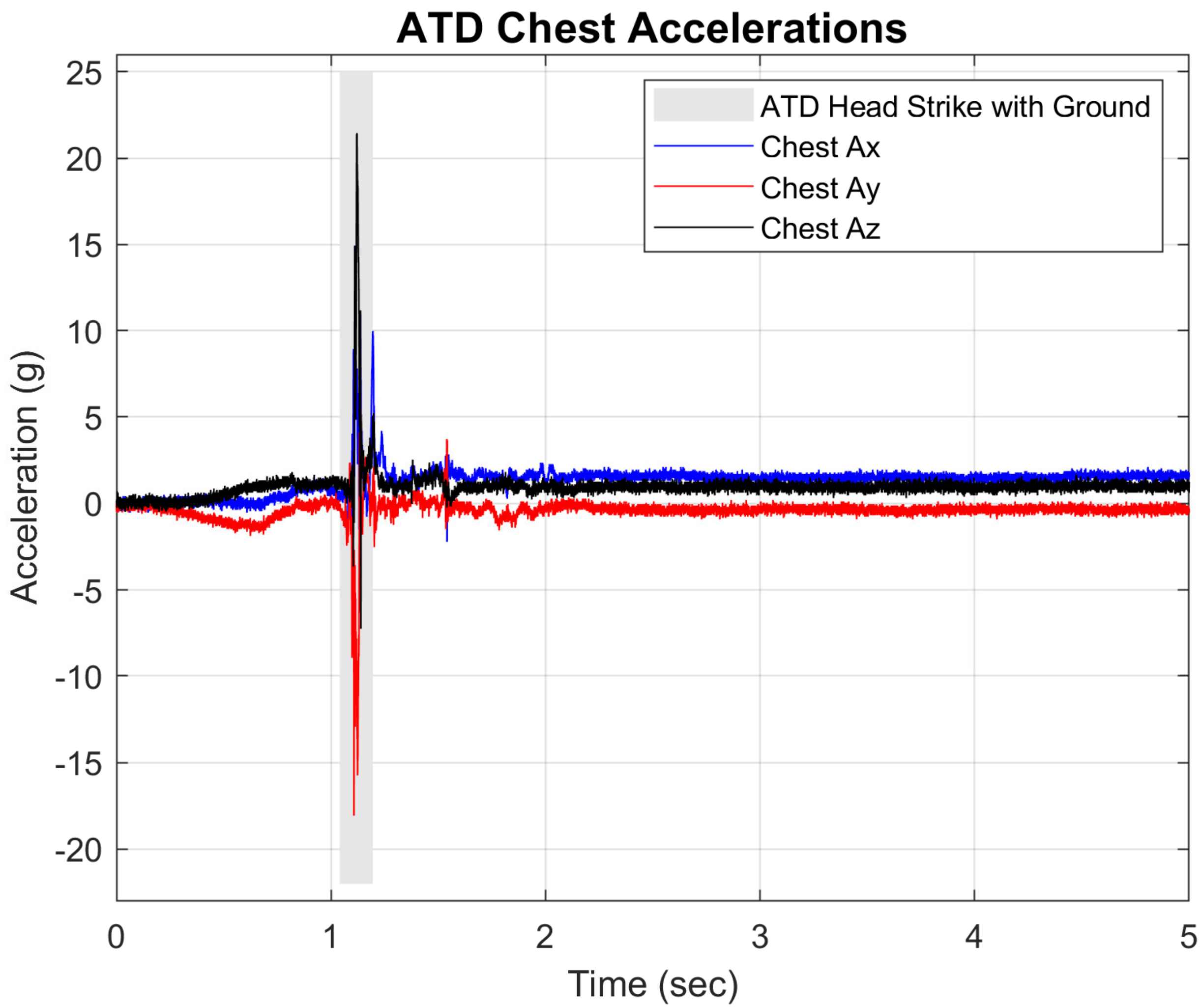
Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



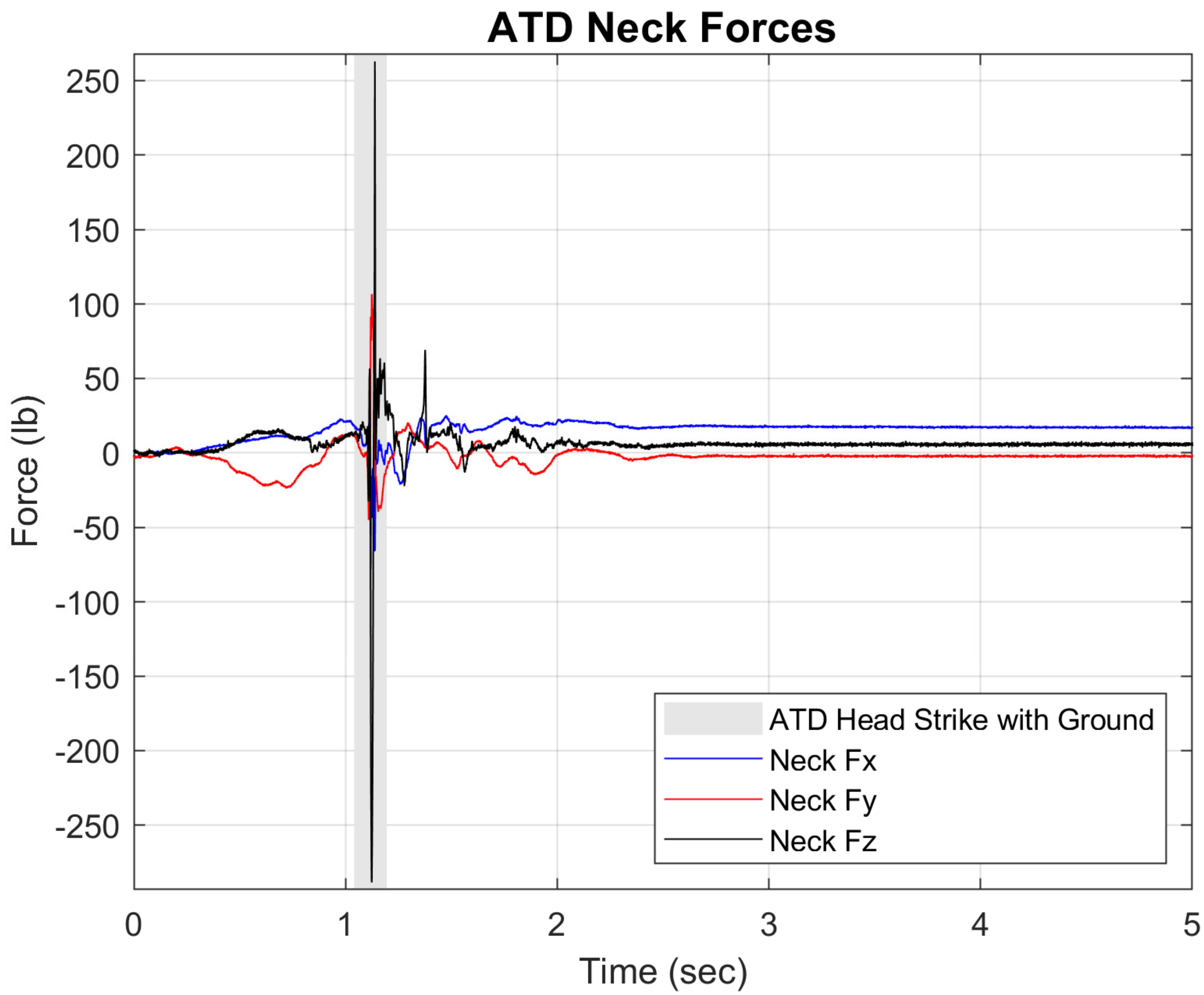
Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



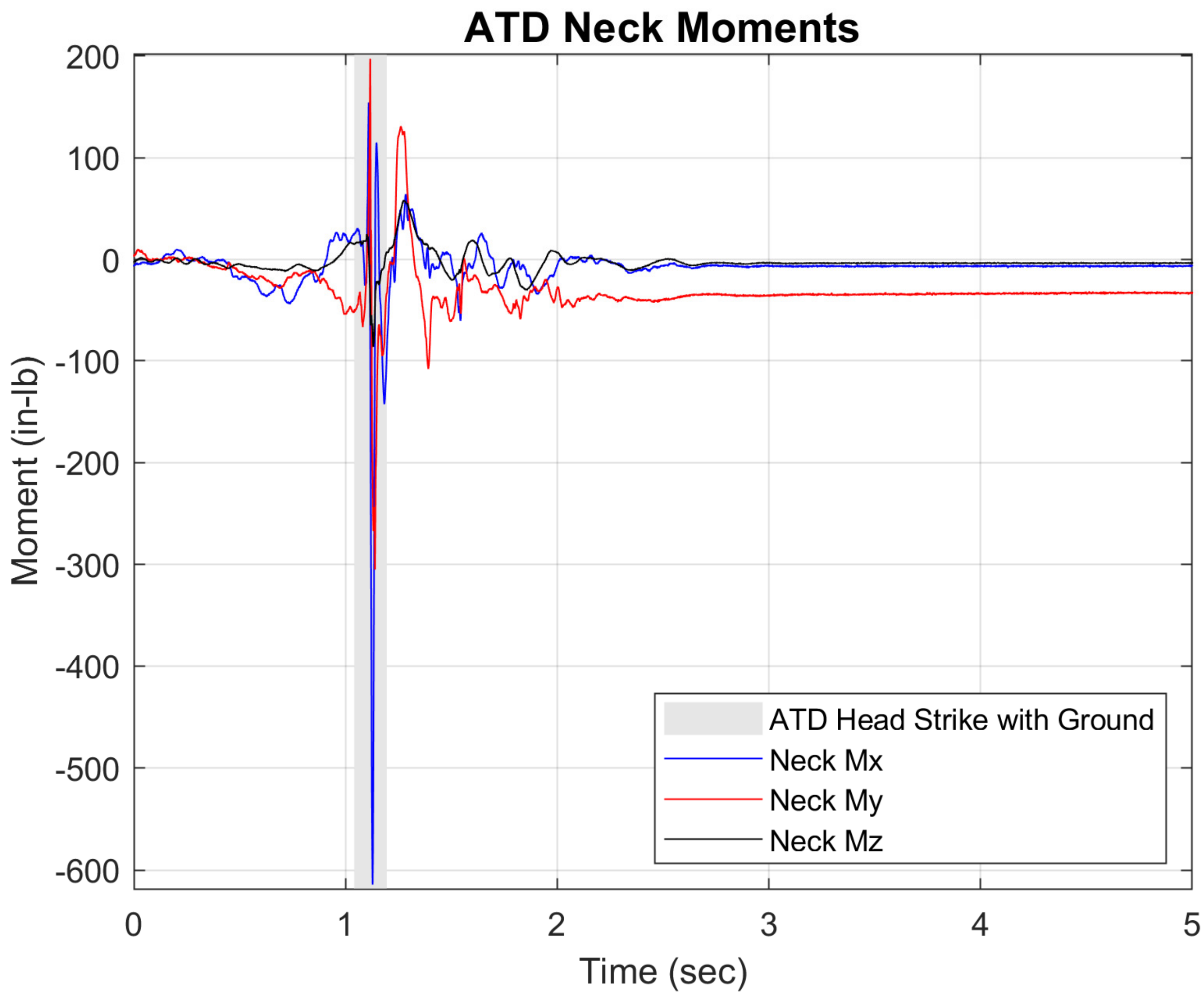
Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



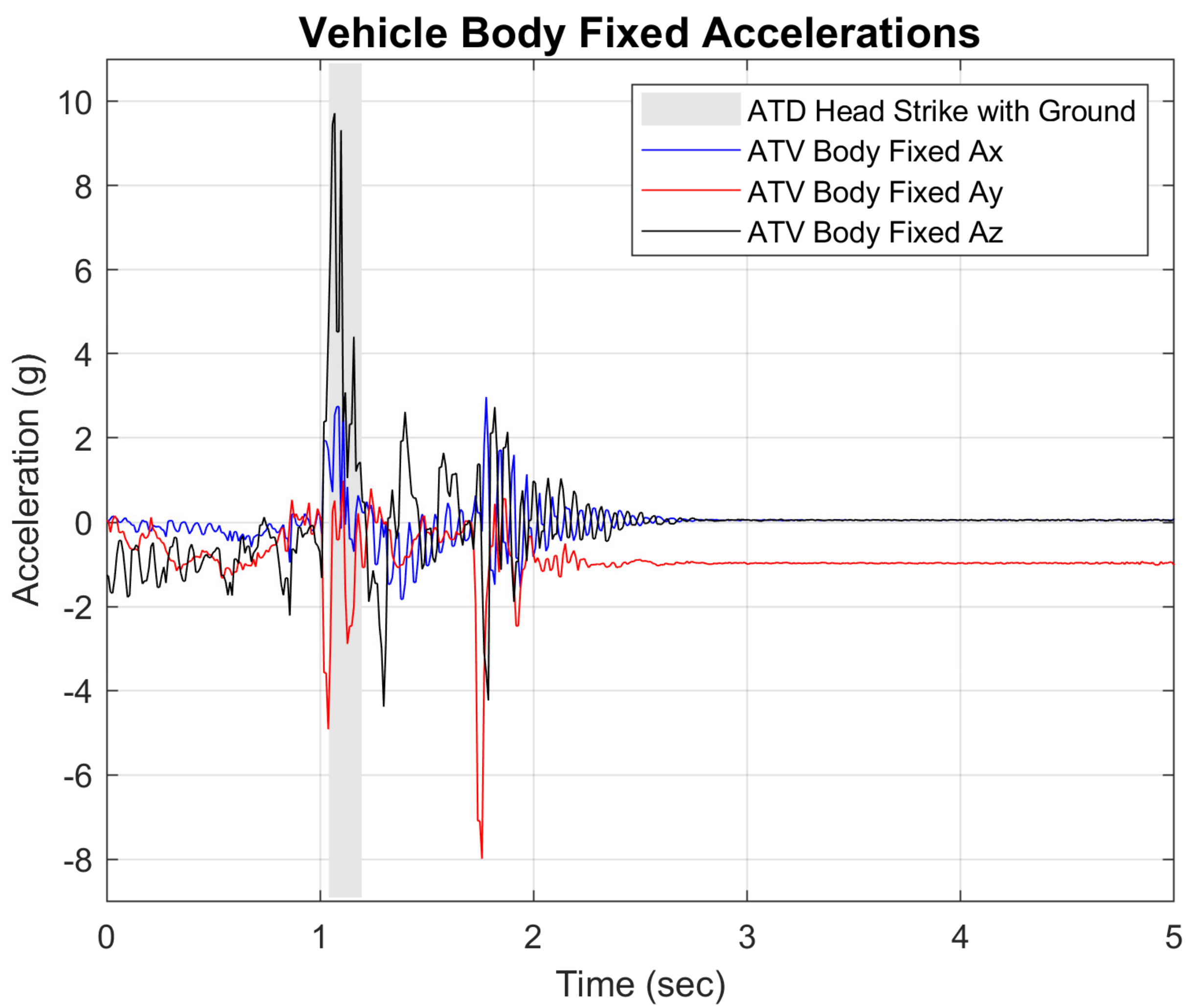
Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



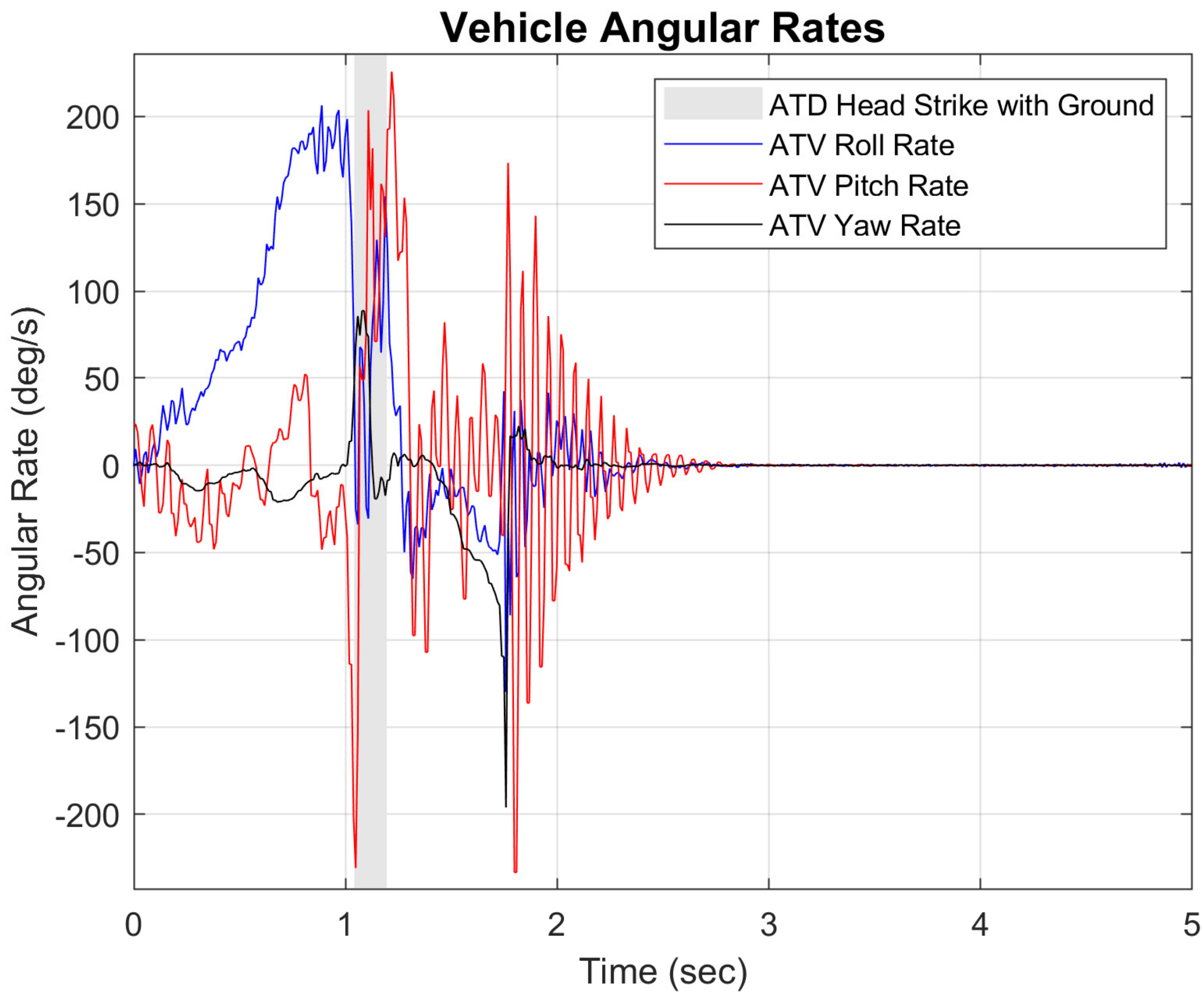
Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



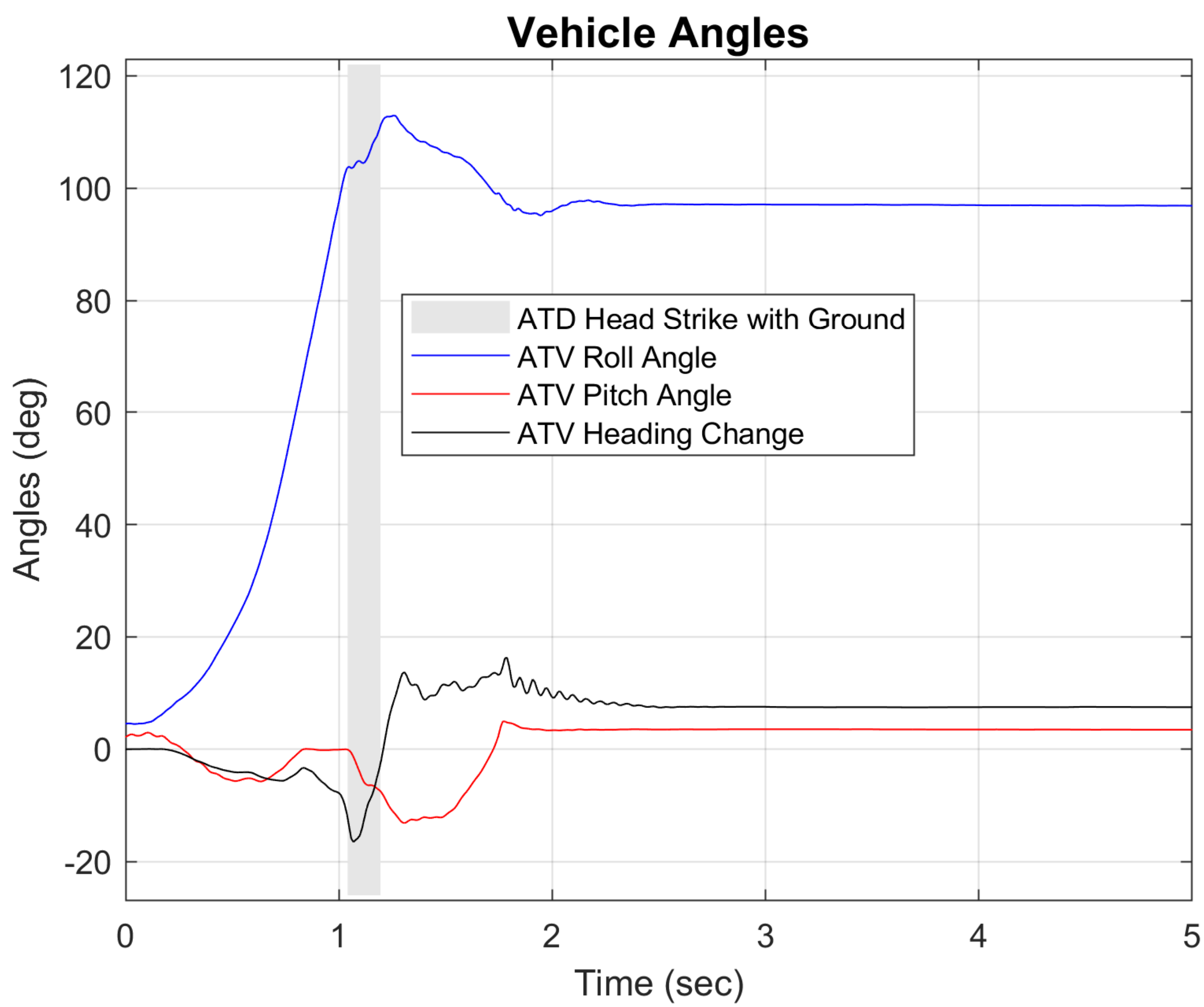
Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

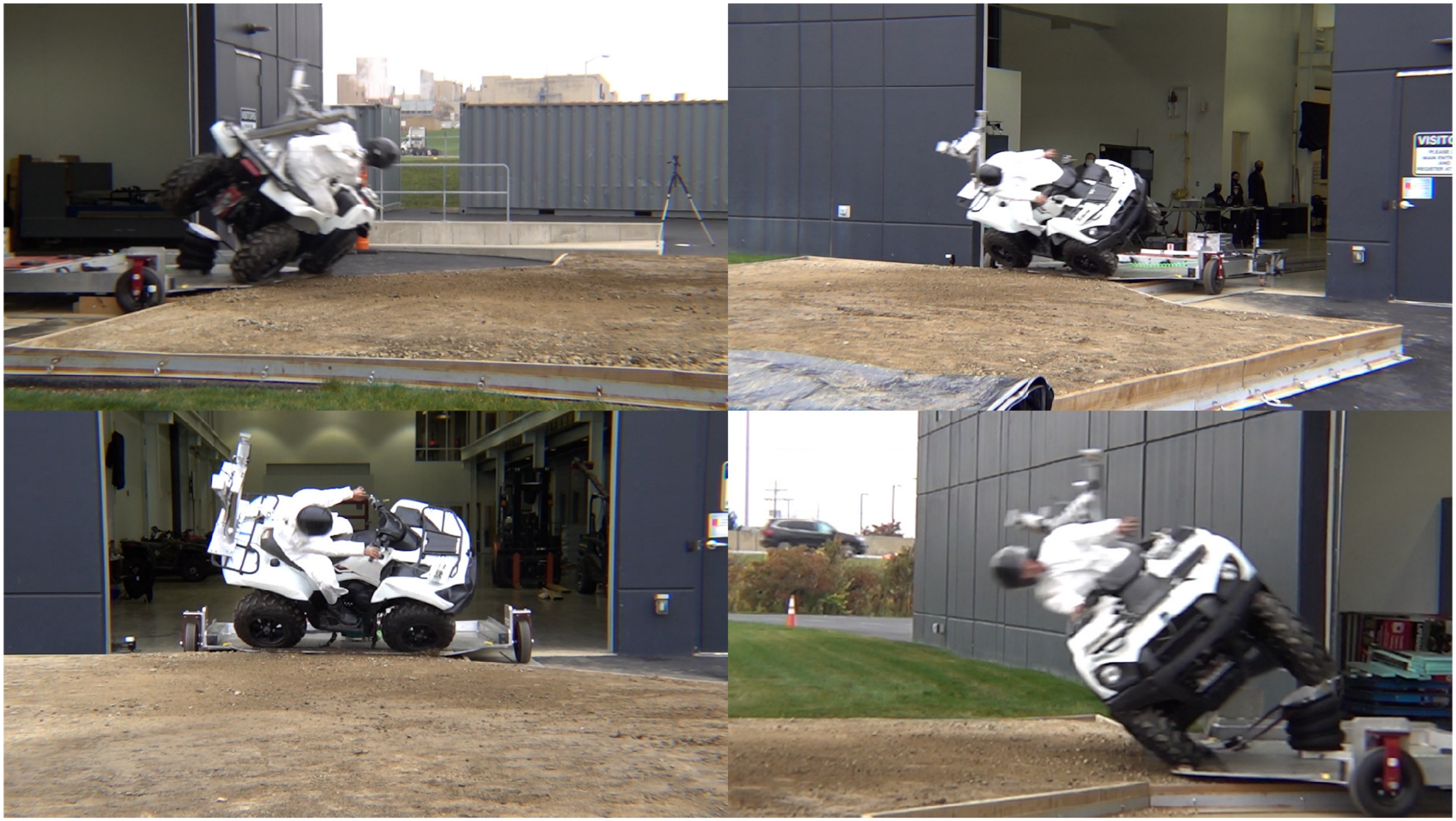


Vehicle F - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Roll Angle = 30° - Time = 0.55 sec

Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Roll Angle = 45° - Time = 0.67 sec



Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Roll Angle = 90° - Time = 0.90 sec

Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

ATD Head Strike - Time = 1.02 sec

Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

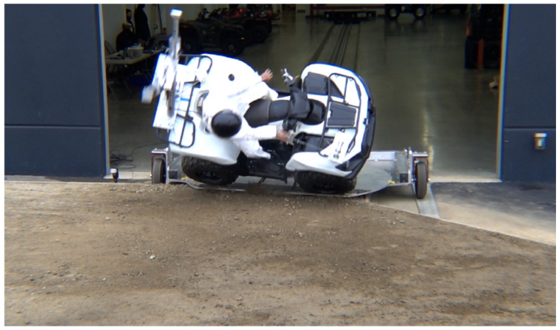
Max Roll Angle = 130.0° - Time = 1.55 sec

Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

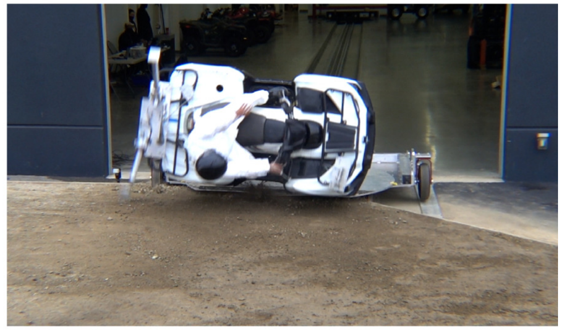
End of Run - Roll Angle = 99.1°

Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

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

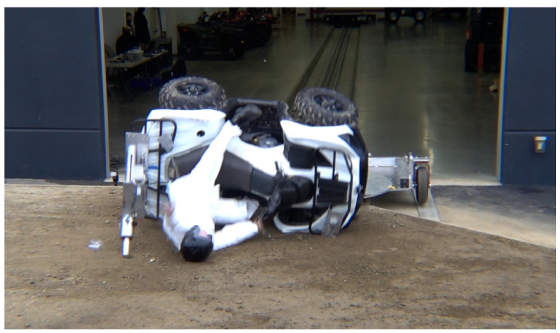


Drone Camera - Roll Angle = 45° - Time = 0.67 sec



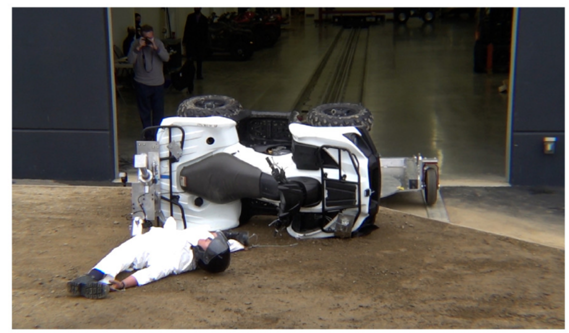
Drone Camera - Roll Angle = 90° - Time = 0.90 sec

Drone Camera - ATD Head Strike - Time = 0.82 sec

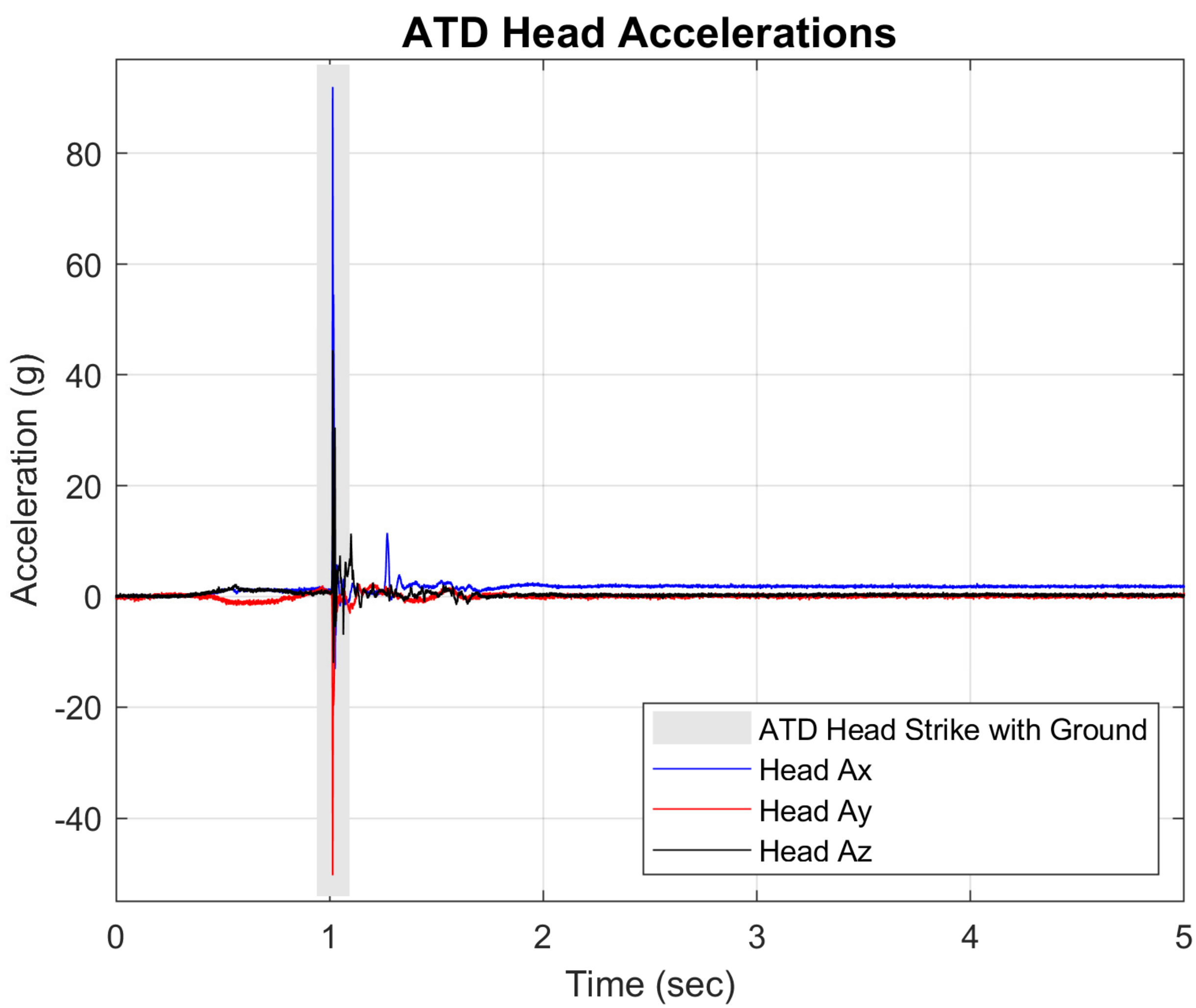


Drone Camera - Max Angle = 130.0° - Time = 1.55 sec

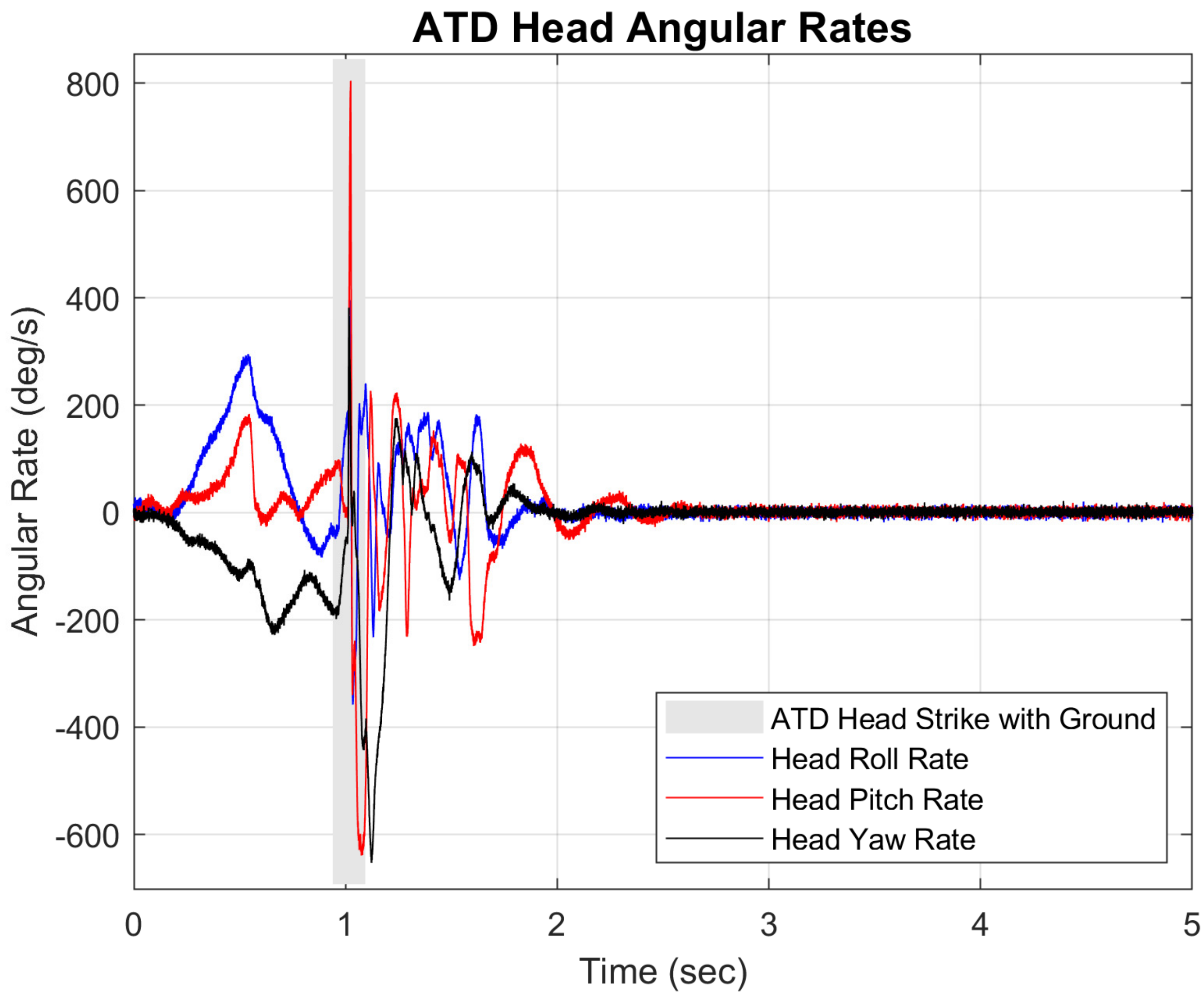
Drone Camera - End of Run - Roll Angle = 99.1°



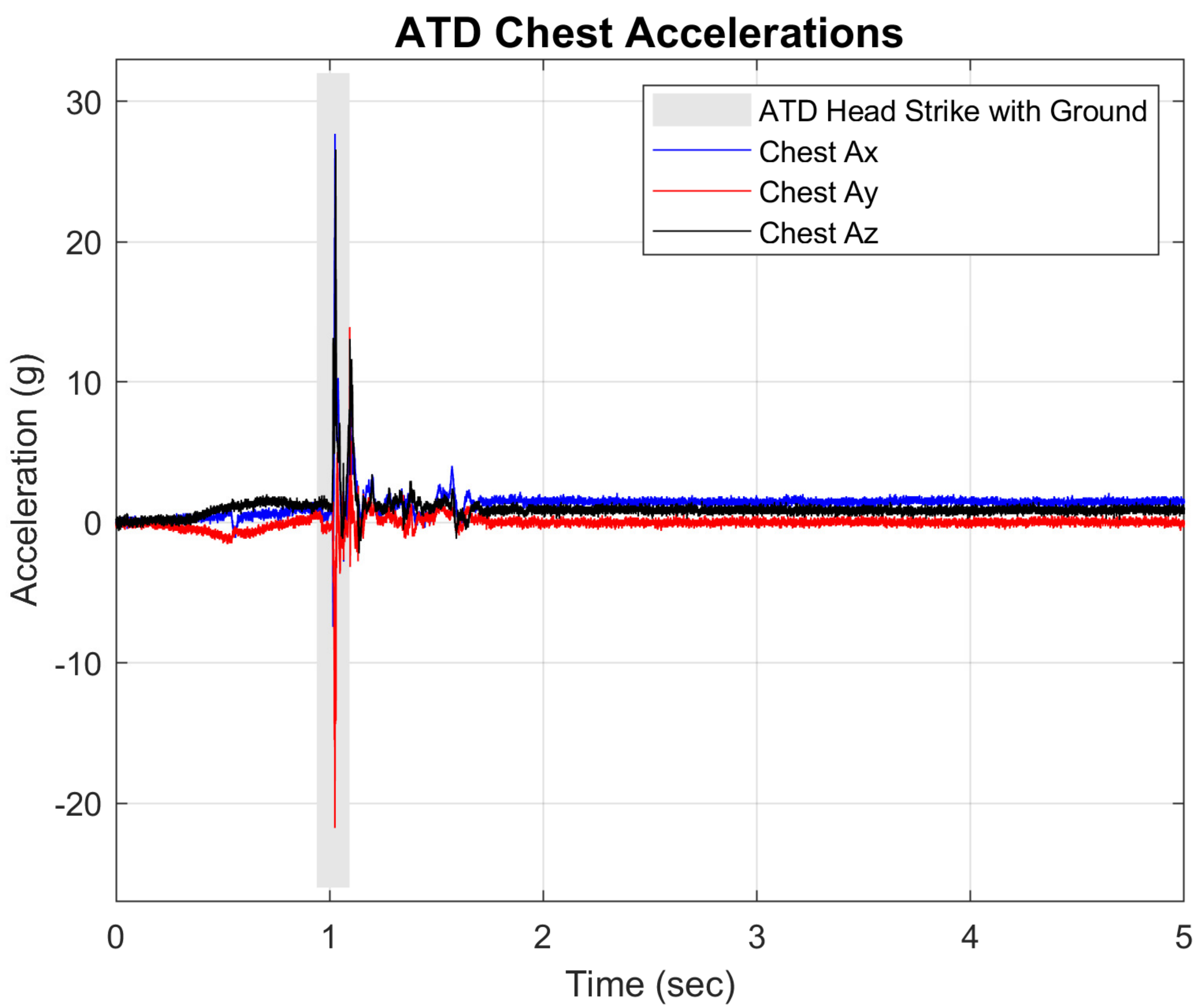
Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



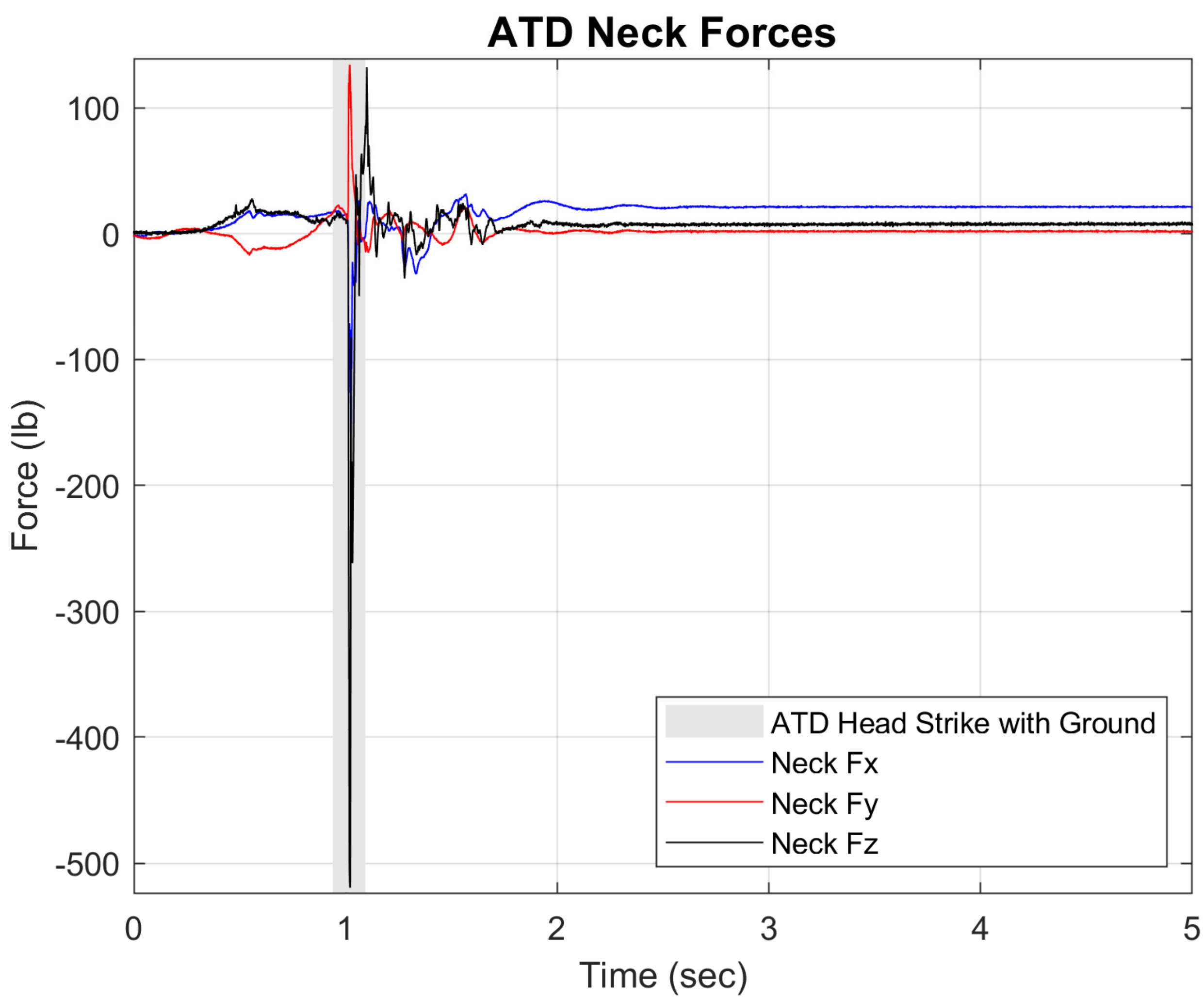
Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



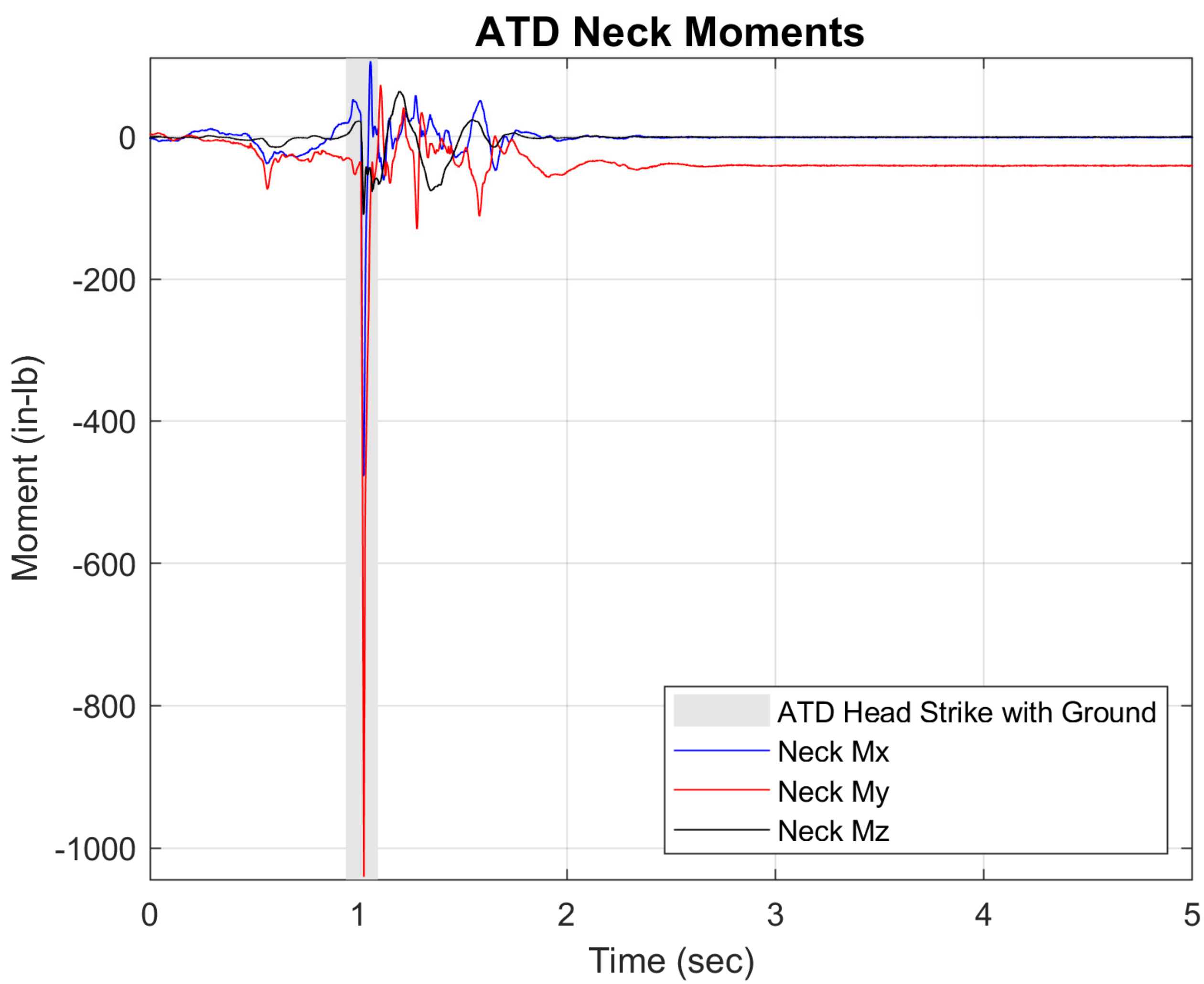
Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



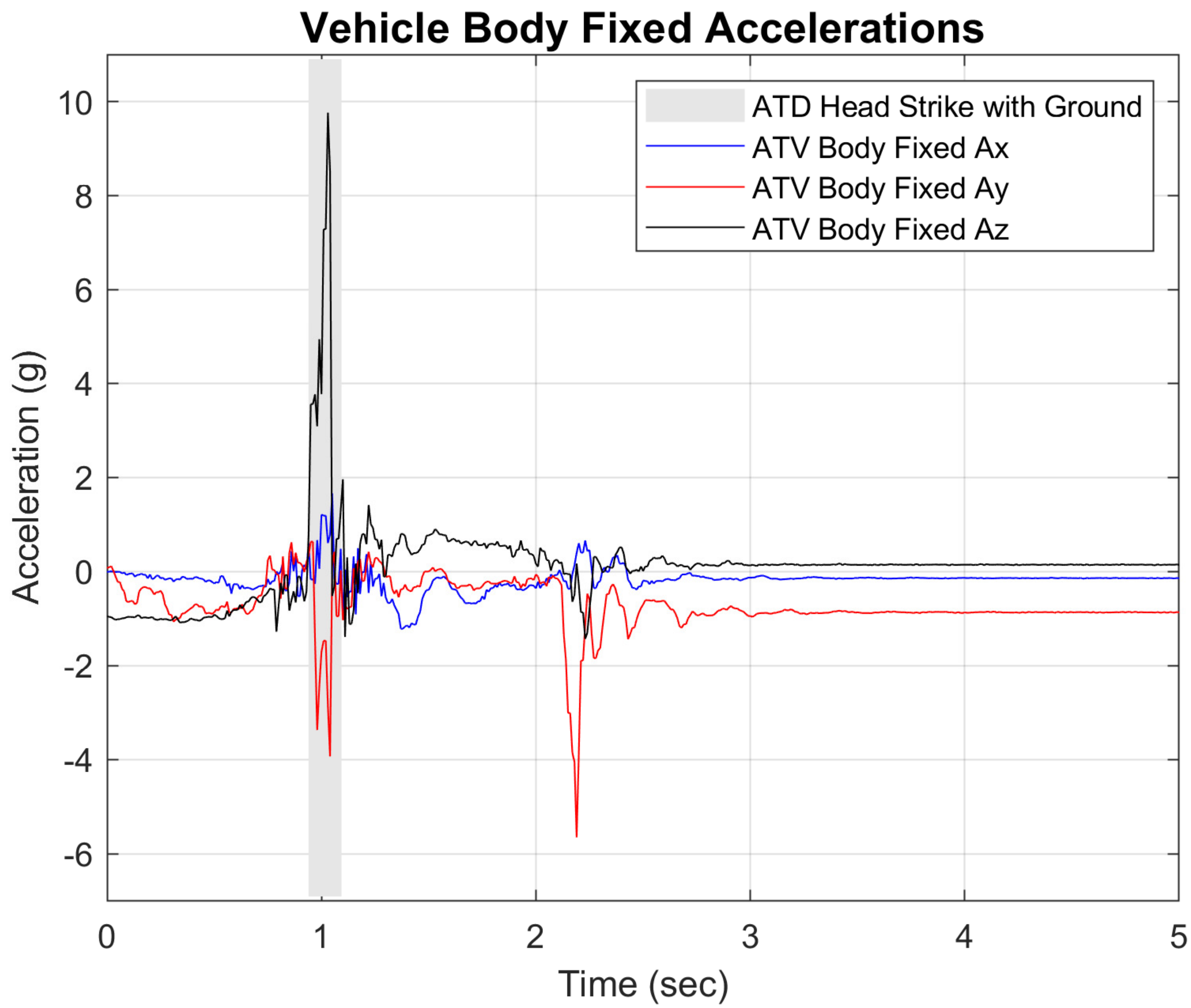
Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



