United States
Consumer Product Safety Commission

June 11, 2024

CPSC Staff[1] Statement on SEA, Ltd. Report "Evaluation of Riding Mowers Equipped with Proof-of-Concept Rollover Protection Systems (ROPS)"

To support the work of CPSC staff to improve the safety of riding mowers, CPSC contracted SEA, Ltd. (SEA) through contract 61320621D0001 to perform the following tasks:

1) Design and construct two adaptable autonomous vehicle control systems, one for steering-wheel-controlled and one for tiller-controlled riding mowers.
2) Perform autonomous rollovers/pitchovers of an instrumented vehicle with an instrumented anthropomorphic test dummy (ATD) seated in the operator's position.
3) Design and fabricate proof-of-concept Rollover Protection Systems (ROPS) as required to evaluate the feasibility and effectiveness of using these devices on riding mowers.
4) Conduct intentional rollover and pitch-over events with and without ROPS installed and with an instrumented ATD and evaluate the impact of the events on the ATD and the vehicles.

The SEA report titled, "Evaluation of Riding Mowers Equipped with Proof-of-Concept Rollover Protection Systems (ROPS)," details the work completed in fiscal year 2023. The contractor conducted a series of dynamic rollover tests to evaluate the rollover resistance of two riding mower samples. To aid in performing the rollover tests safely and repeatedly, the contractor designed and built an autonomous system to remotely operate riding mower samples and used an instrumented anthropometric test dummy to obtain data throughout the rollover events. Furthermore, the contractor designed and constructed proof-of-concept rollover protection systems (ROPS) consisting of aluminum frames designed to provide a survivable space for operators in the event of a rollover. In all tests conducted, the ROPS prevented the mowers from completely rolling over. SEA's testing demonstrates that ROPS has the potential to reduce the likelihood of crushing occupants in lower energy rollovers when used properly, although further study would build upon this preliminary evaluation of the ROPS concept.

This work will assist CPSC staff as they continue to work to improve standards associated with riding mower safety, including working with the Outdoor Power Equipment Institute (OPEI) and other interested parties.

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[1] This statement was prepared by the CPSC staff, and the attached report was produced by SEA, Ltd. for CPSC staff. The statement and report have not been reviewed or approved by, and may not represent the views of, the Commission.

Evaluation of Riding Mowers Equipped with Proof-of-Concept Rollover Protection Systems (ROPS)

Results from Tests on Two 2021 Model Year Vehicles

for:
Consumer Product Safety Commission

April 2024

Vehicle Dynamics Division
7001 Buffalo Parkway
Columbus, Ohio 43229

Evaluation of Riding Mowers Equipped with Proof-of-Concept Rollover Protection Systems (ROPS)

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

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1. OVERVIEW

This report contains results from work conducted by SEA, Ltd. (SEA) for the Consumer Product Safety Commission (CPSC) under CPSC contract 61320621D0001, a contract that covers general testing and evaluation of residential riding mowers. The overall, multi-year long contract includes conducting research, data analysis, design, and construction of proof-of-concept (POC) Rollover Protection Systems (ROPS), to evaluate the feasibility and effectiveness of using these devices on riding mowers.

This report covers the second task order on the contract, Task Order 61320622F1017. The first task order, Task Order 61320621F1016, was completed in FY2022 and it included: reviewing In-Depth Investigation (IDI) reports supplied by CPSC staff to determine scenarios involving mower overturn events, procuring four residential riding mowers, two tractor style mowers and two zero-turn style mowers, making measurements on the mowers of static metrics and properties (center-of-gravity height tests and tilt table tests), designing and constructing safety outriggers for use in dynamic testing, conducting dynamic tests with a human driver to evaluate rollover resistance and vehicle handling, and conducting dynamic tests with a human test driver to develop maneuvers that would cause the mowers to overturn. Details of the work completed in the FY2022 task order can be found in the CPSC report titled *Vehicle Characteristics Measurements of Riding Mowers – Results from Tests on Four 2021 Model Year Vehicles*.[1]

The specific tasks covered in this report for the second task order include:

1. Design and construct two adaptable autonomous vehicle control systems, one for steering-wheel-controlled and one for lever-controlled riding mowers.

