United States
Consumer Product Safety Commission

November 2024

CPSC Staff[1] Statement on SEA, Ltd. (SEA) Report "Evaluation of Additional Aftermarket and Proof-of-Concept Occupant Protection Devices (OPDs) on ATVs"

The SEA, Ltd. (SEA) report titled "Evaluation of Additional Aftermarket and Proof-of-Concept Occupant Protection Devices (OPDs) on ATVs" presents the results of rollover and pitch back testing of two all-terrain vehicles (ATVs) equipped with proof-of-concept (POC) and aftermarket OPDs. This work was conducted for CPSC under Task Order 61320623F1015 of CPSC contract 61320618D0003.

SEA conducted a series of rollover and pitch back tests[2] on a grass hill and on the automated sled test rig. Vehicle E was tested with two types of airbag OPD installed, whereas Vehicle M was tested with an aftermarket OPD installed. SEA also conducted a series of baseline tests with Vehicles E and M without OPDs. This exploratory work examined how aftermarket and POC OPDs can reduce the risk of victims being pinned by the ATV after a rollover or pitch back event.

This report will provide insights to stakeholders and assist CPSC staff as they continue to work to improve standards associated with ATV safety, including working with the Specialty Vehicle Association of America (SVIA) and other interested parties.

[1] This statement was prepared by the CPSC staff, and the attached report was prepared by SEA. The statement and report have not been reviewed or approved by, and may not represent the views of, the Commission.
[2] Test video weblink: https://www.youtube.com/watch?v=ATTKs1c3Kvk&list=PLPbI8bR243fHfYwPJHg5QgRQlGe-_q6Wl&index=17

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Evaluation of Additional Aftermarket and Proof-of-Concept Occupant Protection Devices (OPDs) on ATVs

for:
U.S. Consumer Product Safety Commission

October 2024

Vehicle Dynamics Division
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Columbus, Ohio 43229

Evaluation of Additional Aftermarket and Proof-of-Concept Occupant Protection Devices (OPDs) on ATVs

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."

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1. OVERVIEW

This report contains results from measurements made by SEA, Ltd. (SEA) for the U.S. Consumer Product Safety Commission (CPSC) under CPSC contract 61320618D0003, a contract that covers general testing and evaluation of all-terrain vehicles (ATVs). This report covers work completed under task order 61320623F1015 of contract 61320618D0003.

SEA previously conducted autonomous dynamic rollovers (on a groomed dirt surface) and sled rollovers (using a physical rollover simulator) of ATVs outfitted with aftermarket (AM) OPDs. This work was conducted for CPSC under modification P00001 (requisition number REQ-4400-18-0002) of CPSC contract 61320618D0003.[1] SEA also previously conducted sled rollovers of ATVs outfitted with SEA-designed proof-of-concept (POC) OPDs. This work was conducted for CPSC under task order 613206191F1120 of CPSC contract 61320618D0003.[2] The current task order is an expansion of these previous studies conducted to evaluate the feasibility and effectiveness of Occupant Protection Devices (OPDs) on ATVs.

The objectives of this task order include:

- The contractor and the COR will establish a list of OPDs to test on the SEA Rollover simulator test rig to evaluate the effectiveness of the OPDs.
- Install the appropriate test instrumentation and sensors to measure accelerations, roll angles, and other physical parameters when conducting OPD rollover tests with the rollover simulator and test dummy (Anthropomorphic Test Device (ATD)).
- Refine the previous POC OPD designs from task order 613206191F1120[2] or develop new alternative OPD designs such as airbag technology that can mitigate the risk of ATVs landing on the test dummy or potentially causing harm to the ATV driver. OPDs will not be limited to a metal type structure installed behind the driver. The list of OPDs to test on the rollover simulator test rig will be decided with the COR prior to starting this task order.
- Conduct outdoor rollover tests involving pitch back scenarios with and without OPDs to further explore hazards associated with pitch back rollover scenarios. The list of test scenarios will be decided with the COR prior to starting this task order.
- Using SEA's Vehicle Inertia Measurement Facility (VIMF) and Tilt Table, measure static metrics and properties of each test vehicle in the curb weight plus 95th percentile male loading condition with OPDs and without OPDs. These tests provide results showing how the OPDs affect vehicle weight, center-of-gravity (CG) location, inertia properties, Static Stability Factor (SSF), and Tilt Table Ratio (TTR).

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[1] *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

[2] R*ollover Tests of ATVs Outfitted with Proof-of-Concept Occupant Protection Devices (OPDs) – Results from Tests on Six 2014-2015 Model Year Vehicles,* CPSC Contract 61320618D0003, SEA, Ltd. Report to CPSC, March 2022. https://www.cpsc.gov/s3fs-public/SEA_Report%20_Rollover_Tests_of_ATVs_Proof_Of_Concept_OPDs.pdf?VersionId=g9I0CqeuaqoA6y2JeDim_5TKCLfsYNCh

In pilot studies that involved conducting full-scale dynamic rollovers tests using ATVs with no OPDs[3] and using ATVs with AM OPDs[4], minimum energy and moderate energy levels of maneuver severity were studied. The intent of the moderate energy rollovers is to produce rollover events for ATVs without OPDs resulting in at least 180 degrees of roll angle. The findings of the pilot study using AM OPDs demonstrated that the AM OPDs evaluated were generally effective in eliminating interactions between the ATV and ATD in minimum energy full-scale dynamic rollovers and sled rollovers, but not as much in moderate energy rollovers. For this reason, only moderate energy severity sled rollovers were conducted in the second study using POC OPDs and in this current study. Various sled configuration parameters are tuned to generate moderate energy sled rollover events that are representative of moderate energy dynamic rollover events (see Appendix F for details).

All of the moderate energy tests using the AM OPDs and three of the four tests using energy absorbing POC OPDs[5] resulted in full rollover events, with the final roll angles in the range of 270° or more. In some of these tests there was no major interaction between the ATV and ATD during or at the end of the rollover event because the OPDs provided protection space when the ATV rolled above the ATD and provided clearance distance after the ATV rolled past the ATD. However, in other tests the ATV landed on the ATD during its rollover sequence.

Moderate energy tests using the extended span OPDs provided additional safety to the driver by 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.

Results from the previous studies using AM OPDs and POC OPDs helped guide the process for selecting OPDs to evaluate in this current study. Given the better performance of extended span POC OPDs over energy adsorbing POC OPDs, SEA staff focused on extended span OPDs for this study.

Considerations for selecting or designing OPDs in this previous study included:

- Protect the driver in lateral rollover and rearward pitchover overturn events
- Provide clearance (protection space) for the driver when the ATV is in an upside-down orientation (180° of roll angle)
- Provide clearance between the driver and ATV/OPD after an overturn event with a roll

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[3] *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**

[4] *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**

[5] R*ollover Tests of ATVs Outfitted with Proof-of-Concept Occupant Protection Devices (OPDs) – Results from Tests on Six 2014-2015 Model Year Vehicles,* CPSC Contract 61320618D0003, SEA, Ltd. Report to CPSC, March 2022. **https://www.cpsc.gov/s3fs-public/SEA_Report%20_Rollover_Tests_of_ATVs_Proof_Of_Concept_OPDs.pdf?VersionId=g9I0CqeuaqoA6y2JeDim_5TKCLfsYNCh**

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 the rear mounted aftermarket OPDs evaluated previously
- Not interfere with driver-active operation and control of the ATV
- Not restrict driver visibility
- Be short enough and narrow enough to mitigate potential for impacts with overhead branches and objects near the side of the ATV
- The additional weight of the OPD should not increase the center-of-gravity (CG) height of the vehicle significantly, thus reducing the overturn stability of the vehicle.

Based on the outcomes of the previous studies and with consideration to the list above, this study evaluates three different OPDs. Two of the OPDs evaluated are proof-of-concept (POC) OPDs using airbags (Airbag OPD #1 and Airbag OPD #2) and the other OPD is an aftermarket (AM) auto-deployment OPD (AM OPD).

1. **Airbag OPD #1** – This POC OPD was evaluated to determine the feasibility and effectiveness of using airbags to mitigate lateral rollovers and rearward pitchovers. In this concept design, airbags were mounted horizontally to the front and rear racks of the test vehicle. The front airbags extended laterally from the front rack and diagonally from the rear rack. In this POC study, the airbags were pre-inflated prior to testing.

2. **Airbag OPD #2** – This POC OPD was evaluated to determine the feasibility and effectiveness of using airbags to provide an occupant protection space, a space that protects drivers from injury in the event of lateral rollovers and rearward pitchovers. In this concept design, airbags were mounted vertically to the front and rear racks of the test vehicle. In this POC study, the airbags were pre-inflated prior to testing.

3. **AM OPD** – This OPD is an aftermarket OPD marketed as "…an automatic rollover protection system for ATVs that expands when rollover is irreversible…". Per the AM OPD manufacturer, it is intended for use on a vehicle with a driver and without passenger, on vehicles with speeds below 40 km/h (25 mph), and on vehicles with a maximum weight of 500 kg. The AM OPD evaluated comes with an electronic control unit (ECU) designed to detect irreversible lateral or longitudinal rollover situations. The AM OPD is designed to provide protection against lateral and longitudinal rollover events.

Two ATVs (Vehicle E and Vehicle M), both used by SEA in previous studies conducted for CPSC, were used in this study. Both Airbag OPDs were tested on Vehicle E and the AM OPD was tested on Vehicle M. Both vehicles have straddle seating, and their intended use is for a single occupant, the driver. Both 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 two vehicles used in this study. The vehicle curb weights and maximum speeds are listed, as is information on the vehicle transmission type.

Rearward pitchover tests were conducted using both ATVs with and without OPDs to explore hazards associated with pitch back rollover scenarios. Outdoor pitchover tests were conducted on a portion of SEA's test hill with a nominal slope of 25°. Rearward pitchover tests were also conducted on SEA's sled facility. The rearward pitchover test maneuvers were developed to be just severe enough to result in rearward overturn events.

Lateral rollover tests were performed on SEA's laboratory sled configured for ATV rollover testing. As mentioned, the severity of the rollover tests conducted on the sled are classified 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 rollover sled tests are based off dynamic J-turn (rapid steering) maneuvers conducted on groomed dirt at speeds slightly above 20 mph. The moderate energy rollovers are the same severity as those used in previous moderate energy rollover tests conducted on the sled.

This report has six main sections: Overview, Descriptions of Occupant Protection Devices Evaluated, Laboratory Testing, Rearward Pitchover Testing and Results, Lateral Rollover Testing and Results, and Summary. This report also has six appendices. Appendix A contains laboratory test results, Appendix B contains hill and sled pitchover test results, Appendix C contains sled rollover test results, Appendix D contains photographs of the test equipment, Appendix E contains a description of the ATD and the ATD secure and release system, and Appendix F contains a description of the ATV rollover sled.

Table 1: Test Vehicle Information

Vehicle E Curb Weight: 734.1 lb Maximum Speed: 45.7 mph	Automatic Transmission Independent Rear Suspension 2WD, 4WD, or 4WD Lock
Vehicle M Curb Weight: 931.4 lb Maximum Speed: 66.0 mph	Automatic Transmission Independent Rear Suspension 2WD or 4WD

2. DESCRIPTIONS OF OCCUPANT PROTECTION DEVICES EVALUATED

This section describes the three different OPDs evaluated in this study. Two of the OPDs evaluated are proof-of-concept (POC) designs. The POC designs use airbags for the OPD structure. The rationale for selecting the sizes and positions of the airbags is provided in this section. The third OPD evaluated is an aftermarket (AM) OPD, and a description of it is also provided in this section.

2.1 Description of Airbag OPD #1

In their previous report to CPSC covering the designs of the POC OPDs, SEA stated that the objective of the designs was to further reduce interactions between the ATV and ATD during moderate energy sled tests.[6] Further, they stated that this objective can largely be achieved by:

- Providing clearance (protection 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 objectives were considered in designing both POC airbag OPDs in this study. All the previous POC OPDs or AM OPDs evaluated used rear mounted metal OPD structures only. Both POC airbag OPDs in this study included using airbags at the front and rear of the ATV. Adding OPD structure on the front of the ATV was used to determine if doing so provides additional occupant protection, particularly in lateral rollovers.

It was decided to work with only pre-deployed airbags, the idea being that if POC airbags were not effective in protecting occupants in overturn events, developing their deployment methods would not be necessary. It was assumed that if the bags were effective that deployment methods could be developed, and it was assumed that suitable means of mounting the bags could also be developed.

Two types of airbags were selected and procured, a set of high-pressure low-volume bags, inflated to an internal pressure of 16.0 psi, and a set of lower-pressure higher-volume bags, inflated to 2.7 psi.

In theory, the strength of such bags can be calculated based on the dimensions and inflation pressure without needing to know the specifics of the bag material and thickness. The bags collapse when any portion of the bag goes into longitudinal compression, and the formulas for bag strength reflect this. Calculations of bag strength, combined with the estimated maximum loads in a rollover, were used to calculate the design dimensions of the high-pressure bags. The high-pressure bags were specially made by a custom airbag company. Eight bags were purchased, each

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[6] *Rollover Tests of ATVs Outfitted with Proof-of-Concept Occupant Protection Devices (OPDs) – Results from Tests on Six 2014-2015 Model Year Vehicles,* CPSC Contract 61320618D0003, SEA, Ltd. Report to CPSC, March 2022.
https://www.cpsc.gov/s3fs-public/SEA_Report%20_Rollover_Tests_of_ATVs_Proof_Of_Concept_OPDs.pdf?VersionId=g9I0CqeuaqoA6y2JeDim_5TKCLfsYNCh

with a nominal cross section of 7½" x 7½". Four of the bags were nominally 36 inches long and four were nominally 24 inches long. Inflation ports were provided, and the bags had internal tethers running longitudinally.

Static testing of the strength and stiffness of the bags was done before they were mounted on a vehicle, and the bags were found to be only about 2/3 of the strength that was expected. Further, it proved to be very difficult to mount the bags in any kind of a support structure that held the base of the bag rigidly. Thus, there was significantly more deflection than expected at all load levels. Tests conducted using external tethers of various types resulted in increased strength and stiffness of the bags, but not to the extent desired. Tethers outside of the bags would make for a very complex design to go on a vehicle; to resist forces in all direction might require a "spider web" of tethers. Based on findings from the static tests and on the maximum allowable pressure that would likely prevent the airbags from bursting in use, the Airbag OPD #1 airbag pressures were set to 16.0 psi.

The original intention was to use a total of four-high pressure bags, one on each corner, sticking out and up. This intended orientation was envisioned to provided two potential safety features: 1) the bags could provide overturn resistance, acting like a safety outrigger to mitigate overturn events, and 2) the (upward tilted) bags could provide occupant protection space in the event of an overturn event. While the actual loads involved in a rollover are difficult to predict, the bags procured did not appear to have sufficient strength and stiffness to provide much benefit, using the intended orientation and number of bags.

As a fallback strategy, tests were done with two long bags on each rear corner of the vehicle and two short bags on each front corner of the vehicle: with the front bags horizontal, pointing laterally and the rear bags horizontal, pointing diagonally at 45° angles. Each pair of bags should have strength and stiffness twice those of any bag individually. This airbag configuration would not provide occupant protection space in an overturn event, but it could provide overturn resistance by acting like a set of safety outriggers. That is, this POC OPD was evaluated to determine the feasibility and effectiveness of using airbags to mitigate lateral rollovers and rearward pitchovers.

Figure 1 shows top and side views of Vehicle E outfitted with Airbag OPD #1. This figure provides dimensions of the positions and inflated sizes of the airbags. Front and rear airbag supports were fabricated out of 1"x1" steel tubing, shown in Figure 2. Two 1" wide ratchet straps were used to secure each pair of airbags to the supports and vehicle racks.

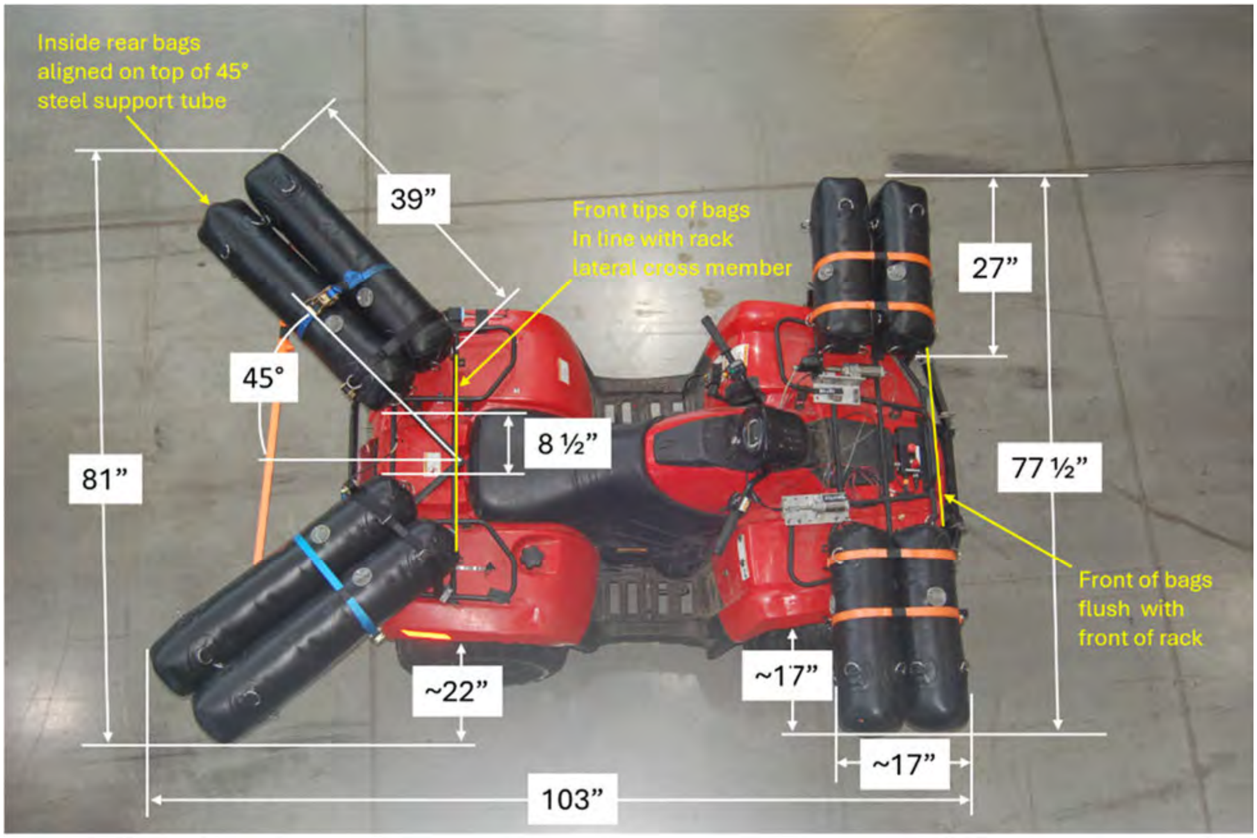

Figure 1: Top and Side Views of Airbag OPD #1 Mounted on Vehicle E
Airbag OPD #1 Airbags were Inflated to 16.0 psi

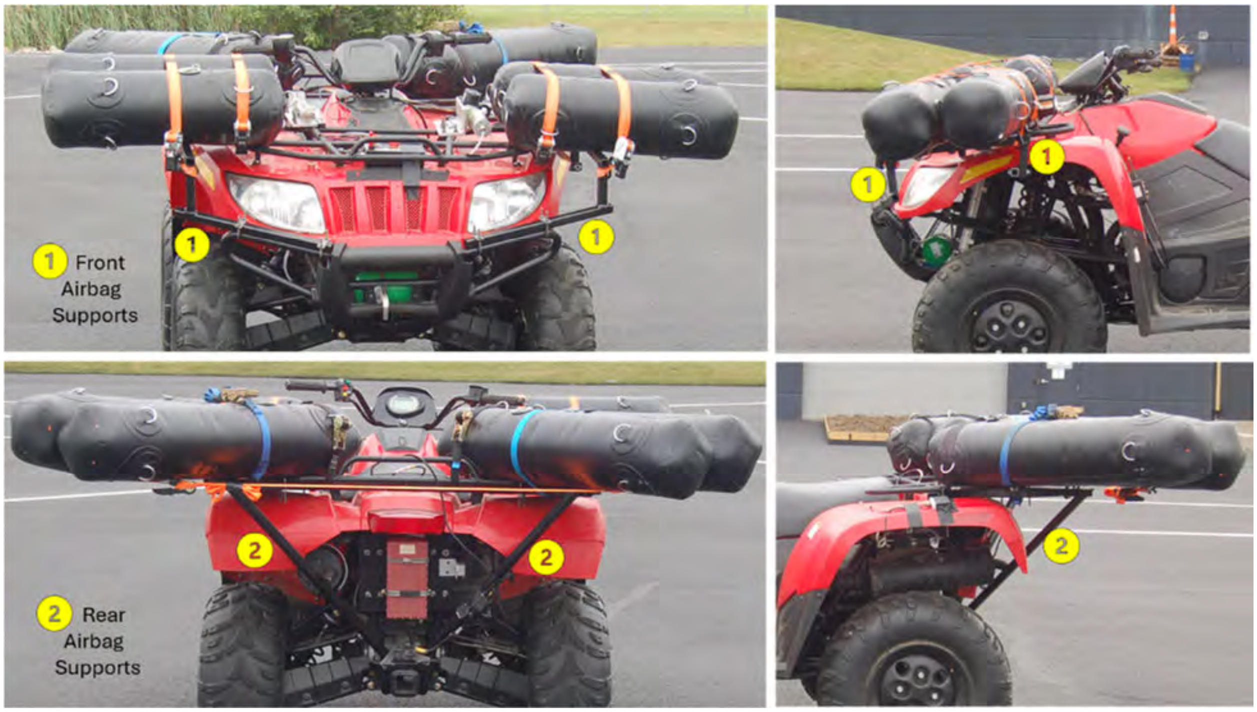

Figure 2: Photos Highlighting Front and Rear Airbag Supports Used on Vehicle E

2.2 Description of Airbag OPD #2

The second method of using air bags was the low-pressure high-volume bag approach. For this approach, commercially available bags for a different application were purchased (exhaust jack systems that are designed to use exhaust gas pressure from a vehicle engine exhaust to inflate a large volume bag). Such systems can be easily modified to be inflated with air rather than exhaust, and modified to hold pressure after they are inflated.

The bags purchased were roughly 26 inches in diameter and 36 inches long. These bags advertised that they were rated to 4 metric tons, about 8,800 lb. Based on observing the bags inflated to various pressures, the Airbag OPD #2 airbag pressures were set to 2.7 psi. This pressure would likely prevent the airbags from bursting in use, and it would provide a theoretical vertical load capacity of over 1,200 lb.

Figure 3 shows side and rear views of Vehicle E outfitted with Airbag OPD #2. This figure shows the positions of the bags and provides the as-inflated sizes of the bags. The same front and rear supports used to support Airbag OPD #1 airbags were used to support the Airbag OPD #2 airbags. Four D-rings were attached to each of the airbags to provide attachment points for the 1" wide ratchet straps used to secure each airbag to the supports and vehicle racks. The D-rings were glued on near the tops of the airbags using white vinyl straps, and these are shown with the hooks from the ratchet straps attached to them on Figure 3.

It was expected that this size and orientation of airbags would provide considerable protection space, mitigate rolling or pitching motion, and in a rear pitchover could serve to keep the occupant inside the normal occupant zone and prevent them from hitting the ground.

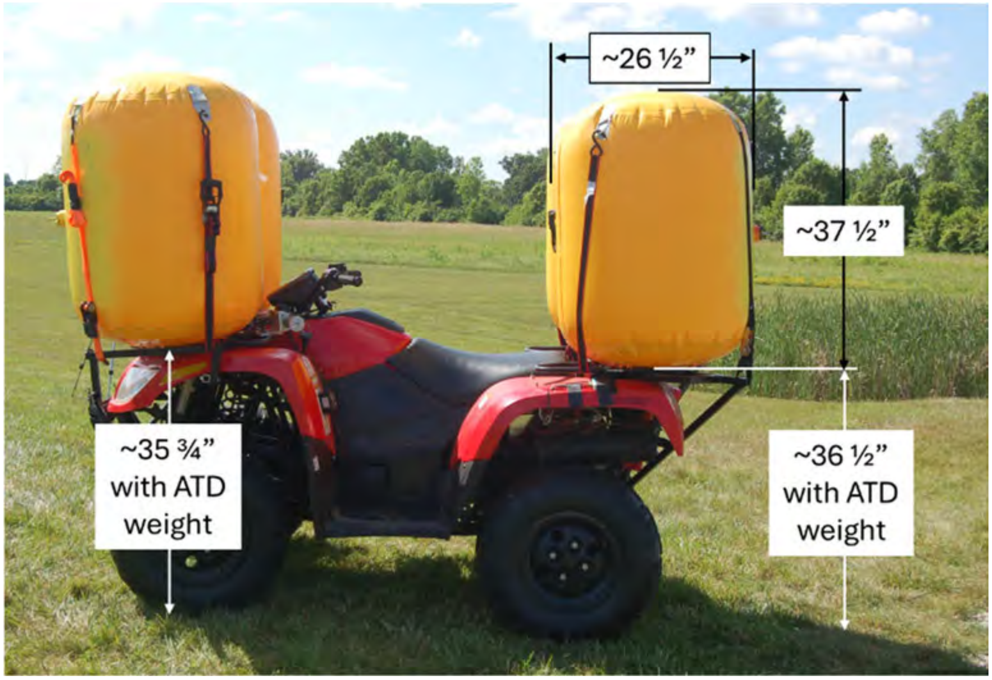

Figure 3: Side and Front Views of Airbag OPD #2 Mounted on Vehicle E
Airbag OPD #2 Airbags were Inflated to 2.7 psi

2.3 Description of AM OPD

Figure 4 shows side and rear views of Vehicle M outfitted with the AM OPD on the SEA Rollover Sled. The AM OPD is a rear mounted OPD designed to provide protection in the event of lateral and longitudinal rollover events. It is an automatic rollover protection system for ATVs designed to expand when rollover is irreversible. The AM OPD evaluated comes with an electronic control unit (ECU) designed to detect lateral or longitudinal irreversible rollover situations. The ECU is equipped with inertial sensors that analyze the real time dynamics of the vehicle. When the ECU system algorithm detects an irreversible tipping condition, it activates the release of high-pressure inert gas inside the AM OPD's expandable structure. The high-pressure gas is stored in a canister inside the base of the OPD's tubular structure. When the ECU algorithm senses an irreversible overturn situation, it sends an electronic signal to a pyrotechnic igniter which releases the high-pressure gas inside the OPD's tubular structure causing it to expand. When the OPD structure

fully expands, it is designed to lock into place thereby providing a protection space to prevent the driver from being crushed or asphyxiated in the event of a rollover. The yellow circle on Figure 4 indicates the general location of the AM OPD system ECU and compressed gas canister.

Per the AM OPD manufacturer, it is intended for use on a vehicle with a driver without passenger, on vehicles with speeds below 40 km/h (25 mph), and of vehicles with maximum weight of 500 kg (1,100 lb).

ECU power is provided by connection to the vehicle battery. The AM OPD system includes a system disconnect switch, an optical interface (LED light), and an acoustic interface (buzzer). The system wiring instructions show how to wire the ECU power so that the ECU is only powered on when the vehicle key is on. With the vehicle key on and the system disconnect on, the system is in Standby mode and the interface light will flash yellow and the interface buzzer will beep. With the vehicle key on and the system disconnect off, the system is in Operation mode and the interface light will be solid green and the interface buzzer will be silent. The system will only go to the Operation state if the system sensors and microcontroller are working correctly and the presence of an undeployed high-pressure air canister is detected. If the system checks are not satisfactory or the gas canister is deployed, system will not go to Operation state, the interface light will be red, and the interface buzzer will beep.

The AM OPD system has an Alert state to warn the driver when a tipping hazard situation is detected. In the Alert state the interface light flashes yellow and the interface buzzer beeps. Bench tests conducted by SEA showed that the Alert buzzer had five levels of alert intensity. During bench tests using slow tilt rates, the lowest level of alert intensity began close to 20° of tilt angle and intensity of the beeping increased to a continuous beeping state close to 35° of tilt angle. Similar alert behavior was observed for both lateral (rollover) and longitudinal (pitchover) tilts.

If the tipping risk does not decrease and an irreversible rollover (or pitchover) condition is sensed, the system progresses to Activation state. In this state the gas-release is activated and the OPD structure is expanded. In this state the interface light will remain red, and the interface buzzer will beep continuously. Per the AM OPD manufacturer, the time from system Activation to full expansion and locking of the OPD structure is below 150 ms.

Figure 5 has rear views of Vehicle M outfitted with the AM OPD. This figure provides dimensions of the AM OPD structure when it is unexpanded and expanded.

Figure 4: Side and Rear Views of Vehicle M with AM OPD on Rollover Sled
Yellow Circle Indicates General Location of ECU and Compressed Gas Canister

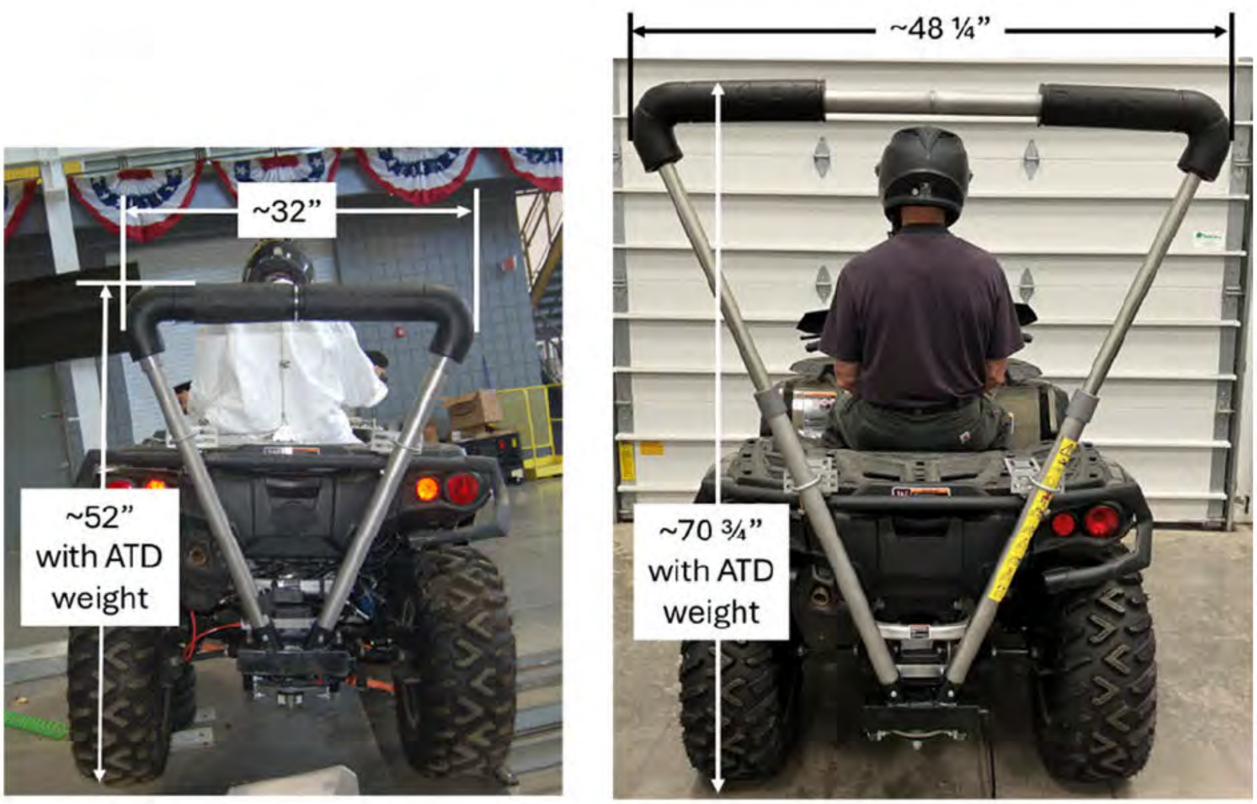

Figure 5: Dimensions of Unexpanded (Left) and Expanded (Right) AM OPD

3. LABORATORY TESTING

This section describes the laboratory measurements made as well as computations of various rollover resistance metrics. This section is divided into four parts: one covering the vehicle loading conditions used for the laboratory tests, one covering the Vehicle Inertia Measurement Facility (VIMF) tests, one covering the Tilt Table tests, and one containing a discussion of the laboratory test results. Complete tabular results from all the measurements and metrics discussed in this section are contained in Appendix A.

3.1 Vehicle Loading Conditions

The two loading conditions described below were used for the laboratory tests.

1. **Driver**
   This is a driver only loading condition, and it is specified to be the vehicle curb condition plus a 213 lb driver. For this loading condition a Hybrid II test dummy weighing 164 lb was used and ballast was added to its lap to bring the driver weight up to nominally 213 lb. The test dummy was seated on each vehicle with its feet on the footrests and its hands attached to the handlebars. This Driver loading condition was used for VIMF and Tilt Table tests conducted in previous studies.[7]

2. **Driver plus OPD**
   This is a Driver loading condition plus an OPD. For Vehicle E there are two OPD conditions, Driver Plus Airbag #1 and Driver Plus Airbag OPD #2; and for Vehicle M there is one OPD condition, Driver Plus AM OPD. For the VIMF and Tilt Table Tests, the airbags used in both Airbag OPDs were uninflated and the structure used in the AM OPD was unexpanded. These represent the conditions of the OPDs in normal driving conditions, with the OPDs undeployed.

The VIMF and Tilt Table tests were conducted in both the Driver and Driver plus OPD conditions. The loading conditions used for the dynamic pitchover and rollover tests included test instrumentation and an anthropomorphic test device (ATD), and these are described in the next section.

3.2 Vehicle Inertia Measurement Facility (VIMF) Tests

Laboratory measurements of vehicle weight (including the four corner weights); vehicle center-of-gravity (CG) position (longitudinal, lateral, and vertical (CG height)); vehicle pitch, roll, and yaw moments of inertia; and roll/yaw product of inertia were made by SEA using their Vehicle Inertia Measurement Facility (VIMF).[8] Measurements of front track width, rear track width, and wheelbase were also made. Page 1 of Appendix D contains photographs of Vehicle M with AM OPD and Vehicle E with no OPD mounted on the SEA VIMF platform.

The vehicle CG longitudinal position is expressed as a distance from the front axle. The vehicle

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[7] *Vehicle Characteristics Measurements of All-Terrain Vehicles – Results from Tests on Twelve 2014-2015 Model Year Vehicles*, HHS Contract HHSP233201400030I, SEA, Ltd. Report to CPSC, January 2017. https://www.cpsc.gov/s3fs-public/SEA_Report_to_CPSC_Vehicle_Characteristics_Measurements_of_All_Terrain_Vehicles.pdf

[8] *The Design of a Vehicle Inertia Measurement Facility*, Heydinger, G.J., Durisek, N.J., Coovert, D.A., Guenther, D.A., and Novak, S.J., SAE Paper No. 950309, February 1995.

CG lateral position is expressed as a lateral distance from the vehicle centerline; CG positions to the right of the centerline are positive. The vehicle CG height is expressed as the distance of the vehicle center of gravity above the road plane.

The moments and product of inertia for a vehicle are computed relative to the vehicle's center of gravity, using an orthogonal coordinate system with its origin at the vehicle center of gravity. The X-axis of the coordinate system is directed forward and parallel to the road plane, the Y-axis is directed to the driver's right and is also parallel to the road plane, and the Z-axis is directed downward.

In addition to the direct measurements provided by the VIMF, another common metric used to characterize vehicle lateral rollover resistance was computed, namely, the Static Stability Factor (SSF).

SSF is a fundamental rollover resistance metric which equals the lateral acceleration in units of g at which rollover begins in the most simplified rollover analysis of a vehicle represented by a rigid body without suspension movement or tire deflections. SSF is given by:

$$SSF = \frac{T_{AVE}}{2 \times H_{CG}}$$

where: T_{AVE} is the Average Track Width, and
H_{CG} is the Vehicle CG Height.

Appendix A contains results from all the VIMF tests conducted on both vehicles, with and without OPDs.

3.3 Tilt Table Tests

The SEA Tilt Table consists of a rigid steel platform mounted on top of a yaw bearing. The yaw bearing allows the platform to be rotated so that lateral tilts (left-side leading and right-side leading), forward tilts (front-end leading), and rearward tilts (rear-end leading) can be conducted without removing and reloading the vehicle. A hydraulic cylinder is used to tilt the yaw bearing and platform assembly, up to 60 degrees from horizontal.

Tilt Table tests were conducted for both vehicles with and without OPDs, and tilts were conducted in four directions: left-side leading, right-side leading, front-end leading, and rear-end leading. Page 2 of Appendix D contains photographs of Vehicle M with AM OPD in a lateral, right-side leading tilt and Vehicle E with no OPD in a longitudinal, rear-end leading tilt.

For the lateral tilts, the outsides of the low side tires were aligned to be parallel to the tilt axis prior to testing. The platform was gradually tilted to the point when both high side tires lifted off the platform. The vehicles were prevented from tilting completely off the platform by straps that restrained further tilting once the high side tires lifted about two to three inches off the platform. The top of the Tilt Table platform is a high friction surface, covered with marine grade safety walk paint. This surface prevents vehicles from sliding sideways during the lateral Tilt Table tests.

For the longitudinal tilts (the forward and rearward tilts), the vehicles were tilted in a direction

nominally parallel to their pitch axis. To prevent the vehicles from rolling during these tests, the park brakes were applied and if necessary, straps were wrapped around the front and/or rear tires and secured to the vehicle chassis. The tilt angles needed to get two-wheel lift during longitudinal Tilt Table tests are greater than the tilt angles needed to get lateral tilt two-wheel lift. As was done during previous longitudinal Tilt Table tests conducted by SEA for CPSC, to prevent the tires from sliding off the Tilt Table platform at high tilt angles, a 2-inch-high trip rail (a 2"x2" square aluminum tube) was used for all longitudinal Tilt Table tests. The tires were rolled up against the 2-inch-high trip rail prior to setting the brakes and applying the roll-preventing tire straps.

For the longitudinal tilts, the low side tires were aligned to be parallel to the tilt axis. The platform was gradually tilted to the point when both high side tires lifted off the platform. The vehicles were prevented from pitching completely off the platform by straps that restrained further tilting once the high side tires lifted about two to three inches off the platform.

The important factors involved in accurate tilt table testing include having a rigid and flat platform; having the ability to produce slow, smooth, and consistent tilt rates; and having accurate and repeatable measures of tilt angle and point of wheel lift. The SEA Tilt Table platform is very rigid, and it was designed to have deflections of less than 0.1 inch. It is also very flat, with a flatness tolerance of ±0.1 inch. The hydraulic cylinder used to tilt the platform is controlled to provide for smooth tilting at rates as slow as 0.1 deg/sec.

A high-accuracy, two-axis (one aligned with the right/left tilt axis, and one aligned with the fore/aft tilt axis) angle sensor is mounted to the platform to record the tilt angles throughout the Tilt Table tests. The point of two-wheel lift is determined visually, and the observer generates a signal that is recorded by the data acquisition system by pushing a button on a handheld trigger. Typically, five or six tilts to two-wheel lift are conducted for each configuration tested. The tests with the closest three angles of two-wheel lift are selected and averaged together to determine the final angle of two-wheel lift. Based on repeatability evaluations conducted using a range of ATV tests, SEA believes that the repeatability of the measurements of two-wheel lift is within ±0.1 degrees.

For left side leading and right side leading tilts, the angle at which two-wheel lift occurs is referred to as the Tilt Table Angle (TTA). In addition to measuring TTA, the Tilt Table test results provide a measure of the rollover resistance metric Tilt Table Ratio (TTR). TTR is the tangent of the TTA. TTR values are lower than SSF values because suspension and tire deflections during the Tilt Table tests reduce the effective track widths below the values based on the rigid body concept that is the basis for SSF. TTR is computed mathematically using:

$$\mathrm{TTR} = \tan(\mathrm{TTA})$$

For front end leading tilts, the angle at which two-wheel lift occurs is referred to here as Forward Tilt Table Angle (FTTA); and for rear end leading tilts, the angle at which two-wheel lift occurs is referred to here as Rearward Tilt Table Angle (RTTA). In addition to measuring FTTA and RTTA, the Tilt Table test results provide measures of a vehicle's pitch-over resistance, metrics referred to here as Froward Tilt Table Ratio (FTTR) and Rearward Tilt Table Angle (RTTR). FTTR and RTTR are computed using:

$$\mathrm{FTTR} = \tan(\mathrm{FTTA}) \quad \text{and} \quad \mathrm{RTTR} = \tan(\mathrm{RTTA})$$

Appendix A contains results from all Tilt Table tests conducted on both vehicles, with and without OPDs.

3.4 Discussion of Laboratory Test Results

Appendix A contains tabular results of the laboratory measurements. Appendix A contains four pages of results, two pages for the VIMF tests and two for the Tilt Table tests. The VIMF results pages contain a table with measurements from the full VIMF tests conducted using the laboratory loading conditions described above. The VIMF measurements in the laboratory loading conditions include those related to the mass (weight), track width, wheelbase, center-of-gravity location, inertia properties, and SSF. The VIMF pages also contain columns of weight-only measurements of the loading conditions used for the dynamic pitchover and rollover tests (which included test instrumentation, an ATD, and OPDs).

The Tilt Table results pages list the Tilt Table angles and Tilt Table ratios for the lateral and longitudinal Tilt Table tests conducted. The tables on these pages also list which wheel lifted first for each Tilt Table test; either Front or Rear for the lateral tilts and either Right or Left for the longitudinal tilts.

Figures 6 and 7 are provided to summarize the fundamental measurements from the laboratory tests. As expected, when adding weight near the ends of a vehicle and above the vehicle CG height, the VIMF measurements show that the OPDs increase total weight, increase CG height which decreases SSF, and increase the roll, pitch, and yaw inertias. The smaller airbags used on the front of Airbag OPD #1 weighed less than the rear airbags used, so the longitudinal CG in this loading condition moved rearward relative to the Driver only loading condition. The same size airbags were used on the front and rear of Airbag OPD #2, so the longitudinal CG moved rearward. The AM OPD used on Vehicle M was rear mounted, which also moved the longitudinal CG rearward. The three bar charts on Figure 6 (Vehicle Weight, CG Height, and CG Longitudinal) and the top chart on Figure 7 (SSF) summarize these key measurements from the VIMF tests.

When adding weight above the vehicle CG height, the lateral Tilt Table angle decreases. This is the case for all three OPD loading conditions, as summarized in the middle chart of Figure 7 (Lateral Tilt Table Angle). The bottom chart of Figure 7 shows that the rear Tilt Table angles also decreased when OPDs were added to both vehicles. For Vehicle E with Airbag OPD #1 and for Vehicle M with AM OPD, the CG Height increased and the CG Longitudinal CG moved rearward. Both the increased height and rearward location of the CG contributed to the lower rear Tilt Table angles for these two OPD conditions. For Vehicle E with Airbag OPD #2, the CG Height increased and the CG Longitudinal moved forward. The net effect of these also resulted in slightly lower rear Tilt Table angle compared to the Driver loading condition.

The static metrics from laboratory tests show that adding the OPDs evaluated in this study reduces the lateral rollover and rearward pitchover resistance of the vehicles. The effects of these changes on lateral stability and tip over resistance during dynamic maneuvers was not investigated as part of these study. However, their influence on vehicle handling and dynamic stability should be considered when evaluating the net safety benefits of outfitting an ATV with an OPD.

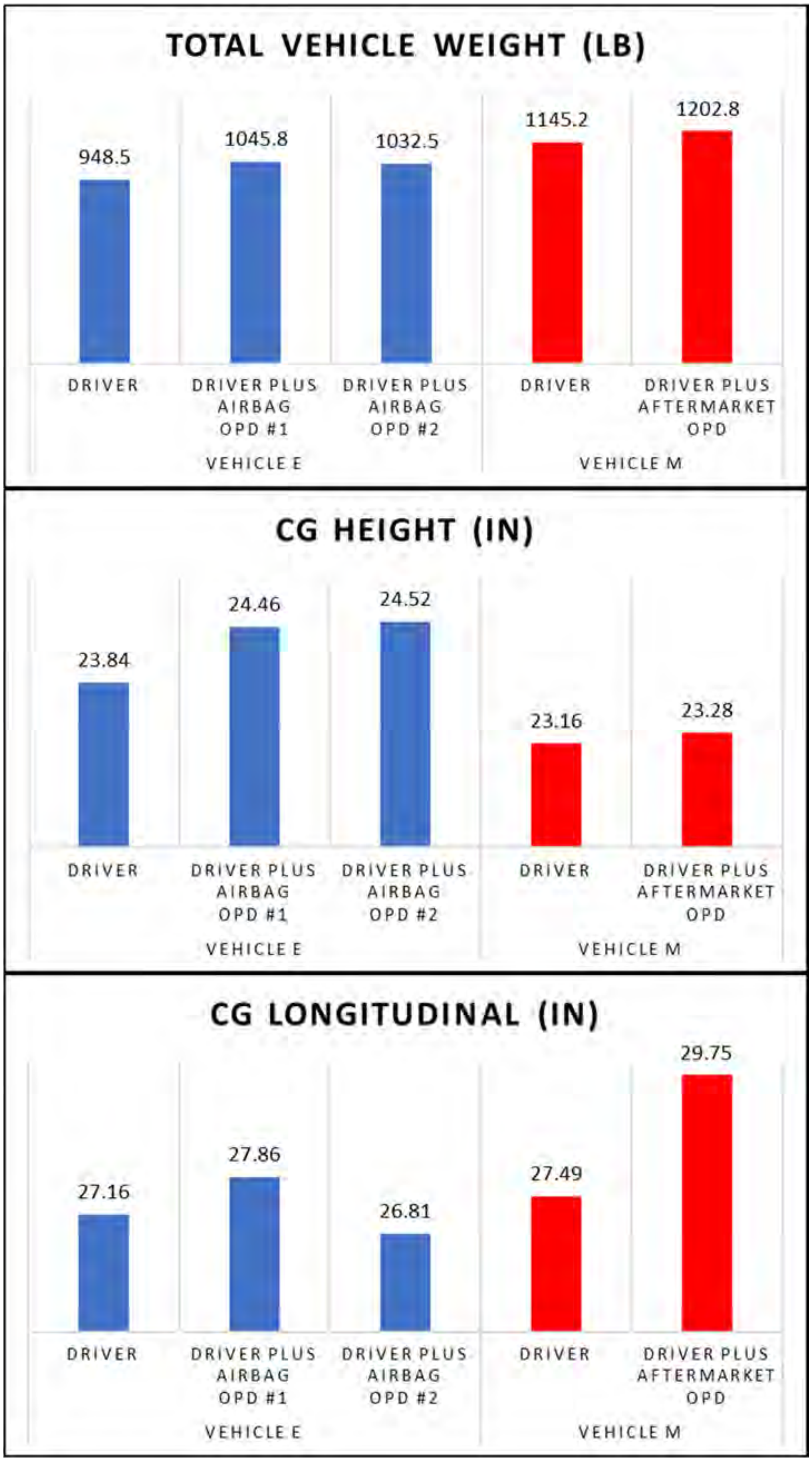

Figure 6: Vehicle Weight and CG Locations without and with OPDS

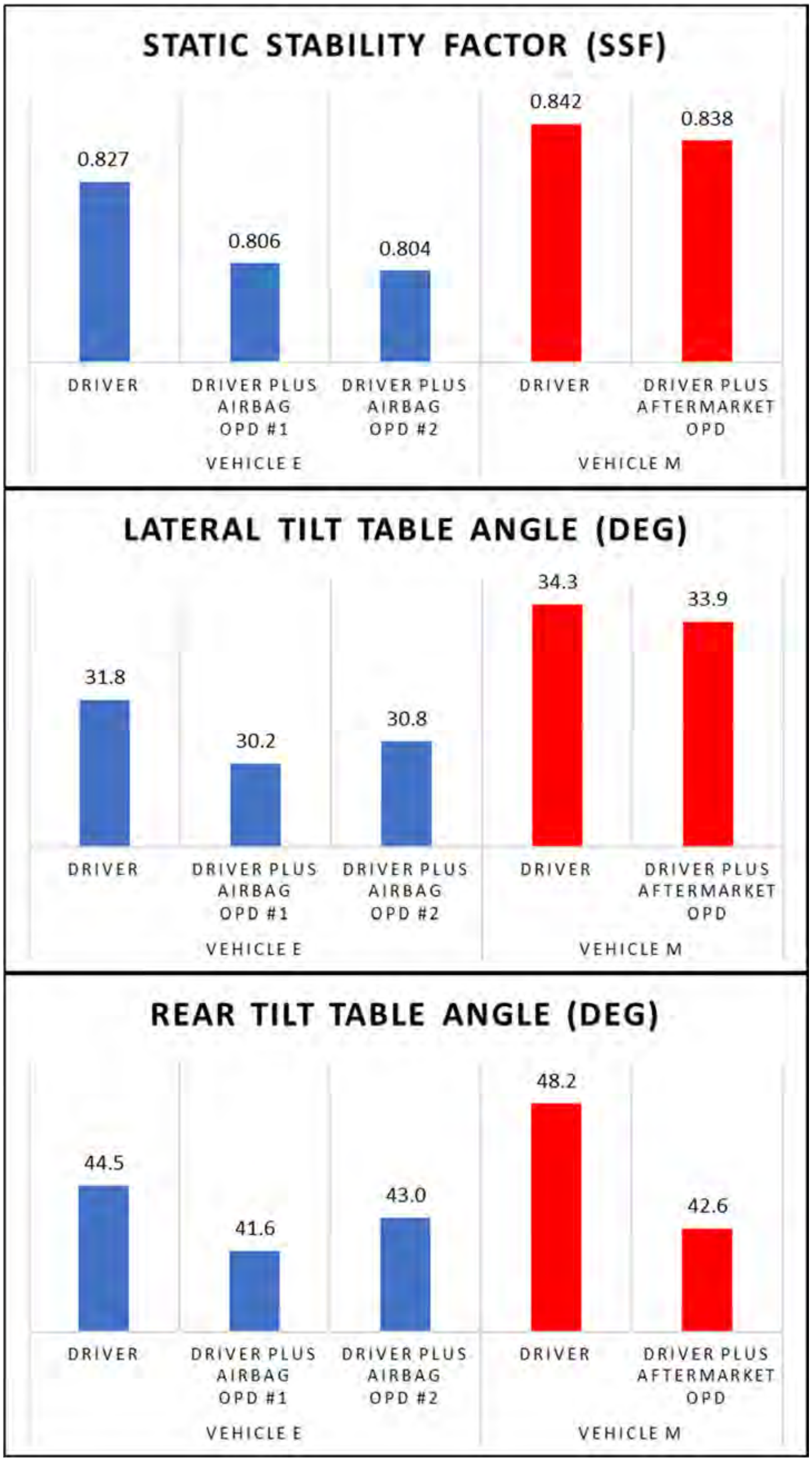

Figure 7: Vehicle SSF and Tilt Tables Angles without and with OPDS

4. REARWARD PITCHOVER TESTING AND RESULTS

This section describes the outdoor rearward pitchover tests conducted on SEA's grass-covered test hill (so called hill pitchover tests) and conducted on SEA's sled facility (so called sled pitchover tests). Hill pitchover and sled pitchover tests were performed on both vehicles with no OPD and with their OPD fitments.

This section is divided into three subsections: one covering the vehicle loading and instrumentation used for the dynamic tests, one covering the hill pitchover tests and their outcomes, and one covering the sled pitchover tests and their outcomes.

4.1 Vehicle Loading and Instrumentation

The loading condition used for all the dynamic tests conducted in this study included an instrumented Hybrid III 50th percentile male anthropomorphic test device (ATD) with a standing pelvis, an ATD secure and release system, vehicle data sensors and a data collection system. For all tests, 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 sit with the rear of its buttocks about 4 to 5 inches from the rear of the seat. The seating and handhold positions of the ATD dictate its forward lean angle, which was set to represent a typical lean angle of a driver the size of the ATD.

For all tests, the ATVs were equipped with an NI CompactRIO (the on-vehicle computer with the actuator and valve controllers, and with data acquisition software), a GPS/IMU (either an OxTS RT1003 or OxTS RT3002), and an auxiliary rate sensor (a sensor capable of measuring rates greater than the RT units). A list of the sensors and their specifications is provided in Table 2. The CompactRIO and sensors are shown on Page 3 of Appendix D. A 12V lithium battery was also used for all tests to power the CompactRIO and sensors. This battery and the network antenna used for wireless communication are shown on Page 4 of Appendix D.

Table 2: Instrumentation Used During Testing

Transducer	Measurement	Range	Accuracy
OxTS RT3002 or OxTS RT1003	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	(Auxiliary) Pitch or Roll Rate	± 400 deg/s	0.5%

For the hill pitchover tests only, components of SEA's ATV Robotic Test Driver (RTD) were used to drive the ATVs up an incline to intentionally induce rearward pitchover events. For these tests, the pneumatically powered versions of the RTD throttle and brake actuators were used. These actuators, as well as the RTD human driver override switch, are shown on Page 5 of Appendix D. No robotic steering control was used during the hill pitchover tests, rather the front wheels were simply aligned straight ahead prior to each nominally straight-line run. The RTD system includes an engine kill circuit which is used while conducting unmanned tests like the hill pitchover tests. The antenna that receives wireless kill circuit signals is shown on Page 4 of Appendix D.

A pneumatic accumulator tank was used to store air needed to operate the pneumatic actuators on the vehicle. This tank and a vehicle-mounted panel containing pneumatic values is shown on Page 6 of Appendix D.

The same ATD used in previous ATV studies, with internal (head, neck, and chest) sensors and onboard wireless data acquisition (DAQ) system, was used in this study. Descriptions and photographs of the ATD sensors and DAQ system are provided in Appendix E. For the hill and sled rearward pitchover tests, the dummy "secure and release" system was comprised of only cable ties securing the ATD's hands to the hand grips of the vehicles. For the sled lateral rollover tests, 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. Appendix E also contains descriptions and photographs of these two versions of the ATV "secure and release" system used in this study.

Table 3 lists the nominal weights of the ATD and instrumentation components added the ATVs. The total weight of these, 211.7 lb, is very close to the Driver weight used in the laboratory tests. Table 2 also lists the weights of the three OPDs evaluated in this study. Appendix A contains details of the vehicle total test weights. Page 1 of Appendix A has values for Vehicle E (No OPD, Airbag #1 OPD, and Airbag OPD #2) and Page 2 of Appendix A has values for Vehicle M (No OPD and AM OPD).

Table 3: Vehicle Loading for Dynamic Hill and Sled Tests

Component	Nominal Weight (lb)
ATD as Tested with Helmet and Clothing	174.0
RT Unit and Roll Rate Sensor with Mounts	10.1
CompactRIO	5.9
Pneumatic Canister, Valves and Actuators	5.1
12V Lithium Battery	6.6
Cables and Miscellaneous	10.0
Nominal Weight Added for Dynamic Tests Without OPD	**211.7**
Additional Weight Added for Tests with Airbag OPD #1	97.1
Additional Weight Added for Tests with Airbag OPD #2	84.4
Additional Weight Added for Tests with AM OPD	59.4
Total Nominal Weight Added for Tests with Airbag OPD #1	**308.8**
Total Nominal Weight Added for Tests with Airbag OPD #2	**296.1**
Total Nominal Weight Added for Tests with AM OPD	**271.1**

4.2 Hill Pitchover Tests

The following five subsections contain a description of the hill pitchover tests, a description of the video results, a description of the ATD results, a description of the vehicle results, and an overview of the hill pitchover test outcomes.

4.2.1 Description of Hill Pitchover Tests

Figure 8 shows Vehicle E positioned at the start of a rearward pitchover test on the hill. The hill pitchover tests started with the vehicle running, with the hand brake applied, in high gear, and facing up the hill. The rear drive wheels were aligned on top of high-friction steel plates located at the base of the 25° slope portion of the hill. The front wheels were placed on a 40° aluminum ramp (the same ramp used during the sled pitchover tests). All the hill pitchover tests started with the vehicles at a pitch angle of 40° relative to horizontal. To start each test, the RTD brake actuator released the brake, and the RTD throttle actuator applied enough throttle to cause the vehicles to climb the ramp and result in rearward pitchovers when the vehicles were not equipped with OPDs. The throttle was dropped two seconds after the start of the test. After the vehicle came to rest at the end of each maneuver, the kill circuit was engaged to shut off the engine. The hill rearward pitchover tests were not designed to replicate any specific real-world pitchover event, rather they were designed to intentionally result in rearward pitchover events.

Results from the hill pitchover tests are contained in the first half of Appendix B. The order in which results are presented for each vehicle-OPD combination is:

- Vehicle E – NO OPD
- Vehicle E – Airbag OPD #1
- Vehicle E – Airbag OPD #2
- Vehicle M – NO OPD
- Vehicle M – AM OPD

This is the same order in which the sled pitchover results are presented in the second half of Appendix B.

Figure 8: Vehicle E Equipped with Airbag OPD #1 on Hill

4.2.2 Description of Video Results

For each of the five vehicle-OPD combinations used in hill pitchover tests there are five pages of results presented in Appendix B. The first two pages contain images taken from the left side video camera used to document the tests. The video images presented are digital JPEG format images of individual video frames from the camera. The GoPro camera used was 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 B depends on the maximum duration of the pitchover event. For all pitchover tests, images are shown for 40° (the start of the test) and 60° of pitch angle, and if achieved during the test, 90°, 120°, 150°, 180°, and 210° of pitch angle. For all tests, images are also included for the time of maximum pitch angle and the end of the run. If the ATD's head struck the ground during the test, an image of this is included. For the longer duration tests, like those when the vehicle pitched forward on to the ramp and rolled rearward, there are additional images (at 0.5 second intervals) to fill in the information of the vehicle motion throughout the tests. For the test conducted on Vehicle M outfitted with the AM OPD, there are two additional images included in the results; these are the video frame when the AM OPD structure first started to expand and the video frame when the AM OPD structure reached its fully expanded state.

The individual video images include titles listing the vehicle pitch angle and time of the image. The times listed are times from when the vehicle pitch rate first starts to increase during the test.

4.2.3 Description of ATD Results

A description of the Anthropomorphic Test Device (ATD), the ATD sensors and data collection system, and the system used to secure and release the ATD during the overturn events conducted in this study is contained in Appendix D. The ATD head, chest, and 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.[9]

The third and fourth pages of results for each of the five vehicle-OPD combinations presented in Appendix B contain results from the ATD sensors. The third pages contain Head Accelerations in the head fixed X, Y, and Z directions; Chest Accelerations in the chest fixed X, Y, and Z directions; and Head Angular Rates about the head roll, pitch, and yaw axes. The fourth page contains Neck Forces in the neck fixed X, Y, and Z directions, and Neck Moments about the roll, pitch, and yaw axes. All the ATD data was zeroed prior to time equals zero seconds, the time when the pitch rate first starts to increase during the test. Therefore, the data presented shows the changes in accelerations, rates, forces, and moments that occurred throughout the event. All the ATD data shown has been filtered using a 1,000 Hz low pass Butterworth filter.

If the ATD's head struck the ground during the test, all graphs containing ATD data include a vertical band (about 0.2 seconds wide) centered around the time when the ATD head first strikes

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

the ground. This band provides a convenient reference for the head strike during the overturn event. The graphs show spikes in the ATD accelerations, rates, forces, and moments within this band.

4.2.4 Description of Vehicle Results

The fifth page for each of the five vehicle-OPD combinations presented in Appendix B contains results from the vehicle sensors. 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. All the vehicle data presented in this report is unfiltered.

The vehicle results graphs included contain Vehicle Pitch Rate, Vehicle Pitch Angle, and Vehicle Body Fixed Accelerations in the vehicle body fixed X, Y, and Z directions. As with the ATD graphs, time equals zero seconds is the time when the pitch rate first starts to increase during the test. Accordingly, the pitch rate plots start near 0.0 deg/sec and the pitch angle graphs start near 40 deg.

If the ATD's head struck the ground during the test, all graphs containing vehicle data also include a vertical band (about 0.2 seconds wide) centered around the time when the ATD head first strikes the ground. These bands provide context regarding the timing of sequences during the event. For example, the initial set of spikes in the vehicle acceleration plots indicate when the rear part of the vehicle, or the rear portion of the OPD, first strikes the ground. The head-strike bands are generally close to the initial acceleration peaks, in some cases before the peaks if the ATD head strikes the ground before the vehicle or OPD do, and in other cases after.

4.2.5 Overview of Hill Pitchover Test Outcomes

The images contained in Appendix B provide visual details of the vehicle and ATD motions, and the data provides details of the vehicle and ATD measurements, throughout the hill pitchover events. The following five figures (Figures 9-13) provide information on the test outcomes for the five vehicle-OPD combinations used during the hill pitchover tests. Each of the five figures contain an image of the vehicle at its maximum pitch angle and a final image of the event with the vehicle at rest. Below these images, each figure has a narrative box summarizing the test outcome.

Figures 9 and 12 contain results from the tests with no OPDs, on Vehicle E and Vehicle M, respectively. Both tests with no OPD resulted in the vehicle pitching rearward beyond 180° and with the vehicle remaining on top of the ATD after the test.

Figure 10 contains results from the test on Vehicle E outfitted with Airbag OPD #1. Airbag OPD #1 prevented Vehicle E from pitching to 90°. Soon after maximum pitch angle was achieved, the ATD released from the vehicle and fell to the ground. After the ATD fell from the vehicle, the vehicle pitched forward onto the ramp. Then the vehicle rolled rearward, with the rear wheels rolling over the ATD.

Results from the test on Vehicle E outfitted with Airbag OPD #2 are in Figure 11. Airbag OPD

#2 limited the vehicle rearward pitch motion to about 105°. The vehicle came to rest nose up, balanced on Airbag OPD #2, and the ATD remained within the confines of Airbag OPD #2.

Figure 13 contains results from the test using the AM OPD on Vehicle M. The AM OPD deployed and fully expanded prior to the time the vehicle reached its maximum pitch angle. The first video evidence of the AM OPD structure expanding was when the pitch angle was 76.3° and it was fully expanded by 76.7°, and the time between these video frames is less than 100 ms (see Page 21 of Appendix B for images). Contact between the base of the OPD structure and ground limited the pitch angle to 80.4°. The ATD fell between the opening in the expanded OPD structure and came to rest on the ground. After the vehicle achieved its maximum pitch angle, it pitched forward onto the ramp. Then the vehicle rolled rearward, with the rear wheels rolling against the ATD.

Max Pitch Angle = 211.2° - Time = 2.44 sec

End of Run - Pitch Angle = 184.5°

NARRATIVE

With NO OPD, Vehicle E pitched rearward beyond 180° and landed on the ATD. The vehicle remained on top of the ATD at rest.

Figure 9: Hill Pitchover – Vehicle E – NO OPD

Max Pitch Angle = 82.2° - Time = 0.91 sec

End of Run - Pitch Angle = 3.6°

NARRATIVE

Airbag OPD #1 prevented Vehicle E from pitching to 90°. Soon after maximum pitch angle was achieved, the ATD released from the vehicle and fell to the ground. The throttle was released two seconds after the start of the maneuver, which allowed the vehicle to pitch forward onto the ramp. Then the vehicle rolled rearward, with the rear wheels rolling over the ATD.

Figure 10: Hill Pitchover – Vehicle E – Airbag OPD #1

Max Pitch Angle = 105.1° - Time = 1.71 sec

End of Run - Pitch Angle = 89.0°

NARRATIVE

With Airbag OPD #2, Vehicle E pitched rearward to a maximum near 105°. The vehicle came to rest balanced on Airbag OPD #2. The ATD remained within the confines of Airbag OPD #2.

Figure 11: Hill Pitchover – Vehicle E – Airbag OPD #2

Max Pitch Angle = 197.6° - Time = 2.83 sec

End of Run - Pitch Angle = 188.1°

NARRATIVE

Like Vehicle E with NO OPD, Vehicle M pitched rearward beyond 180° and landed on the ATD. The vehicle remained on top of the ATD at rest.

Figure 12: Hill Pitchover – Vehicle M – NO OPD

Max Pitch Angle = 80.4° - Time = 2.47 sec

End of Run - Pitch Angle = 3.2°

NARRATIVE

The AM OPD deployed and fully expanded prior to the time the vehicle reached its maximum pitch angle. The first video evidence of the AM OPD structure expanding was when the pitch angle was 76.3° and it was fully expanded by 76.7°, and the time between these video frames is less than 100 ms. Contact between the base of the OPD structure and ground limited the pitch angle to 80.4°. The ATD fell between the opening in the expanded OPD structure and came to rest on the ground. After the vehicle achieved its maximum pitch angle, it pitched forward onto the ramp. Then the vehicle rolled rearward, with the rear wheels rolling against the ATD.

Figure 13: Hill Pitchover – Vehicle M – AM OPD

4.3 Sled Pitchover Tests

The following three subsections contain descriptions of the sled pitchover tests, descriptions of the sled video, ATD, and vehicle results, and an overview of the sled pitchover test outcomes.

4.3.1 Description of Sled Pitchover Tests

Figure 14 shows Vehicle M positioned at the start of a rearward pitchover test on the sled cart. The sled pitchover tests were conducted with the ATV engines not running and with them in high gear. The rear wheels were on top of a high-friction steel surface at the base of the sled cart. The RTD hand brake actuator was applied to hold the ATV from rolling rearward off the cart prior to test initiation. The front wheels were placed on a 40° aluminum ramp (the same ramp during the hill pitchover tests). Therefore, all the sled pitchover tests started with the vehicles at a pitch angle of 40° relative to horizontal. Figure 14 shows the aluminum ramp attached to the sled cart used for the sled lateral rollover tests. The sled cart does not move during the sled pitchover tests. Figure 14 also shows the topsoil (representative of SEA's groomed dirt surface) used to fill the sled landing pit.

For the hill pitchover tests starting on a 40° incline the engine torque was used to pitch the vehicles over. In the sled situation with no engine torque used, some additional force was needed to produce the pitchover events. For the sled pitchover tests, a long-stroke pneumatic cylinder was used to substitute for the engine torque, as seen in the left photo of Figure 15. The rod of the cylinder extended through the aluminum plate supporting the vehicle, and there was a push rod cut to the correct length from the end of the cylinder rod to the bottom of the vehicle, as seen in the right photo of Figure 15.

A 4-way manual valve was used to extend and retract the cylinder. The sizes of the valve and hose, and the size and flow capacity of the pneumatic reservoir, were selected to provide the appropriate push force and stroke to generate sled pitch rates that matched the pitch rates measured on the hill. The 4-way valve was used to extend the cylinder to start each sled pitchover test. The RTD released the brake when the rearward pitch motion began. Once pitchover was achieved, the cylinder was quickly retracted so that if the vehicle pitched forward and the front wheels landed on the ramp, the cylinder would not be in the way. The rod between the cylinder and the bottom of the vehicle was also configurated so that it fell out of the way after the vehicle first pitched rearward.

The air pressure delivered to the cylinder used during the sled pitchover tests was adjusted to give the correct pushing force and speed. The peak pitch rates in the hill pitchover tests prior to vehicle or OPD contact with the ground ranged from about 70 deg/sec to 110 deg/sec. The peak pitch rates prior to vehicle or OPD contact with the ground during the sled pitchover tests were also within this range. The sled rearward pitchover tests were not designed to replicate any specific real-world pitchover event, rather they were designed to result in rearward pitchover events.

Figure 14: Vehicle M Equipped with AM OPD on Sled Pitchover Cart

Figure 15: Pneumatic Cylinder & Extension Push Rod used to Produce Sled Pitchovers

4.3.2 Descriptions of Video, ATD, and Vehicle Results

The video, ATD, and vehicle results from the sled pitchover tests are contained in the second half of Appendix B, in pages 26-50. As with the hill pitchover test results, there are five pages of results for each of the five vehicle-OPD combinations used in sled pitchover tests. The first two pages for each vehicle-OPD combination contain the video results, the third and fourth pages contain the ATD sensor results, and fifth page contains the vehicle sensor results. The collection of results presented for the sled pitchover tests is the same as for the hill pitchover tests. Likewise, as is the case for hill pitchover time domain plots, time zero on the sled pitchover time domain plots represents the time when the pitch rate first starts to increase during the test.

4.3.3 Overview of Sled Pitchover Test Outcomes

The images contained in Appendix B provide visual details of the vehicle and ATD motions, and the data provides details of the vehicle and ATD measurements, throughout the sled pitchover events. The following five figures (Figures 16-20) provide information on the test outcomes for the five vehicle-OPD combinations used during the sled pitchover tests. Each of the five figures contain an image of the vehicle at its maximum pitch angle and a final image of the event with the vehicle at rest. Below these images, each figure has a narrative box summarizing the test outcome.

Figures 16 and 19 contain results from the tests with no OPDs, on Vehicle E and Vehicle M, respectively. Both tests with no OPD resulted in the vehicle pitching rearward to near 180° and with the vehicle remaining on top of the ATD after the test.

Figure 17 contains results from the test on Vehicle E outfitted with Airbag OPD #1. Airbag OPD #1 prevented Vehicle E from pitching to 90°. Near the time of maximum pitch angle, the ATD released from the vehicle. Then, as with the hill pitchover test, the vehicle pitched forward onto the ramp. As the vehicle pitched forward and then rolled rearward, it pushed the ATD rearward, and the ATD remained behind the upright vehicle at rest.

Results from the test on Vehicle E outfitted with Airbag OPD #2 are shown in Figure 18. Airbag OPD #2 limited the vehicle rearward pitch motion to about 80°. Like on the hill pitchover test, the vehicle came to rest balanced on Airbag OPD #2, and the ATD remained within the confines of Airbag OPD #2.

Figure 20 contains results from the test using the AM OPD on Vehicle M. The AM OPD deployed and fully expanded prior to the time the vehicle reached its maximum pitch angle. The first video evidence of the AM OPD structure expanding was when the pitch angle was 76.2° and it was fully expanded by 77.1°, and the time between these video frames is less than 100 ms (see Page 46 of Appendix B for images). Contact between the OPD structure and ground limited the pitch angle to 82.2°. The ATD's helmet first landed on the top structure of the expanded OPD. Then the ATD's arms and legs landed on the side structures of the OPD. The vehicle did not pitch forward back onto the ramp, possibly because the weight of the ATD head and limbs prevented it from doing so. The vehicle ended balanced at a pitch angle of 67.9°.

Max Pitch Angle = 189.9° - Time = 2.51 sec

End of Run - Pitch Angle = 175.7°

NARRATIVE

With NO OPD, Vehicle E pitched rearward beyond 180° and landed on the ATD. The vehicle remained on top of the ATD at rest.

Figure 16: Sled Pitchover – Vehicle E – NO OPD

Max Pitch Angle = 63.3° - Time = 0.52 sec

End of Run - Pitch Angle = -7.9°

NARRATIVE

Airbag OPD #1 prevented Vehicle E from pitching to 90°. Near the time of maximum pitch angle, the ATD released from the vehicle. Then, like on the hill pitchover test, the vehicle pitched forward onto the ramp. As the vehicle pitched forward and then rolled rearward, it pushed the ATD rearward, and the ATD remained behind the upright vehicle at rest.

Figure 17: Sled Pitchover – Vehicle E – Airbag OPD #1

Max Pitch Angle = 78.3° - Time = 0.84 sec

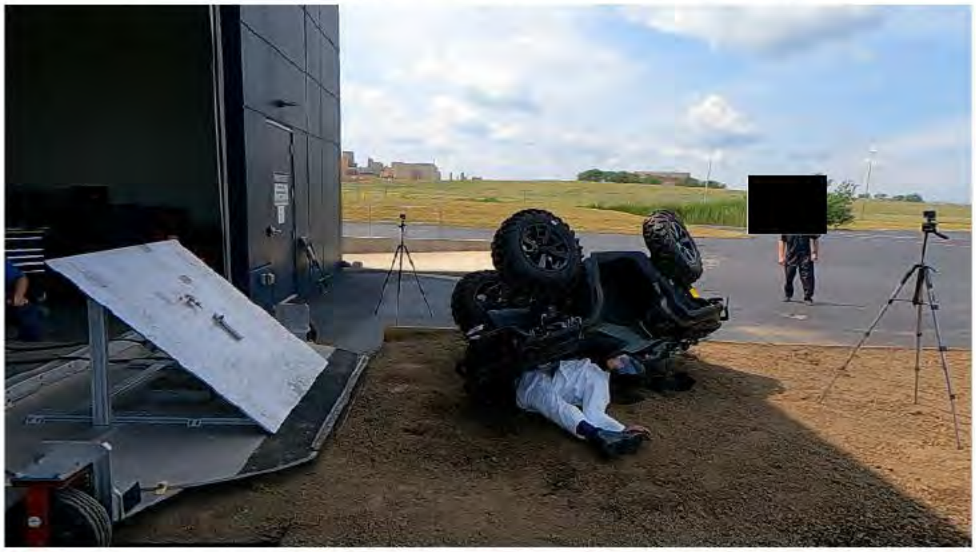
End of Run - Pitch Angle = 66.2°

NARRATIVE

Airbag OPD #2 limited the vehicle rearward pitch motion to about 80°. Like on the hill pitchover test, the vehicle came to rest balanced on Airbag OPD #2, and the ATD remained within the confines of Airbag OPD #2.

Figure 18: Sled Pitchover – Vehicle E – Airbag OPD #2

Max Pitch Angle = 177.8° - Time = 3.26 sec



End of Run - Pitch Angle = 177.4°

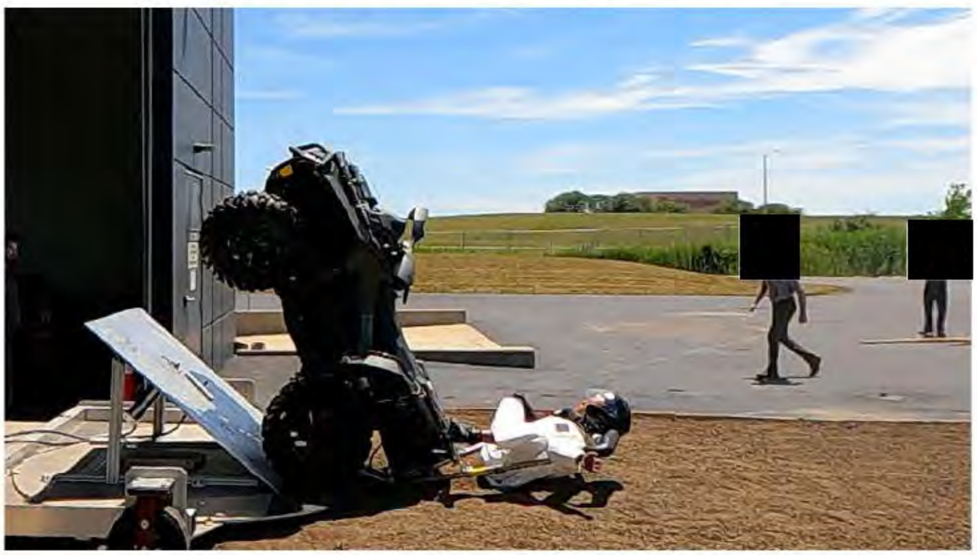
NARRATIVE

Like Vehicle E, with NO OPD, Vehicle M pitched rearward to near 180° and landed on the ATD. The vehicle remained on top of the ATD at rest.

Figure 19: Sled Pitchover – Vehicle M – NO OPD

Max Pitch Angle = 82.2° - Time = 0.96 sec

End of Run - Pitch Angle = 67.9°



NARRATIVE

The AM OPD deployed and fully expanded prior to the time the vehicle reached its maximum pitch angle. The first video evidence of the AM OPD structure expanding was when the pitch angle was 76.2° and it was fully expanded by 77.1°, and the time between these video frames is less than 100 ms. Contact between the OPD structure and ground limited the pitch angle to 82.2°. The ATD's helmet landed on the top structure of the expanded OPD, then the ATD's arms and legs landed on the side structures of the OPD. The vehicle did not pitch forward back onto the ramp, possibly because the ATD head and limbs prevented it from doing so. The vehicle ended balanced at a pitch angle of 67.9°.

Figure 20: Sled Pitchover – Vehicle M – AM OPD

5. LATERAL ROLLOVER TESTING AND RESULTS

This section describes the sled rollover tests conducted on SEA's laboratory sled configured for ATV rollover testing. Tests categorized as moderate energy rollovers were performed using Vehicles E and M, with and without OPDs. The same vehicle loading and instrumentation used for the rearward pitchover tests, as described on Section 4.1, was used for the sled lateral rollover tests. The same sled cart used during the sled pitchover tests was used, but for the sled rollover tests it is accelerated to speed and decelerated at the end of the sled rail to cause the vehicles to rollover on the topsoil-filled sled landing pit.

This section is divided into three parts: one describing the sled lateral rollover tests, one describing video, ATD, and vehicle results, and one providing an overview of the sled rollover test outcomes.

5.1 Description of Sled Lateral Rollover Tests

Figure 21 shows Vehicle E on the rollover sled cart positioned near the start of a lateral rollover test on the sled. Various sled configuration parameters were tuned to generate sled rollover events 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 studies. Appendix F 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 close to 200 deg/s.[10] Appendix E contains a description of the ATD secure and release system used during ATV lateral rollover tests conducted on the sled.

Figure 21: Vehicle E without OPD on Rollover Sled Cart

[10] *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

Results from the sled rollover tests are contained in Appendix C. The order results are presented for each vehicle-OPD combination is:

- Vehicle E – NO OPD
- Vehicle E – Airbag OPD #1
- Vehicle E – Airbag OPD #2 – 2 Low-Pressure Airbags Front and Rear
- Vehicle E – Airbag OPD #2A – 2 Low-Pressure Airbags Rear Only
- Vehicle E – Airbag OPD #2B – 1 Low-Pressure Airbag Front and Rear
- Vehicle E – Airbag OPD #2C – 1 Low-Pressure Airbag Rear Only
- Vehicle M – NO OPD
- Vehicle M – AM OPD

The list of vehicle-OPD combinations above includes all the vehicle-OPD combinations evaluated in the rearward pitchover tests; and it includes three additional combinations used for Vehicle E, namely, Airbag OPD #2A, Airbag OPD #2B, and Airbag OPD #2C. The baseline Airbag OPD #2 used two rear and two front airbags. As mentioned previously, adding OPD structure on the front of the ATV was used to determine if doing so provides additional occupant protection, particularly in lateral rollovers. The lateral rollover test using Airbag OPD #2 resulted in a test outcome with the ATV rolling to a maximum roll angle of about 104°, and with the ATV coming to rest at a roll angle close to 90°. This test outcome drove the decision to test Vehicle E during two tests without a front airbag: one using two rear airbags (Airbag OPD #2A) and one using one rear airbag (Airbag OPD #2C). To test all cases Vehicle E was also tested using only one rear and one front airbag (Airbag OPD #2B).

5.2 Descriptions of Video, ATD, and Vehicle Results

The video, ATD, and vehicle results from the sled lateral rollover tests are contained in Appendix C. The video results from the sled lateral rollover tests contain four-view composites for each sequential snapshot image presented. The four views are from four GoPro cameras synchronized using a remote start feature. The views are from cameras located to provide a rear view, a side view, a left view, and an oblique angle view of the vehicle and ATD during the rollover events. The same video frame rate (60 frames per second) used during the pitchover tests was used for the lateral rollover tests.

For all rollover tests, images are shown for 30°, 60°, and 90° of roll angle, and if achieved during the test, 180° and 270° of roll angle. For all tests, images are also included for the time of maximum roll angle and the end of the run. If the ATD's head struck the ground during the test, an image of this is included. For the test conducted on Vehicle M outfitted with the AM OPD, there are two additional images included in the results; these are the video frame when the AM OPD structure first started to expand and the video frame when the AM OPD structure reached its fully expanded state. The composite video images include titles listing the vehicle roll angle and time of the image. The times listed are times from when sled braking was first applied.