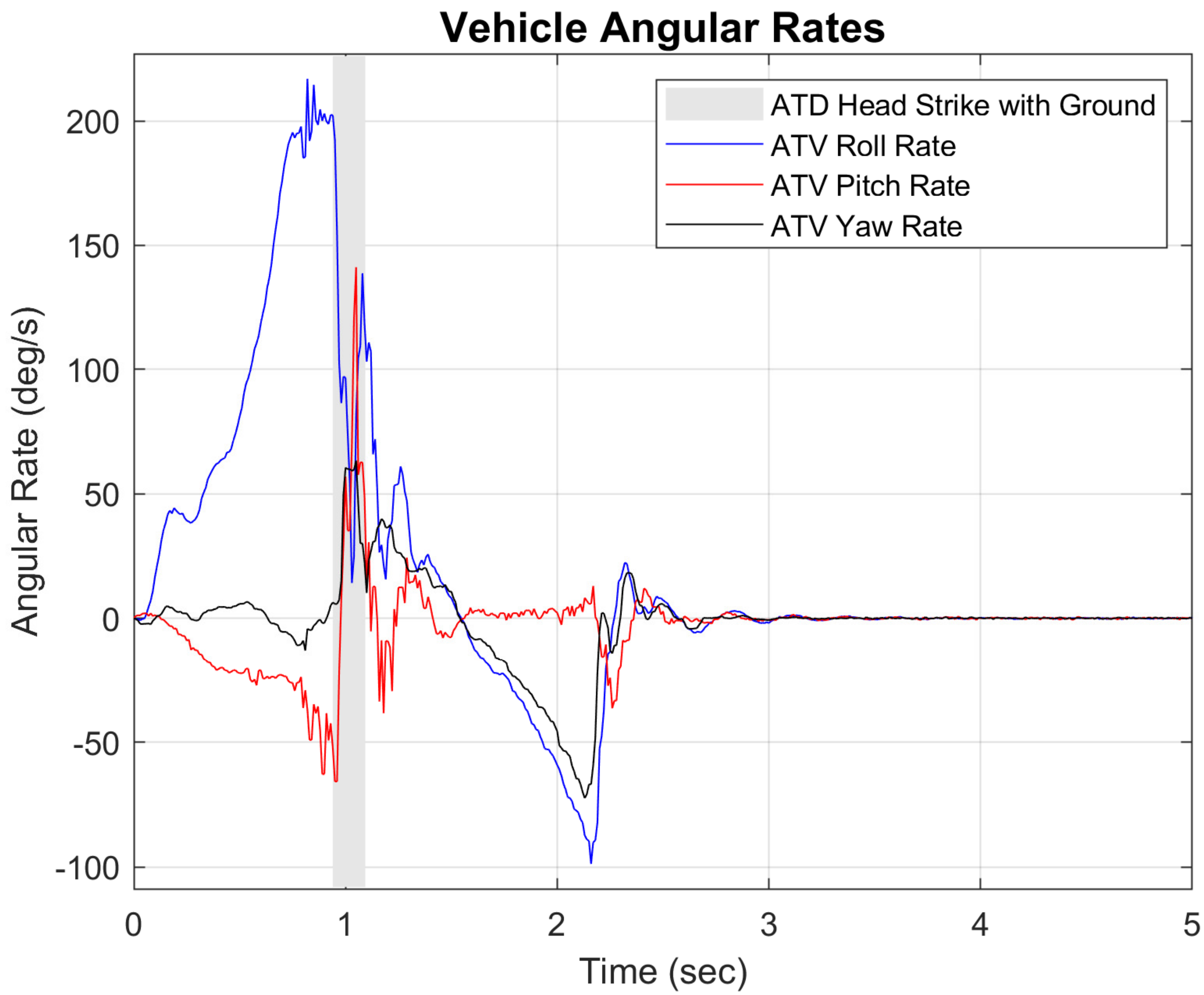
Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



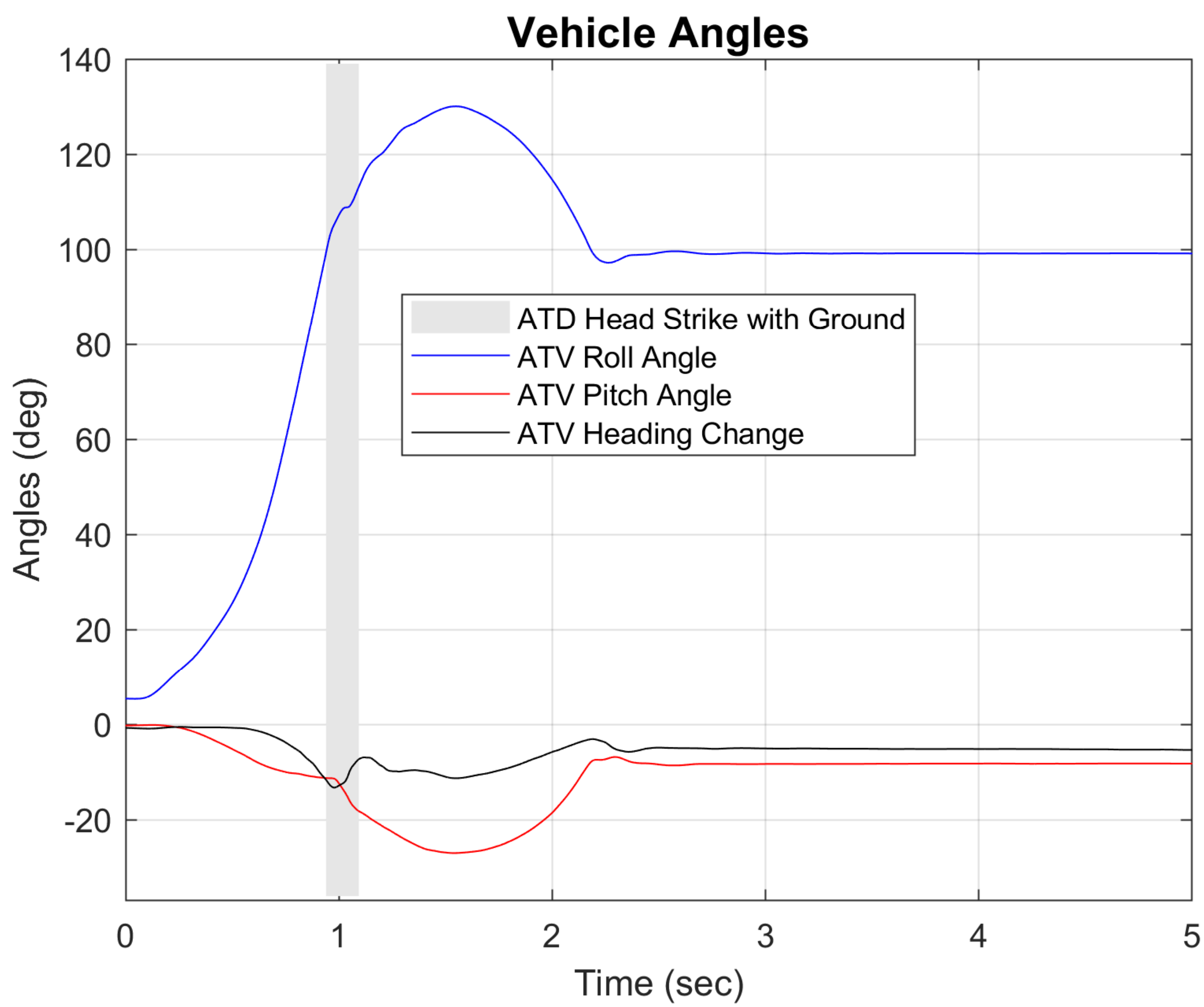
Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD



Vehicle G - Sled Moderate Energy Rollover – POC #3 – Extended Span OPD

Roll Angle = 30° - Time = 0.54 sec

Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD

Roll Angle = 45° - Time = 0.68 sec

Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD

Roll Angle = 90° - Time = 0.95 sec

Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD

ATD Head Strike - Time = 1.10 sec

Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD

Roll Angle = 180° - Time = 1.60 sec

Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD

Max Roll Angle = 197.3° - Time = 2.06 sec

Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD

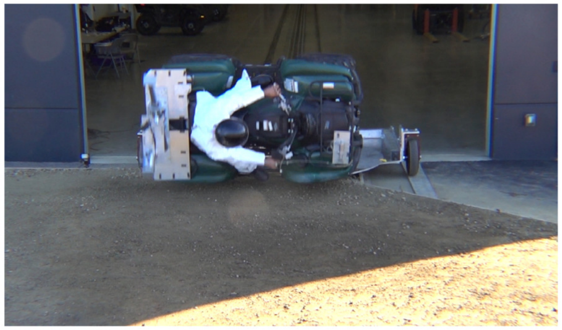
End of Run - Roll Angle = 100.5°

Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD

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

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

Drone Camera - Roll Angle = 90° - Time = 0.95 sec



Drone Camera - ATD Head Strike - Time = 1.10 sec

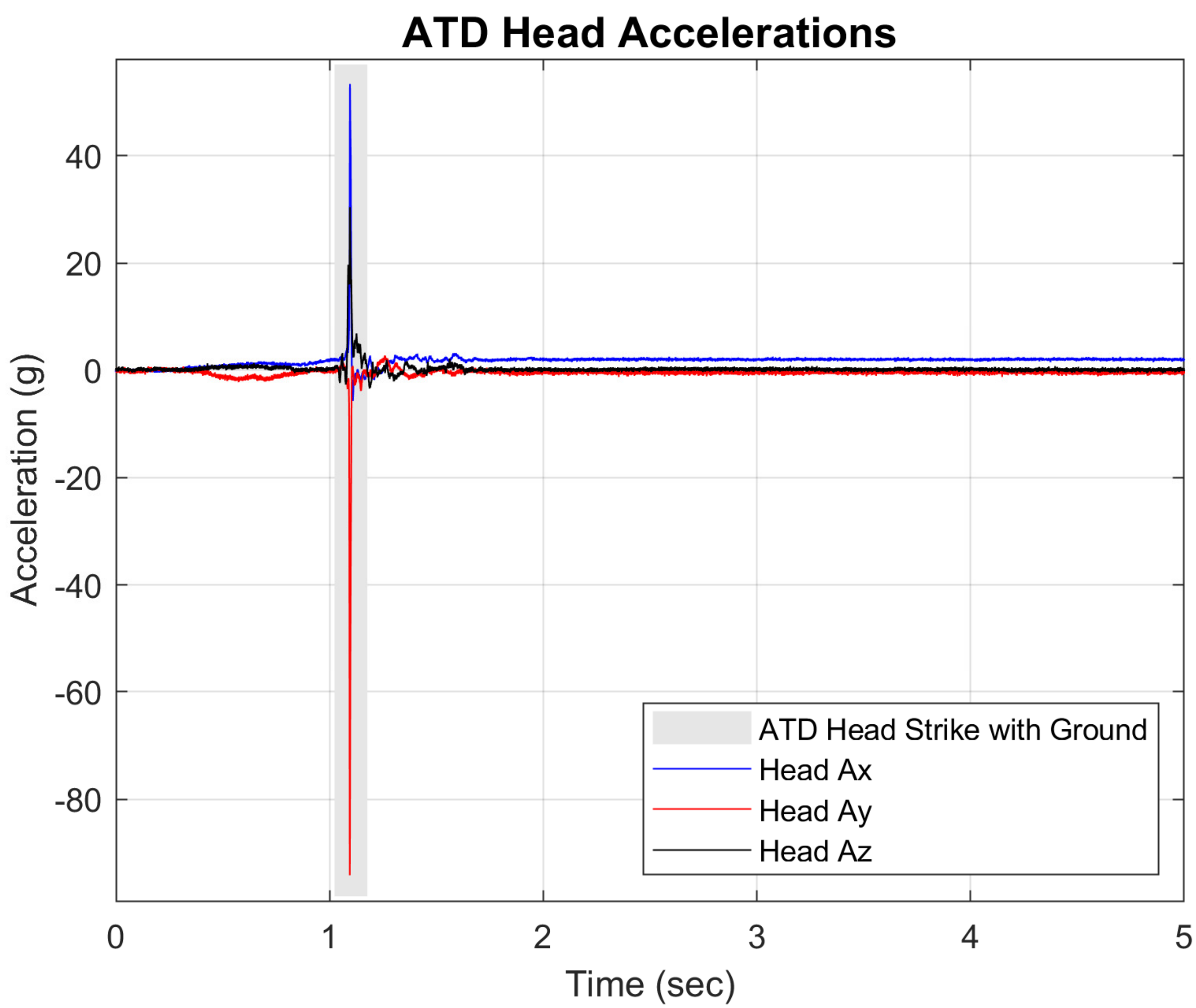
Drone Camera - Roll Angle = 180° - Time = 1.60 sec

Drone Camera - Max Angle = 197.3° - Time = 2.06 sec

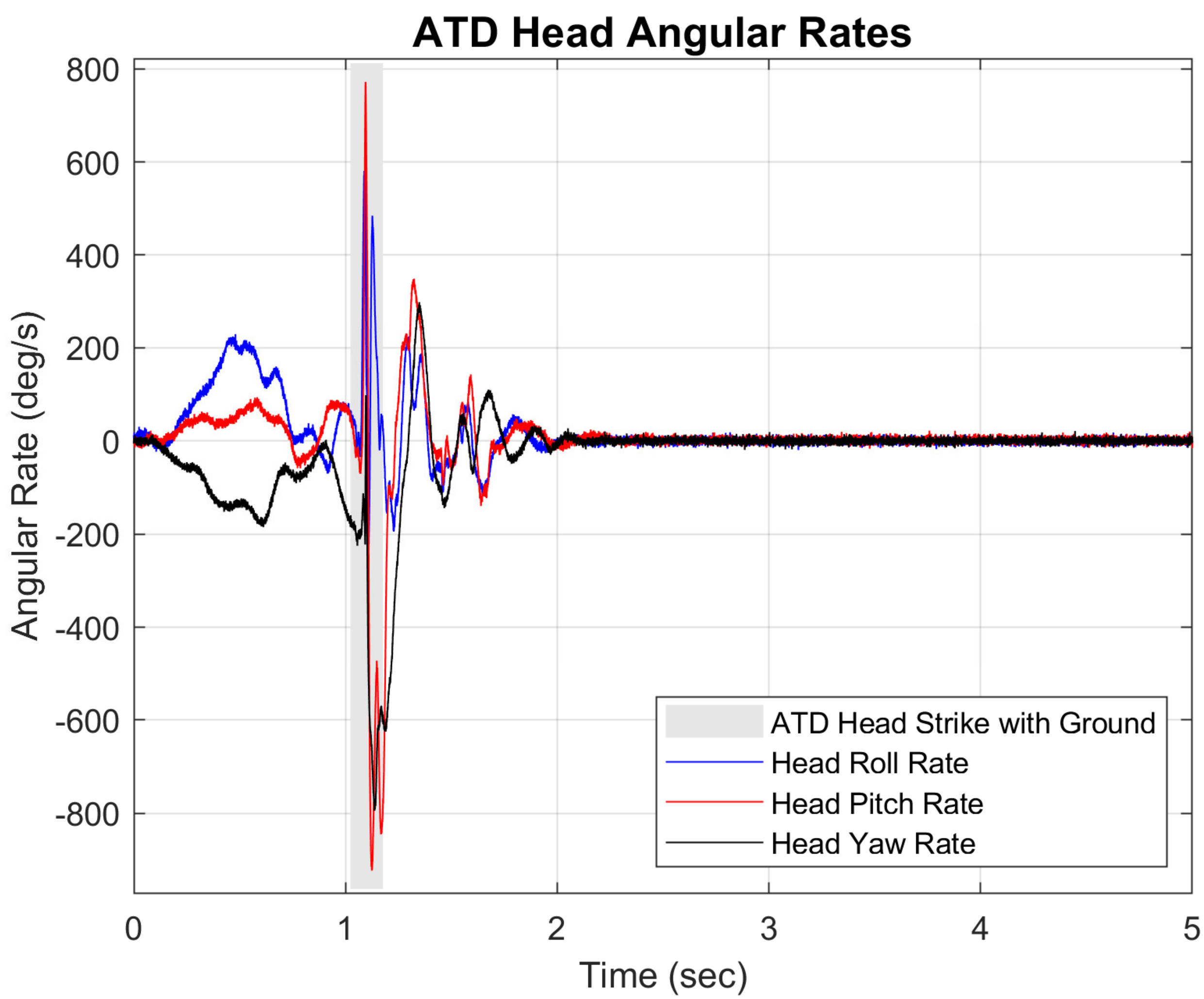
Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD

Drone Camera - End of Run - Roll Angle = 100.5°

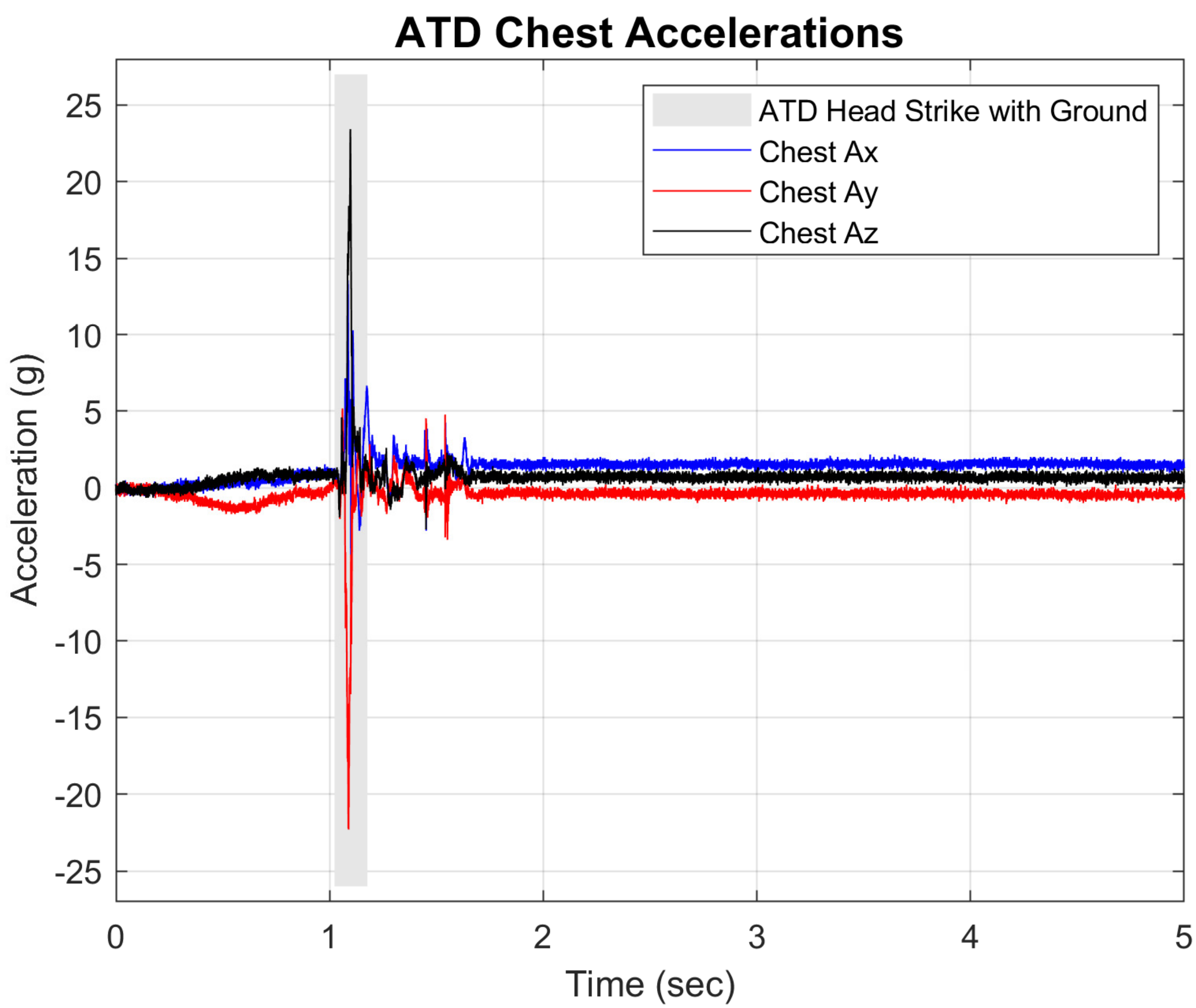
Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD



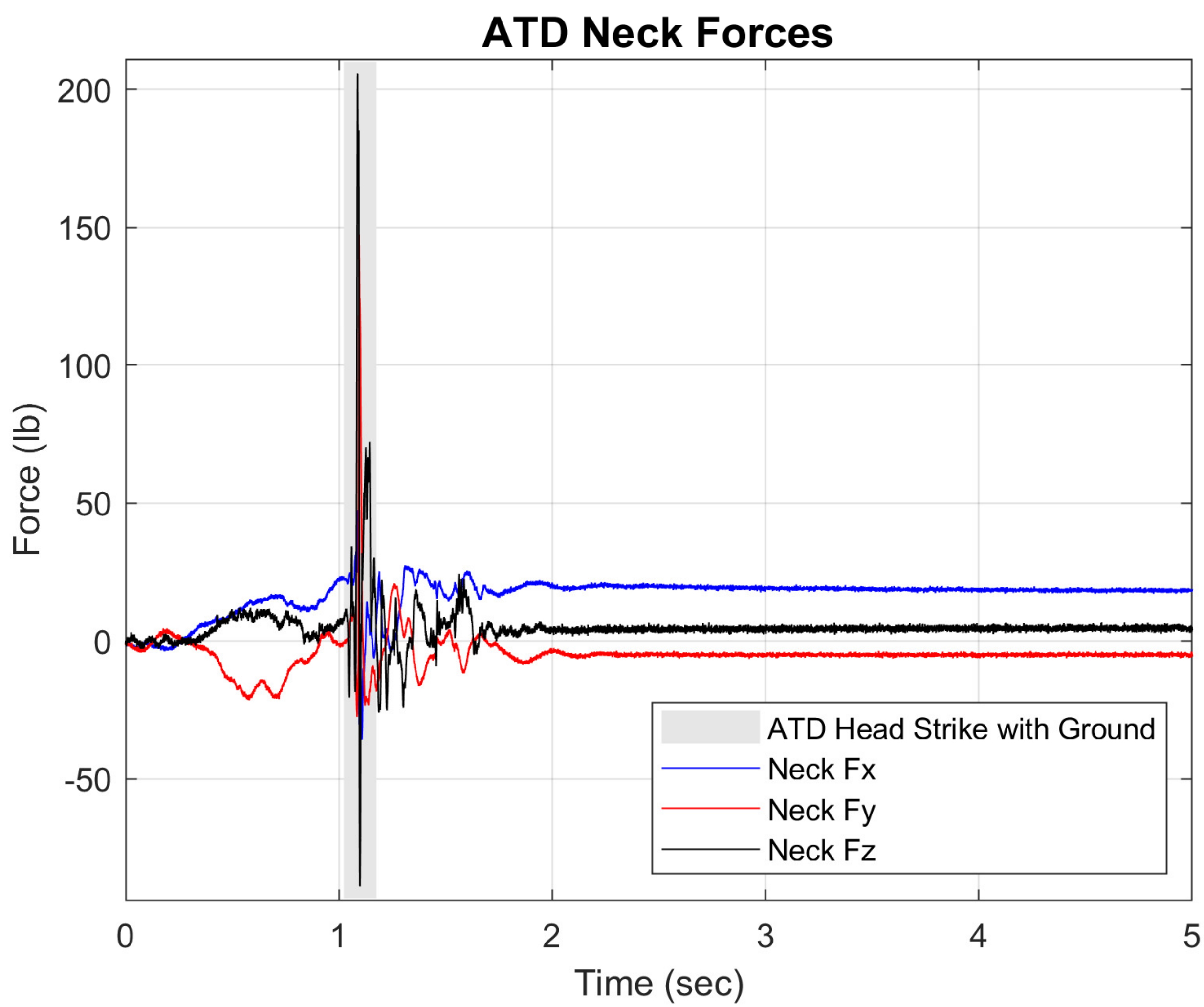
Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD



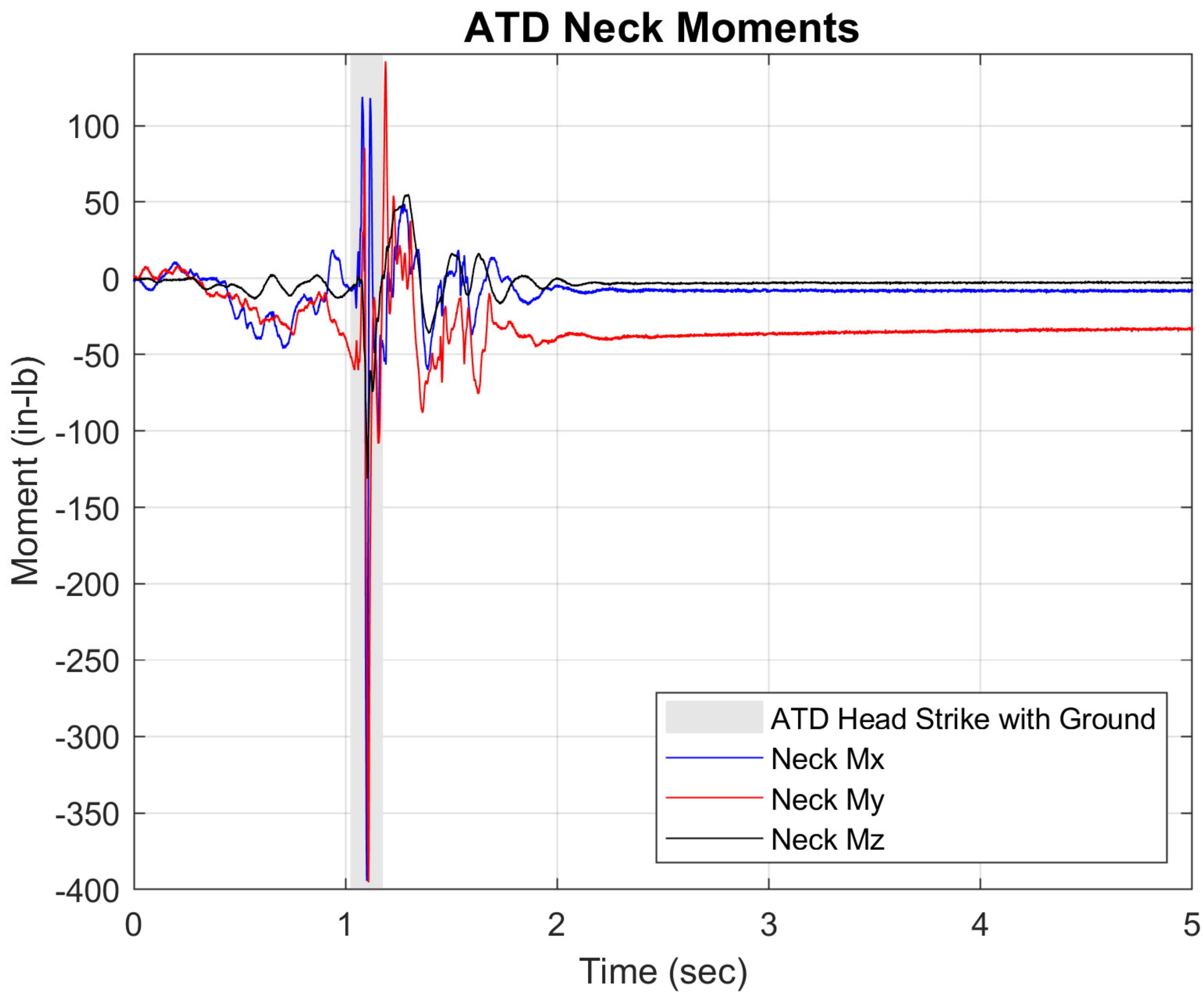
Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD



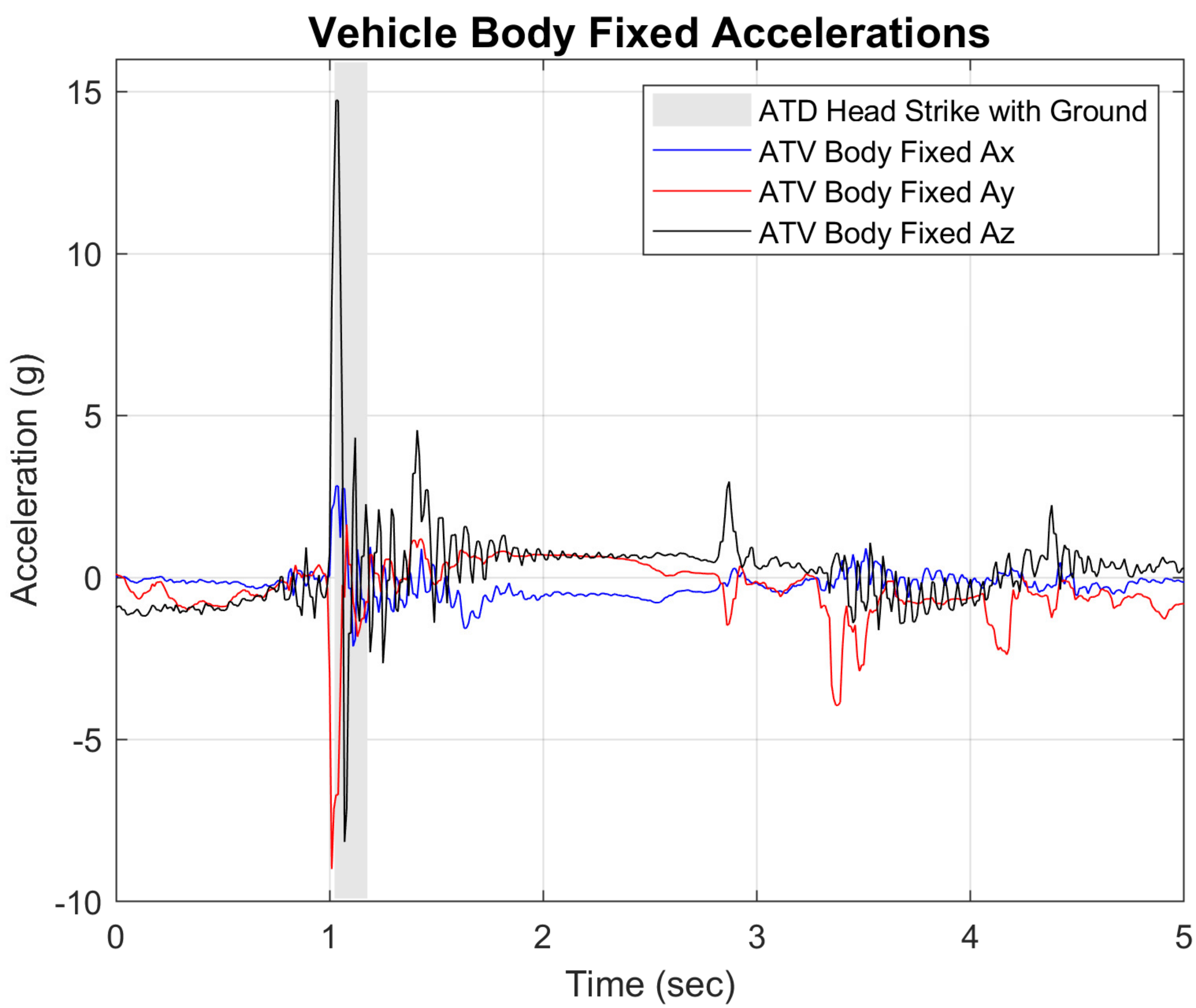
Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD



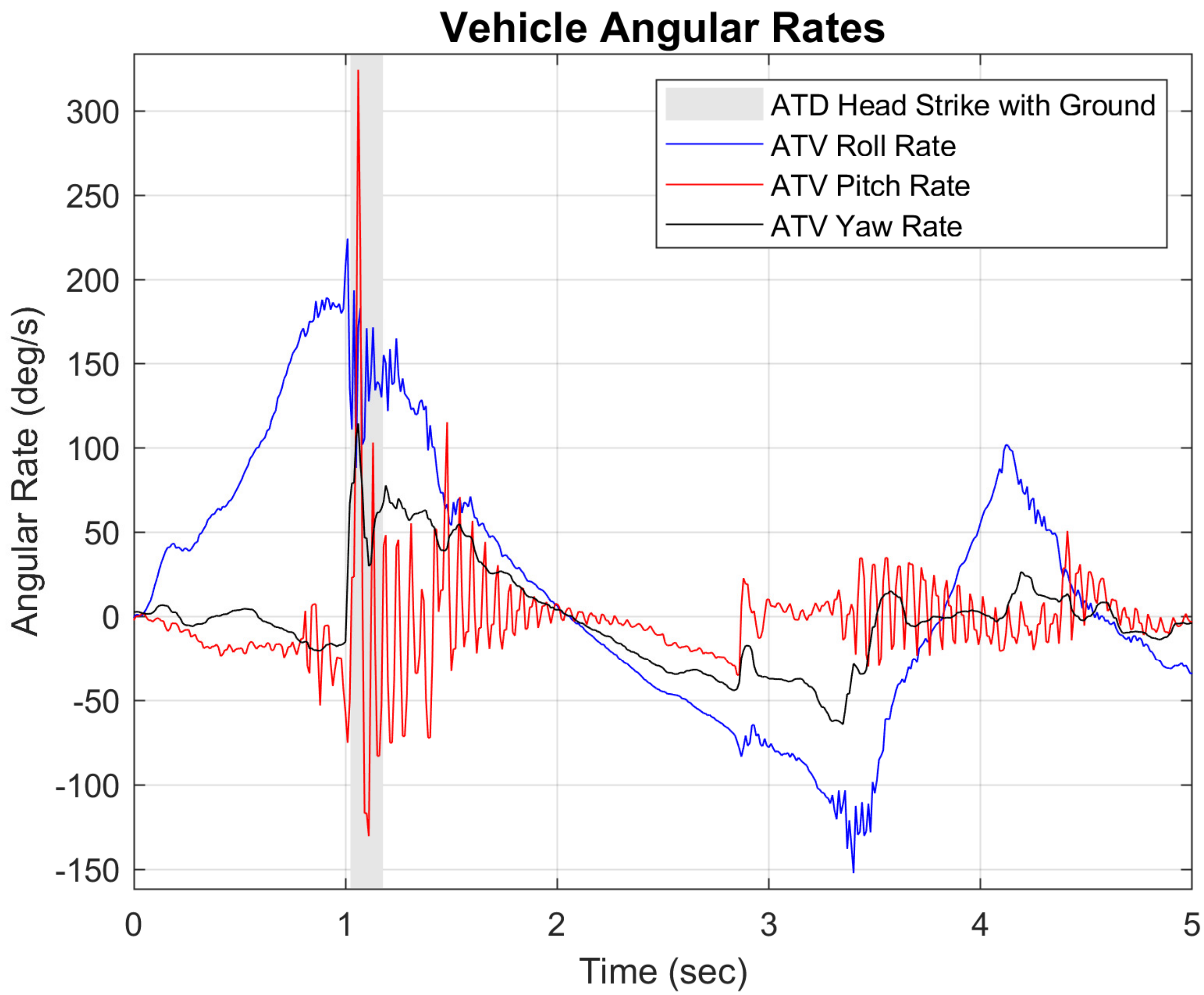
Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD



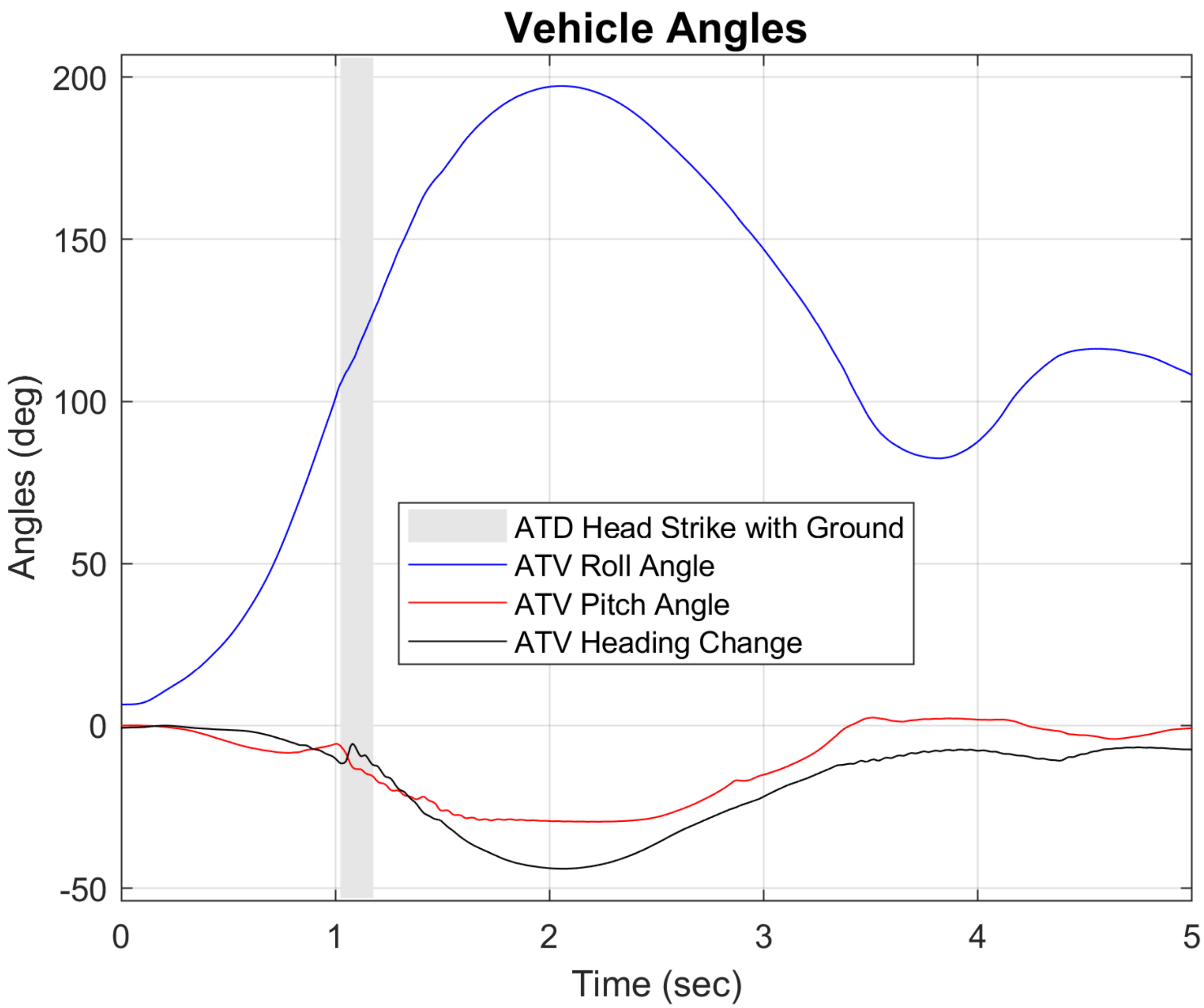
Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD



Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD



Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD



Vehicle C - Sled Moderate Energy Rollover – POC #3 Extra – Extended Span OPD

Roll Angle = 30° - Time = 0.53 sec

Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

Roll Angle = 45° - Time = 0.67 sec

Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

Roll Angle = 90° - Time = 0.92 sec

Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

ATD Head Strike - Time = 1.05 sec

Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

Max Roll Angle = 177.9° - Time = 1.98 sec

Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

End of Run - Roll Angle = 107.0°

Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

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

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

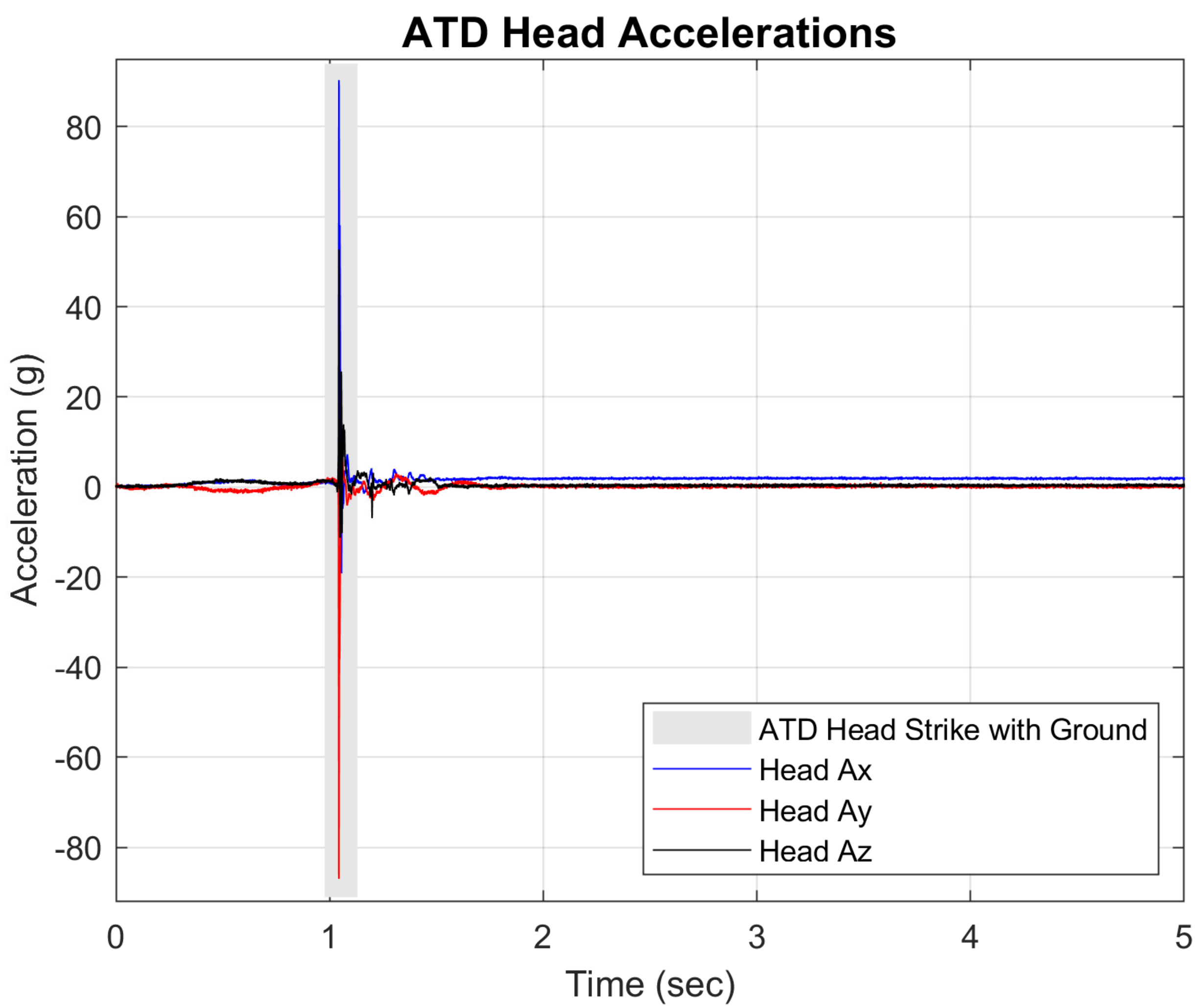
Drone Camera - Roll Angle = 90° - Time = 0.92 sec

Drone Camera - ATD Head Strike - Time = 1.05 sec

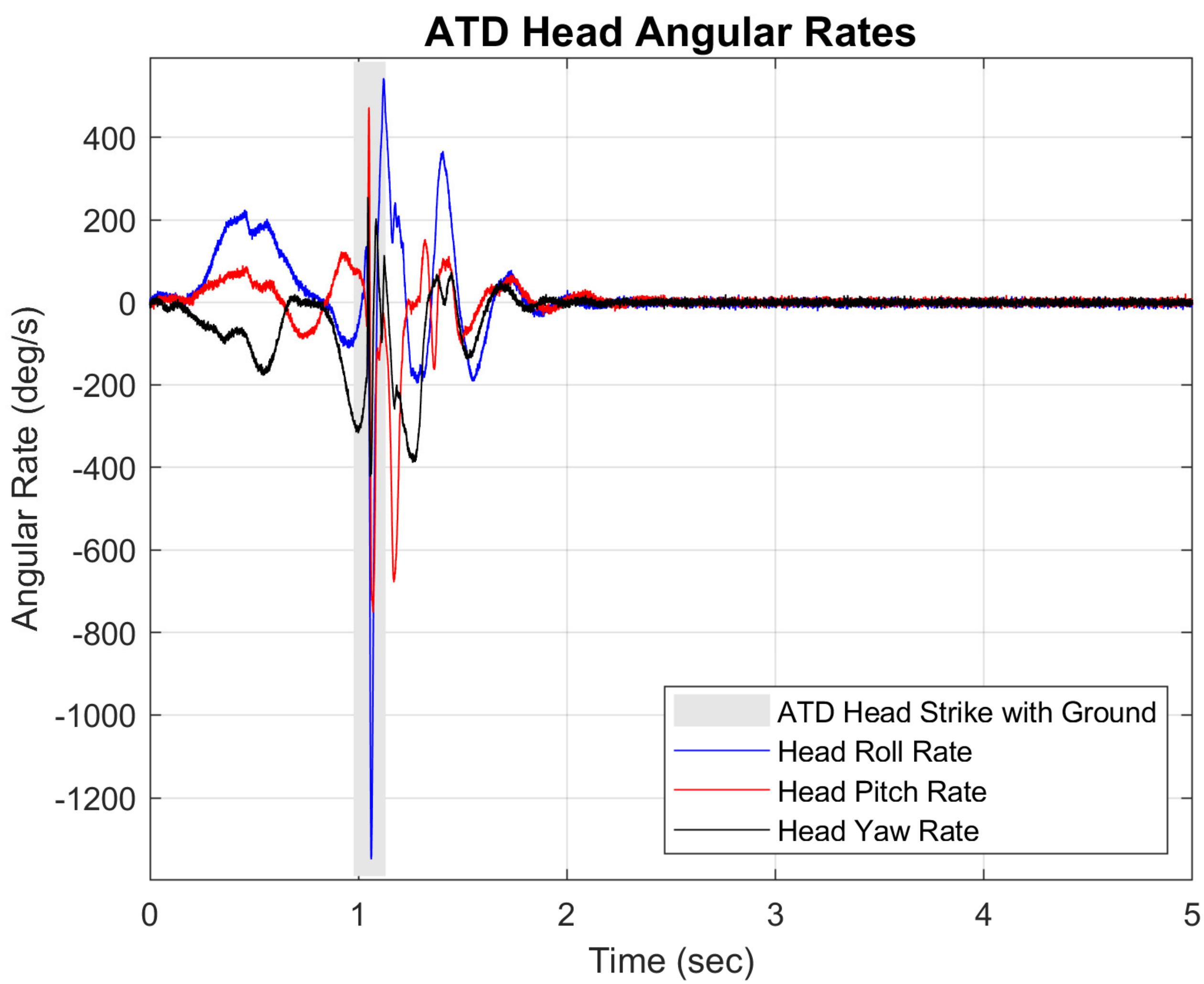
Drone Camera - Max Angle = 177.9° - Time = 1.98 sec

Drone Camera - End of Run - Roll Angle = 107.0°

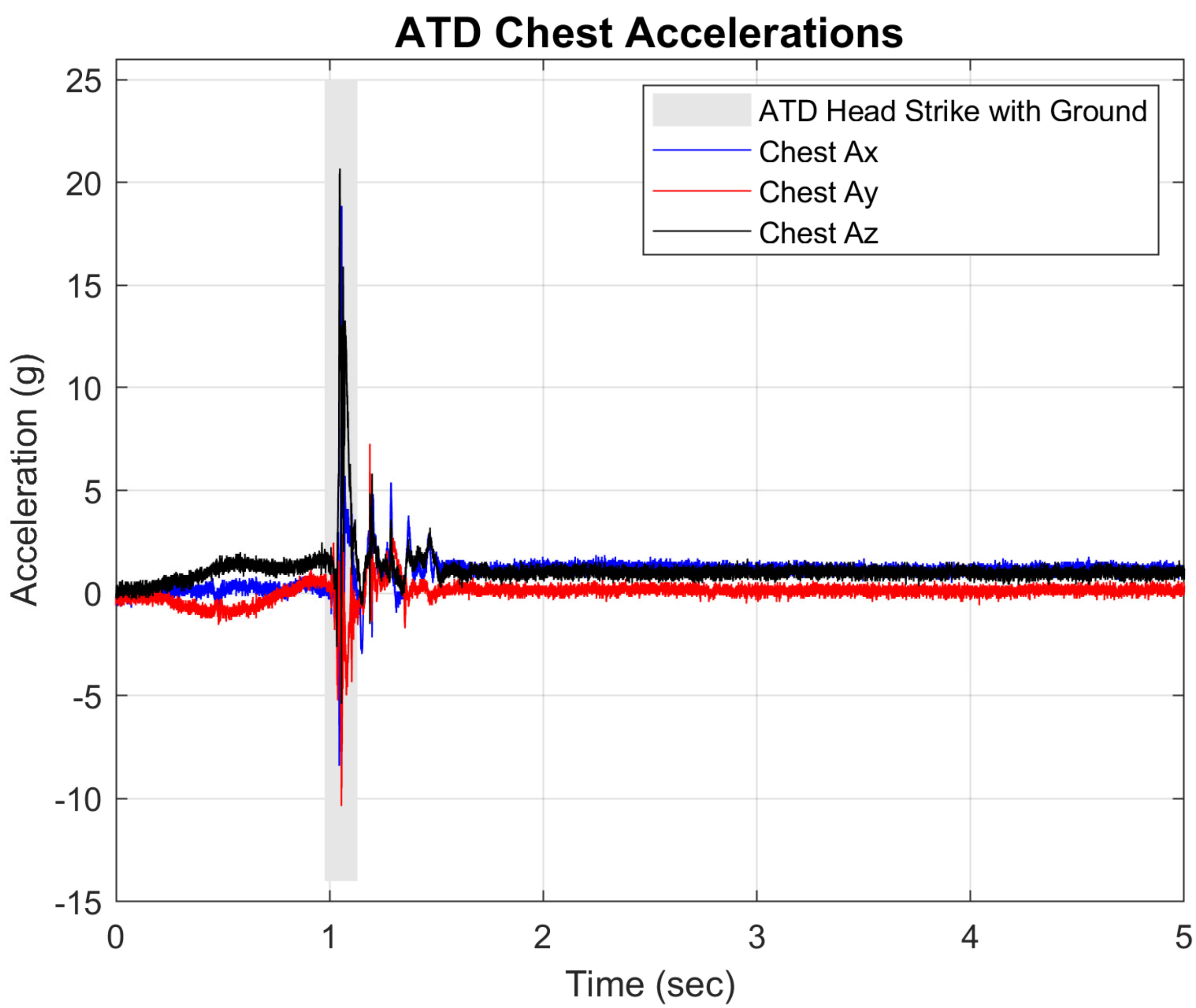
Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