2. Perform autonomous rollovers/pitchovers of an instrumented vehicle with an instrumented anthropomorphic test dummy (ATD) seated in the operator's position.

3. Develop and build an ATD secure-and-release system.

4. Design and fabricate proof-of-concept Rollover Protection Systems as required to evaluate the feasibility and effectiveness of using these devices on riding mowers.

5. Conduct intentional rollover and pitch-over events of one tractor style mower and one zero-turn style mower (using available mowers selected from the previous study). Conduct tests with and without POC ROPS installed, with an instrumented ATD seated in the operator's position, and evaluate the impact of the events on the ATD and the vehicles.

In addition to these tasks, SEA made center-of-gravity location and inertia measurements using their Vehicle Inertia Measurement Facility (VIMF) of the two mowers in their autonomous test load condition, with the ATD in the seat and the POC ROPS installed.

An outcome of the previous FY2022 task order was the establishment of test maneuvers designed to intentionally overturn the mowers. For both styles of mowers, the test maneuver that resulted

[1] *Vehicle Characteristics Measurements of Riding Mowers – Results from Tests on Four 2021 Model Year Vehicles*, CPSC Contract 61320621D000, SEA, Ltd. Report to CPSC, February 2023. https://www.cpsc.gov/s3fs-public/Vehicle-Characteristics-Measurements-of-Riding-Mowers-February-8-2023.pdf?VersionId=PNB0vjeBAWrGS11zq9yQ7xOr00iQ7kJz

in rearward tip-up pitchover events involved applying sudden traction control from a stopped condition with the mowers facing up a 25° grass-covered slope. For the tractor style mowers, the test maneuver that resulted in a lateral rollover event involved driving the mower along a 20° grass-covered slope and having the uphill front tire hit a ramp feature on the sloped surface. For the zero-turn mowers tested, no lateral rollover events happened during numerous efforts to cause tip-up while driving along cross slope surfaces and hitting ramps. The front caster wheels on the zero-turn mowers caused the vehicles to steer downhill when the ramp was encountered during these maneuvers, so the mowers did not rollover. An alternative maneuver, a so-called quasi-lateral rollover maneuver, was developed. This maneuver starts with the mower stopped facing up a 20° grass-covered slope with a steep ramp close behind one of the rear wheels. The maneuver involves backing rearward down the ramp, which serves as the overturn-causing obstacle.

The maneuvers described above were used to intentionally overturn the two mowers tested in this study. The angles of the sloped surfaces used to facilitate the deliberate overturn events exceed the maximum operating angles provided by the manufacturers of the mowers. The Operator's Manuals for all four of the residential mowers tested during the FY2022 study contain warnings related to mowing or operating the mowers on sloped surfaces. For the four mowers tested previously, the manuals warn against mowing or operating the mowers on slopes with maximum angles ranging from 12° to 15°. All four Operator's Manuals also contain the message that failure to adhere to the safety labels, warnings, and/or instructions could result in serious injury or death.

The two mowers used were the small tractor style mower (Vehicle A) and the small zero-turn mower (Vehicle C) used in the previous study. Table 1 contains the measured curb weights, measured maximum speeds, and tire specifications for the two mowers. These two smaller mowers are most different in size from larger commercial mowers that require ROPS, and they were selected with concurrence from CPSC staff. POC ROPS were designed, fabricated, and tested on the two mowers.

American National Standards Institute ANSI/OPEI B71.1[2] does not require ROPS for the mowers tested. ROPS were not offered as original equipment options for the mowers tested, and based on internet searches no aftermarket ROPS were available for these mowers.

This report has four chapters: Overview, Design of Proof-of-Concept Rollover Protection Systems, Description of Testing, and Description of Test Results. This report also has four appendices. Appendix A contains results from laboratory measurements, Appendix B contains results from the dynamic tests, Appendix C contains photographs of the test equipment and test setup, and Appendix D contains descriptions of the ATD and ATD secure and release system.

2 *American National Standard for Consumer Turf Care Equipment – Pedestrian-Controlled Mowers and Ride-On Mowers – Safety Specifications*, ANSI/OPEI B71.1-2017.