As with the pitchover test results, the video results are presented before the ATV and vehicle results. For the rollover tests, each composite video image uses a full page and the number of video pages for each vehicle-OPD combination varies in Appendix C, depending on how much the vehicle rolled during the test.

The collection of ATD and vehicle results presented for the sled lateral rollover tests is the same as the pitchover tests. There are two pages of ATD results and one page of vehicle results following the video results. However, for the sled lateral rollover tests, time zero for the ATD and vehicle time domain plots represents the time from when sled braking was first applied. Also, for the sled tests, the vehicle data includes pitch rate, yaw rate, pitch angle, and heading (change in yaw angle).

5.3 Overview of Sled Rollover Test Outcomes

The images contained in Appendix C provide visual details of the vehicle and ATD motions, and the data provides details of the vehicle and ATD measurements, throughout the sled rollover events. The following eight figures (Figures 22-29) provide information on the test outcomes for the eight vehicle-OPD combinations used during the sled rollover tests. Each of the eight figures contain a final image of the event with the vehicle at rest, and either an image of the vehicle at its maximum roll angle or at 180° of roll angle. Below these images, each figure has a narrative box summarizing the test outcome.

Figure 22 contains results from the test on Vehicle E with no OPD. With no OPD, Vehicle E rolled beyond 180°. During the roll sequence, the vehicle landed on the ATD and remained on top of the ATD after the test.

Figure 23 contains results from the test on Vehicle E outfitted with Airbag OPD #1. Airbag OPD #1 did not prevent Vehicle E from rolling over. Soon after contacting the ground, the right-side front and rear airbags bent somewhat under the right side of the vehicle, reducing their effectiveness to act as rollover-preventing outriggers. With Airbag OPD #1, Vehicle E rolled beyond 180°. During the roll sequence, the vehicle landed on the ATD and remained on top of the ATD after the test.

Results from the test on Vehicle E outfitted with Airbag OPD #2 are in Figure 24. Airbag OPD #2 limited the vehicle roll motion to about 104°. The vehicle came to rest with a roll angle close to 90°. During the roll sequence, the ATD released from the vehicle and remained between the front and rear airbags at rest.

Figure 25 contains results from the test using Vehicle E outfitted with Airbag OPD #2A. This configuration with two low-pressure airbags mounted at the rear of vehicle did not prevent the vehicle from rolling over to its final roll angle near 270°. However, this airbag configuration did provide protection space for the ATD, as shown in the top image at 180° of roll angle. There was little interaction between the ATD and the vehicle or airbags throughout the rollover event.

Airbag OPD #2B limited the vehicle roll motion to about 122°, as shown in Figure 26. The vehicle came to rest with a roll angle close to 90°. During the roll sequence, the ATD released from the vehicle and remained between the front and rear airbags at rest.

Figure 27 contains results from the test using Vehicle E outfitted with Airbag OPD #2C. The single rear-mounted, low-pressure airbag prevented the vehicle from rolling to 180°. The airbag deflected as the vehicle rolled to its maximum measured roll angle of 170.8°. Then the airbag caused the vehicle to roll back to its final roll angle of 115.6°. The airbag provided a protection space for the ATD as the ATV rolled to its maximum angle, and there was little interaction between the ATD and the vehicle or airbags throughout the event.

Results from the rollover test on Vehicle M with no OPD are in Figure 28. With no OPD, Vehicle M rolled to a final roll angle close to 270°. During this event, the vehicle landed on and rolled over ATD. The top image of Figure 28, at 180° of roll angle, shows a time when the entire weight of the vehicle was on the ATD.

Figure 29 contains results from the test using Vehicle M outfitted with the AM OPD. The AM OPD deployed and fully expanded prior to the time the vehicle reached a roll angle of 90°. The first video evidence of the AM OPD structure expanding was when the roll angle was 74.4° and it was fully expanded by 87.4°, and the time between these video frames is less than 100 ms (see Pages 72 and 73 of Appendix C for images). Contact between the expanded OPD structure and ground limited the roll angle to 184.6°, and it supported the vehicle at its final roll angle of 176.1°. The AM OPD provided a protection space for the ATD, and there was no interaction between the ATD and the vehicle or OPD after the ATD disengaged from the vehicle.

Max Roll Angle = 206.4° - Time = 2.33 sec

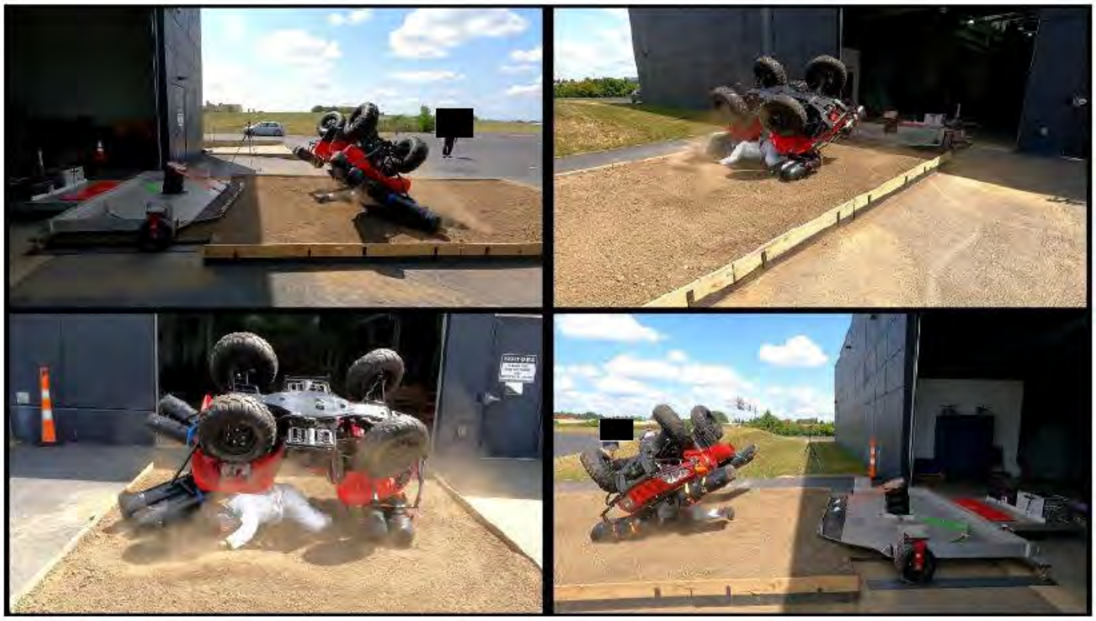
End of Run - Roll Angle = 153.8°

NARRATIVE

With NO OPD, Vehicle E rolled beyond 180°. The vehicle landed on and remained on top of the ATD at rest.

Figure 22: Sled Rollover – Vehicle E – NO OPD

Max Roll Angle = 211.2° - Time = 1.80 sec



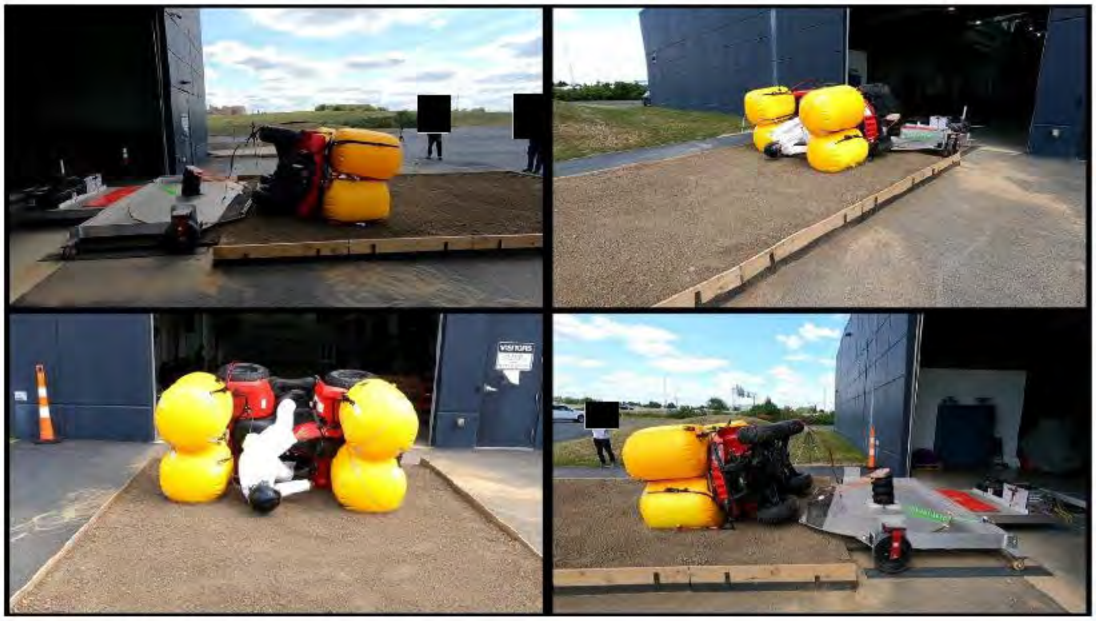
End of Run - Roll Angle = 175.0°

NARRATIVE

Airbag OPD #1 did not prevent Vehicle E from rolling over. Soon after contacting the ground, the right-side front and rear airbags bent somewhat under the right side of the vehicle, reducing their effectiveness to act as rollover-preventing outriggers. With Airbag OPD #1, Vehicle E rolled beyond 180°. During the roll sequence, the vehicle landed on the ATD and remained on top of the ATD at rest.

Figure 23: Sled Pitchover – Vehicle E – Airbag OPD #1

Max Roll Angle = 103.7° - Time = 1.26 sec



End of Run - Roll Angle = 88.8°

NARRATIVE

Airbag OPD #2 limited the vehicle roll motion to about 104°. The vehicle came to rest with a roll angle close to 90°. During the roll sequence, the ATD released from the vehicle and remained between the front and rear airbags at rest.

Figure 24: Sled Pitchover – Vehicle E – Airbag OPD #2

Roll Angle = 180° - Time = 2.04 sec

End of Run - Roll Angle = 274.3°

NARRATIVE

This configuration with two low-pressure airbags mounted at the rear of vehicle did not prevent the vehicle from rolling over to its final roll angle near 270°. However, this airbag configuration did provide protection space for the ATD, as shown in the top image at 180° of roll angle. There was little interaction between the ATD and the vehicle or airbags throughout the rollover event.

Figure 25: Sled Pitchover – Vehicle E – Airbag OPD #2A

Max Roll Angle = 122.4° - Time = 1.34 sec

End of Run - Roll Angle = 90.5°

NARRATIVE

Airbag OPD #2B limited the vehicle roll motion to about 122°. The vehicle came to rest with a roll angle close to 90°. During the roll sequence, the ATD released from the vehicle and remained between the front and rear airbags at rest.

Figure 26: Sled Pitchover – Vehicle E – Airbag OPD #2B

Max Roll Angle = 170.8° - Time = 2.14 sec

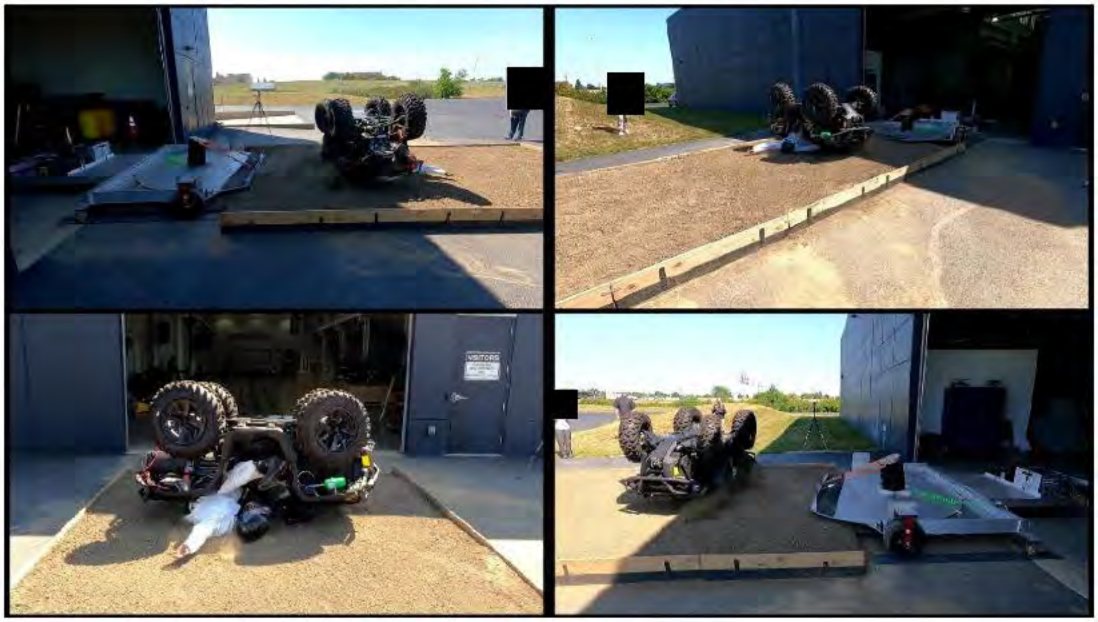
End of Run - Roll Angle = 115.6°

NARRATIVE

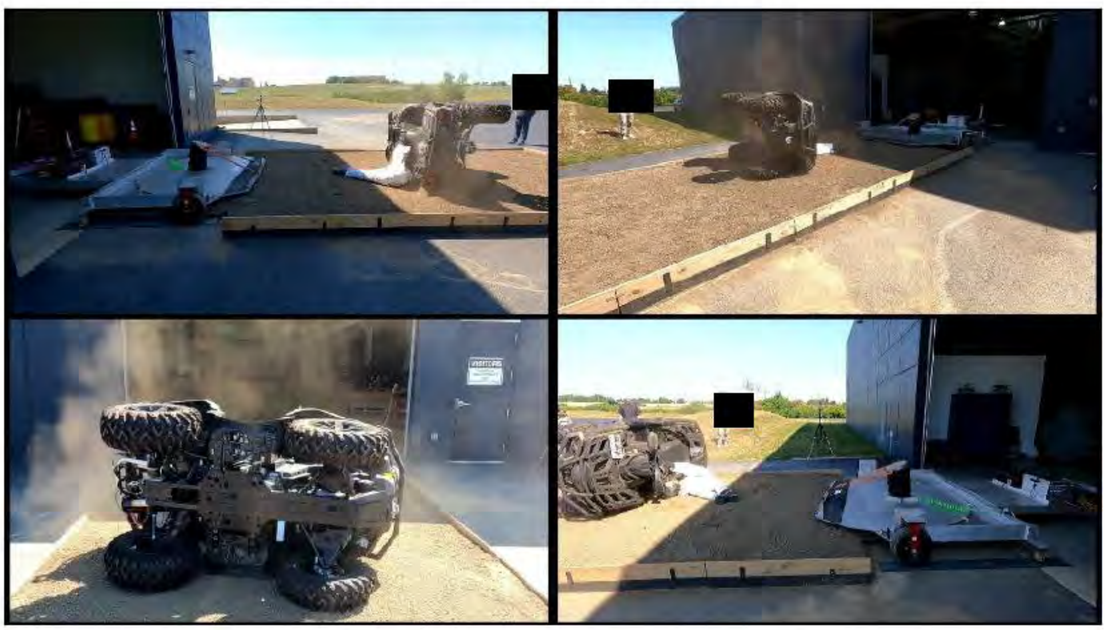
The single rear-mounted, low-pressure airbag prevented the vehicle from rolling to 180°. The airbag deflected as the vehicle rolled to its maximum measured roll angle of 170.8°. Then the airbag caused the vehicle to roll back to its final roll angle of 115.6°. The airbag provided a protection space for the ATD as the ATV rolled to its maximum angle, and there was little interaction between the ATD and the vehicle or airbags throughout the event.

Figure 27: Sled Pitchover – Vehicle E – Airbag OPD #2C

Roll Angle = 180° - Time = 1.39 sec



End of Run - Roll Angle = 274.0°



NARRATIVE

With no OPD, Vehicle M rolled to a final roll angle close to 270°. During this event, the vehicle landed on and rolled over ATD. The top image above, at 180° of roll angle, shows a time when the entire weight of the vehicle was on the ATD.

Figure 28: Sled Pitchover – Vehicle M – NO OPD

Max Roll Angle = 184.6° - Time = 2.63 sec

End of Run - Roll Angle = 176.1°

NARRATIVE

The AM OPD deployed and fully expanded prior to the time the vehicle reached a roll angle of 90°. The first video evidence of the AM OPD structure expanding was when the roll angle was 74.4° and it was fully expanded by 87.4°, and the time between these video frames is less than 100 ms. Contact between the expanded OPD structure and ground limited the roll angle to 184.6°, and it supported the vehicle at its final roll angle of 176.1°. The AM OPD provided a protection space for the ATD, and there was no interaction between the ATD and the vehicle or OPD after the ATD disengaged from the vehicle.

Figure 29: Sled Pitchover – Vehicle M – AM OPD

6. SUMMARY

This summary contains four sections. The first section provides a summary of the head injury criterion values measured during all tests conducted. This is followed by summary comments regarding tests conducted using the three OPDs evaluated in this study: Airbag OPD #1, Airbag OPD #2, and the AM OPD.

6.1 Summary of Measured Head Injury Criterion (HIC) Values

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 test, 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 ATD data acquisition trigger to fifteen seconds after the trigger). For all tests when the ATD's head struck the ground, the peak HIC values occurred around the time when the ATD's head first struck the ground.

Figure 30 contains a bar chart showing the HIC_{15} and HIC_{36} values for all tests. In all tests, the ATD was wearing a large DOT FMVSS 218 certified open face helmet with a full-face shield. 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[11]) 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 determined likely to result in concussions.[12]

For the hill and sled pitchover tests of Vehicle E with Airbag OPD #2, the ATD's head never hit the ground, so the HIC values are very small for these tests. The average HIC_{15} and HIC_{36} values for the other pitchover tests (excluding Airbag OPD #2 tests) are 96 and 50, respectively. For the lateral rollover tests, the HIC_{15} values averaged 170 and the HIC_{36} values averaged 99, and these values are in the range of values measured in previous studies involving moderate energy sled

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[11] *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

[12] 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.

rollover tests. The lower HIC values in the pitchover tests is attributed to the fact that pitchover tests conducted can be classified as less severe than the rollover tests conducted, if one considers the peak angular rate attained prior to the vehicle or OPD contacting the ground. The peak pitch rates in the hill and sled pitchover tests prior to vehicle or OPD contact with the ground ranged from about 70 deg/sec to 110 deg/sec. The peak roll rates in the sled rollover tests prior to vehicle or OPD contact with the ground ranged from about 170 deg/sec to 200 deg/sec.

The average HIC values are at levels that would suggest that moderate or severe head injuries are not likely to occur during overturn events like those conducted in the study. However, some of the tests had HIC_{15} values near or above 250, suggesting that concussions could have occurred during these events. As stated before, all tests were conducted with a helmet on the ATD.

Except for the pitchover tests conducted using Vehicle E with Airbag OPD #2, the OPDs evaluated in this study did not significantly impact how the ATD released from the vehicle during the overturn events. Accordingly, the ranges of HIC values measured during tests with OPDs are generally in the range of HIC values measured with no OPD.

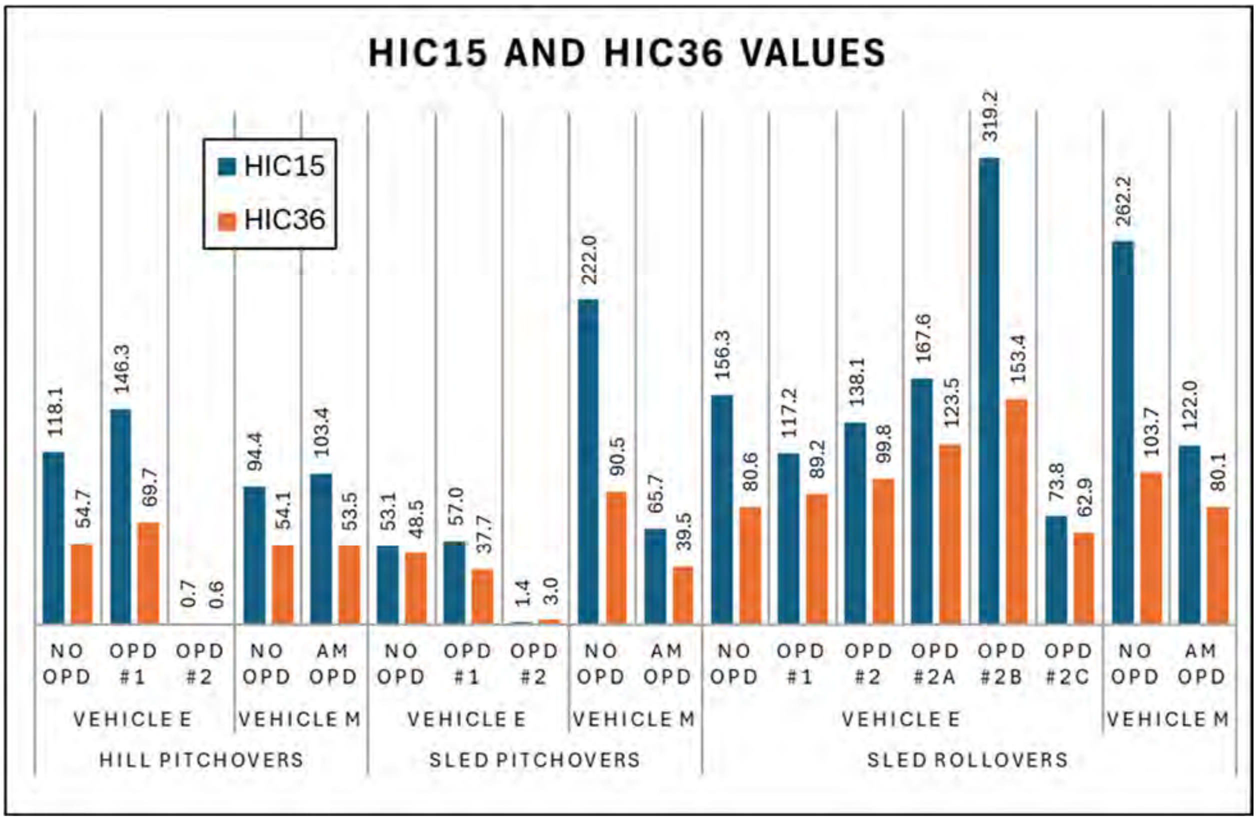

Figure 30: HIC_{15} and HIC_{36} Values From All Tests

6.2 Summary of Tests using POC Airbag OPD #1

POC Airbag OPD #1 was comprised of using eight airbags, inflated to an internal pressure of 16.0 psi, with two at each corner of the vehicle mounted to extend horizontally from the front and rear racks of Vehicle E. The rationale for using the Airbag OPD #1 configuration was to investigate if airbags could be used to mitigate the potential for rearward pitchovers and lateral rollovers.

Vehicle E outfitted with Airbag OPD #1 did not overturn during hill and sled pitchover tests. In these tests, Airbag OPD #1 limited the maximum rearward pitch angles to less than 90°. In both the pitchover tests conducted using Airbag OPD #1, the vehicle pitched forward back on to the ramp and then it rolled rearward; with the vehicle rear tires rolling over the ATD in the hill test and with the vehicle pushing the ATD rearward in the sled test.

During the moderate energy lateral rollover test, the leading side airbags of Airbag OPD #1 bent somewhat under the leading side of the vehicle and the vehicle ultimately landed on the ATD and remained upside down on top of the ATD. The configuration of POC Airbag OPD #1 used front and rear airbags. Given that using both front and rear airbags did not prevent the vehicle from overturning in the rollover test, no rollover tests were conducted using only rear mounted airbags.

As mentioned, the rearward pitchover tests conducted can be classified as less severe than the rollover tests conducted, since prior to the vehicle or OPD contacting the ground the pitch rates in the pitchover tests were less than the roll rates in the rollover tests. This is likely the reason Airbag OPD #1 prevented rearward pitchovers but did not prevent lateral rollover.

The use of stiffer high-pressure, horizontally mounted airbags at different mounting locations and orientations could improve rollover resistance. However, the alternative concept of using vertically mounted low-pressure airbags (Airbag OPD #2 configurations) were found to be more effective in preventing rollovers in the moderate energy sled tests conducted.

6.3 Summary of Tests using POC Airbag OPD #2

The baseline configuration of POC Airbag OPD #2 was comprised of using four high volume airbags, inflated to an internal pressure of 2.7 psi, with two at each end of the vehicle mounted to extend vertically from the front and rear racks of Vehicle E. The rationale for using the Airbag OPD #2 configuration was to investigate if airbags could be used to provide occupant protection space in rearward pitchovers and lateral rollovers.

Vehicle E outfitted with the baseline configuration of Airbag OPD #2 did not overturn during hill and sled pitchover tests or during the sled moderate energy rollover test. In the rearward pitchover tests, Airbag OPD #2 not only limited rearward pitch angles, but it also supported the vehicle in a nose-up orientation at the end of both the hill and sled tests. The ATD remained within the confines of OPD #2 during these pitchover tests, so the ATD never hit the ground and the resulting HIC values were negligible.

Airbag OPD #2 limited vehicle roll angle to about 104° during the sled rollover test. During this test, the ATD released from the vehicle and remained between the front and rear airbags at rest.

The second configuration using high volume, low-pressure airbags, Airbag OPD #2A, used only the rear two vertically mounted airbags. Airbag OPD #2A did not prevent the vehicle from rolling over and had a final roll angle near 270°. However, Airbag OPD #2 did provide protection space for the ATD and there was little interaction between the ATD and the vehicle or airbags throughout the rollover event.

Airbag OPD #2B used one vertical airbag on the front of the vehicle and one on the rear. Like Airbag OPD #2, Airbag OPD #2B limited vehicle roll angle (to about 122°) during the sled rollover

test, and the ATD released from the vehicle and remained between the front and rear airbags at rest.

Airbag OPD #2C, using a single rear-mounted, low-pressure vertical airbag, prevented the vehicle from rolling to 180°. The airbag deflected as the vehicle rolled to its maximum measured roll angle of 170.8°. Then the airbag caused the vehicle to roll back to its final roll angle of 115.6°. The airbag provided a protection space for the ATD as the ATV rolled to its maximum angle, and there was little interaction between the ATD and the vehicle or airbags throughout the event.

The pre-inflated large low-pressure airbags (Airbag OPD #2 configurations) were found to provide either tip over resistance or, in the case of the lateral rollover test using Airbag OPD #2A, occupant protection space in all tests conducted in this study.

During both rollover tests conducted using front and rear airbags (Airbag OPD #2 and Airbag OPD #2B), the front airbag lessened the contact between the front fender and the ground when the vehicle rolled to near 90°. During these two tests, the front and rear airbags appeared to share the load needed to prevent the vehicle from rolling over. The vehicle slid sideways supported by the airbags, with little angular motion of the vehicle about a vertical axis.

No efforts were made to design or implement inflators needed to deploy these airbags in an overturn event, or to design or implement sensors needed to detect the need to deploy the airbags. However, technology for detecting deployment events and for inflating pressure-holding airbags for use in rollover events exists, and it is used in the automative industry for deploying side curtain airbags. Automotive side curtain airbags are designed to deploy rapidly when rollover or side impact crashes are detected. They generally use high-pressure gas storage containers that when deployed fill the airbag to a low pressure. They deploy rapidly enough to provide occupant protection, and unlike frontal and other side airbags, which start deflating upon deployment, curtain side airbags are designed to remain inflated for up to 10 seconds.[13] The technology for side curtain airbag crash-detecting sensors, inflators, structural composition, and packaging could be transferred for use in OPD airbags for ATVs.

While the OPD #2 configurations effectively provided occupant protection, further work to develop optimal size, shape, placement, packaging, and deployment of low-pressure airbags would be needed to produce a final OPD product.

6.4 Summary of Tests using AM OPD

The AM OPD evaluated is a complete automatic rollover protection system for ATVs designed to expand when rollover (or pitchover) is irreversible. The AM OPD evaluated comes with an electronic control unit (ECU) designed to detect lateral or longitudinal irreversible rollover situations. The ECU is equipped with inertial sensors that analyze the real time dynamics of the vehicle. When the ECU system algorithm detects an irreversible tipping condition, it activates the release of high-pressure inert gas inside the AM OPD's expandable structure. The high-pressure gas is stored in a canister inside the base of the OPD's tubular structure. When the ECU algorithm senses an irreversible overturn situation, it sends an electronic signal to a pyrotechnic igniter which releases the high-pressure gas inside the OPD's tubular structure causing it to expand. When the OPD structure fully expands, it is designed to lock into place thereby providing a protection space

[13] **https://www.iihs.org/topics/airbags**

to prevent the driver from being crushed or asphyxiated in the event of a rollover. Per the AM OPD manufacturer, it is intended for use on a vehicle with a driver and without a passenger, on vehicles with speeds below 40 km/h (25 mph), and of vehicles with maximum weight of 500 kg (1,100 lb).

The AM OPD was tested on Vehicle M. The AM OPD provided tip-over resistance in the hill and sled rearward pitchover tests. In both tests, the AM OPD ECU detected an irreversible tipping condition, and it sent a signal to deploy the OPD structure. In both tests, the AM OPD metal structure deployed fully prior to 80° of rearward pitch angle. Video data from both tests showed that the time from the first deployment movement of the AM OPD structure until it was fully expanded was less than 100 ms.

In the moderate energy sled lateral rollover test, the AM OPD system detected an irreversible tipping condition, and it fully expanded the OPD structure prior to 90° of roll angle, which was also prior to the time the OPD structure first contacted the ground in this test. The full deployment time of the AM OPD structure, again based on video data, was less than 100 ms during this test. The AM OPD prevented the vehicle from rolling much past 180°, and it supported the vehicle in an upside-down orientation near 180° at the end of the test. The AM OPD provided a protection space for the ATD, and there was no interaction between the ATD and the vehicle or OPD after the ATD disengaged from the vehicle.

The AM OPD performed as advertised in the tests conducted, as it prevented the vehicle from overturning in the pitchover tests and it provided a protection space to prevent the driver from being crushed or asphyxiated in the rollover test. There was no noticeable permanent deformation or damage to the AM OPD structure after any of the tests conducted in this study.

Two different AM OPDs were evaluated in a previous study.[14] In full scale dynamic and sled moderate energy tests conducted using these AM OPDs, the vehicle rolled beyond 270° and in some cases the vehicle landed on the ATD. In full scale dynamic and sled minimum energy tests these other two OPDs prevented the vehicle from rolling over or onto the ATD. Based on its performance in the moderate energy sled rollover test, it is believed that the AM OPD evaluated in this study would also prevent vehicles from rolling over in less severe events like the previous minimum energy rollover tests.

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[14] *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**

Vehicle E - VIMF Results and Test Weights

	Driver	Driver Plus Airbag OPD #1	Driver Plus Airbag OPD #2	Instrumentation and ATD	Instrumentation, ATD, and Airbag OPD #1	Instrumentation, ATD, and Airbag OPD #2
VIMF Test Number	8803	8805	8804			
Total Vehicle Weight (lb)	948.5	1045.8	1032.5	947.7	1045.0	1037.2
Left Front Weight (lb)	219.6	231.4	242.6	226.8	238.6	235.1
Right Front Weight (lb)	213.2	231.2	235.7	210.1	228.1	229.7
Left Rear Weight (lb)	253.0	291.1	272.0	245.9	284.0	278.2
Right Rear Weight (lb)	262.7	292.1	282.2	265.1	294.5	294.2
Front Track Width (in)	39.80	39.80	39.80	39.90	39.90	39.90
Rear Track Width (in)	39.05	39.05	39.05	38.10	38.10	38.10
Average Track Width (in)	39.43	39.43	39.43	39.00	39.00	39.00
Wheelbase (in)	49.95	49.95	49.95	50.80	50.80	50.80
CG Longitudinal (in)	27.16	27.86	26.81	27.39	28.12	28.04
CG Lateral (in)	0.07	0.01	0.06	0.03	-0.01	0.19
CG Height (in)	23.84	24.46	24.52			
Roll Inertia - I_{XX} (ft-lb-s^2)	66	77	74			
Pitch Inertia - I_{YY} (ft-lb-s^2)	105	131	125			
Yaw Inertia - I_{ZZ} (ft-lb-s^2)	93	123	114			
Roll/Yaw - I_{XZ} (ft-lb-s^2)	2	6	3			
SSF	0.827	0.806	0.804			

Vehicle M - VIMF Results and Test Weights

	Driver	Driver Plus Aftermarket OPD	Instrumentation and ATD	Instrumentation, ATD, and Aftermarket OPD
VIMF Test Number	8742	8743		
Total Vehicle Weight (lb)	1145.2	1202.8	1142.9	1202.3
Left Front Weight (lb)	255.9	248.6	269.0	256.4
Right Front Weight (lb)	269.5	249.7	276.2	265.4
Left Rear Weight (lb)	312.6	343.4	289.8	331.0
Right Rear Weight (lb)	307.2	361.1	307.9	349.5
Front Track Width (in)	39.90	39.90	39.90	39.90
Rear Track Width (in)	38.10	38.10	38.10	38.10
Average Track Width (in)	39.00	39.00	39.00	39.00
Wheelbase (in)	50.80	50.80	50.80	50.80
CG Longitudinal (in)	27.49	29.75	26.57	28.75
CG Lateral (in)	0.15	0.30	0.43	0.44
CG Height (in)	23.16	23.28		
Roll Inertia - I_{XX} (ft-lb-s^2)	80	81		
Pitch Inertia - I_{YY} (ft-lb-s^2)	146	171		
Yaw Inertia - I_{ZZ} (ft-lb-s^2)	128	151		
Roll/Yaw - I_{XZ} (ft-lb-s^2)	15	20		
SSF	0.842	0.838		

Vehicle E - Tilt Table Results

		Driver	Driver Plus Airbag OPD #1	Driver Plus Airbag OPD #2
Lateral Direction: Right Tilt	**Right Tilt First Wheel Lift**	Front	Rear	Front
	Right Tilt Angle (TTA) (deg)	32.0	30.1	30.9
	Right Tilt Ratio (TTR)	0.626	0.579	0.598
Lateral Direction: Left Tilt	**Left Tilt First Wheel Lift**	Front	Rear	Front
	Left Tilt Angle (TTA) (deg)	31.6	30.3	30.6
	Left Tilt Ratio (TTR)	0.616	0.583	0.592
	Average Lateral TTA (deg)	**31.8**	**30.2**	**30.8**
	Average Lateral TTR	**0.621**	**0.581**	**0.595**
Longitudinal Direction: Front Tilt	**Front Tilt First Wheel Lift**	Left	Right	Left
	Front Tilt TTA (FTTA) (deg)	**46.9**	**46.5**	**47.3**
	Front Tilt TTR (FTTR)	**1.070**	**1.055**	**1.085**
Longitudinal Direction: Rear Tilt	**Rear Tilt First Wheel Lift**	Left	Left	Left
	Rear Tilt TTA (RTTA) (deg)	**44.5**	**41.6**	**43.0**
	Rear Tilt TTR (RTTR)	**0.983**	**0.887**	**0.934**

Vehicle M - Tilt Table Results

		Driver	Driver Plus Aftermarket OPD
Lateral Direction: Right Tilt	**Right Tilt First Wheel Lift**	Rear	Rear
	Right Tilt Angle (TTA) (deg)	34.2	33.8
	Right Tilt Ratio (TTR)	0.678	0.669
Lateral Direction: Left Tilt	**Left Tilt First Wheel Lift**	Rear	Rear
	Left Tilt Angle (TTA) (deg)	34.5	33.9
	Left Tilt Ratio (TTR)	0.687	0.672
	Average Lateral TTA (deg)	**34.3**	**33.9**
	Average Lateral TTR	**0.682**	**0.671**
Longitudinal Direction: Front Tilt	**Front Tilt First Wheel Lift**	Right	Left
	Front Tilt TTA (FTTA) (deg)	**51.9**	**51.2**
	Front Tilt TTR (FTTR)	**1.277**	**1.245**
Longitudinal Direction: Rear Tilt	**Rear Tilt First Wheel Lift**	Left	Right
	Rear Tilt TTA (RTTA) (deg)	**48.2**	**42.6**
	Rear Tilt TTR (RTTR)	**1.117**	**0.919**

Start of Test - Pitch Angle = 40°

Pitch Angle = 60° - Time = 0.75 sec

Pitch Angle = 90° - Time = 1.19 sec

Pitch Angle = 120° - Time = 1.47 sec

ATD Head Strike - Time = 1.48 sec

Pitch Angle = 150° - Time = 1.80 sec

Hill Pitchover - Vehicle E - NO OPD

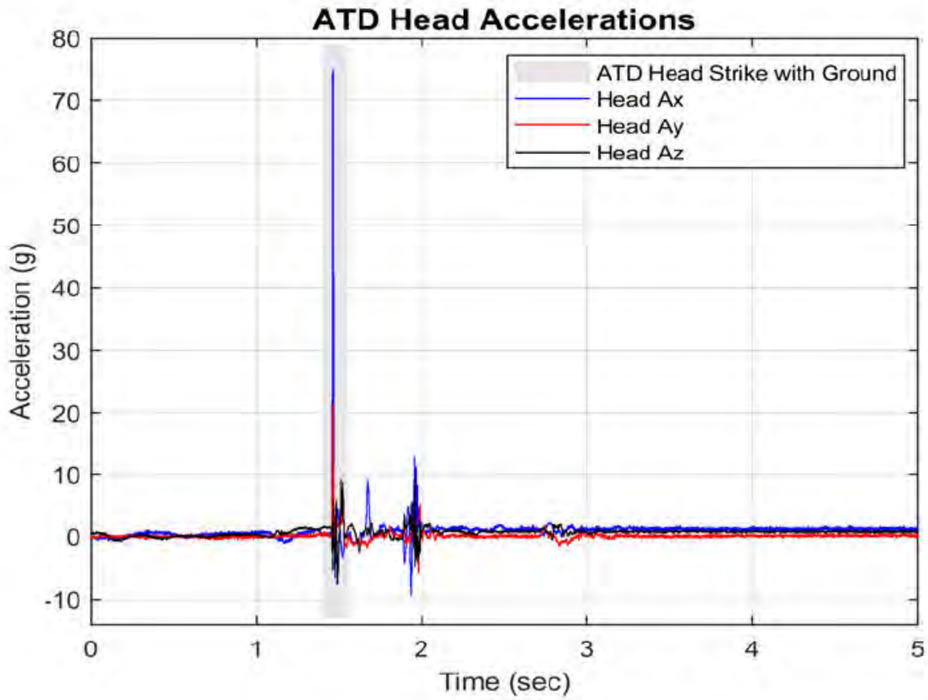
Pitch Angle = 180° - Time = 2.00 sec

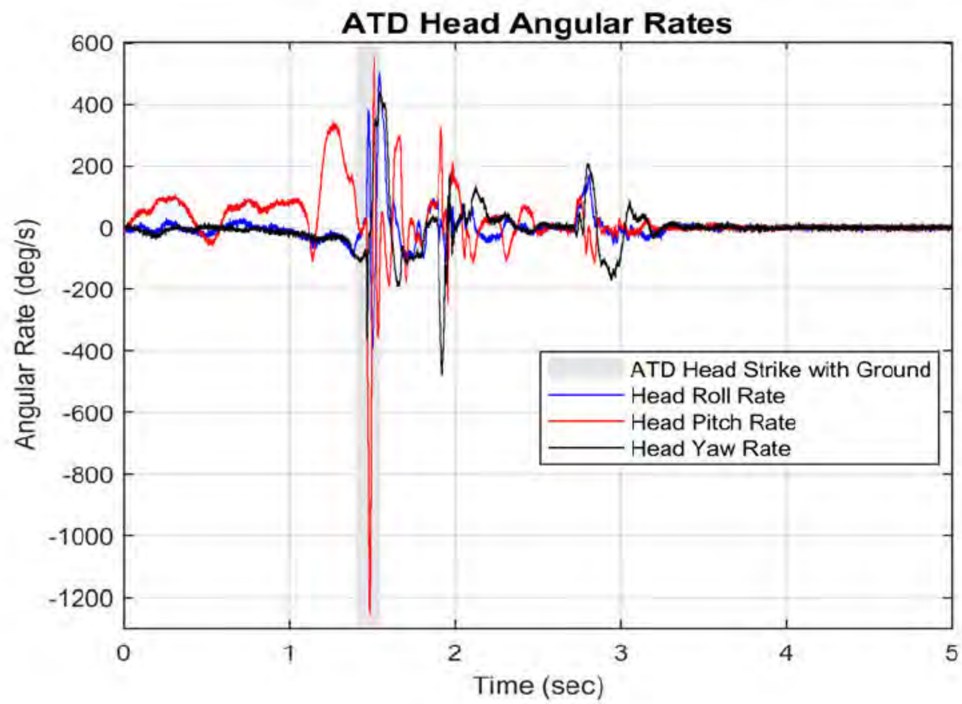
Pitch Angle = 210° - Time = 2.36 sec

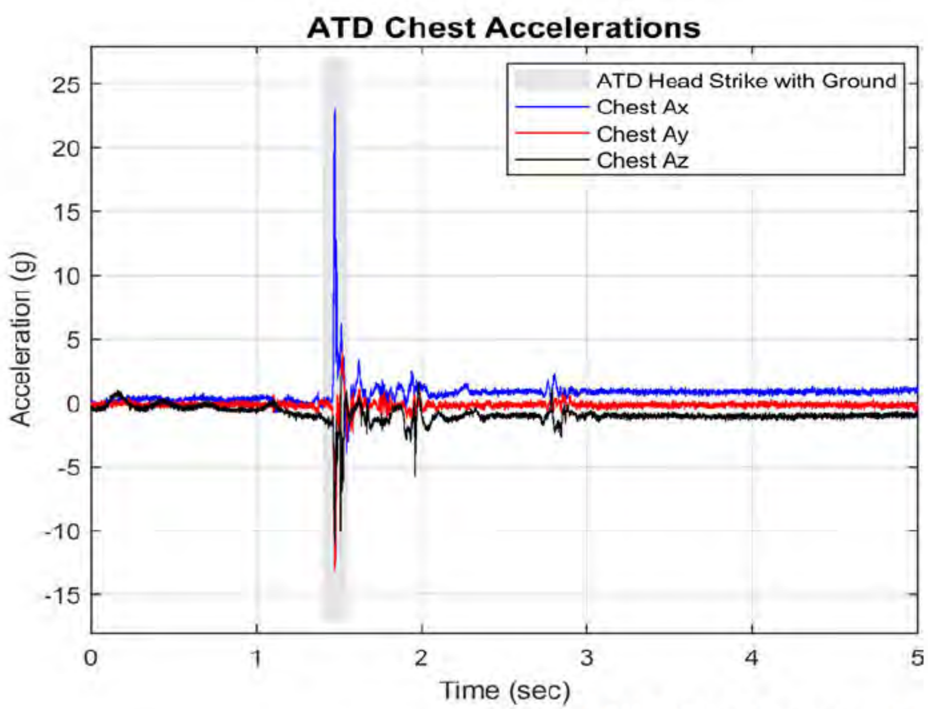
Max Pitch Angle = 211.2° - Time = 2.44 sec