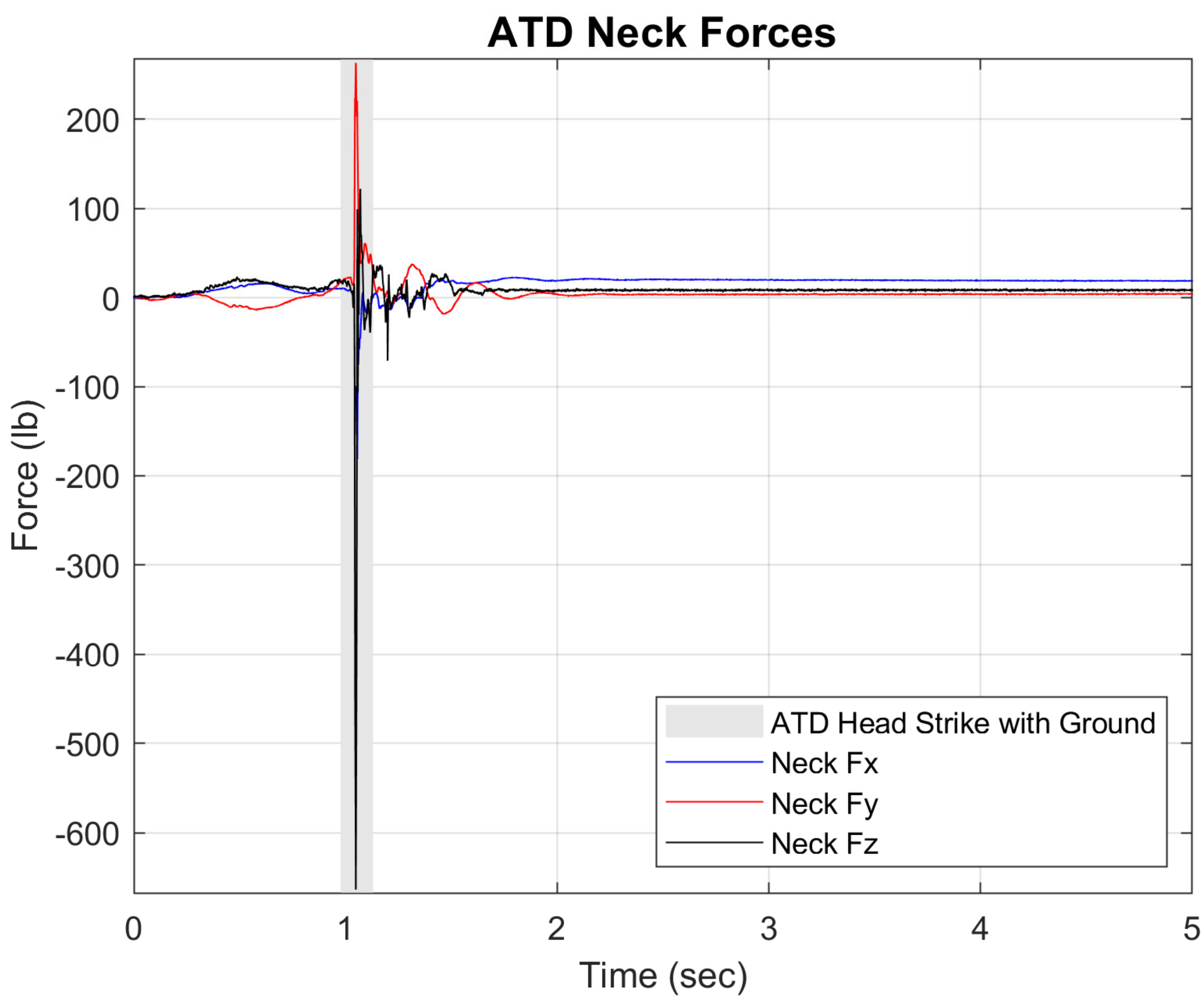
Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



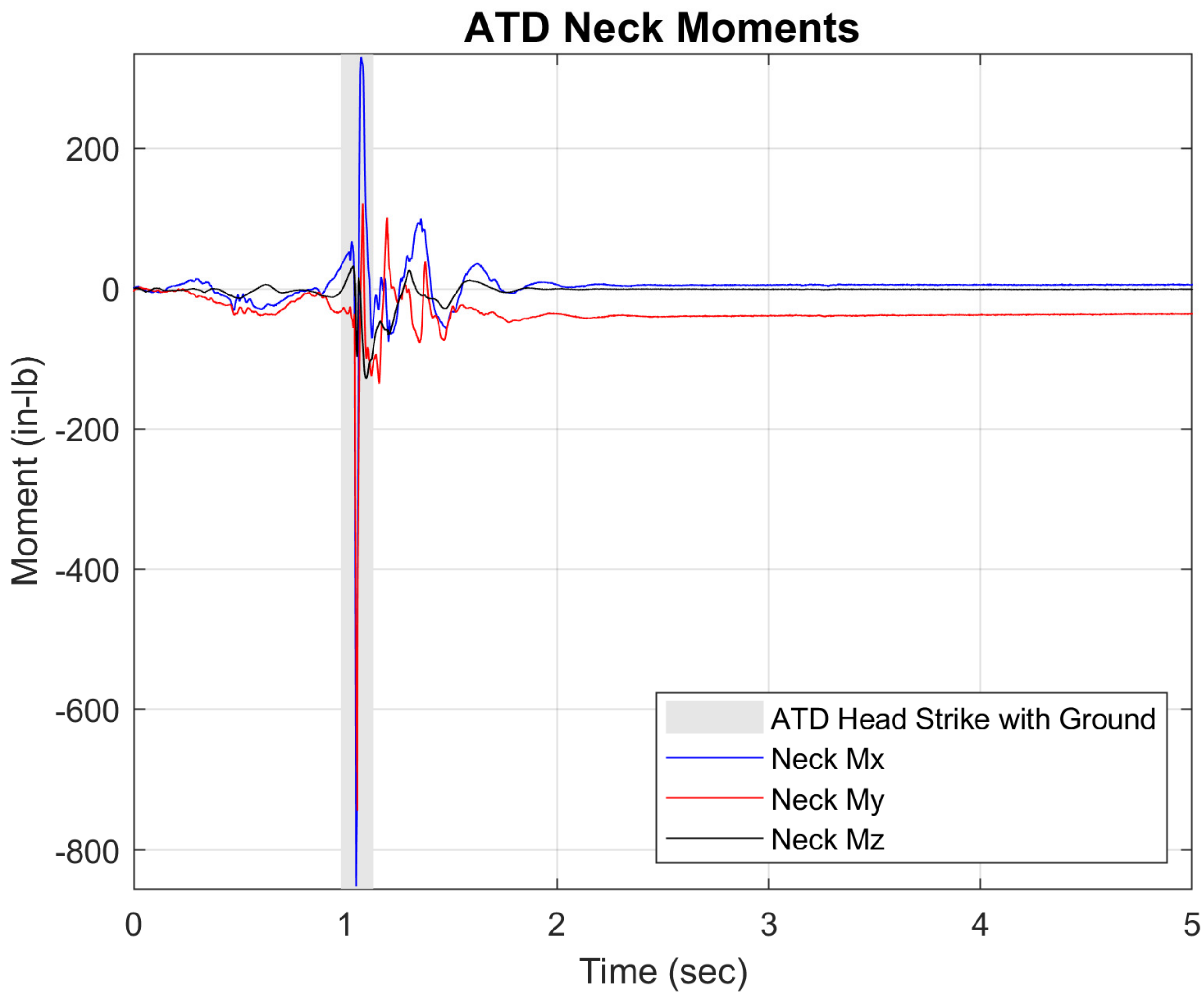
Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



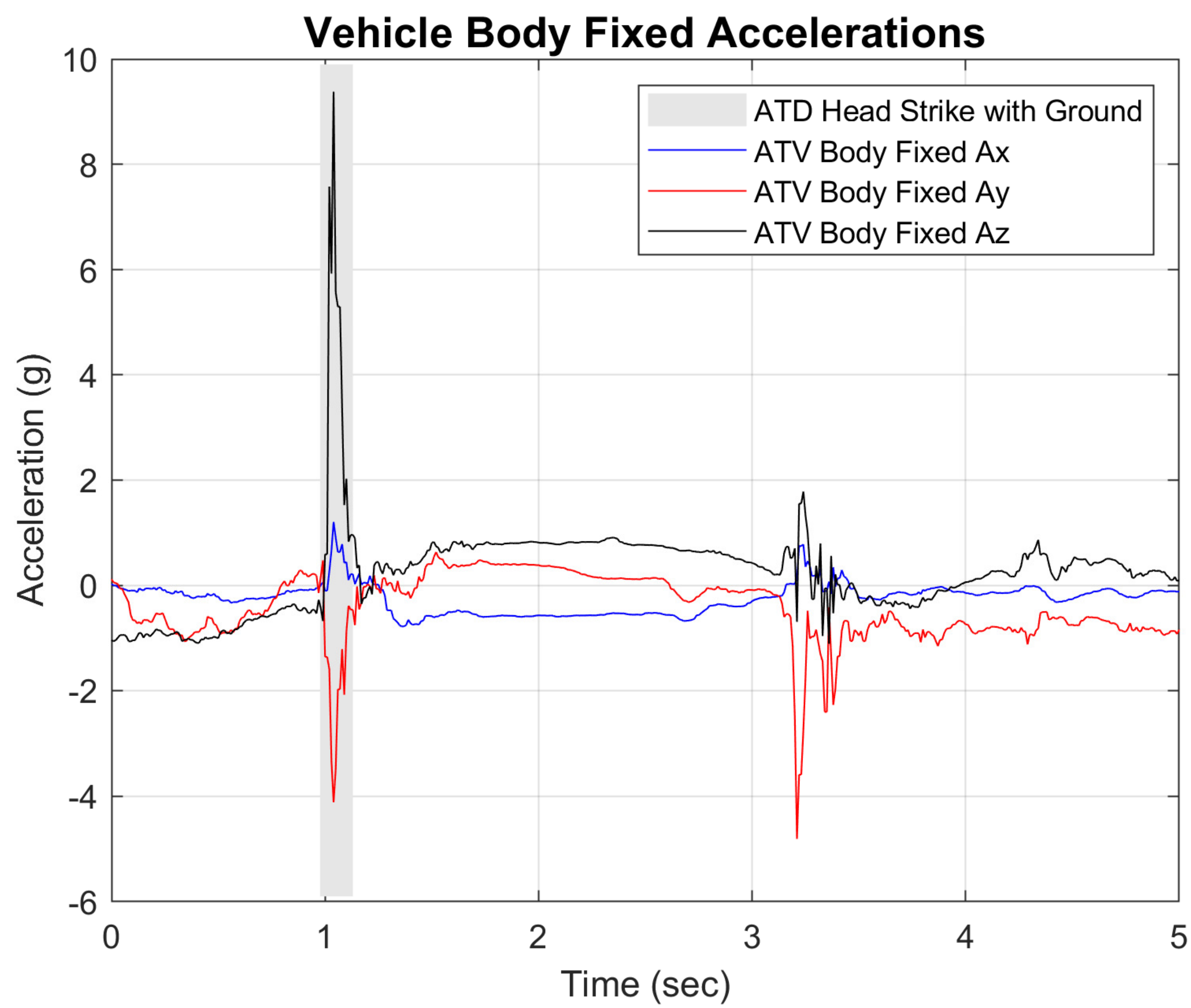
Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



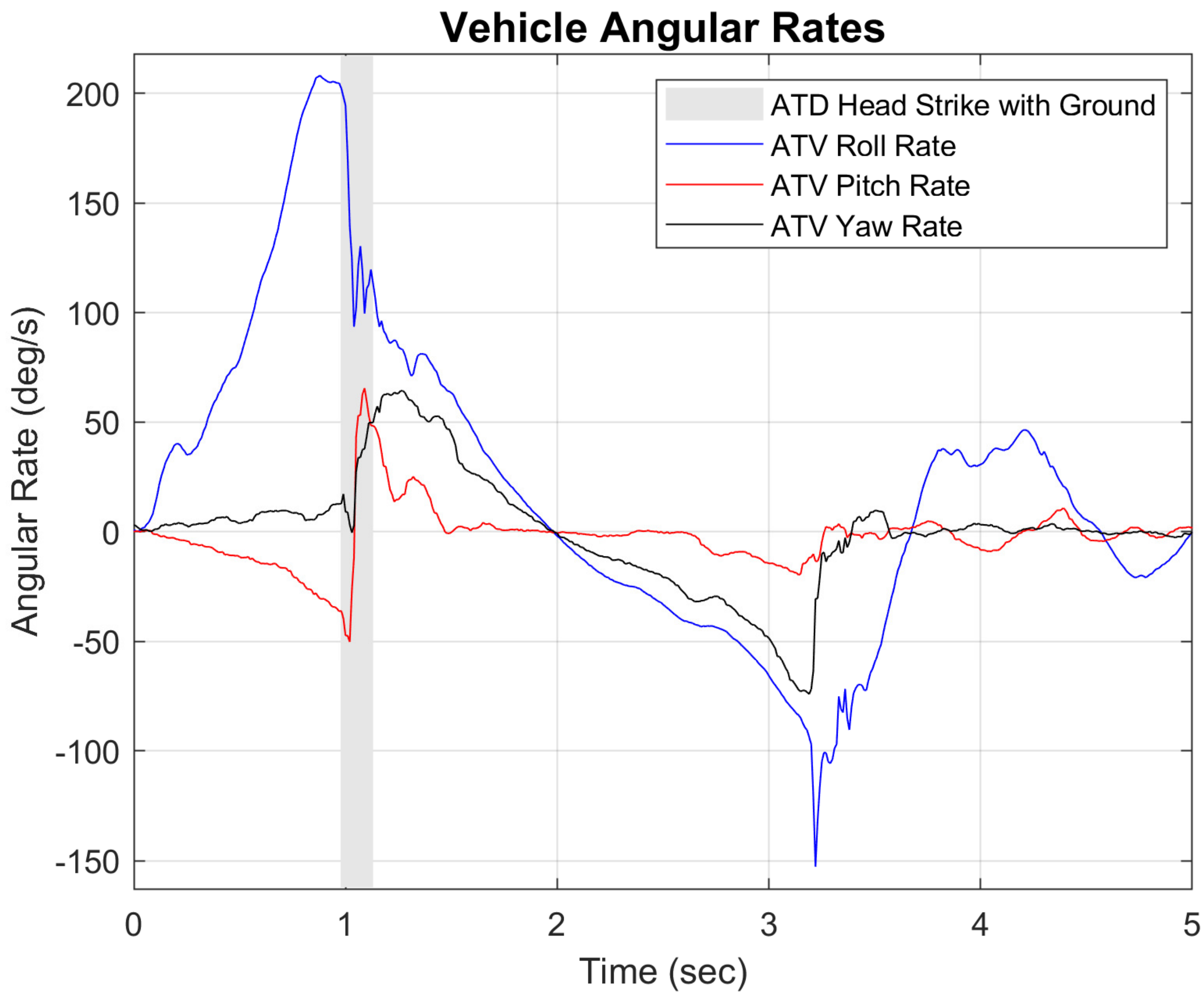
Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



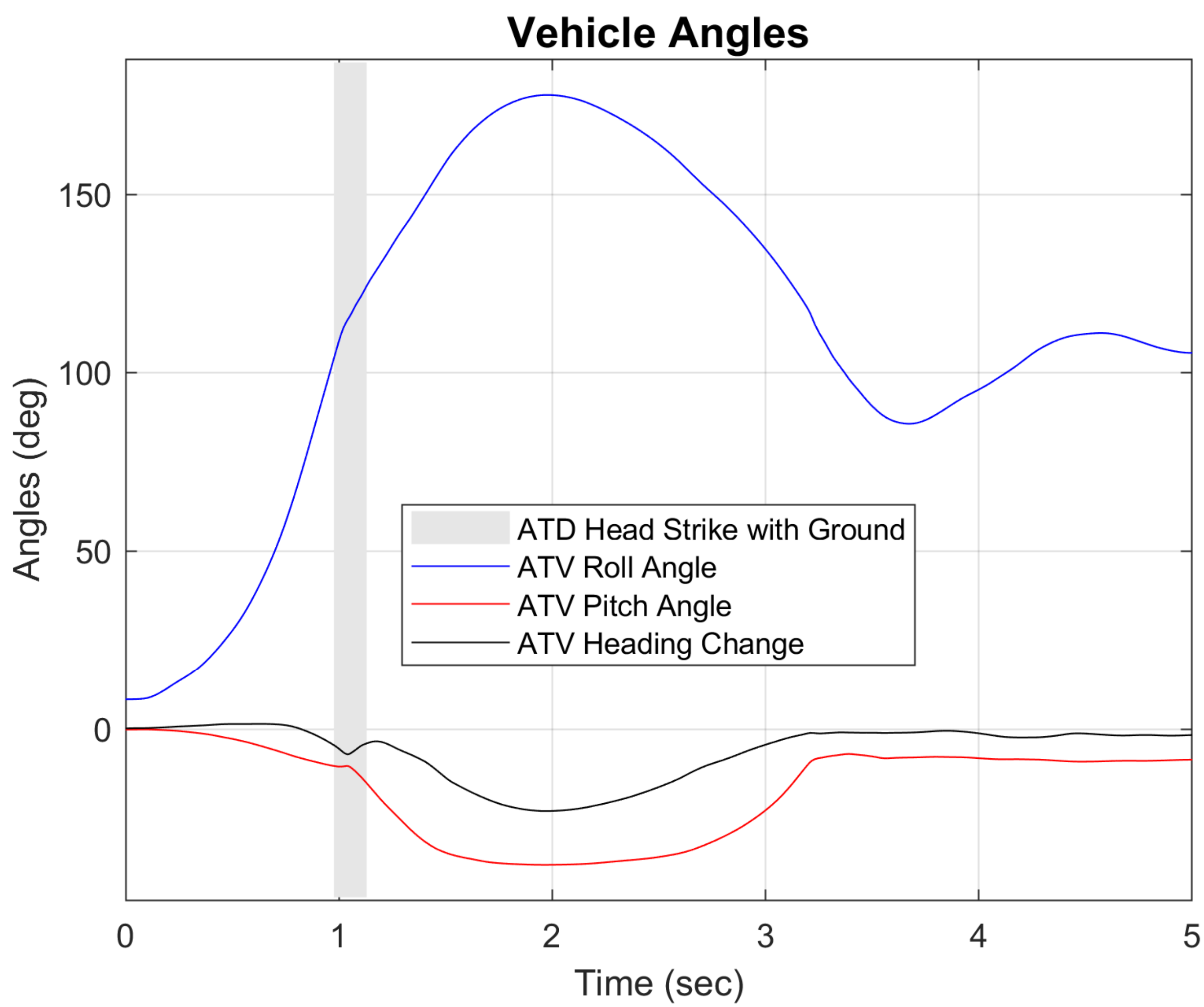
Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



Vehicle E - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

Roll Angle = 30° - Time = 0.52 sec

Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

Roll Angle = 45° - Time = 0.65 sec

Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

Roll Angle = 90° - Time = 0.90 sec

Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

ATD Head Strike - Time = 0.98 sec

Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

Max Roll Angle = 171.5° - Time = 2.08 sec

Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

End of Run - Roll Angle = 118.0°

Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

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

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

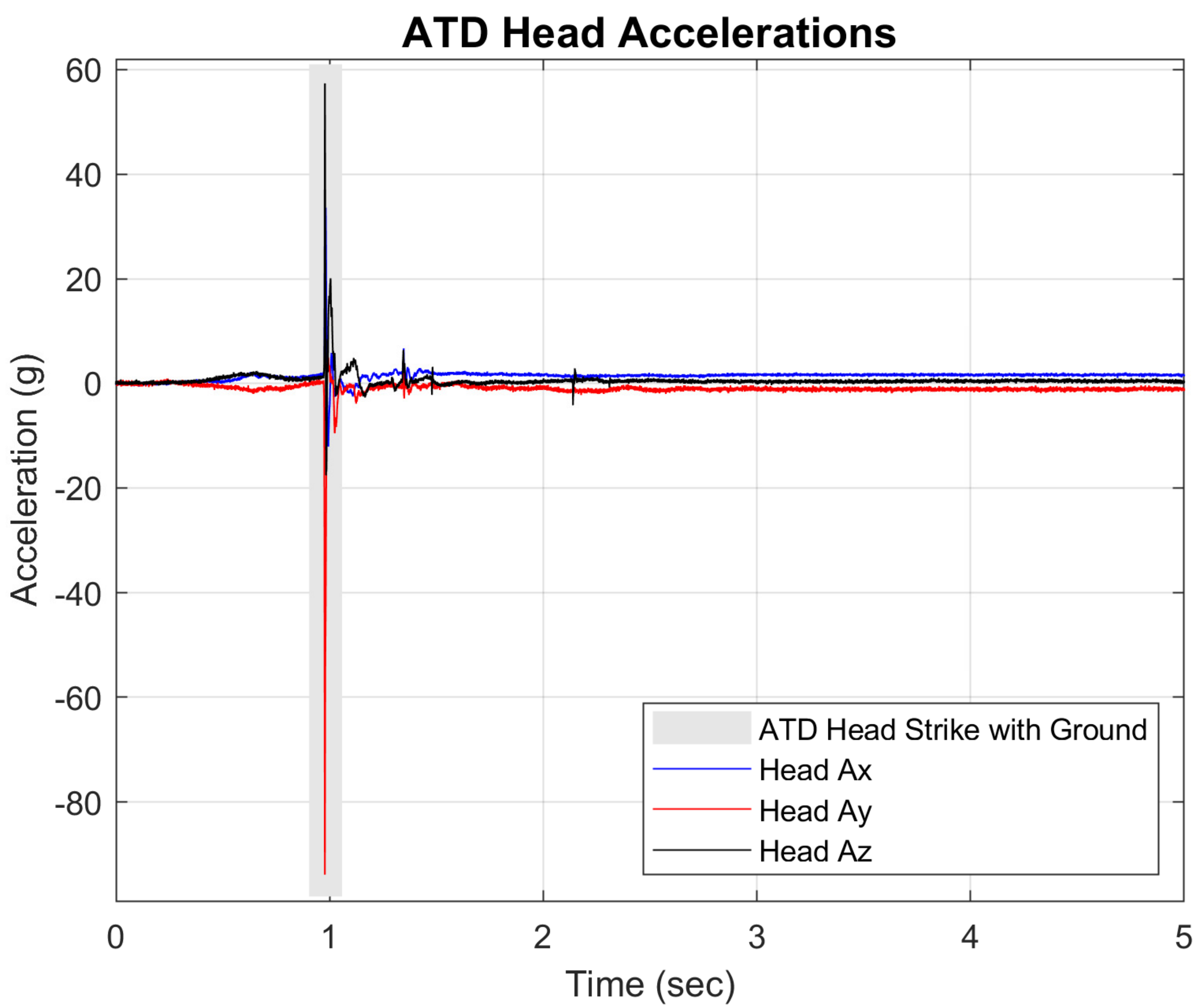
Drone Camera - Roll Angle = 90° - Time = 0.90 sec

Drone Camera - ATD Head Strike - Time = 0.98 sec

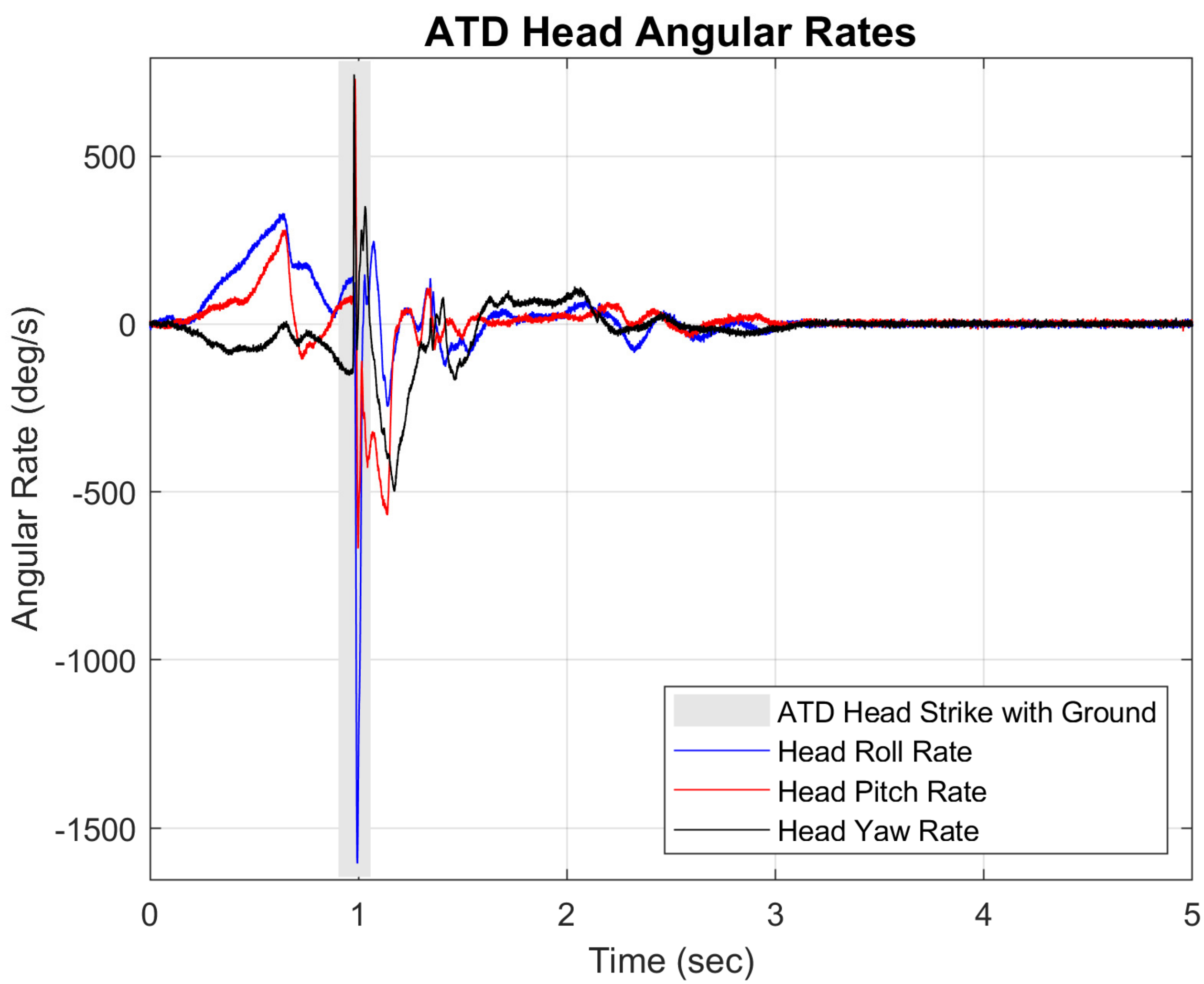
Drone Camera - Max Angle = 171.5° - Time = 2.08 sec