Table 1: Test Vehicle Information and Tire Specifications		
Vehicle A **Small Tractor Mower**	Curb Weight: 271.5 lb Maximum Speed: 5.30 mph	
	Front Tires	Rear Tires
Tire Size	13X5.00-6 2 Ply	16X6.50-8 2 Ply
Tire Pressure (psi)	20	14
Vehicle C **Small Zero-Turn Mower**	Curb Weight: 458.4 lb Maximum Speed: 6.75 mph	
	Front Tires	Rear Tires
Tire Size	11X4-5	18X6.5-8
Tire Pressure (psi)	46	11

2. DESIGN OF PROOF-OF-CONCEPT ROLLOVER PROTECTION SYSTEMS

In designing a ROPS for a mower, it is useful to begin by looking at actual overturn incidents. A review of 55 incidents was made by SEA as part their work in the previous mower study.[3] These incidents were provided by CPSC and they are ones that contained some level of detail in what happened in the incident. A few items stood out. Some accidents happen on nearly flat ground. Many accidents seem to be from a combination of slope, turning sharply, and possibly other factors such as bumps. The vehicles' wheelbase is not a lot greater than the track width, unlike passenger cars. Therefore, overturns that are a combination of pitching and rolling are possible. Rearward pitches caused by sudden acceleration were common.

The more severe incidents often involved vehicles losing directional control and going into places where there was no intention of mowing, then going down very steep slopes on which no reasonable mower could resist tipping. One might call these very steep slopes "drop offs" rather than slopes. Finally, it was noted that a significant number of fatalities involved mowers overturning into water, where the rider was trapped and killed. Whether the death was from crushing or drowning was usually unknown based on the provided information.

The most thorough standard covering ROPS for mowers is ISO Standard 21299[4]. Standard ANSI/OPEI B71.1 references this standard and covers consumer turf care equipment. Standard ANSI/OPEI B71.4 also references this standard and covers commercial turf care equipment. The ANSI/OPEI standards typically tell when ROPS are needed, and they refer to the ISO standard, but they do not cover the details of the ROPS required.

ISO 21299 primarily covers the size and strength of the ROPS. The size requirements are incorporated by defining a "survival space", or as the standard calls it, a "Deflection-Limiting Volume (DLV)," and requires that no part of this survival space touch the ground plane in any turnover. The survival space corresponds to an operator leaning forward in a forward pitchover, leaning backwards in a backward pitchover, and leaning to the side in a side rollover. The operator is assumed to be wearing a lap belt and the pelvis is assumed to stay in the seat. Figure 1 illustrates the concepts outlined in ISO 21299.

The top two images of Figure 1 show the deflection-limiting volume in rear tilt (top left image) and front tilt (top right image) directions. The blue dot is the rear of the head in a rear tilt. The red dot indicates the forehead point in a front tilt. The bottom image of Figure 1 shows the left tilt limiting volume. The right tilt is opposite. The red dot on this image indicates the outside shoulder point. The "SIP" points in Figure 1 indicate the Seat Index Point (SIP) which is assumed not to move relative to the mower during the turnovers.

[3] *Vehicle Characteristics Measurements of Riding Mowers – Results from Tests on Four 2021 Model Year Vehicles*, CPSC Contract 61320621D000, SEA, Ltd. Report to CPSC, February 2023. https://www.cpsc.gov/s3fs-public/Vehicle-Characteristics-Measurements-of-Riding-Mowers-February-8-2023.pdf?VersionId=PNB0vjeBAWrGS11zq9yQ7xOr00iQ7kJz

[4] *Powered Ride-on Turf Care Equipment – Roll-over Protective Structures (ROPS) – Test Procedures and Acceptance Criteria*, ISO Standard 21299, April 2009.