End of Run - Pitch Angle = 184.5°

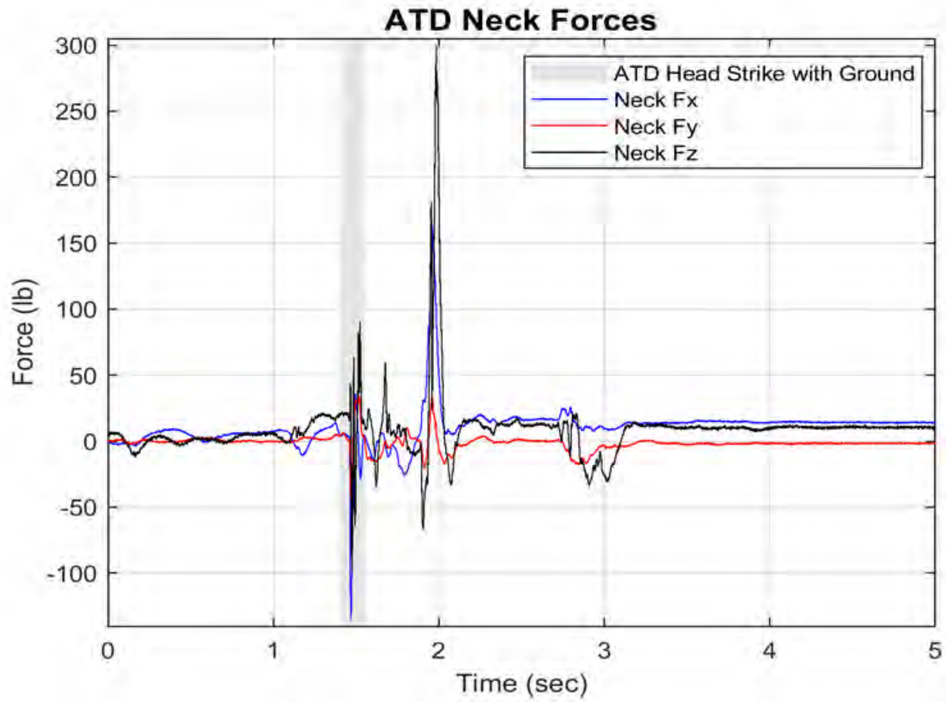
Hill Pitchover - Vehicle E - NO OPD

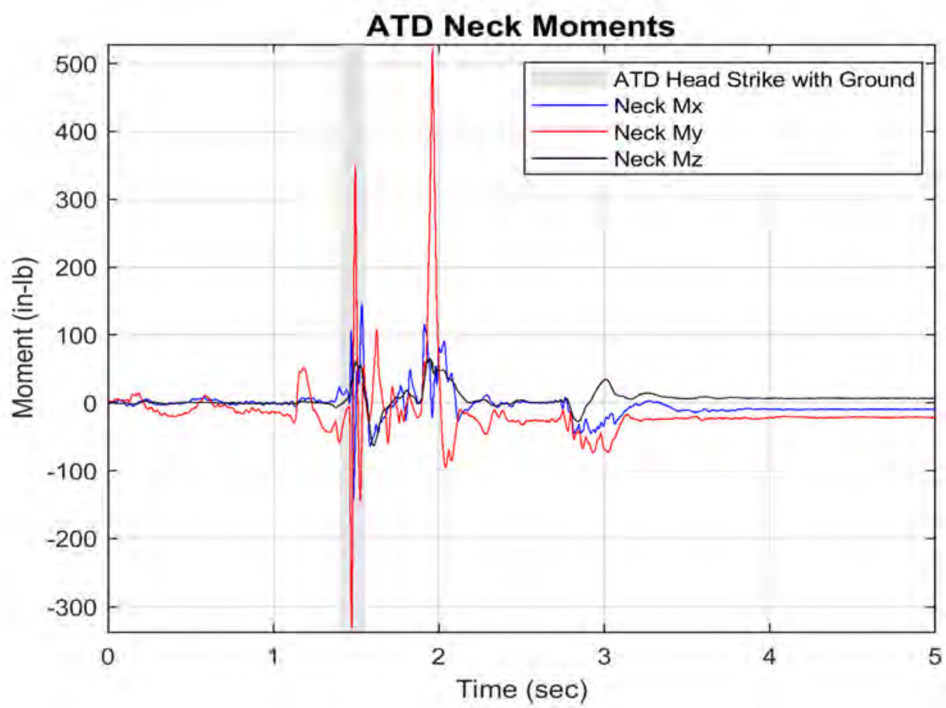




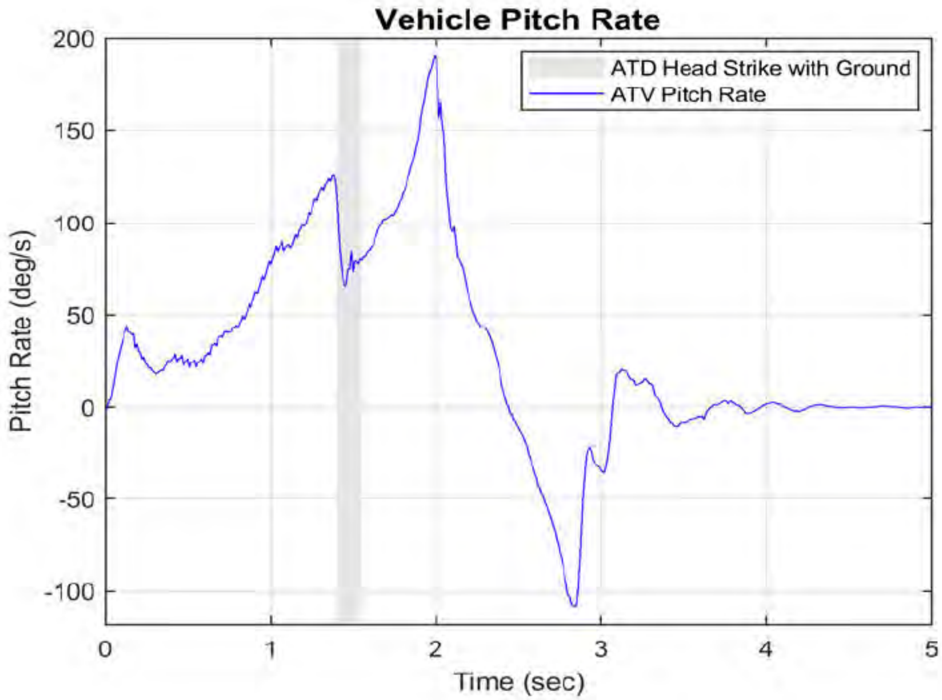


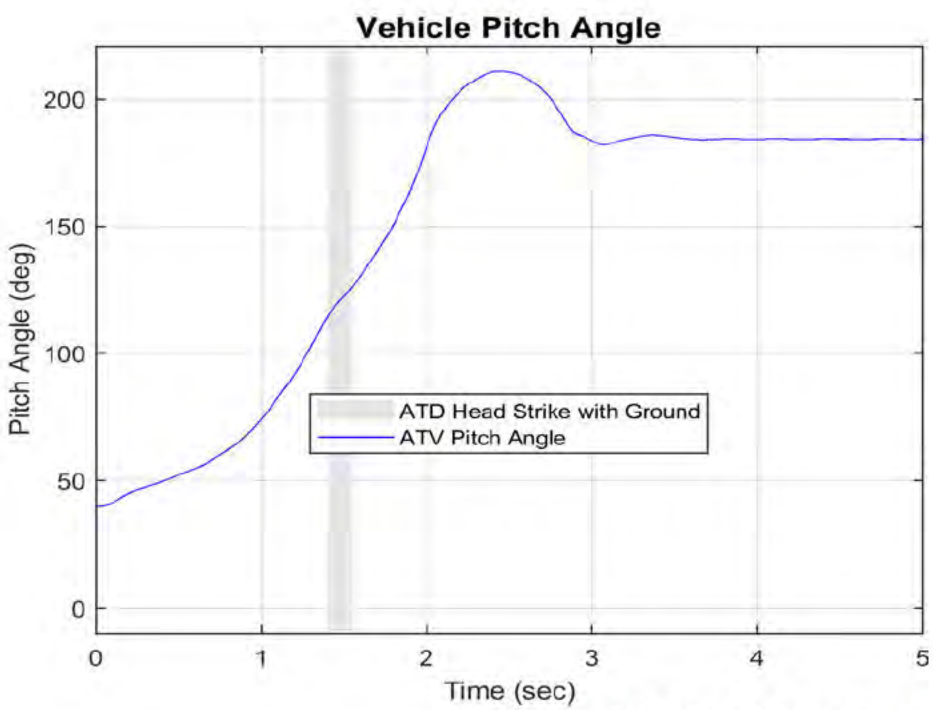
Hill Pitchover - Vehicle E - NO OPD

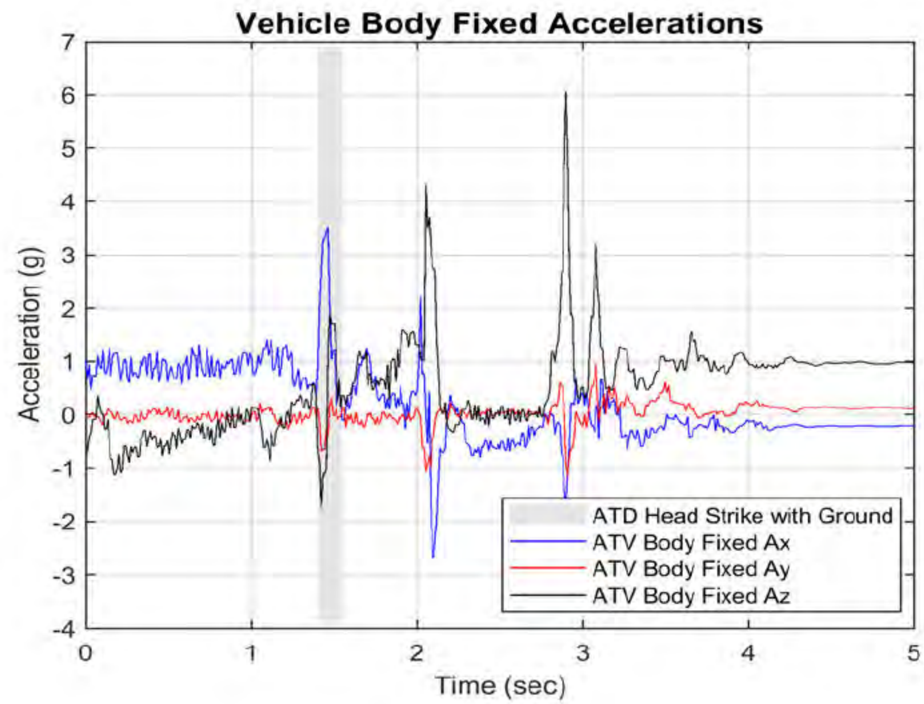




Hill Pitchover - Vehicle E - NO OPD







Hill Pitchover - Vehicle E - NO OPD

Start of Test - Pitch Angle = 40°

Pitch Angle = 60° - Time = 0.53 sec

Max Pitch Angle = 82.2° - Time = 0.91 sec

ATD Head Strike - Time = 1.26 sec

Pitch Angle = 76.5° - Time = 2.00 sec

Pitch Angle = 78.6° - Time = 2.50 sec

Hill Pitchover - Vehicle E - OPD #1

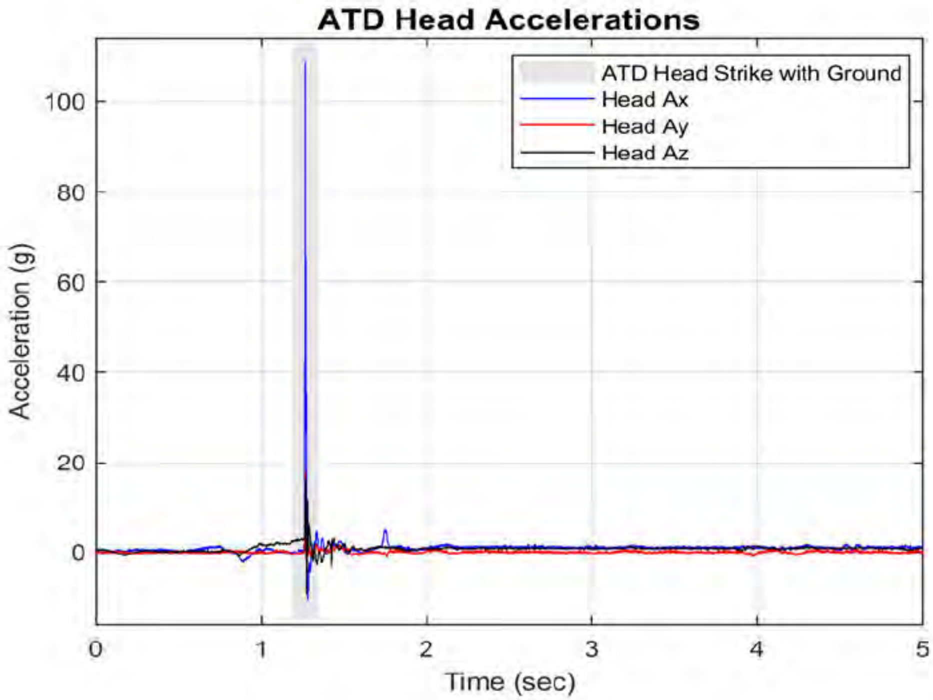
Pitch Angle = 68.1° - Time = 3.00 sec

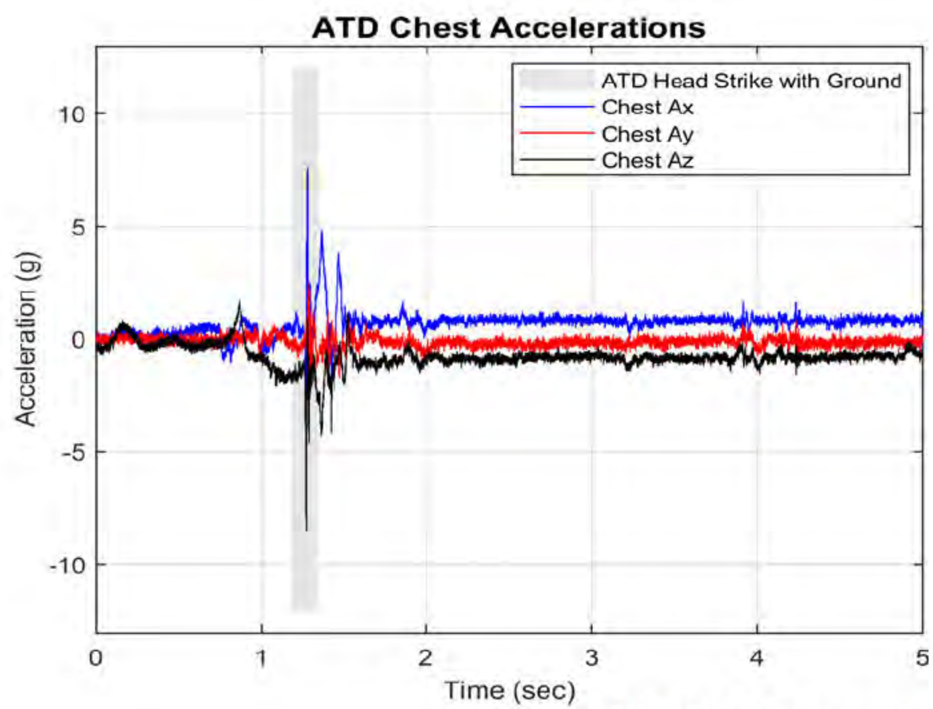
Pitch Angle = 47.4° - Time = 3.50 sec

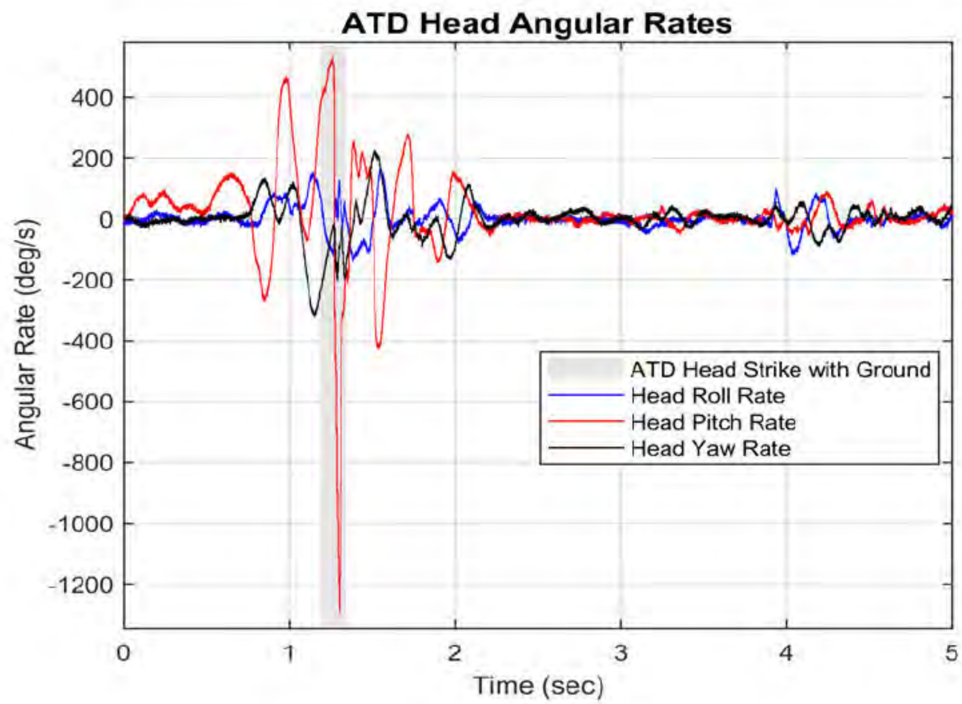
End of Run - Pitch Angle = 3.6°

Pitch Angle = 15.8° - Time = 4.00 sec

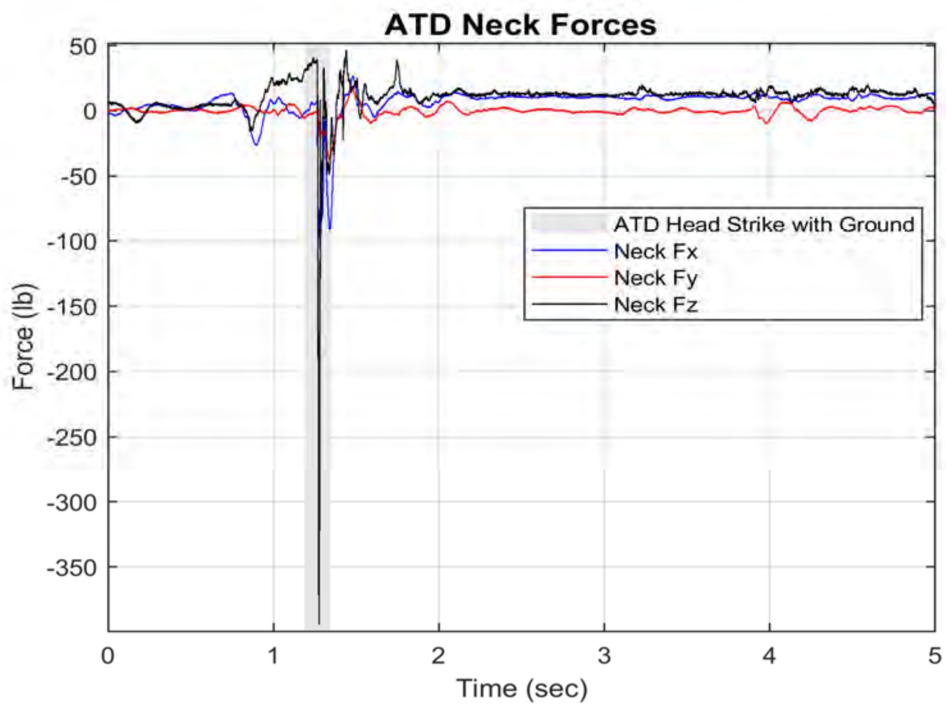
Hill Pitchover - Vehicle E - OPD #1

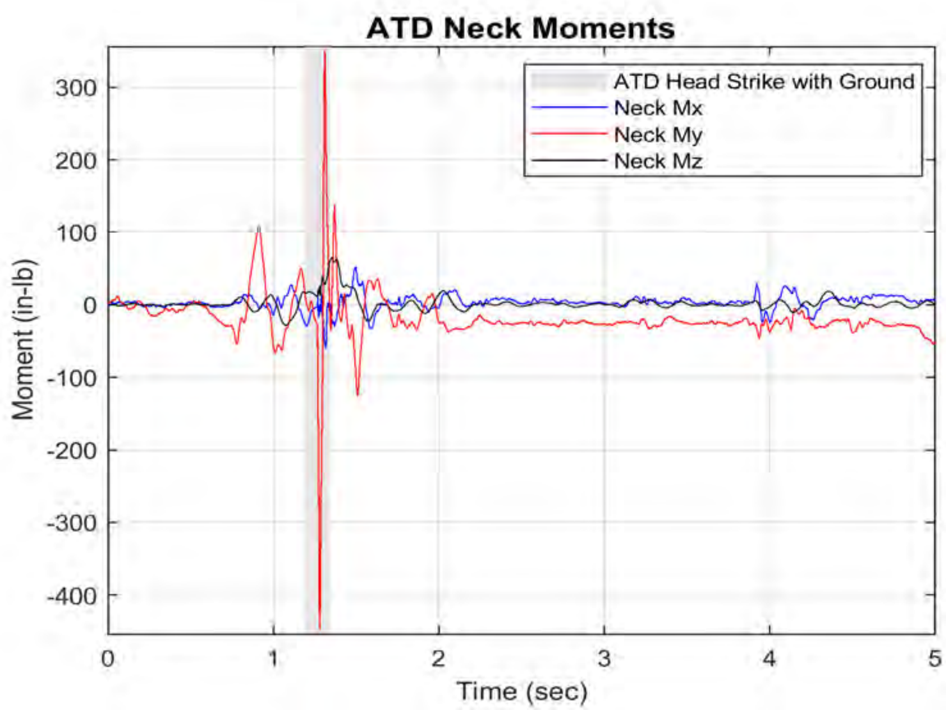




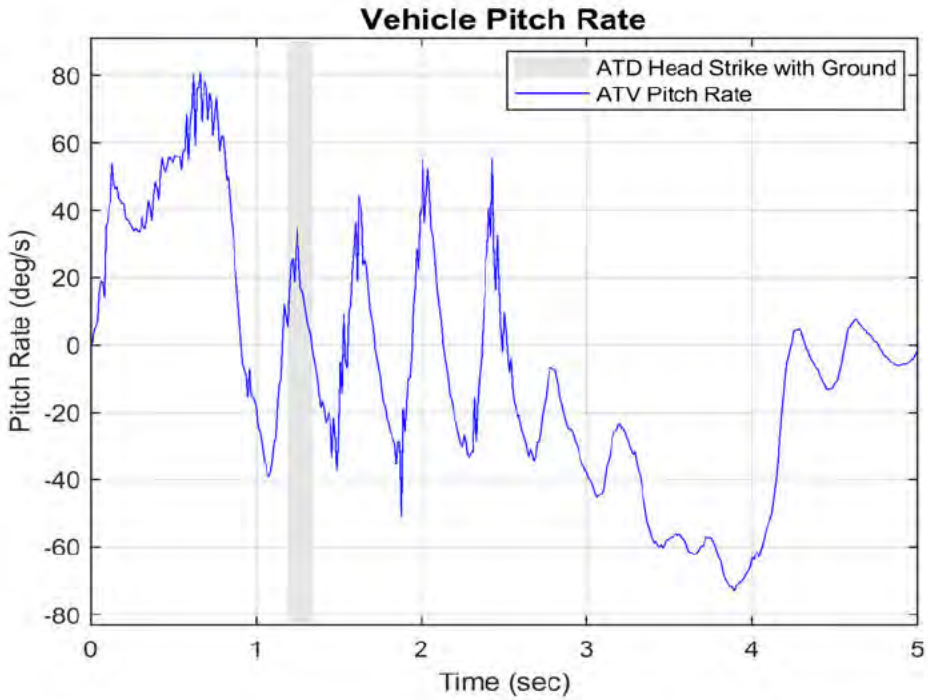


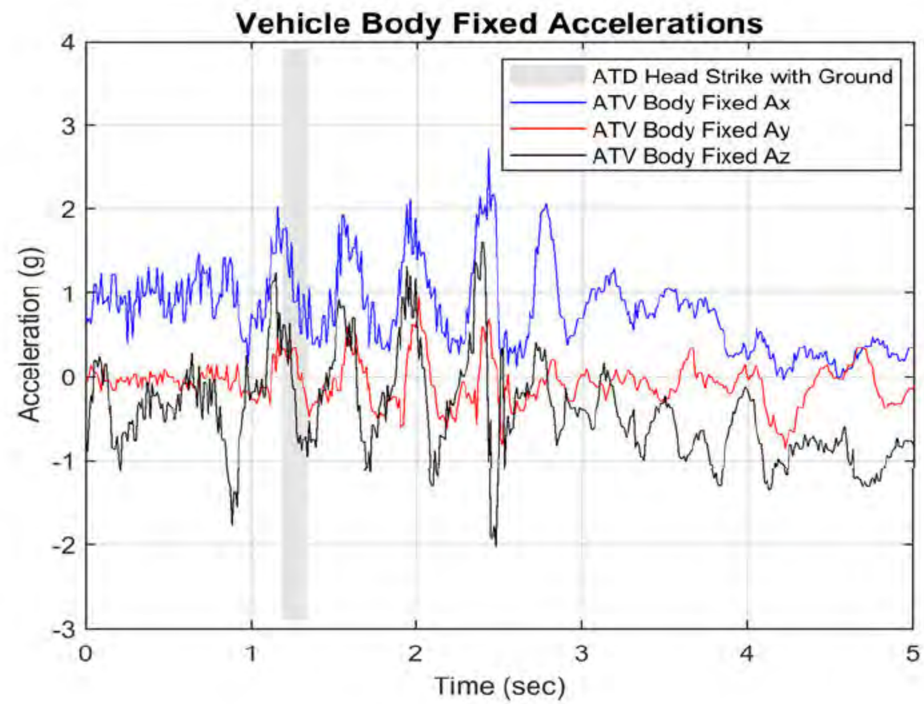
Hill Pitchover - Vehicle E - OPD #1

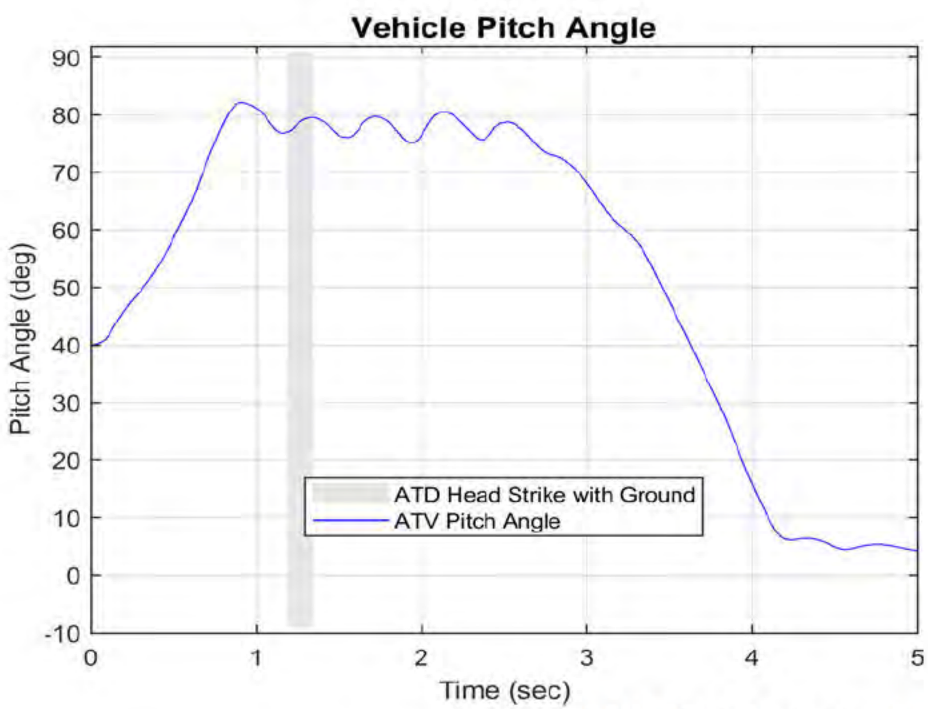




Hill Pitchover - Vehicle E - OPD #1







Hill Pitchover - Vehicle E - OPD #1

Start of Test - Pitch Angle = 40°

Max Pitch Angle = 105.1° - Time = 1.71 sec

Pitch Angle = 60° - Time = 0.57 sec

Pitch Angle = 92.8° - Time = 2.50 sec

Pitch Angle = 90° - Time = 0.94 sec

Pitch Angle = 90.1° - Time = 3.00 sec

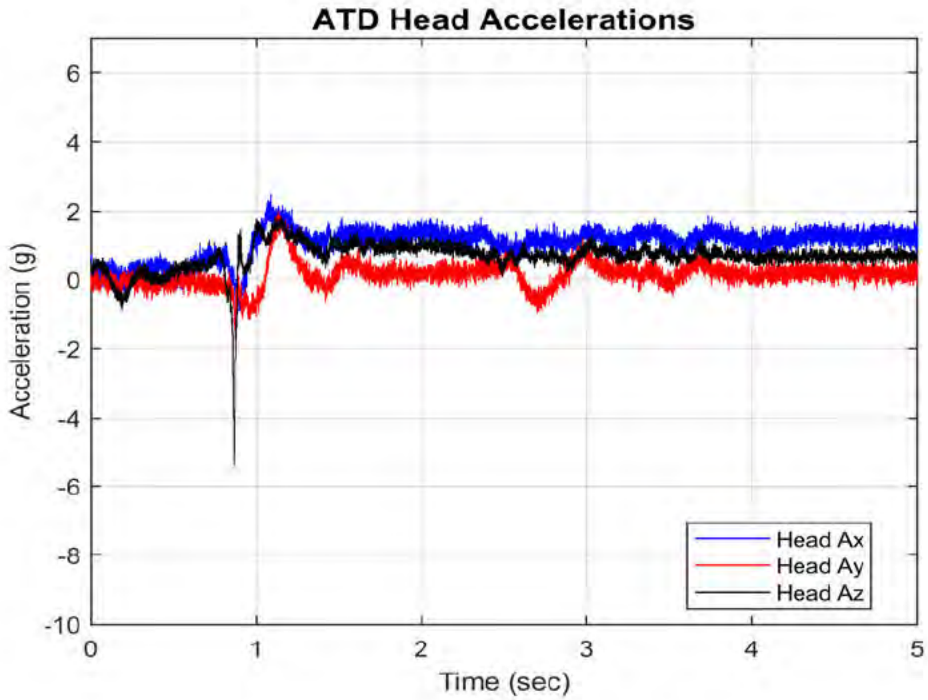
Hill Pitchover - Vehicle E - OPD #2

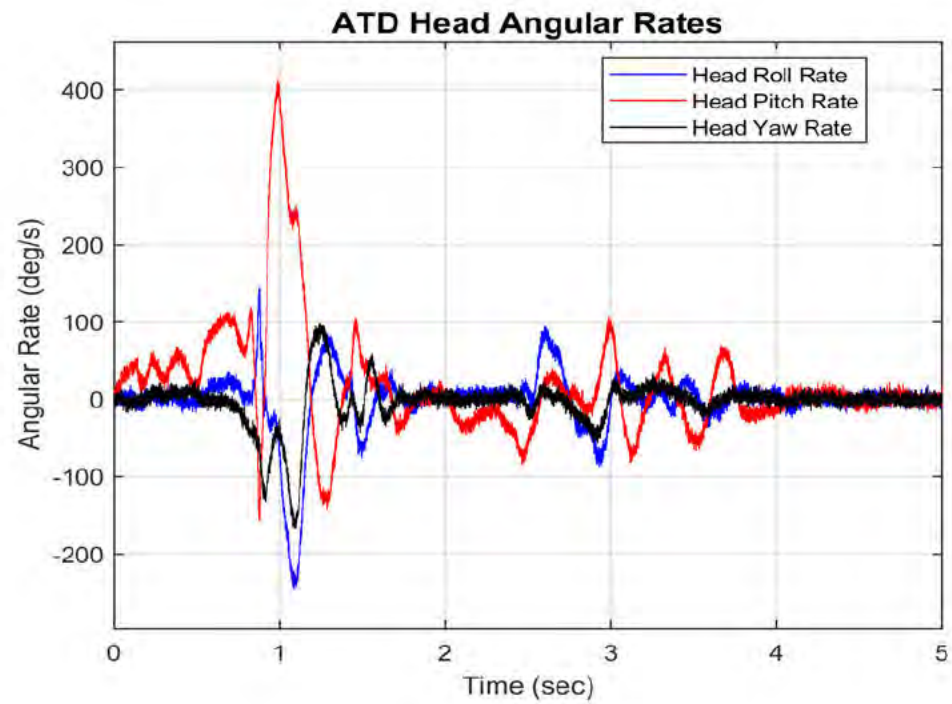
Pitch Angle = 90.2° - Time = 3.50 sec

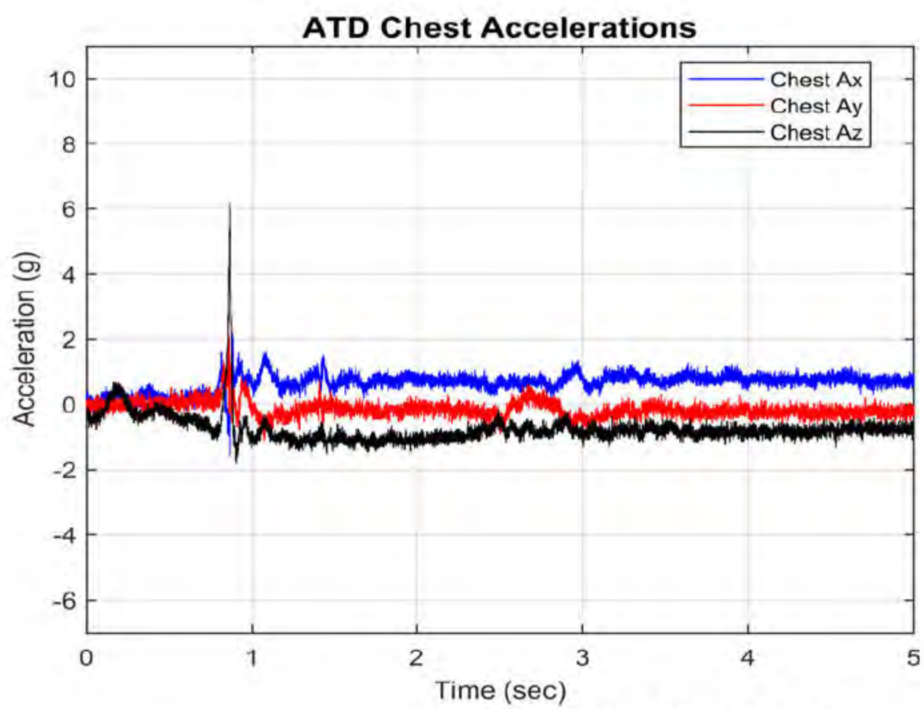
Pitch Angle = 89.2° - Time = 4.00 sec

End of Run - Pitch Angle = 89.0°

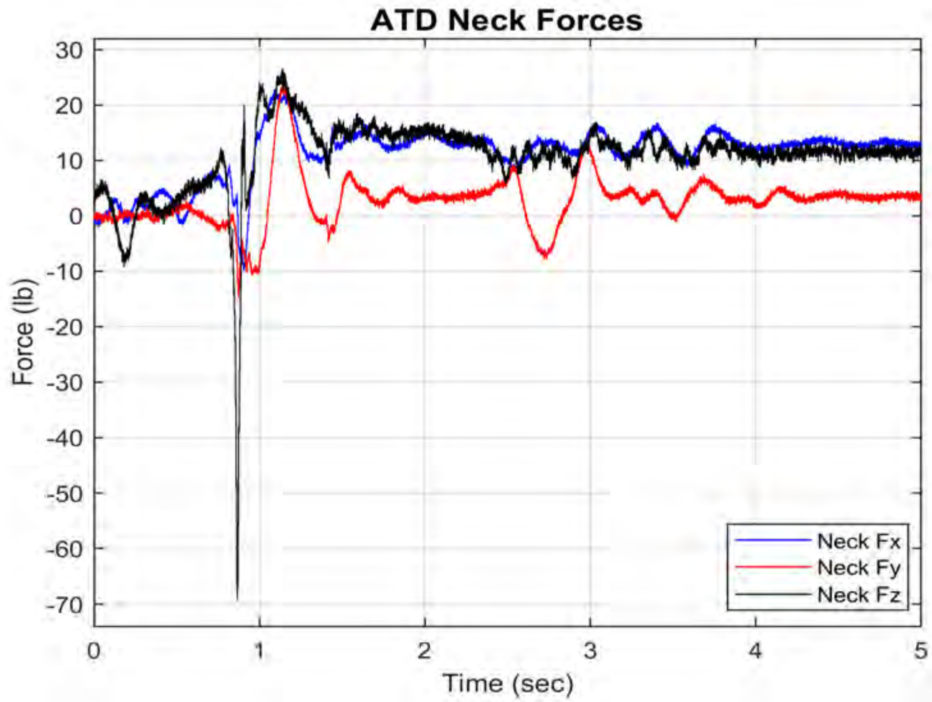
Hill Pitchover - Vehicle E - OPD #2

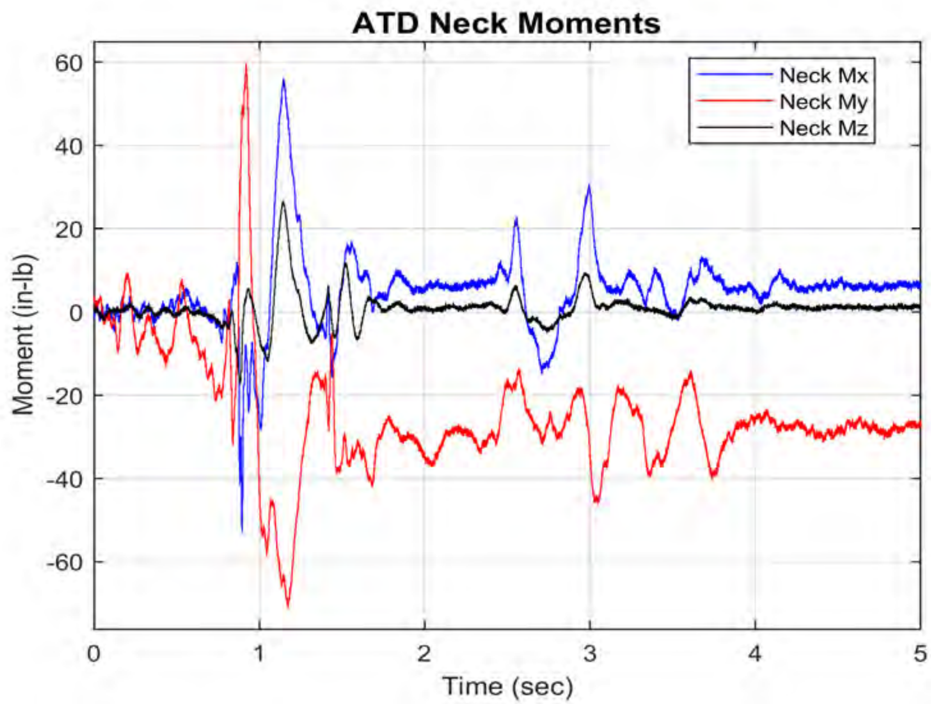




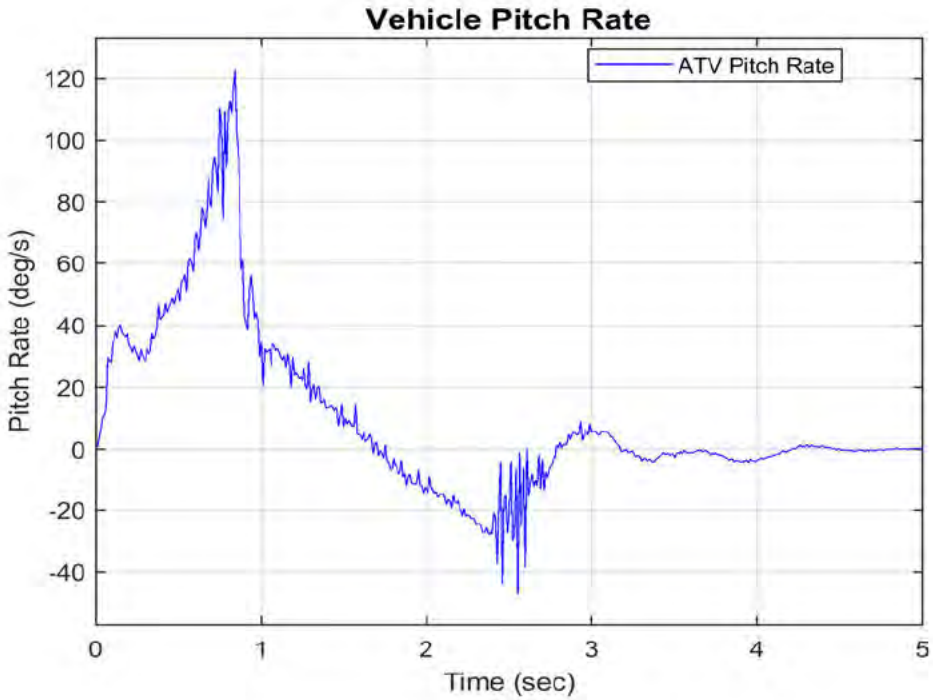


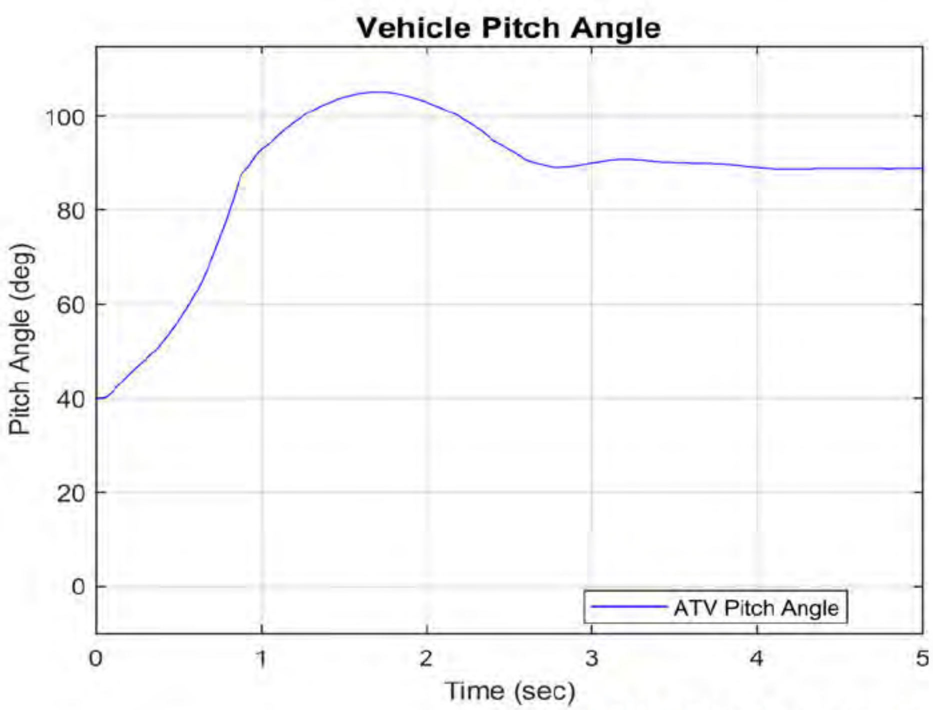
Hill Pitchover - Vehicle E - OPD #2

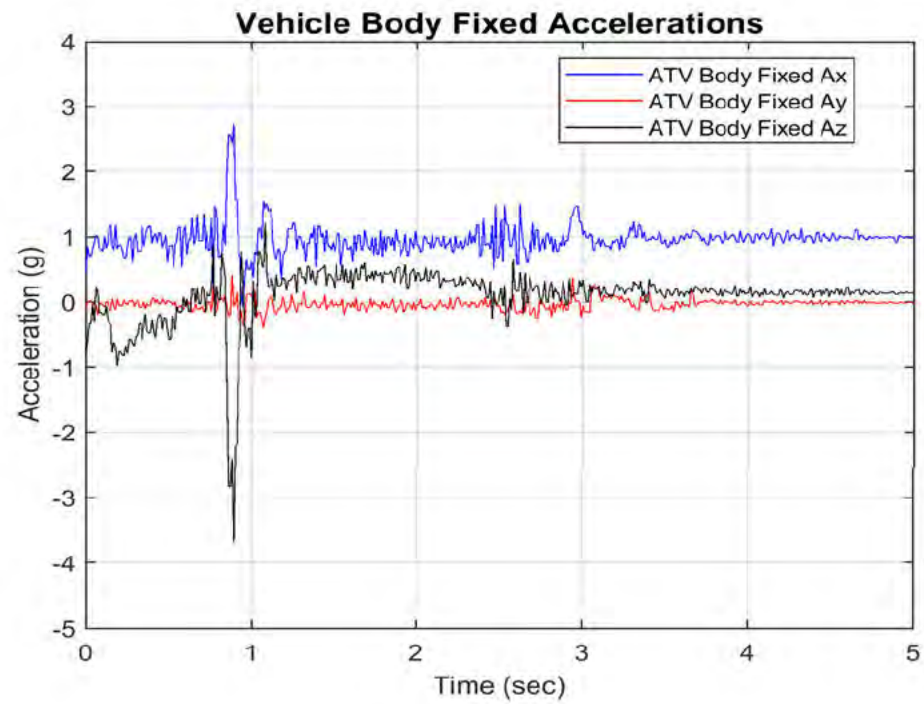




Hill Pitchover - Vehicle E - OPD #2







Hill Pitchover - Vehicle E - OPD #2

Start of Test - Pitch Angle = 40°

ATD Head Strike - Time = 1.40 sec

Pitch Angle = 60° - Time = 0.84 sec

Pitch Angle = 120° - Time = 1.87 sec

Pitch Angle = 90° - Time = 1.31 sec

Pitch Angle = 150° - Time = 2.28 sec

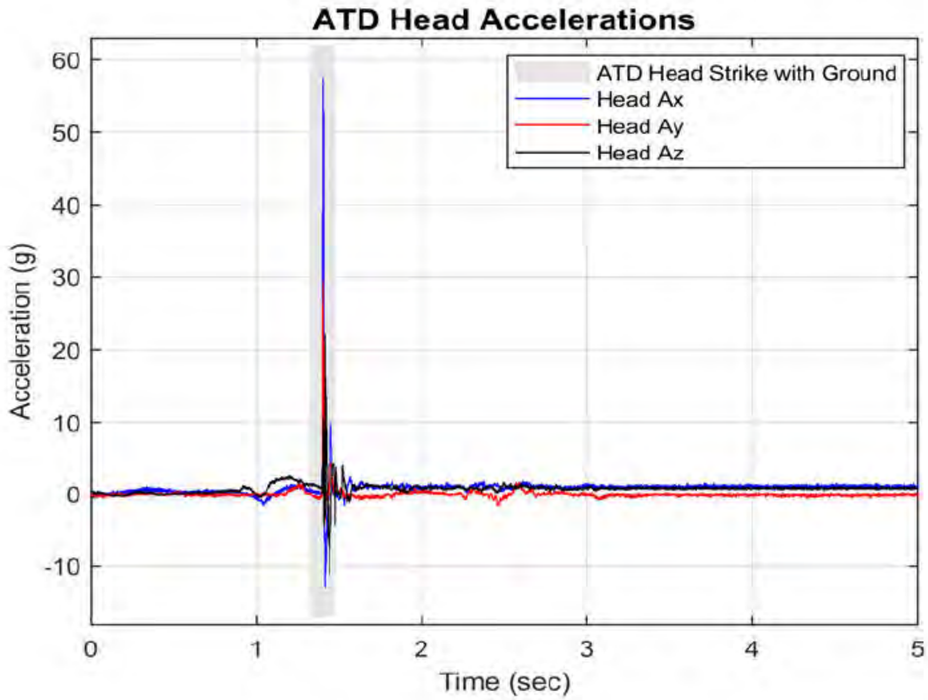
Hill Pitchover - Vehicle M - NO OPD

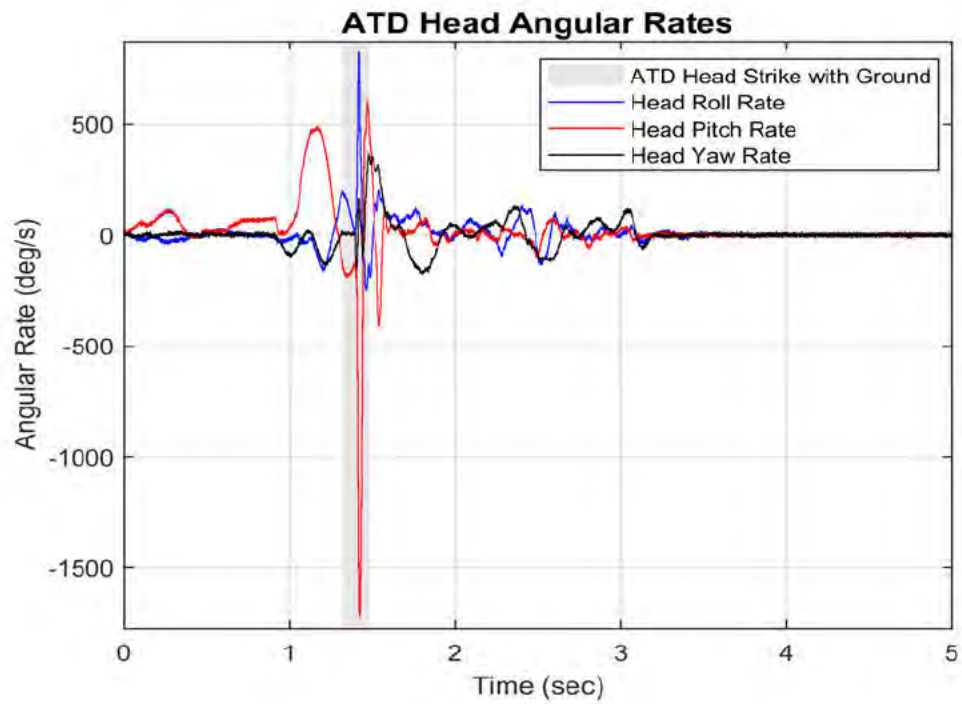
Pitch Angle = 180° - Time = 2.49 sec

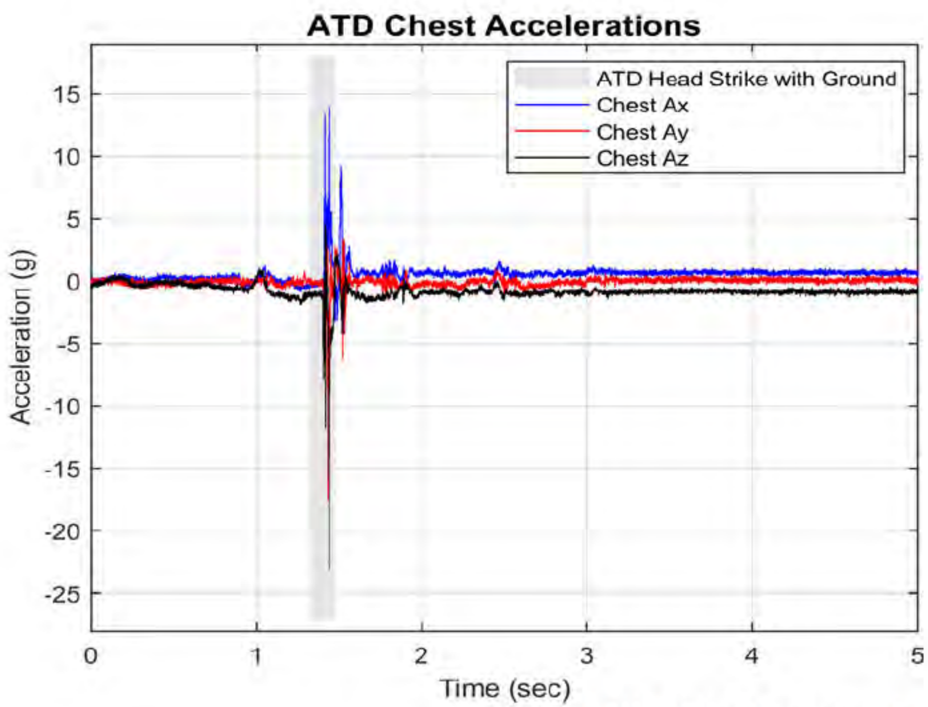
Max Pitch Angle = 197.6° - Time = 2.83 sec

End of Run - Pitch Angle = 188.1°

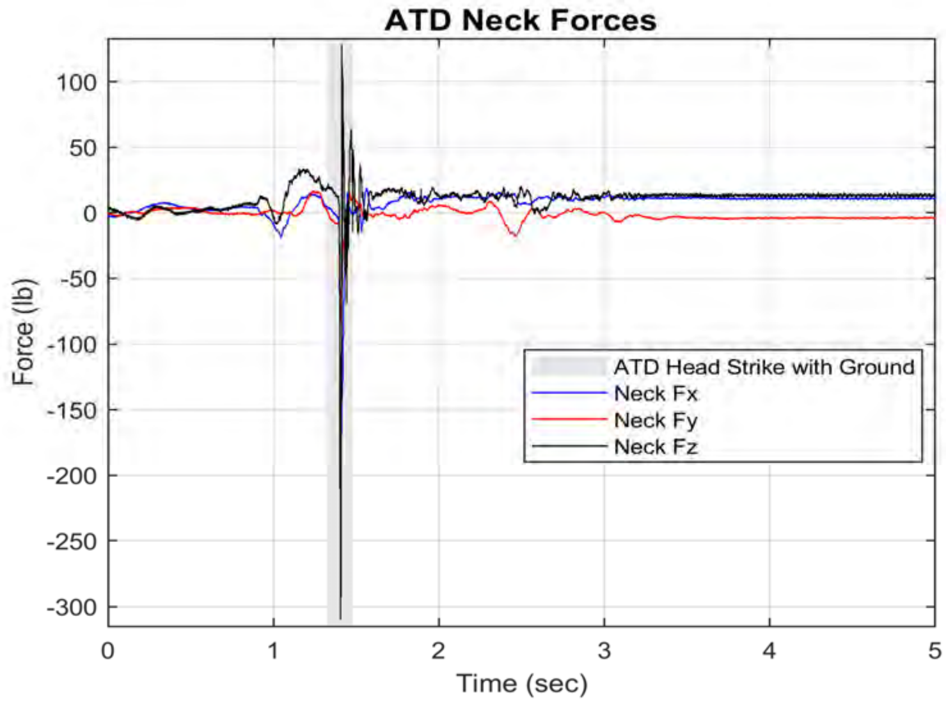
Hill Pitchover - Vehicle M - NO OPD

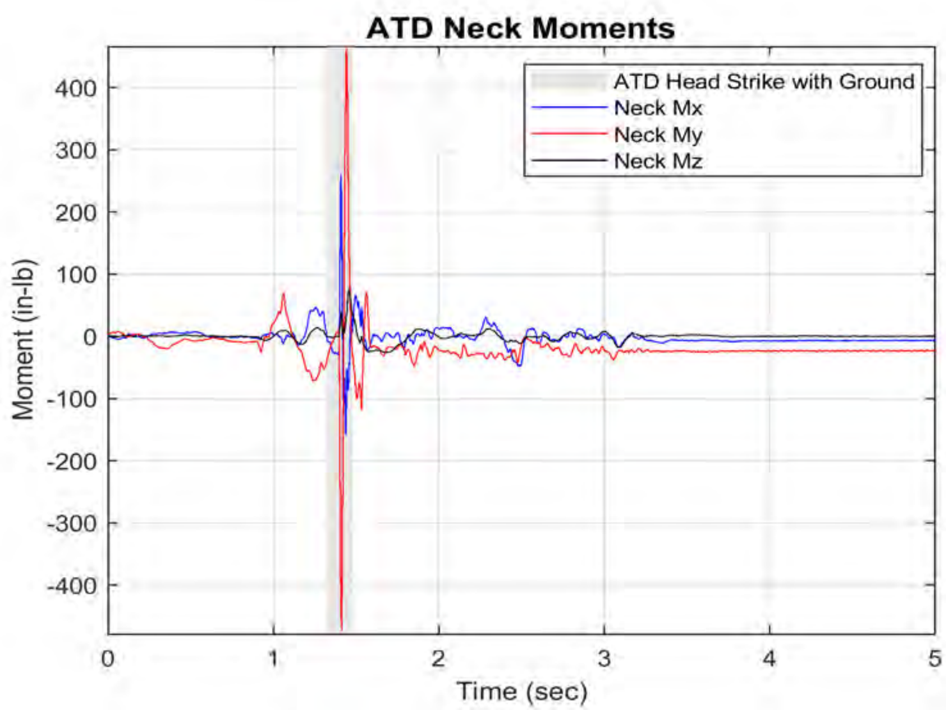




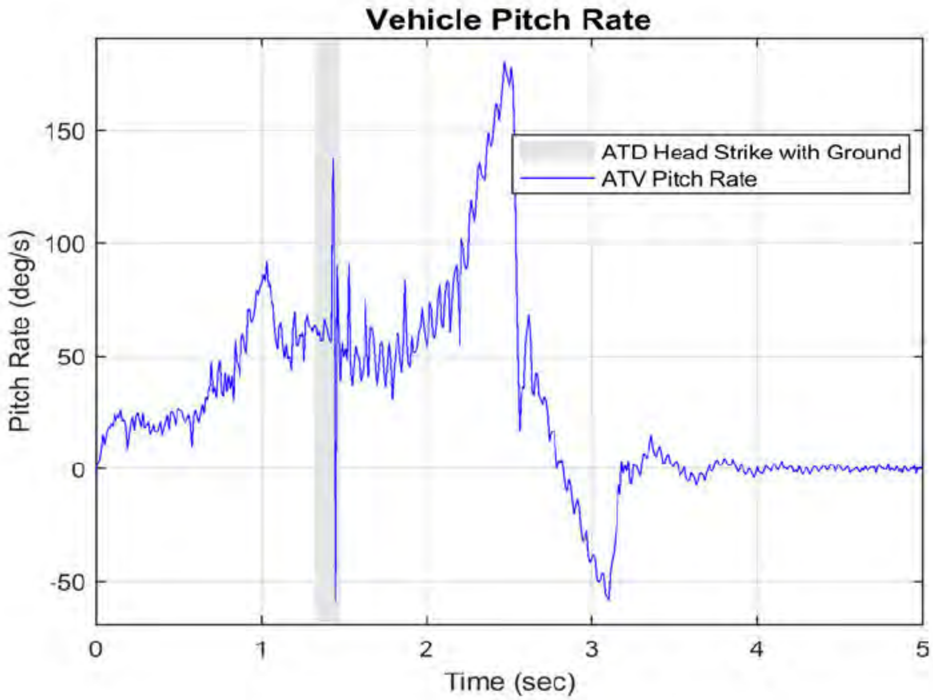


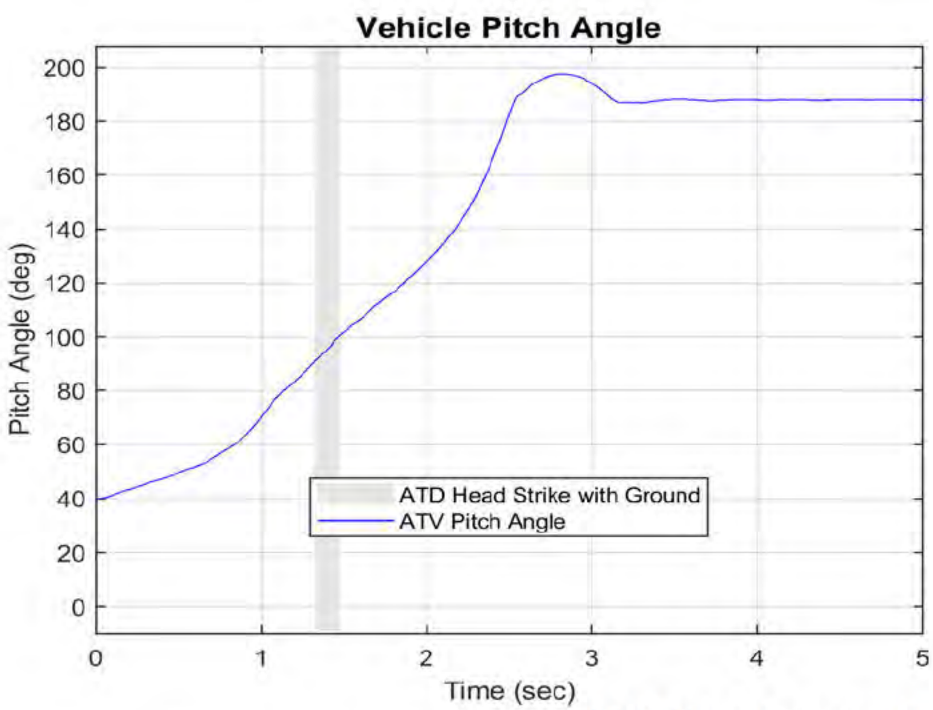
Hill Pitchover - Vehicle M - NO OPD

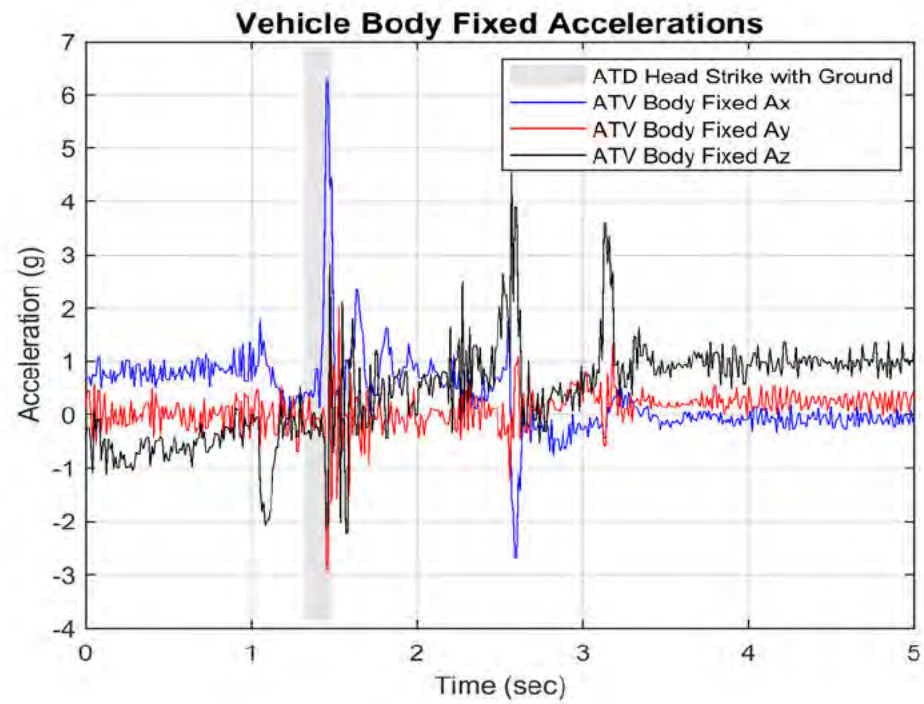




Hill Pitchover - Vehicle M - NO OPD







Hill Pitchover - Vehicle M - NO OPD

Start of Test - Pitch Angle = 40°

OPD Fully Expanded - Time = 1.19 sec - Pitch Angle = 76.7°

Pitch Angle = 60° - Time = 0.82 sec

ATD Head Strike - Time = 1.46 sec

OPD First Expanding - Time = 1.10 sec - Pitch Angle = 76.3°

Max Pitch Angle = 80.4° - Time = 2.47 sec

Hill Pitchover - Vehicle M - AM OPD

Pitch Angle = 77.4° - Time = 3.50 sec

Pitch Angle = 65.6° - Time = 5.00 sec

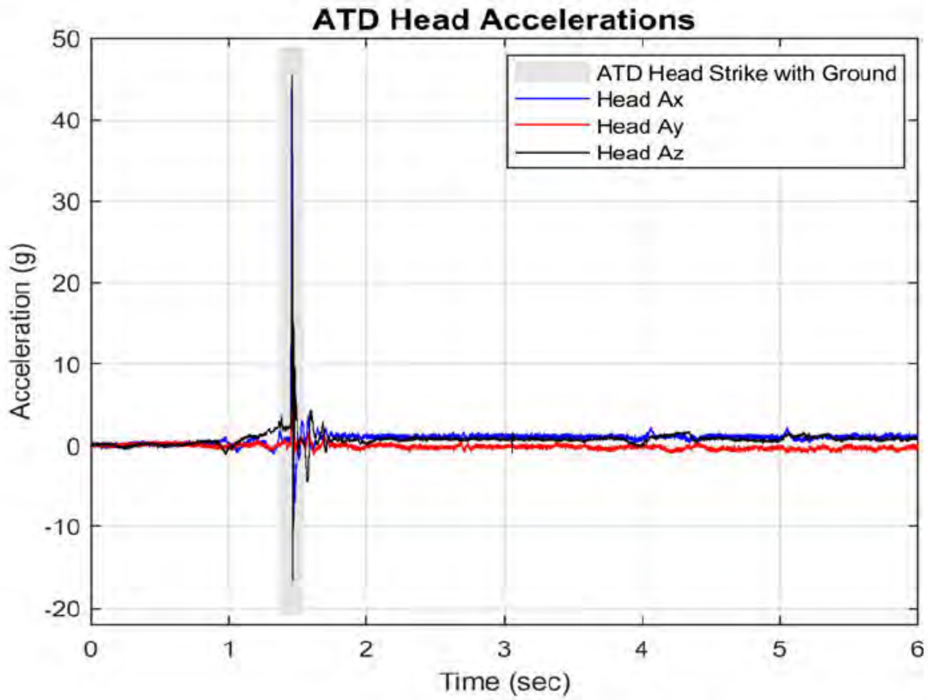
Pitch Angle = 80.4° - Time = 4.00 sec

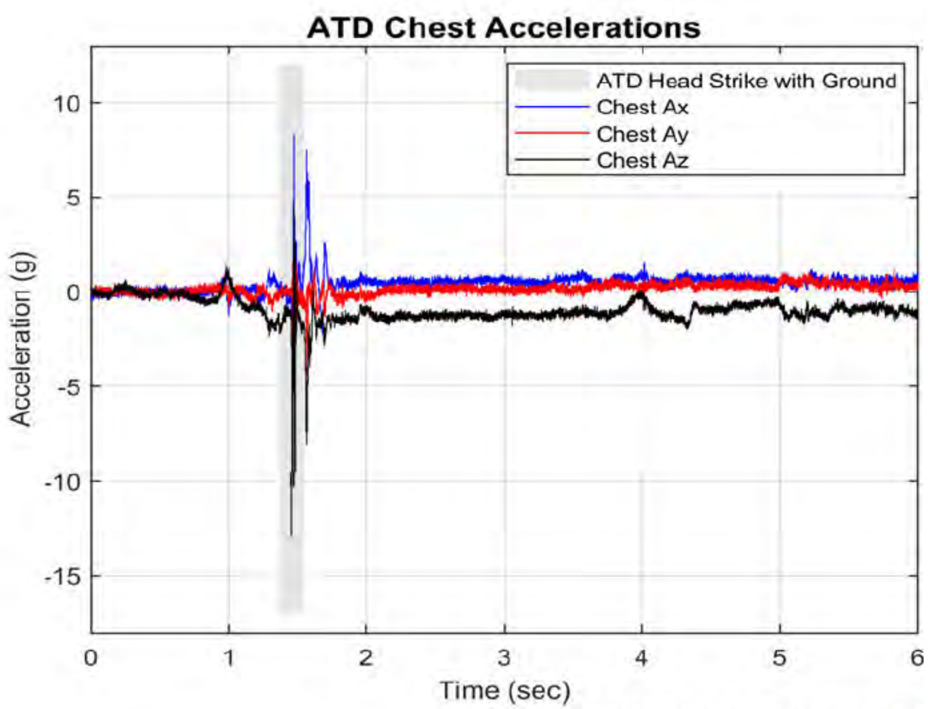
Pitch Angle = 54.2° - Time = 5.50 sec

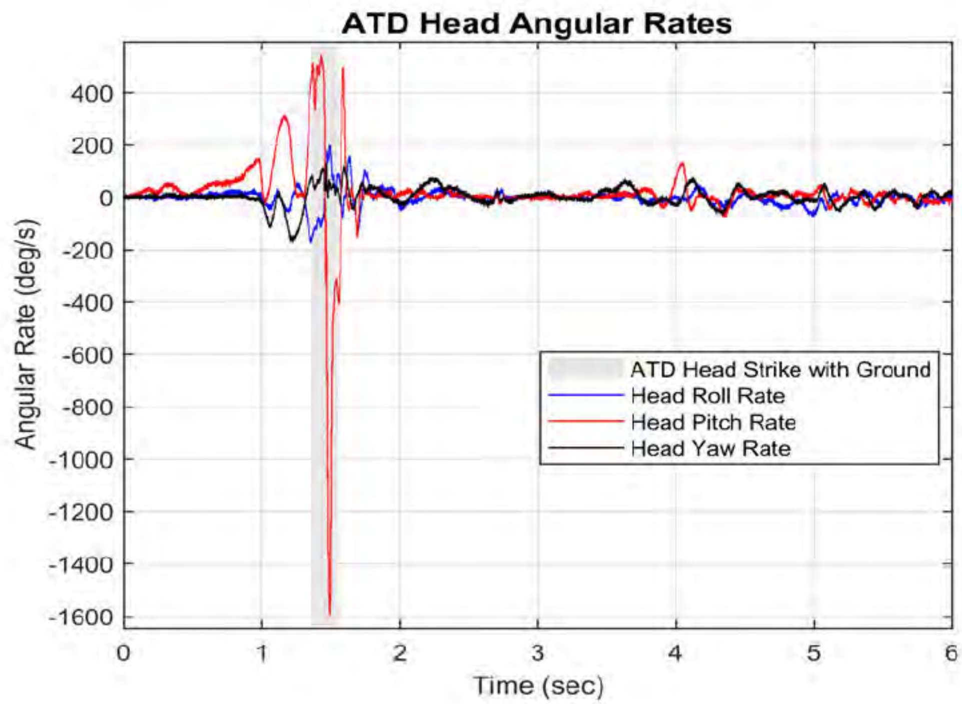
Pitch Angle = 76.2° - Time = 4.50 sec

End of Run - Pitch Angle = 3.2°

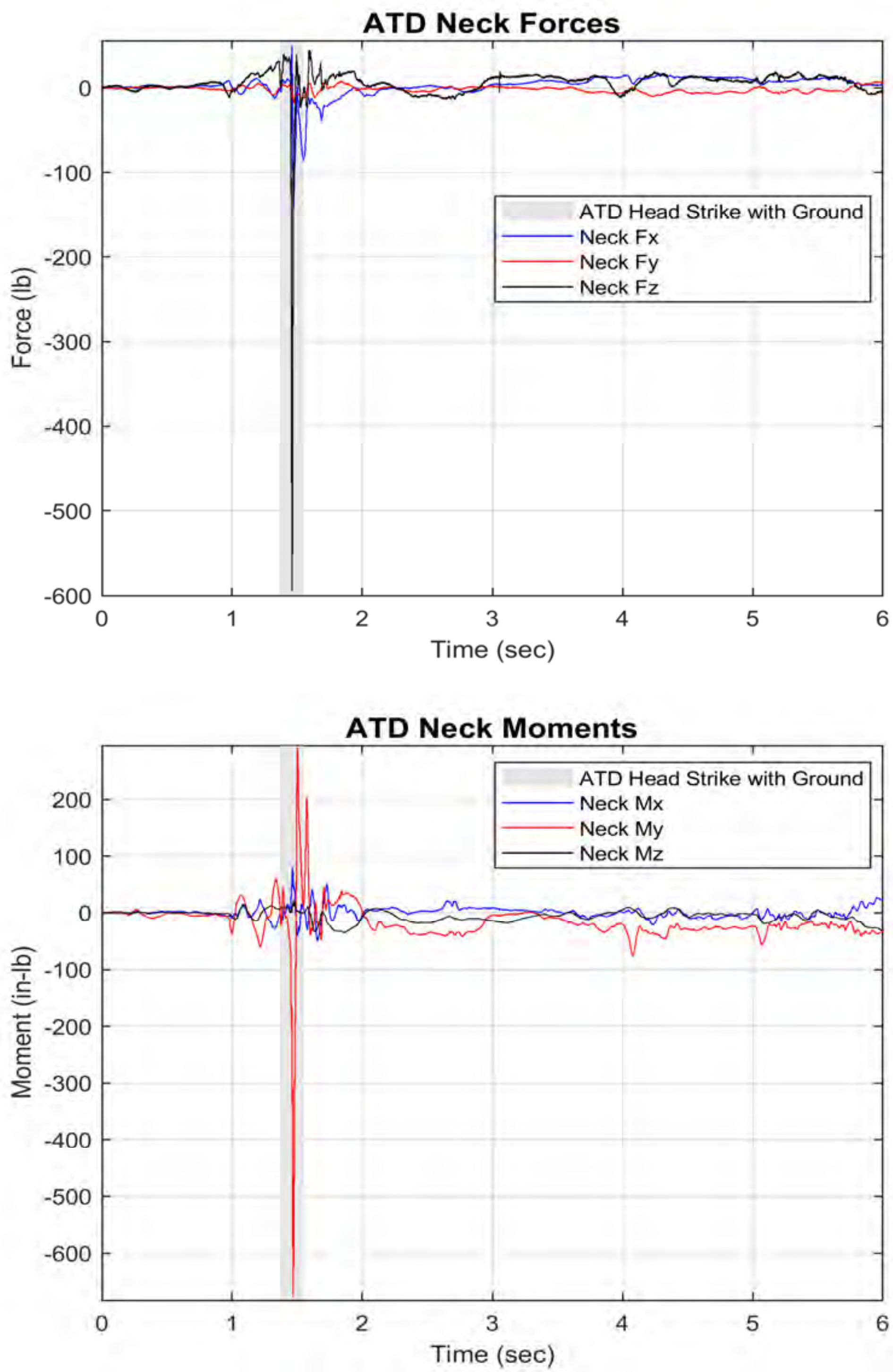
Hill Pitchover - Vehicle M - AM OPD



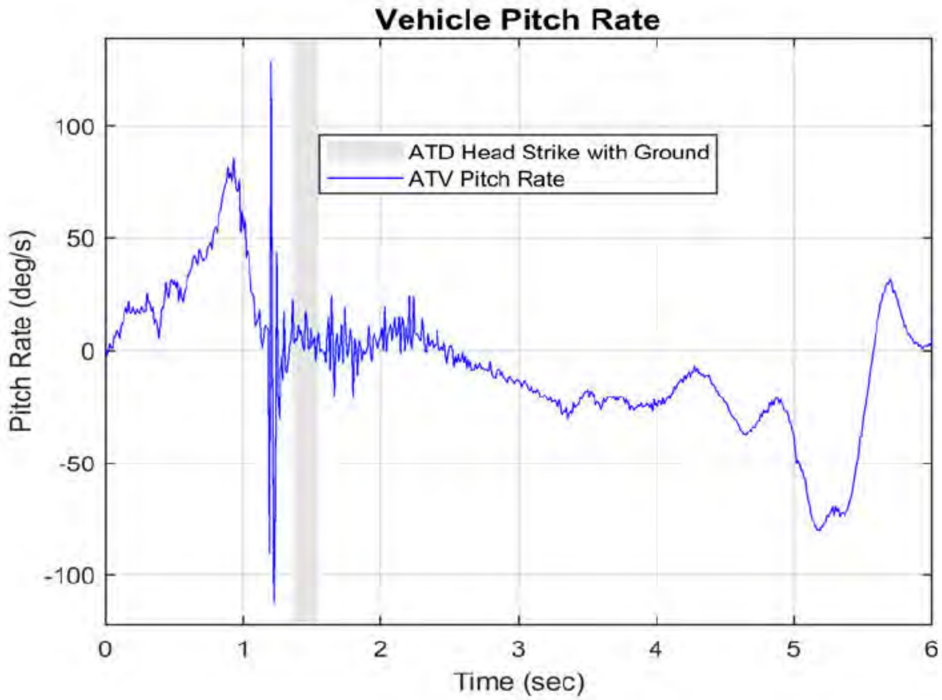


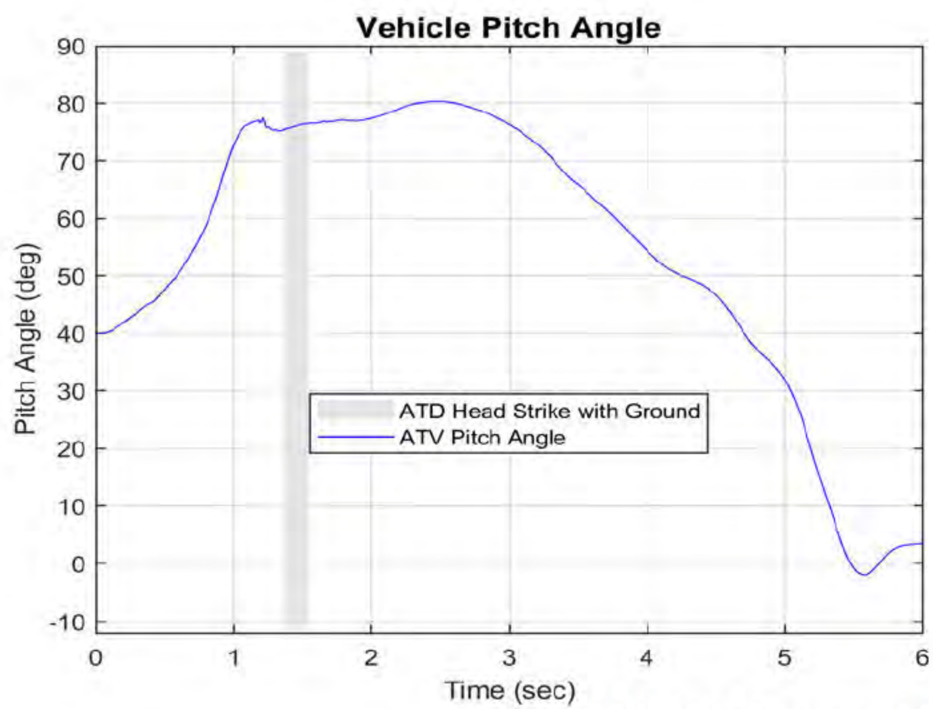


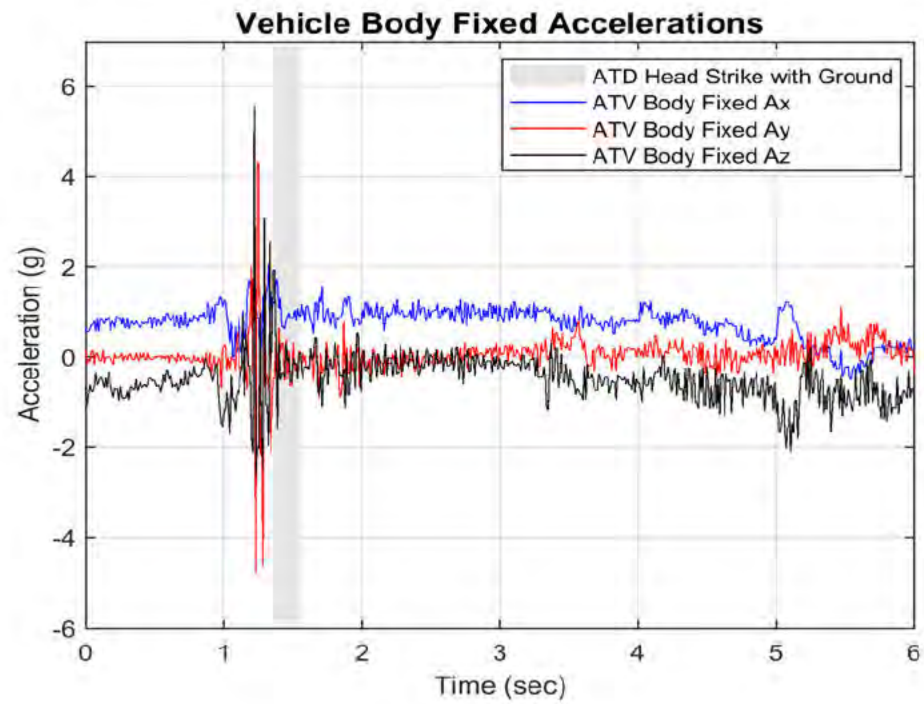
Hill Pitchover - Vehicle M - AM OPD



Hill Pitchover - Vehicle M - AM OPD







Hill Pitchover - Vehicle M - AM OPD

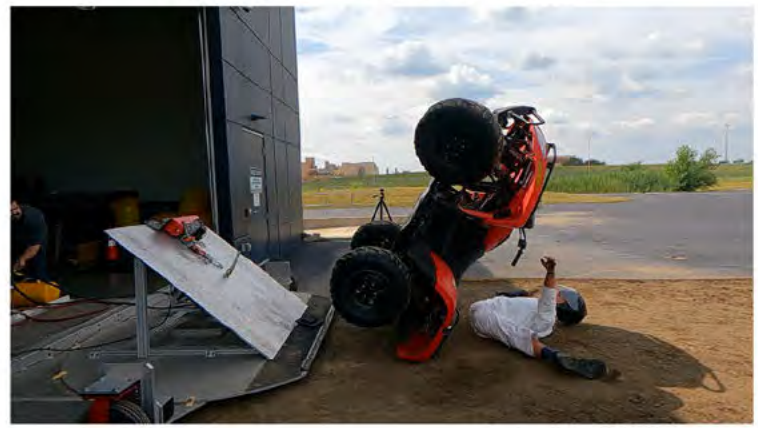
Start of Test - Pitch Angle = 40°

Pitch Angle = 60° - Time = 0.38 sec

Pitch Angle = 90° - Time = 0.76 sec

ATD Head Strike - Time = 0.88 sec

Pitch Angle = 120° - Time = 1.36 sec



Pitch Angle = 150° - Time = 1.81 sec

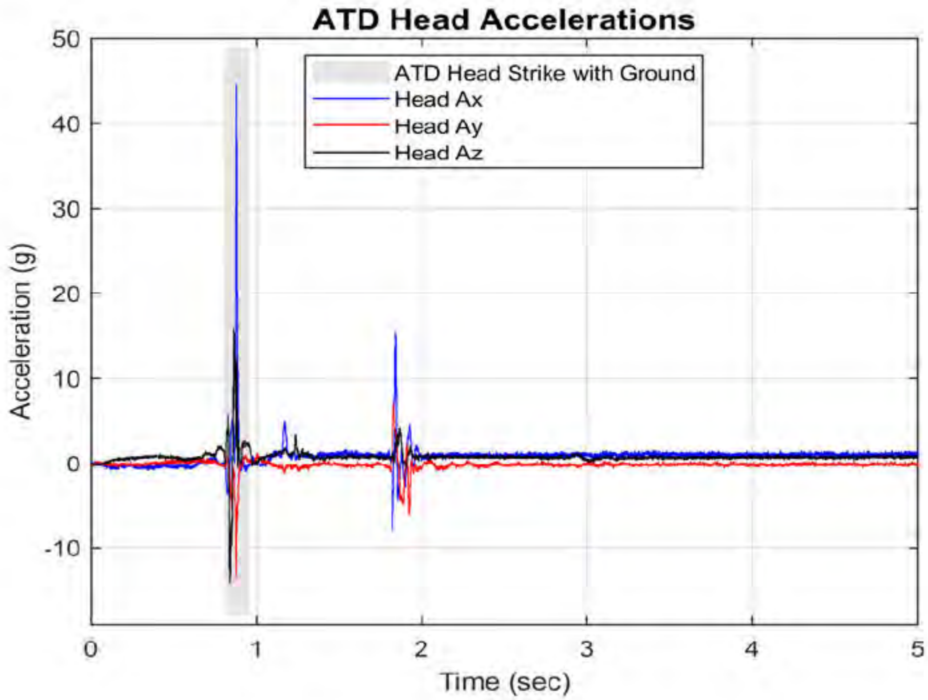
Sled Pitchover - Vehicle E - NO OPD

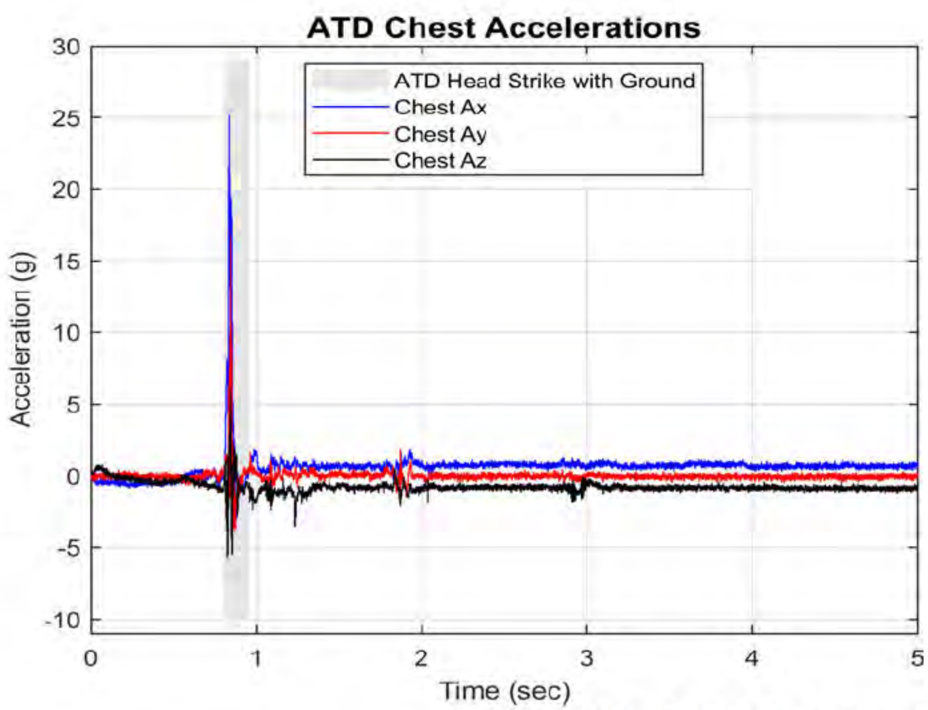
Pitch Angle = 180° - Time = 2.16 sec

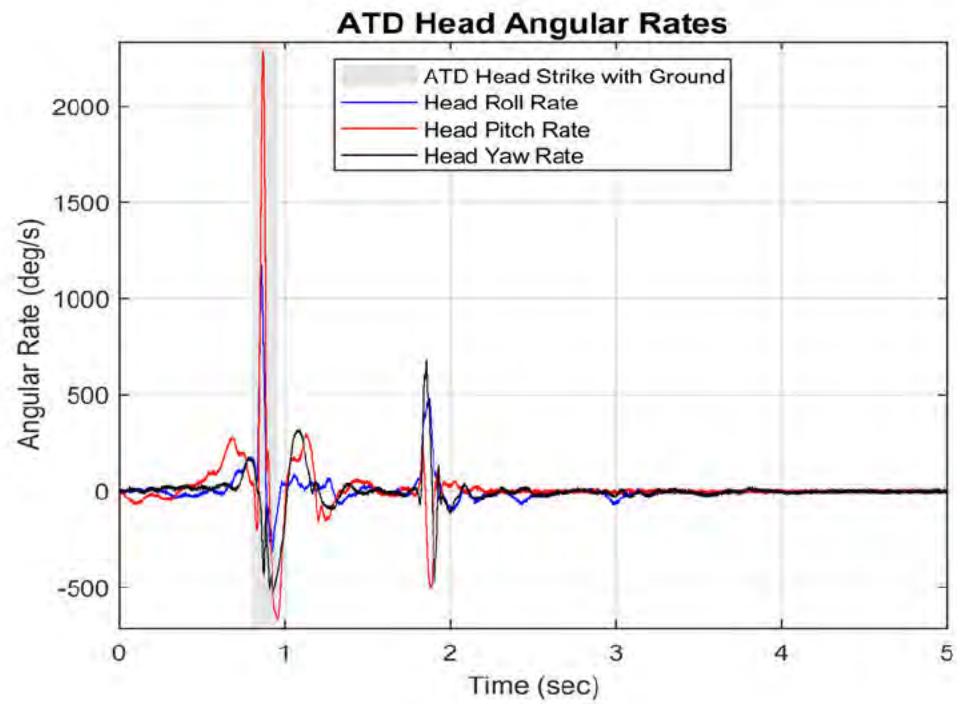
Max Pitch Angle = 189.9° - Time = 2.51 sec