Drone Camera - End of Run - Roll Angle = 118.0°

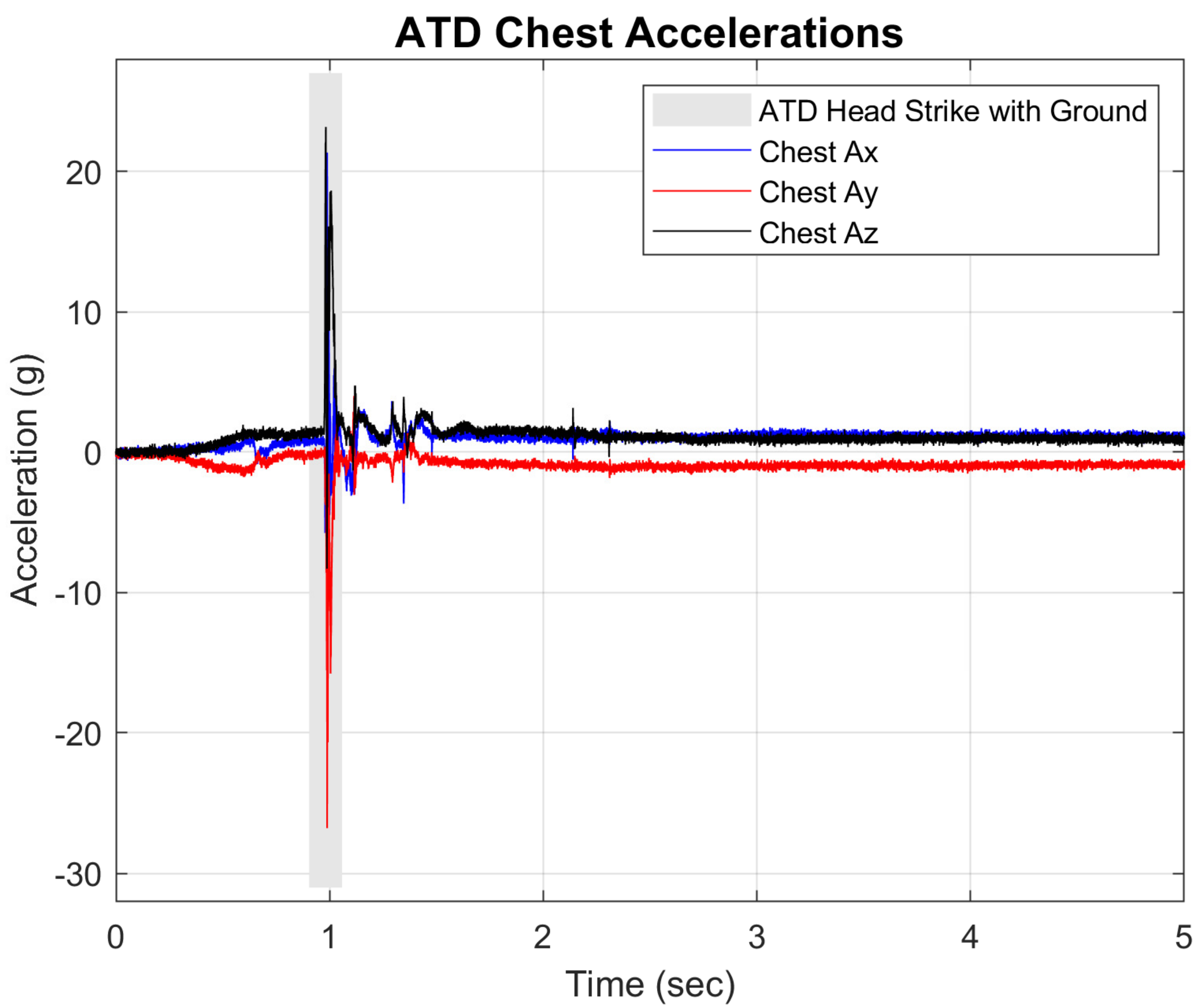
Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



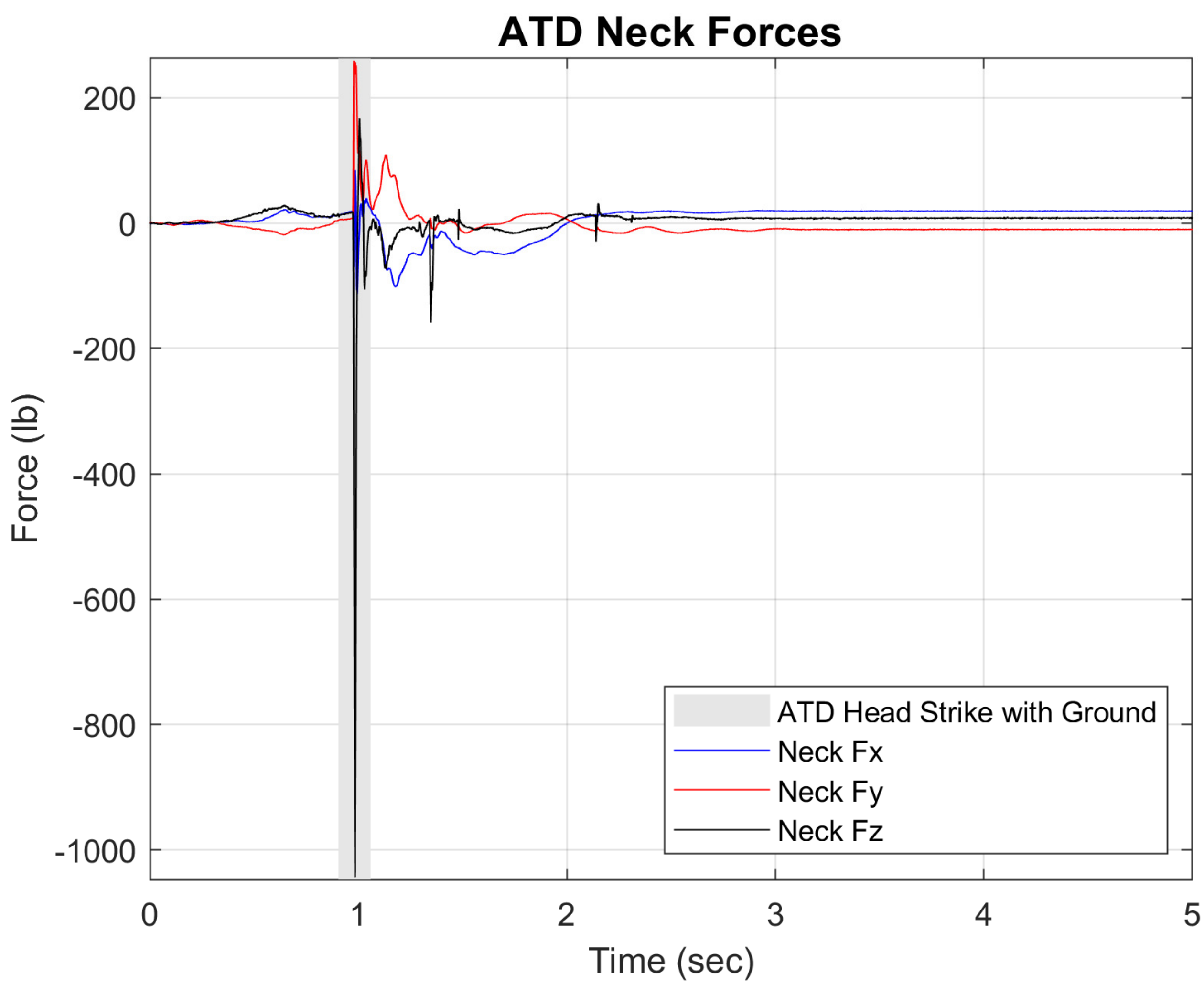
Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



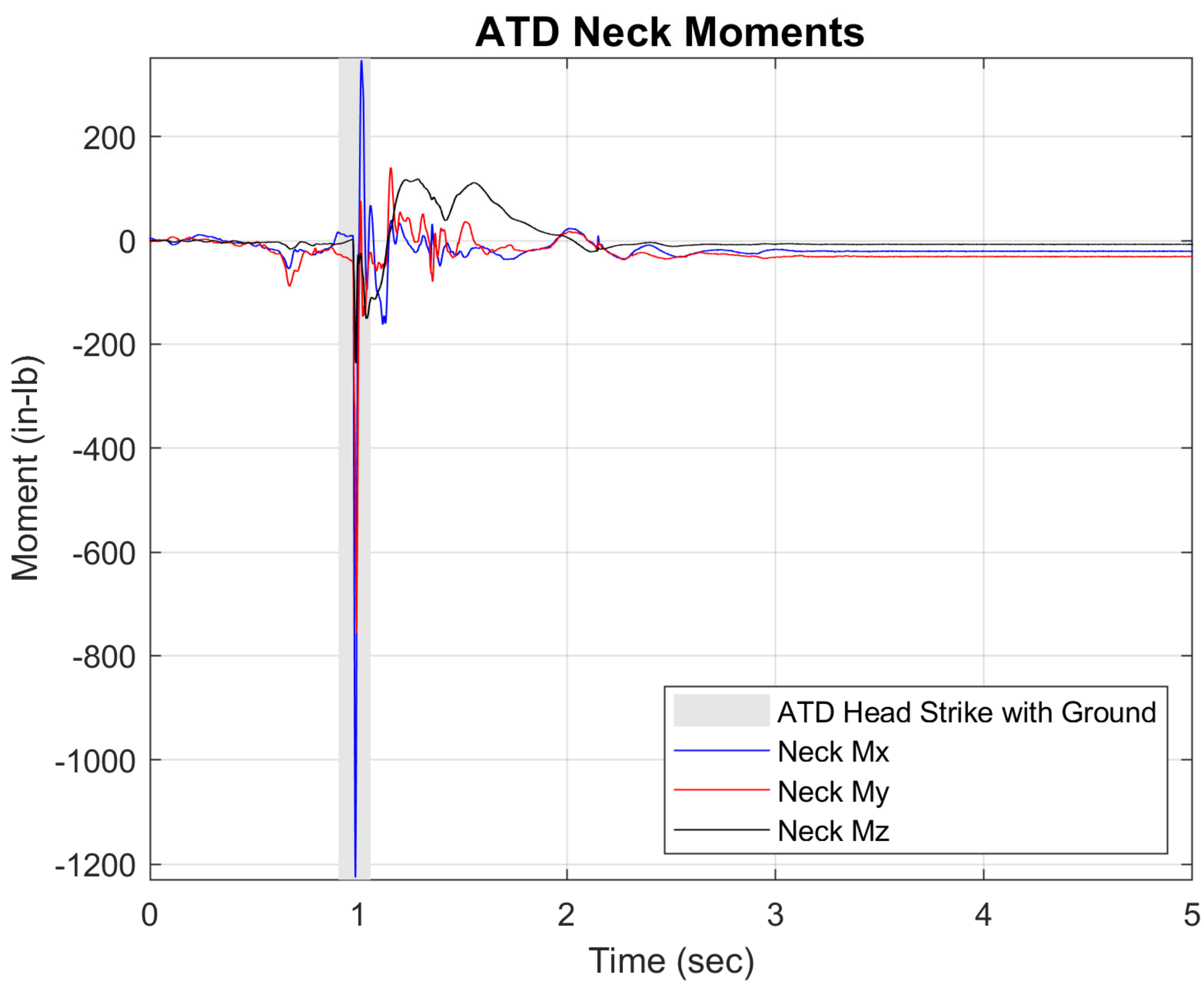
Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



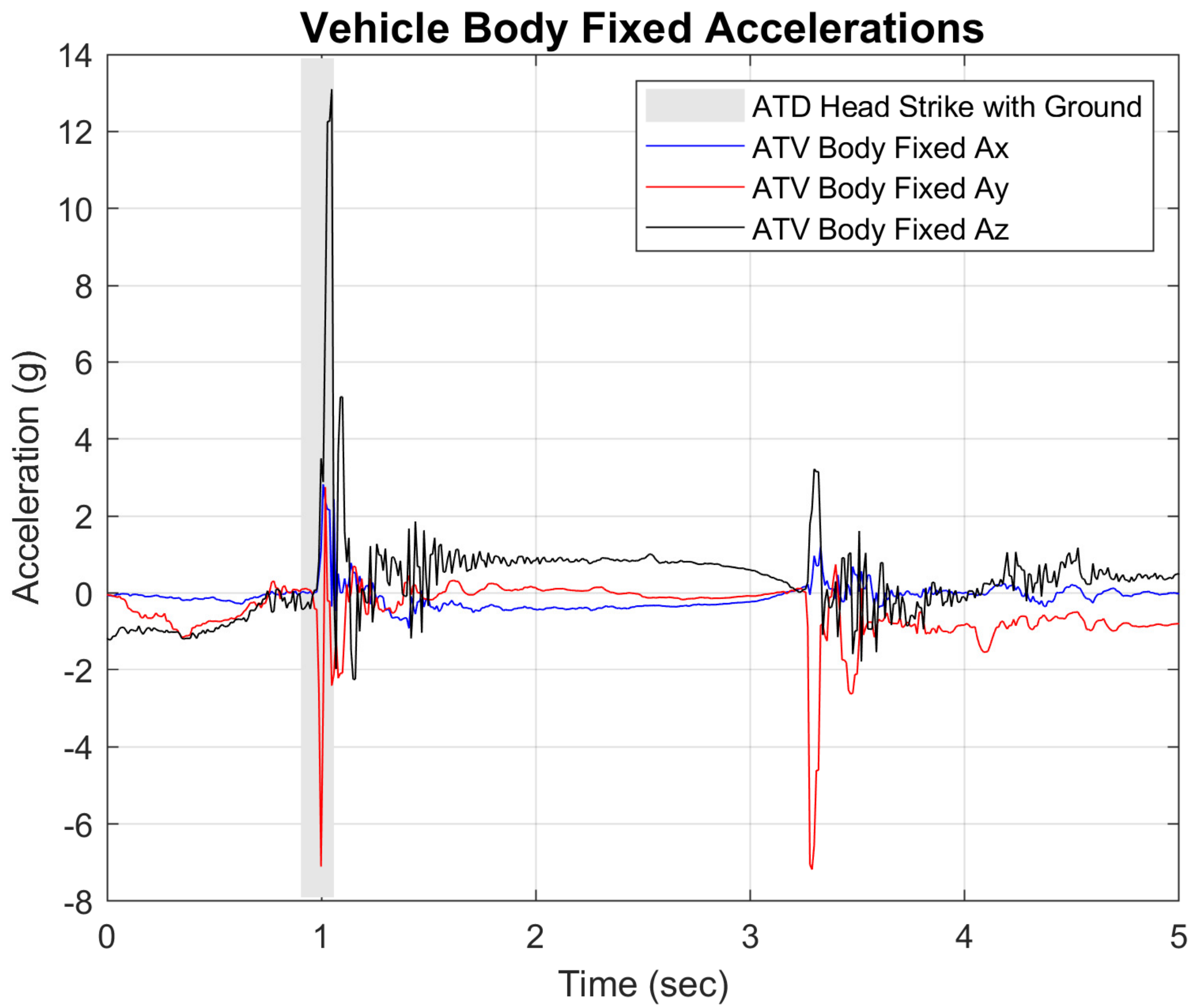
Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



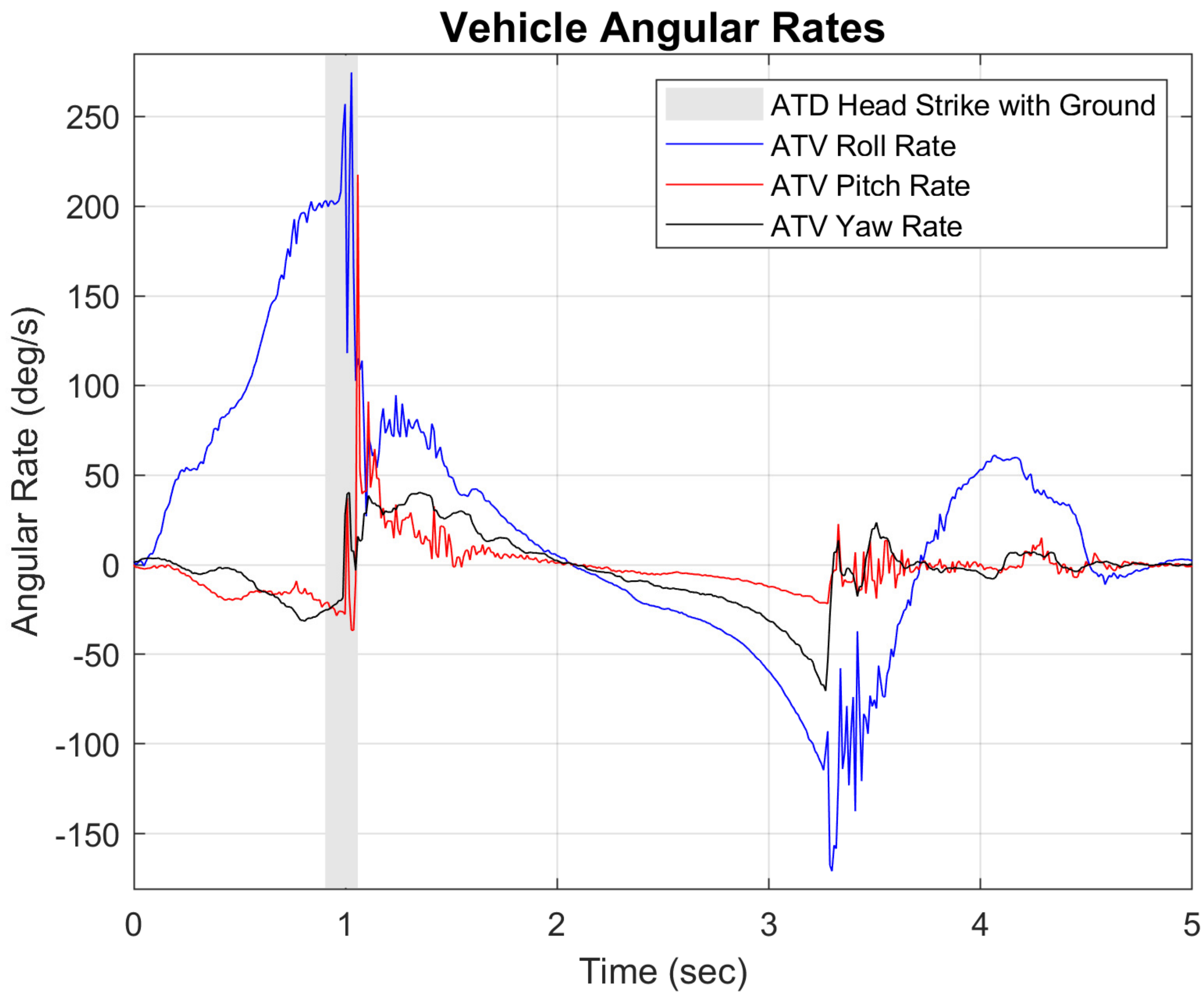
Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



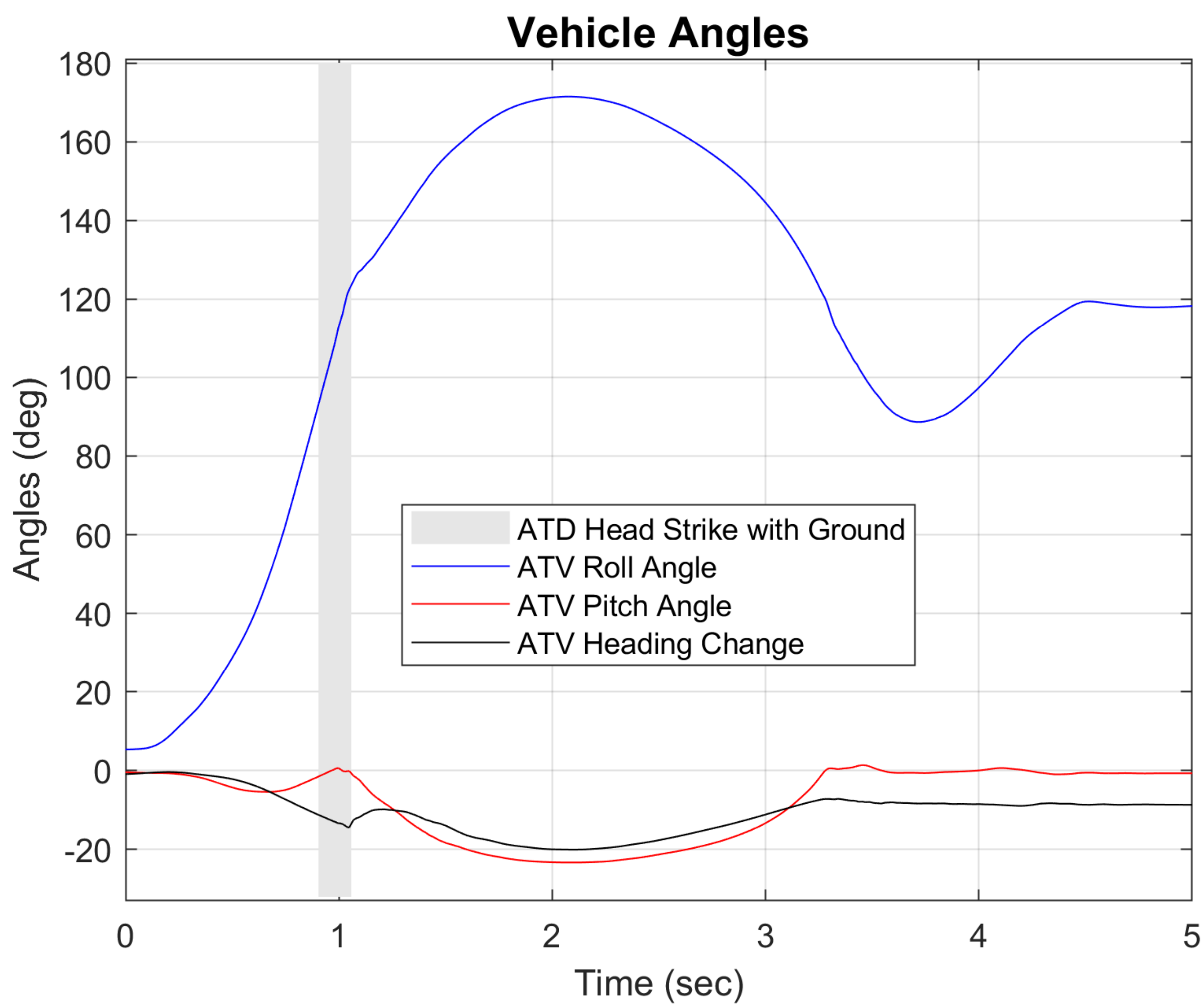
Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD



Vehicle J - Sled Moderate Energy Rollover – POC #5 – Extended Span OPD

Appendix B: Description of ATV Rollover Simulator

SEA's laboratory sled, configured for ATV rollover testing, was used to simulate the dynamic test rollovers performed on the groomed dirt surface. Many of the major components, instrumentation and control algorithms for ATV sled rollover testing are similar to those used for the previous sled roll testing on ATVs.[1,2] 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. For the ATV rollover configuration, the vehicle is placed on the edge of a non-rolling sled platform. The sled platform is accelerated up to the desired test speed and then decelerated so that it stops precisely as the vehicle rolls off the edge of the platform, and onto a dirt rollover landing pit. The ATV is free to roll beyond 90°.

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

Various components of the ATV Rollover Sled are shown on Figure B.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 B.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 B.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 B.3.