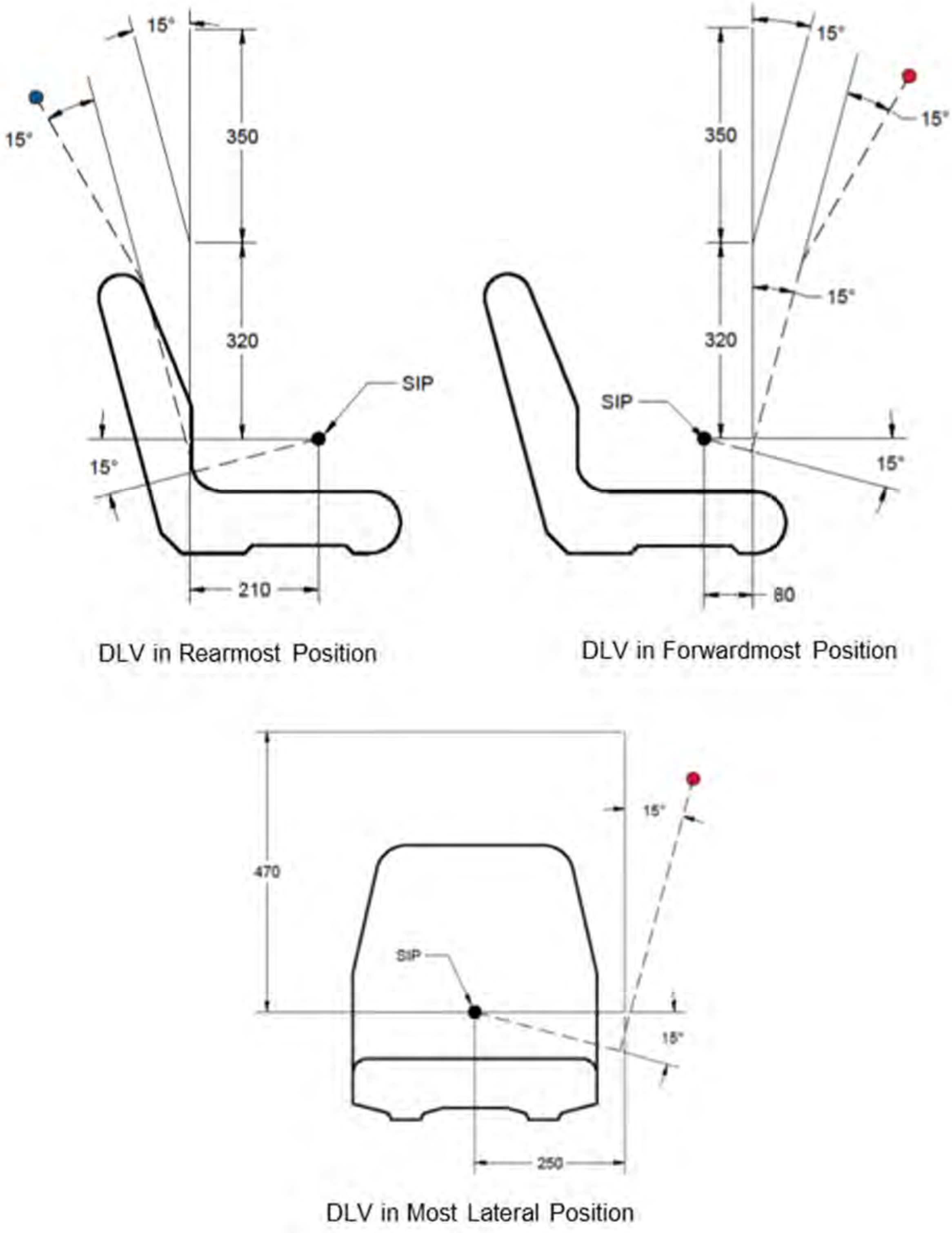

Figure 1: Images Showing Ranges of Deflection-Limiting Volume (DLV)
(Dimensions shown are in millimeters.)

Figure 2 shows, on an example vehicle, the plane through which any part of the deflection-limiting volume should not pass during a front tip over. Usually, the forehead point is the most critical.