End of Run - Pitch Angle = 175.7°

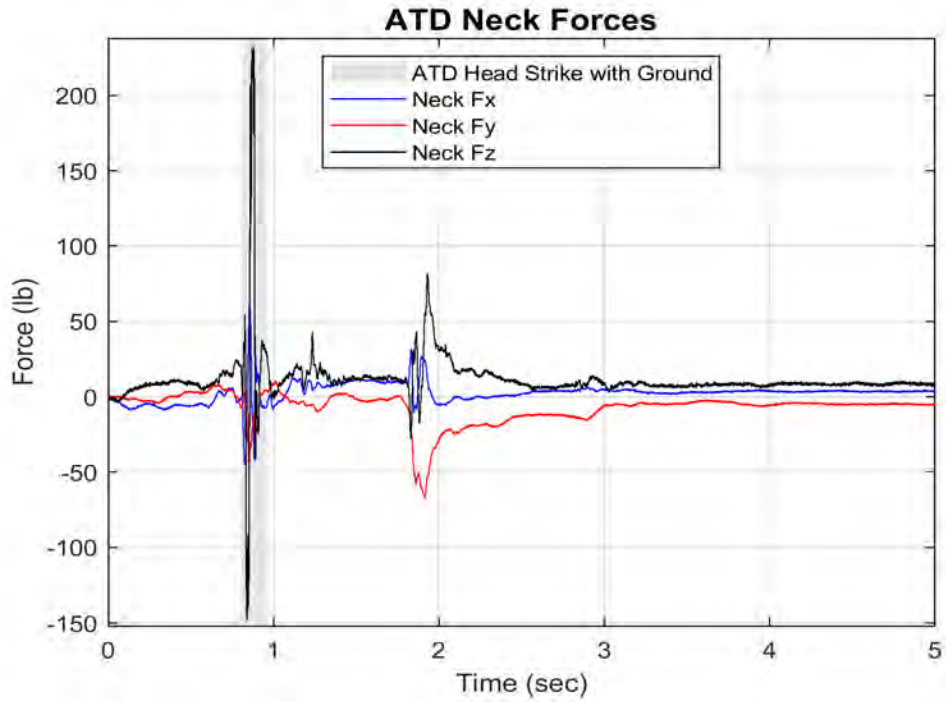
Sled Pitchover - Vehicle E - NO OPD

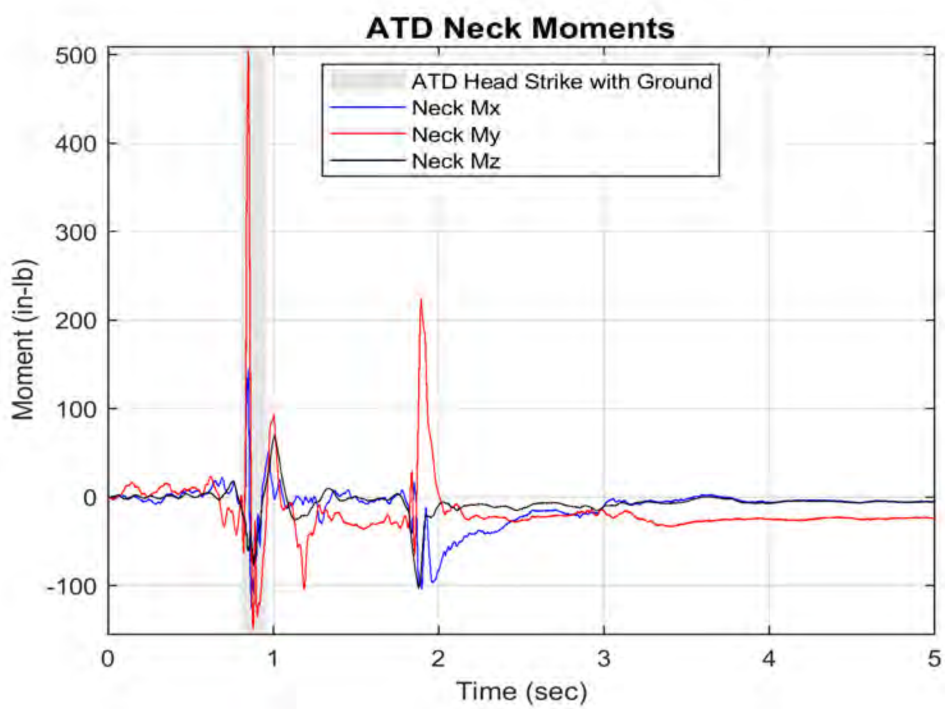




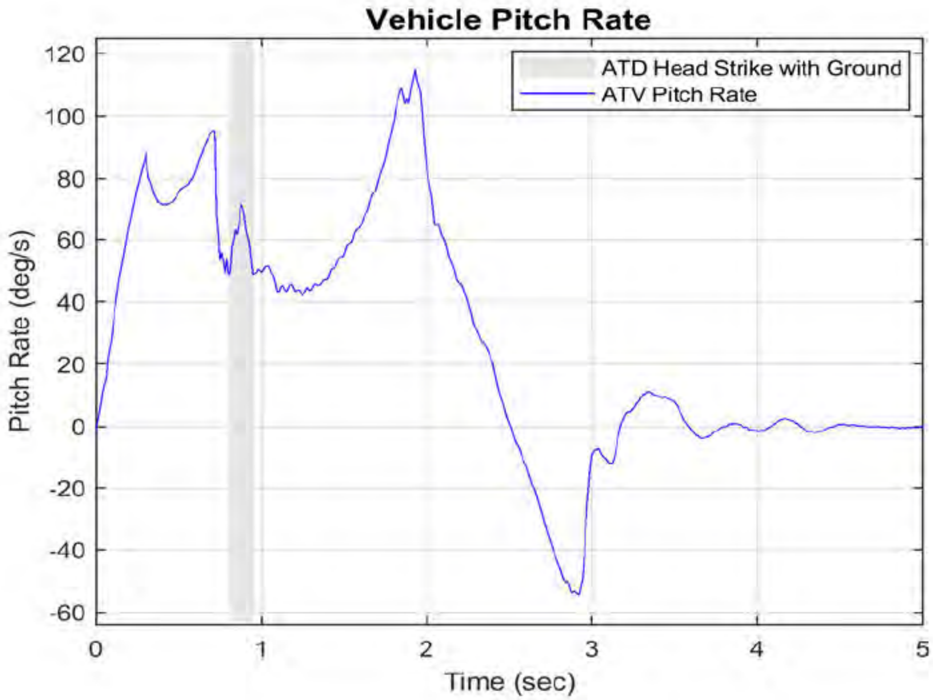


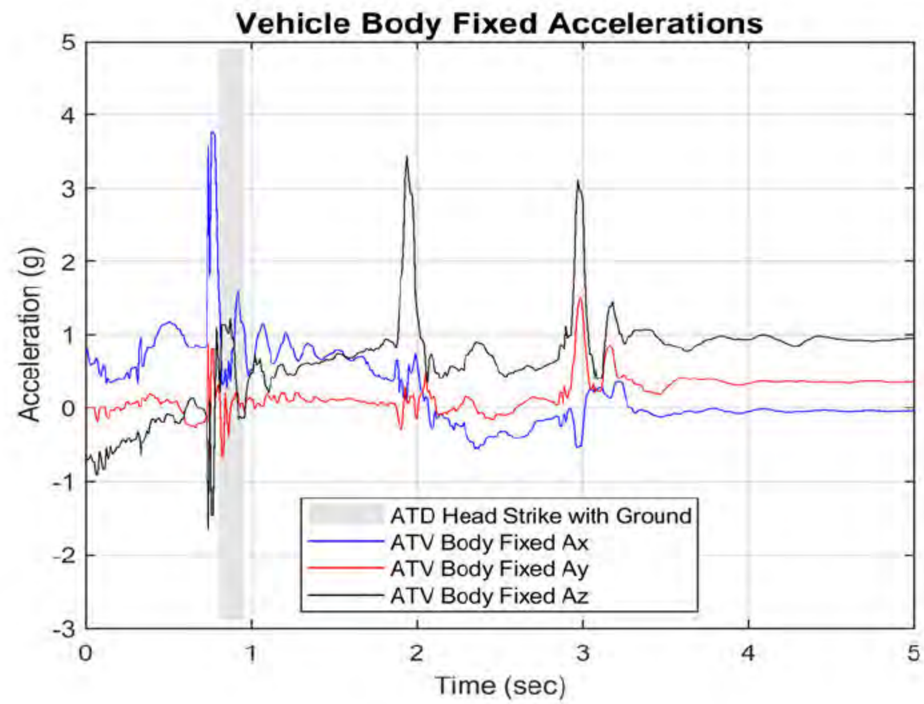
Sled Pitchover - Vehicle E - NO OPD

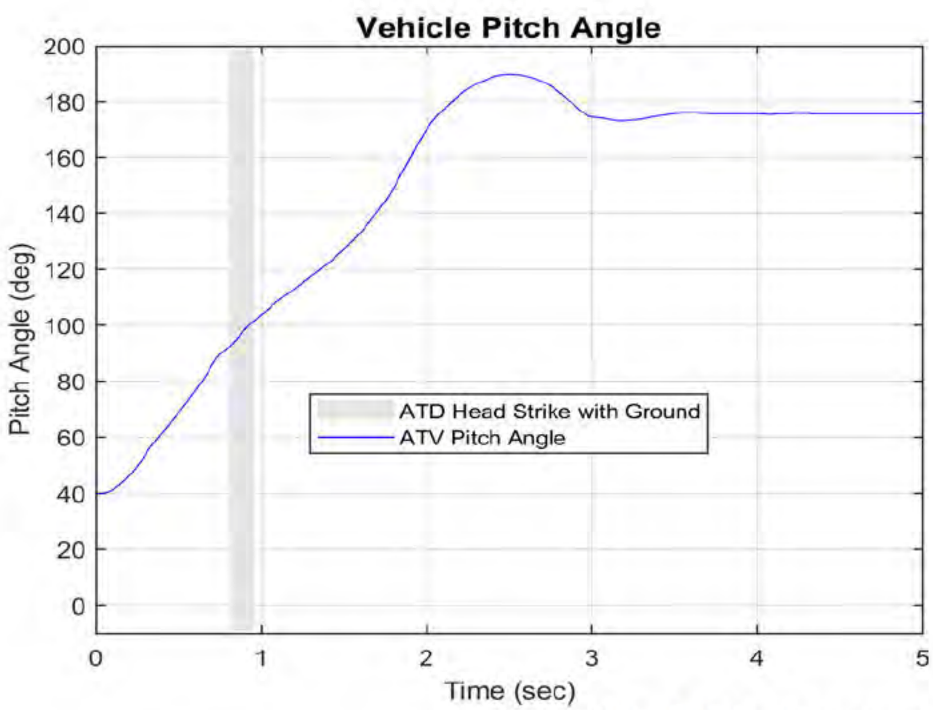




Sled Pitchover - Vehicle E - NO OPD







Sled Pitchover - Vehicle E - NO OPD

Start of Test - Pitch Angle = 40°

Pitch Angle = 60° - Time = 0.38 sec

Max Pitch Angle = 63.3° - Time = 0.52 sec

ATD Head Strike - Time = 0.90 sec

Pitch Angle = 21.1° - Time = 1.50 sec

Pitch Angle = 3.4° - Time = 2.00 sec

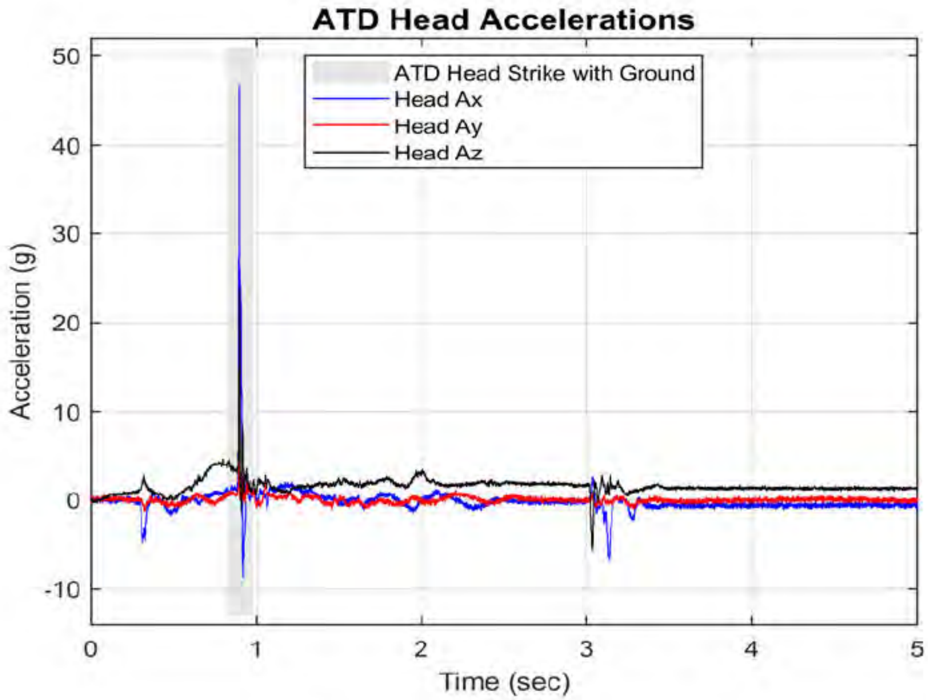
Sled Pitchover - Vehicle E - OPD #1

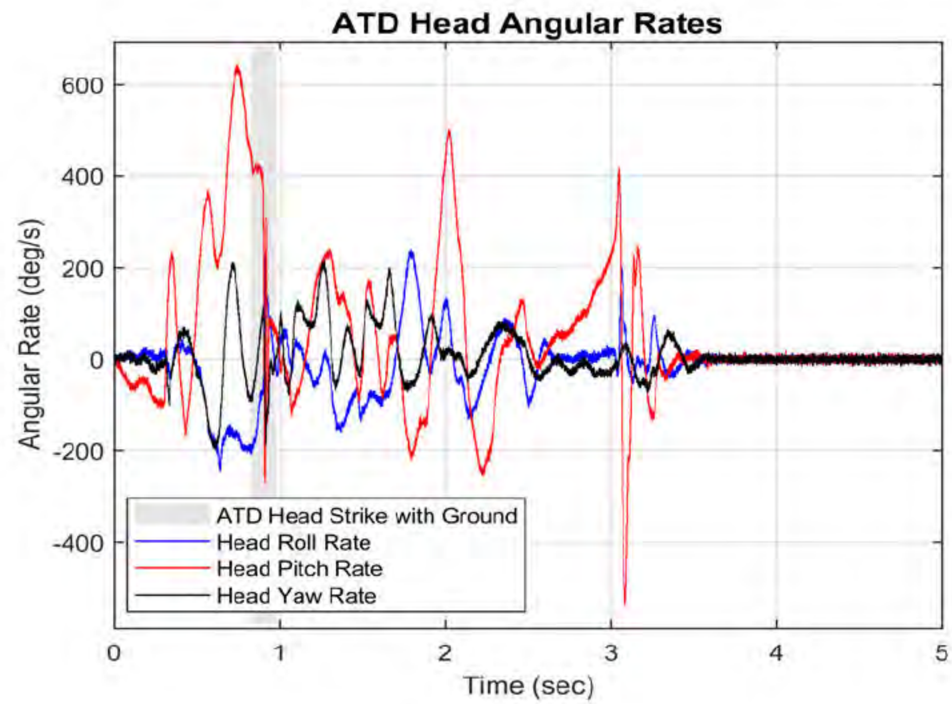
Pitch Angle = -1.0° - Time = 2.50 sec

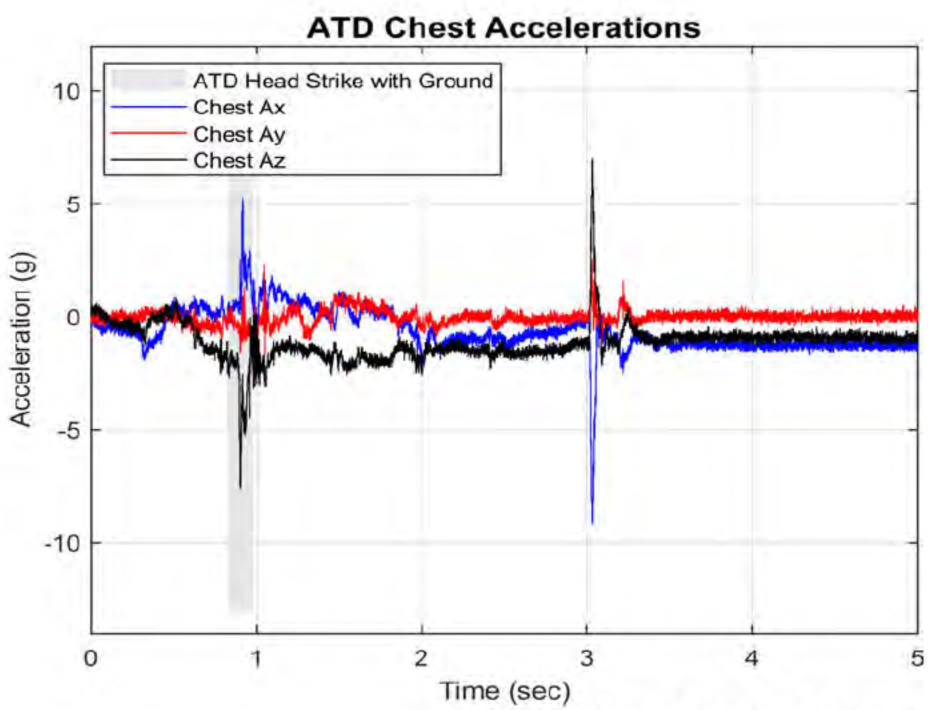
Pitch Angle = -8.4° - Time = 3.00 sec

End of Run - Pitch Angle = -7.9°

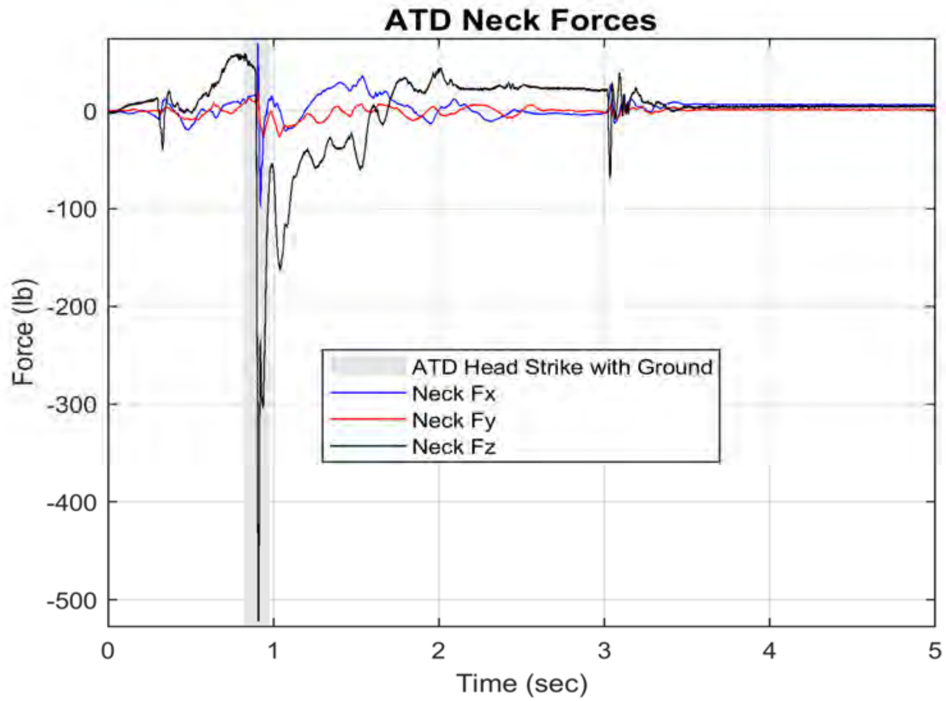
Sled Pitchover - Vehicle E - OPD #1

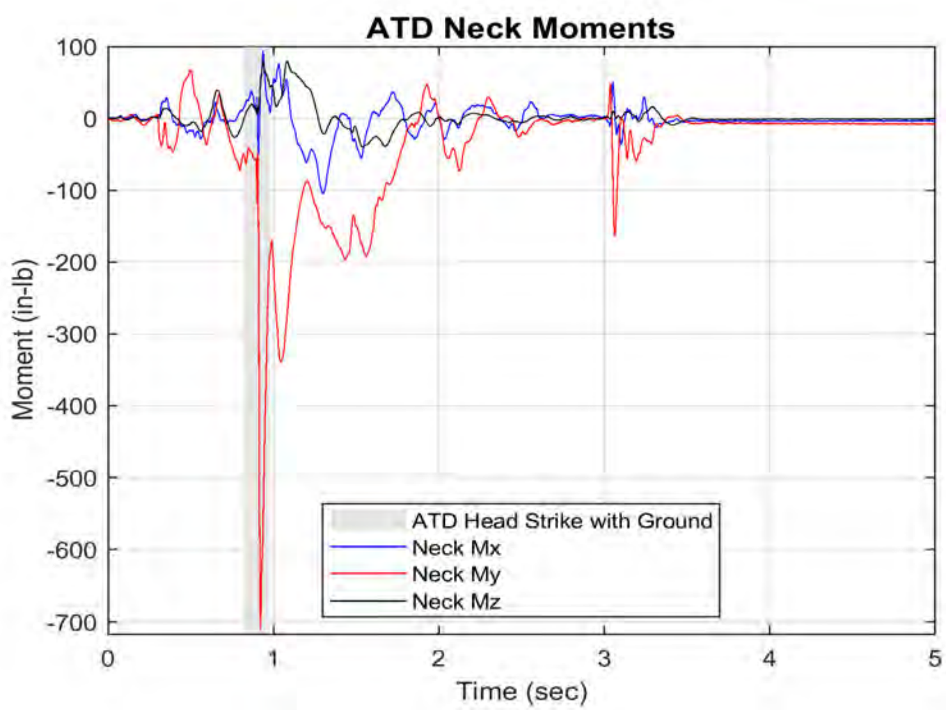




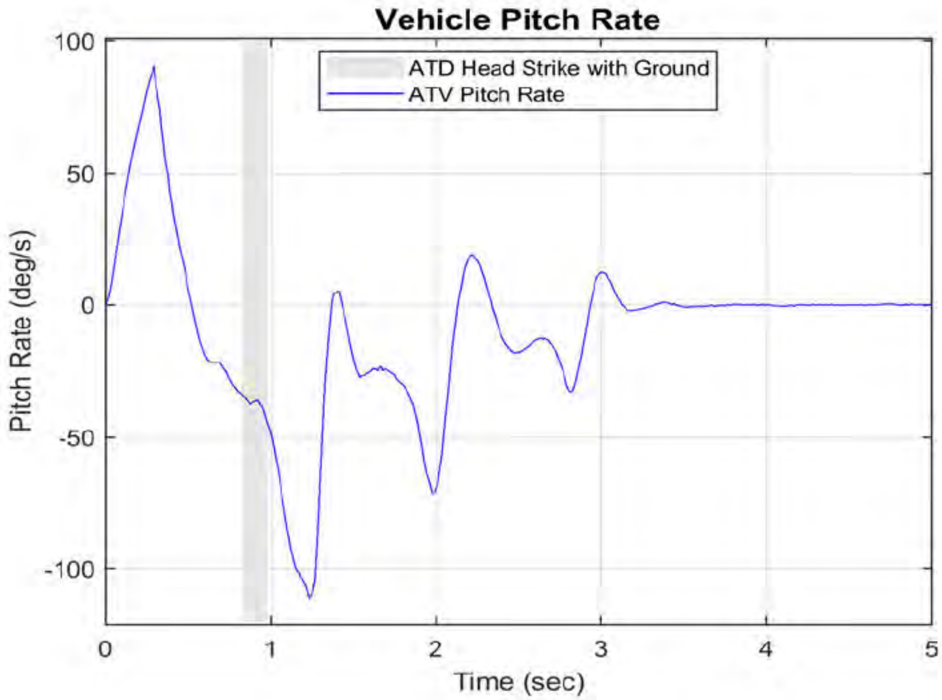


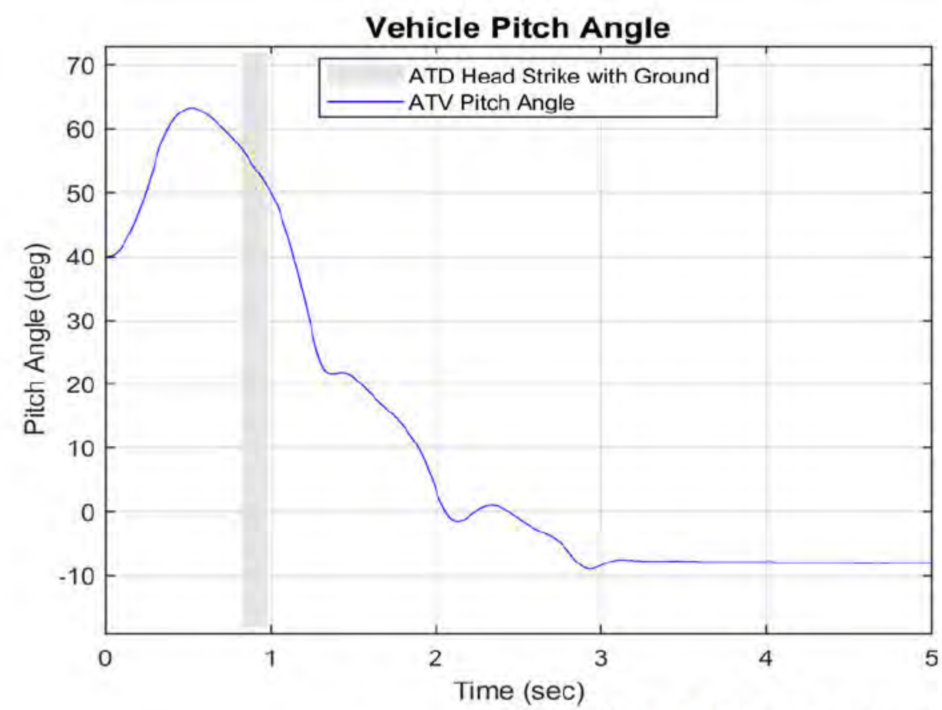
Sled Pitchover - Vehicle E - OPD #1

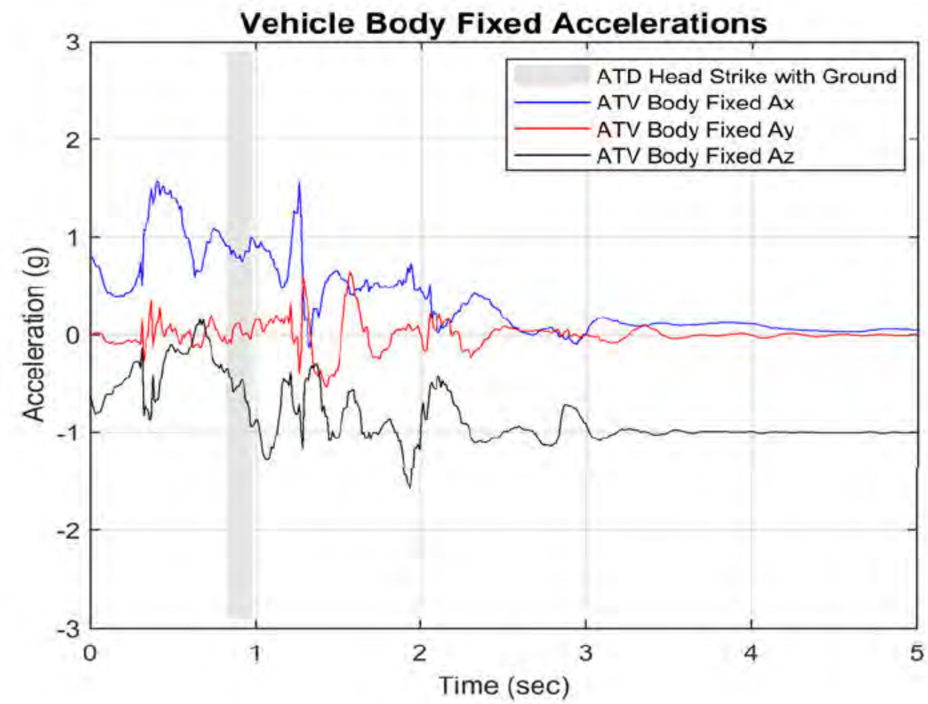




Sled Pitchover - Vehicle E - OPD #1







Sled Pitchover - Vehicle E - OPD #1

Start of Test - Pitch Angle = 40°

Pitch Angle = 60° - Time = 0.44 sec

Max Pitch Angle = 78.3° - Time = 0.84 sec

Pitch Angle = 59.7° - Time = 1.50 sec

Pitch Angle = 54.9° - Time = 2.00 sec

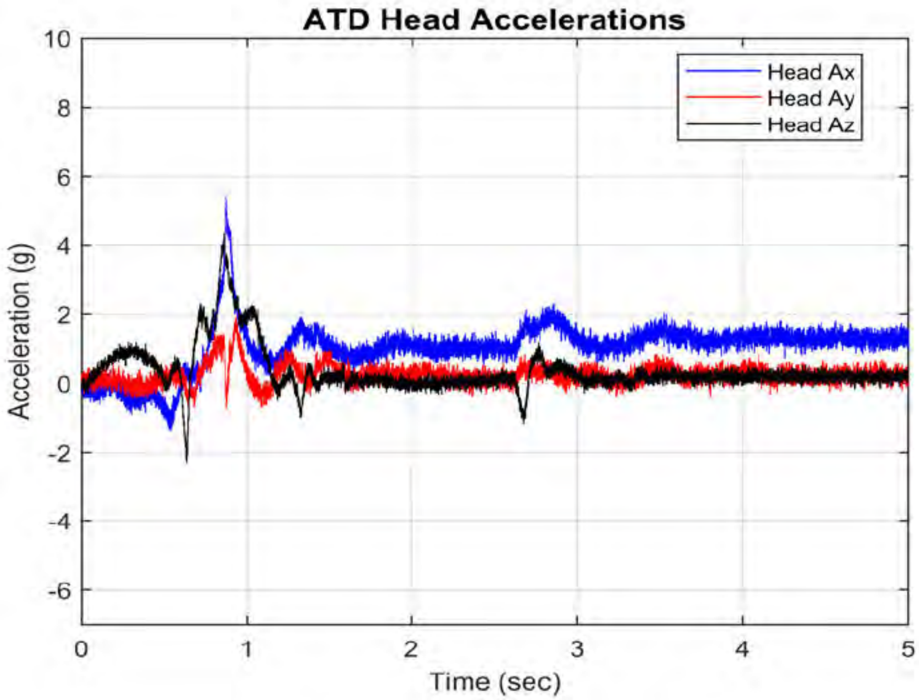
Pitch Angle = 60.0° - Time = 2.50 sec

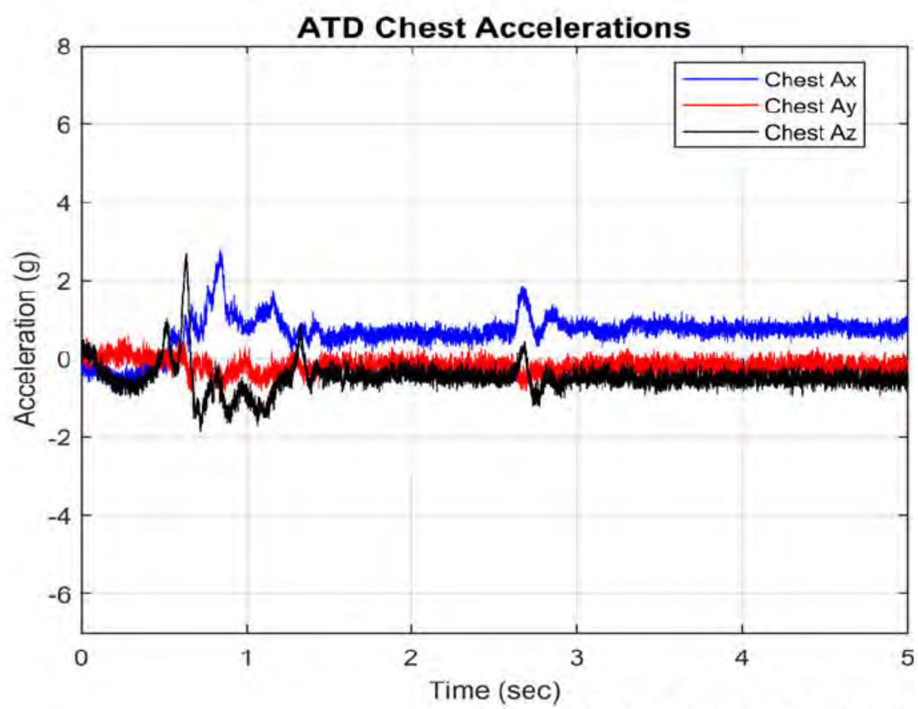
Sled Pitchover - Vehicle E - OPD #2

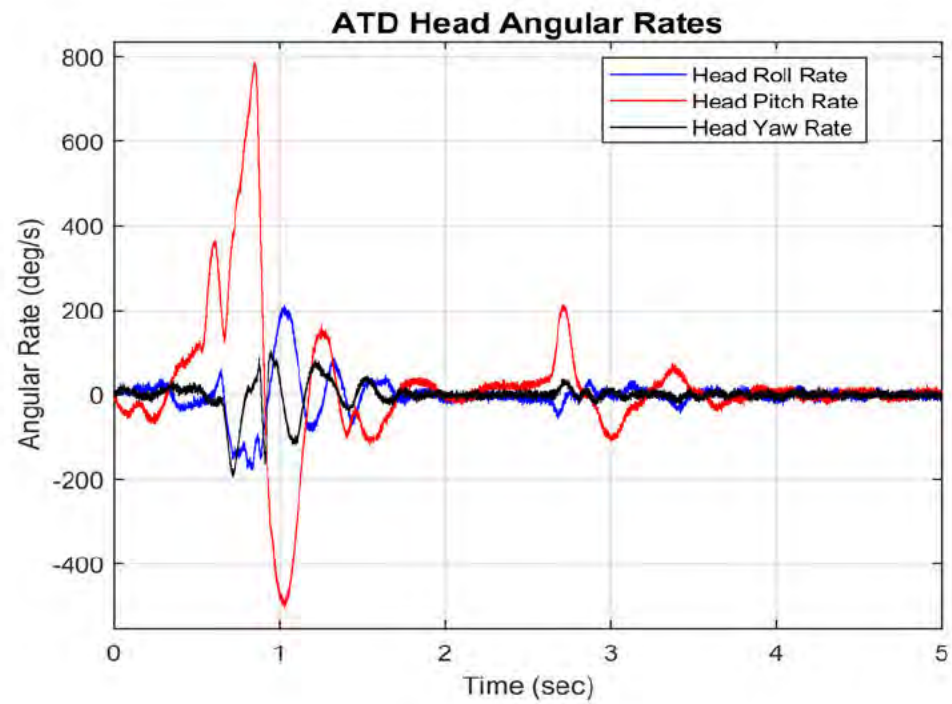
Pitch Angle = 66.8° - Time = 3.00 sec

End of Run - Pitch Angle = 66.2°

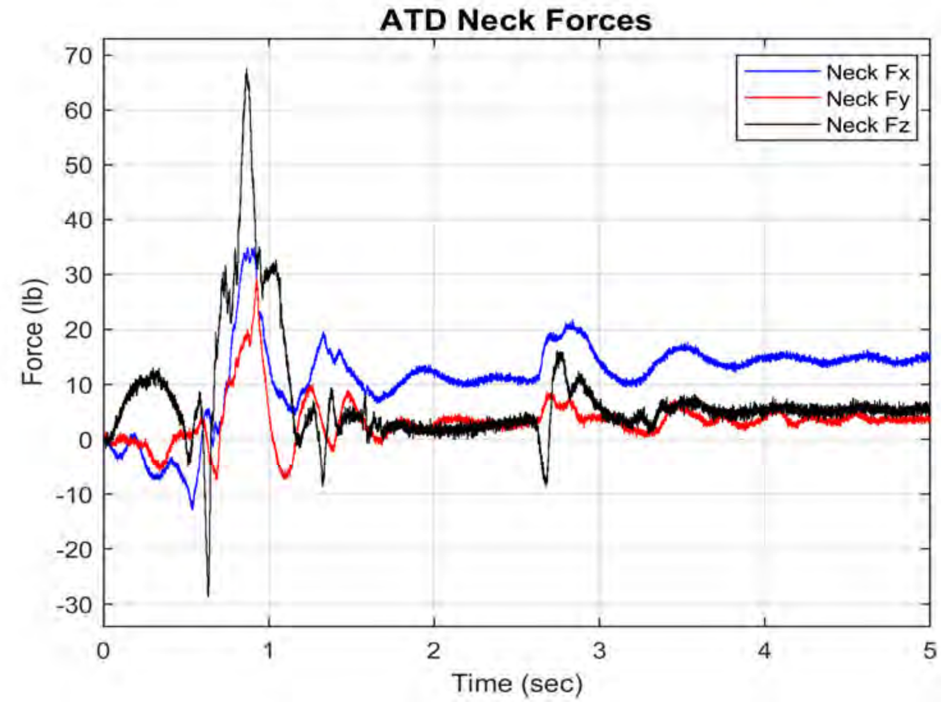
Sled Pitchover - Vehicle E - OPD #2

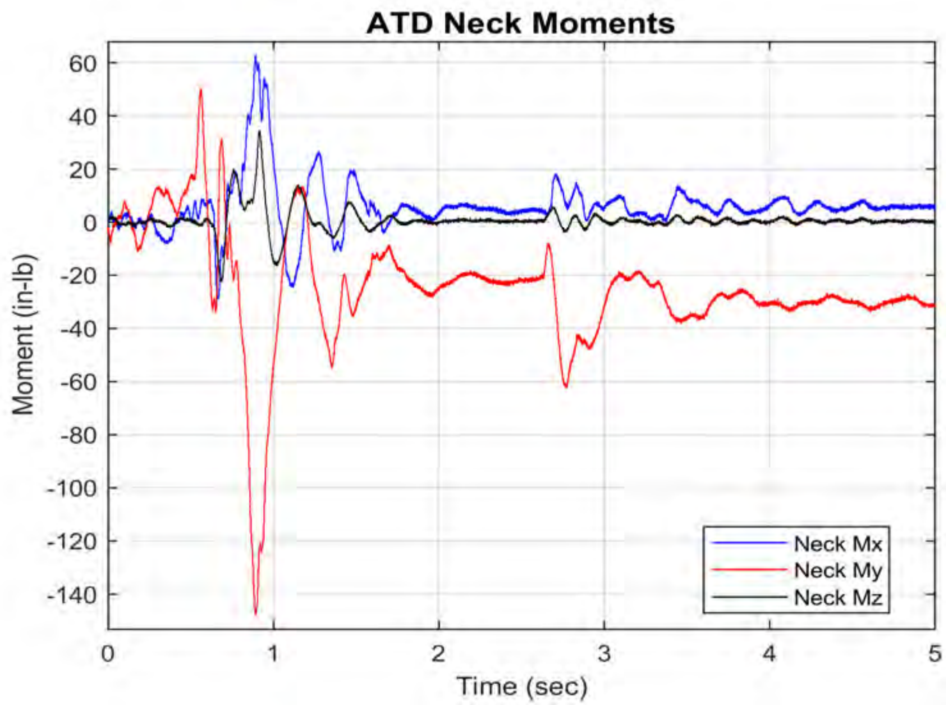




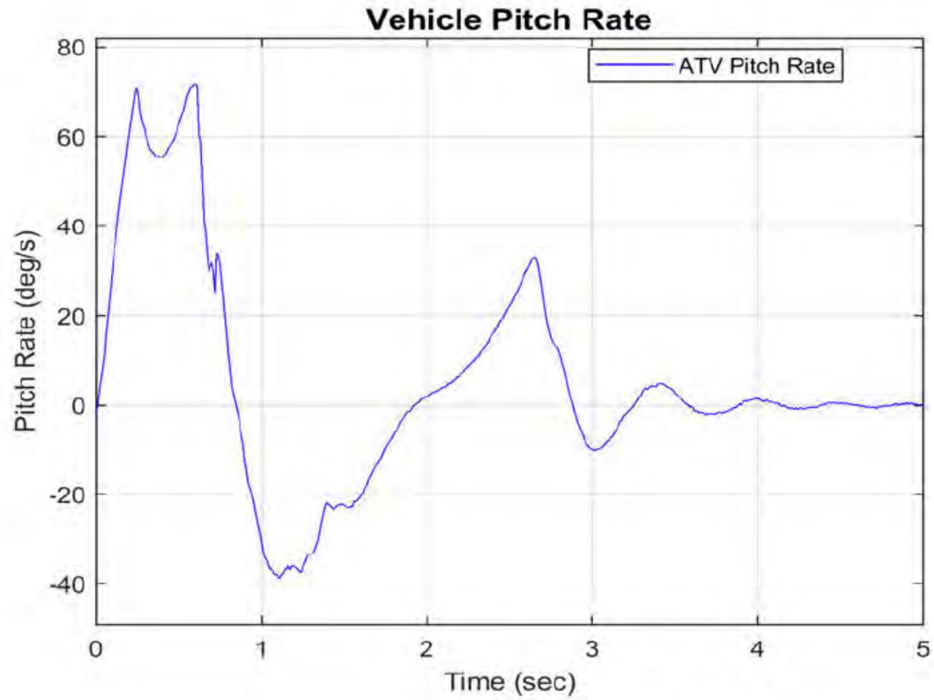


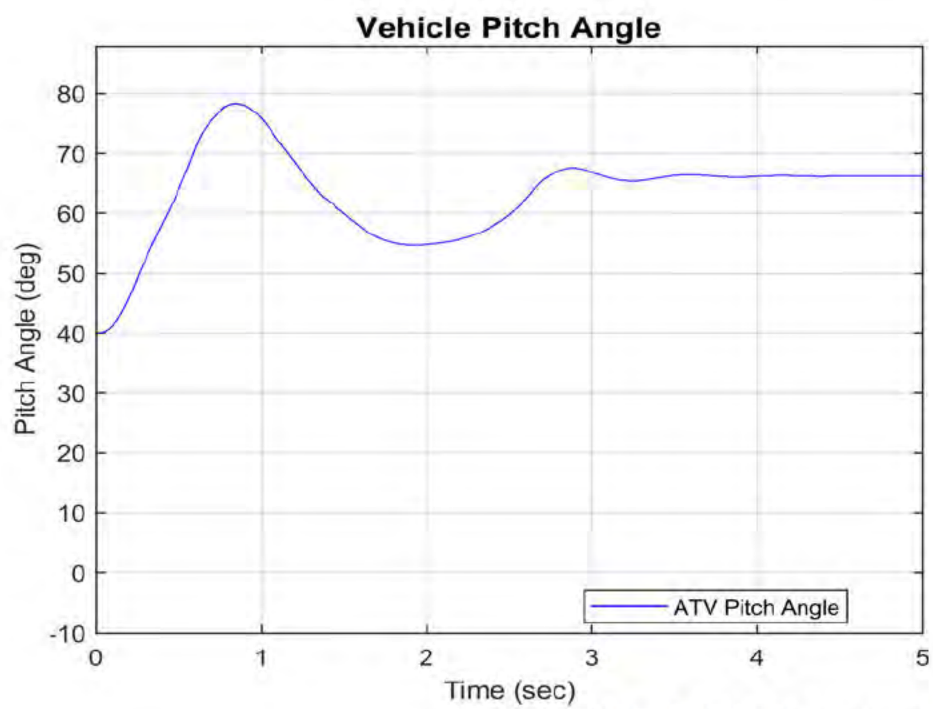
Sled Pitchover - Vehicle E - OPD #2

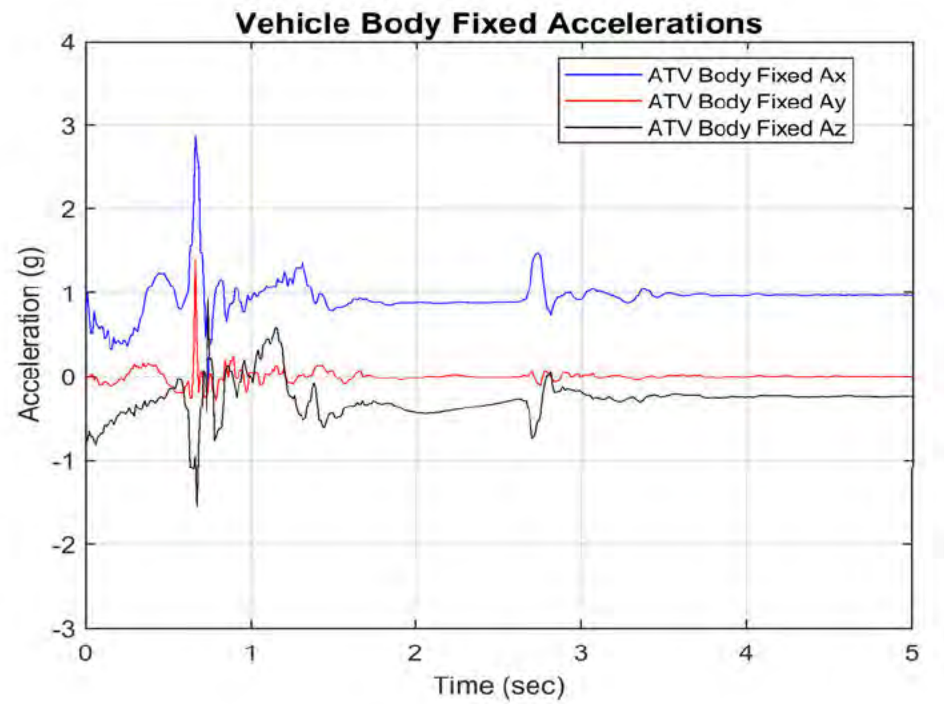




Sled Pitchover - Vehicle E - OPD #2







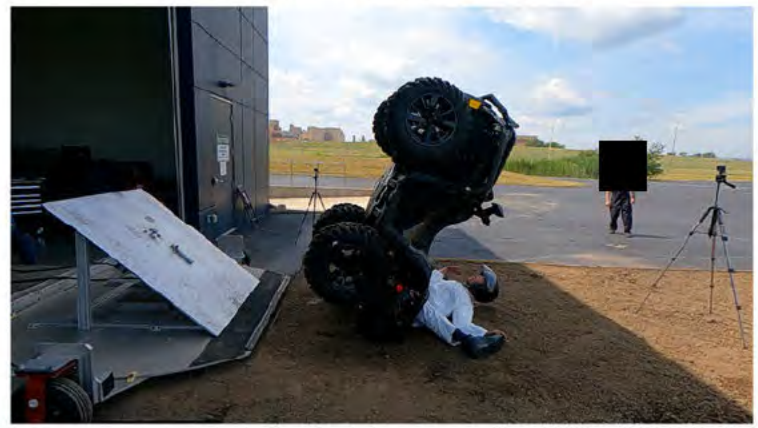
Sled Pitchover - Vehicle E - OPD #2

Start of Test - Pitch Angle = 40°

ATD Head Strike - Time = 0.87 sec

Pitch Angle = 60° - Time = 0.40 sec

Pitch Angle = 120° - Time = 1.91 sec



Pitch Angle = 90° - Time = 0.84 sec

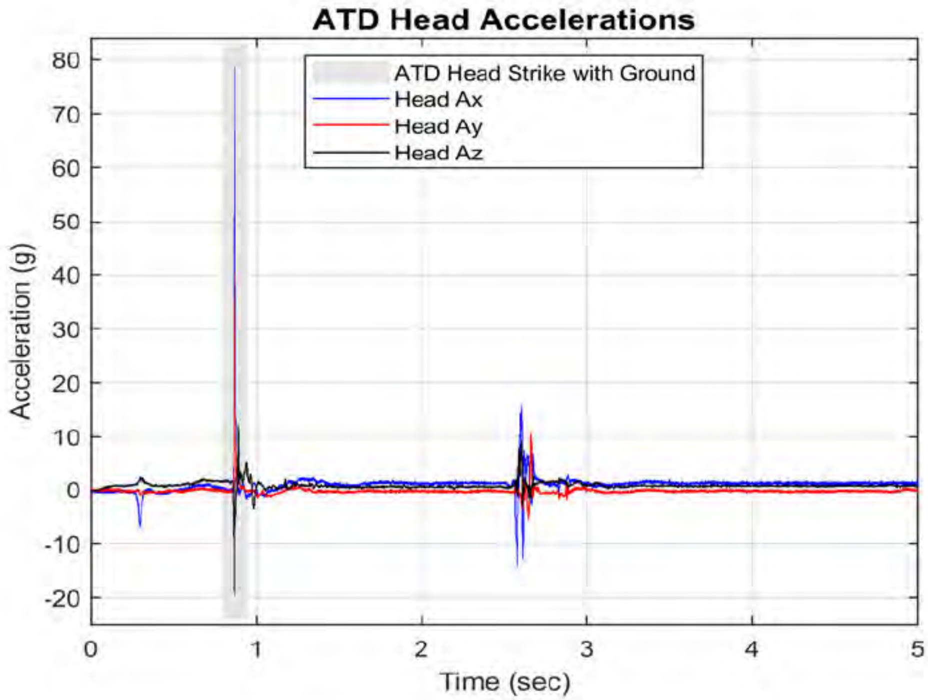
Pitch Angle = 150° - Time = 2.58 sec

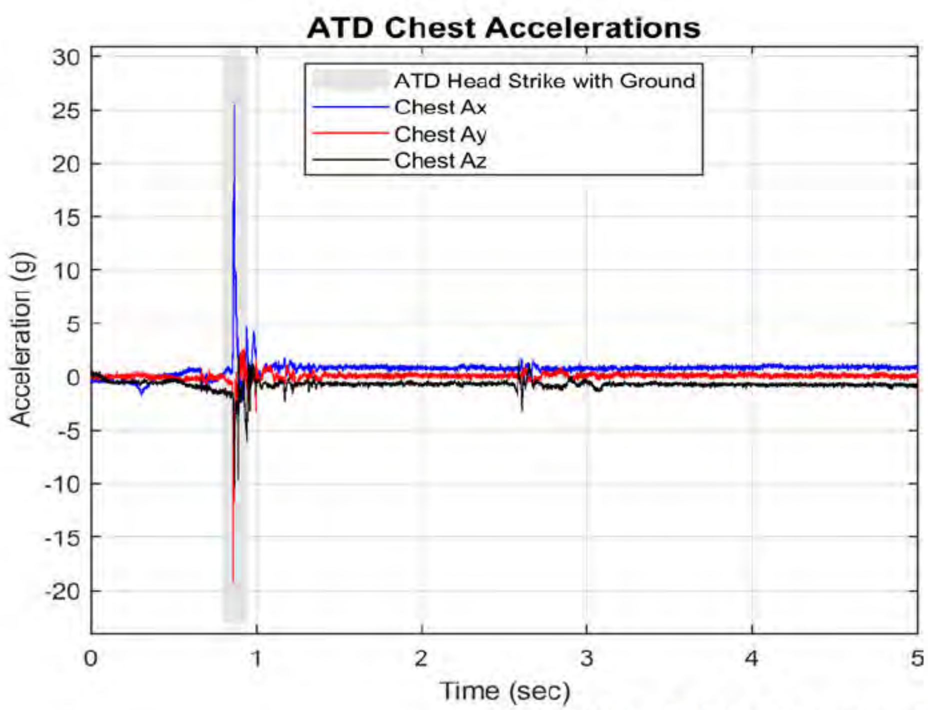
Sled Pitchover - Vehicle M - NO OPD

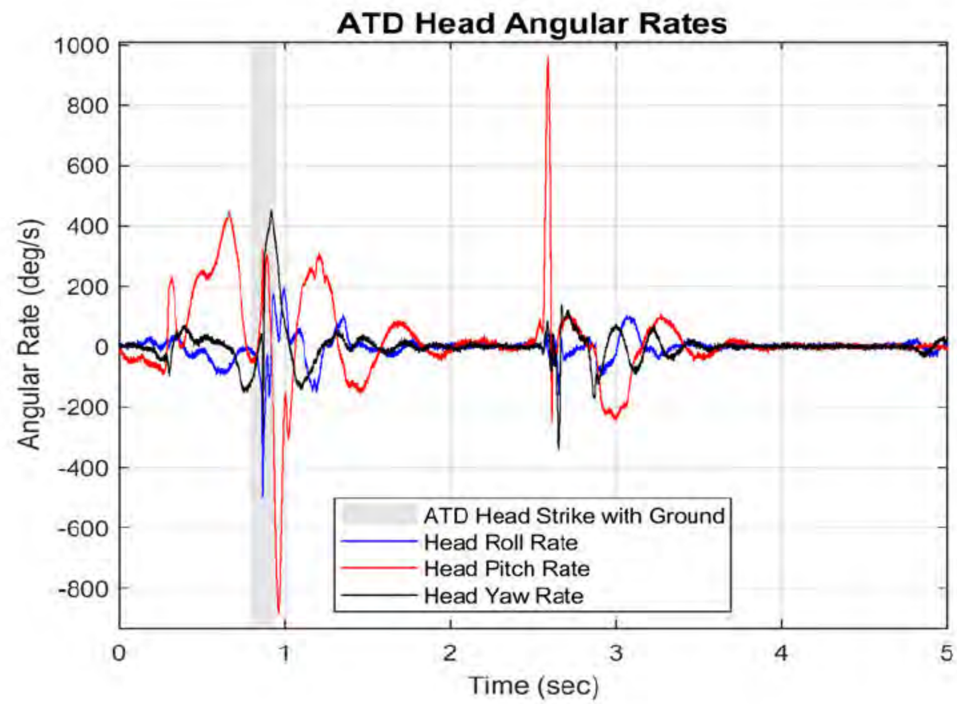
Max Pitch Angle = 177.8° - Time = 3.26 sec