---

[1] *ATV Rollover Tests and Verification of a Physical Rollover Simulator – Results from Tests on Six 2014-2015 Model Year Vehicles*, HHS Contract HHSP233201400030I, SEA, Ltd. Report to CPSC, October 2019. **https://www.cpsc.gov/s3fs-public/SEA%20Report%20to%20CPSC%20-%20ATV%20Rollover%20Simulator%20%286b%20cleared%29_Redacted.pdf?mlCsq67xfdq8x94QejoFtK37zwXdLLJV**

[2] *Rollover Tests of ATVs Outfitted with Occupant Protection Devices (OPDs) – Results from Tests on Six 2014-2015 Model Year Vehicles,* CPSC Contract 61320618D0003, SEA, Ltd. Report to CPSC, January 2020. **https://www.cpsc.gov/s3fs-public/SEA-Report-to-CPSC-ATVs-OPDs-final-redacted_0.pdf?VRu656v4QtP5rKIiw0kuSQP_hW49TVDK**

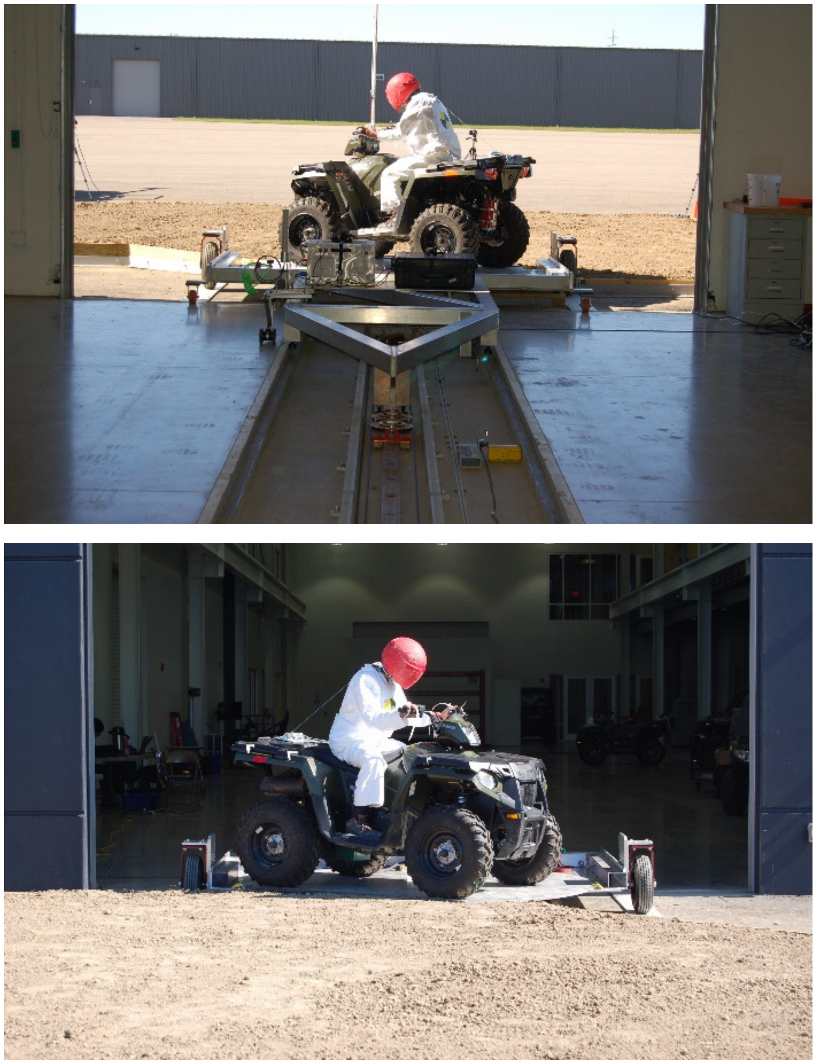
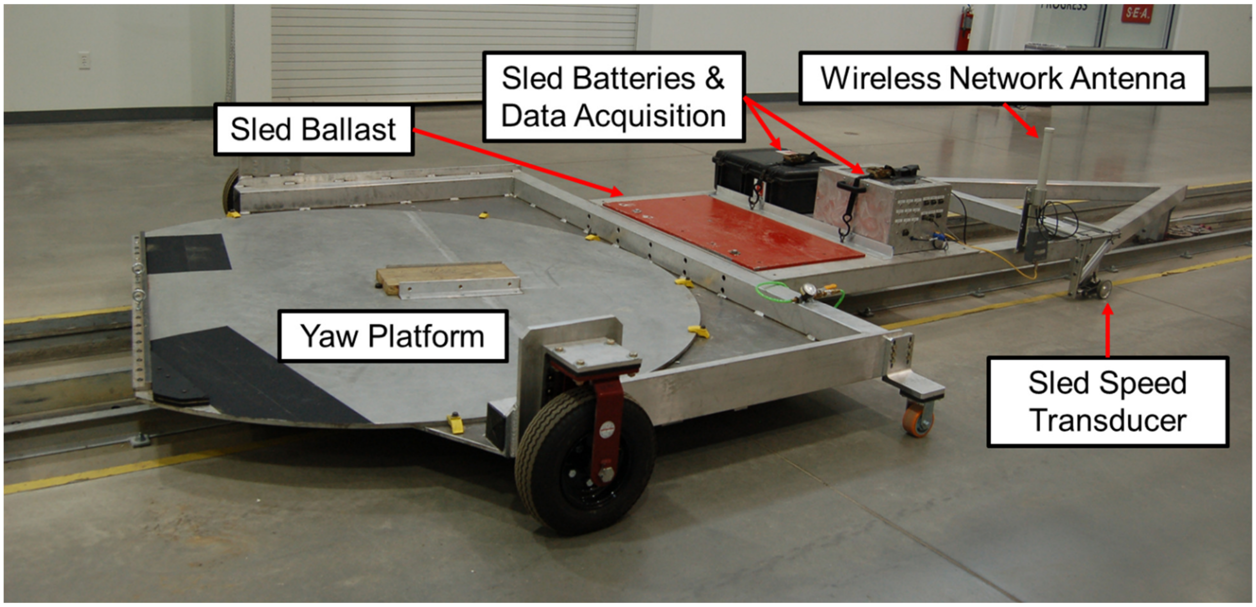


Figure B.1: Views of ATV Rollover Simulator Along the Direction of Sled Translation

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



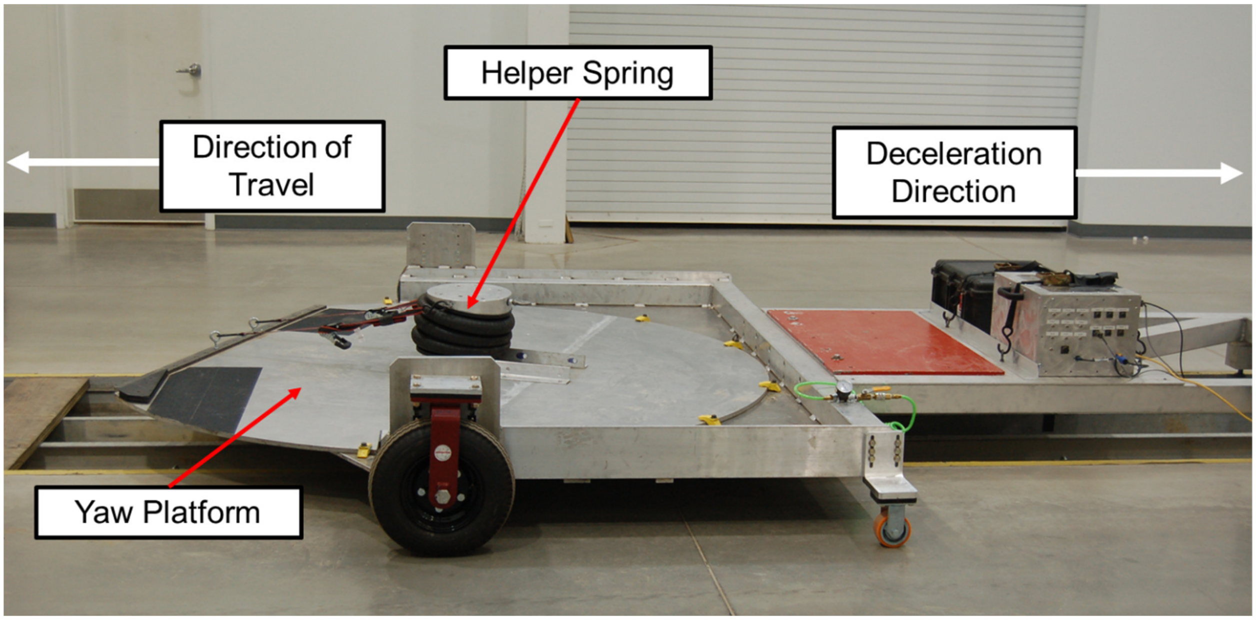


Figure B.3: ATV Rollover Sled Components
Top: Without Helper Spring – Bottom: With Helper Spring

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

1. Sled Entry Speed

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

2. Sled Acceleration and Deceleration

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

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

3. Platform Yaw Angle

As mentioned, the yaw platform can be oriented such that the sled deceleration translates the desired lateral acceleration (Ay) and longitudinal acceleration (Ax) to the vehicle. To achieve the appropriate ratio of ATV longitudinal to lateral acceleration at the onset of the sled rollovers, the platform edge was rotated 0° for the moderate energy runs, as shown in Figure B.4. Also, a trip rail and sandpaper surface beneath the leading tires of the ATV were used to assure that the ATV did not slide off the platform prior to reaching the desired location of the stopping point of the sled (with the platform edge over the rollover pit). A 1.0 in high trip rail was used for the moderate energy runs. The friction provided by the sandpaper surface is likely adequate for preventing the ATV from sliding off the platform prematurely, the trip rails were used to make sure this did not happen. The trip rails do not have a significant influence in the rollover dynamics of the ATV, as the tires basically simply roll over the trip rail.

4. Vehicle Steer Angle

Constant magnitude left steering was used leading up to the rollovers during the dynamic rollover tests the moderate energy sled tests are intended to represent. 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 B.5. The block angle used for all tests was 10°.

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 angles during the rollover. The helper spring, an air bladder similar to ones used on suspensions of commercial vehicles, was used to set the initial roll angle. Figure B.6 shows the helper spring situated beneath an ATD. The helper spring is inflated to the pressure needed to produce the desired initial roll angle. A pressure of 6.0 psi caused a 7.0° initial roll angle in the case shown on Figure B.6. In addition to contributing to greater roll rates and angles by setting the initial roll angle, the helper spring also provides gains in the maximum roll rates and angles because it does exert some upward force on the left side of the ATV during the first 20-30 degrees of the rollover event. Knowledge gained from the previous sled tests conducted on ATVs without OPDs and with aftermarket OPDs was used to set the initial roll angles for this study with POC OPDs. For each vehicle, the initial roll angle used in this study was the same roll angle used in the previous studies.

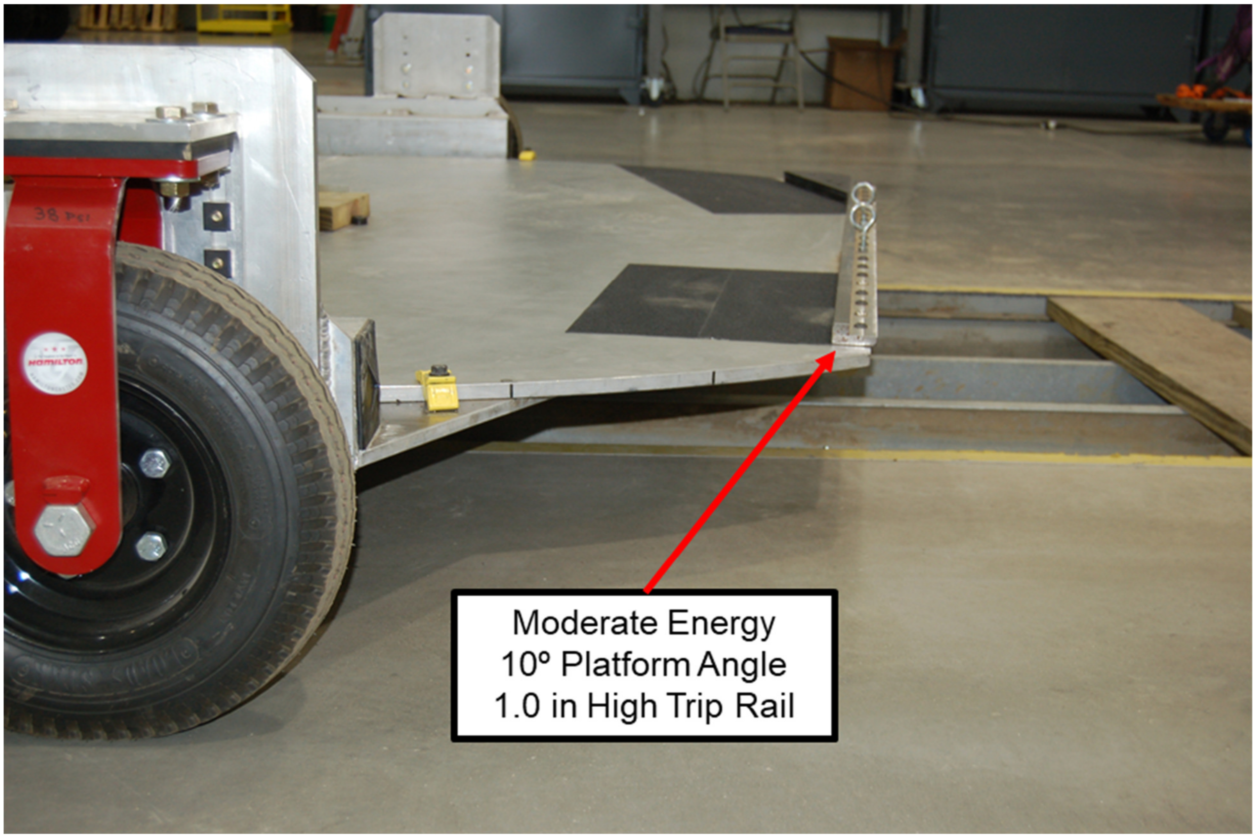


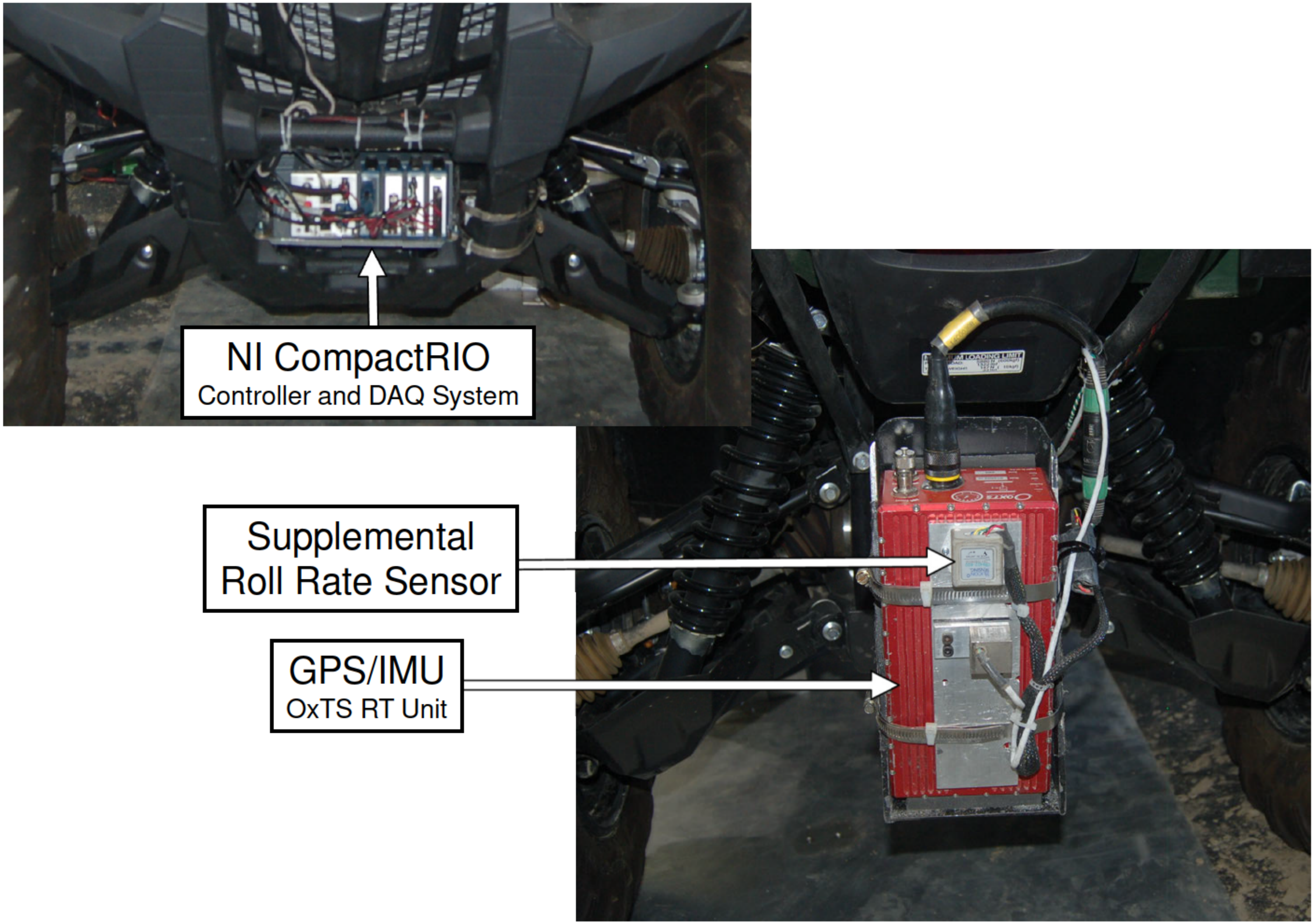
Figure B.4: Platform Yaw Angle and Trip Rail used for Moderate Energy ATV Sled Rollovers

Figure B.5: Photo Showing Steer Angle Block

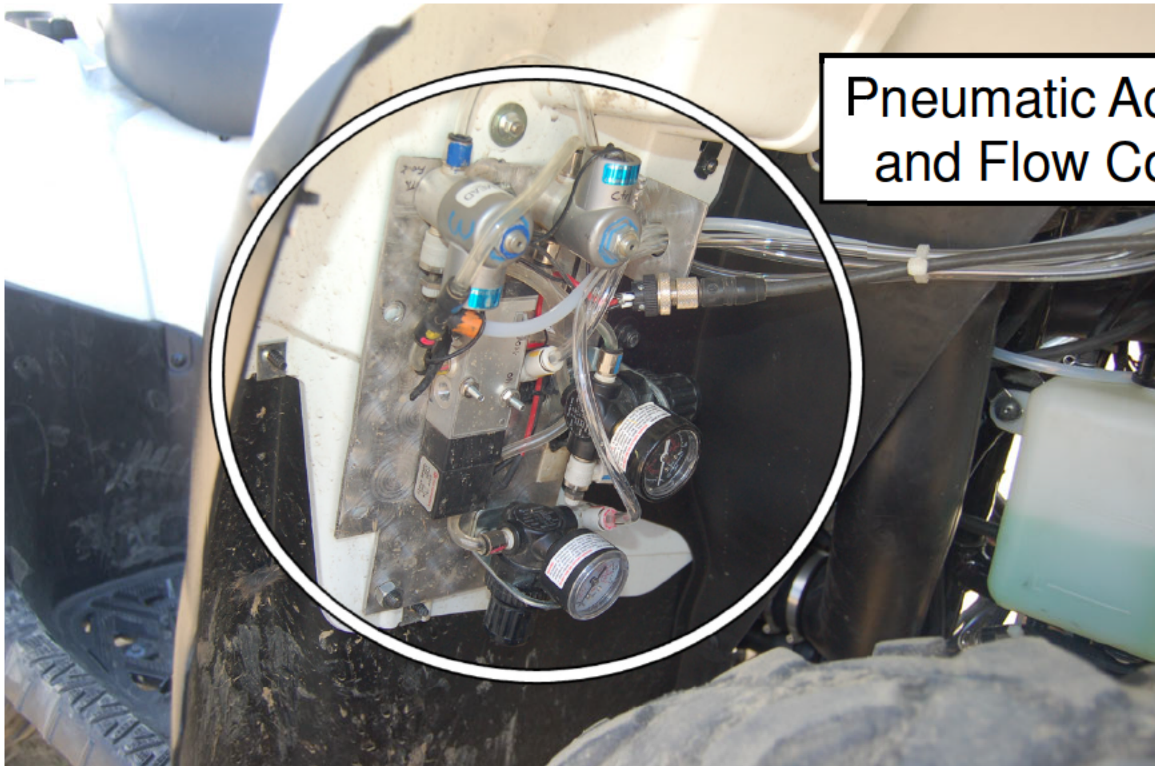
Figure B.6: Photo Showing Helper Spring used to Set ATV Initial Roll Angle

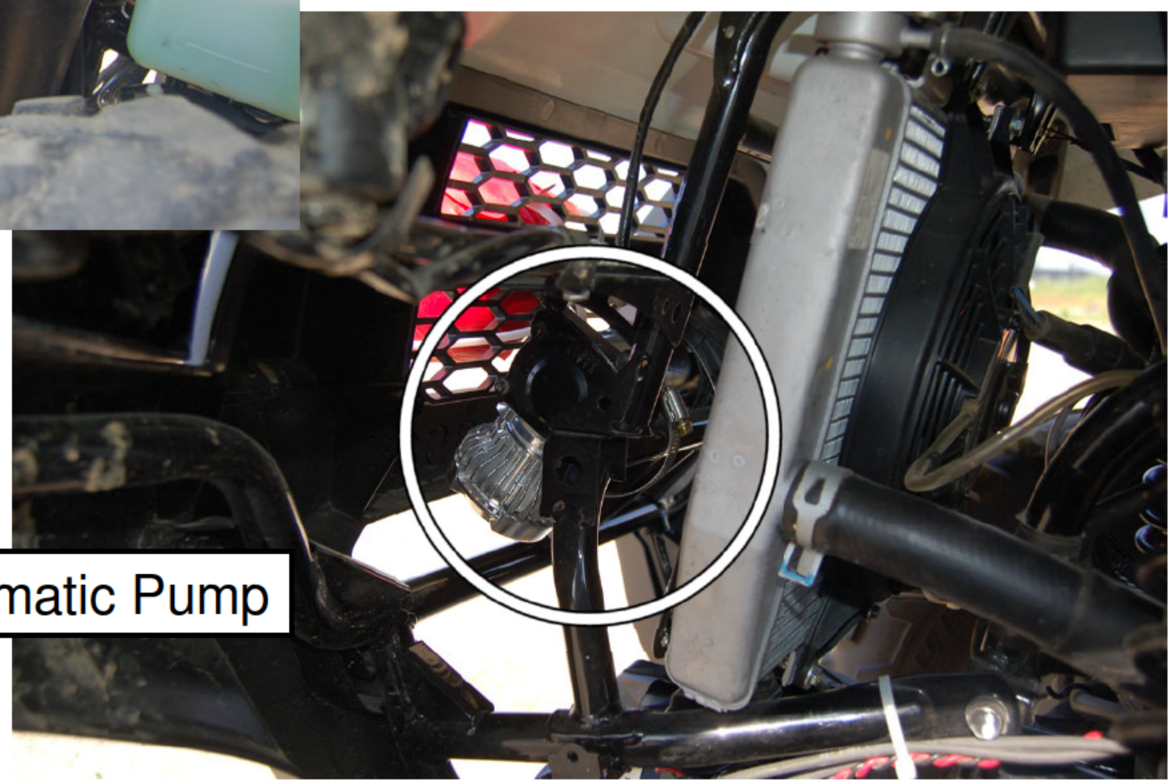
Side and Front Views of Test Vehicle on Sled and Outfitted with POC #5

ATV Controller/DAQ and Sensors

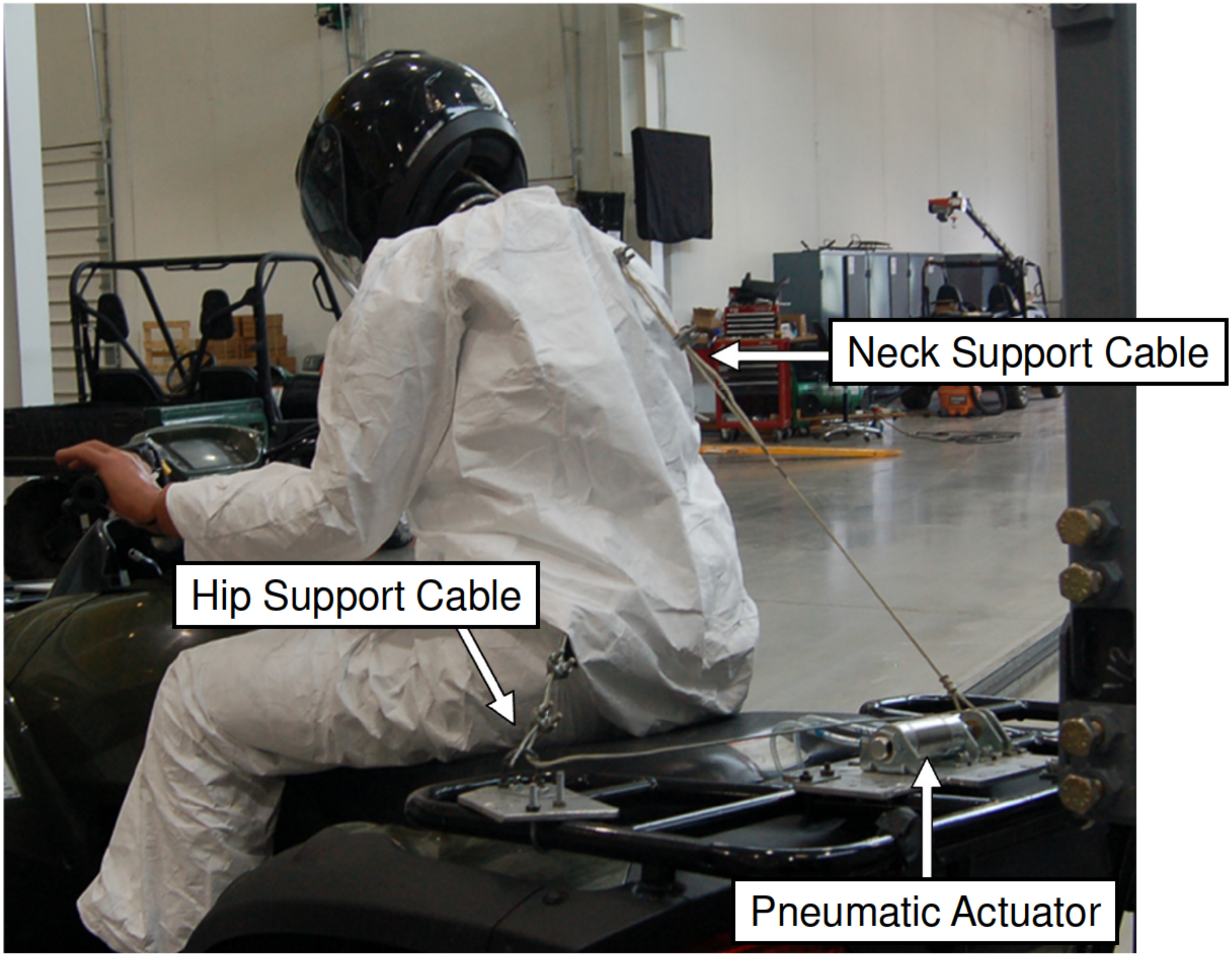


ATV Sled Rollover Pneumatic Valves and Pump

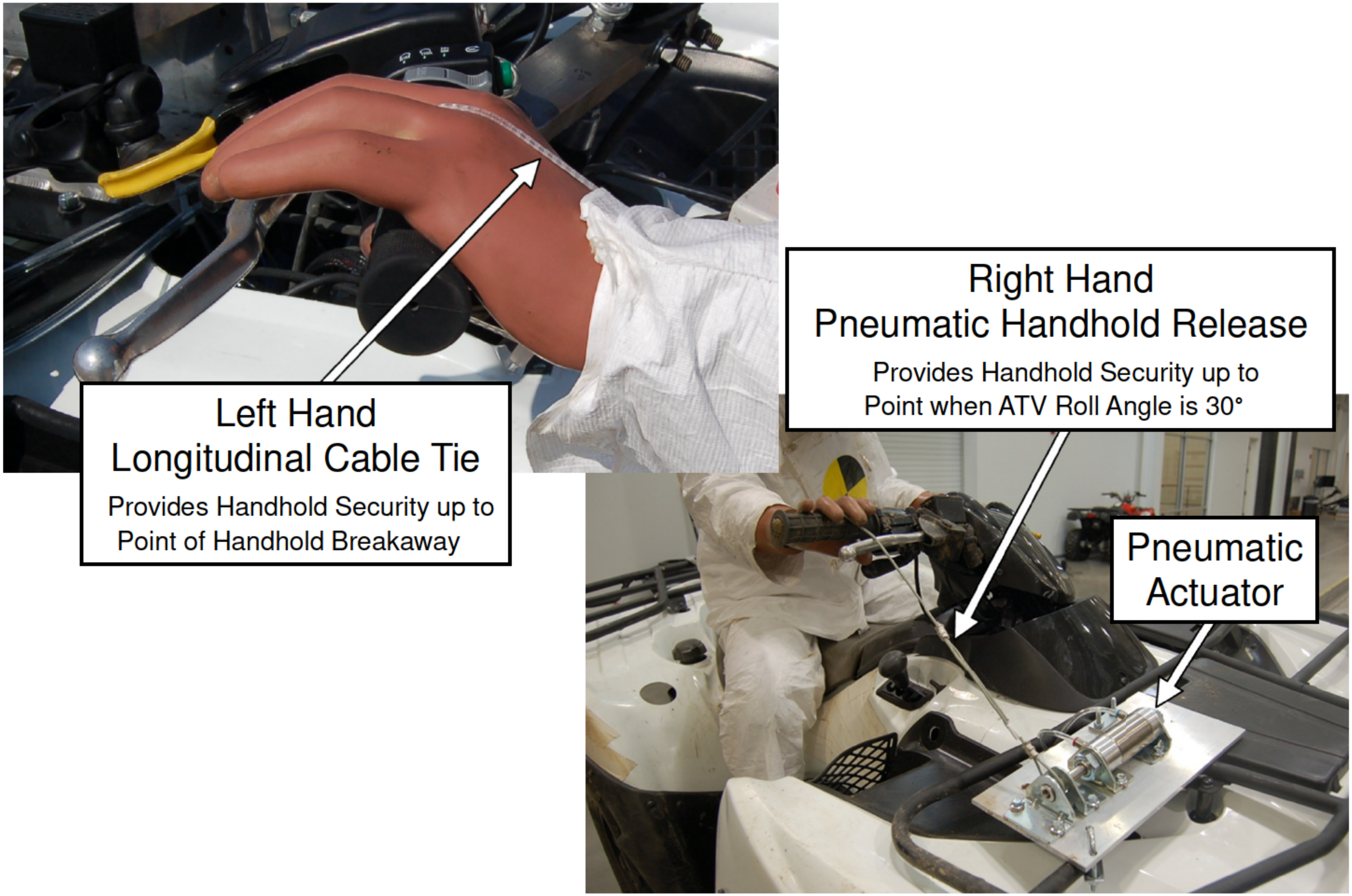




ATV Sled – ATD Body Portion of the Secure and Release System



ATV Sled – ATD Hand Portion of Secure and Release System



Appendix D: Description of ATD and ATD Secure and Release System

For all the 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 full-face helmet was used on the ATD and its clothing included disposable pants, disposable long-sleeved shirt, socks, and boots.