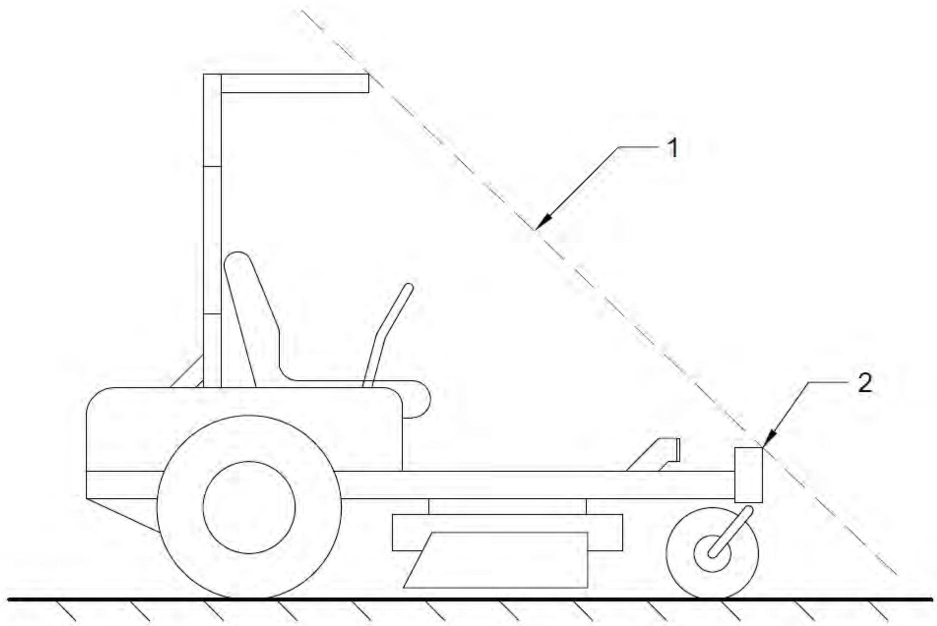

Figure 2: Image Showing Plane of DLV in Front Tip Over

In terms of strength, ISO 21299 requires that ROPS withstand roughly two times the curb weight of the mower (without occupant) if the force is applied:

1. To the top of the ROPS laterally.
2. To the top of the ROPS longitudinally in either forward or rearward directions. There is also a requirement that most of the force be on one side of the ROPS.
3. In a downward direction near the top of the ROPS.

The forces are applied one at a time, not all together. For most mowers the longitudinal force requirement is the most challenging.

After performing some calculations, it became clear that for mowers not designed for a ROPS, which would include the two mowers used in our testing, the forces required by ISO 21299 could deflect and damage the frames of the mowers. ROPS cannot easily be added to mowers that are not designed to handle a ROPS. In the beginning of the first phase of our work on mowers, we examined numerous commercially available riding mowers. It was observed that for mowers with a ROPS, the ROPS was incorporated into the frame of the machine; it was not added as an extra piece. This meant that any ROPS we designed needed to include considerations of the frame strength of the mowers we were using.

It was determined during meetings between CPSC and SEA staff, that the POC ROPS to be designed for testing would ideally be designed to fully cover the ISO 21299 standard. It should be noted that not all existing ROPS are designed to meet all parts of the ISO 21299 standard, since the ANSI/OPEI standards are voluntary standards. Many of the commercially available riding mower ROPS examined appeared to be too short to meet the requirement for the forward tilt. Some existing mower ROPS have a forward extension that allows the ROPS to meet the standard and keep a reasonable total height.

The minimum requirements for the proof-of-concept ROPS design were:

1. Meet the ISO standard regarding the deflection-limiting volume in all directions.
2. Theoretically meet the ISO standard in terms of ROPS strength. However, the strength requirement was not tested due to the chance of mower damage.
3. Have the ROPS reinforce the mower frame as much as reasonably possible, and/or have the ROPS distribute the forces on the mower frame such that the frames were not damaged.

Desirable features on the proof-of-concept ROPS were:

1. Have the ROPS be as light as possible, to minimally affect the center-of-gravity (CG) location of the mower.
2. If a forward extension is used, have it high enough that the rider does not hit their head on the forward extension when getting on or off the mower.
3. Have a hinge, as any production ROPS would need to have for mowing under trees.

Regarding the last item, it was decided to not use a hinge in the proof-of-concept ROPS, as this feature complicated the design considerably. The objective of this project was not to design a ROPS that was ready for mass production, but rather to design a ROPS prototype to test whether a ROPS protected the occupant or not.

Early in the design process it was decided to use a ROPS with upper and lower halves. The upper half would be common between both mowers tested, and the lower half would be unique to each of the two mowers. It was decided that the upper pieces would be aluminum to keep the weight and CG height of the ROPS down, and the lower pieces would be steel for greater strength, particularly strength in impacts.