End of Run - Pitch Angle = 177.4°

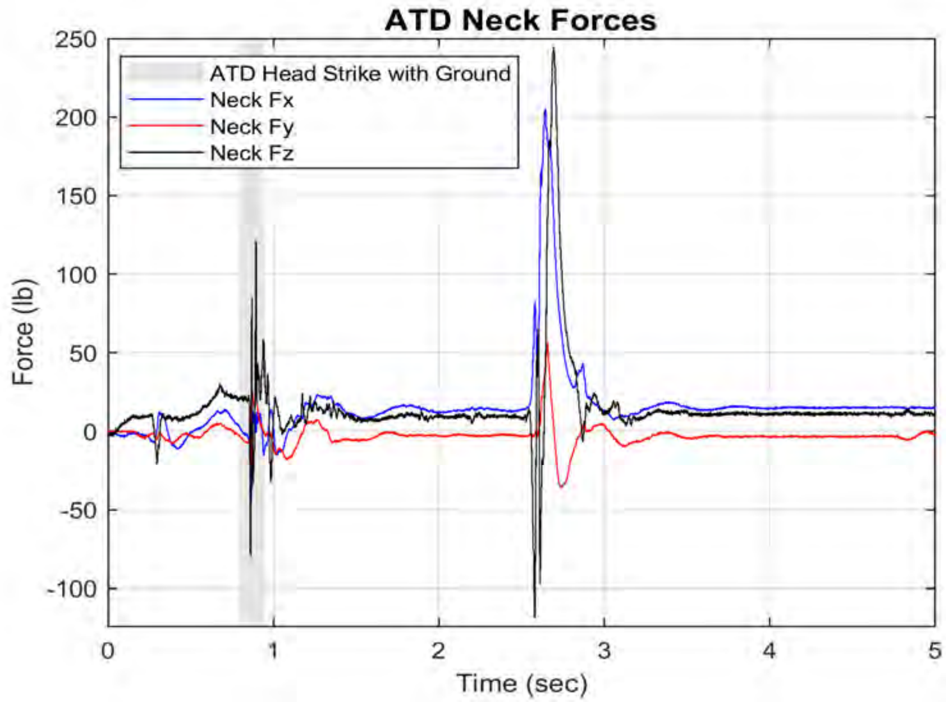
Sled Pitchover - Vehicle M - NO OPD

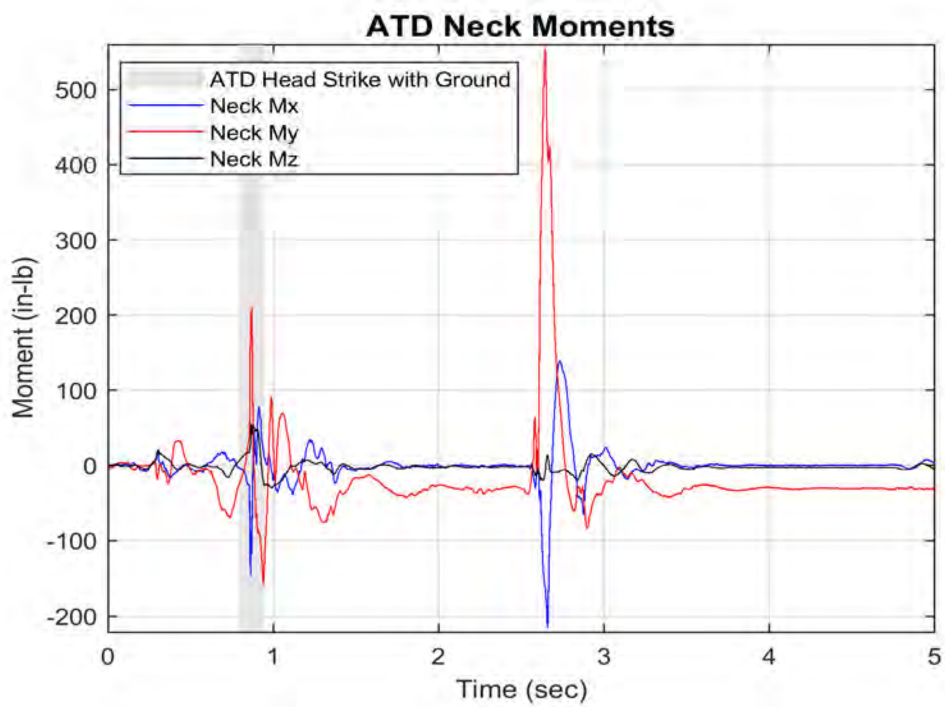




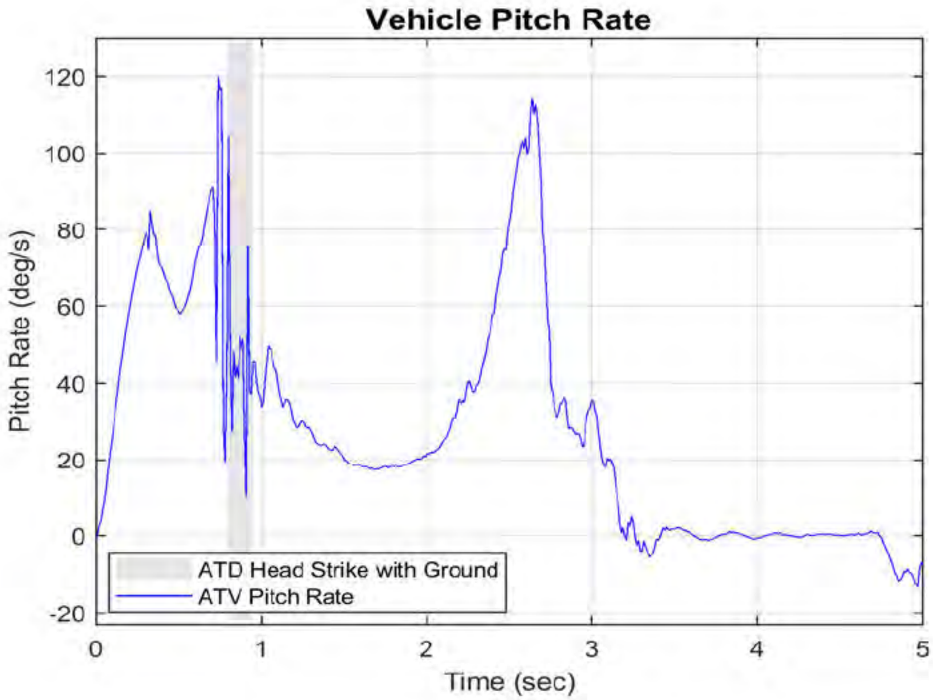


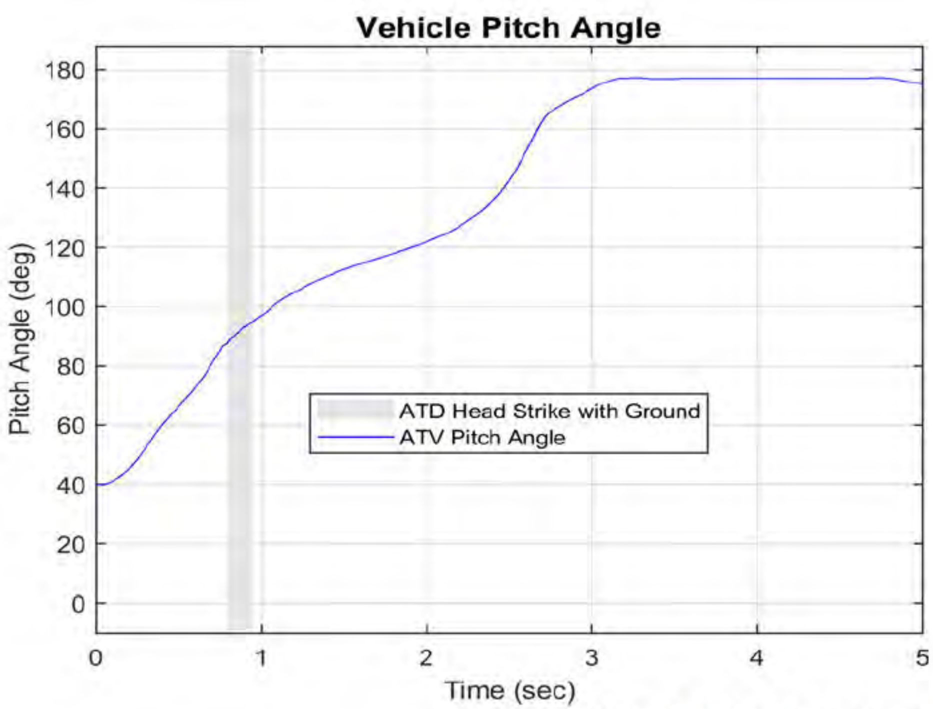
Sled Pitchover - Vehicle M - NO OPD

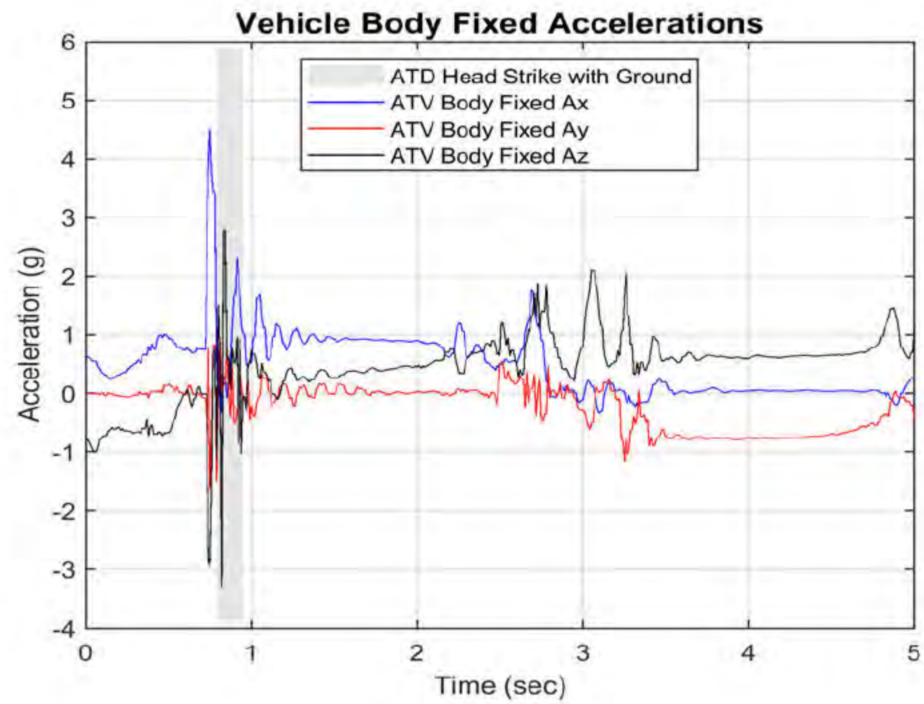




Sled Pitchover - Vehicle M - NO OPD



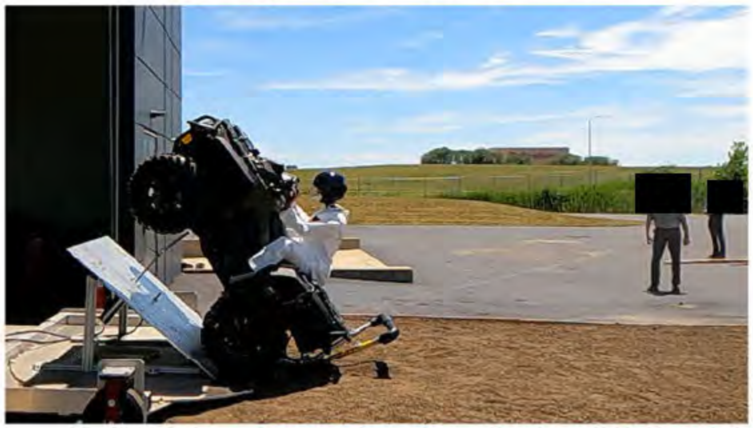




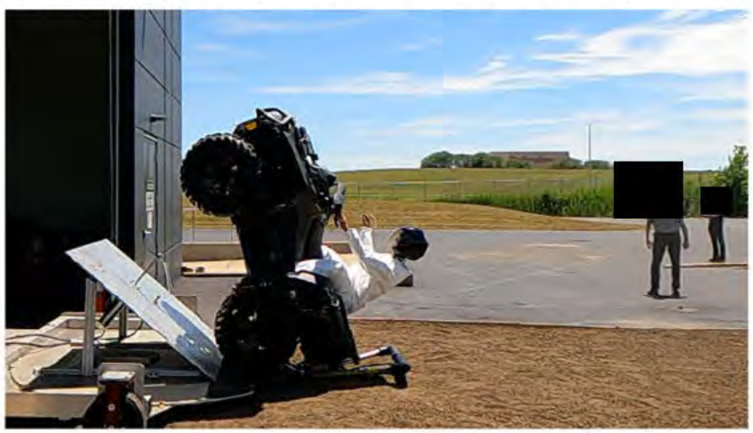
Sled Pitchover - Vehicle M - NO OPD

Start of Test - Pitch Angle = 40°

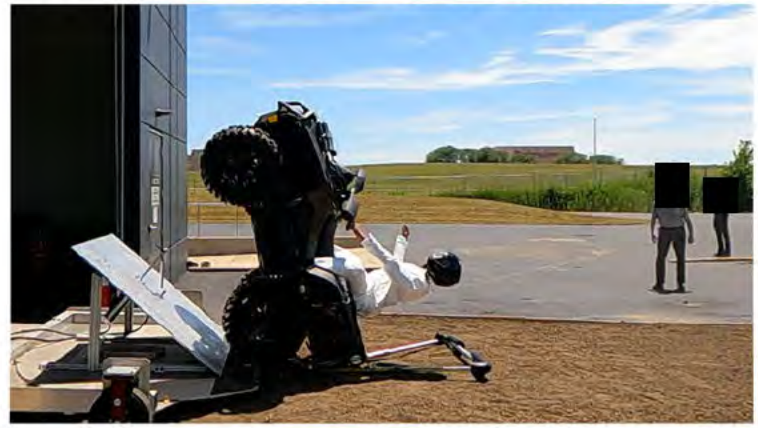
Pitch Angle = 60° - Time = 0.41 sec



OPD First Expanding - Time = 0.67 sec - Pitch Angle = 76.2°

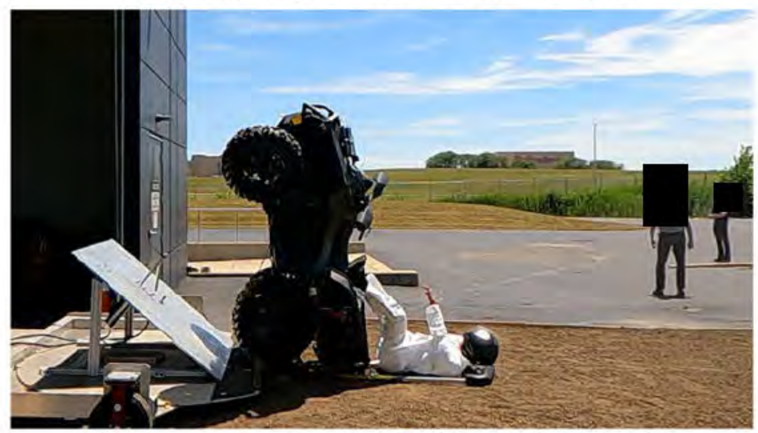


OPD Fully Expanded - Time = 0.75 sec - Pitch Angle = 77.1°



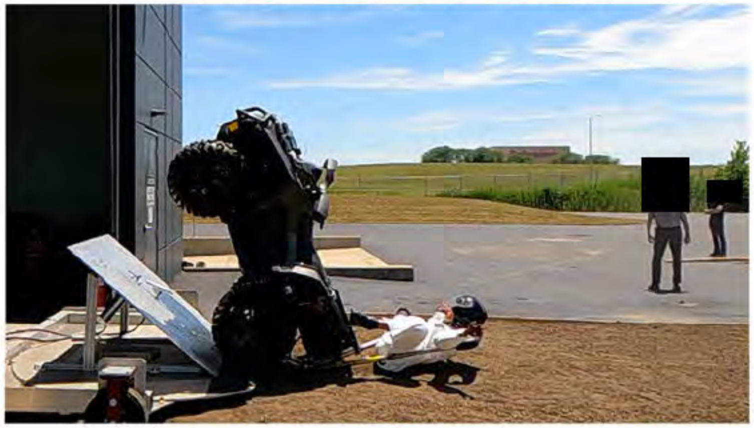
ATD Head Strike - Time = 0.88 sec

Max Pitch Angle = 82.2° - Time = 0.96 sec



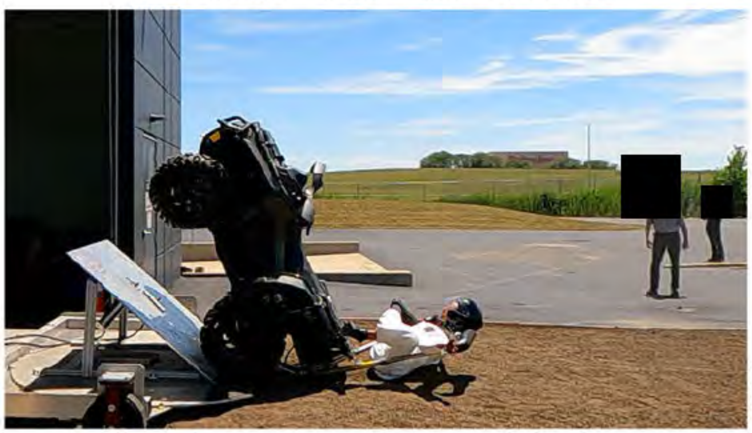
Sled Pitchover - Vehicle M - AM OPD

Pitch Angle = 61.3° - Time = 1.50 sec

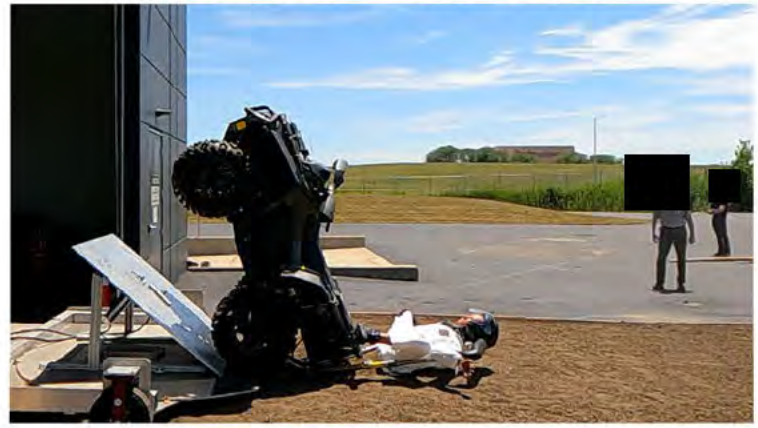


Pitch Angle = 66.5° - Time = 2.00 sec

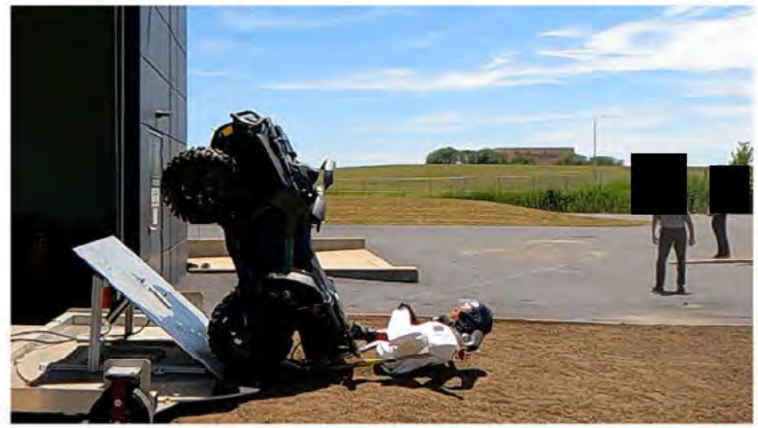
Pitch Angle = 71.0° - Time = 2.50 sec



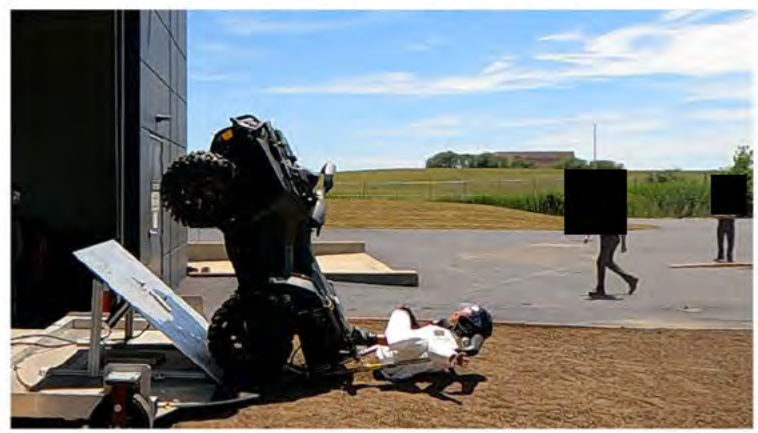
Pitch Angle = 67.8° - Time = 3.00 sec



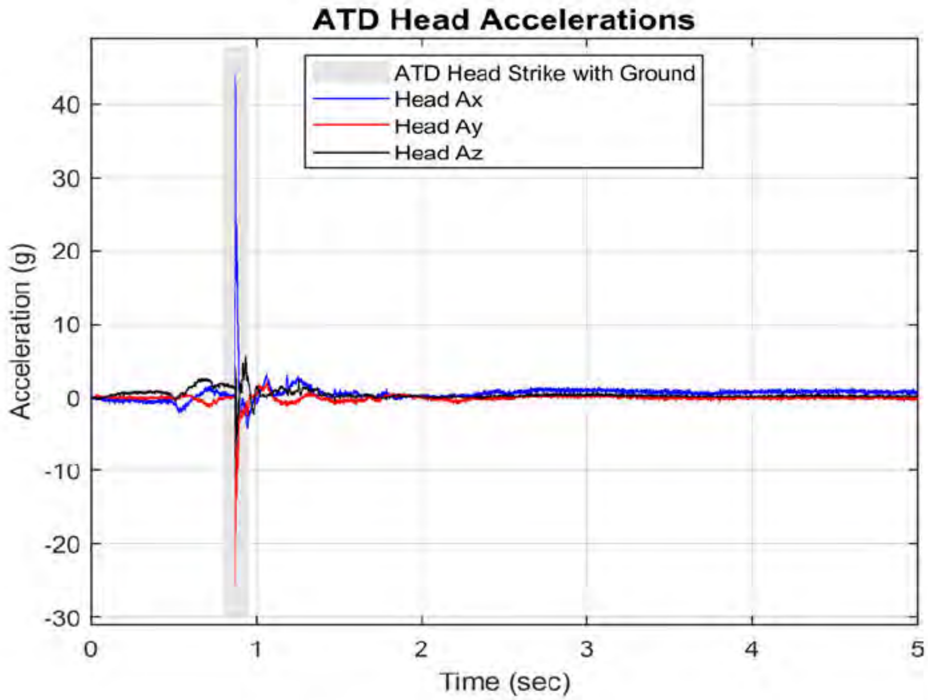
Pitch Angle = 67.4° - Time = 3.50 sec

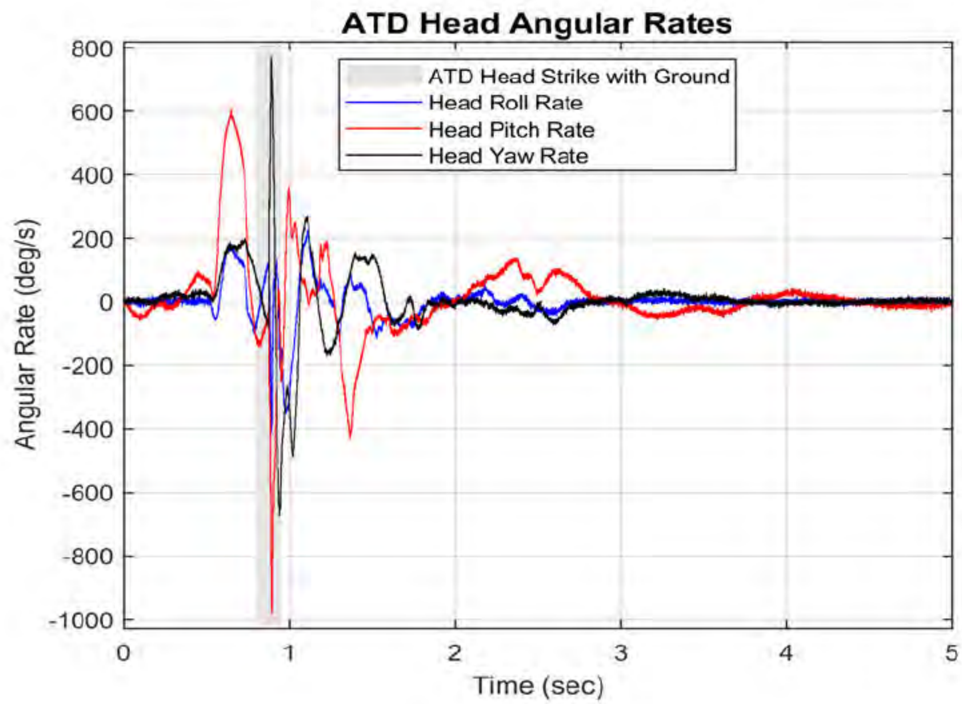


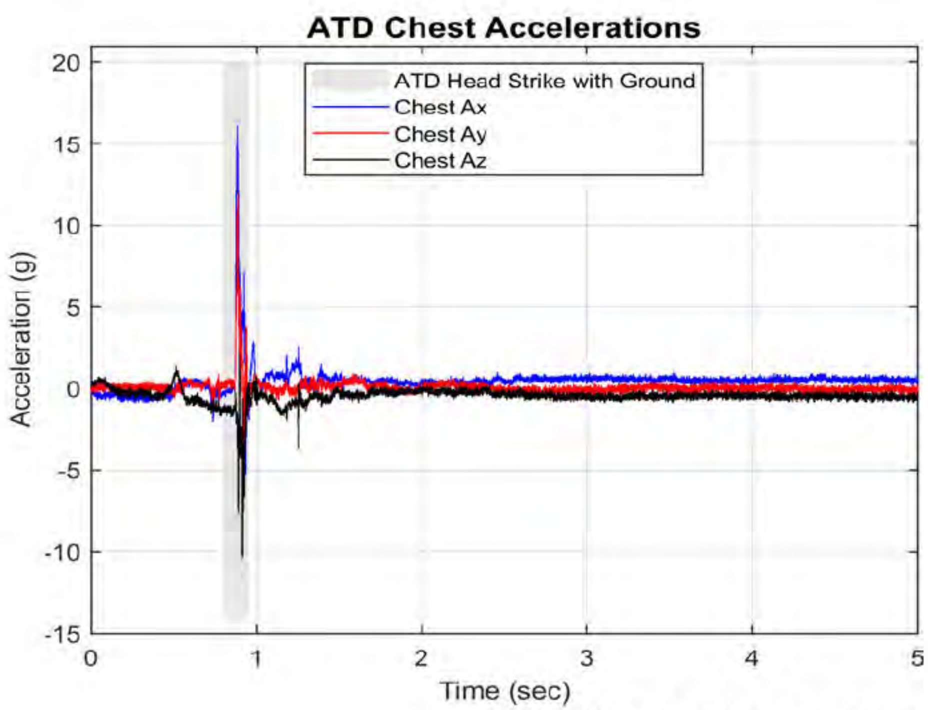
End of Run - Pitch Angle = 67.9°



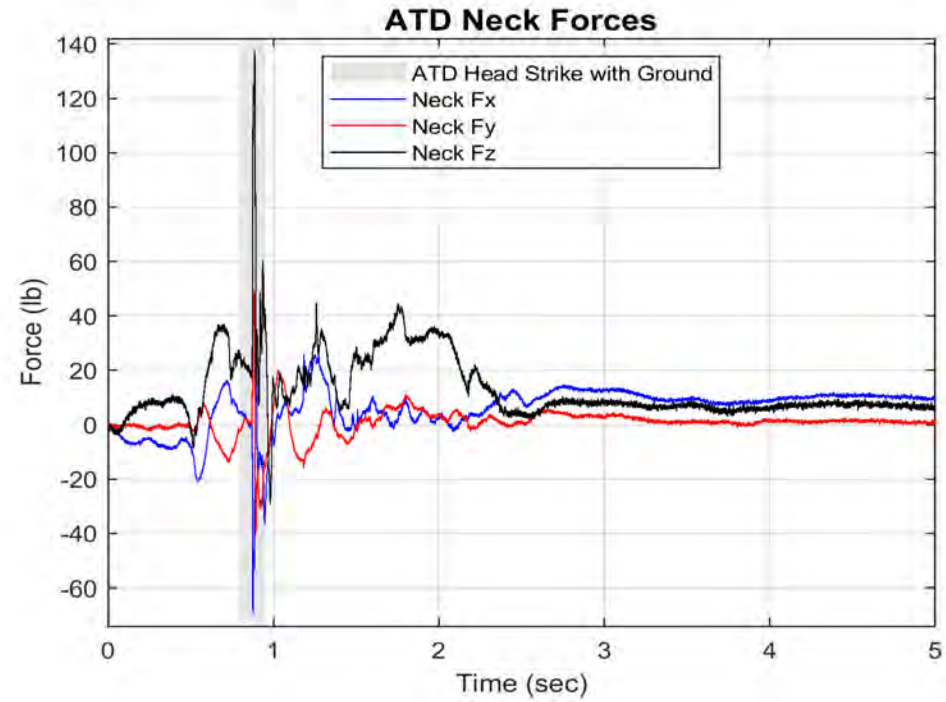
Sled Pitchover - Vehicle M - AM OPD

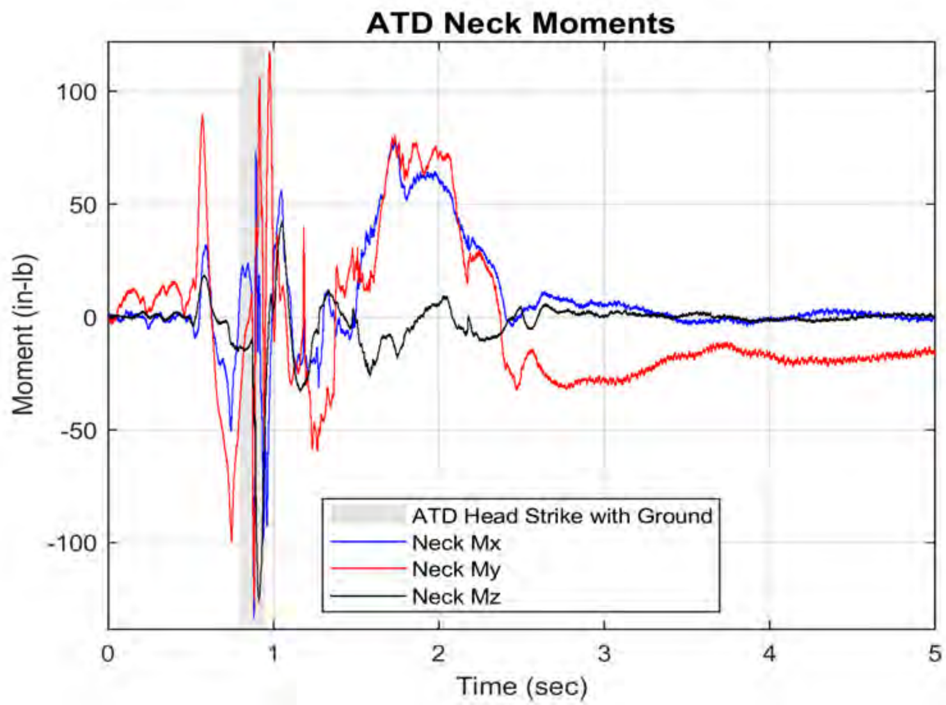




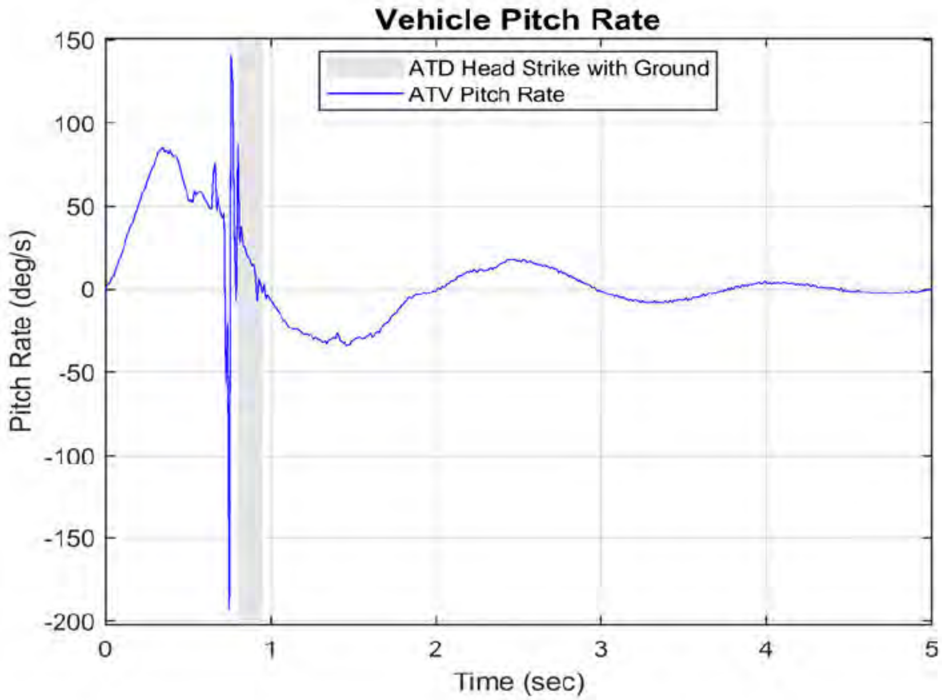


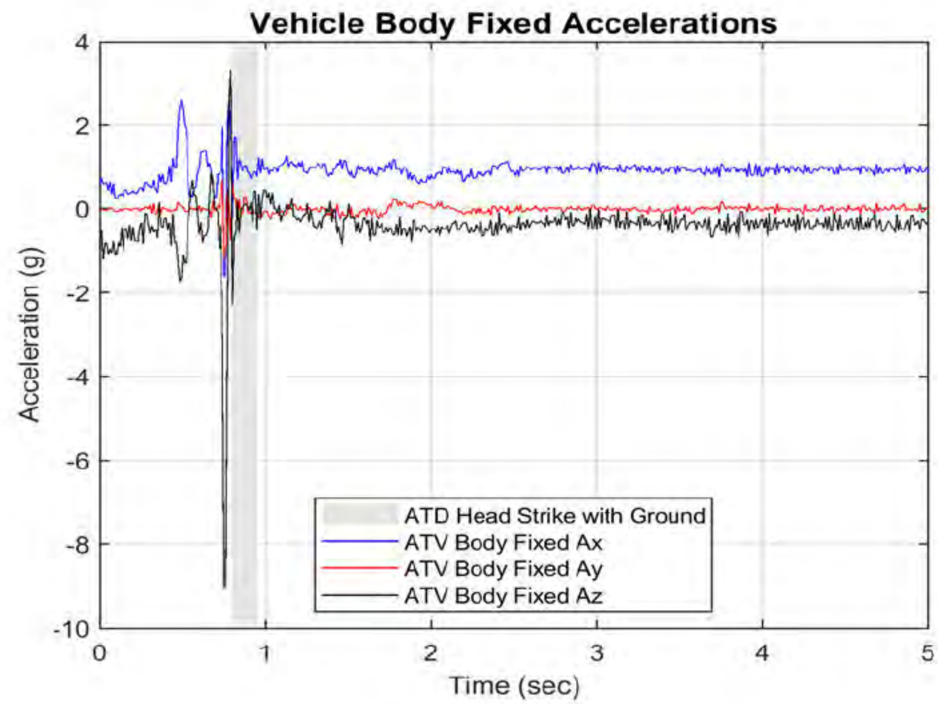
Sled Pitchover - Vehicle M - AM OPD

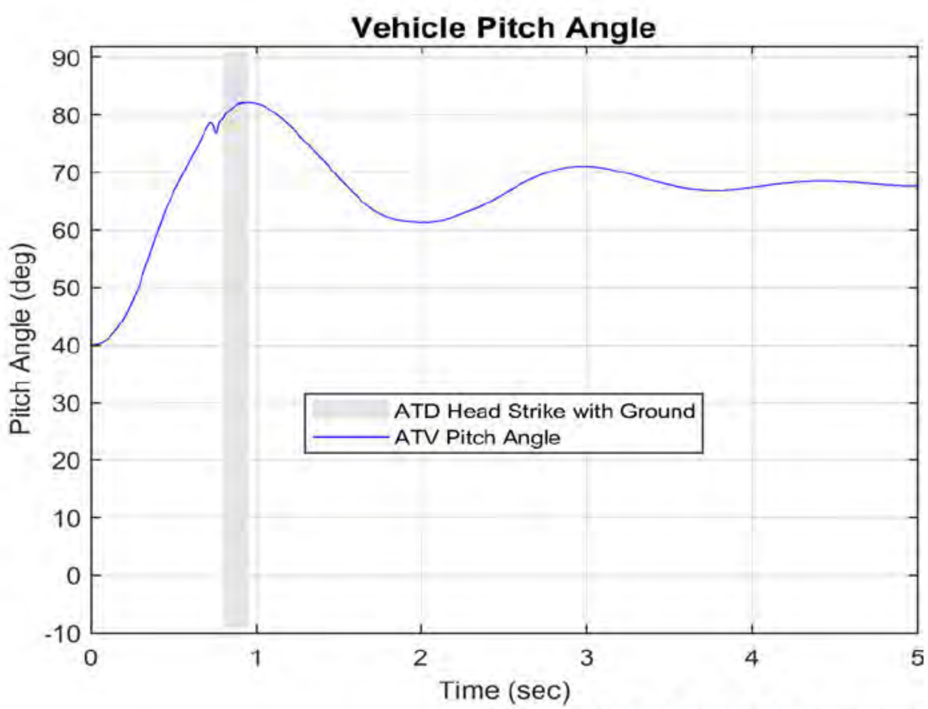




Sled Pitchover - Vehicle M - AM OPD

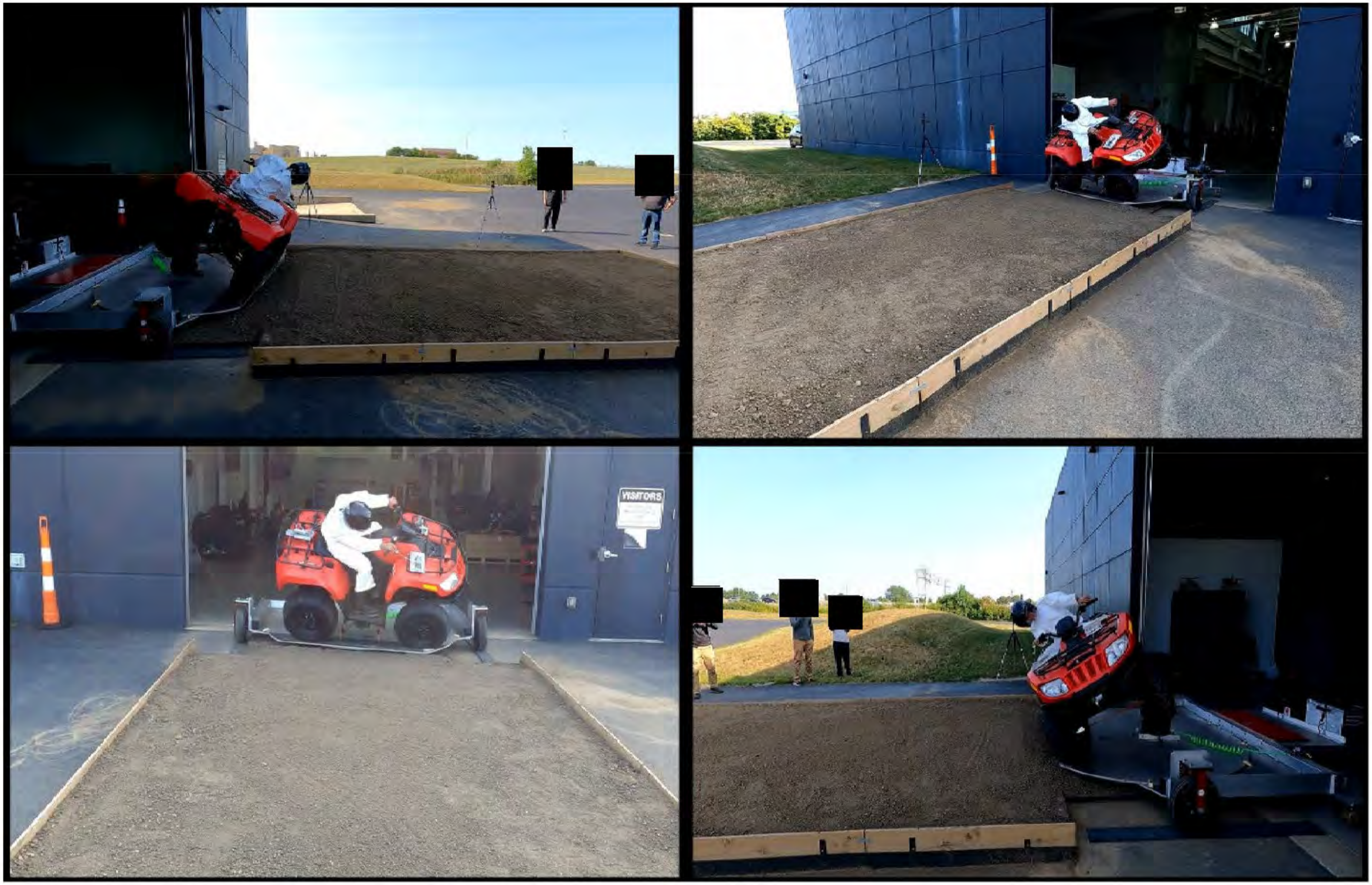






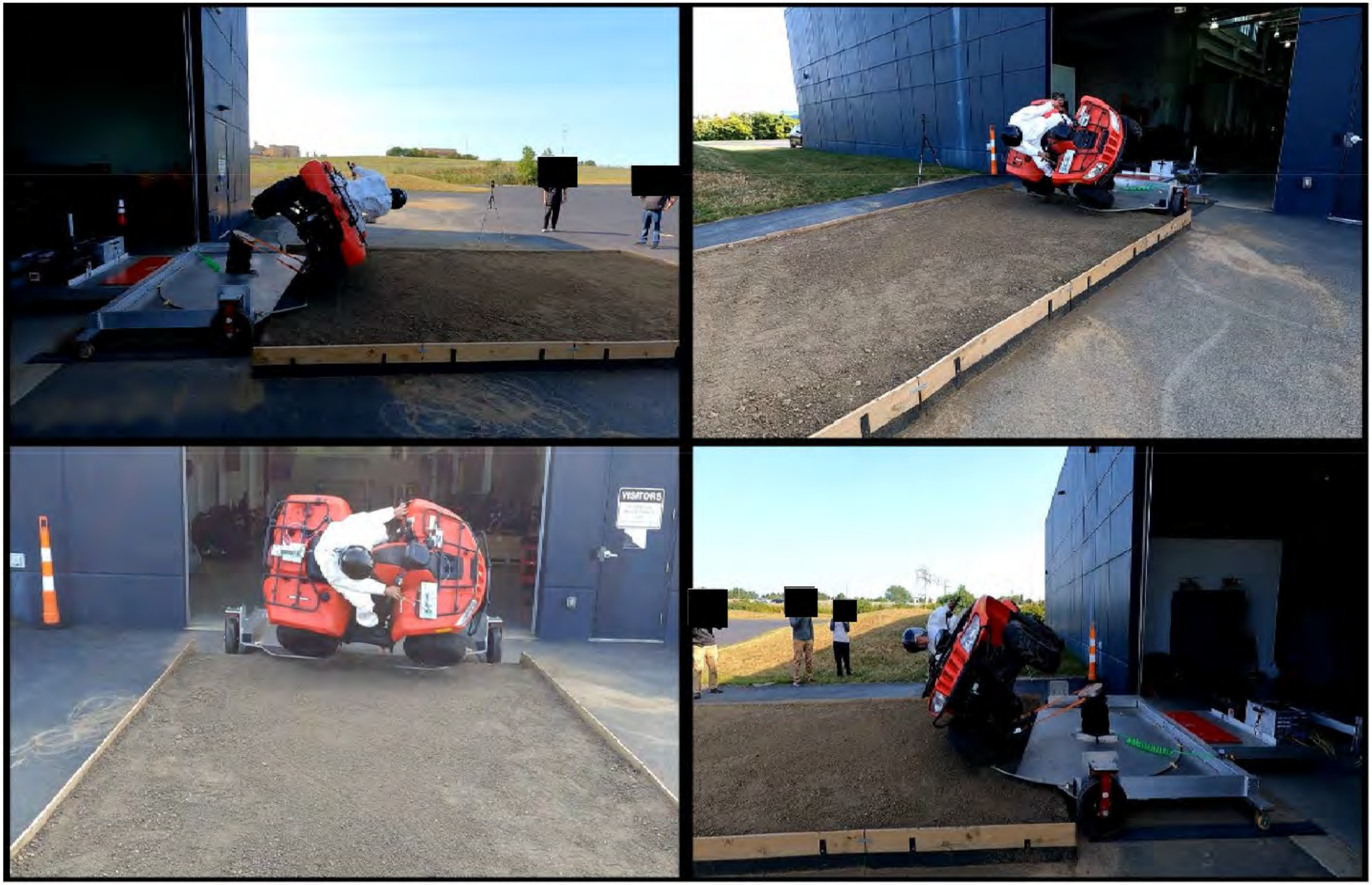
Sled Pitchover - Vehicle M - AM OPD

Roll Angle = 30° - Time = 0.69 sec



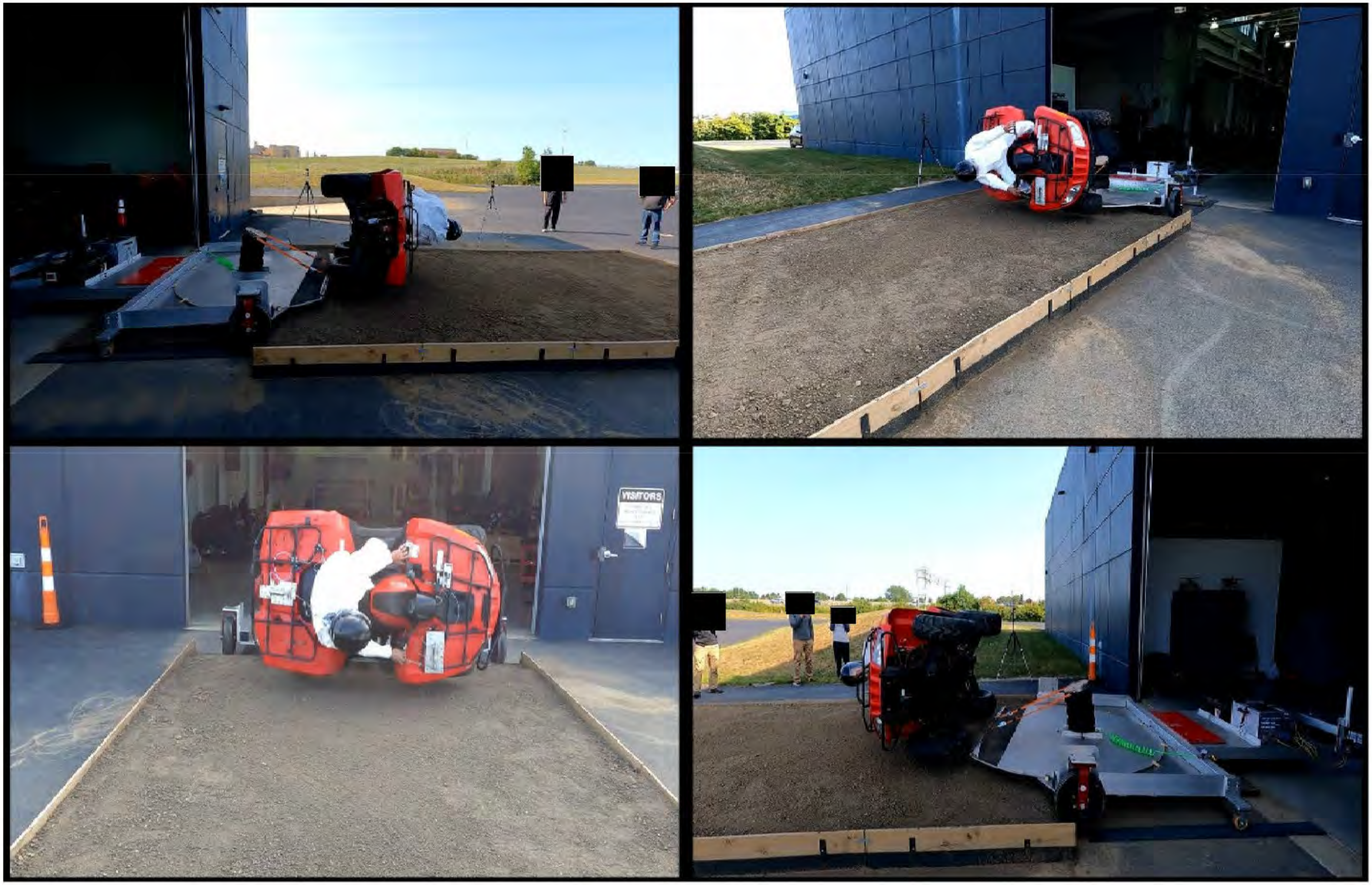
Sled Rollover - Vehicle E - NO OPD

Roll Angle = 60° - Time = 0.98 sec



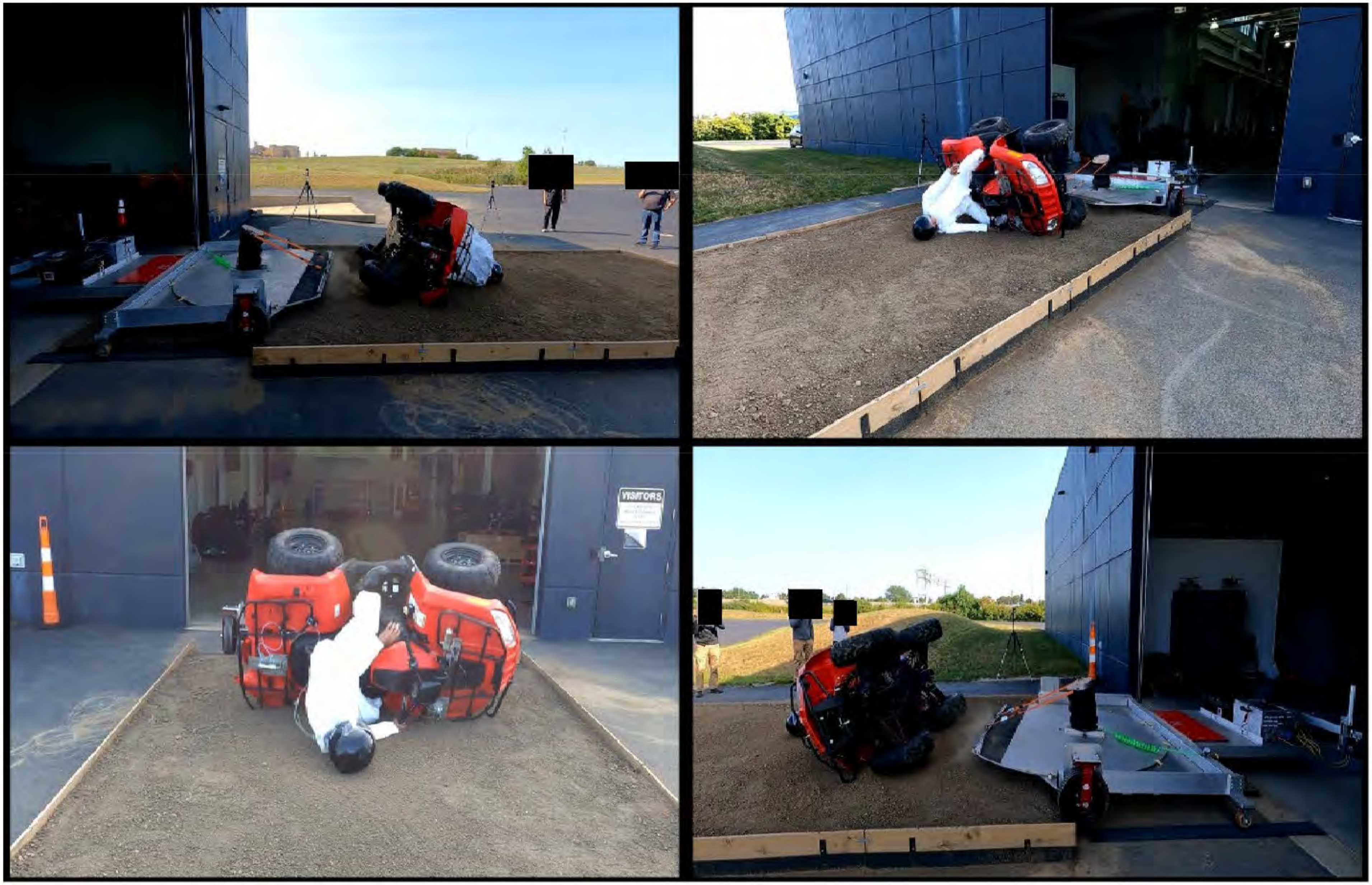
Sled Rollover - Vehicle E - NO OPD

Roll Angle = 90° - Time = 1.16 sec



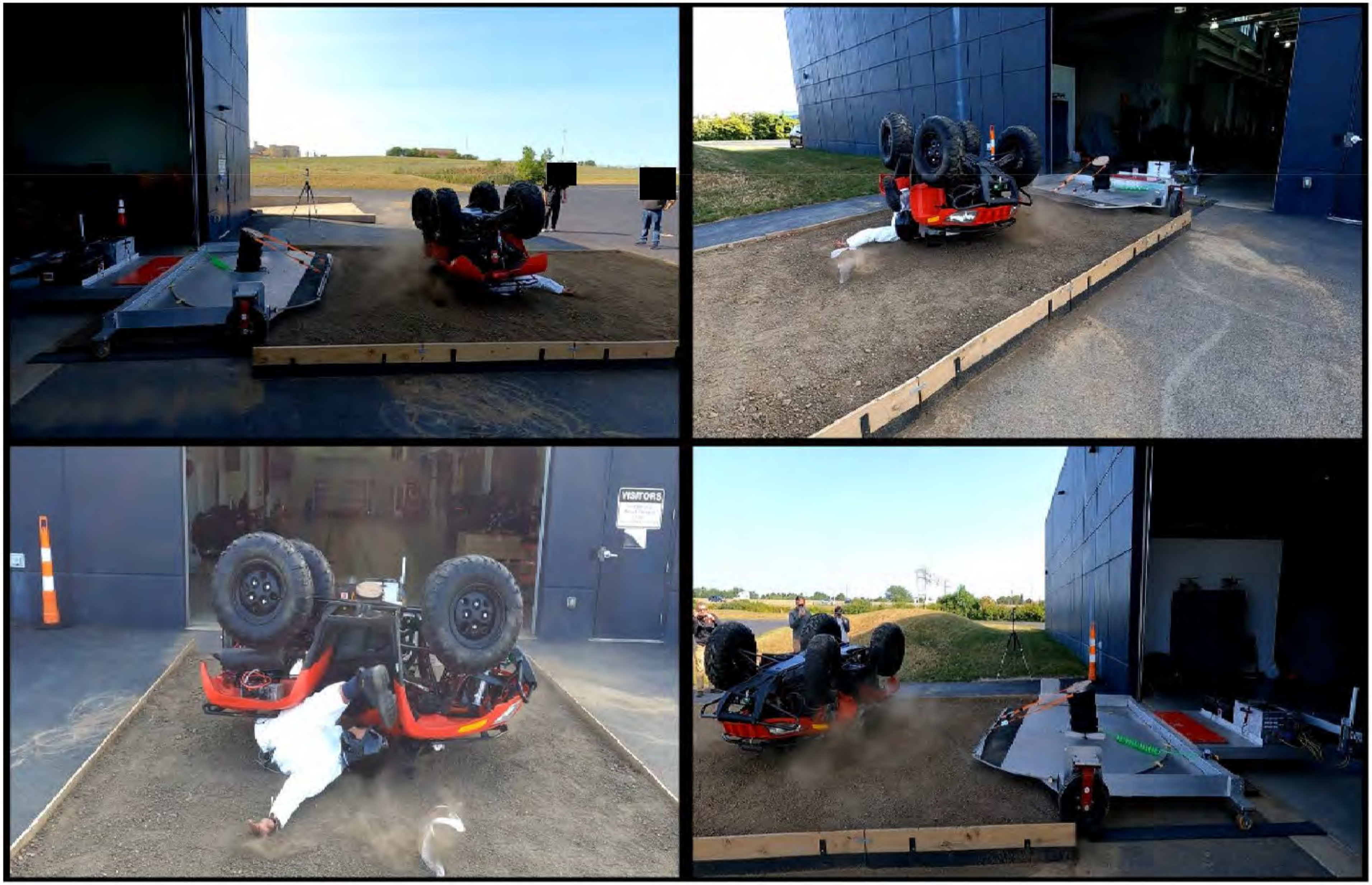
Sled Rollover - Vehicle E - NO OPD

ATD Head Strike - Time = 1.31 sec



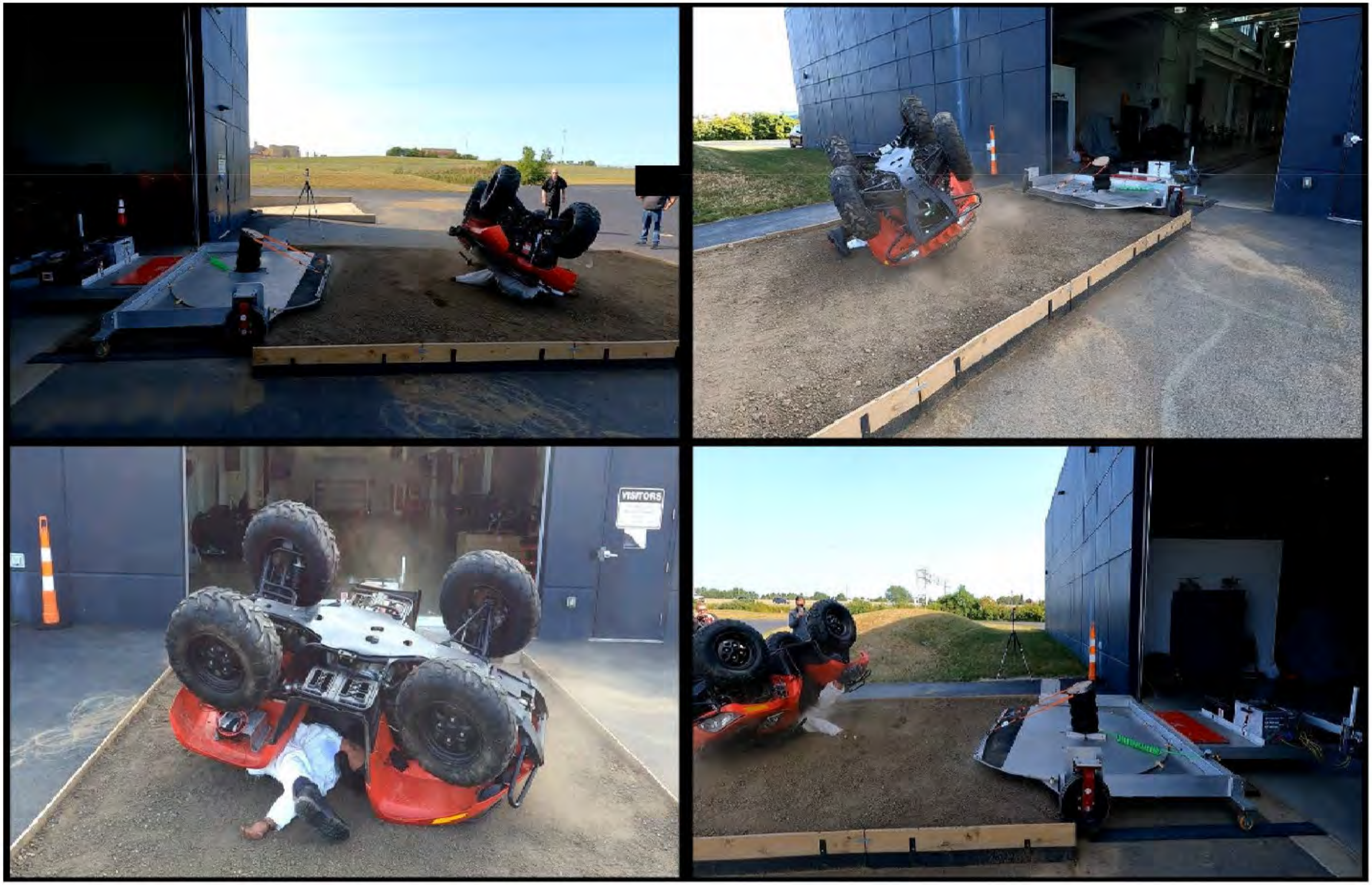
Sled Rollover - Vehicle E - NO OPD

Roll Angle = 180° - Time = 1.78 sec



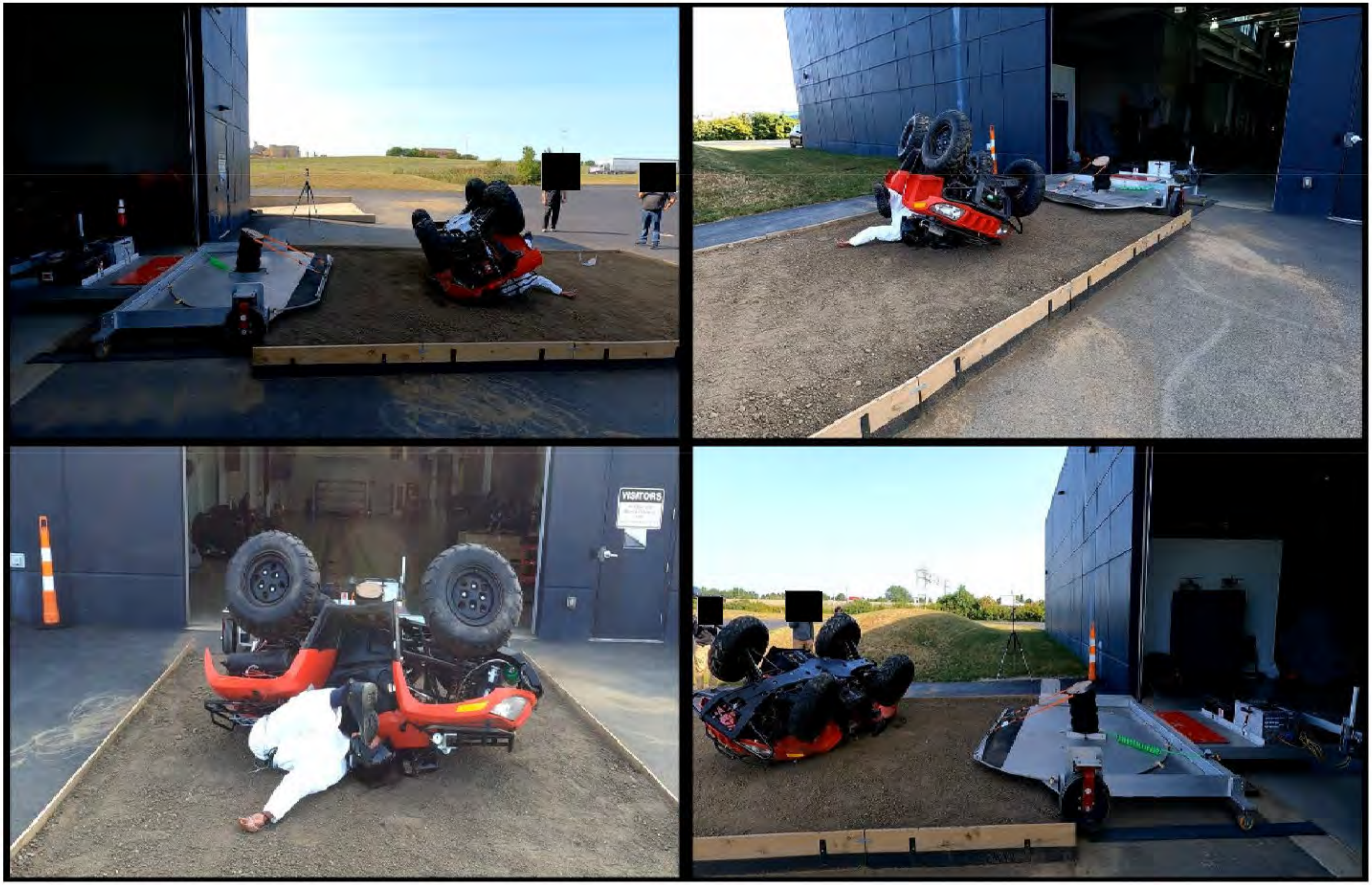
Sled Rollover - Vehicle E - NO OPD

Max Roll Angle = 206.4° - Time = 2.33 sec

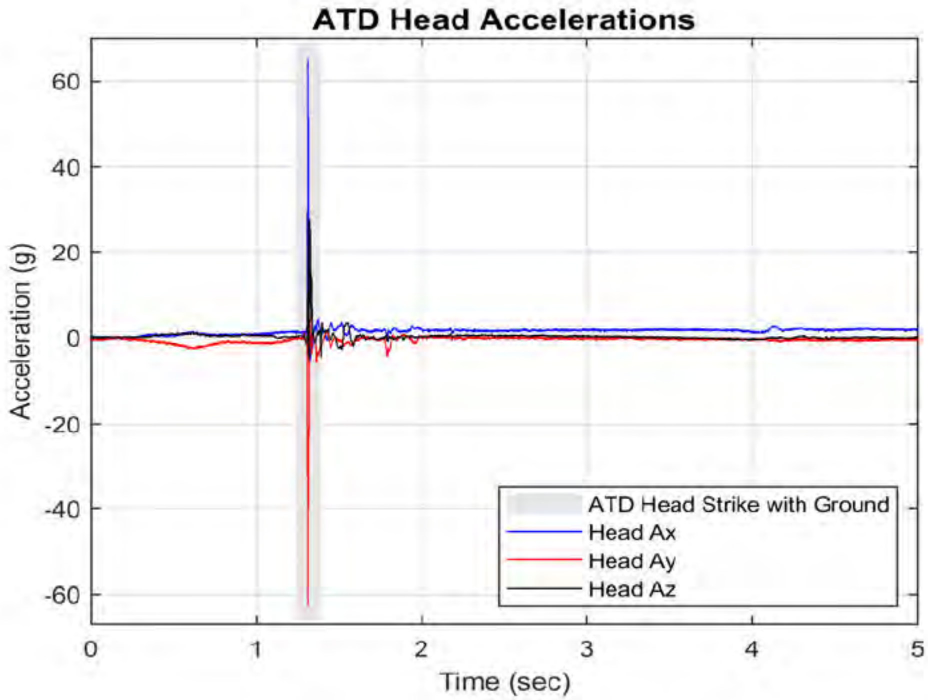


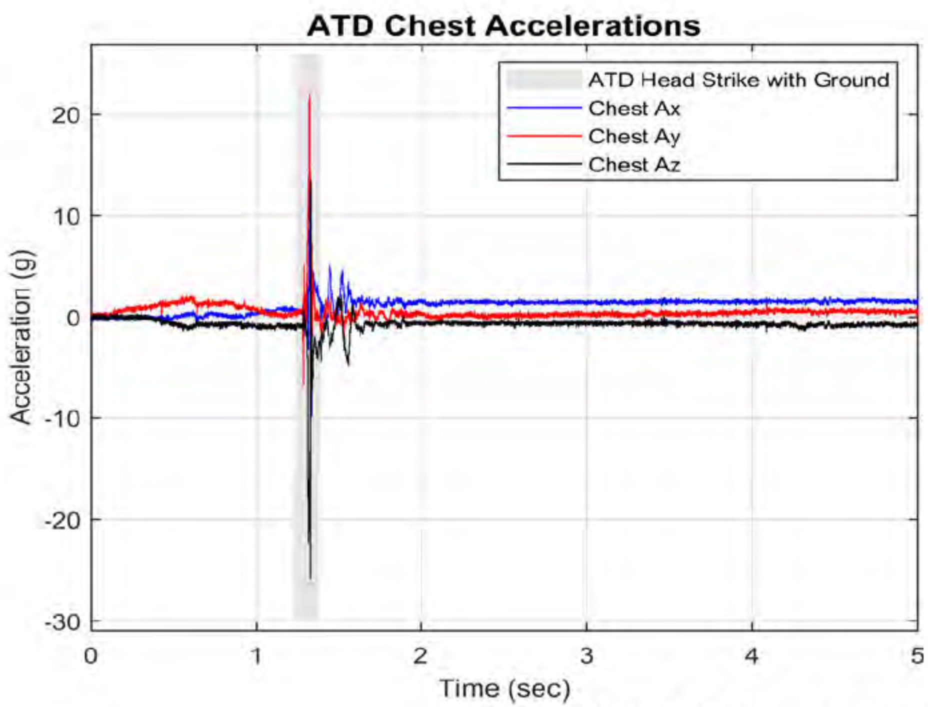
Sled Rollover - Vehicle E - NO OPD

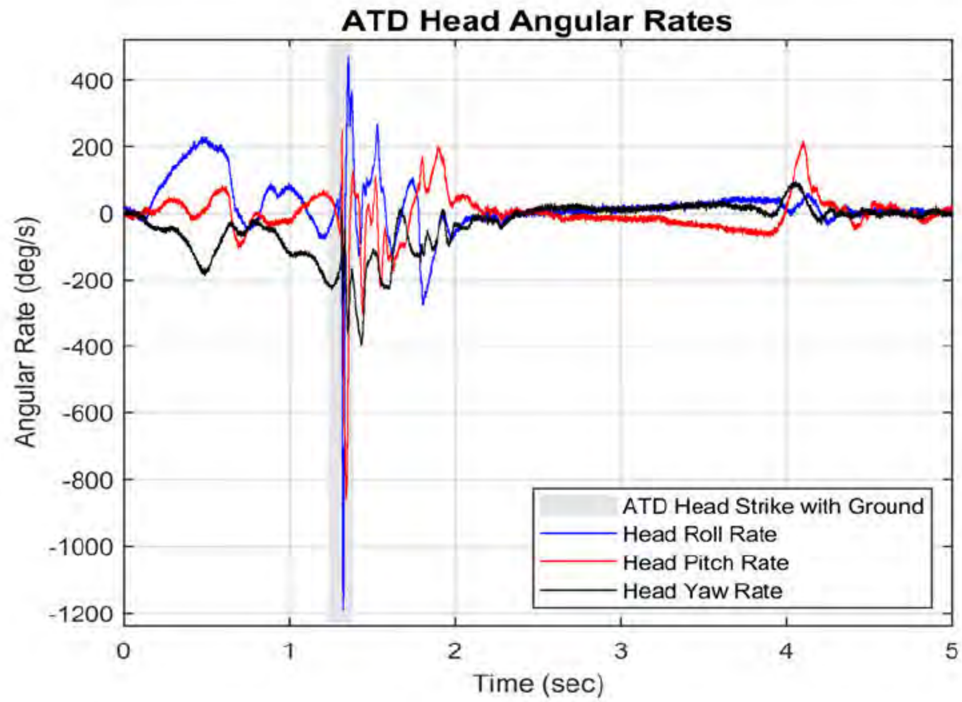
End of Run - Roll Angle = 153.8°



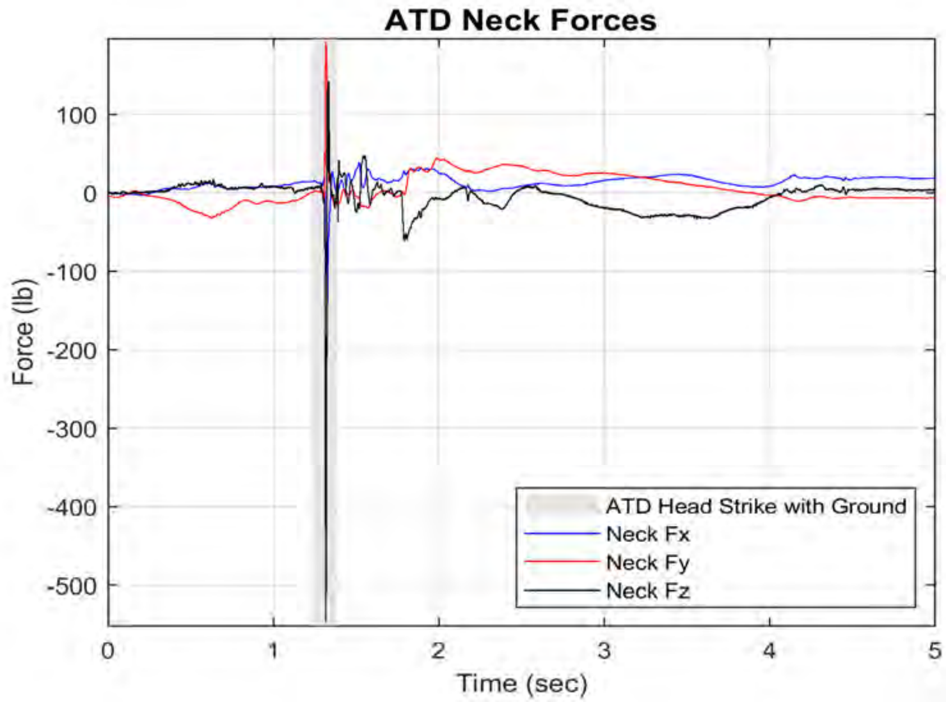
Sled Rollover - Vehicle E - NO OPD

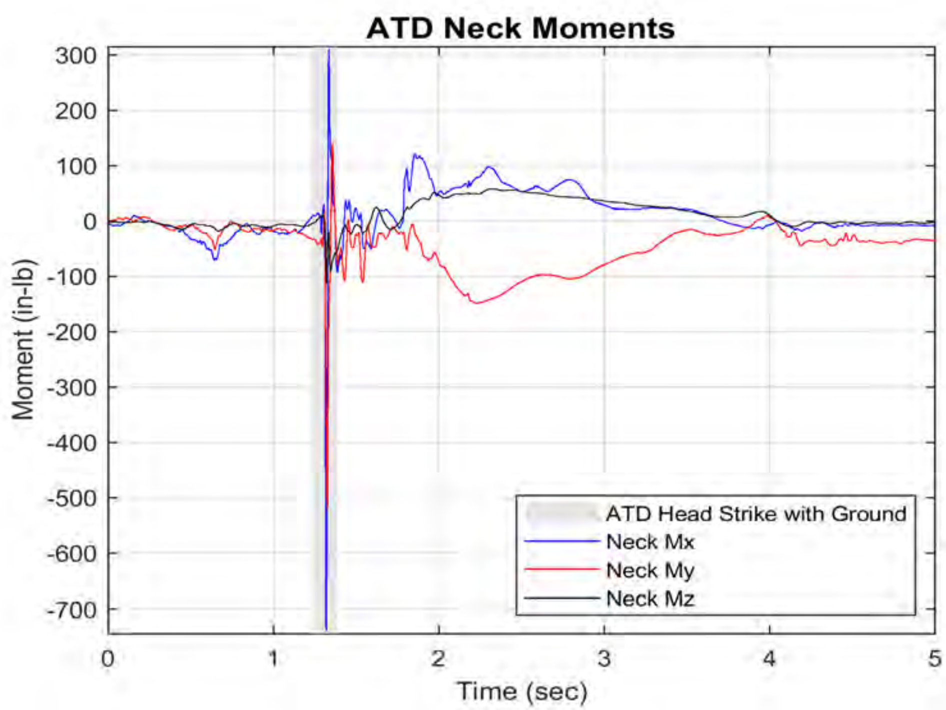




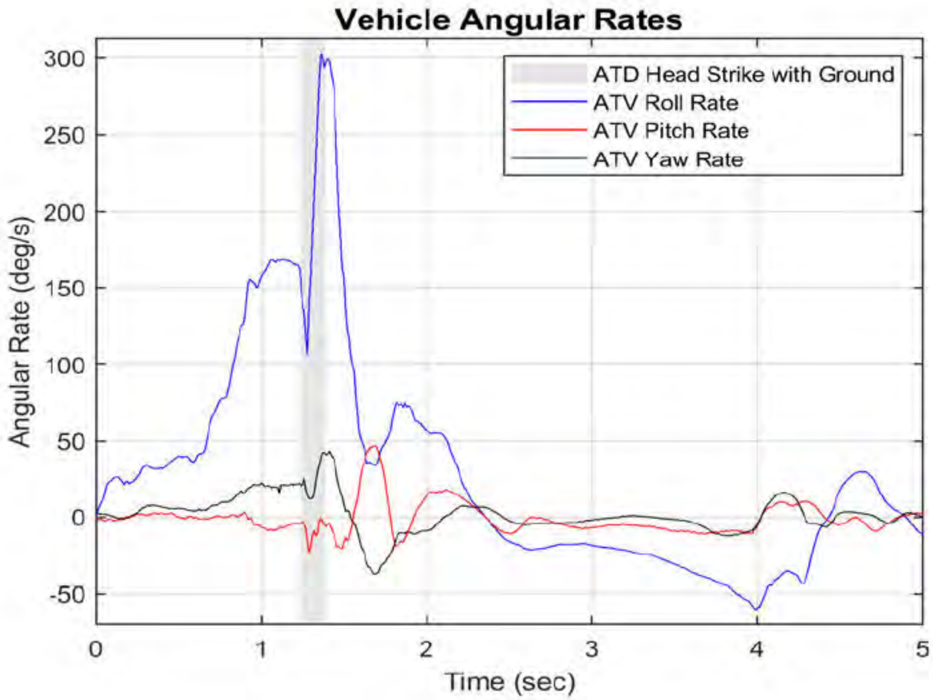


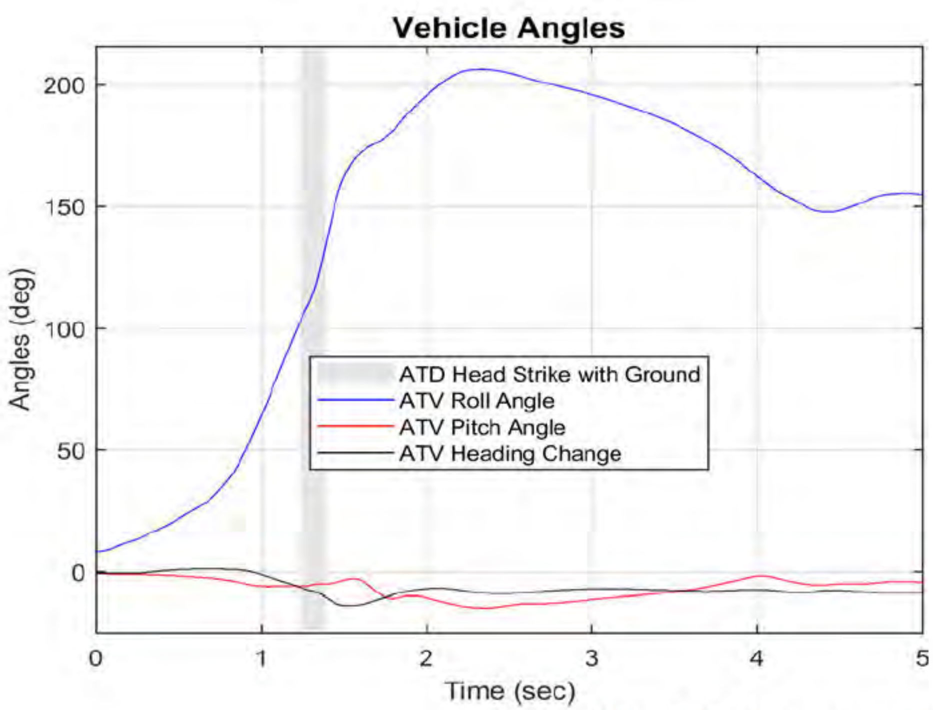
Sled Rollover - Vehicle E - NO OPD

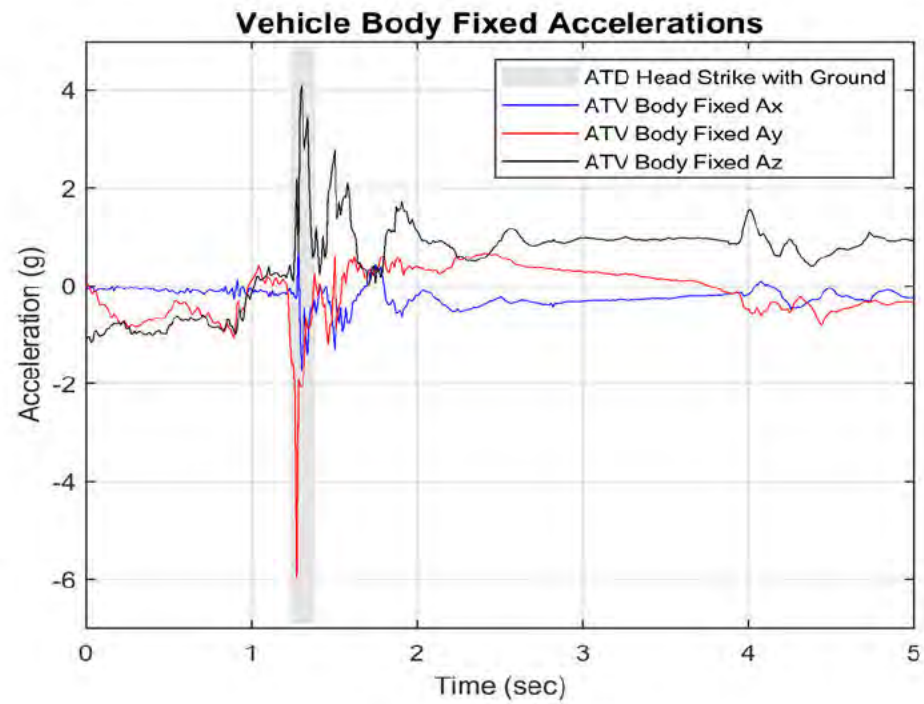




Sled Rollover - Vehicle E - NO OPD

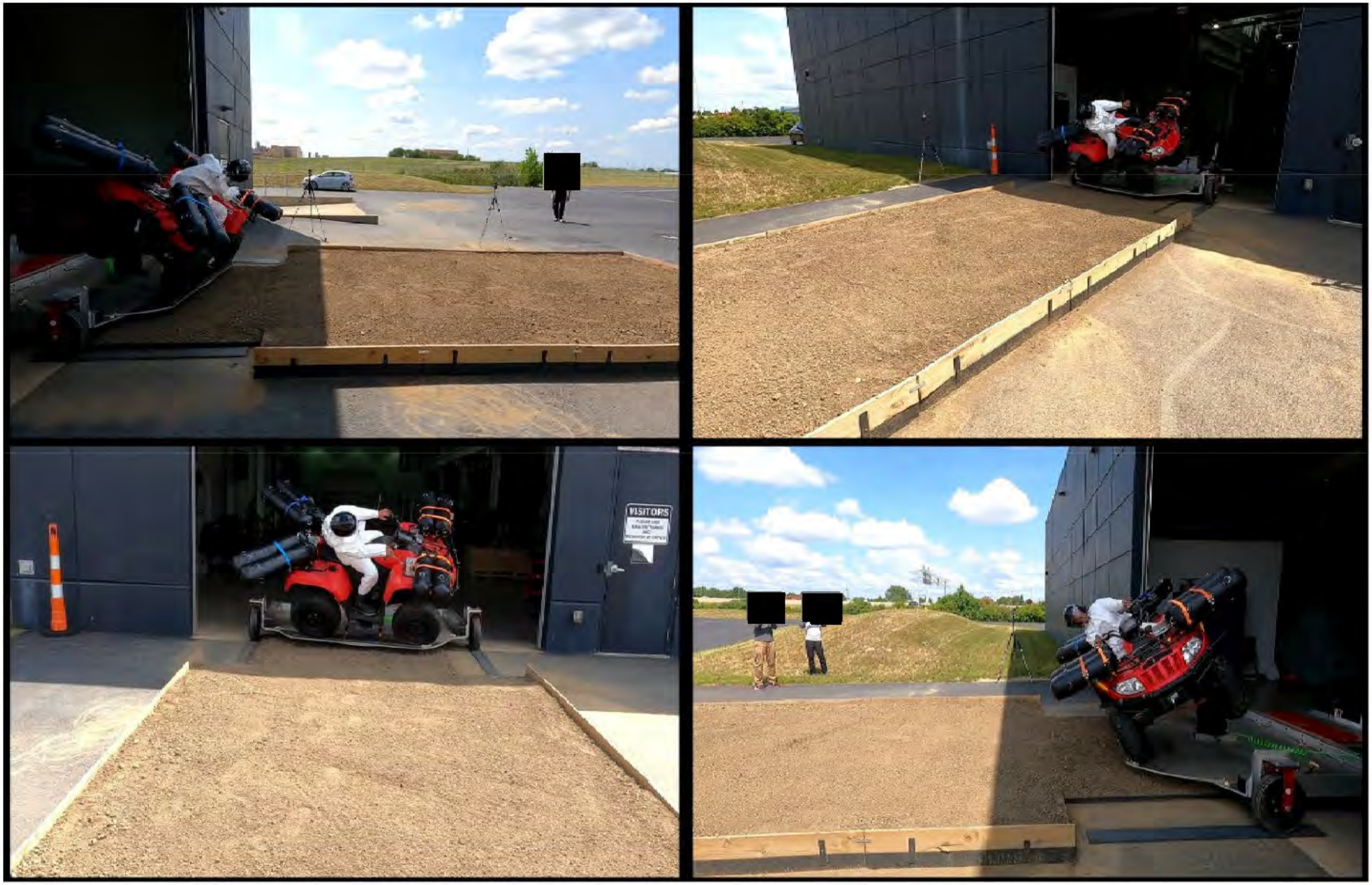






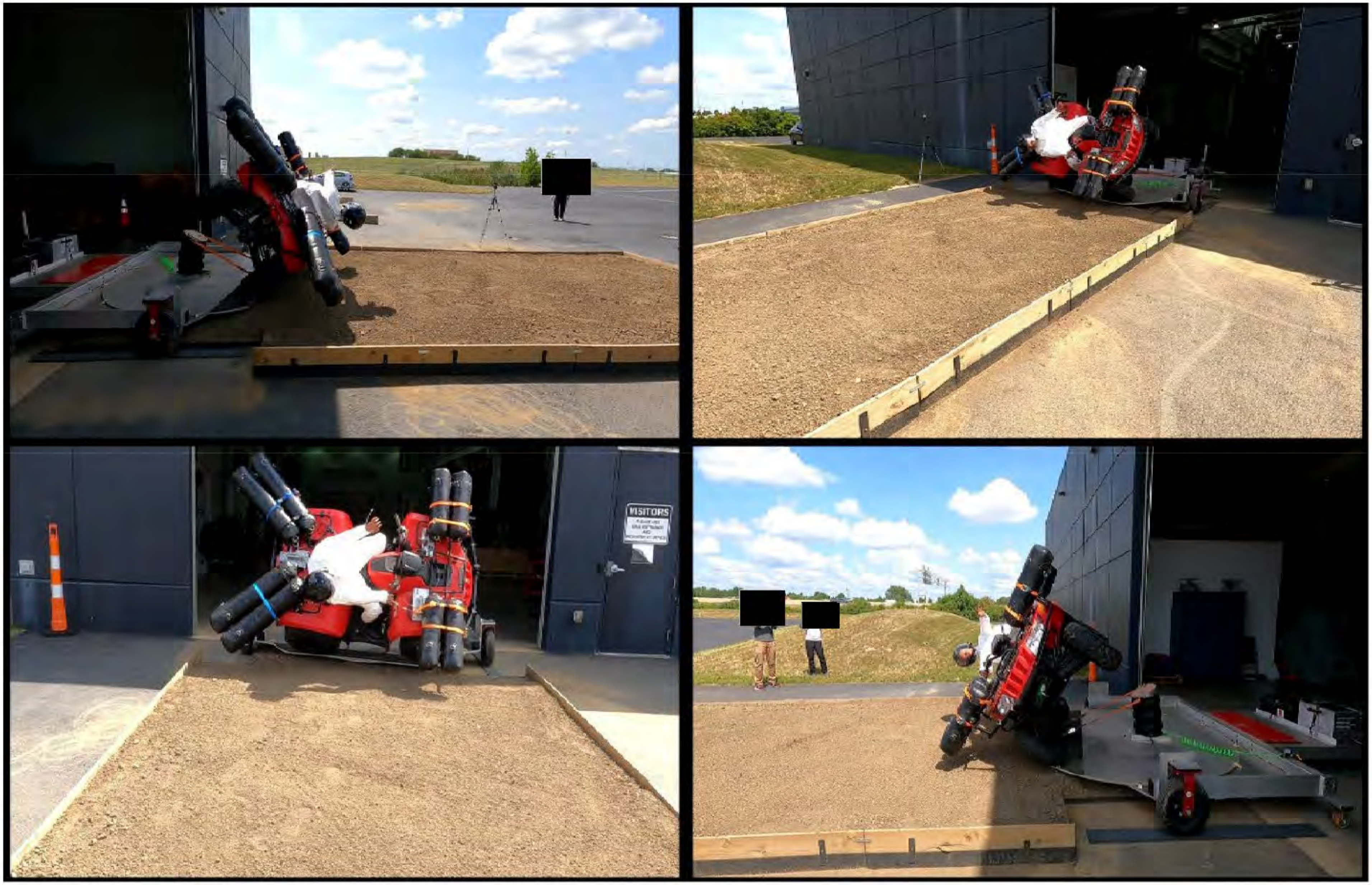
Sled Rollover - Vehicle E - NO OPD

Roll Angle = 30° - Time = 0.64 sec



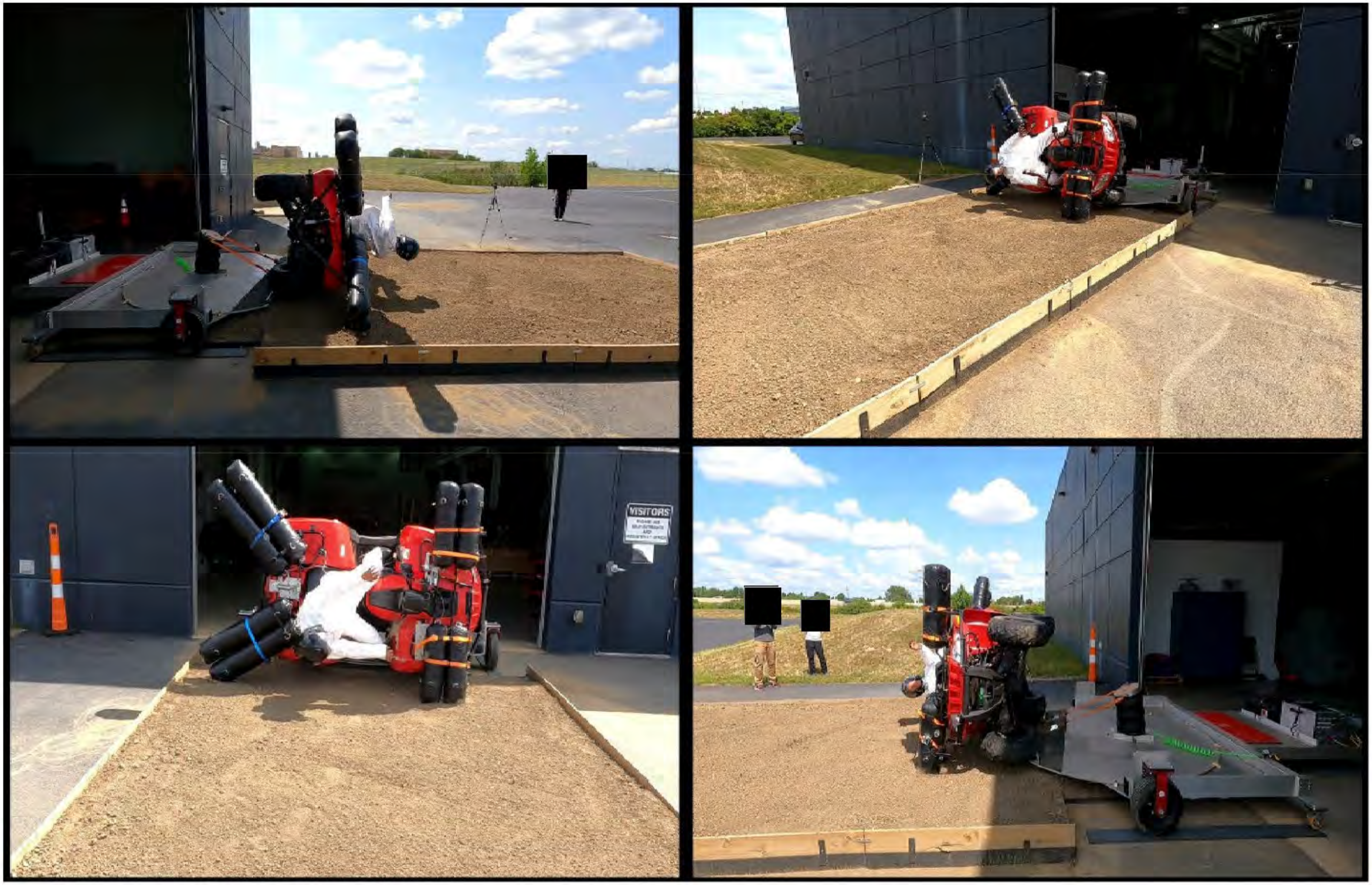
Sled Rollover - Vehicle E - OPD #1

Roll Angle = 60° - Time = 0.91 sec



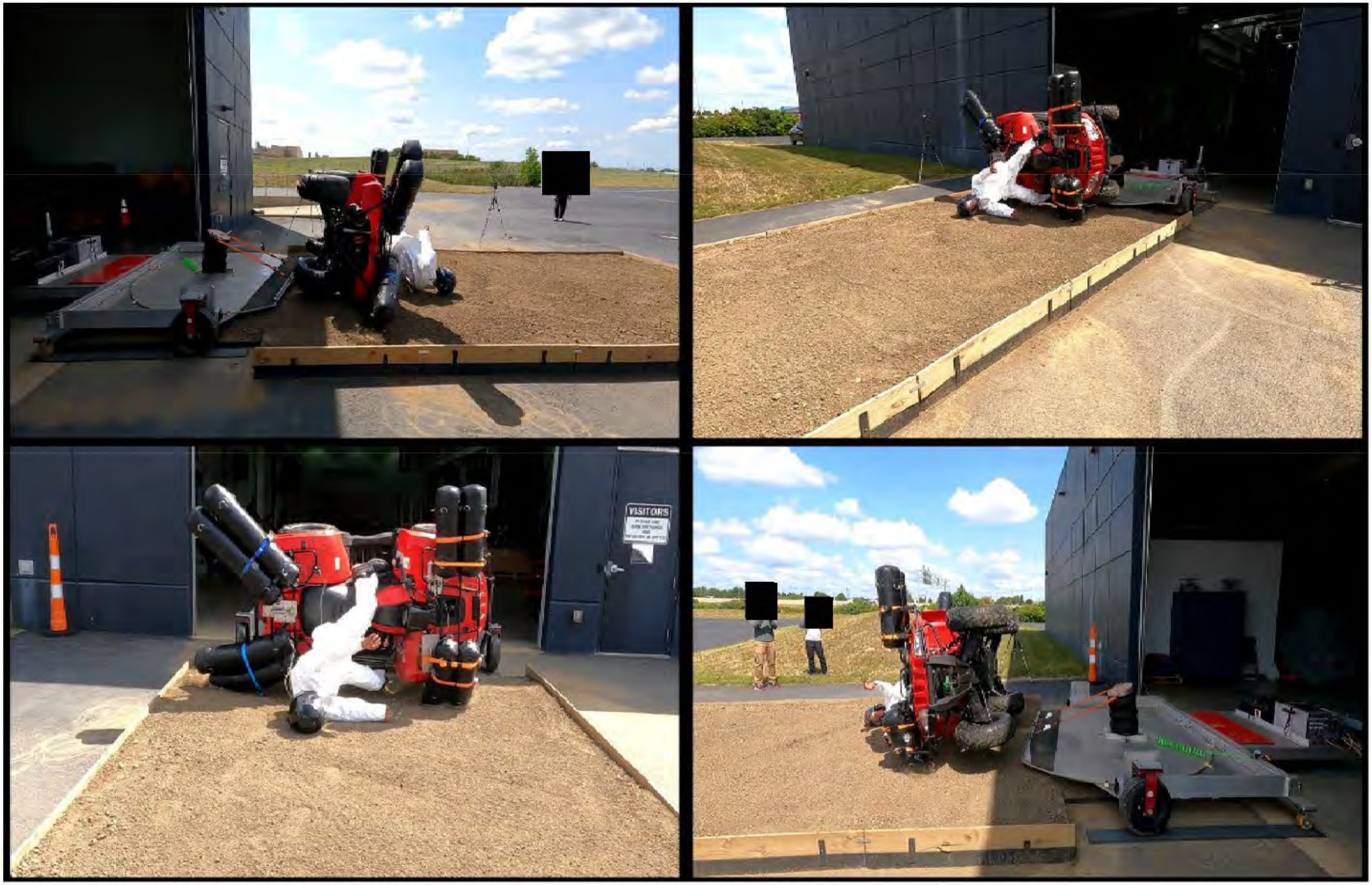
Sled Rollover - Vehicle E - OPD #1

Roll Angle = 90° - Time = 1.09 sec



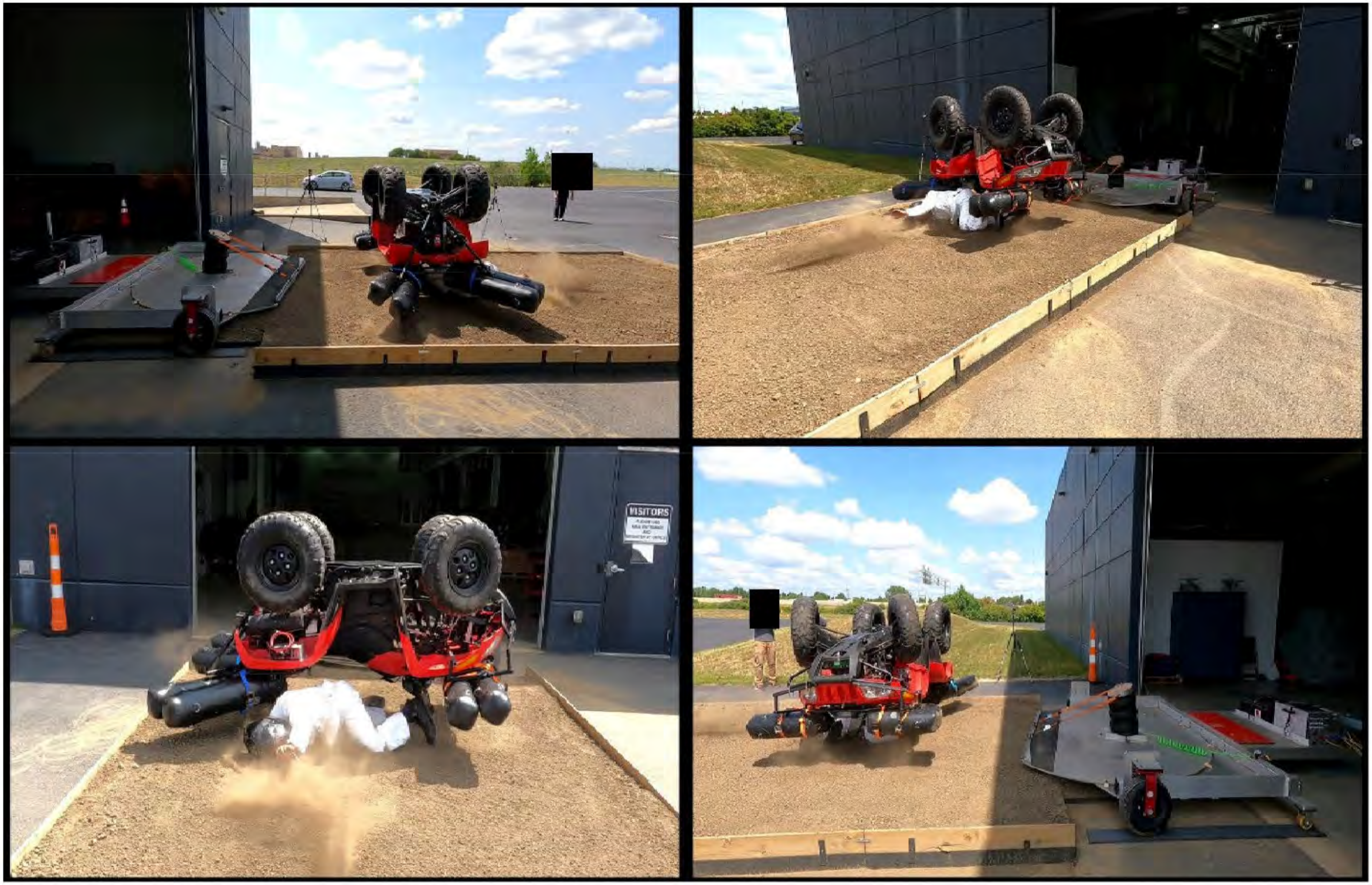
Sled Rollover - Vehicle E - OPD #1

ATD Head Strike - Time = 1.25 sec



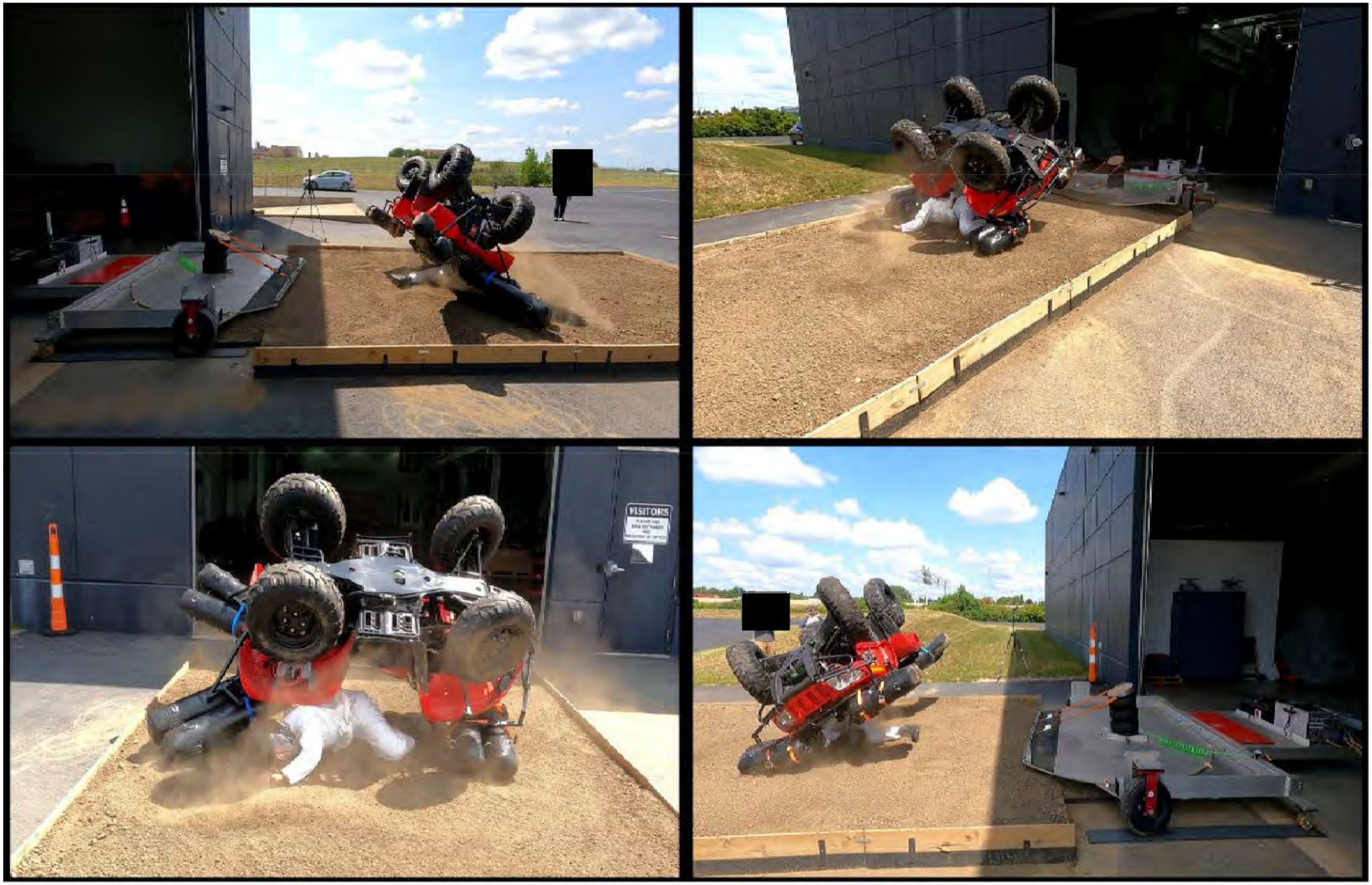
Sled Rollover - Vehicle E - OPD #1

Roll Angle = 180° - Time = 1.55 sec



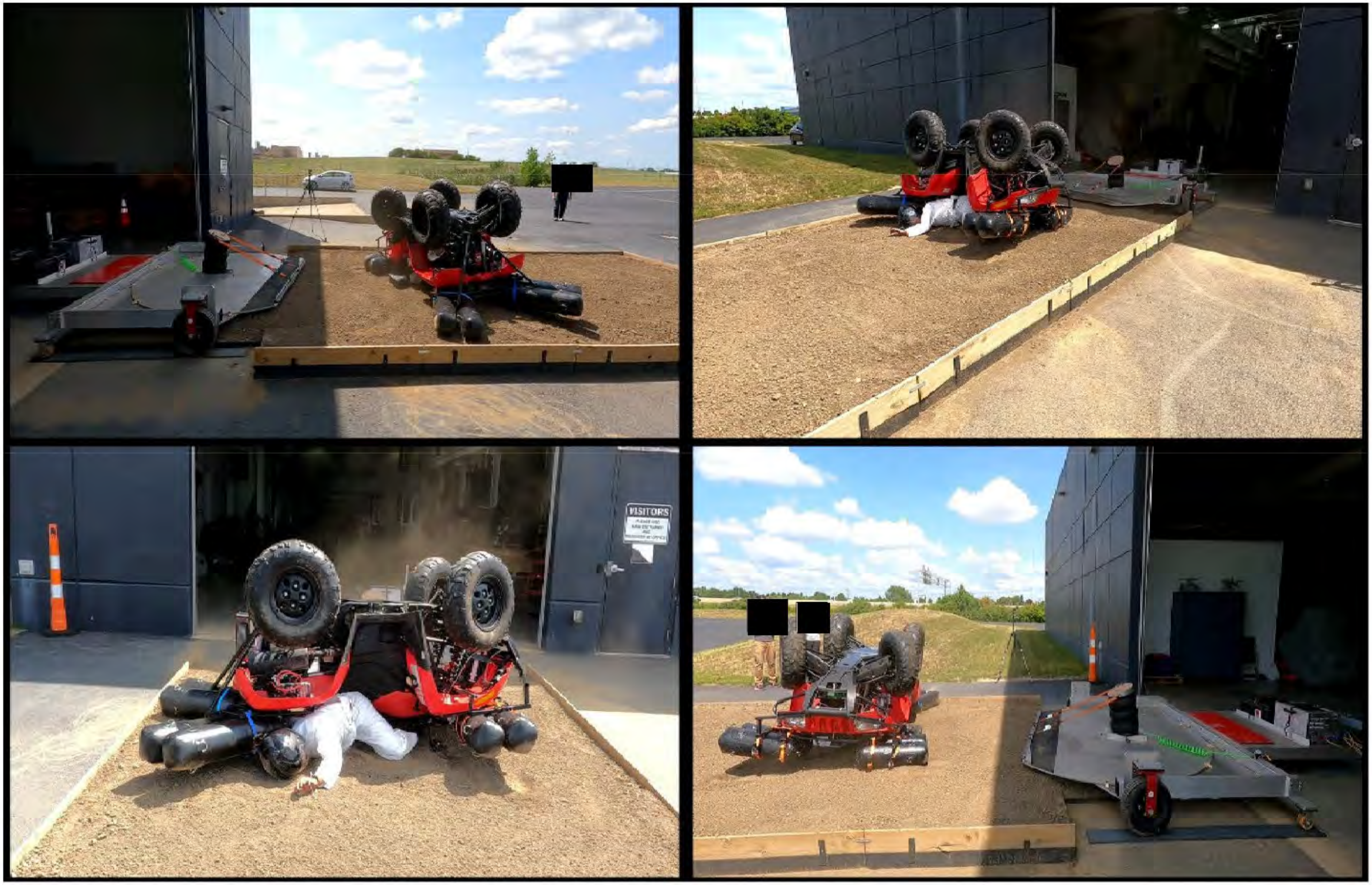
Sled Rollover - Vehicle E - OPD #1

Max Roll Angle = 211.2° - Time = 1.80 sec

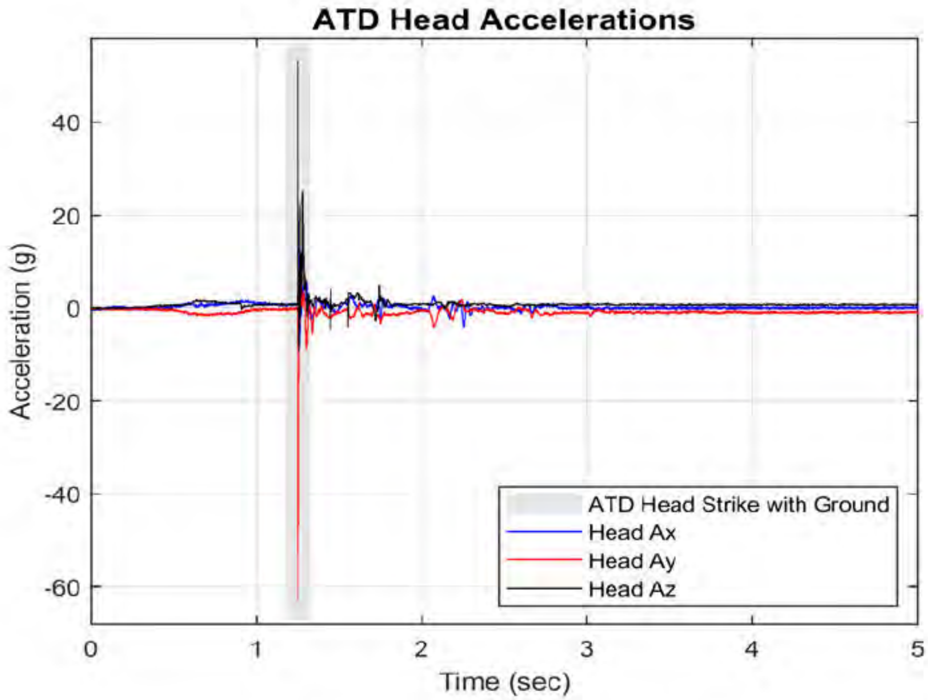


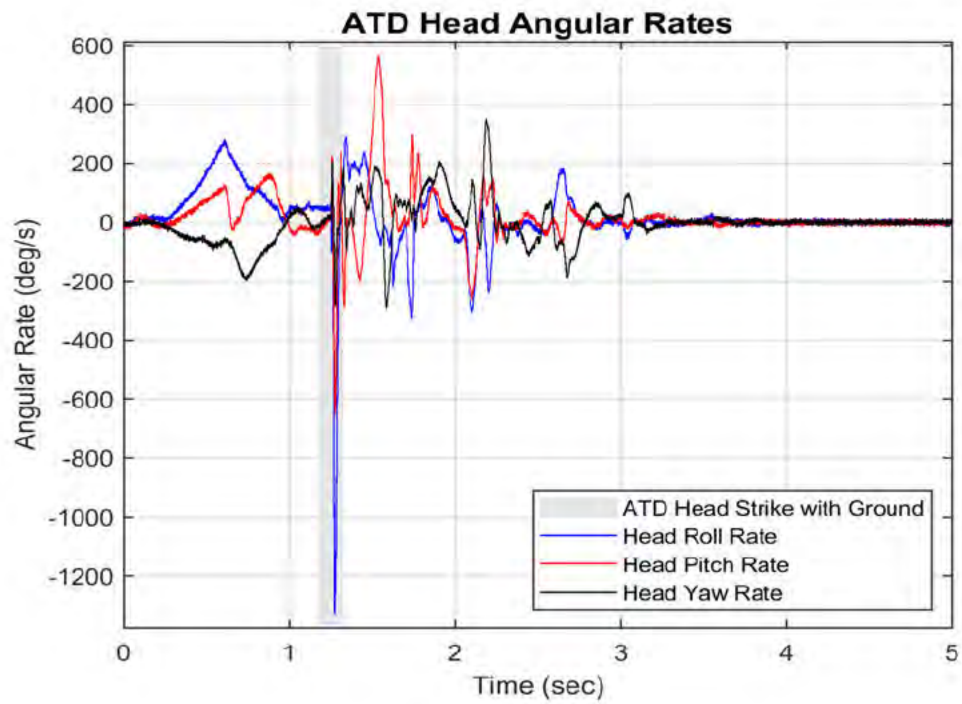
Sled Rollover - Vehicle E - OPD #1

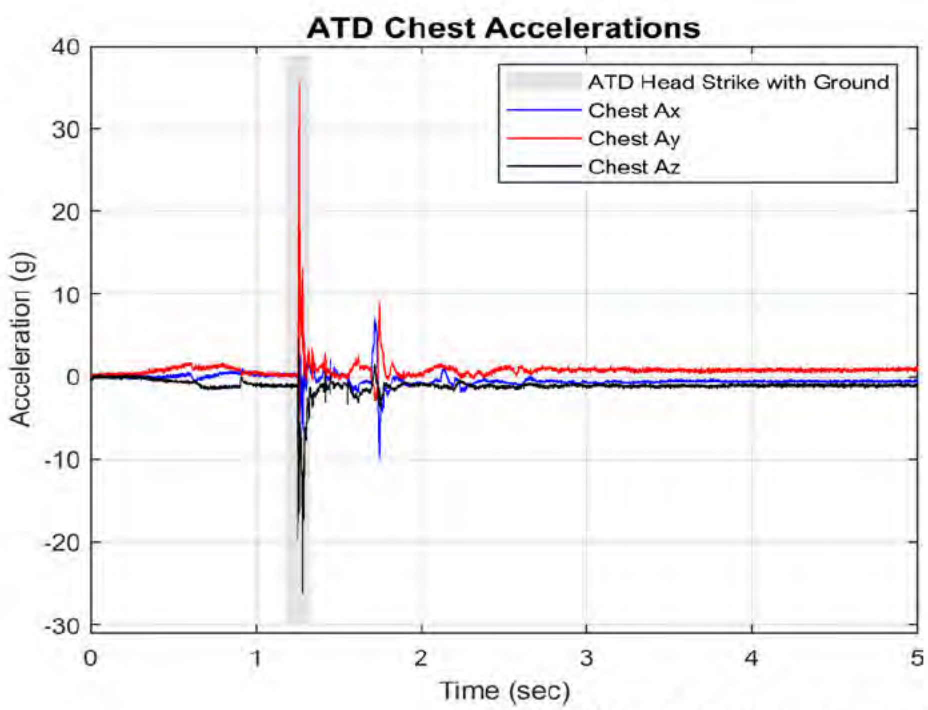
End of Run - Roll Angle = 175.0°