ATD Instrumentation

The ATD was instrumented with a so-called six degree-of-freedom sensor (three linear accelerometers and three angular rate sensors) in its head, with a six-axis upper neck load cell (three forces and three moments) mounted between the ATD's head and upper neck, and with a triaxial acceleration sensor (three linear accelerometers) in its chest. Table D.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 D.1 shows the DTS Nano Slice package (which includes the Nana Base slice as well as ancillary bridge and battery slices), the DTS 6DX Pro sensor, and the mg-sensor GmbH upper neck load cell 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 D.2. Figure D.2 also indicates the general location of the triaxial chest acceleration sensor, which is mounted on the ATD's spine.

Table D.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
mg-sensor GmbH N6ALB11A	Upper Neck Forces F_x, F_y, and F_z	± 8.9 kN (± 2,000 lb)	0.5% FS
	Upper Neck Moments M_x, M_y, and M_z	± 283 Nm (± 209 ft-lb)	0.5% FS
Endevco 7264-2KTZ-2-360	Chest X, Y and Z Accelerations	± 2,000 g	1% of Reading

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

The Head Injury Criterion (HIC) is a metric, based on the resultant magnitudes and durations of ATD head accelerations, developed for assessing potential injury levels in crash events. HIC is often used in studies to access injury potential during automotive crashes, it is also used by researchers conducting studies not involving automotive crashes[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:

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

Where, $a(t)$ is the resultant acceleration of the A_X, A_Y and A_Z acceleration measurements computed using the following equation:

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

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 D.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 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] 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.

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

However, during a dynamic event like an ATV rollover event, it is believed that handhold strength will be significantly lower than the levels measured during quasi-static tests in laboratories. For example, the dynamic vibrations of the vehicle, the change in handhold orientation as the handlebars move, and the surprise of needing to hang on all reduce handhold capacity during an ATV rollover event. Zellner and Kebschull conducted ATV rollover tests with a Motorcycle Anthropometric Test Device (MATD), and to secure the MATD hands to the handlebar grips they used a single wrap of cloth tape that provided a tear away force (perpendicular to the hand grip) of 80 lb.[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.

Cable ties were used to secure the ATD's left hand during the sled tests. The cable ties selected fit conveniently in the open wrist area of the ATD. A single cable tie was looped through the wrist, looped through the second and third fingers of the ATD's hand, and secured snuggly to the ATV hand grips. These longitudinally directed cable ties provide for a handhold strength of close to 80 lb for the left hand. During some sled tests conducted during the previous study of ATV rollovers without OPDs, the right-hand cable ties used during these tests 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 subsequent tests, a pneumatic actuator system like the one used to secure and release the hip and neck cables is used to secure and release the ATD's right hand. A 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, like how the cable tie was positioned. The pneumatic actuator releases the cable at 30° of roll angle, the same time

---

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

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.

the hip and neck cables are released. Figure D.3 shows the cable tie arrangement used to secure the ATD's left hand and the pneumatic handhold and release system used to secure the ATD's right hand.

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 D.4 shows an overall view of this system. Figure D.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 around the ATD's neck to not crimp the ATD instrumentation wires, was used to secure the neck cable to the ATD, as shown on Figure D.6.

The hip support cable and neck support cable are both securely attached to the ATV via loops held by the rod in the pneumatic actuator. At the specified roll angle, the valve controlling the pneumatic actuator is opened to retract the rod and release both cables. The bulk of the ATD weight is then released from the ATV. For all the dynamic and sled tests conducted, a specified roll angle of 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.

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 the types of ATV rollovers conducted.

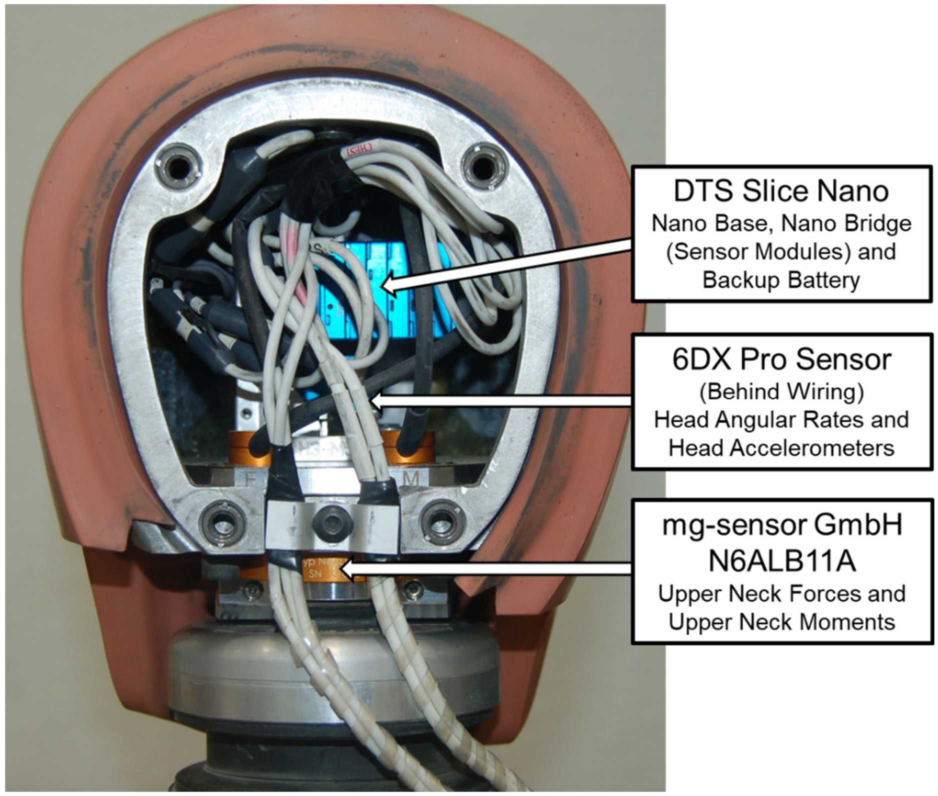


Figure D.1: Instrumentation in ATD Head

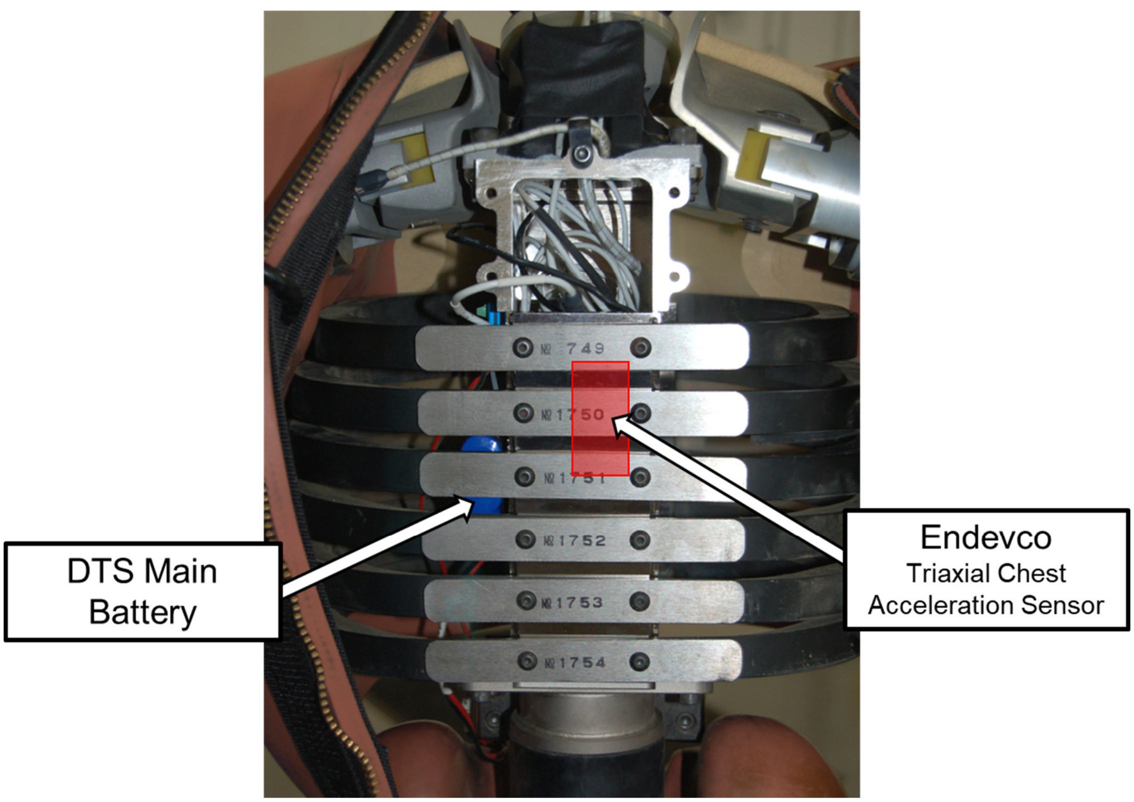


Figure D.2: Instrumentation in ATD Chest

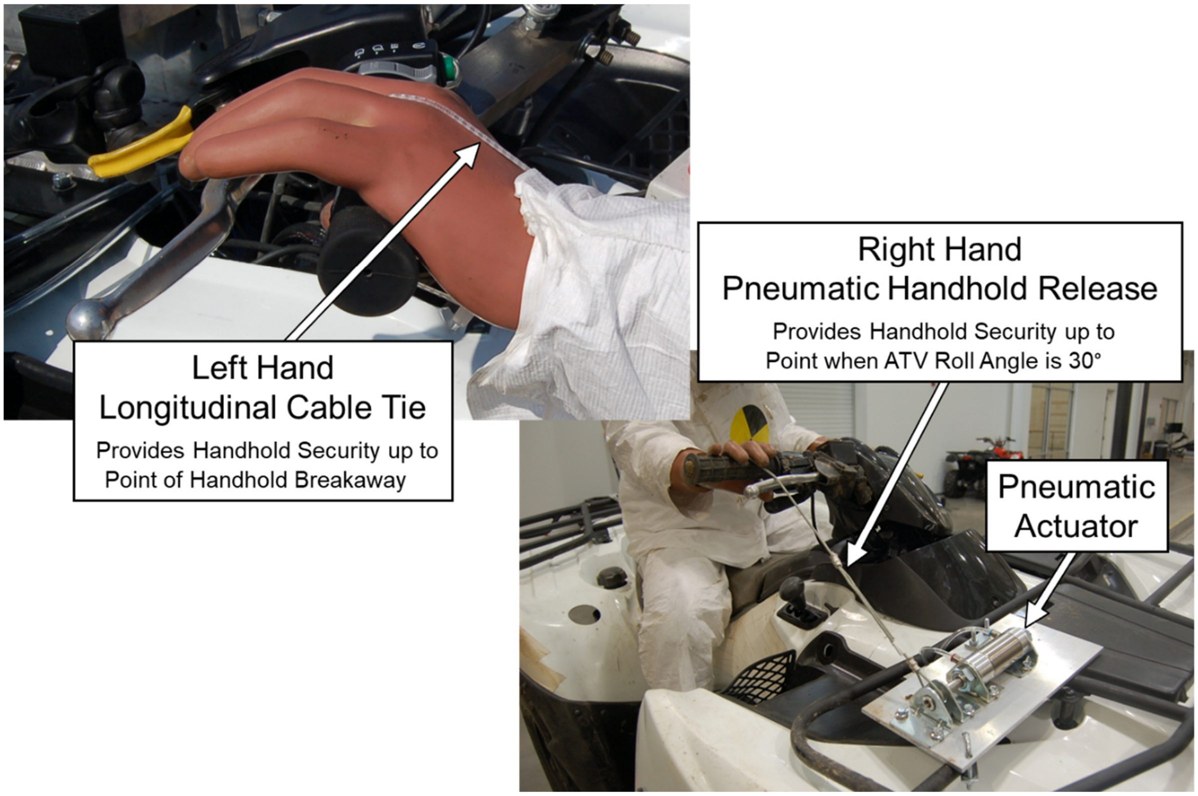


Figure D.3: Left Hand Cable Tie and Right Hand Pneumatic Handhold Release

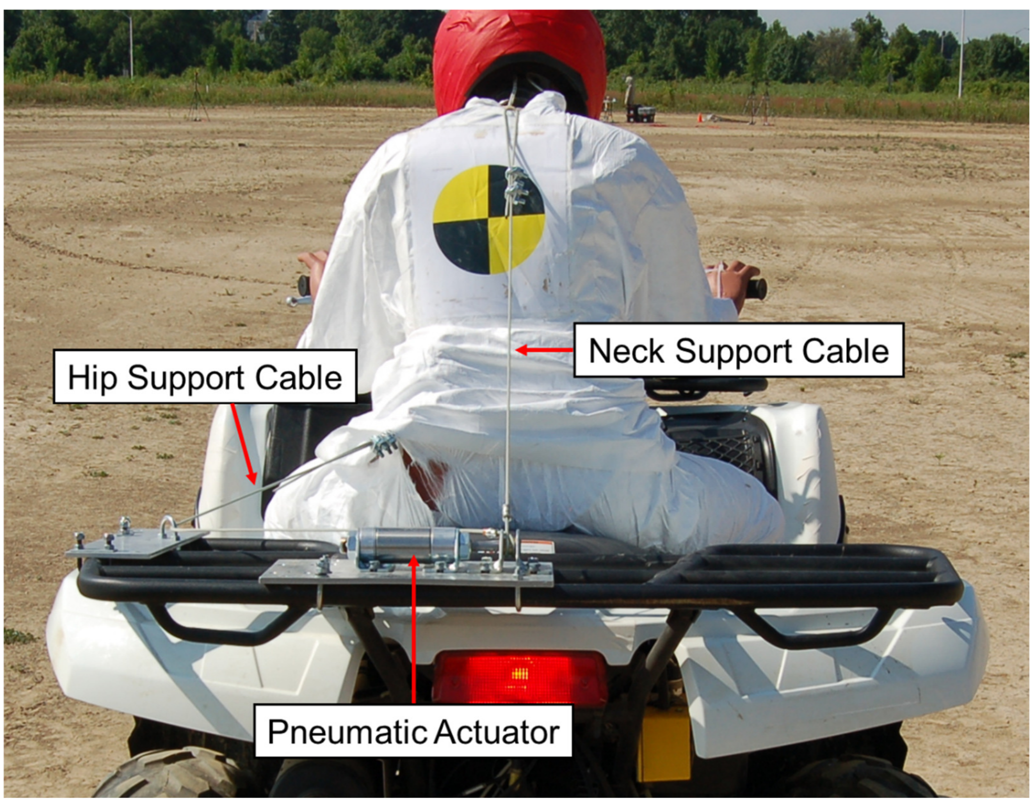


Figure D.4: Wire Rope Cable Arrangement used to Secure the ATD's Hip and Neck

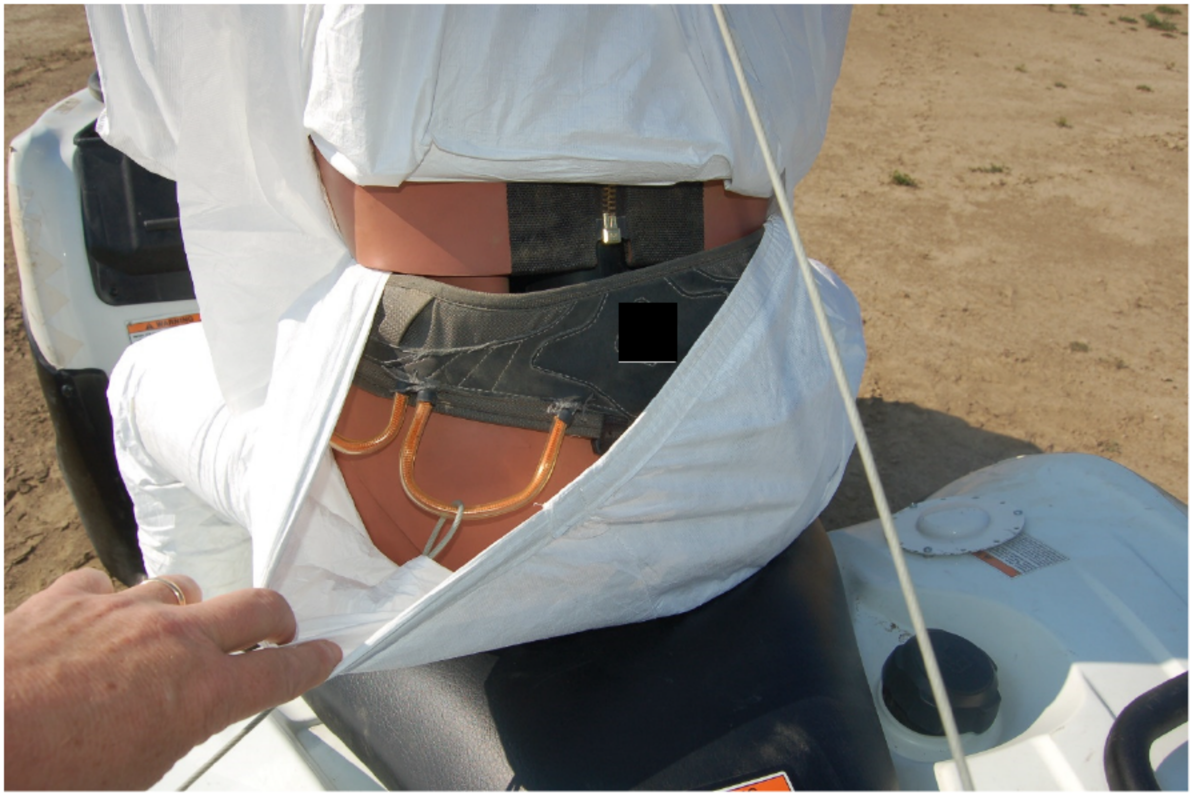


Figure D.5: Harness used for Attaching the Hip Cable to the ATD

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

Appendix E: Description of Video Equipment

Five digital video cameras were used to videotape the sled tests. Each camera was set to capture images at 60 frames per second. Sequences taken from the videos are used to generate the sled test images contained in Appendix A. The video cameras (and therefore the image sequences) are synchronized using a light flash mounted near the edge of the sled rollover pit. The flash is connected to a pressure sensitive ribbon switch. The ribbon switch was positioned to trigger the flash at the time when the sled starts to decelerate at the end of the run, and this synchronizes the sled and ATV data time to the video time. This trigger time is reference time zero used on the graphs and for the titles provided on the image sequences in Appendix A.

Figure E.1 is a schematic representation of the orientation of the video cameras as arranged during the sled rollover tests. None of the cameras were panned during the tests. Cameras 1 through 4 were mounted on tripods. Camera 5 was used to record videos from an elevated (overhead) perspective, and images from this camera are referred to as Drone Camera images. For the sled tests an actual drone (unmanned aerial vehicle) with camera was not used. Rather, for the sled rollover tests the overhead (Drone Camera) video was taken using Camera 5 mounted on a tall ladder about 10 feet above the rollover pit landing area.

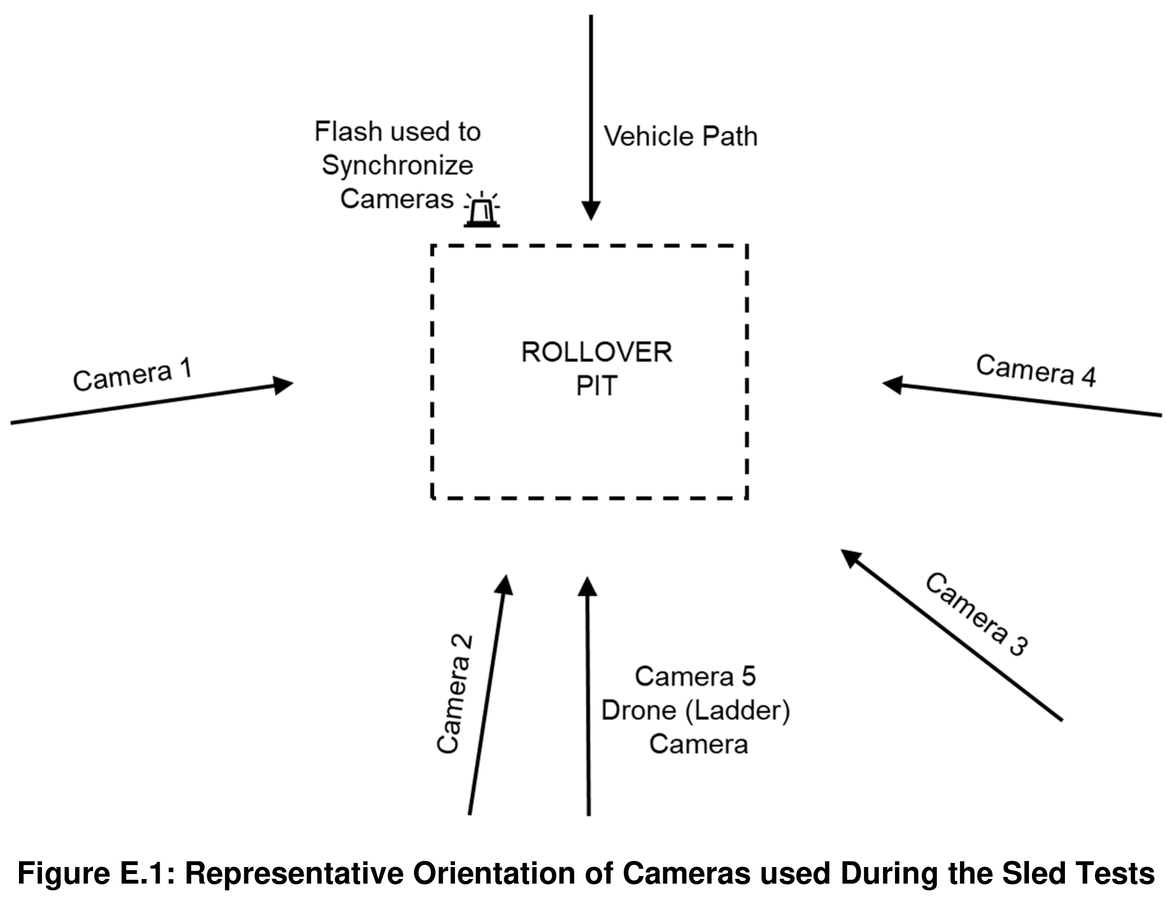


Figure E.1: Representative Orientation of Cameras used During the Sled Tests