Dimensionally, the ROPS was designed primarily around the forward tilt condition. This was done by first locating the Seat Index Point, a procedure for which is found in SAE Surface Vehicle Standard J1163[5]. The exact procedure was not followed, but a simplified procedure was followed that provided a Seat Index Point within a fraction of an inch of what would result from the full procedure. This level of accuracy was sufficient for achieving the testing goals.

After the Seat Index Point was found, the dimensions of this point were located relative to points on the mower. The dimensions given in Figure 1 were used to calculate the location of various points in the Deflection-Limiting Volume relative to the points on the mower. From the dimensions of the mower and the locations of various points on the Deflection Limiting Volume, the dimensions of the ROPS were determined.

It was decided that a forward extension would be used on the ROPS to meet the ISO forward tilt requirement. Regarding the requirement that the operator be able to get on and off the mower without hitting his head on the ROPS forward extension, a mockup was made with the tentative dimensions of the ROPS and tested with two adult male test subjects. This confirmed that the overall dimensions were good with respect to not hitting the driver's head.

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[5] *Determining Seat Index Point*, SAE Surface Vehicle Standard J1163, August 2016.

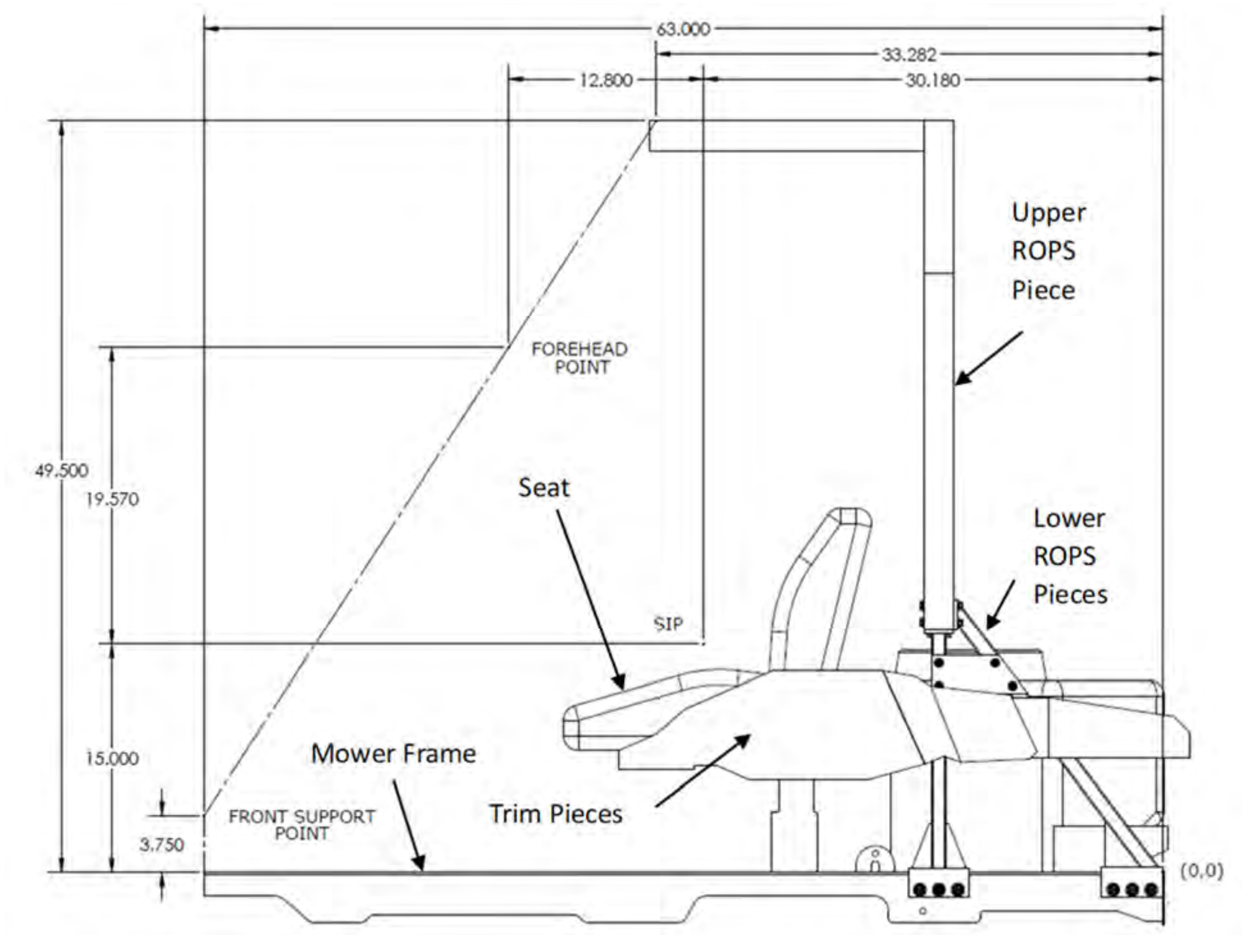

Figure 3: Layout Used to Determine Dimensions of ROPS for Zero-Turn Mower Tested
(Dimensions shown are in inches.)

Figure 3 shows the layout used to determine the dimensions of the ROPS for the zero-turn mower. In particular, the 33.282 inch dimension, the forward reach of the forward extension, was determined. Based on Figure 1, this dimension was necessary to meet the ISO 21299 standard for the zero-turn mower.

Figure 4 shows the layout used to determine the dimensions of the ROPS for the tractor style mower. Since the same upper ROPS piece was used as on the zero-turn mower, this layout shows that the dimensions of the forward extension that meet the ISO 21299 standard for the zero-turn mower also meet the standard for the tractor style mower.

The width of the upper part of the ROPS was determined by the side tilt conditions and the shoulder point in Figure 1. Since the two mowers tested were not of the same width, it would have been possible to use a narrower upper part to the ROPS on the wider (zero-turn) mower, however this was a minor consideration and for simplicity we used the same upper part for both mowers. The width of the upper part of the ROPS is 30 inches.