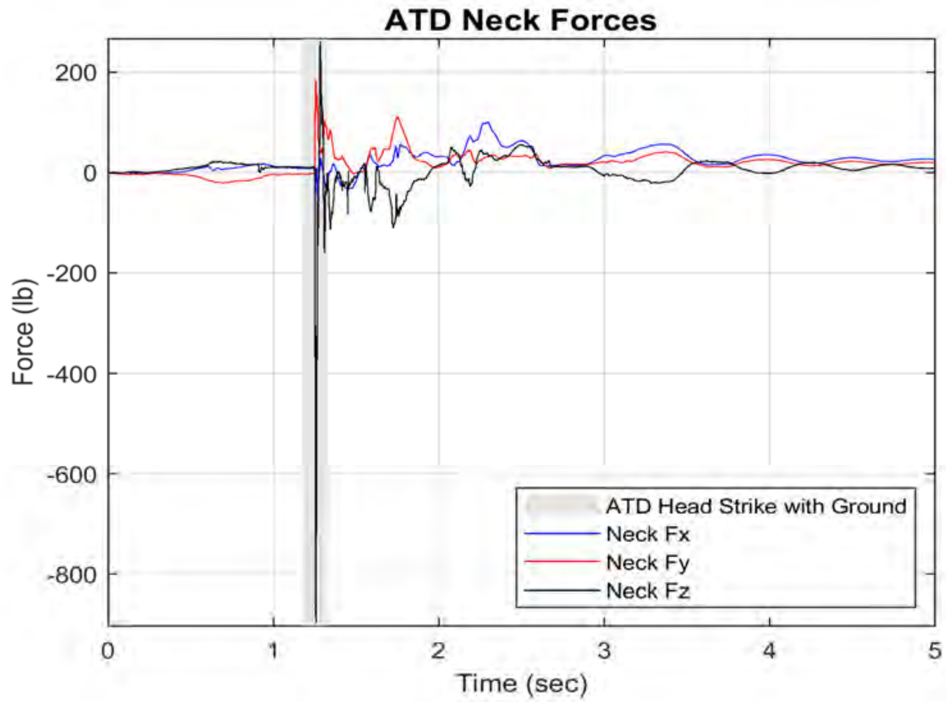
Sled Rollover - Vehicle E - OPD #1

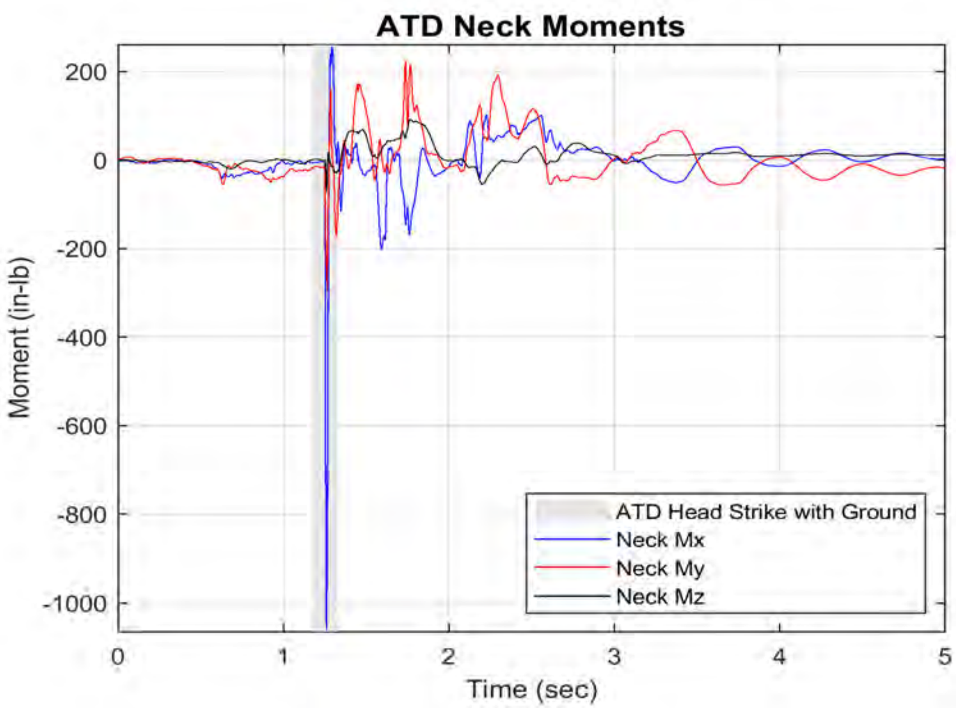




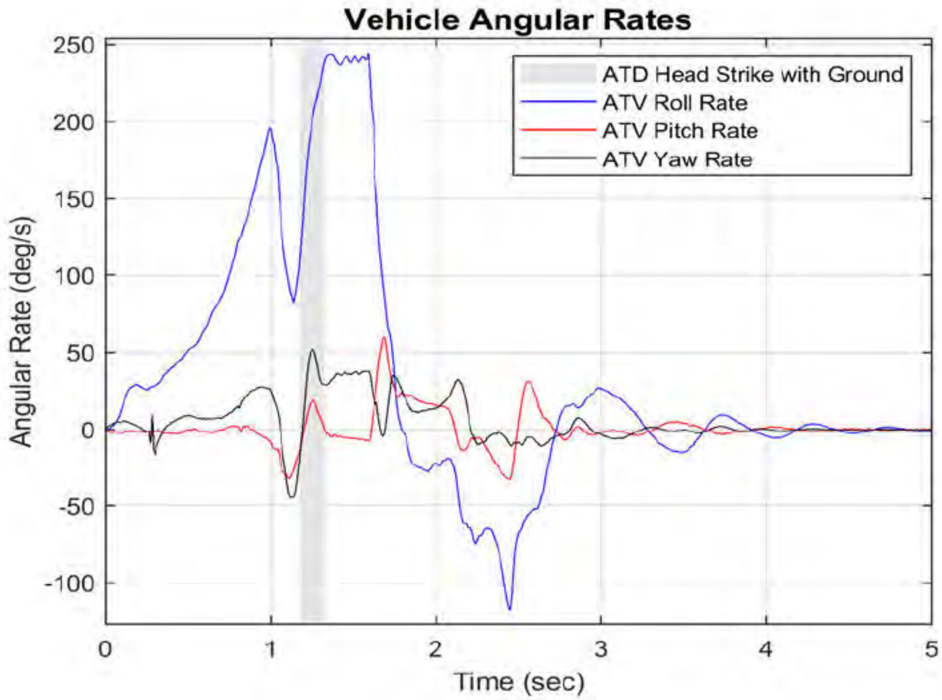


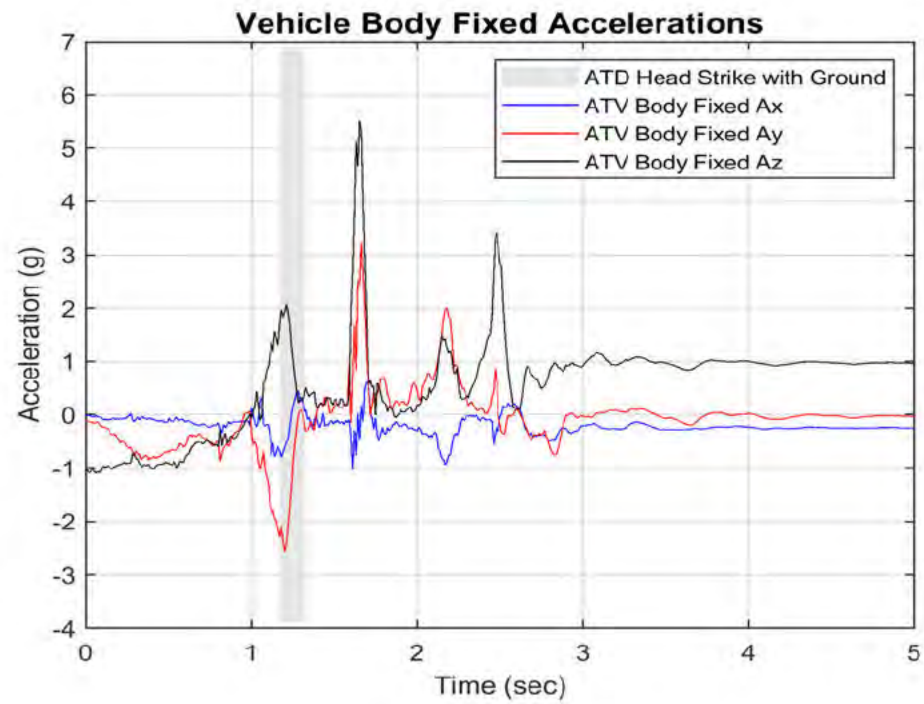
Sled Rollover - Vehicle E - OPD #1

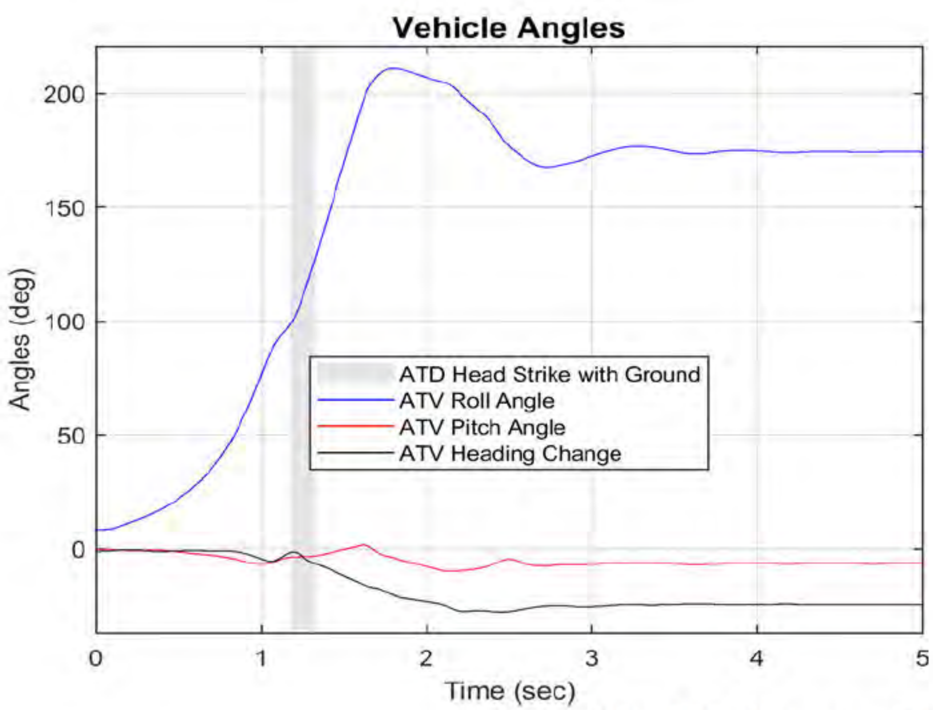




Sled Rollover - Vehicle E - OPD #1





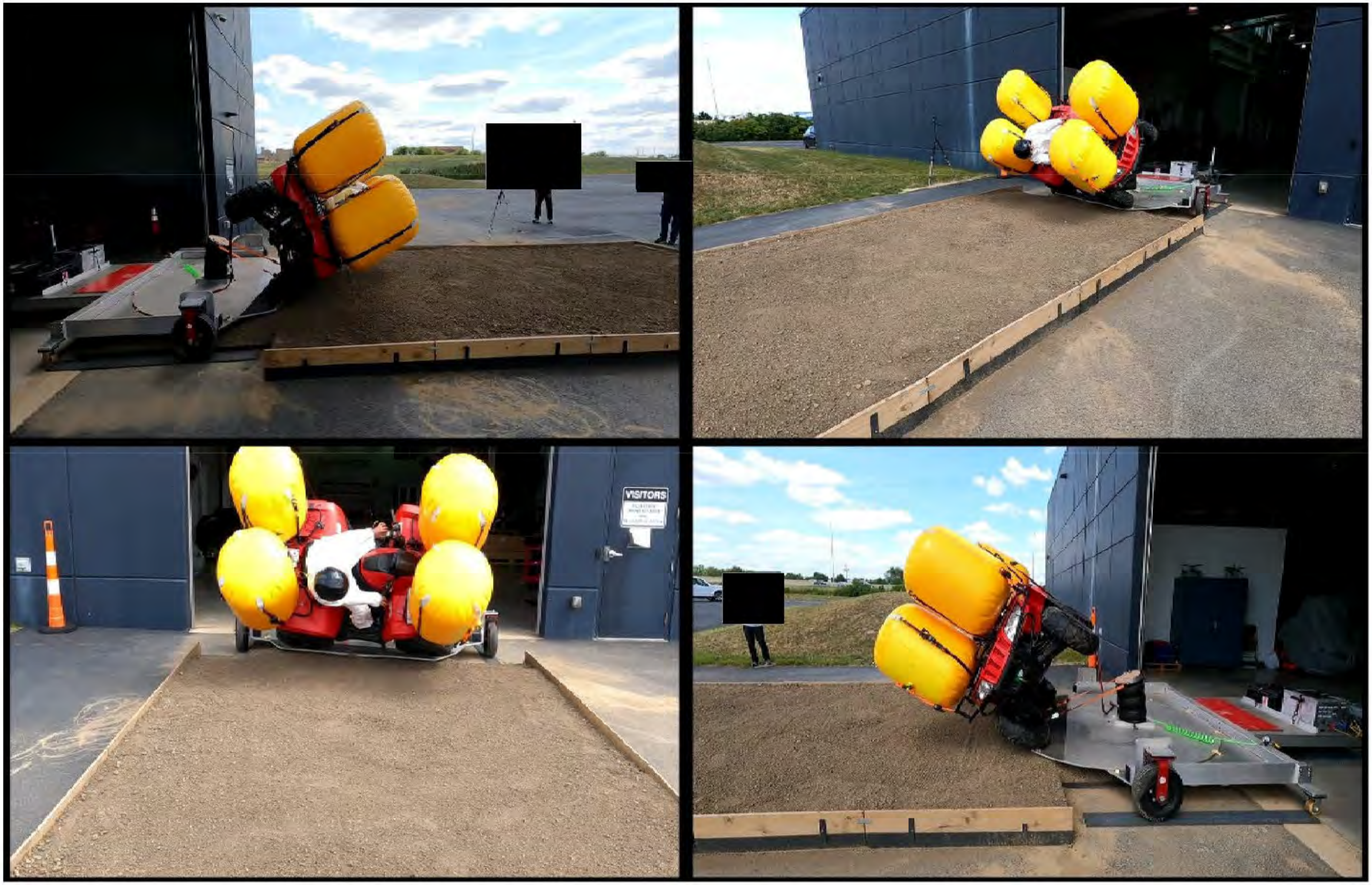


Sled Rollover - Vehicle E - OPD #1

Roll Angle = 30° - Time = 0.69 sec

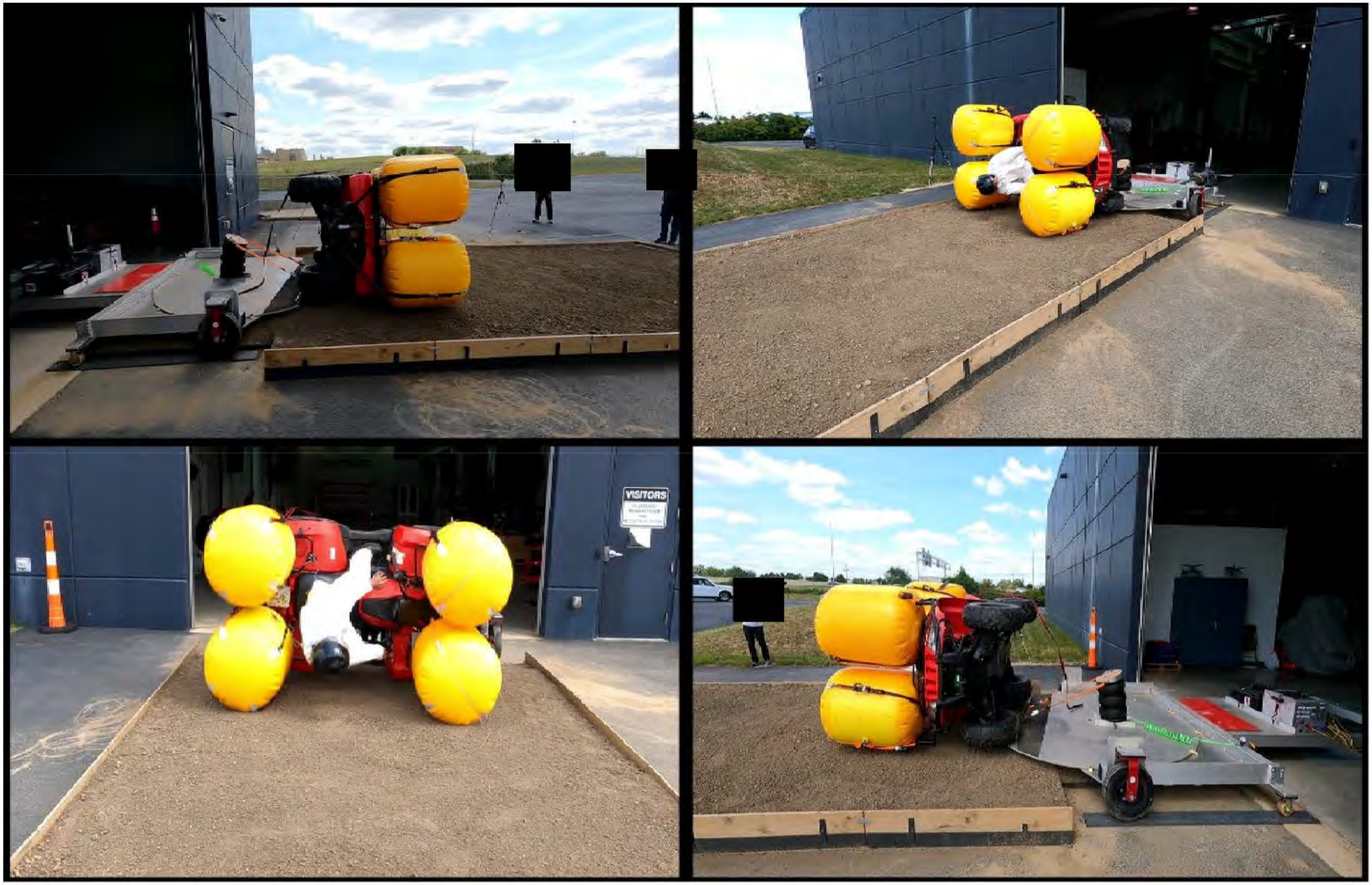
Sled Rollover - Vehicle E - OPD #2

Roll Angle = 60° - Time = 0.99 sec



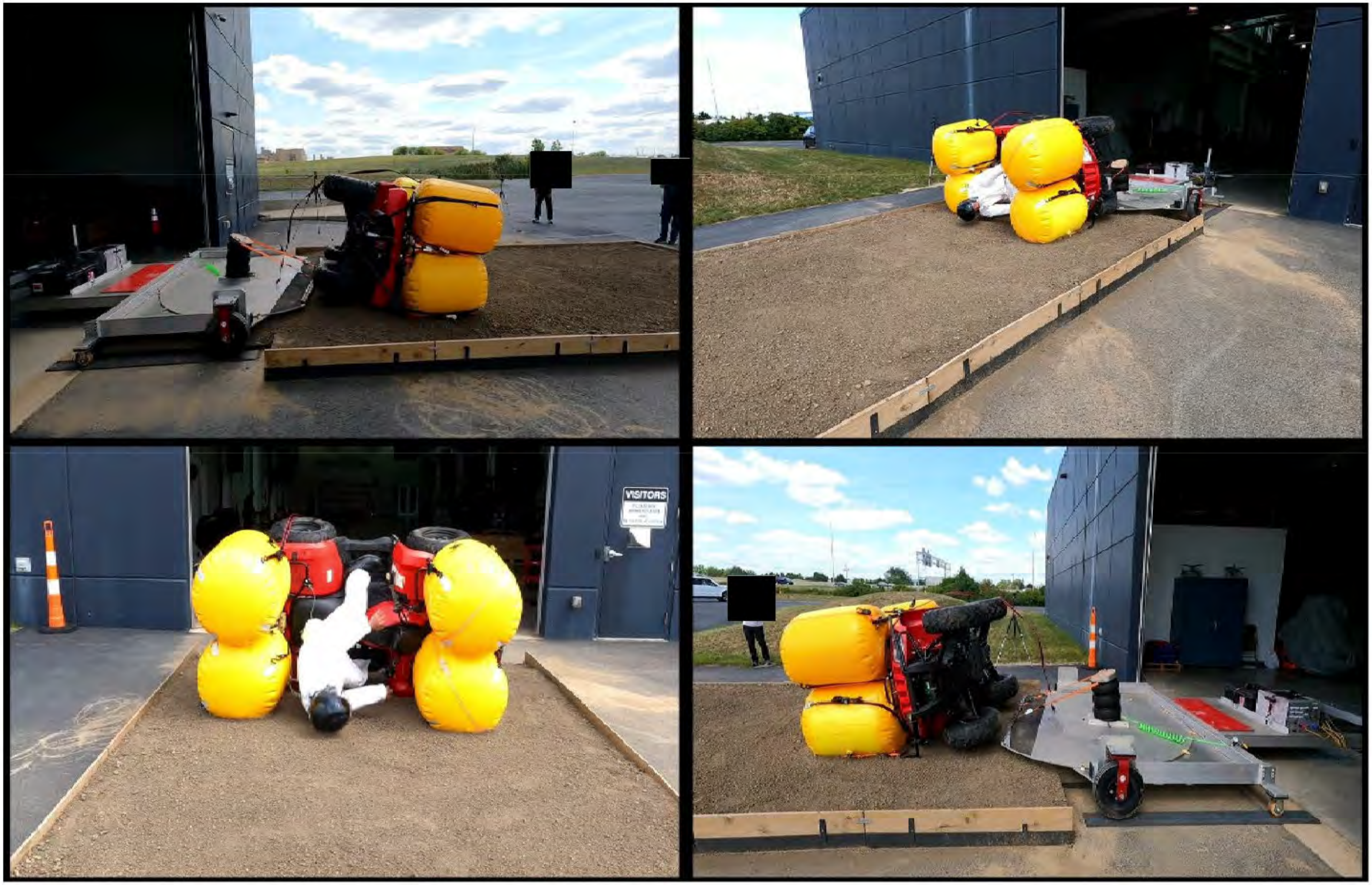
Sled Rollover - Vehicle E - OPD #2

Roll Angle = 90° - Time = 1.16 sec



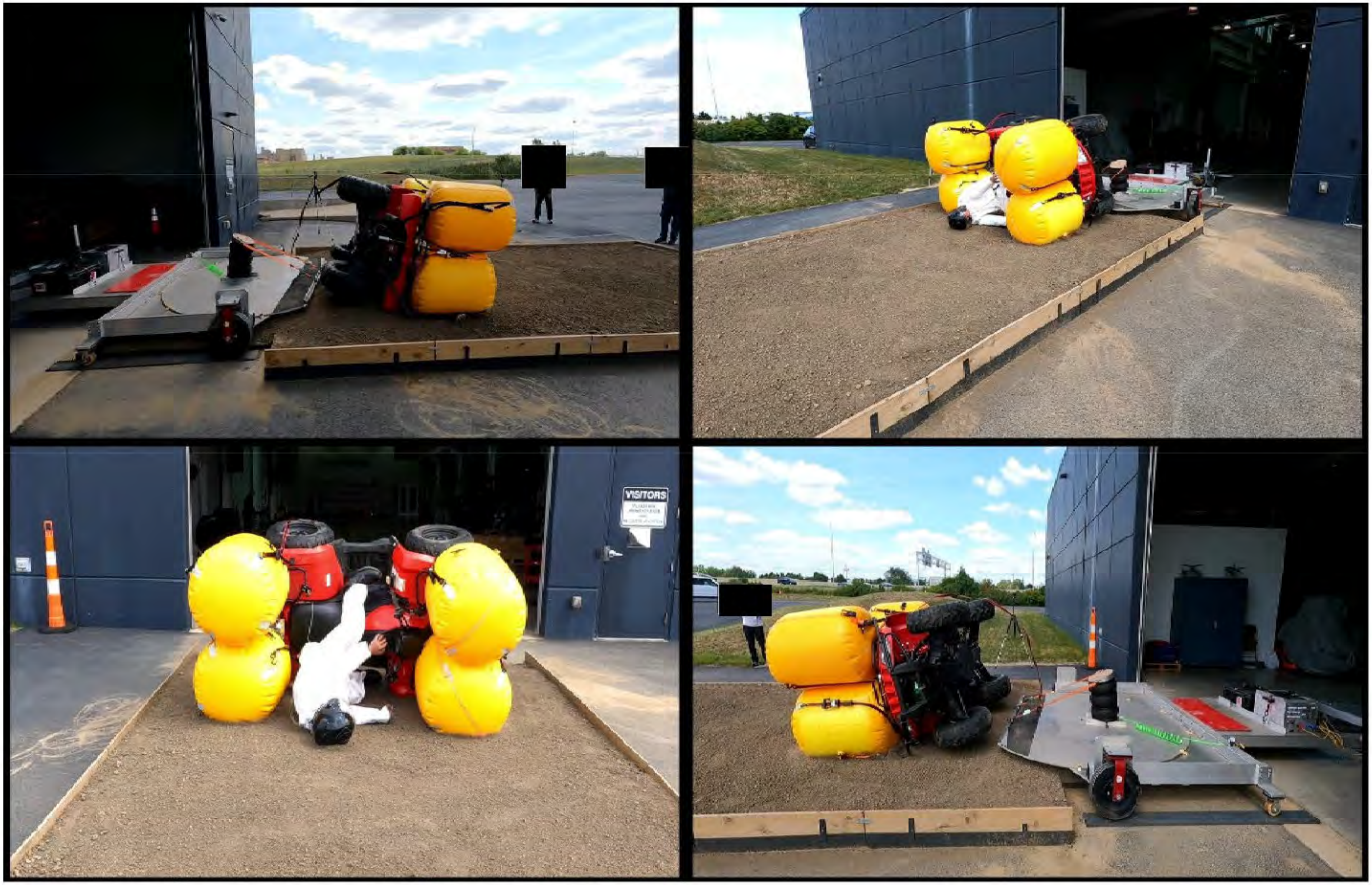
Sled Rollover - Vehicle E - OPD #2

Max Roll Angle = 103.7° - Time = 1.26 sec



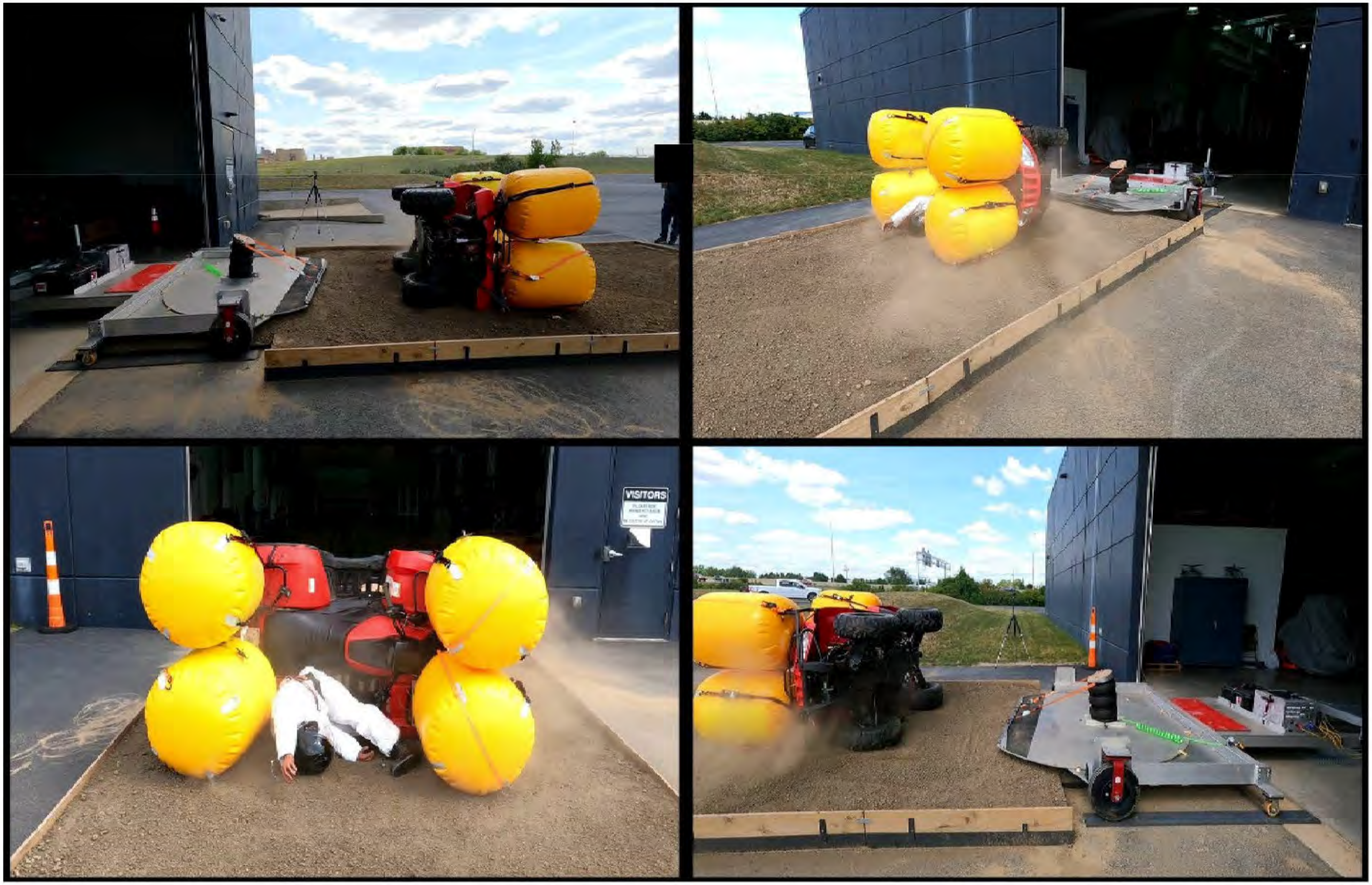
Sled Rollover - Vehicle E - OPD #2

ATD Head Strike - Time = 1.28 sec

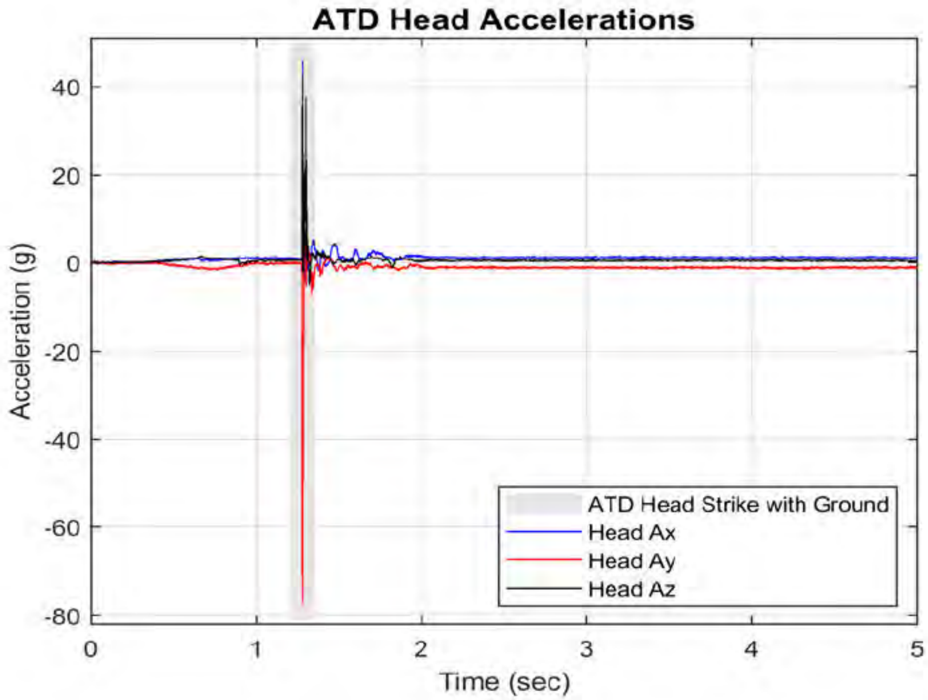


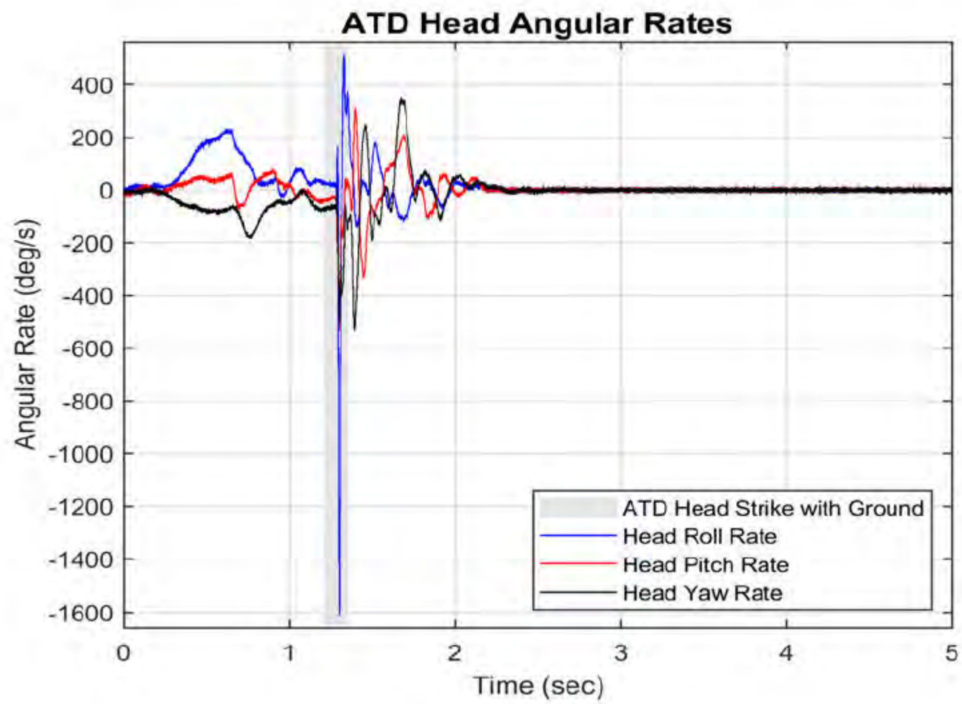
Sled Rollover - Vehicle E - OPD #2

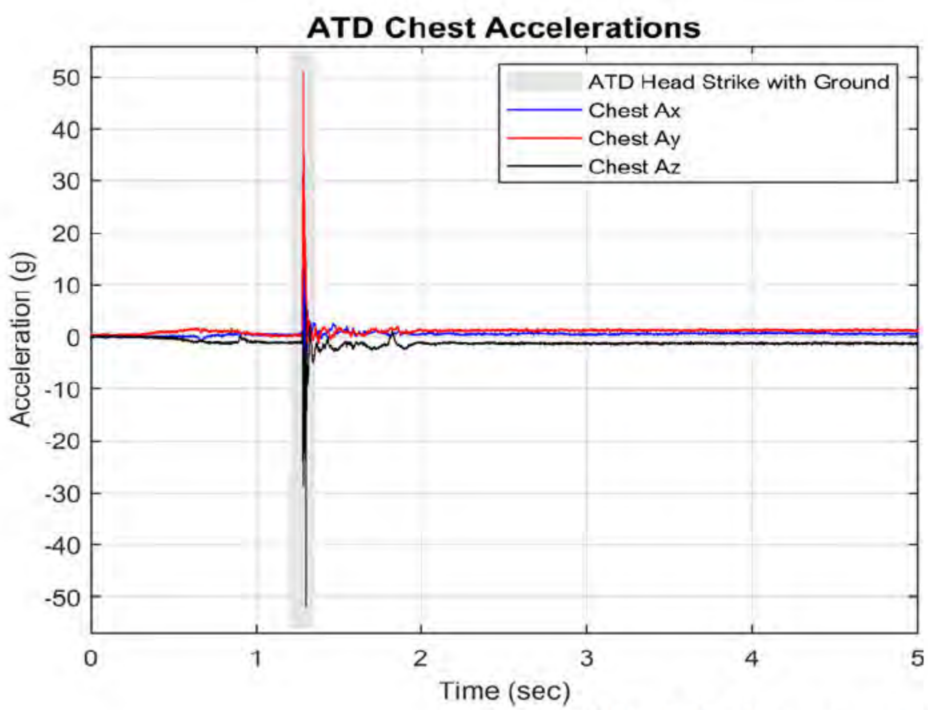
End of Run - Roll Angle = 88.8°



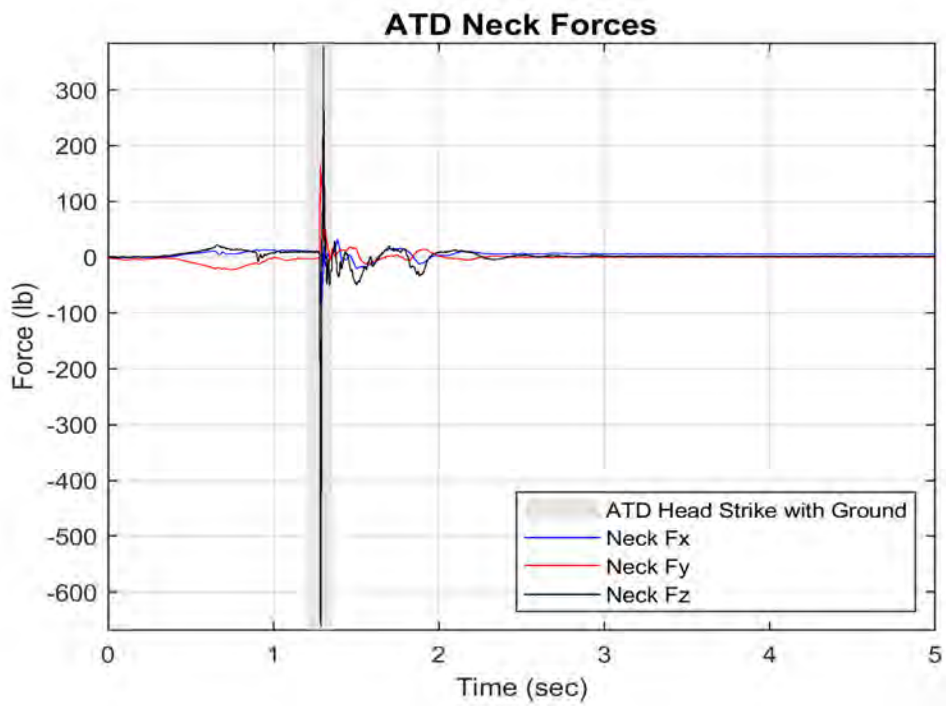
Sled Rollover - Vehicle E - OPD #2

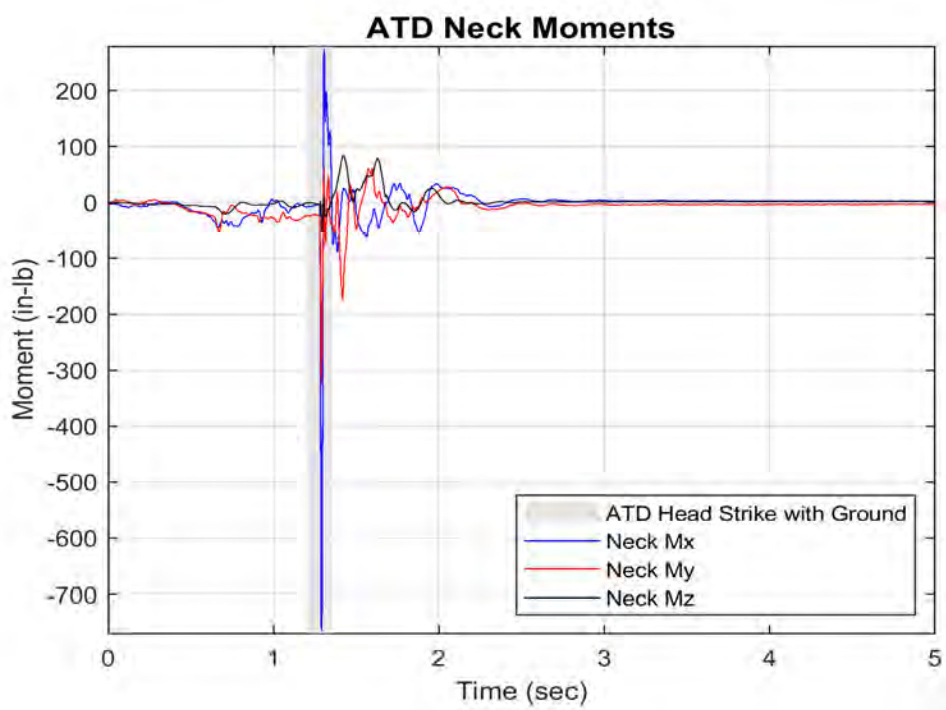




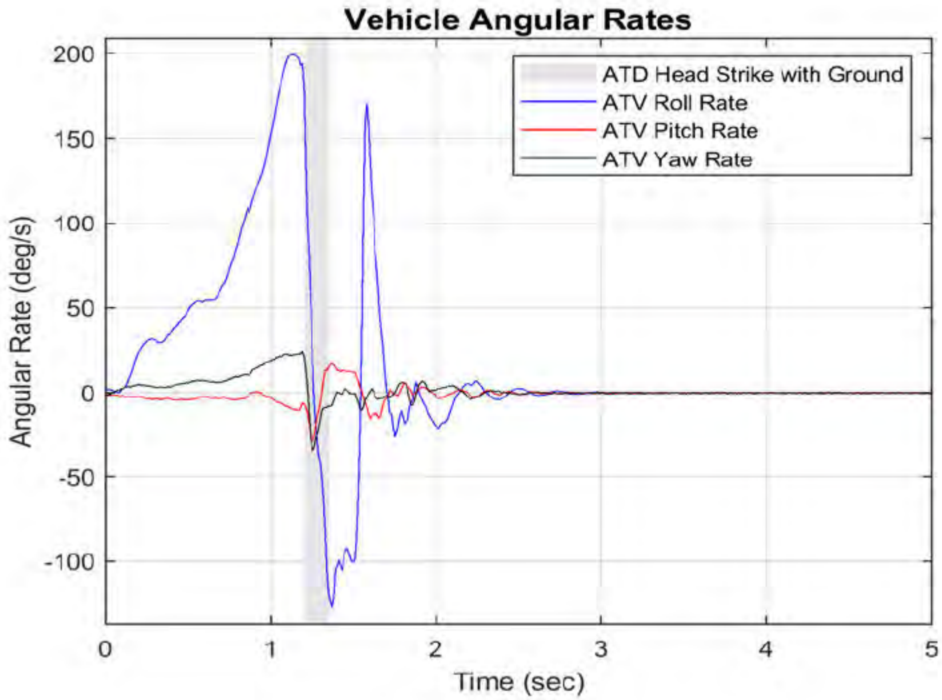


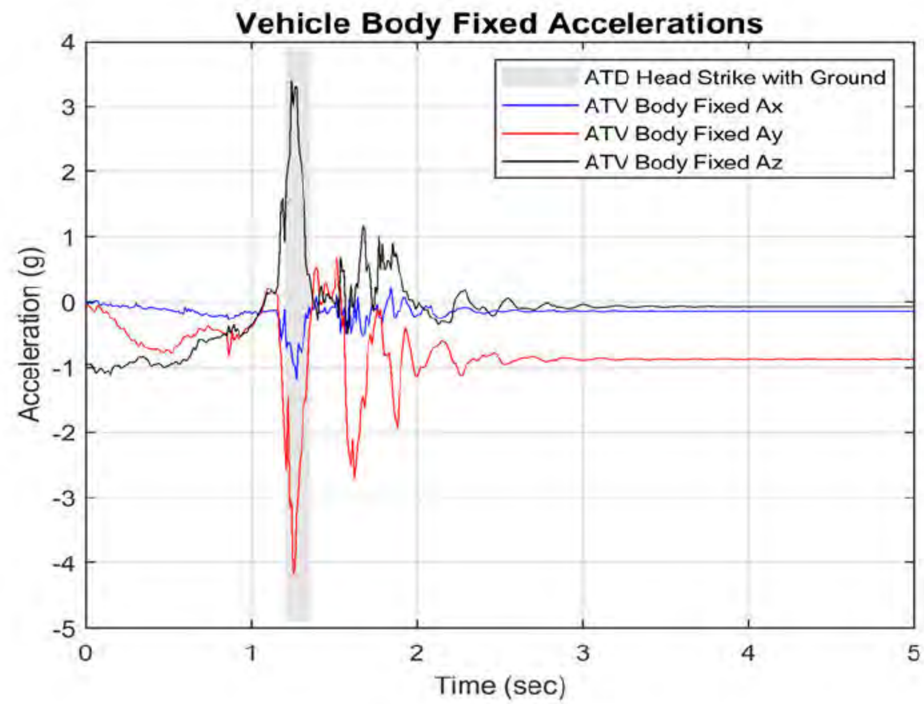
Sled Rollover - Vehicle E - OPD #2

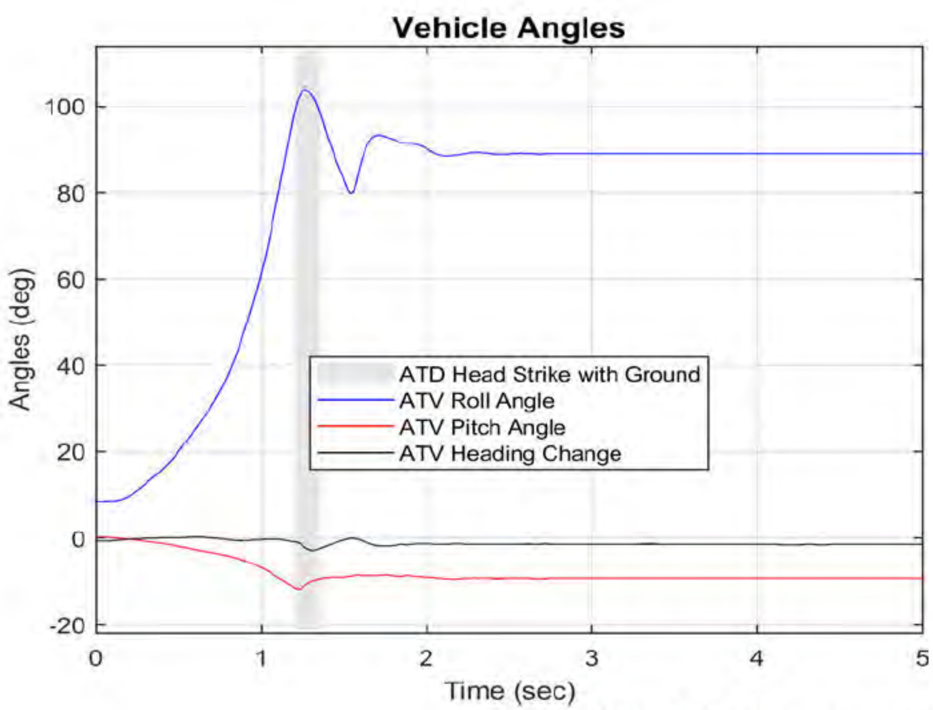




Sled Rollover - Vehicle E - OPD #2

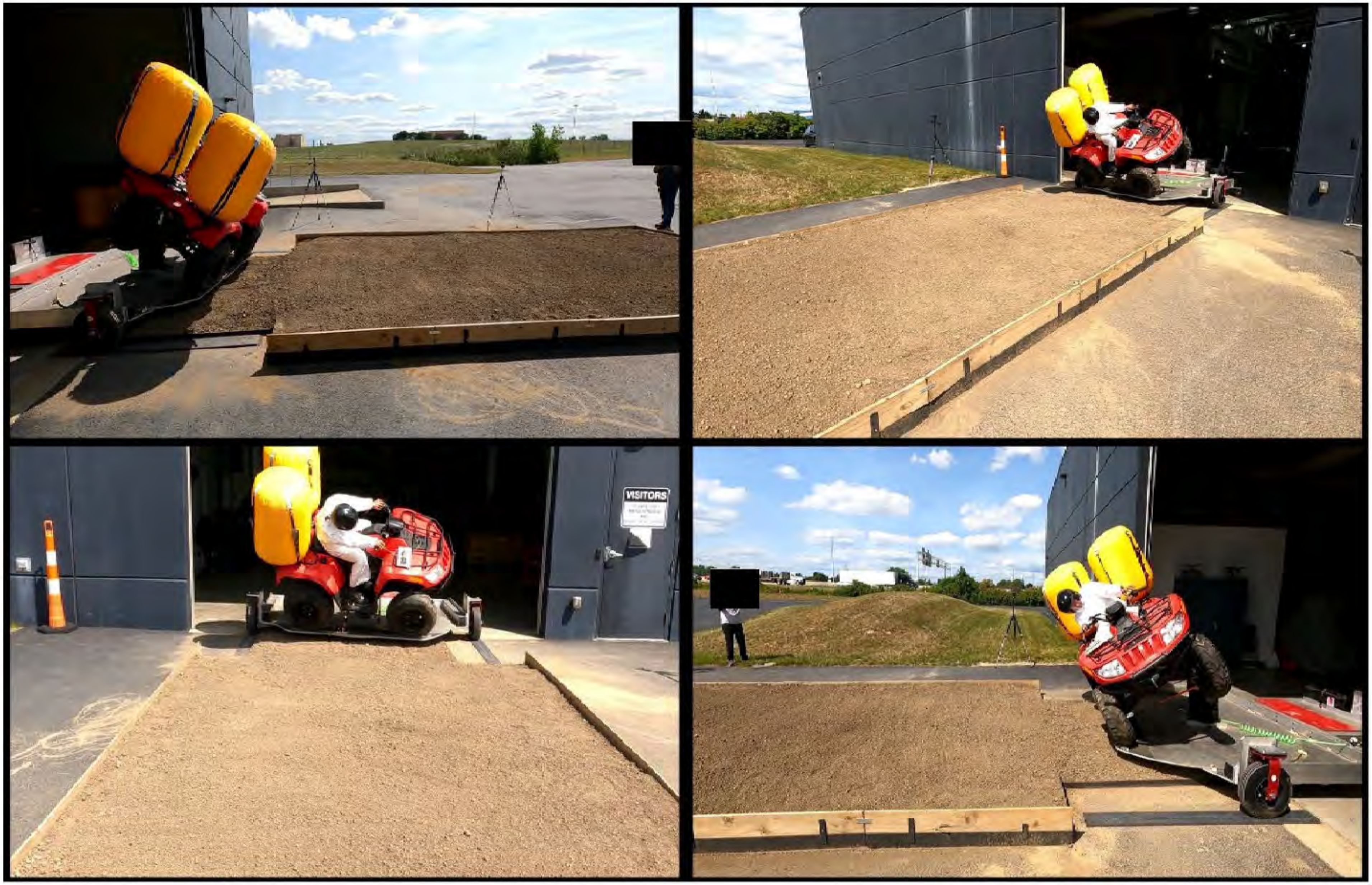






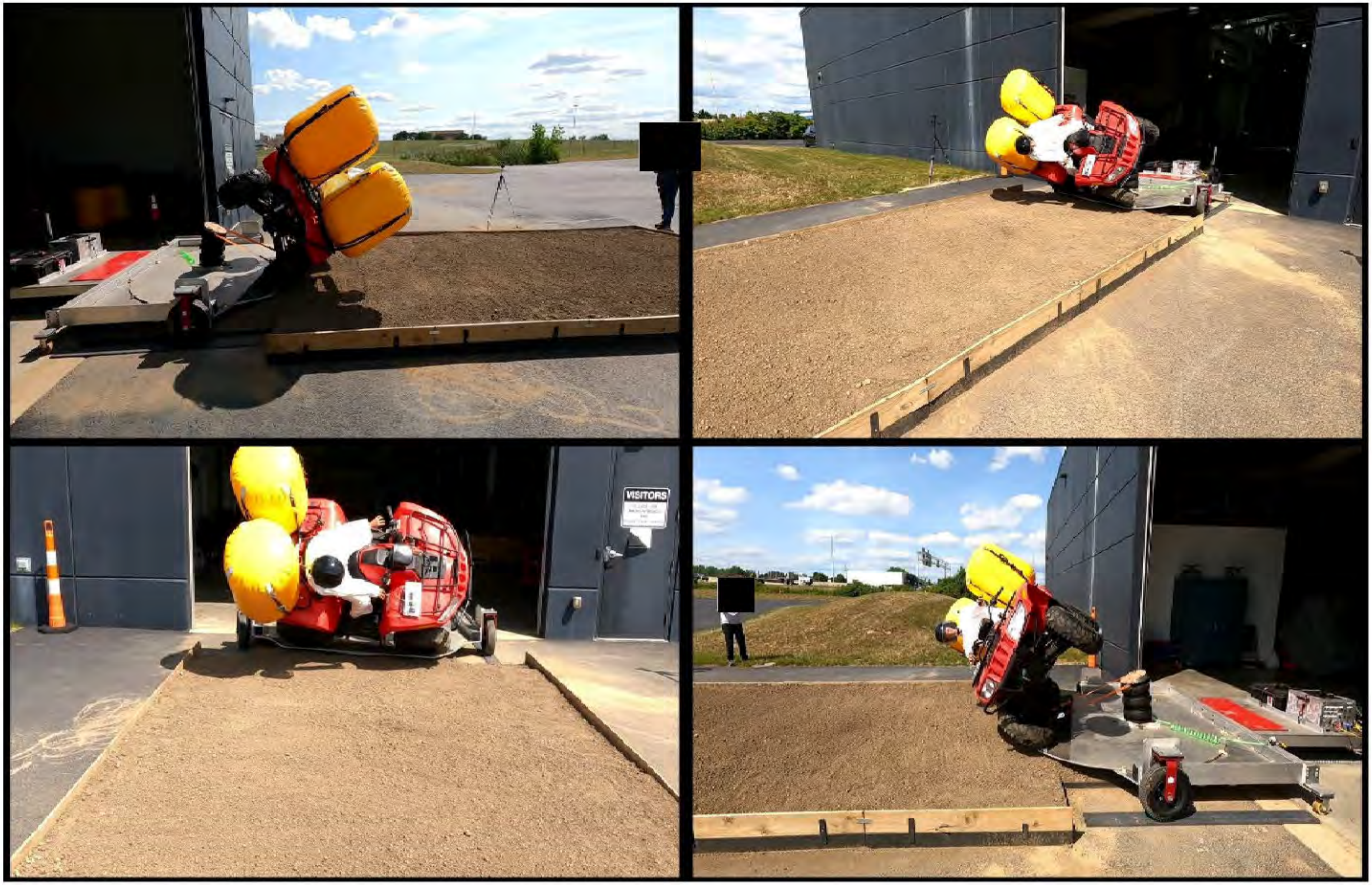
Sled Rollover - Vehicle E - OPD #2

Roll Angle = 30° - Time = 0.56 sec



Sled Rollover - Vehicle E - OPD #2A

Roll Angle = 60° - Time = 0.86 sec



Sled Rollover - Vehicle E - OPD #2A

Roll Angle = 90° - Time = 1.02 sec

Sled Rollover - Vehicle E - OPD #2A

ATD Head Strike - Time = 1.20 sec

Sled Rollover - Vehicle E - OPD #2A

Roll Angle = 180° - Time = 2.04 sec

Sled Rollover - Vehicle E - OPD #2A

Roll Angle = 270° - Time = 3.61 sec

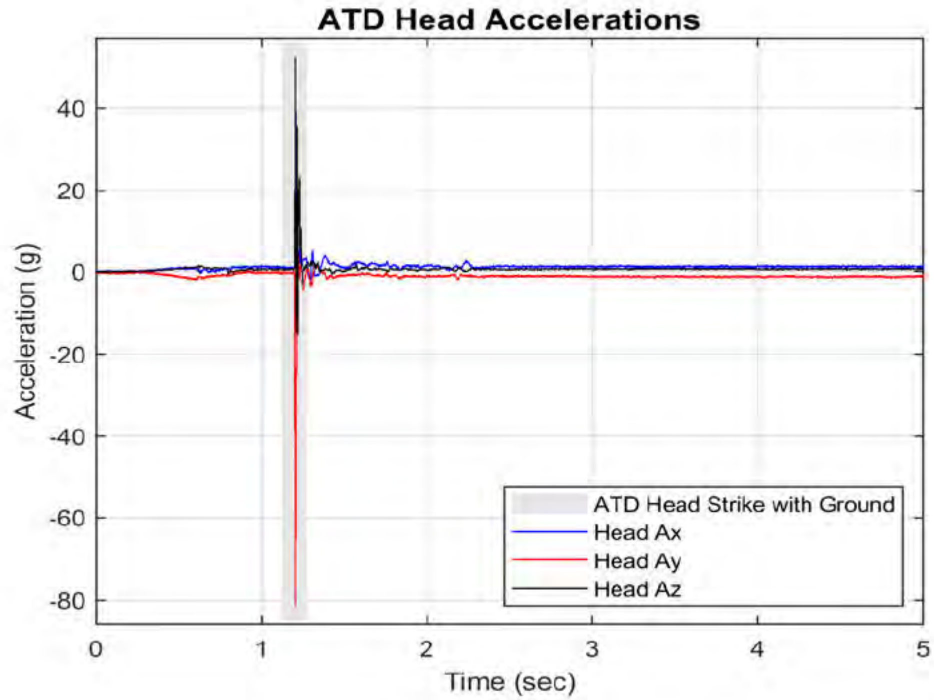
Sled Rollover - Vehicle E - OPD #2A

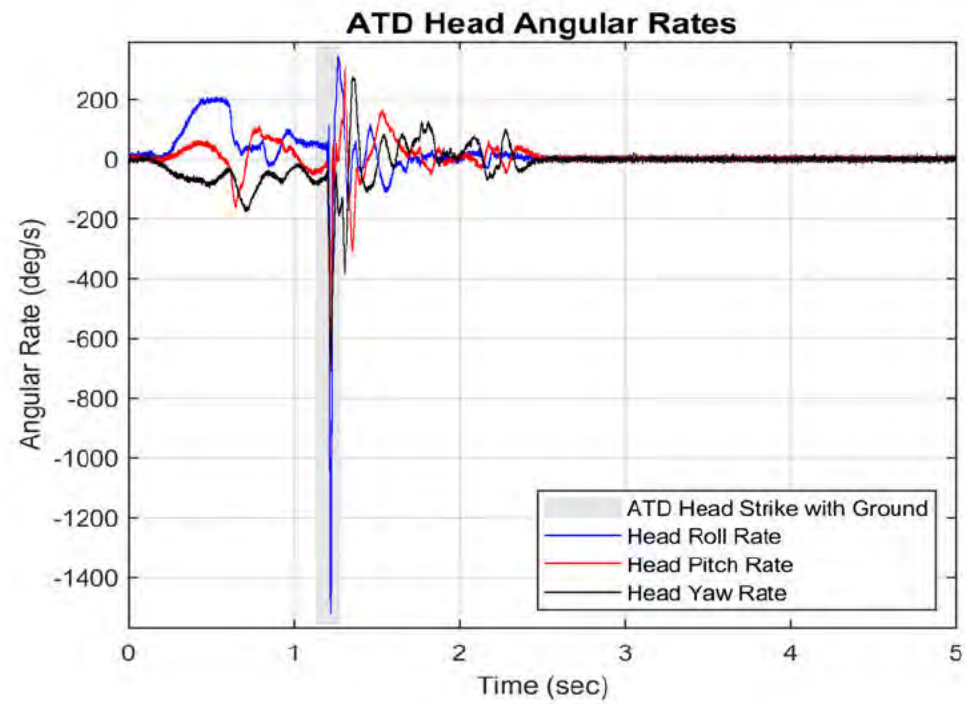
Max Roll Angle = 286.7° - Time = 3.98 sec

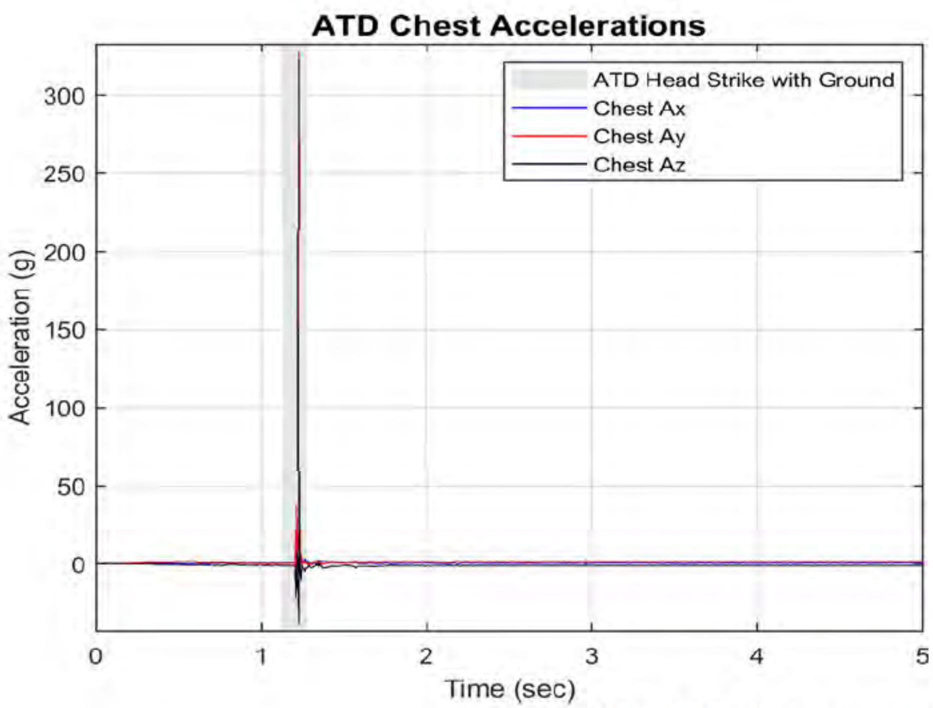
Sled Rollover - Vehicle E - OPD #2A

End of Run - Roll Angle = 274.3°

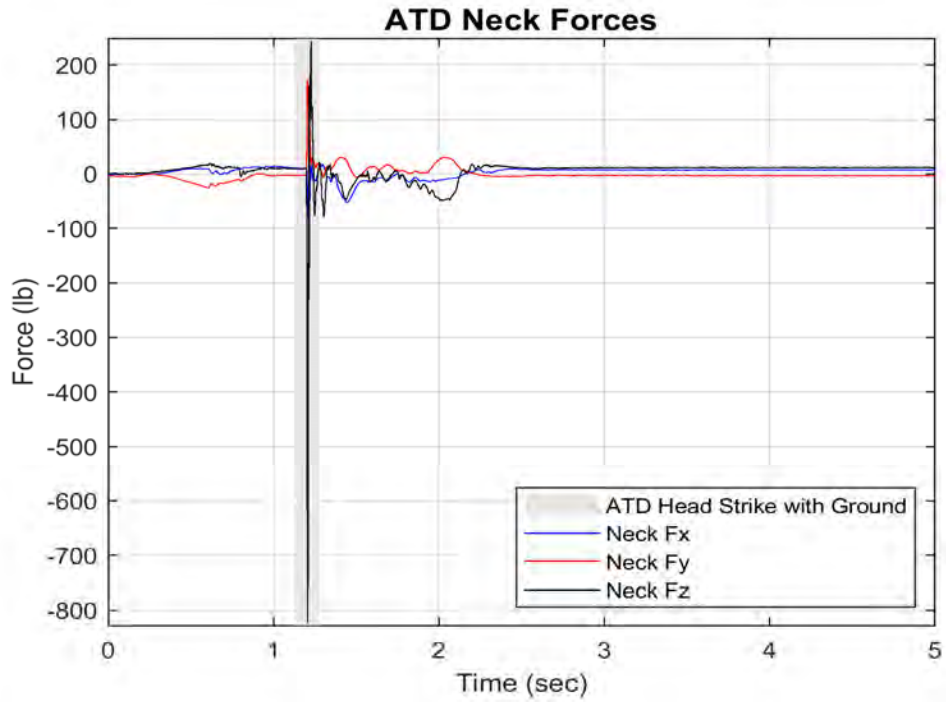
Sled Rollover - Vehicle E - OPD #2A

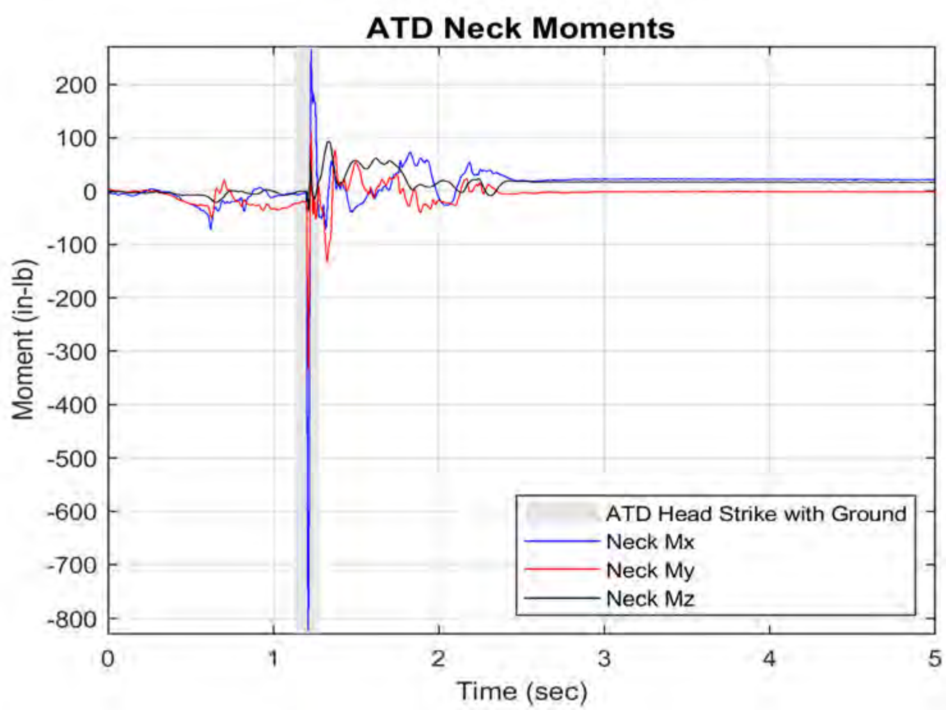




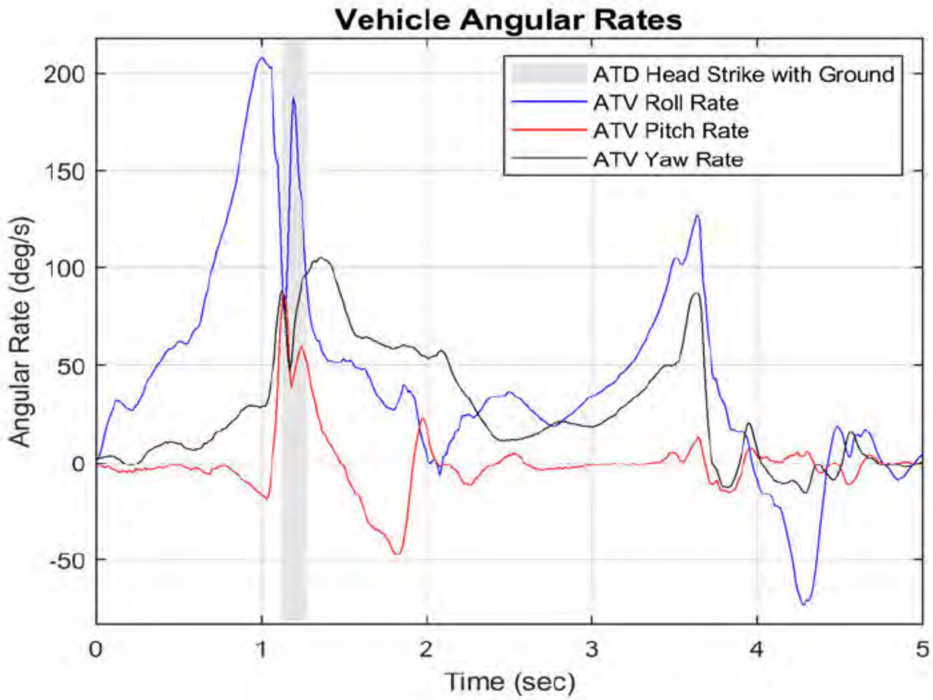


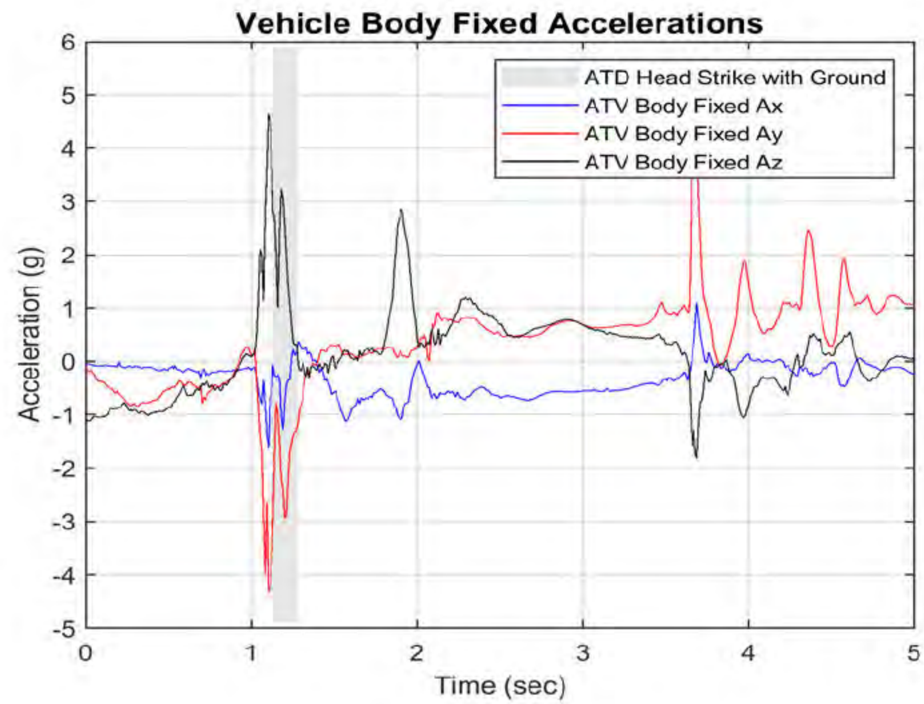
Sled Rollover - Vehicle E - OPD #2A





Sled Rollover - Vehicle E - OPD #2A



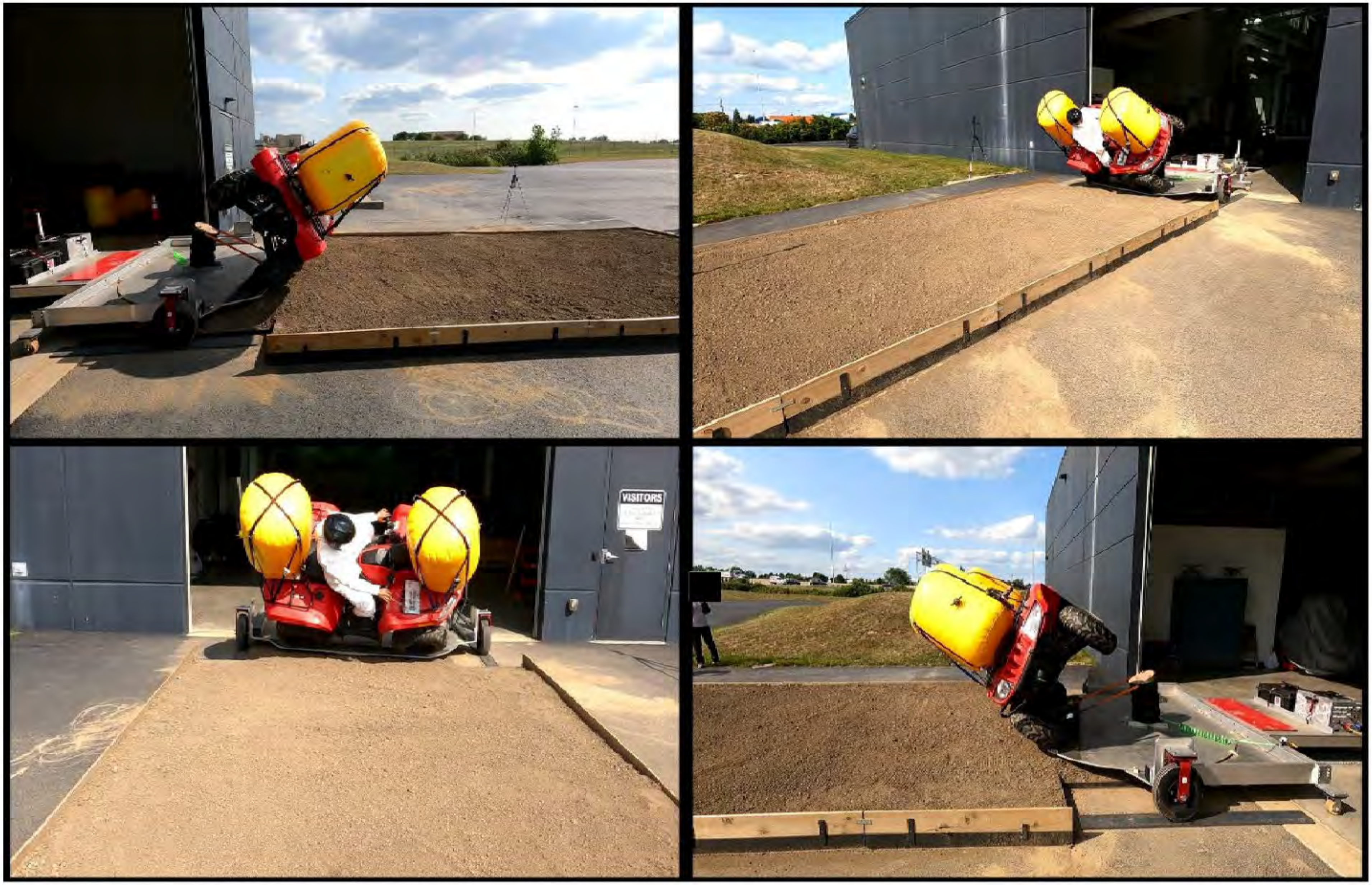


Sled Rollover - Vehicle E - OPD #2A

Roll Angle = 30° - Time = 0.68 sec

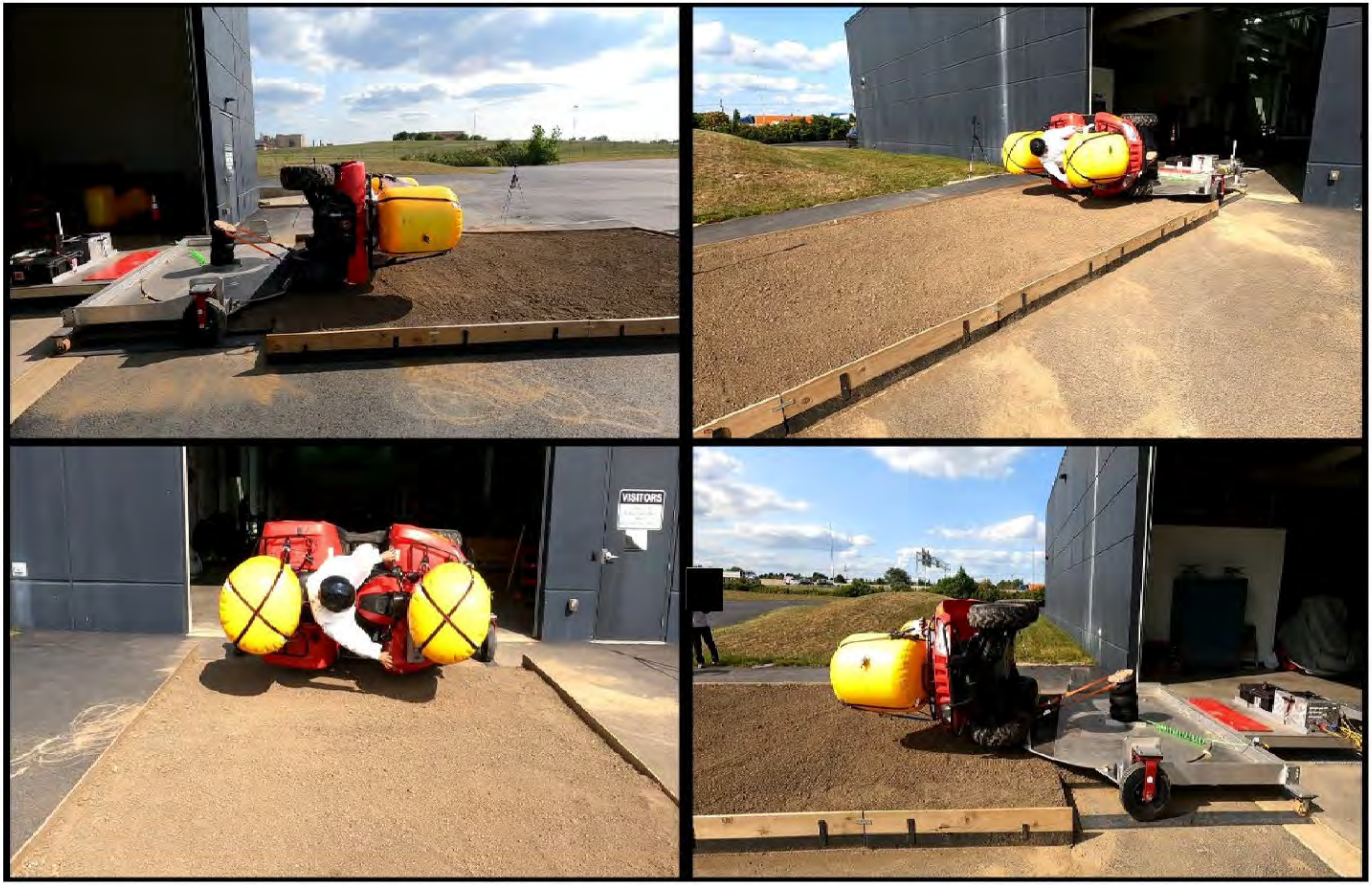
Sled Rollover - Vehicle E - OPD #2B

Roll Angle = 60° - Time = 0.96 sec



Sled Rollover - Vehicle E - OPD #2B

Roll Angle = 90° - Time = 1.12 sec

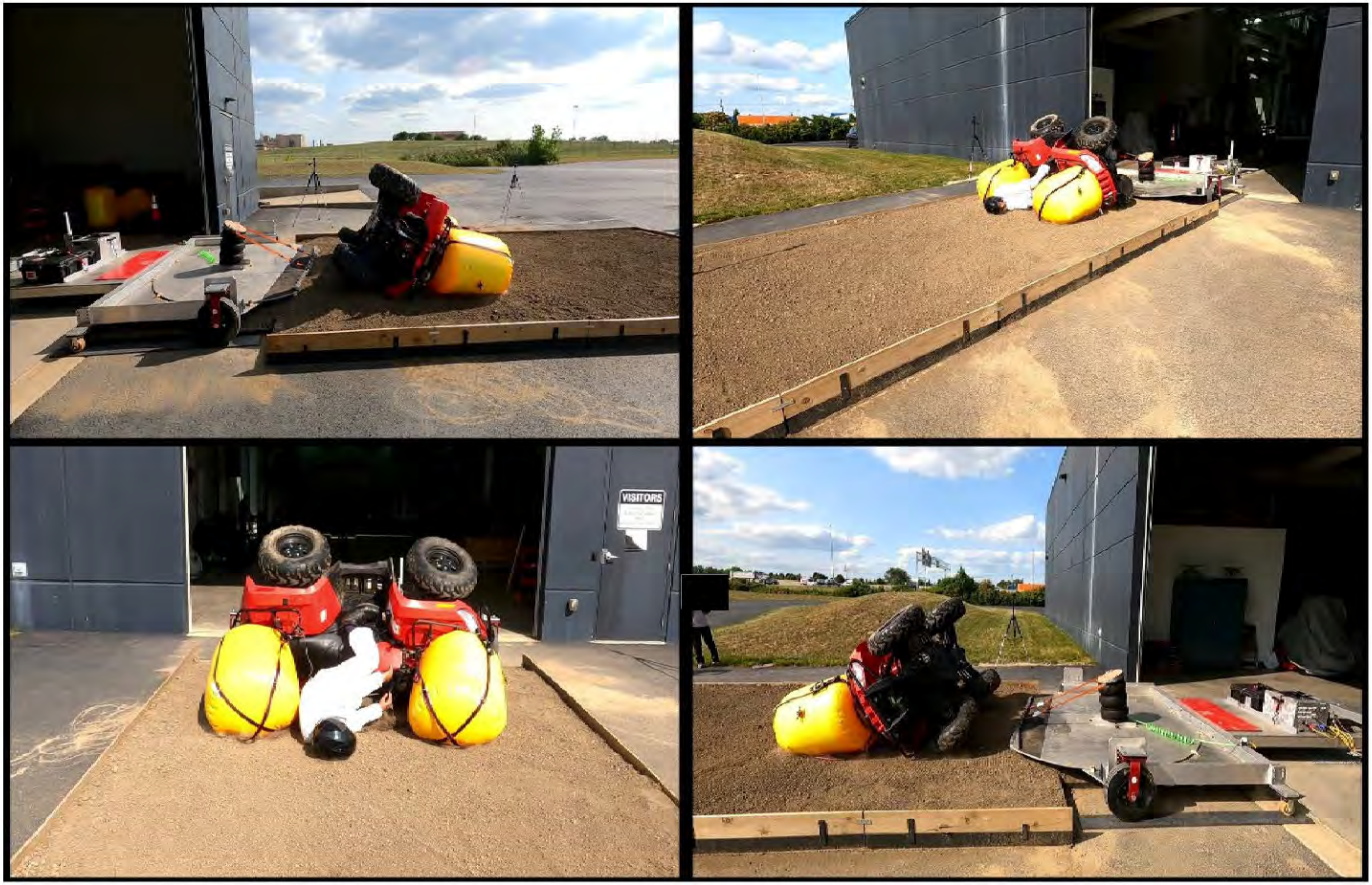


Sled Rollover - Vehicle E - OPD #2B

ATD Head Strike - Time = 1.32 sec

Sled Rollover - Vehicle E - OPD #2B

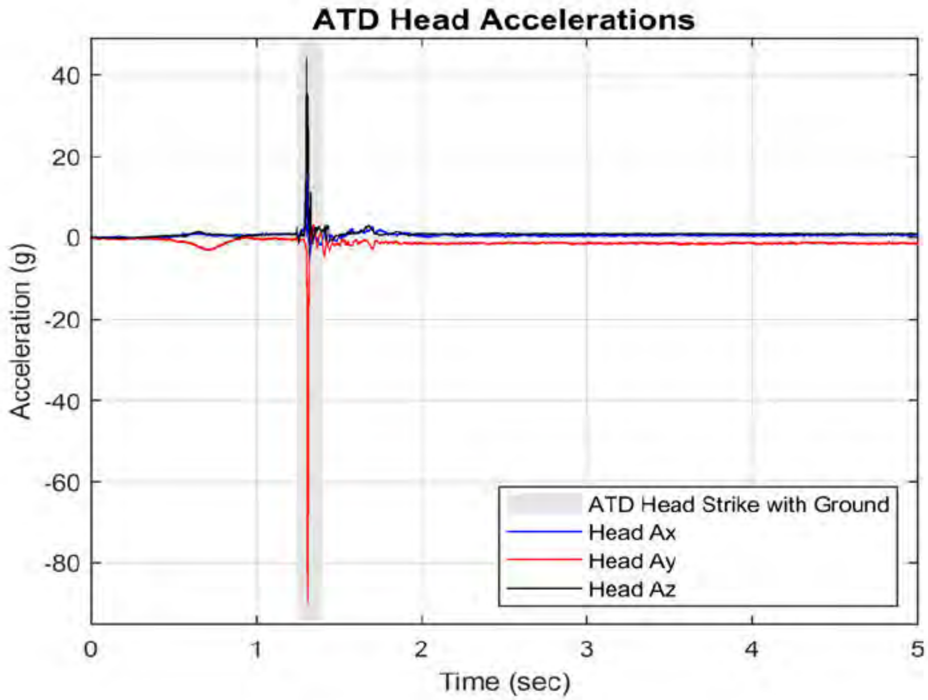
Max Roll Angle = 122.4° - Time = 1.34 sec

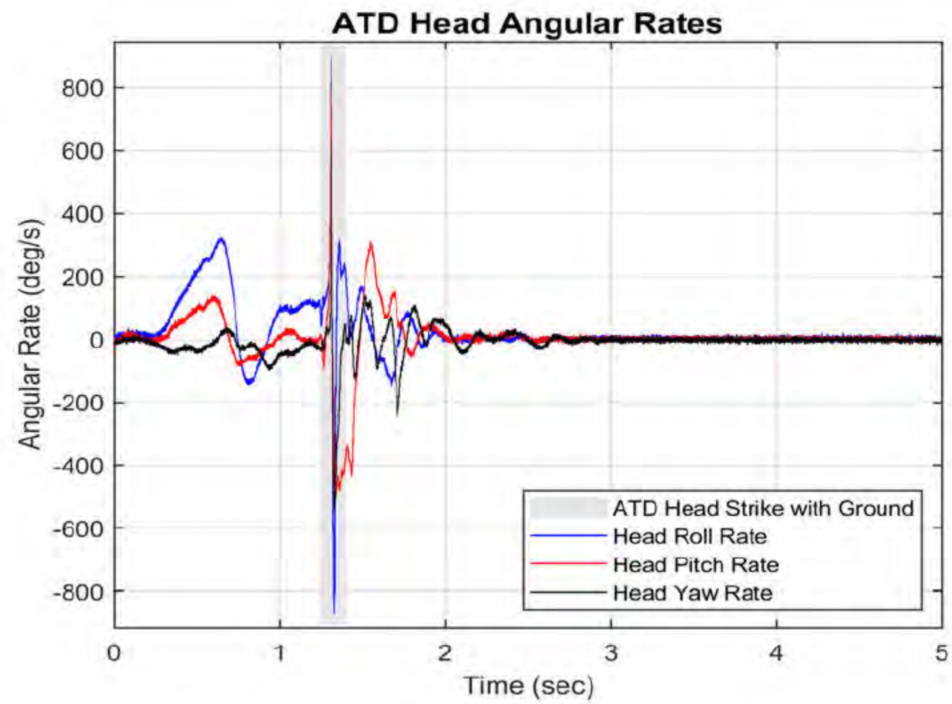


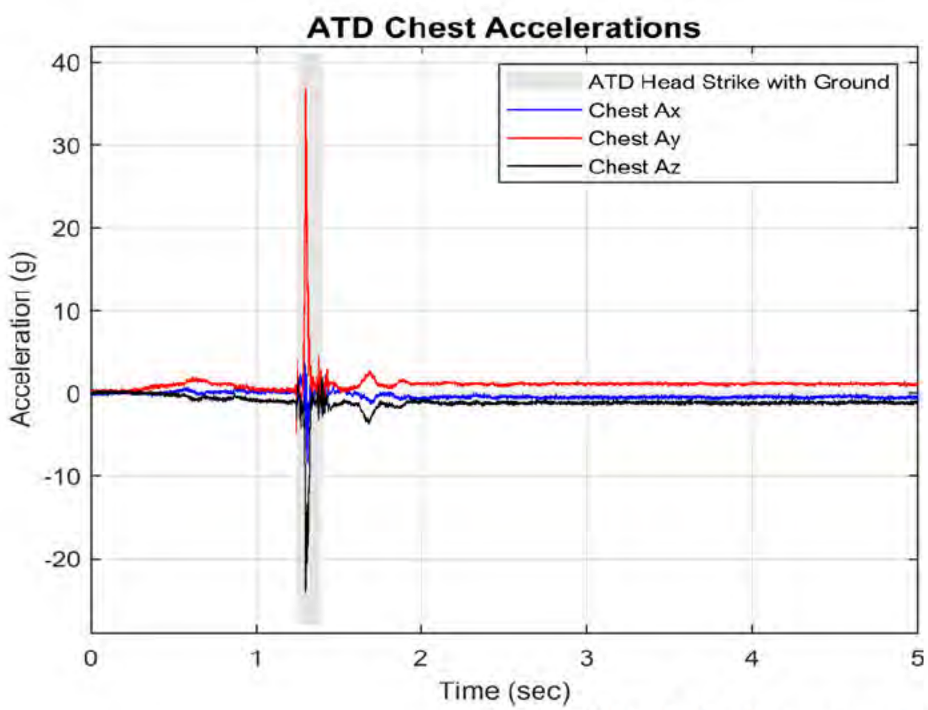
Sled Rollover - Vehicle E - OPD #2B

End of Run - Roll Angle = 90.5°

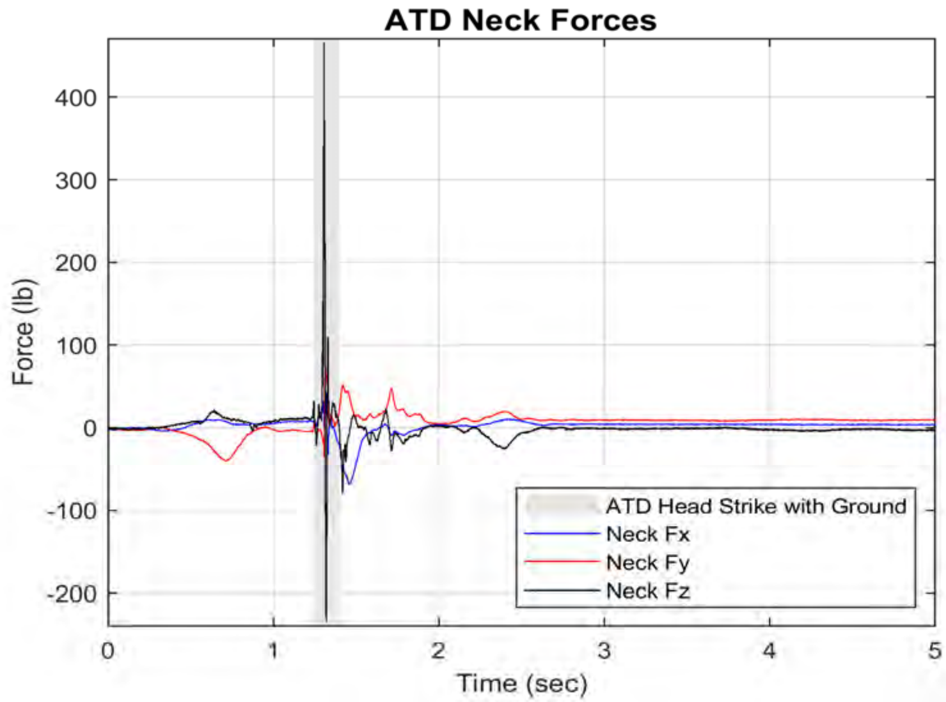
Sled Rollover - Vehicle E - OPD #2B

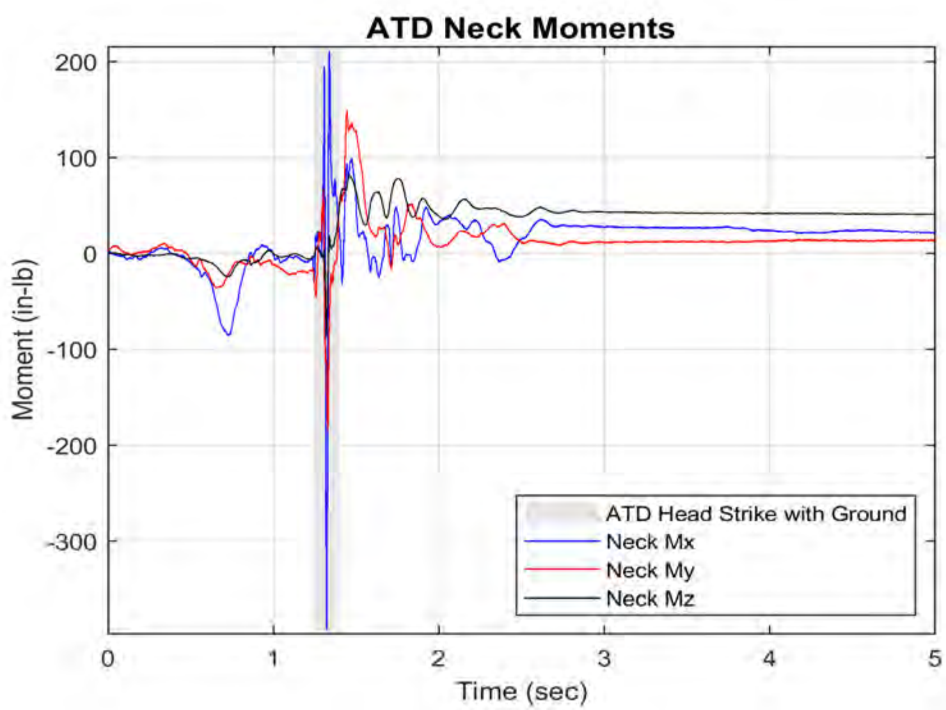




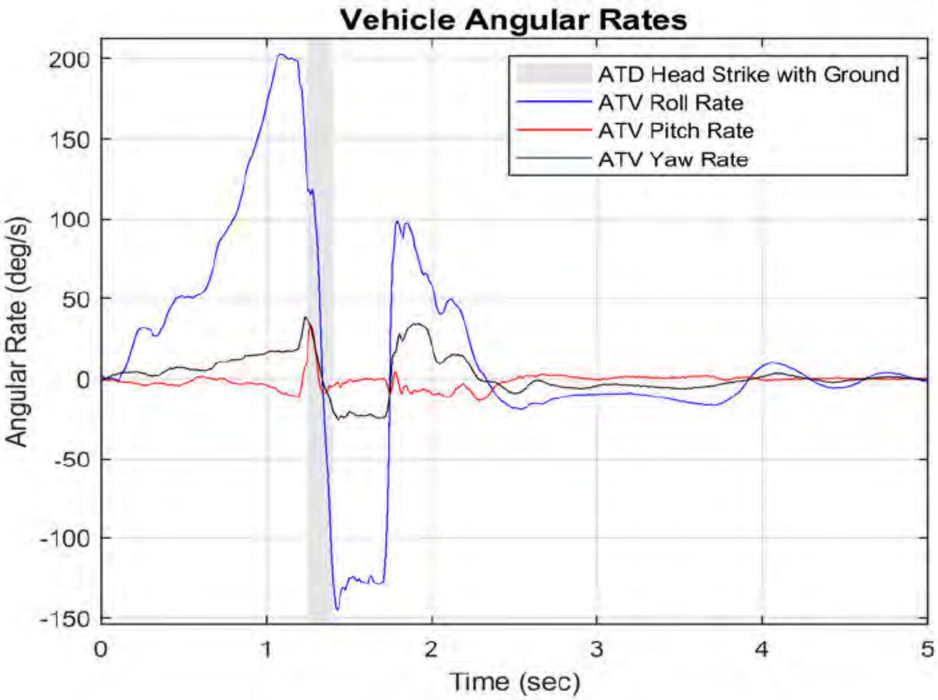


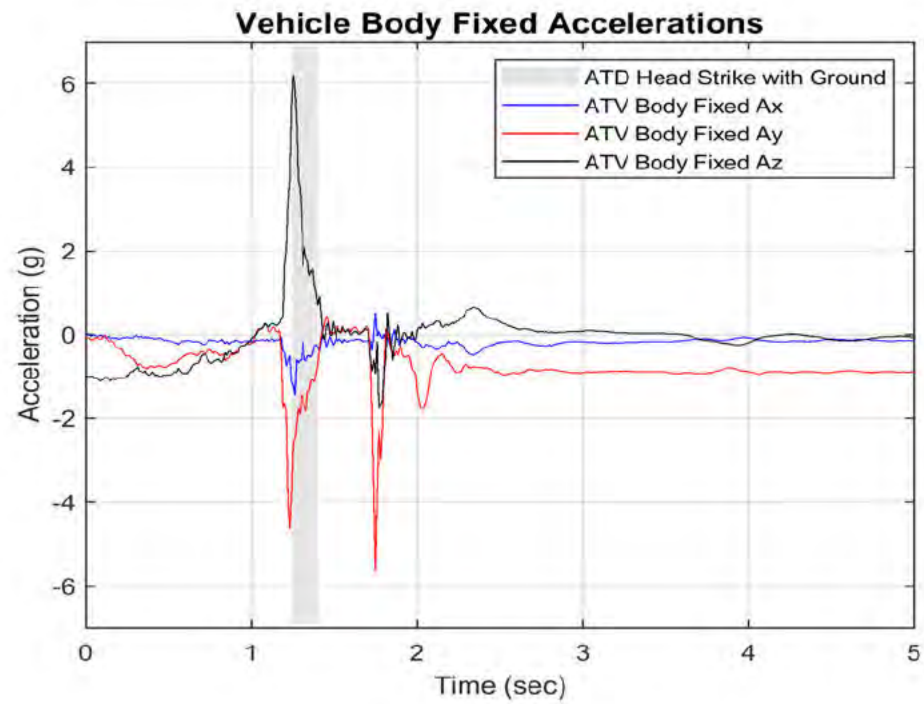
Sled Rollover - Vehicle E - OPD #2B

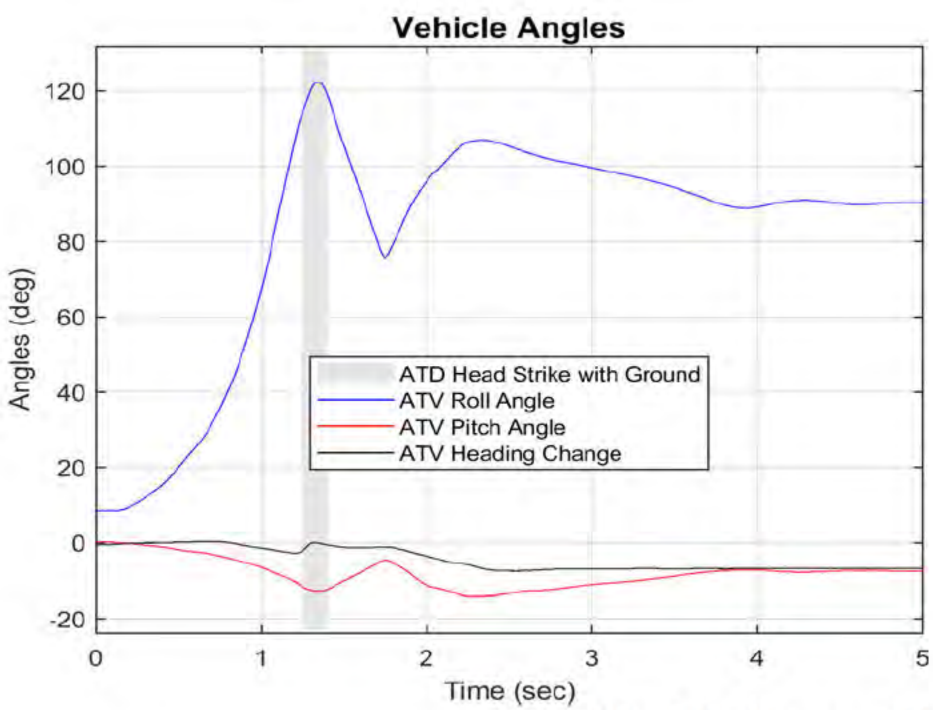




Sled Rollover - Vehicle E - OPD #2B







Sled Rollover - Vehicle E - OPD #2B

Roll Angle = 30° - Time = 0.60 sec

Sled Rollover - Vehicle E - OPD #2C

Roll Angle = 60° - Time = 0.87 sec

Sled Rollover - Vehicle E - OPD #2C

Roll Angle = 90° - Time = 1.03 sec

Sled Rollover - Vehicle E - OPD #2C

ATD Head Strike - Time = 1.12 sec

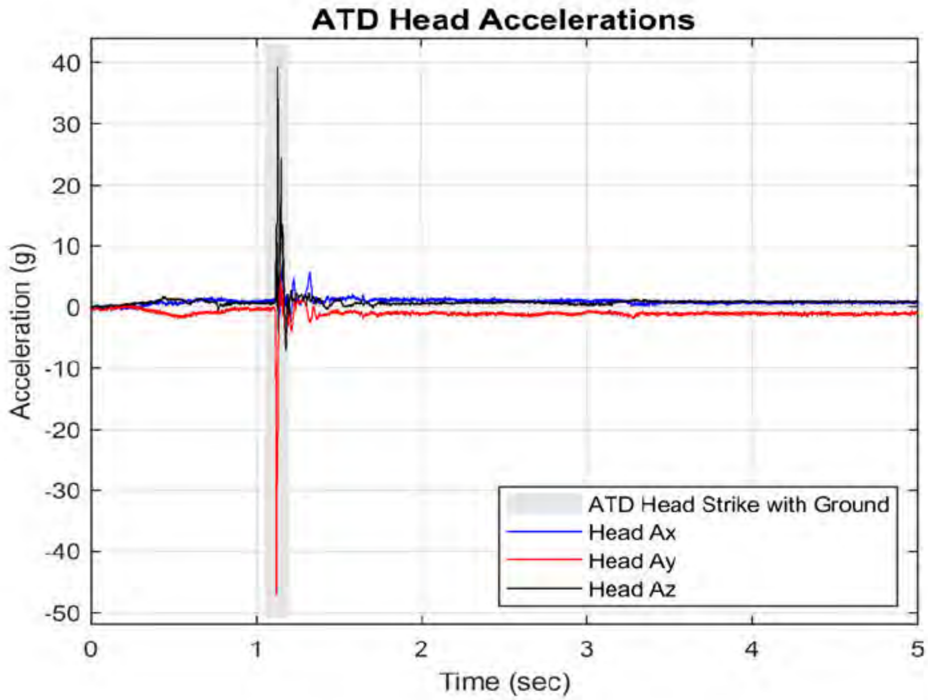
Sled Rollover - Vehicle E - OPD #2C

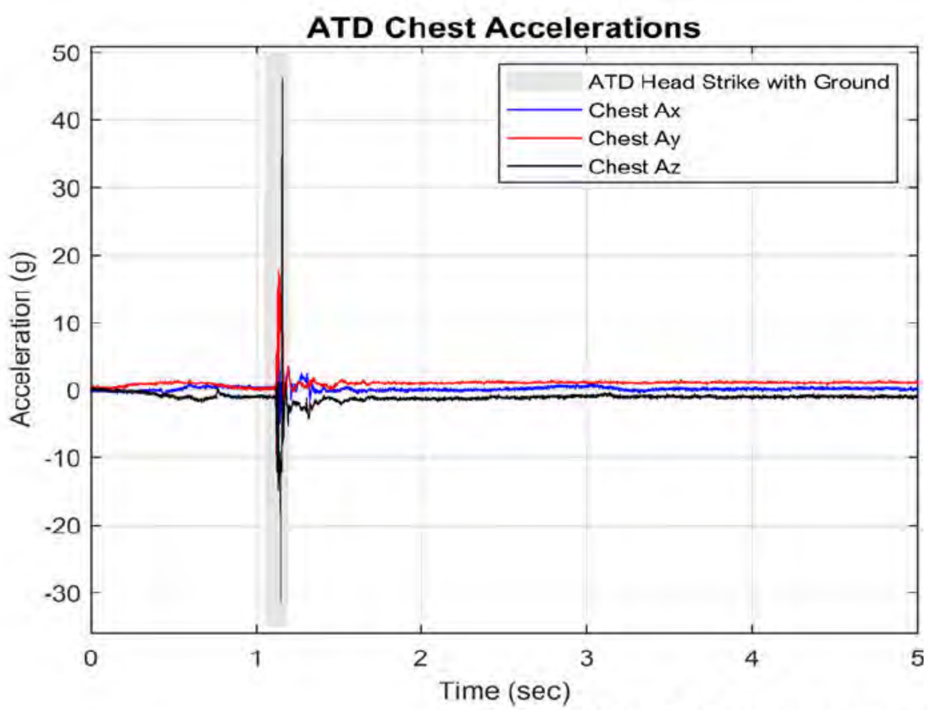
Max Roll Angle = 170.8° - Time = 2.14 sec