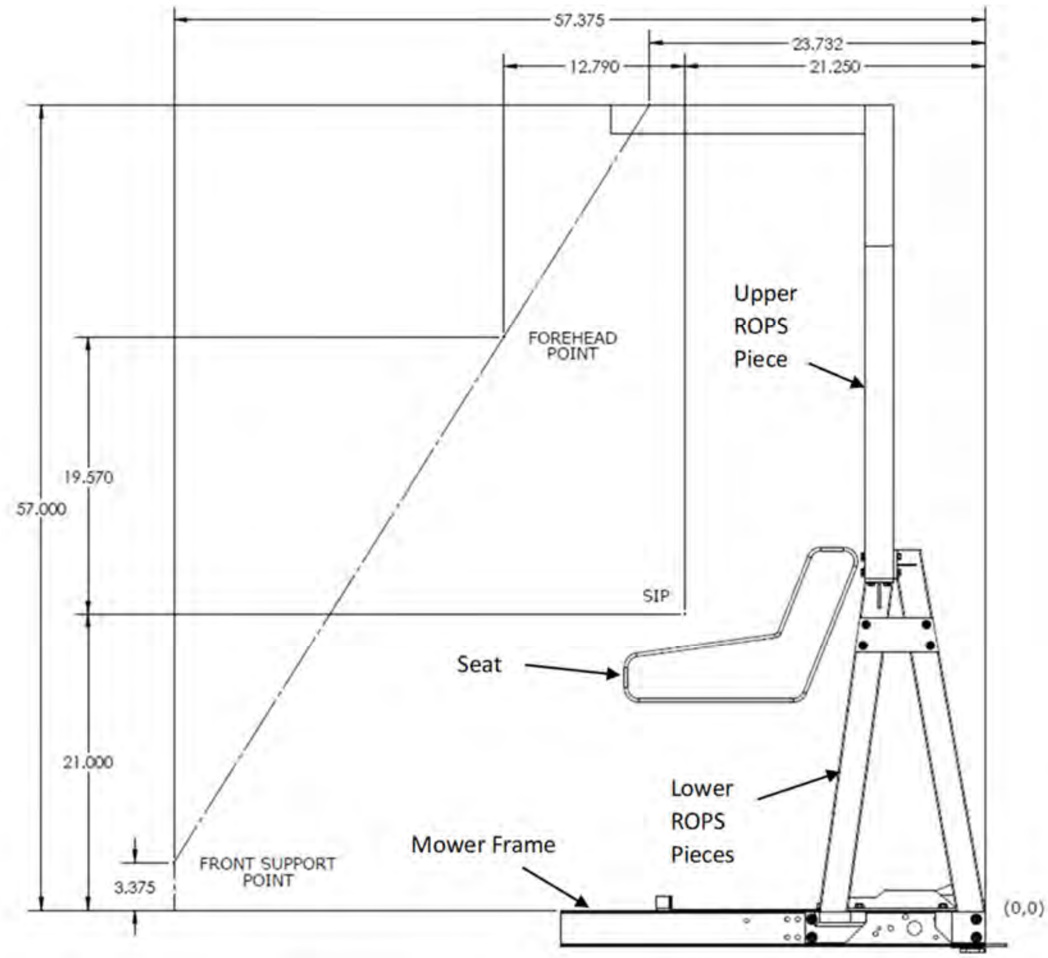

Figure 4: Layout Used to Determine Dimensions of ROPS for Tractor Style Mower Tested (Dimensions shown are in inches.)

ISO 21299 specifies the forces that the ROPS must withstand, and once the dimensions were known the bending and twisting moments could be calculated. To withstand bending and twisting while retaining light weight, triangulated sections were used if possible, and if not possible then deep sections (with large area moments of inertia) were used.

Another design requirement is that the ROPS must not interfere with any major parts of the mower, such as the engine. The ROPS did require slight trimming of some plastic or metal trim pieces original to the mowers. Again, because the purpose of this design was to test the effectiveness of a ROPS versus a mower with no ROPS, we were not attempting to design something that was ready for mass production on a specific mower. In particular, the design of the lower part of the ROPS depended heavily on the requirement to work around existing major parts of the mower, such as the engine. For the tractor mower there was also very limited clearance laterally between the rear tires and the frame.