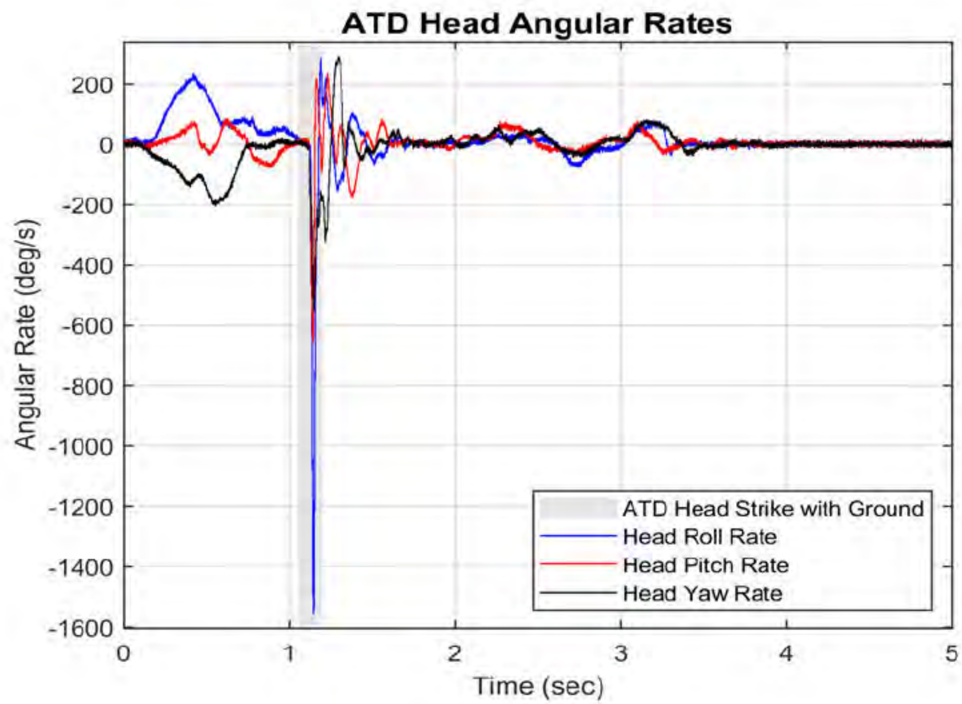
Sled Rollover - Vehicle E - OPD #2C

End of Run - Roll Angle = 115.6°

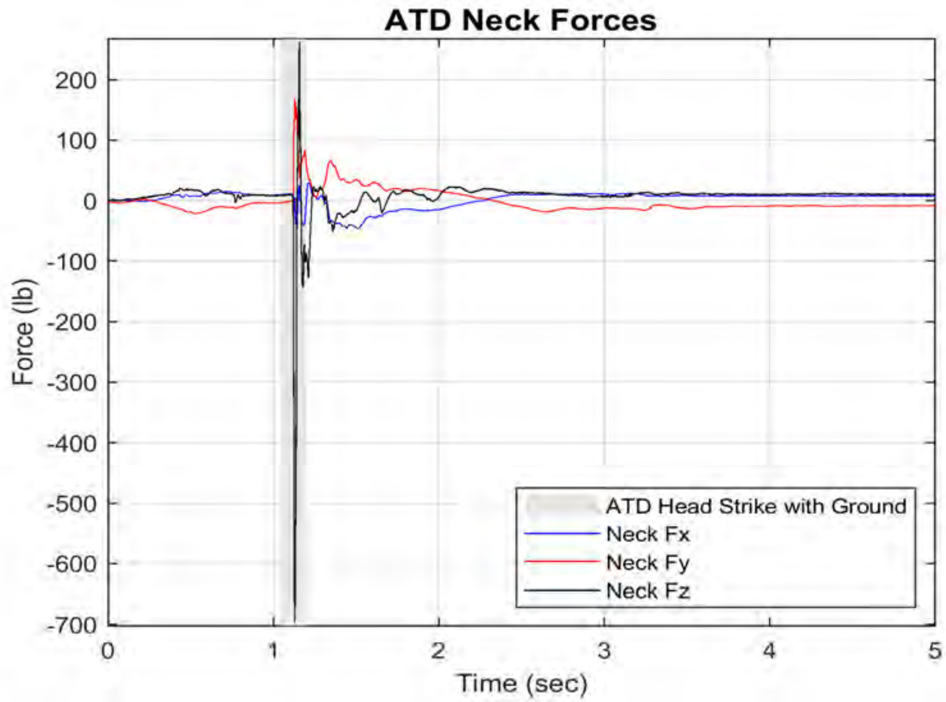
Sled Rollover - Vehicle E - OPD #2C

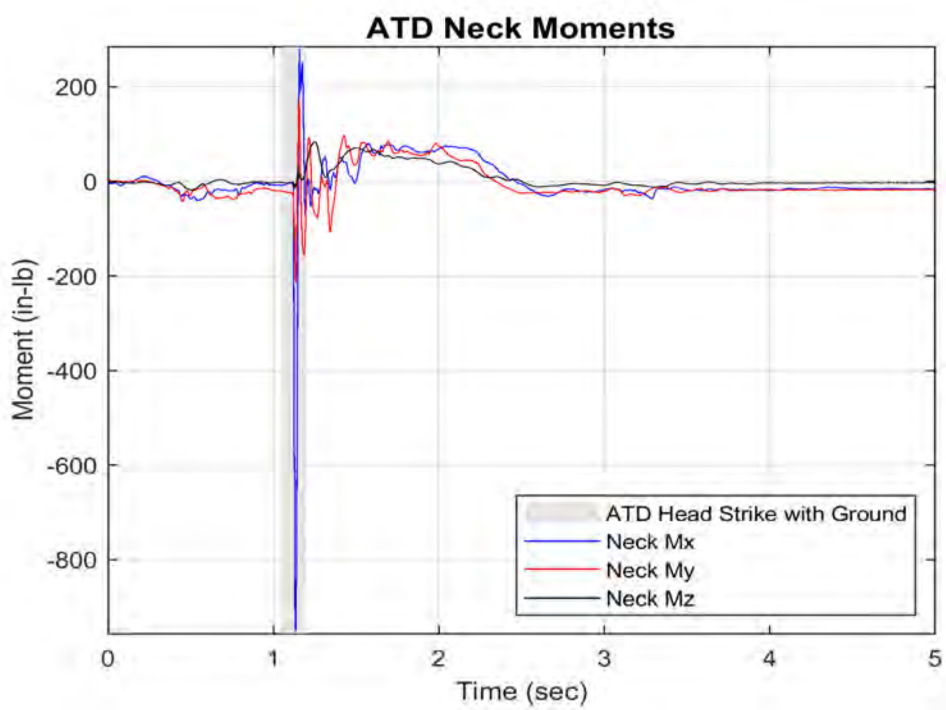




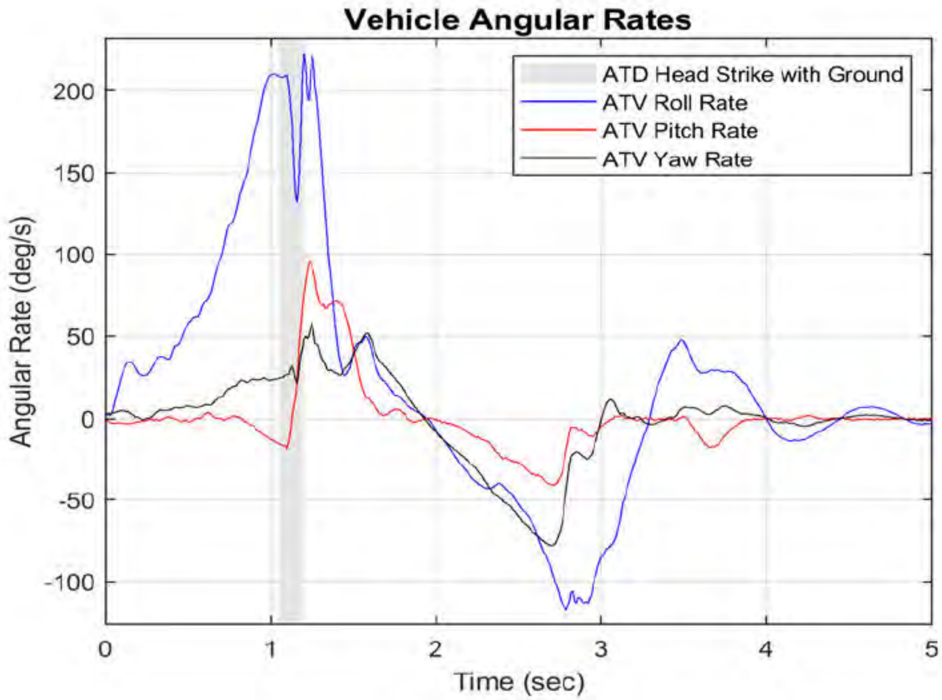


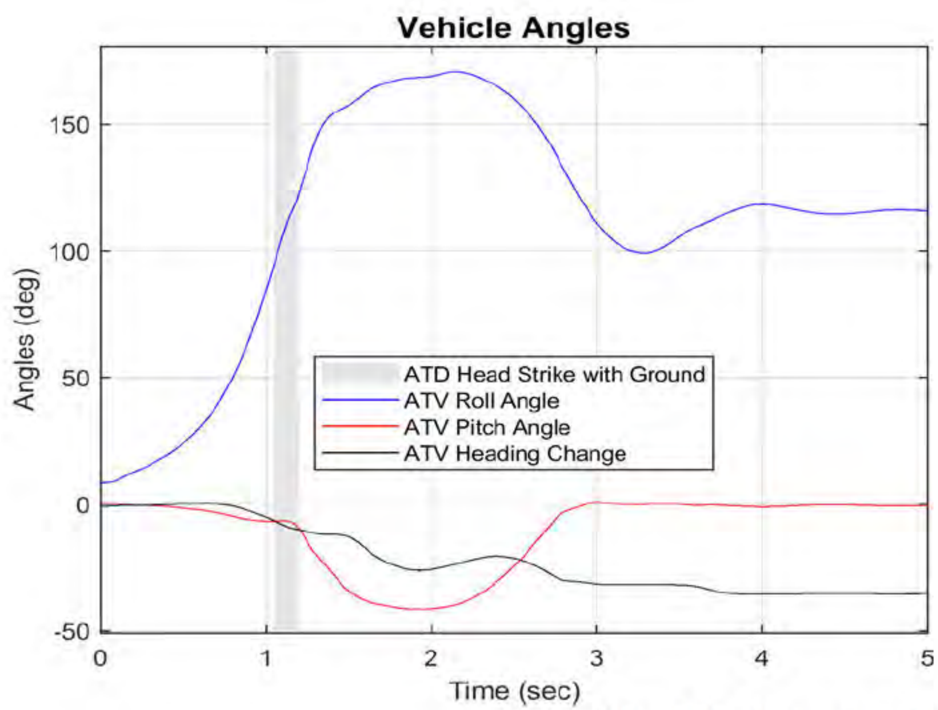
Sled Rollover - Vehicle E - OPD #2C

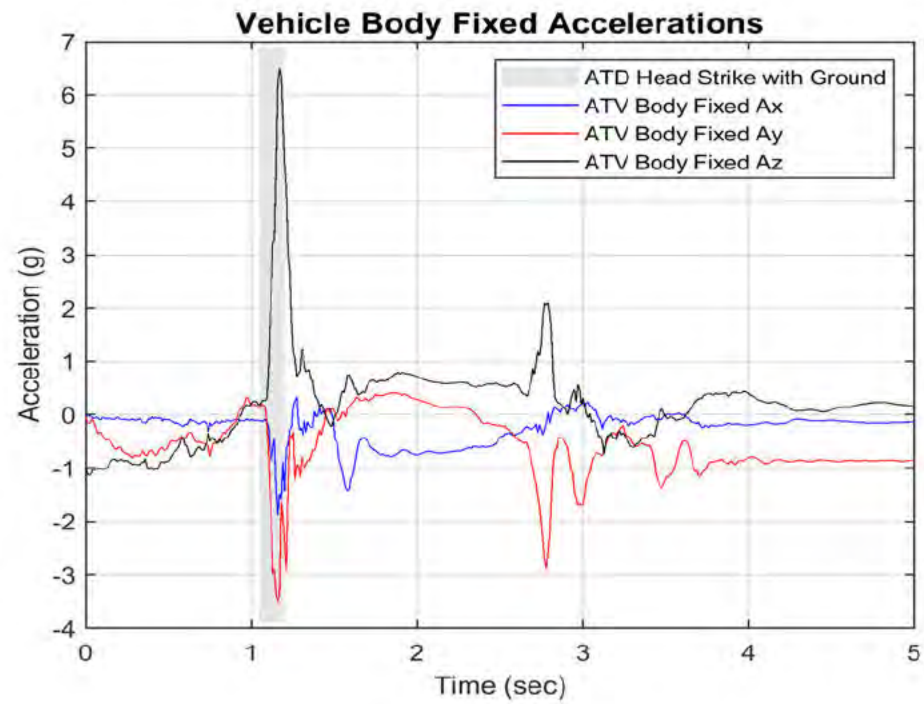




Sled Rollover - Vehicle E - OPD #2C

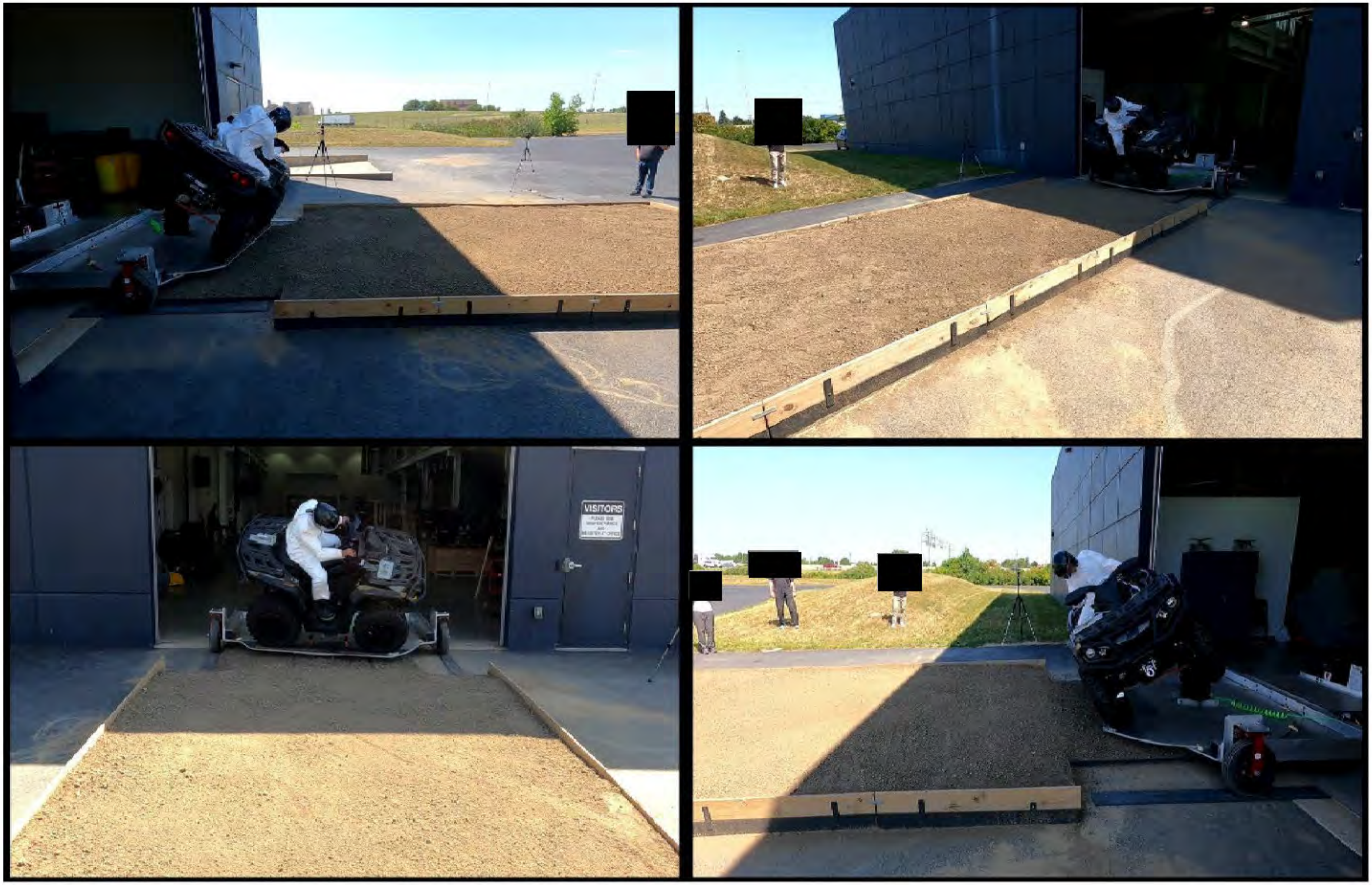






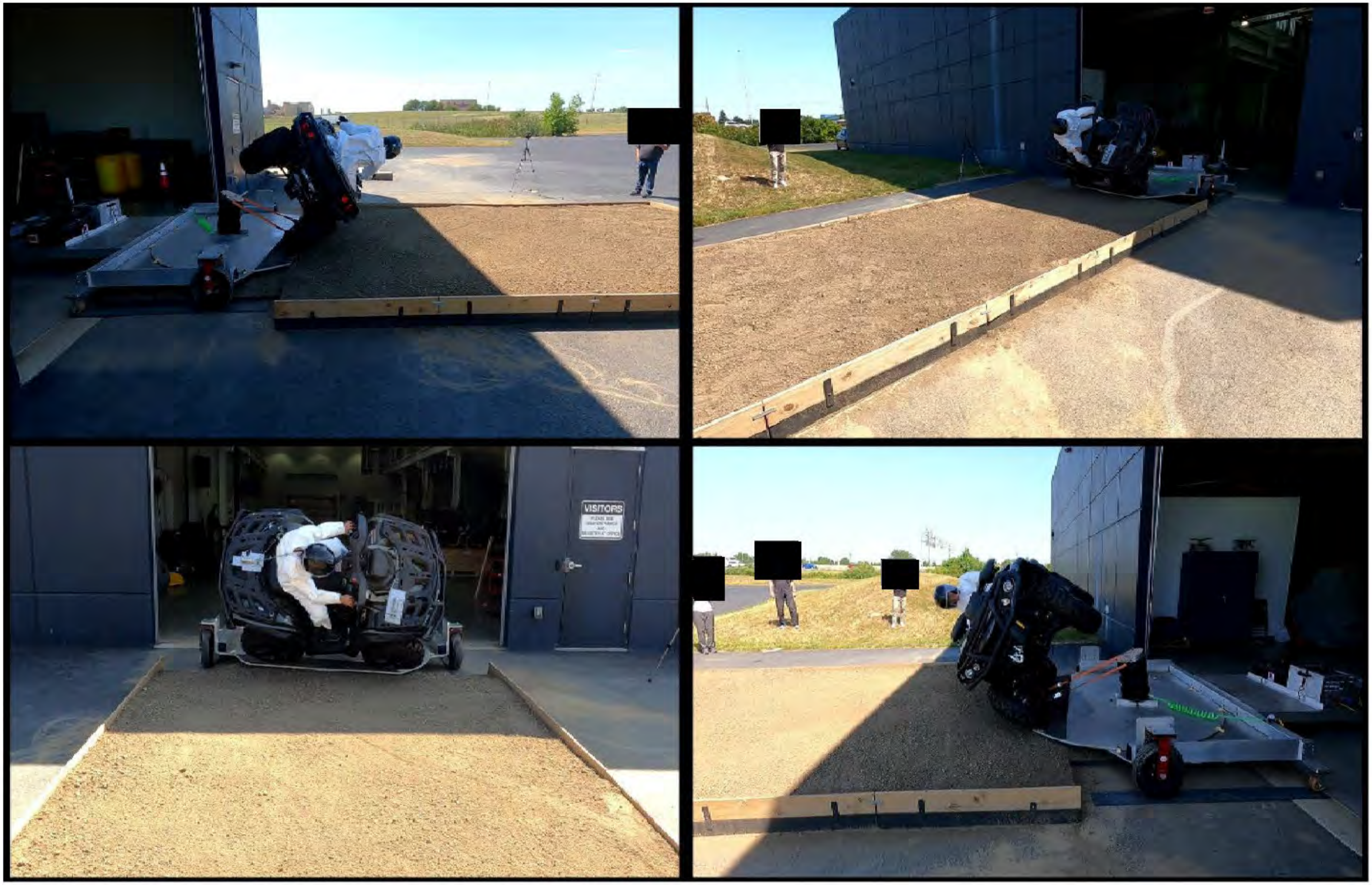
Sled Rollover - Vehicle E - OPD #2C

Roll Angle = 30° - Time = 0.54 sec



Sled Rollover - Vehicle M - NO OPD

Roll Angle = 60° - Time = 0.83 sec

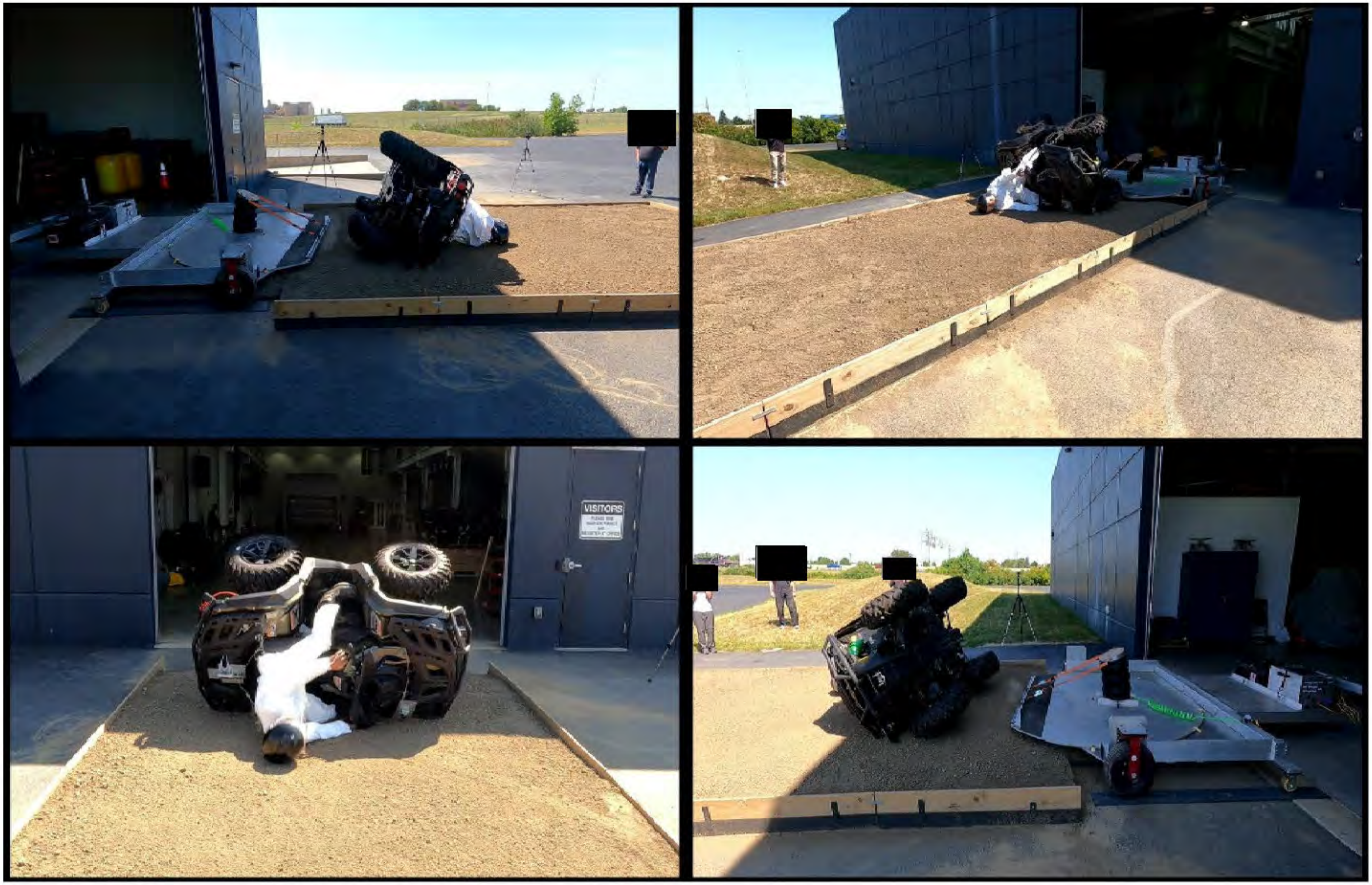


Sled Rollover - Vehicle M - NO OPD

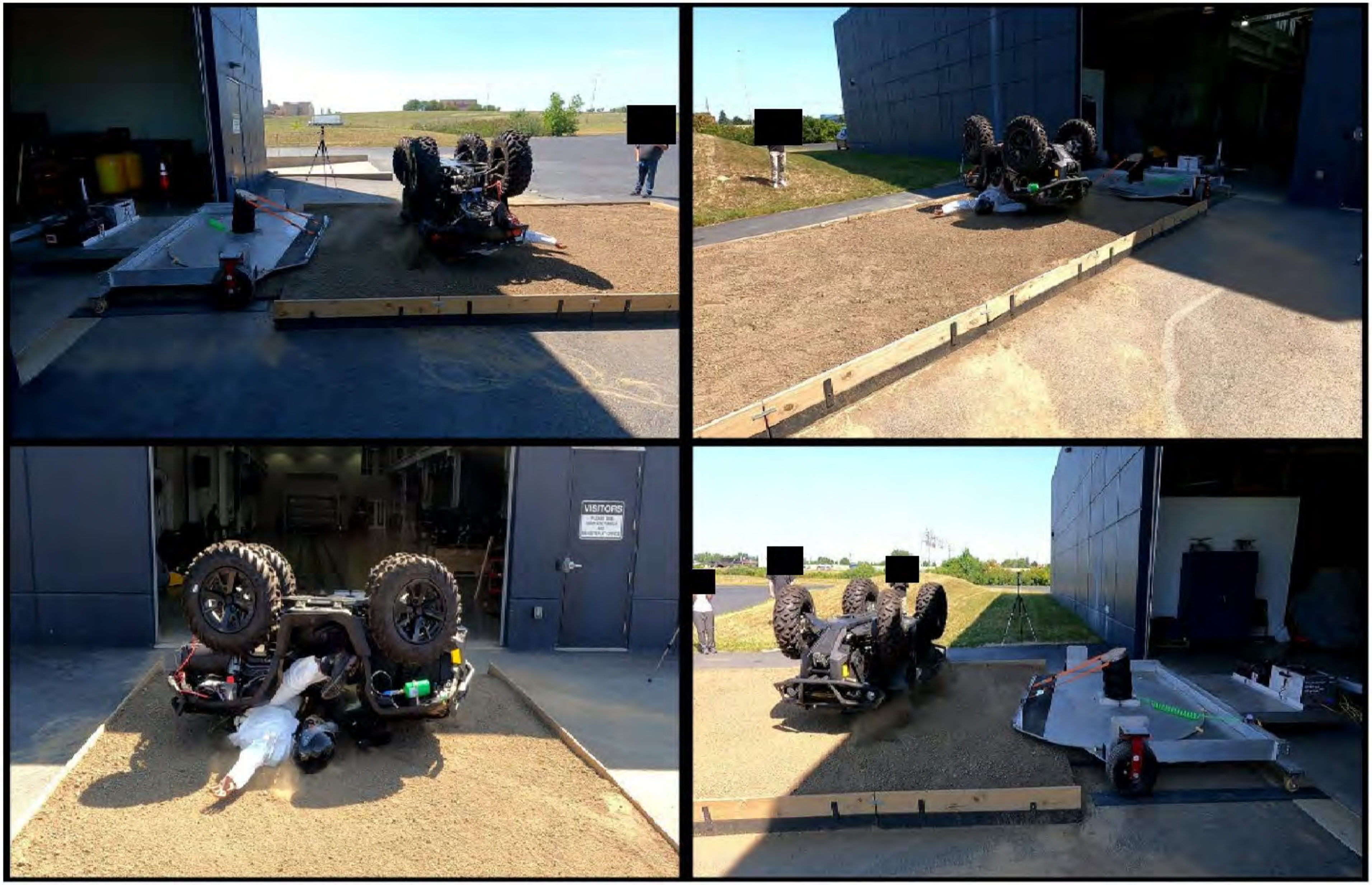
Roll Angle = 90° - Time = 1.00 sec

Sled Rollover - Vehicle M - NO OPD

ATD Head Strike - Time = 1.15 sec

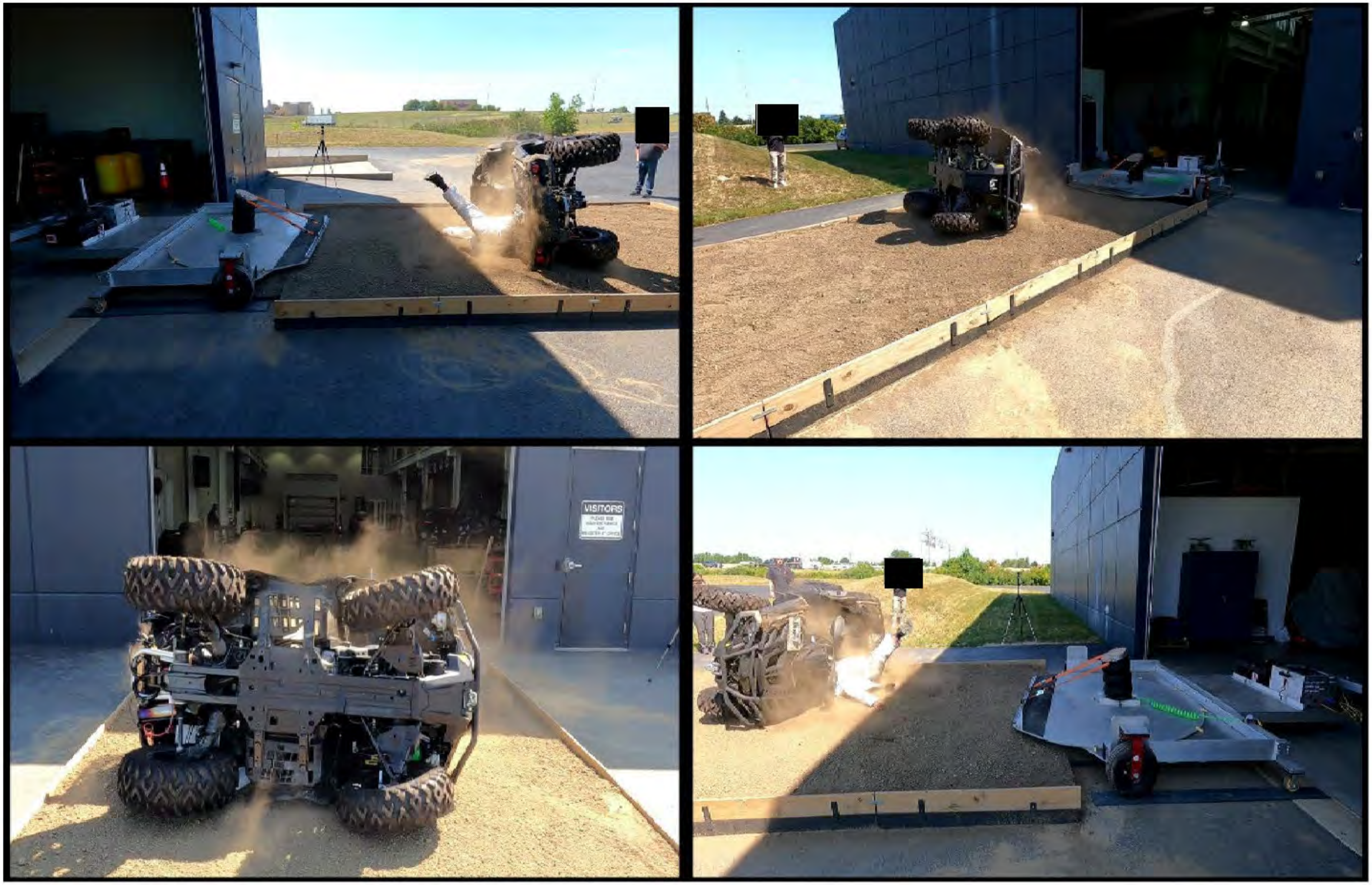


Roll Angle = 180° - Time = 1.39 sec



Sled Rollover - Vehicle M - NO OPD

Roll Angle = 270° - Time = 2.02 sec

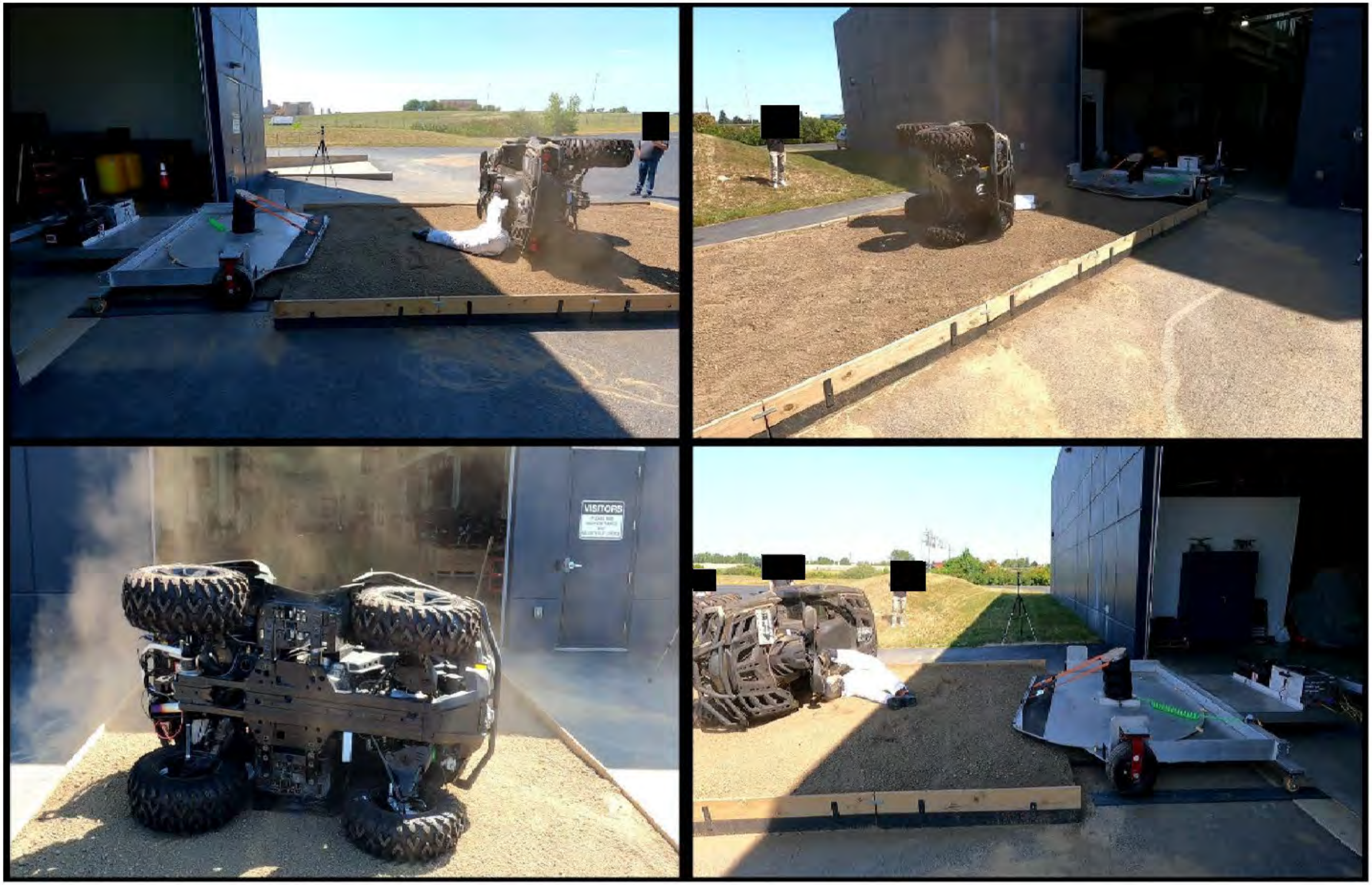


Sled Rollover - Vehicle M - NO OPD

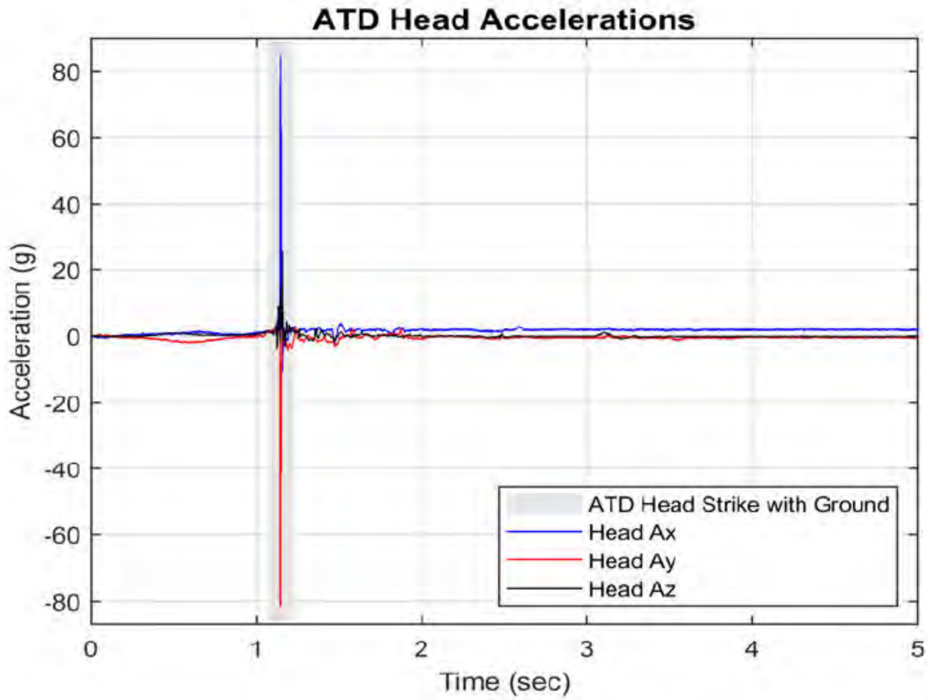
Max Roll Angle = 300.4° - Time = 2.63 sec

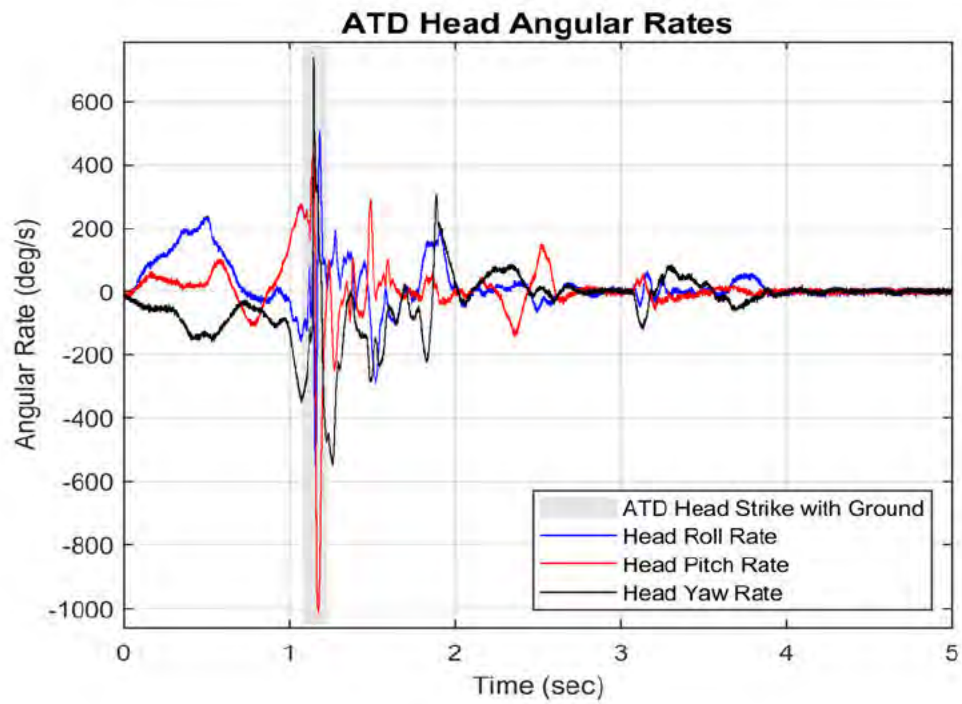
Sled Rollover - Vehicle M - NO OPD

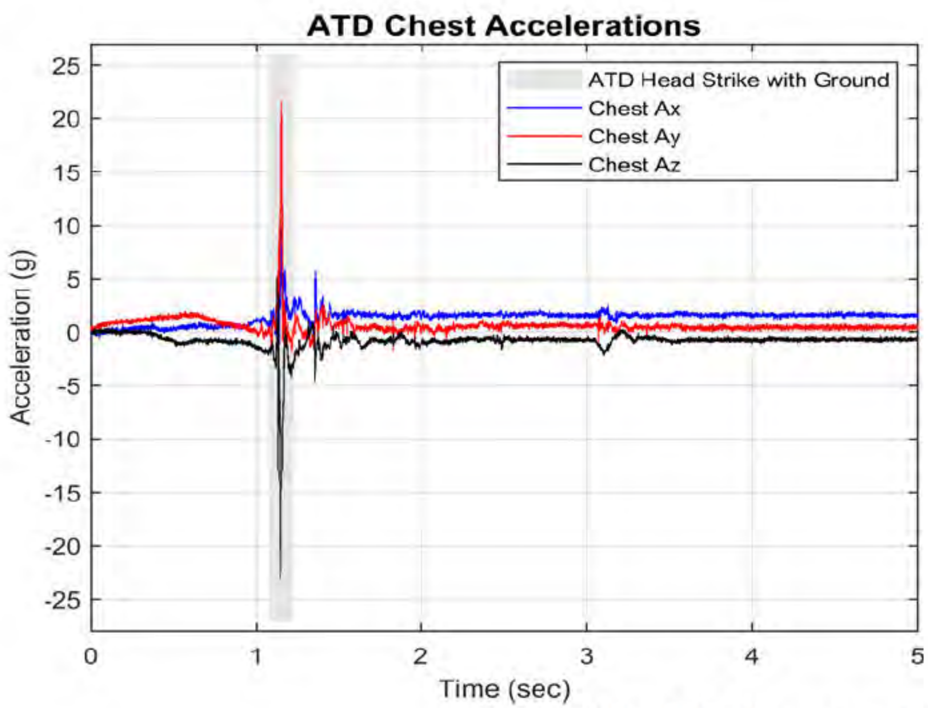
End of Run - Roll Angle = 274.0°



Sled Rollover - Vehicle M - NO OPD







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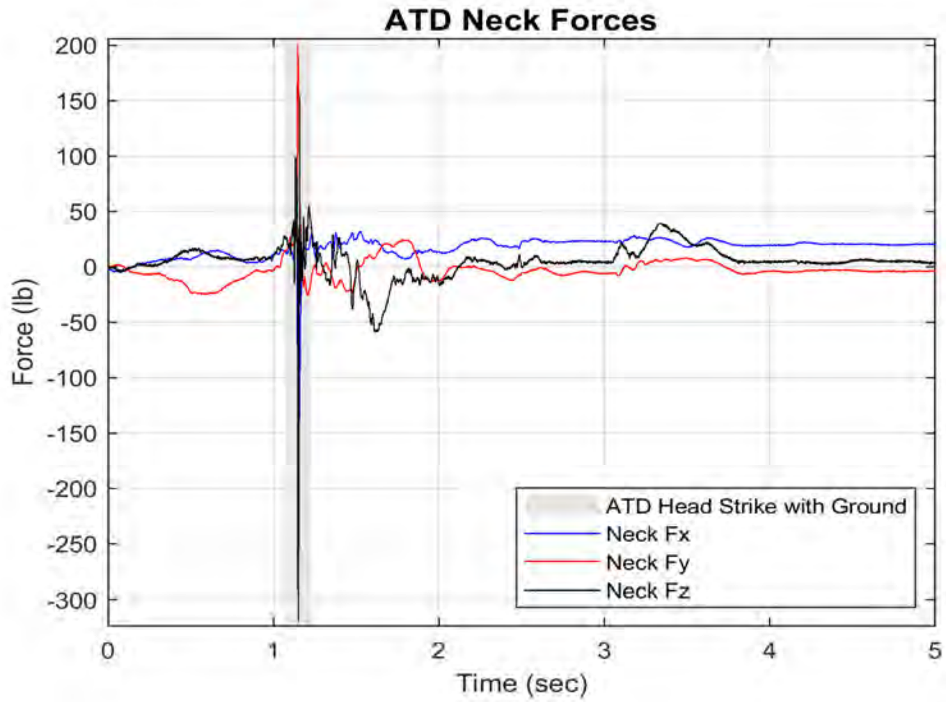

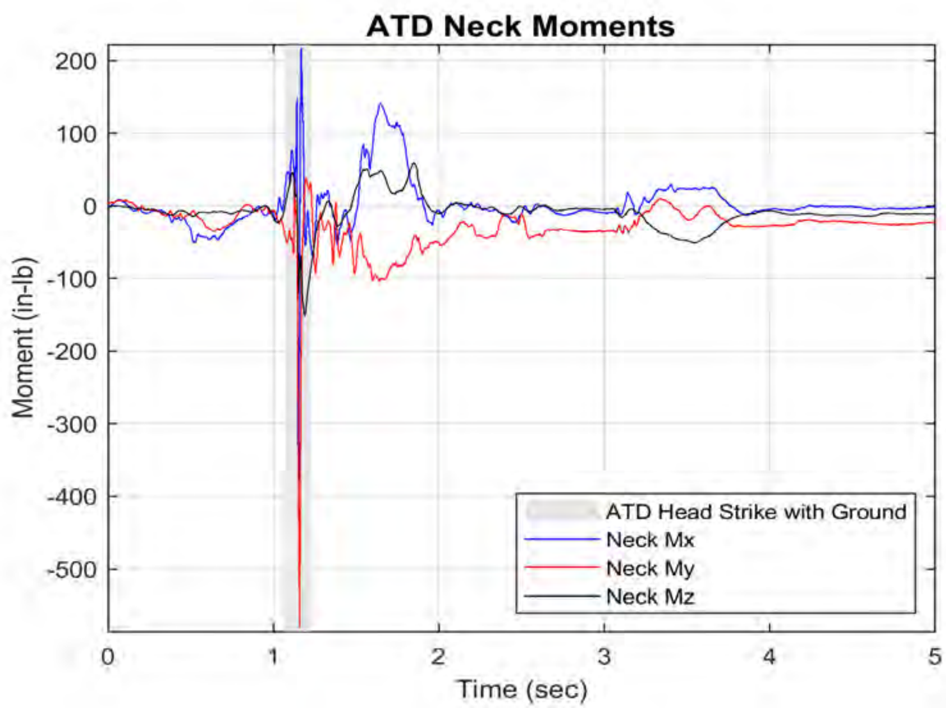

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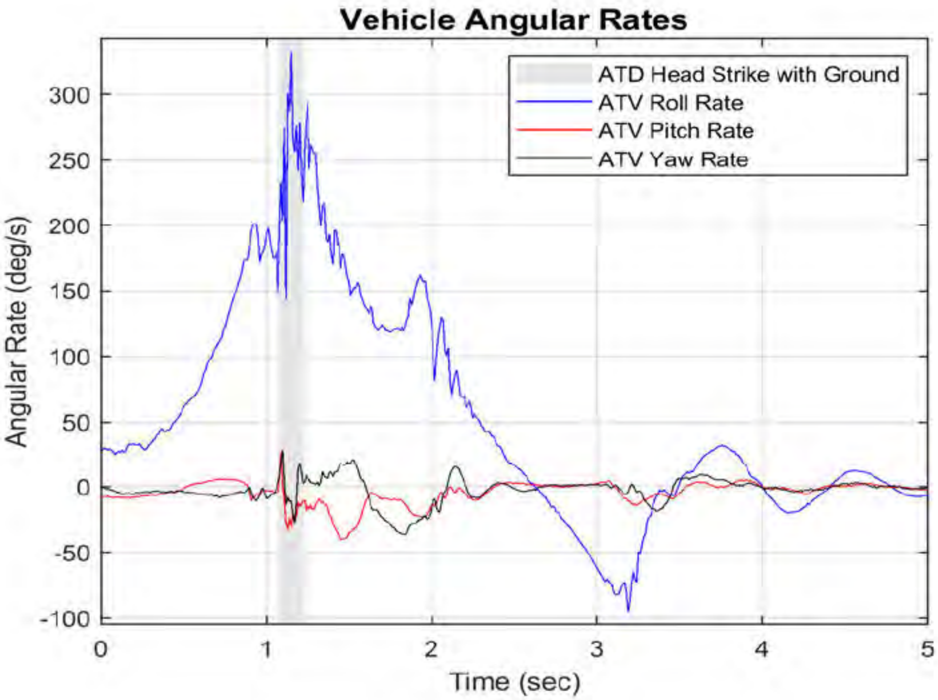
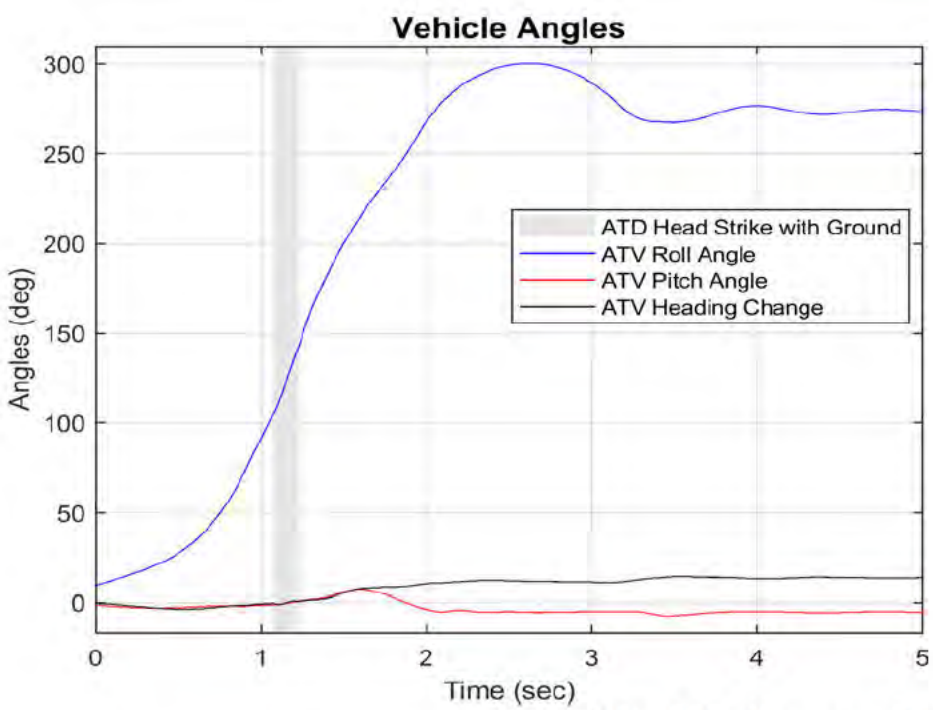
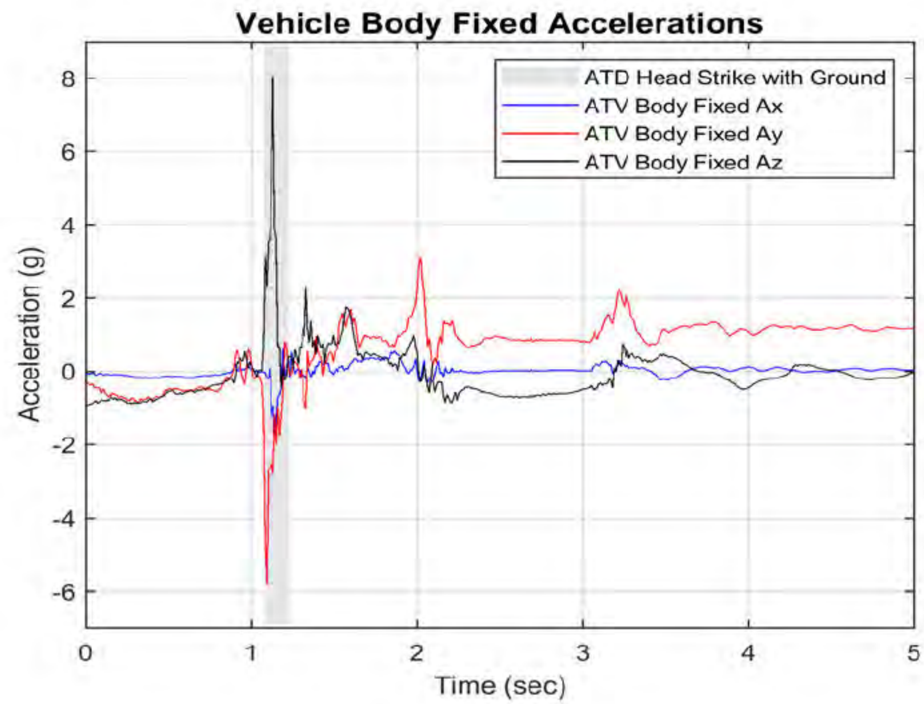
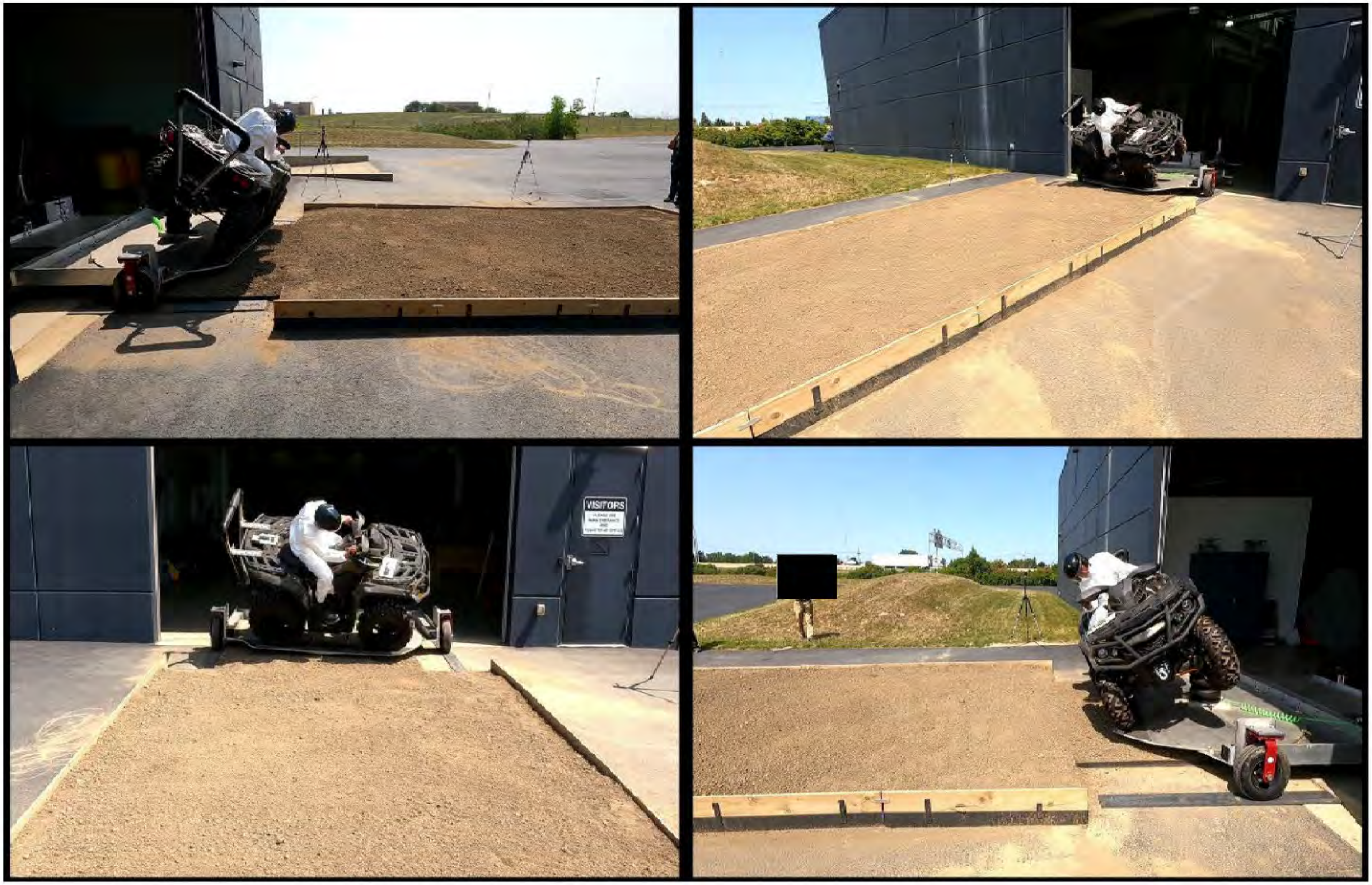






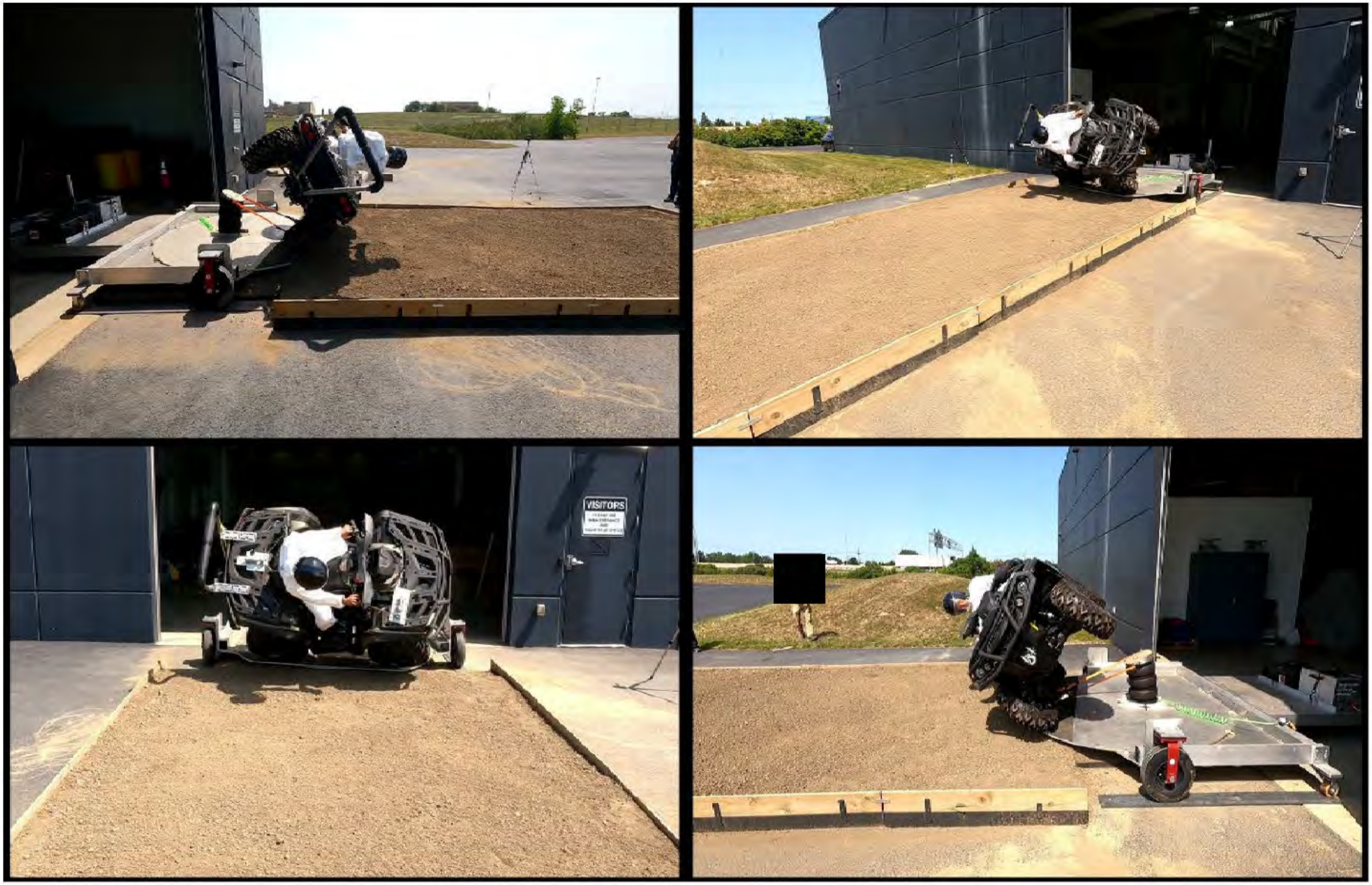
Sled Rollover - Vehicle M - NO OPD

Roll Angle = 30° - Time = 0.64 sec



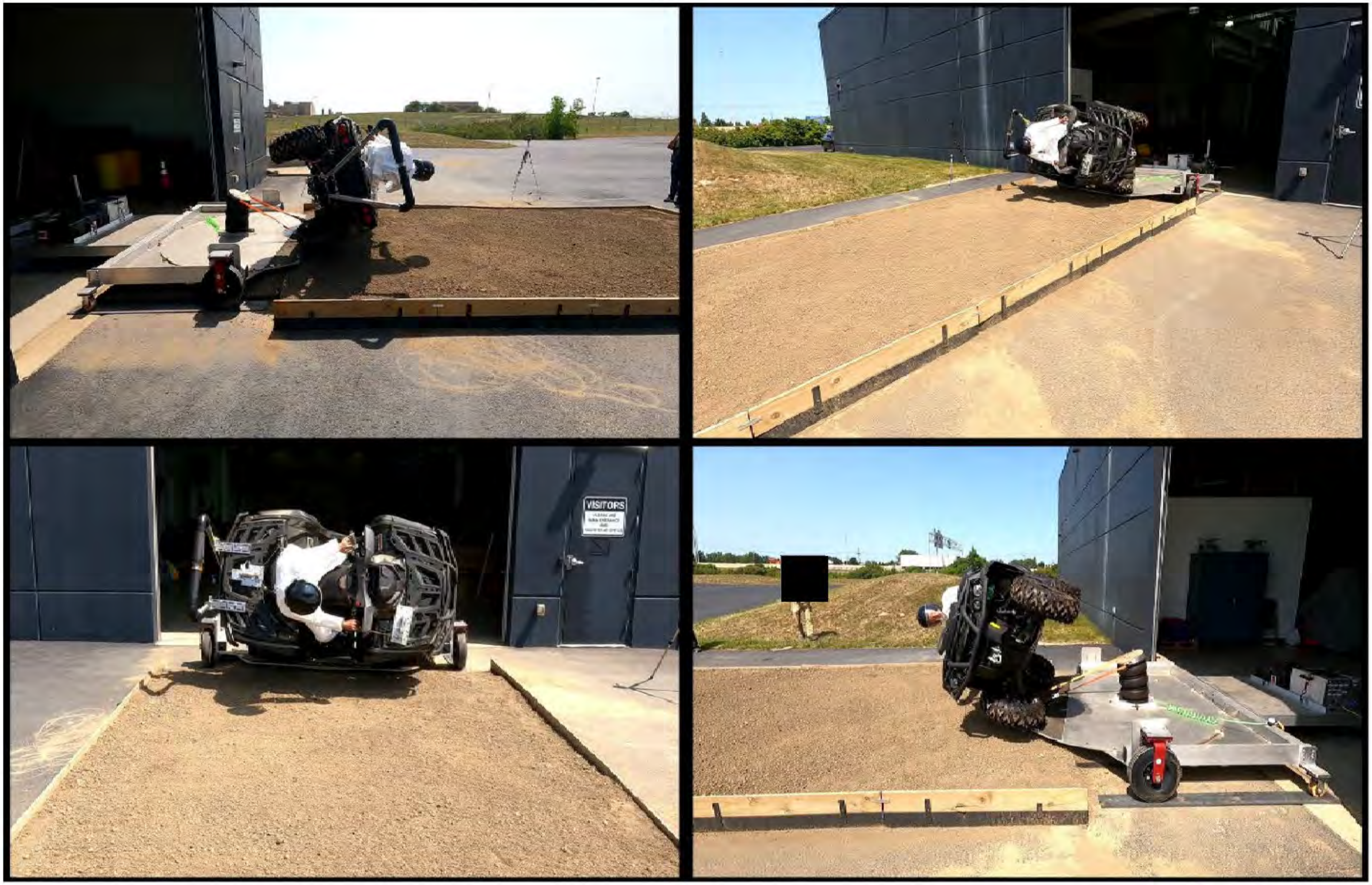
Sled Rollover - Vehicle M - AM OPD

Roll Angle = 60° - Time = 0.92 sec



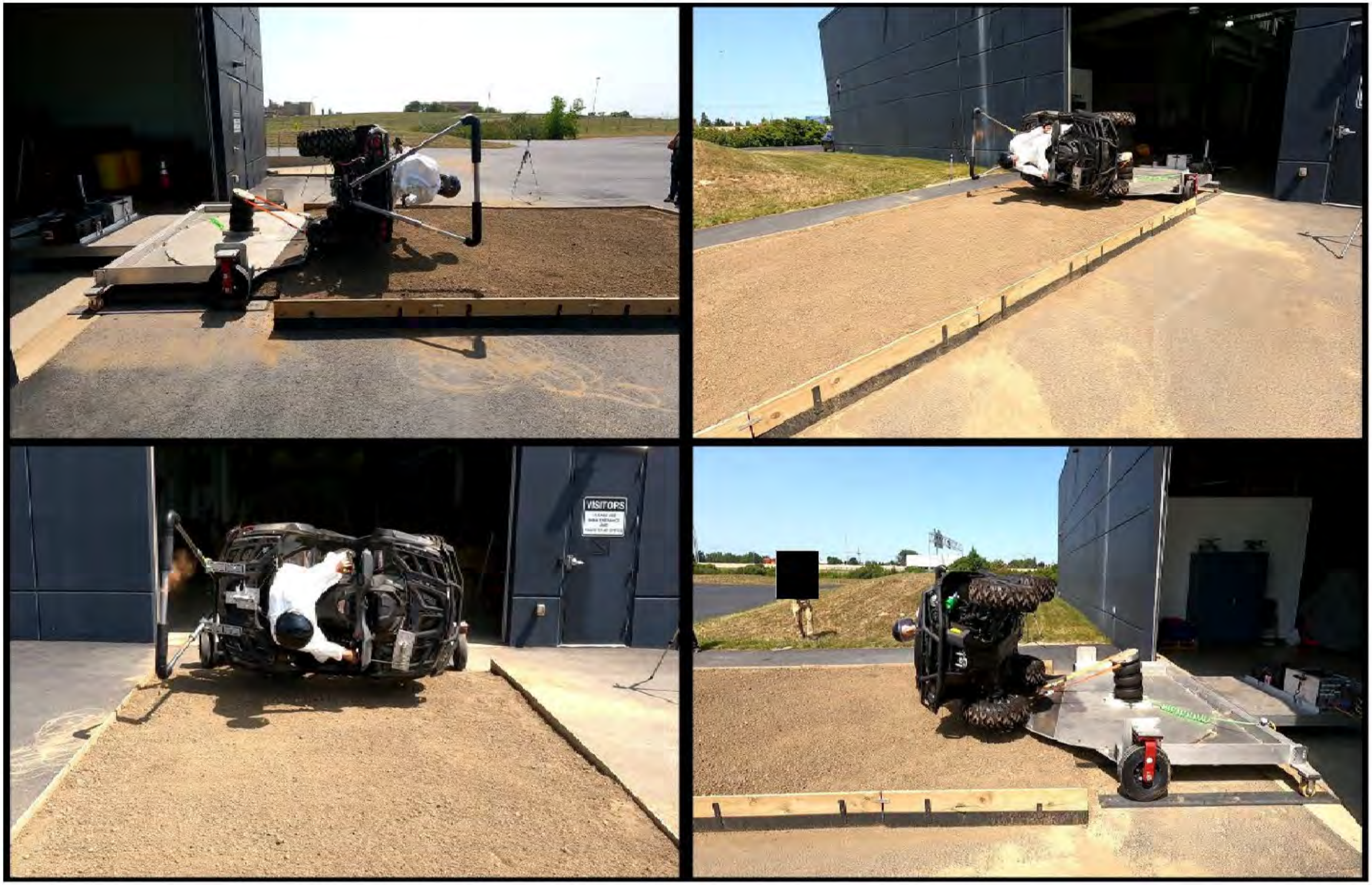
Sled Rollover - Vehicle M - AM OPD

OPD First Expanding - Time = 1.00 sec - Roll Angle = 74.4°



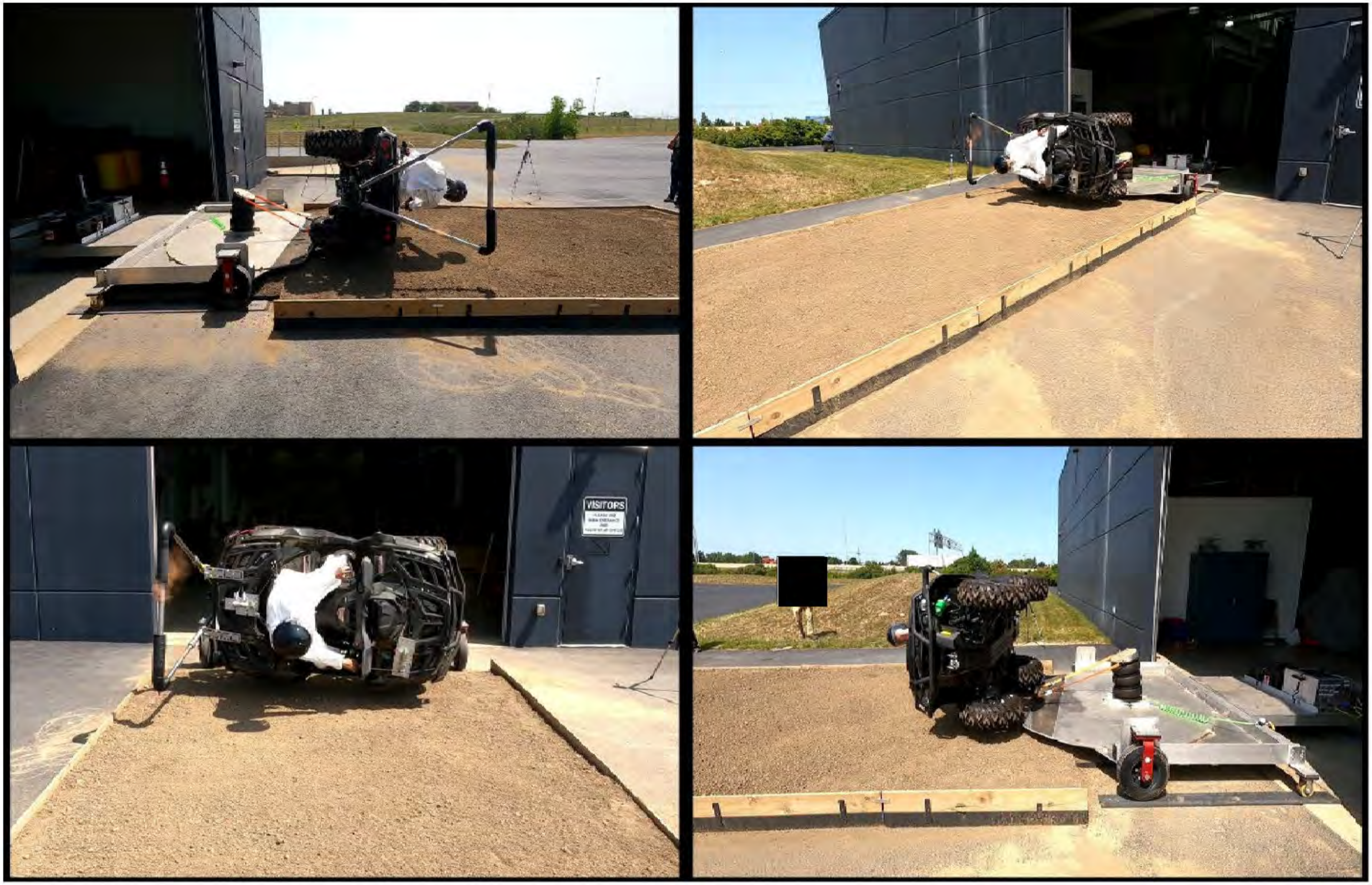
Sled Rollover - Vehicle M - AM OPD

OPD Fully Expanded - Time = 1.07 sec - Roll Angle = 87.4°



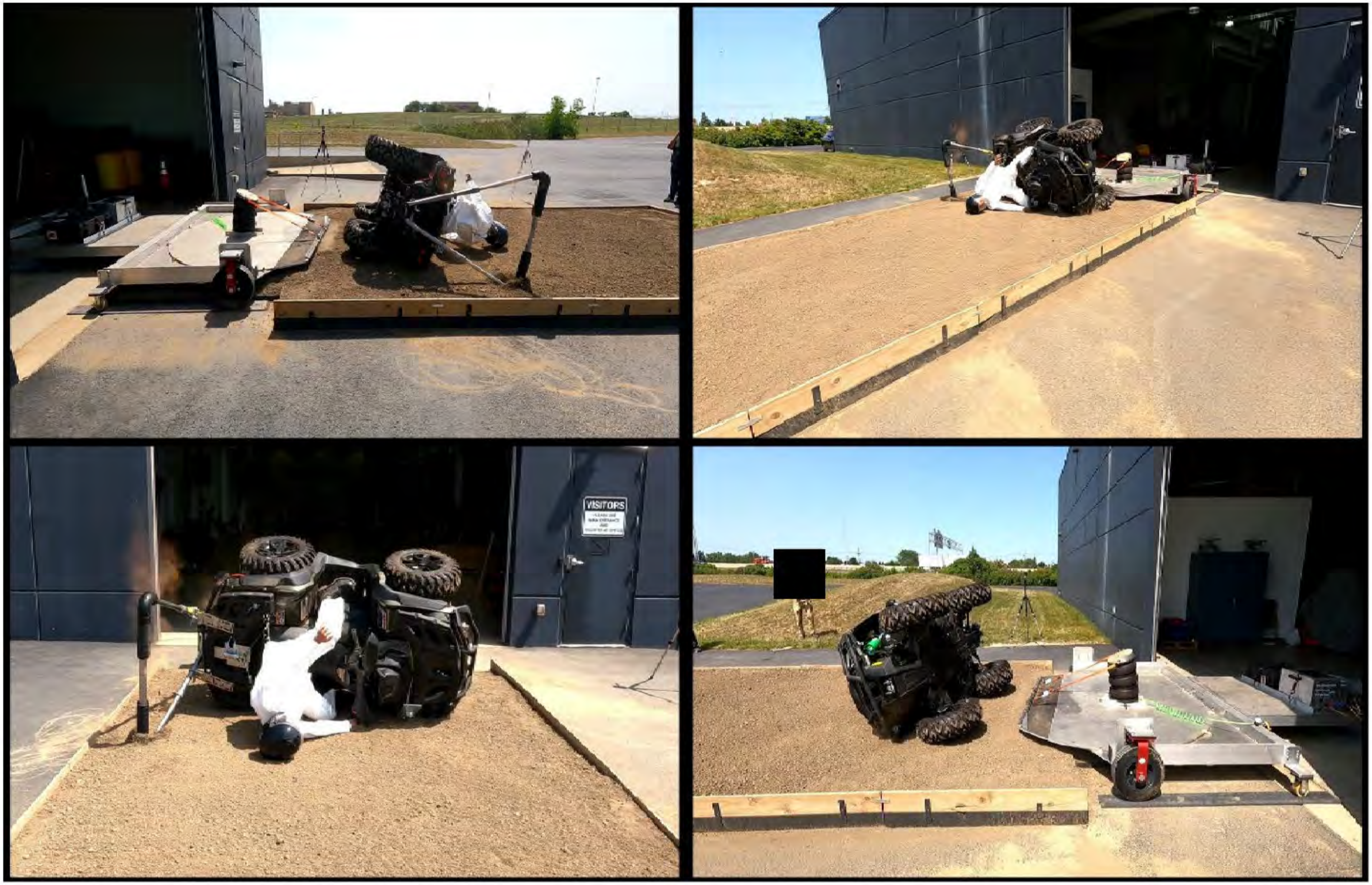
Sled Rollover - Vehicle M - AM OPD

Roll Angle = 90° - Time = 1.09 sec



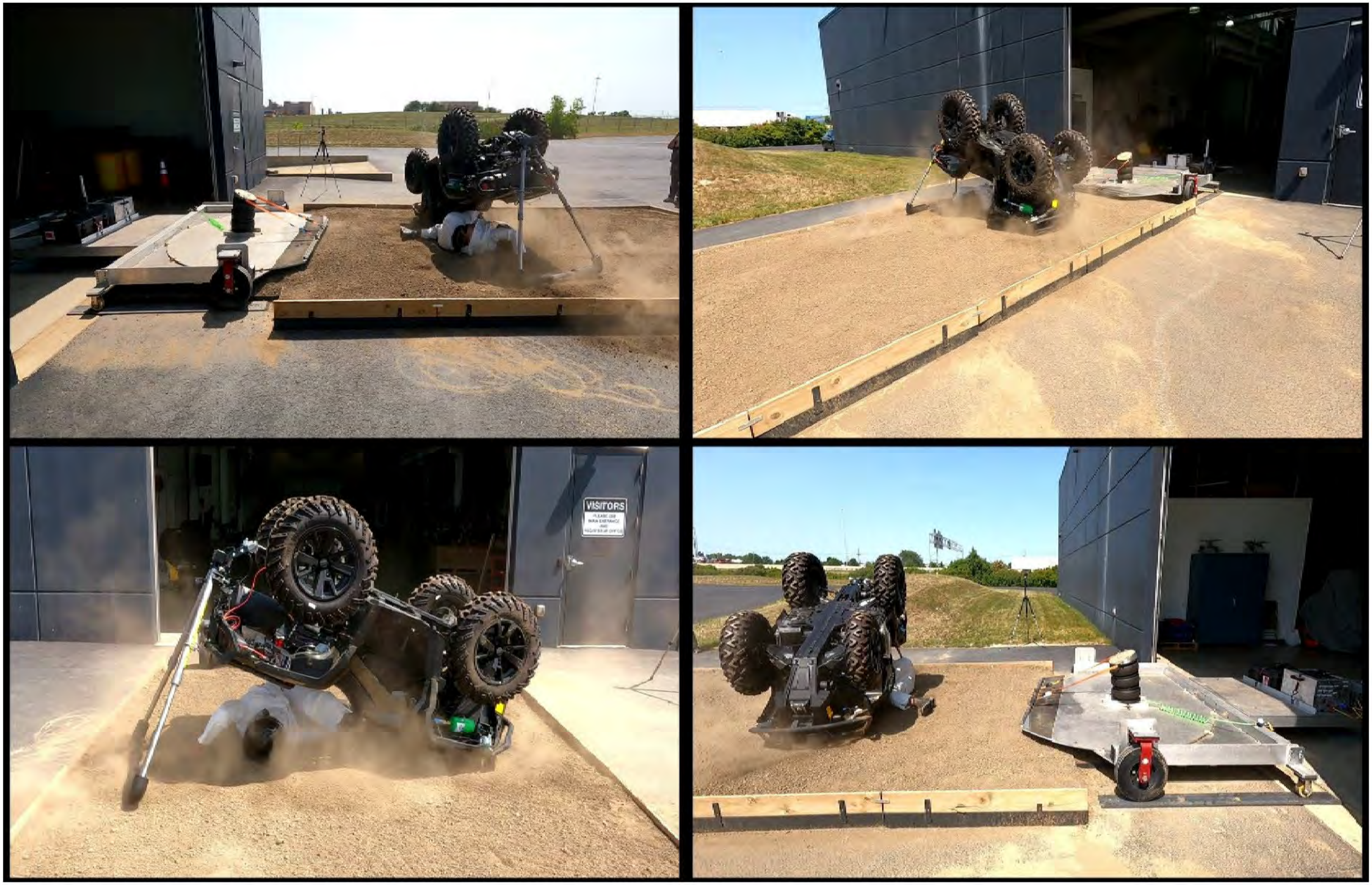
Sled Rollover - Vehicle M - AM OPD

ATD Head Strike - Time = 1.21 sec



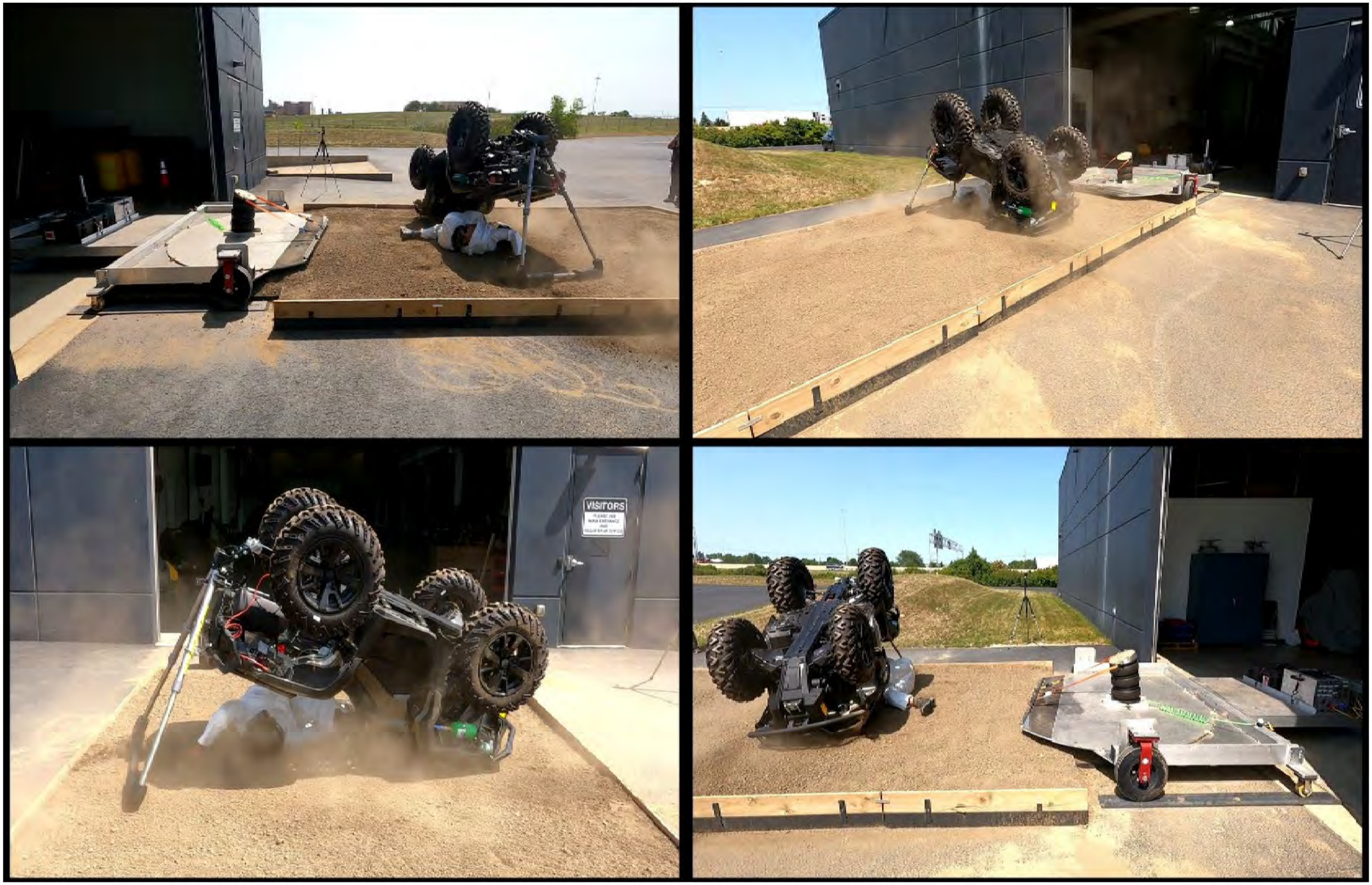
Sled Rollover - Vehicle M - AM OPD

Roll Angle = 180° - Time = 2.38 sec



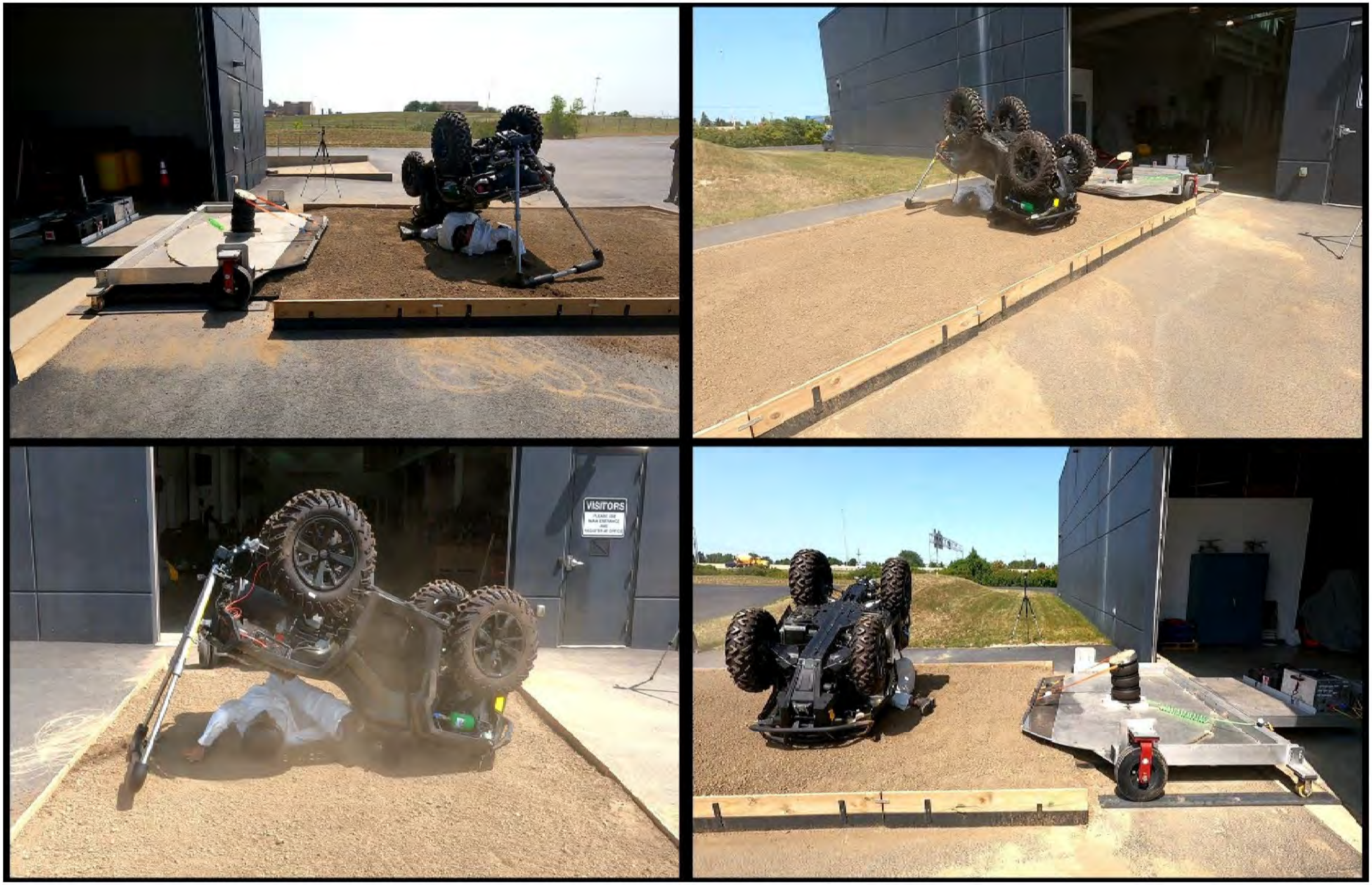
Sled Rollover - Vehicle M - AM OPD

Max Roll Angle = 184.6° - Time = 2.63 sec

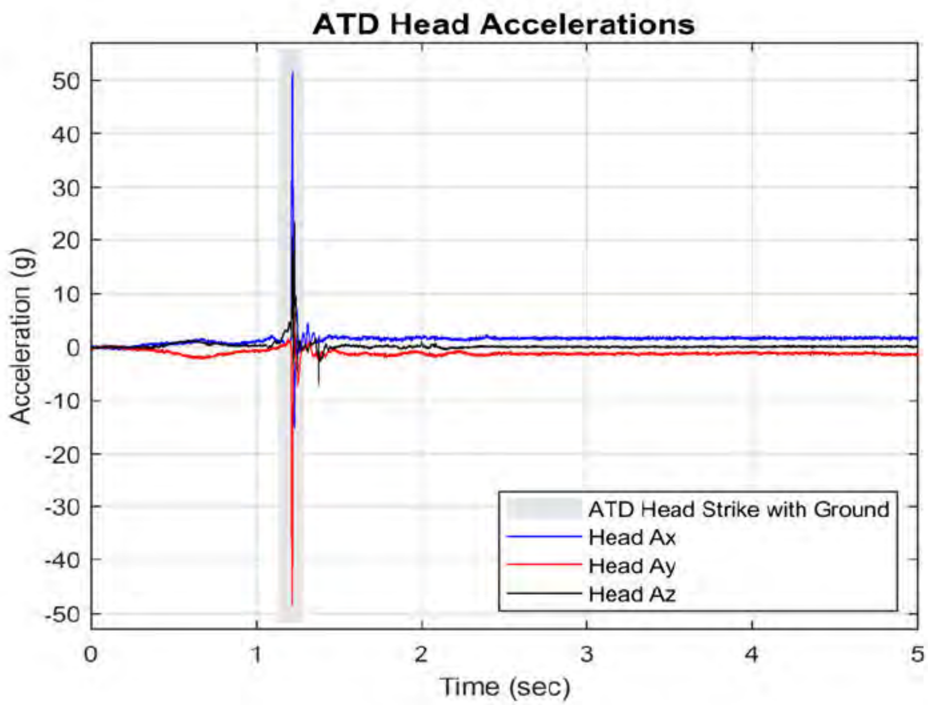


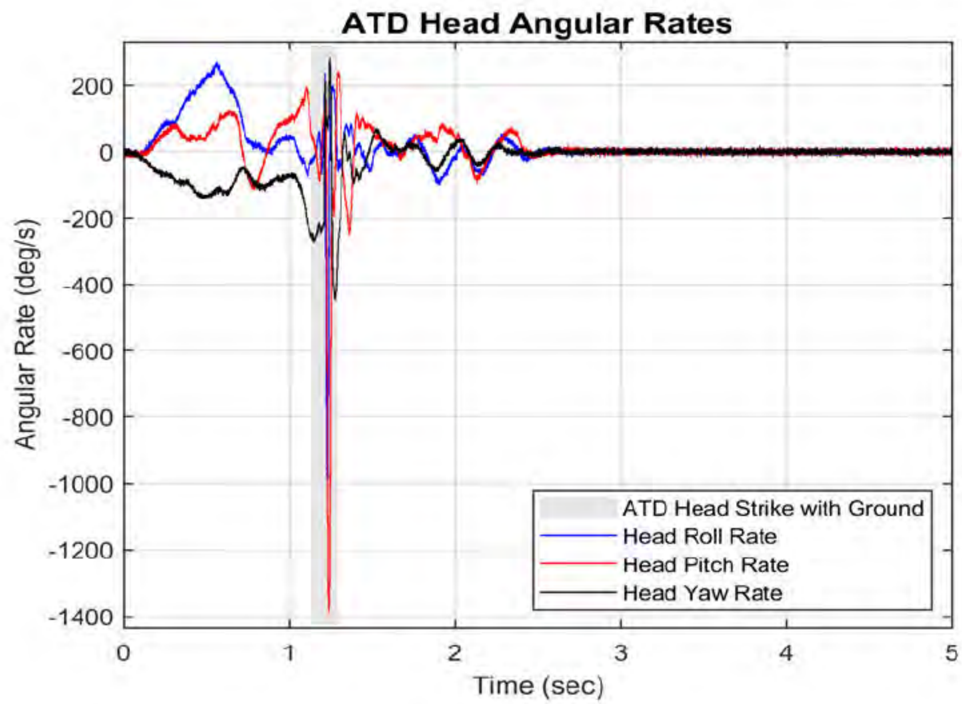
Sled Rollover - Vehicle M - AM OPD

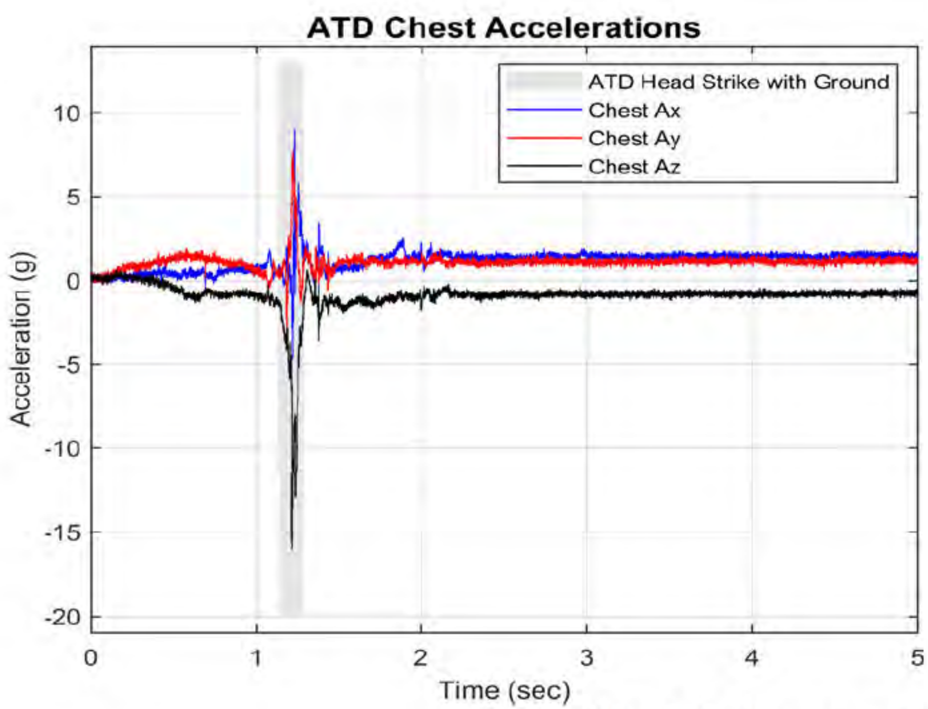
End of Run - Roll Angle = 176.1°



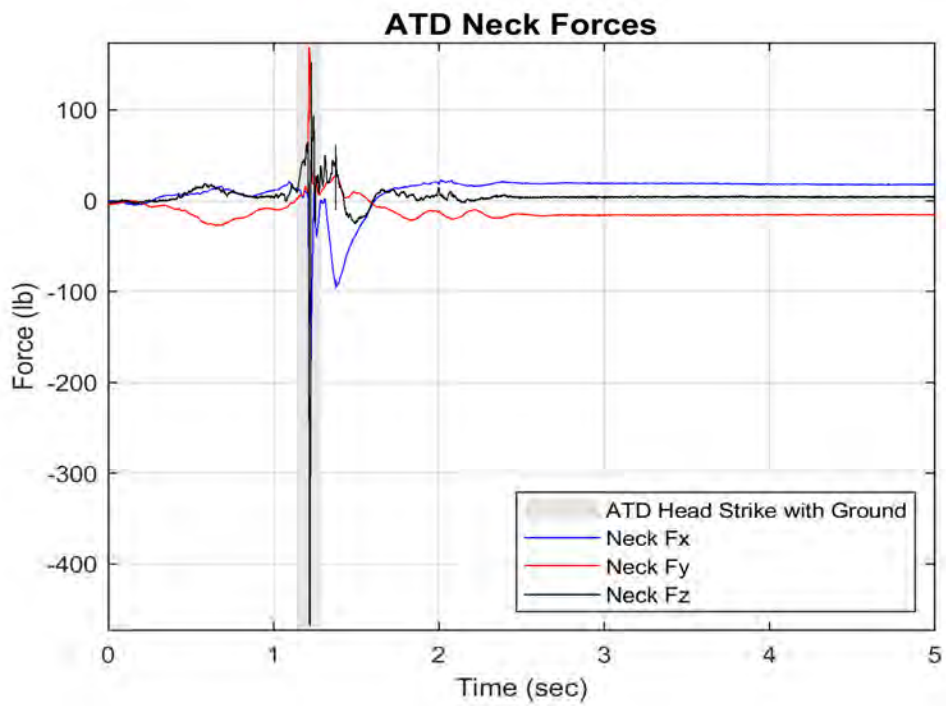
Sled Rollover - Vehicle M - AM OPD

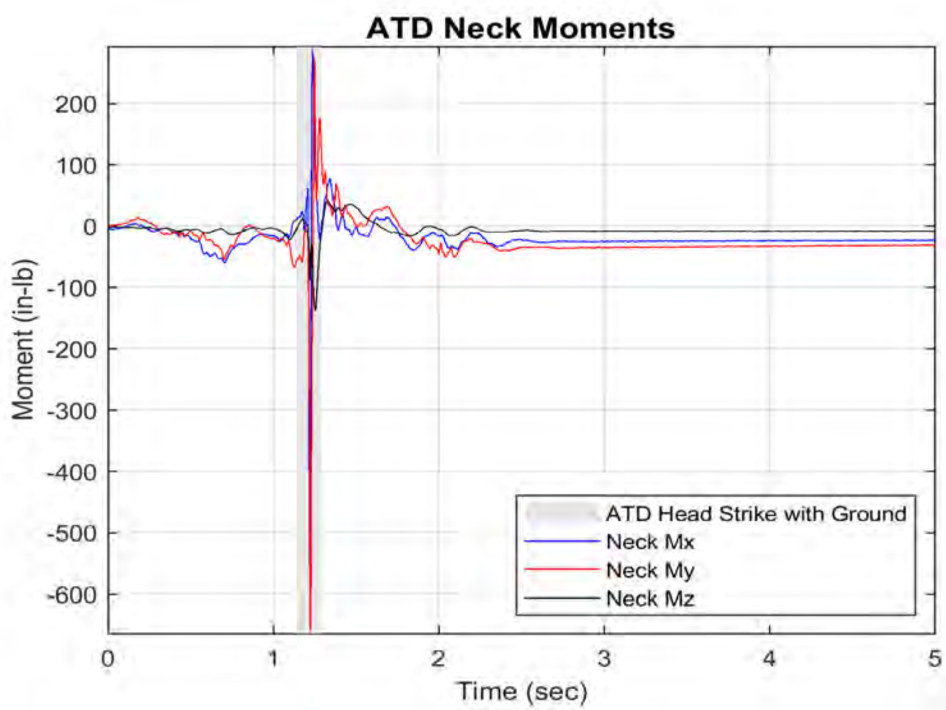




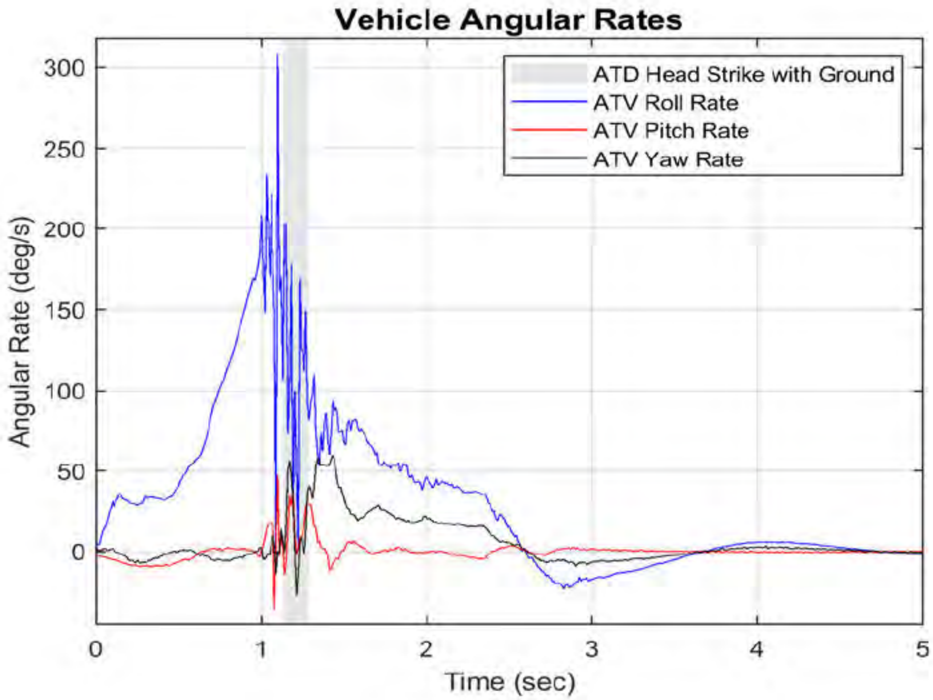


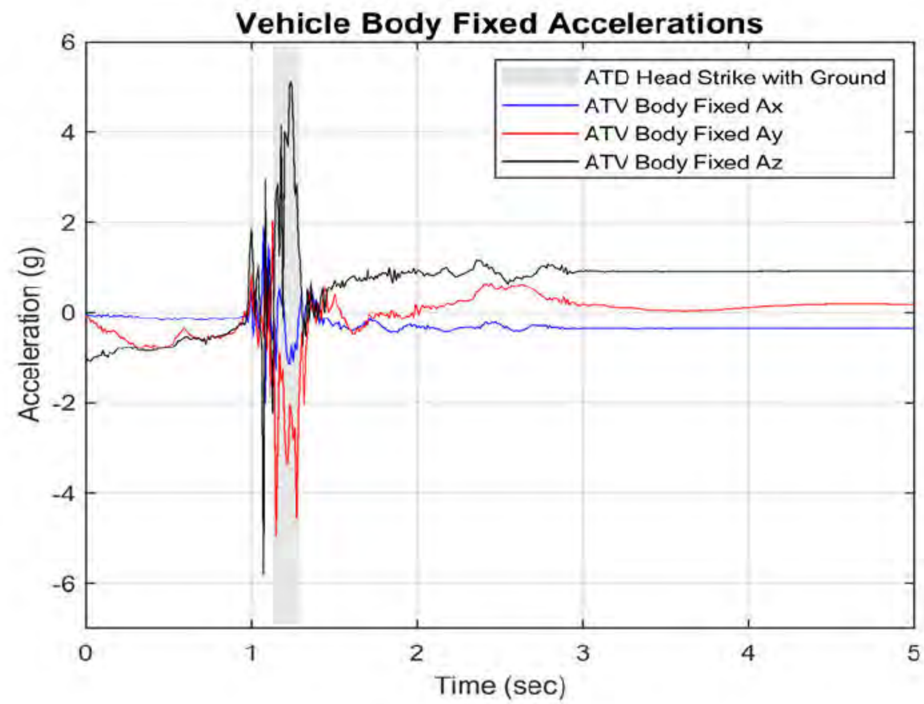
Sled Rollover - Vehicle M - AM OPD

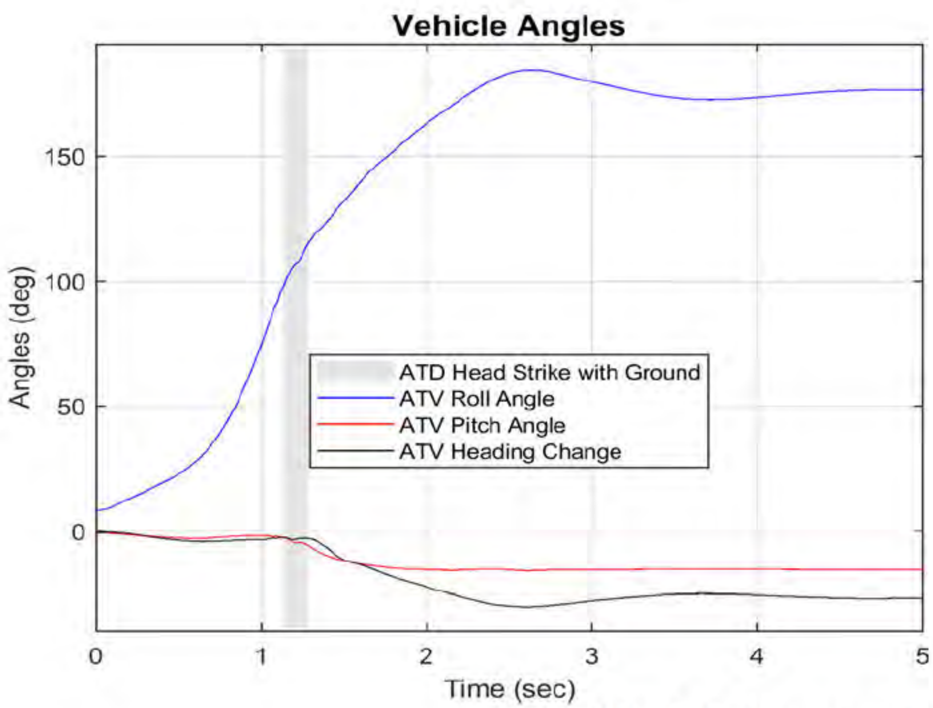




Sled Rollover - Vehicle M - AM OPD





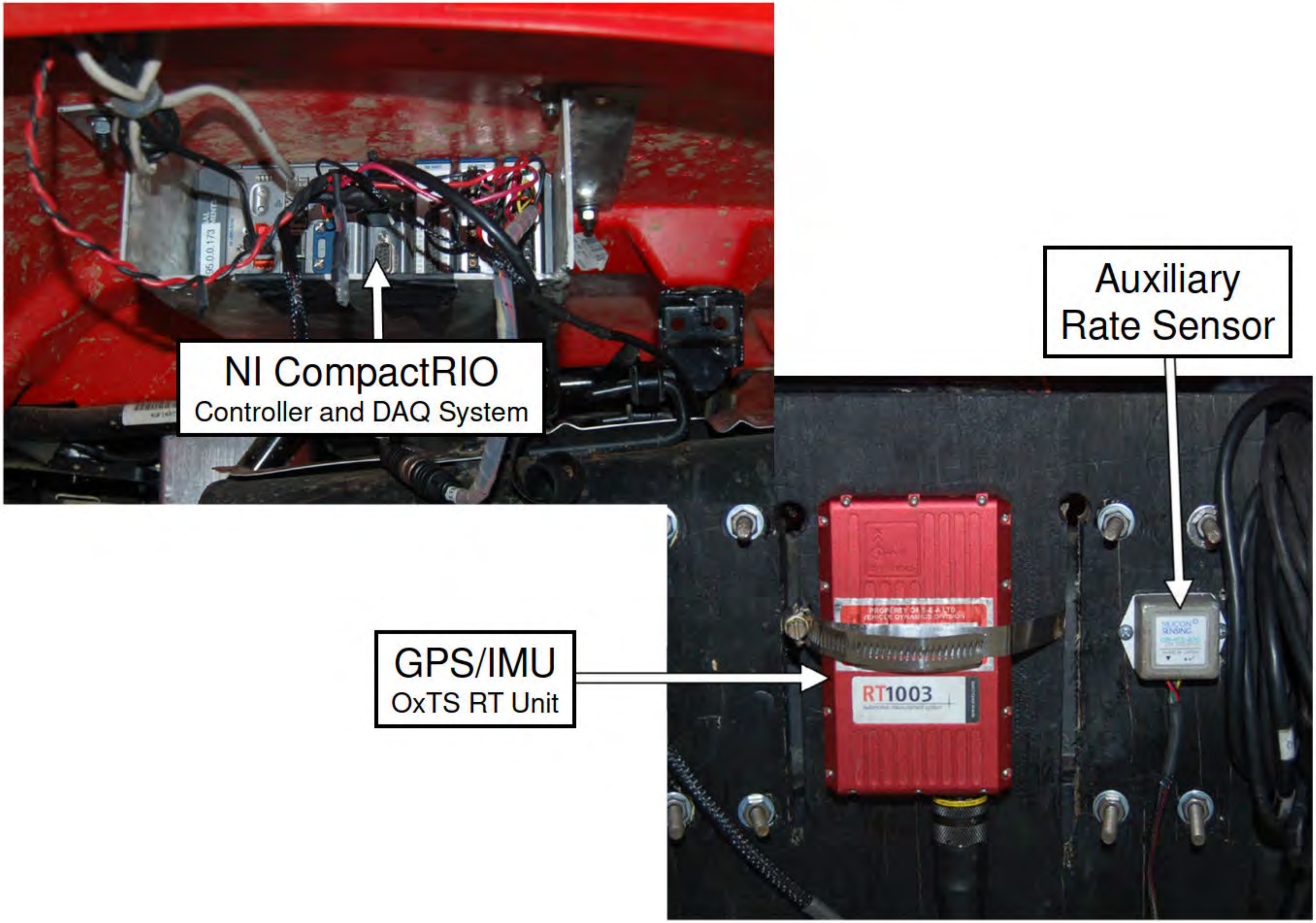


Sled Rollover - Vehicle M - AM OPD

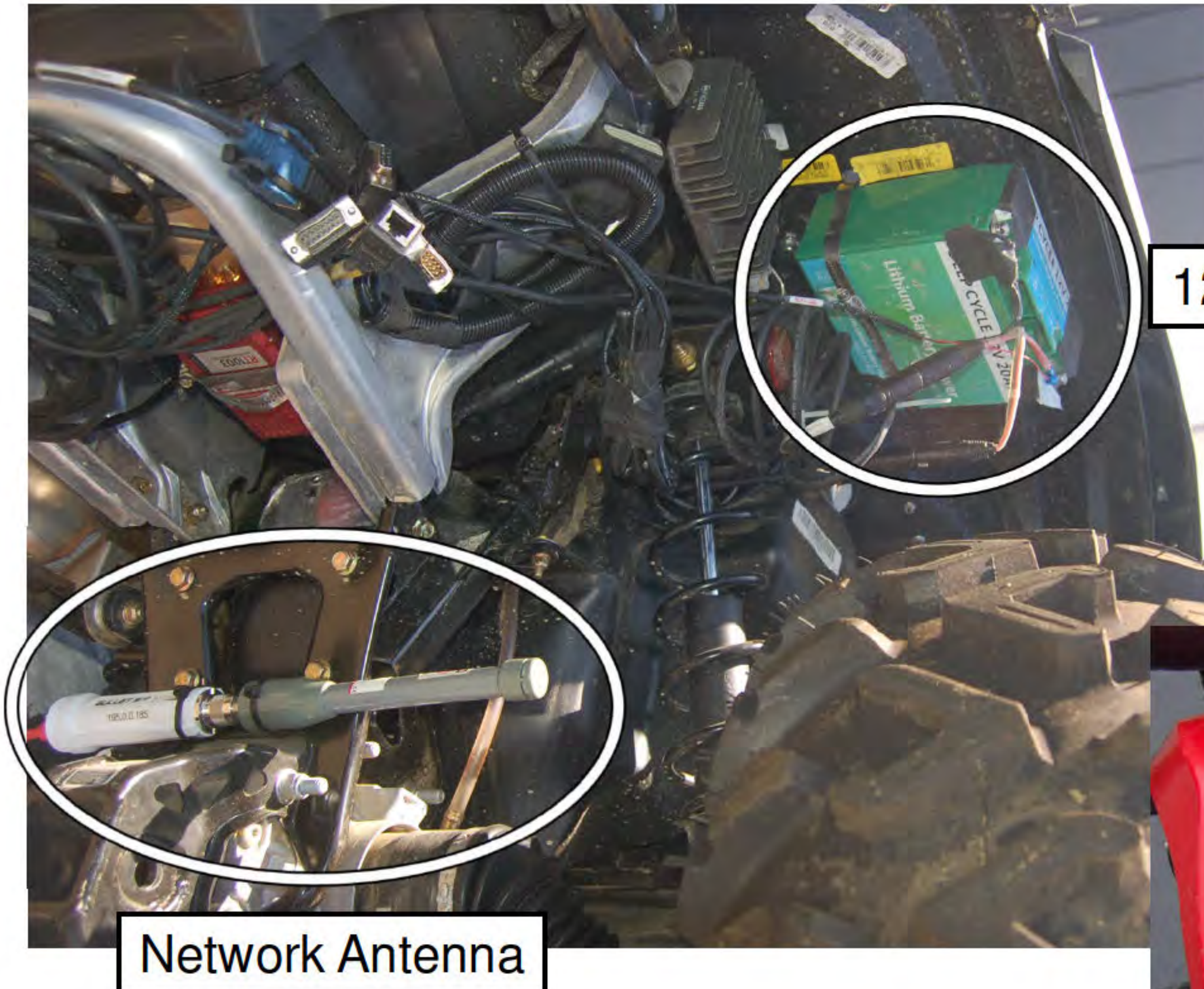
Photographs of Vehicles on SEA VIMF Platform

Photographs of Vehicles on SEA Tilt Table

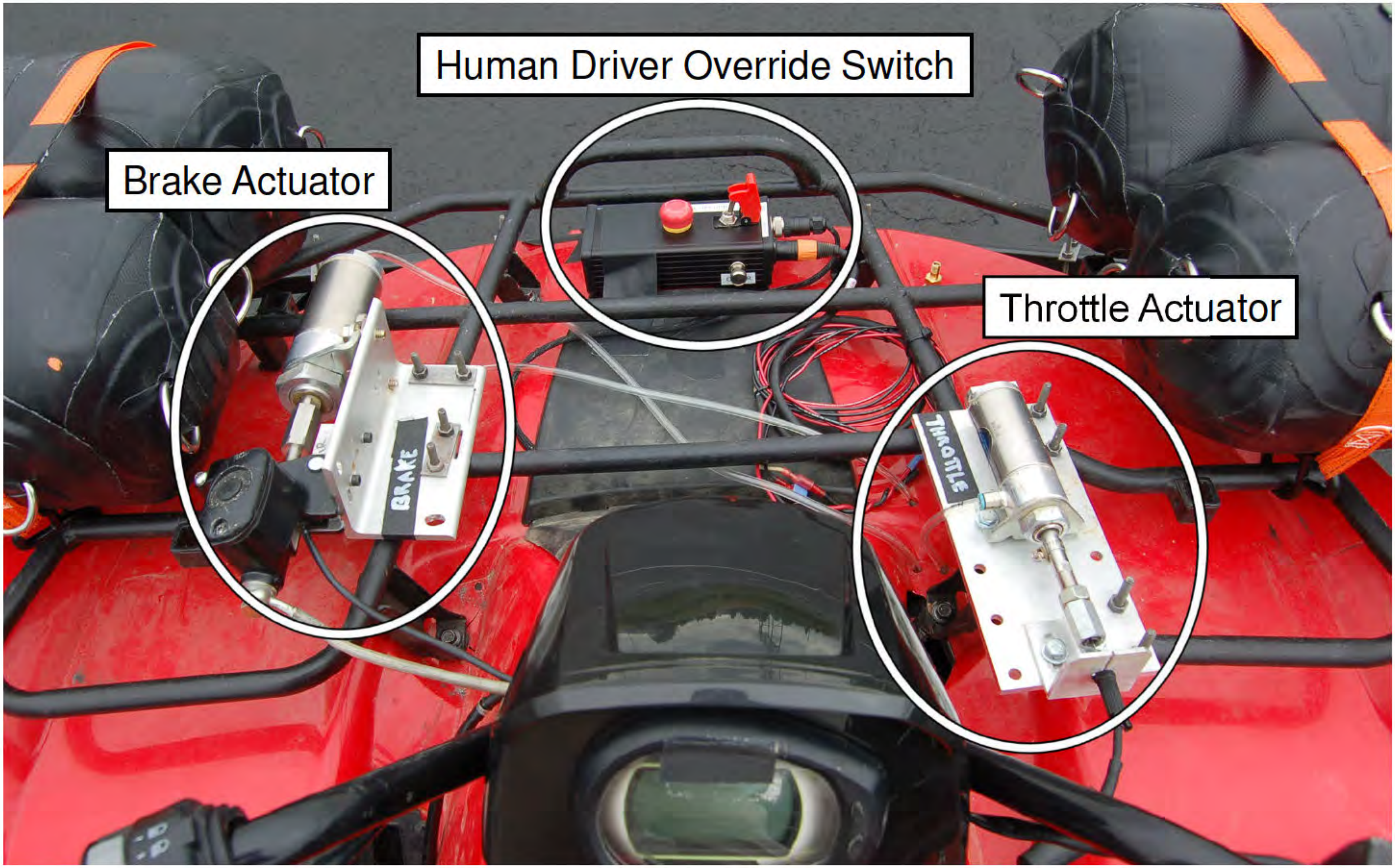
ATV Controller/DAQ and Sensors



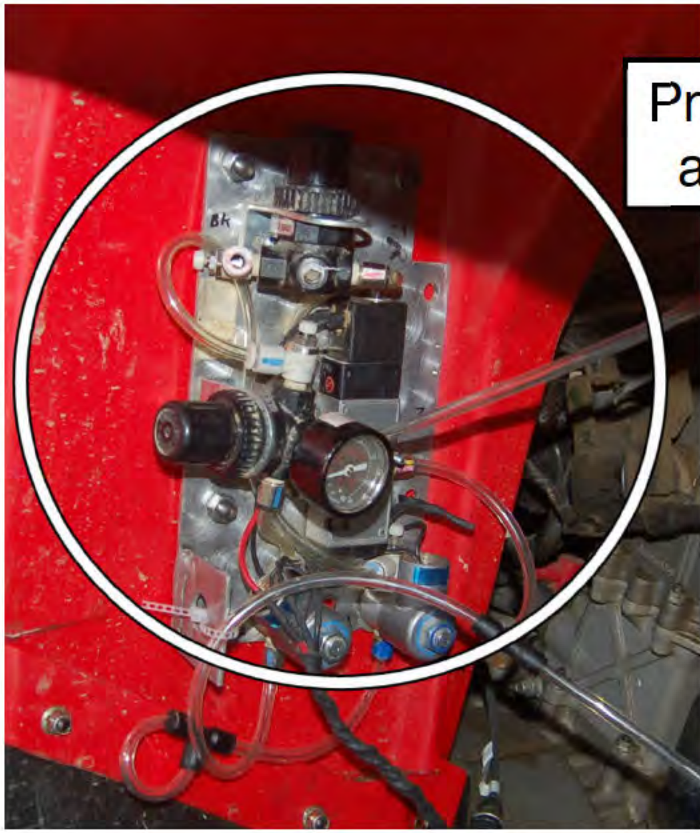
Photographs of 12V Lithium Battery, Network Antenna, and Kill Circuit Antenna

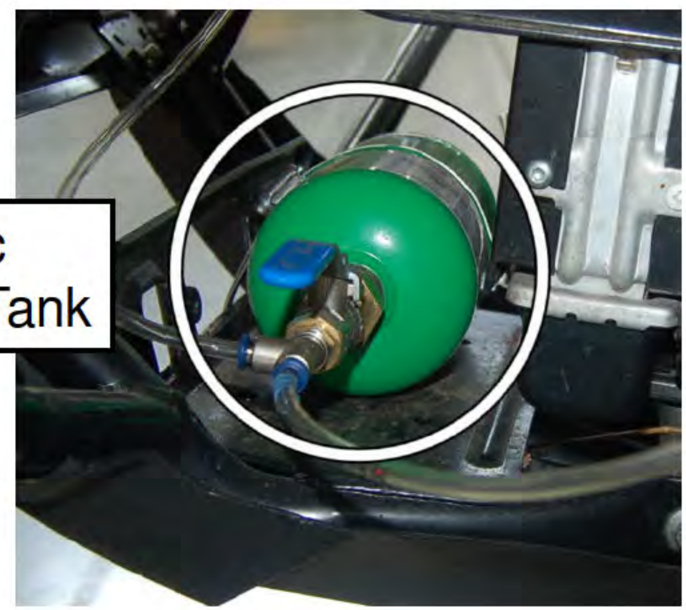


Photographs of ATV Robotic Test Driver (RTD) Components



ATV Pneumatic Valves and Tank





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

For all tests, an instrumented Hybrid III 50th percentile male Anthropomorphic Test Device (ATD) with a standing pelvis was used as the surrogate driver. The ATD's clothing included disposable pants, disposable long-sleeved shirt, socks, and boots.

ATD Instrumentation

The ATD was instrumented with a 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 E.1 lists the sensors used in the ATD. A DTS Nano Slice data acquisition system (Nano Base 3000-20100 microprocessor) was used to acquire all ATD data at a sampling rate of 10 kHz. Figure E.1 shows the DTS Nano Slice package (which includes the Nano 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 E.2. Figure E.2 also indicates the general location of the triaxial chest acceleration sensor, which is mounted on the ATD's spine.

Table E.1: ATD Instrumentation

Transducer	Measurement	Range	Linearity
DTS 6DX Pro Sensor 2K-1500	Head X, Y and Z Accelerations	± 2,000 g	1% of Reading
	Head Roll, Pitch, and Yaw Rates	± 1,500 deg/s	1% of Reading
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 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 mowers tip overs to assess potential head injury levels.

HIC was computed using the following equation:

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

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

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

Prior to computing the HIC values, the accelerations were filtered using a 1,000 Hz Butterworth low-pass filter. For each data run, HIC values were computed for time durations $(t_2 - t_1)$ of 15 milliseconds and 36 milliseconds. The HIC value is the maximum value of the calculation shown on the right side of Equation E.1, as the time range (with a duration of either 15 or 36 milliseconds) is swept across the entire time span of the event, from five seconds before the trigger to fifteen seconds after the trigger. These time range duration limits are commonly used, and they are denoted as HIC_{15} and HIC_{36}, respectively. For all of the tip over tests conducted, all of the peak 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 tip overs, and to design a system that allowed the ATD to disengage or release from the ATV at an appropriate time during the tip over event. A single system was designed which would both secure the ATD during the runup phase and release it at the appropriate time during the rollover event.

Grip strength, the amount of force someone can apply while gripping an object, is different from handhold strength, the amount of force required to breakaway someone's grip while holding an object. Research shows that healthy, college-aged, males and females have quasi-static handhold strengths (holding forces) of approximately one times their body weight when holding onto a steel, 1" diameter, horizontal, overhead bar.[3] Research also shows that size, shape and orientation of

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

[2] Gao, D. and Wampler, C.W., *Head Injury Criterion, Assessing the Danger of Robot Impact*, IEEE Robotics and Automation Magazine 1070-9932/09, December 2009.

[3] Young, J.G., *Biomechanics of Hand/Handhold Coupling and Factors Affecting the Capacity to Hang On*, PhD Dissertation, University of Michigan, 2011.

the object being held can significantly affect handhold strength. Tests were conducted at SEA to evaluate handhold strength while holding onto a horizontal 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 tip over 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 and the surprise of needing to hang on all reduce handhold capacity during a tip over event. Zellner and Kebschull conducted rollover tests on all-terrain vehicles with a Motorcycle Anthropomorphic 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.

Previous evaluations of various ATD handhold methods conducted by SEA led to the conclusion that using cable ties is believed to be a more repeatable and less problematic attachment method than using the other attachment methods considered. SEA has used cable ties to secure ATD hands to the handlebars of ATV during previous studies conducted for CSPC. For this testing the same cable ties were used to secure the ATD hands, 11-inch-long ladder cable ties (Cable Ties Plus SKU number CP-08472-NA). These cable ties provide a consistent loop breaking force very close to 80 lb, within 3 lb for all samples tested by SEA.

A cable tie fits 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 grip. Figure E.3 shows the ATD hands secured to the ATV hand grips. These cable ties were the only ATV restraint used during the rearward pitchover tests conducted on the hill and on the sled.

Cable ties were also used to secure the ATD's left hand during the sled lateral rollover tests. During some sled tests conducted during previous studies of ATV rollovers, the right-hand cable ties used during these tests broke during the acceleration phase of the runup to the rollover pit. 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 30º of roll angle, the same time the hip and neck cables are released. Figure E.4 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

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[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.

designed to secure the ATD to the ATV at its left hip and neck, and to release it depending on the roll angle of the vehicle. This system allows for releasing the ATD at any specified roll angle. Figure E.5 shows the hip support cable (leading a waist harness belted on the ATD) used to secure the ATD's hip. 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 E.5.

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 overturn events. The overall motion of the ATD during the dynamic and sled overturn tests is thought to be representative of how a human driver would respond in the types of ATV overturn tests conducted.

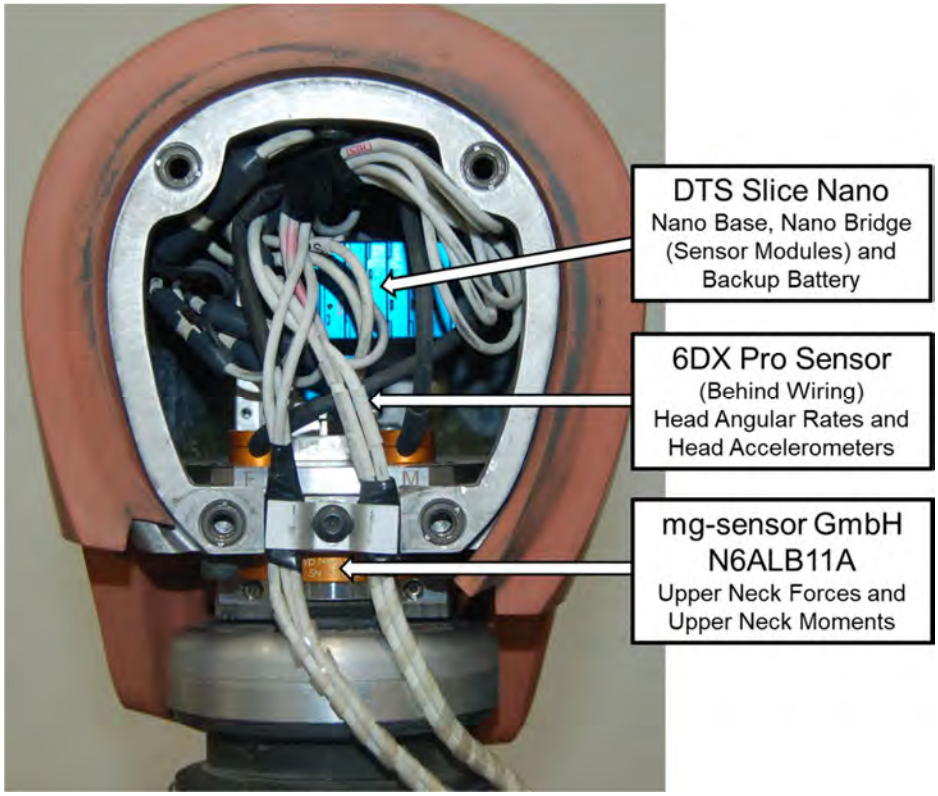


Figure E.1: Instrumentation in ATD Head

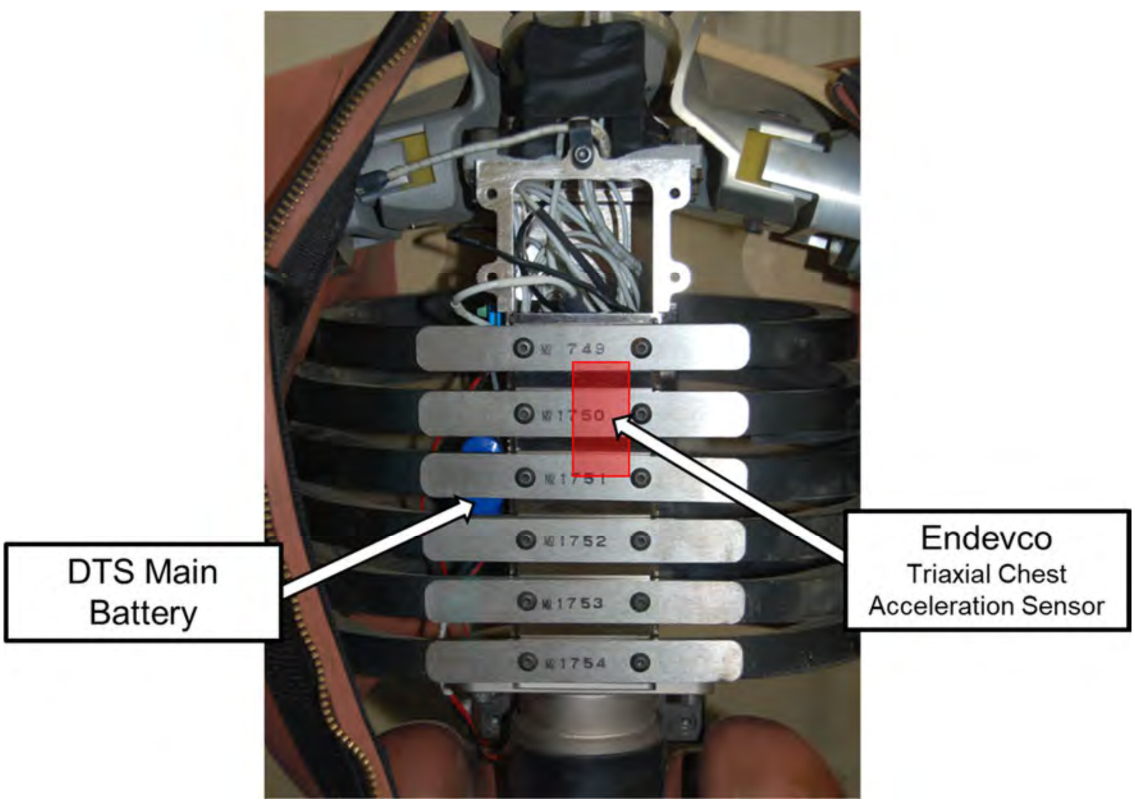


Figure E.2: Instrumentation in ATD Chest

Figure E.3: Handhold Cable Ties Used on Hill and Sled Pitchover Tests

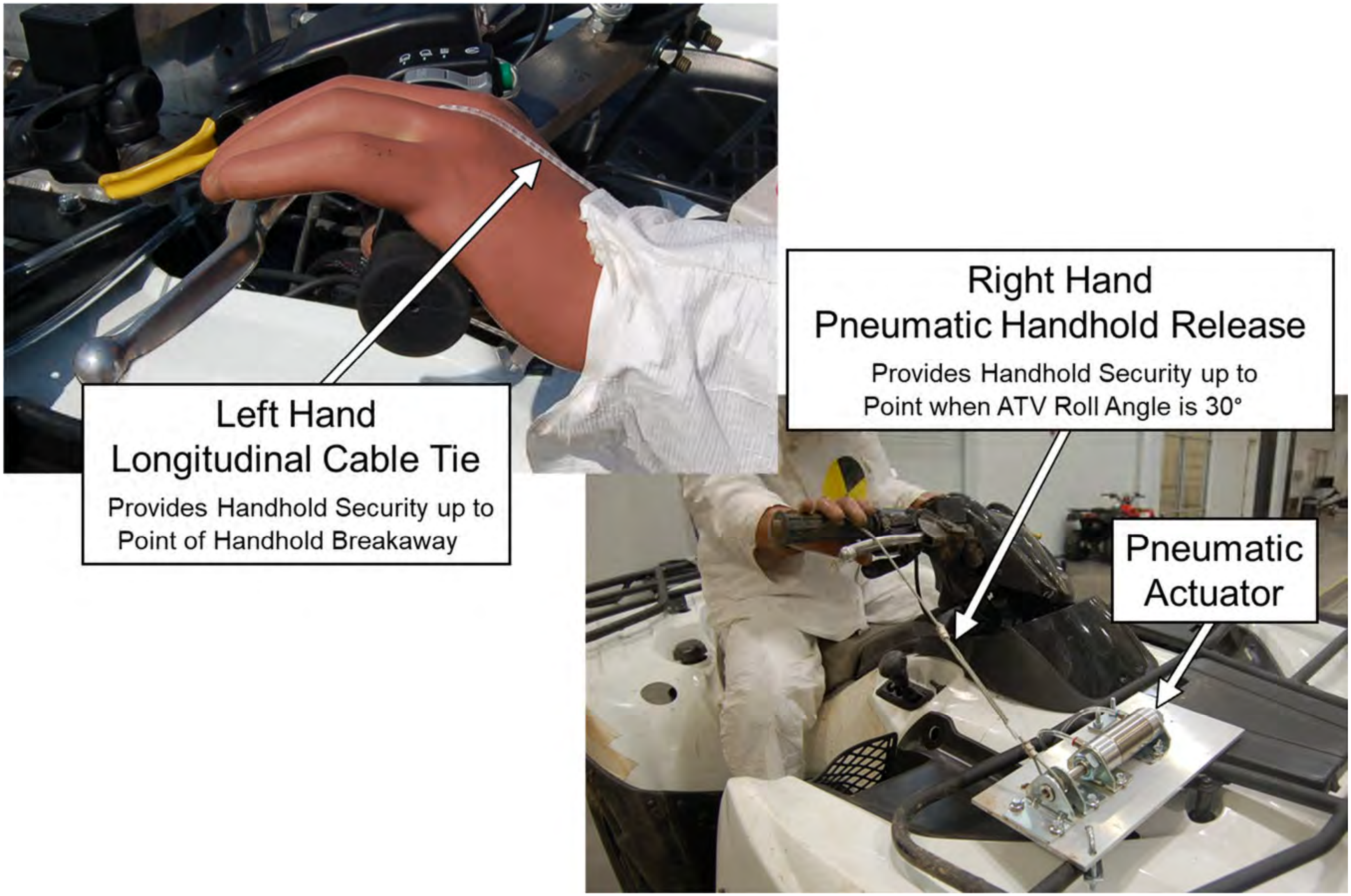


Figure E.4: Left Hand Cable Tie and Right Hand Restraint Cable Used on Sled Lateral Rollover Tests

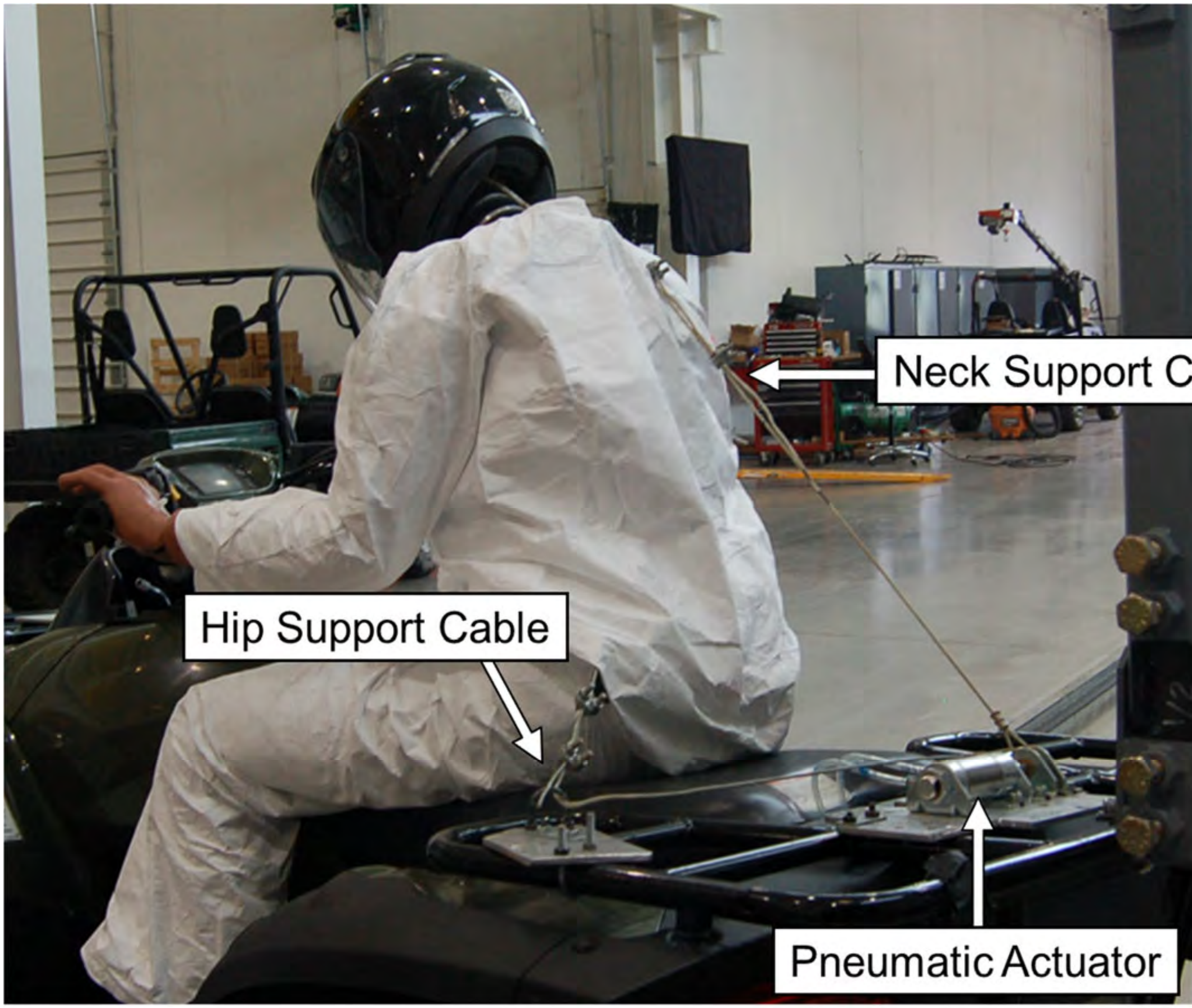


Figure E.5: Neck and Hip Restraint Cables Used on Sled Lateral Rollover Tests

Appendix F: Description of ATV Rollover Simulator

SEA's laboratory sled, configured for ATV rollover testing, was used to simulate the dynamic test rollovers performed on the groomed dirt surface. The major components, instrumentation and control algorithms for ATV sled rollover testing are those used for the previous sled roll testing on ATVs.[1,2,3] A 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 when the ATV separates, its lateral acceleration, longitudinal acceleration, and roll rate are like the moderate energy dynamic rollover test values. Then the ATV rolls onto a dirt rollover landing pit. The ATV is free to roll beyond 90°.

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

Figure F.2 shows a view of the sled rollover landing pit, which is outside of the laboratory. Only the end of the sled, the portion with the sled platform on top of it, extends outdoors at the end of the run when the sled is being decelerated to a stop. At the point when the vehicle rolls off the platform, the platform is situated above the dirt landing area.

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

3 R*ollover Tests of ATVs Outfitted with Proof-of-Concept Occupant Protection Devices (OPDs) – Results from Tests on Six 2014-2015 Model Year Vehicles,* CPSC Contract 61320618D0003, SEA, Ltd. Report to CPSC, March 2022. https://www.cpsc.gov/s3fs-public/SEA_Report%20_Rollover_Tests_of_ATVs_Proof_Of_Concept_OPDs.pdf?VersionId=g9I0CqeuaqoA6y2JeDim_5TKCLfsYNCh

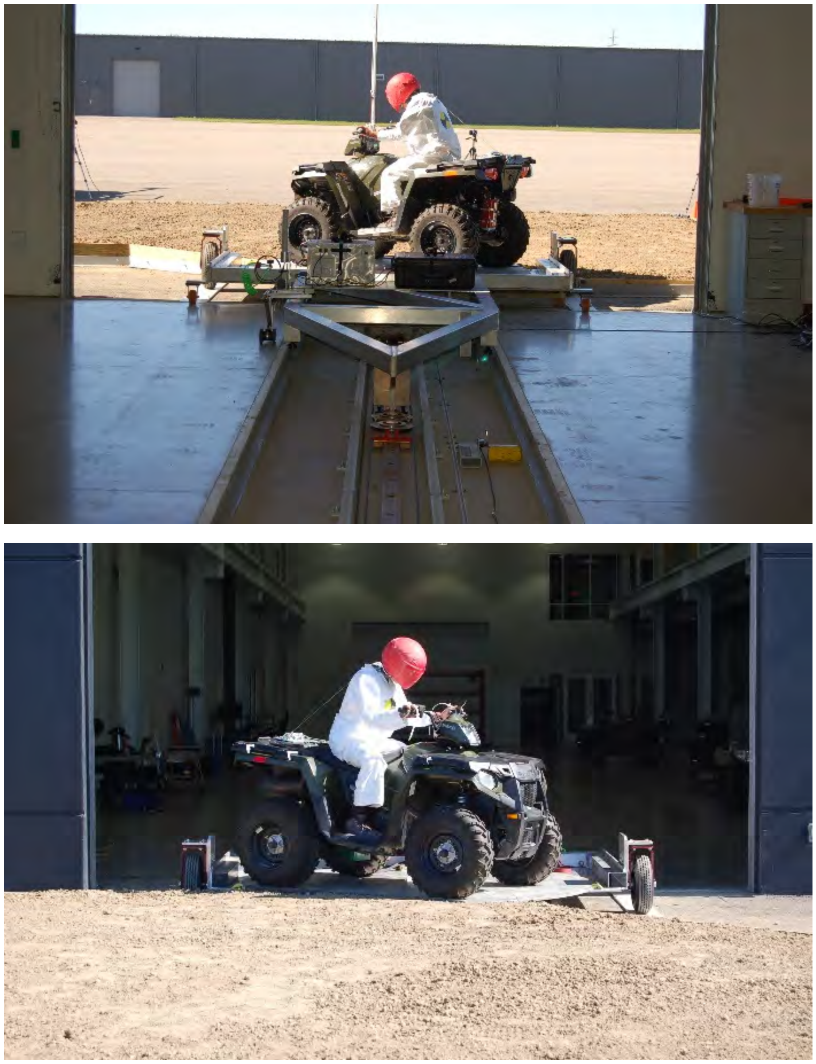
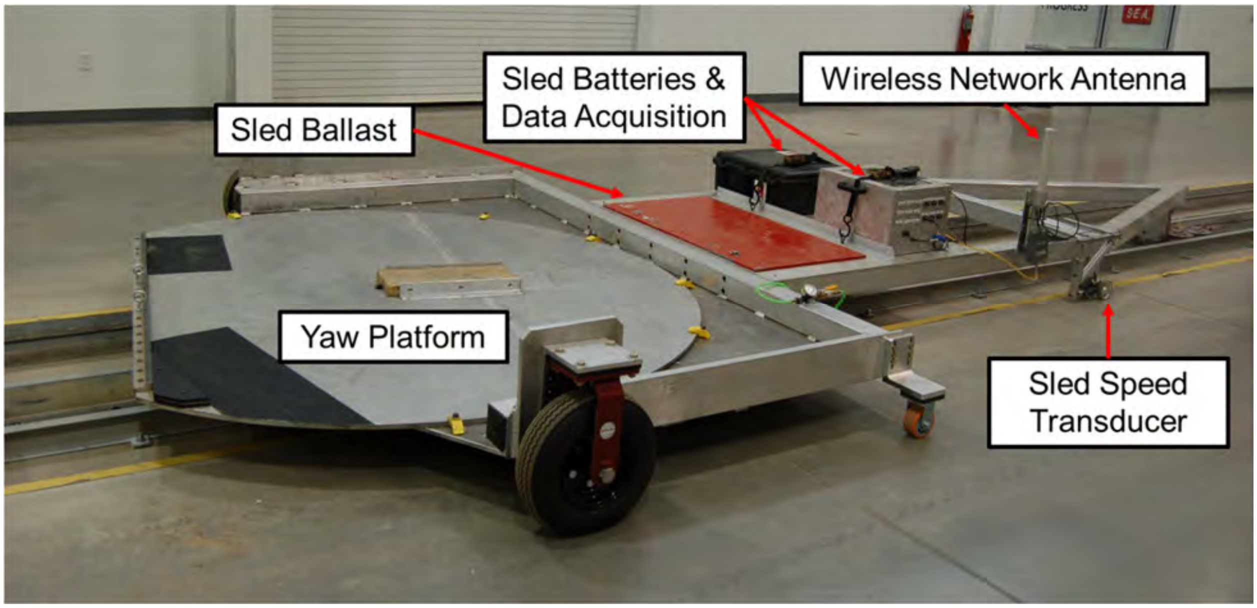


Figure F.1: Views of ATV Rollover Simulator Along the Direction of Sled Translation

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



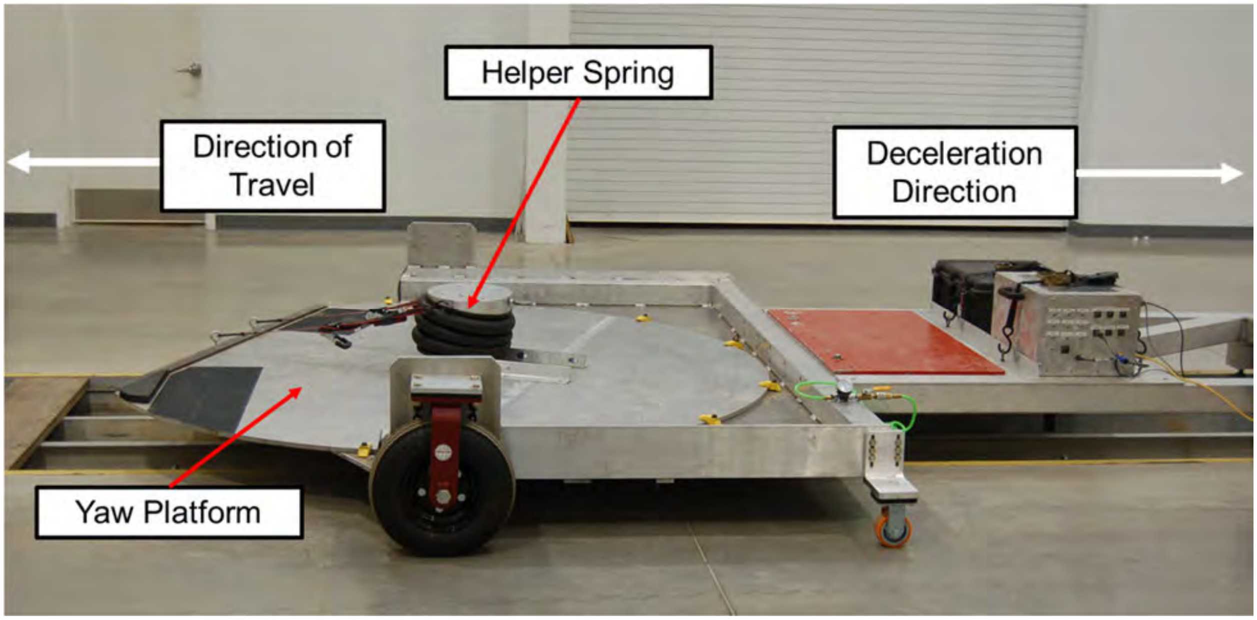


Figure F.3: ATV Rollover Sled Components
Top: Without Helper Spring – Bottom: With Helper Spring

The ATV Rollover Simulator was designed with the following list of variables or parameters that were adjusted to achieve simulated rollover events which match moderate energy dynamic 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 tunable by varying amperage applied to the brake. 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 and sled brake trigger position. For the trial runs, the vehicles and ATD were 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). 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 10° for the moderate energy runs, as shown in Figure F.4. Also, a trip rail and sandpaper surface beneath the leading tires of the ATV were used to assure that the ATV did not slide off the platform prior to reaching the desired location of the stopping point of the sled (with the platform edge over the rollover pit). A 1.0 in high trip rail was used for the moderate energy runs. The friction provided by the sandpaper surface is likely

to be 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 pass 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 that 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 F.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 the sled rollover tests. Starting with the ATV initially rolled in the direction of the rollover helps generate greater roll energy in the test, and results in greater maximum roll rates and angles during the rollover. The helper spring, an air bladder like ones used on suspensions of commercial vehicles, was used to set the initial roll angle. Figure F.6 shows the helper spring situated beneath an ATD. For both vehicles tested in this study, the initial roll angles were set close to 9.0° by using a helper spring pressure of close to 10.0 psi.

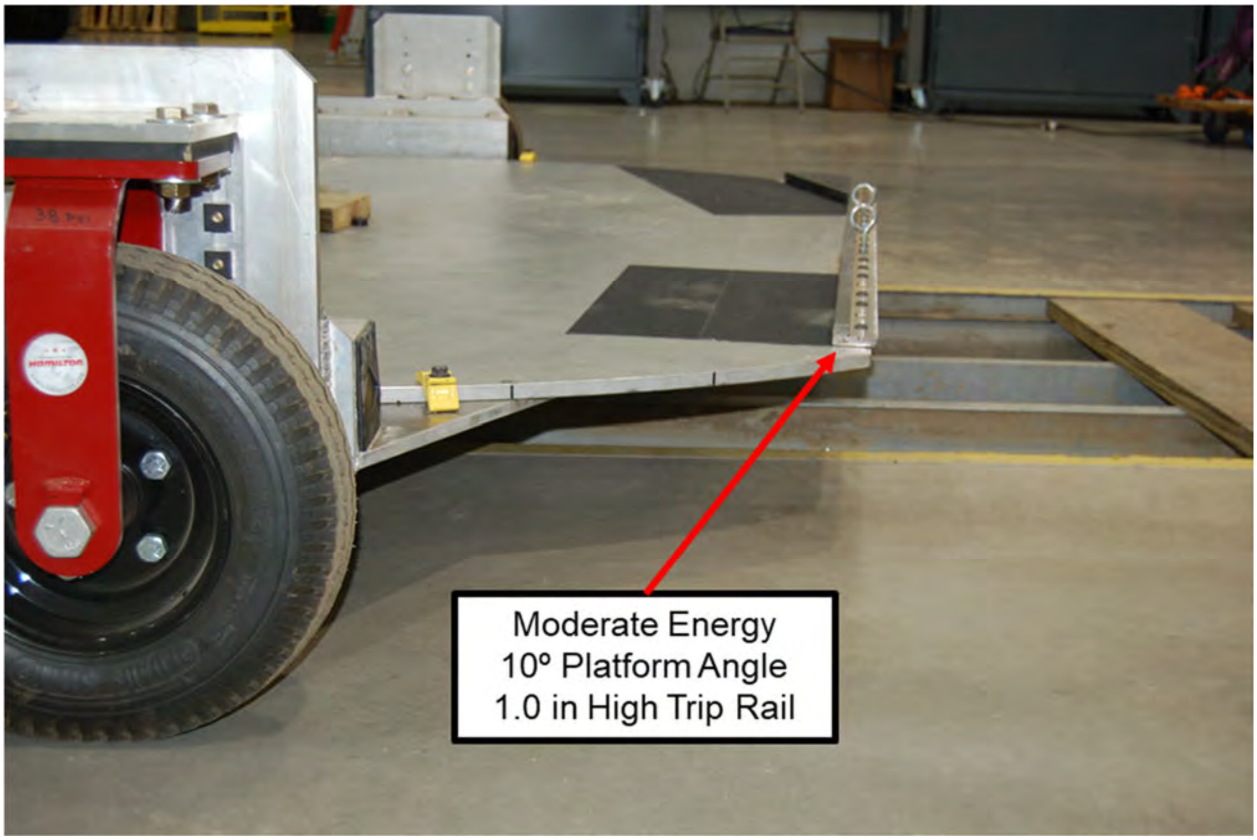


Figure F.4: Platform Yaw Angle and Trip Rail
used for Moderate Energy ATV Sled Rollovers

Figure F.5: Photo Showing Steer Angle Block

Figure F.6: Photo Showing Helper Spring used to Set ATV Initial Roll Angle