The same upper section of the ROPS was used for both mowers, and it was made of aluminum, 2"x2"x¼" tubular sections, with angled braces for extra support. The upper corners of the upper section frame were angled rather than square, as this would be a desirable feature if mowing under trees.

The lower section of the ROPS was made in four main pieces for each mower, with smaller brace pieces to bolt the two main pieces together. There were two left and two right pieces, symmetric left/right except for a few clearance holes. Figures 5-8 show the ROPS from various angles, with captions for each photo. The ROPS installed on the tractor style mower and zero-turn mower are shown on Figures 9 and 10, respectively.


Figure 5: Left Photo: Overall View of Upper Section (Shiny Aluminum) and Lower Section (Steel Painted Gray) for the Zero-Turn Mower
Right Photo: Oblique View of Upper Section of the ROPS used on Both Mowers


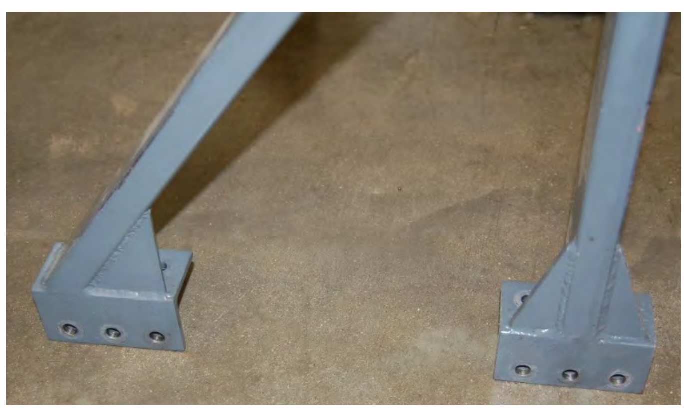

Figure 6: Left Photo: View of Connections Between the Upper and Lower Sections of the ROPS for the Zero-Turn Mower
Right Photo: View of Feet of the Lower Section Connections for the Zero-Turn Mower
(The feet are large to reinforce the mower frame in this area, which is not strong enough to withstand significant force.)

Figure 7: Photo Showing Top of the Lower ROPS Section for the Tractor Mower

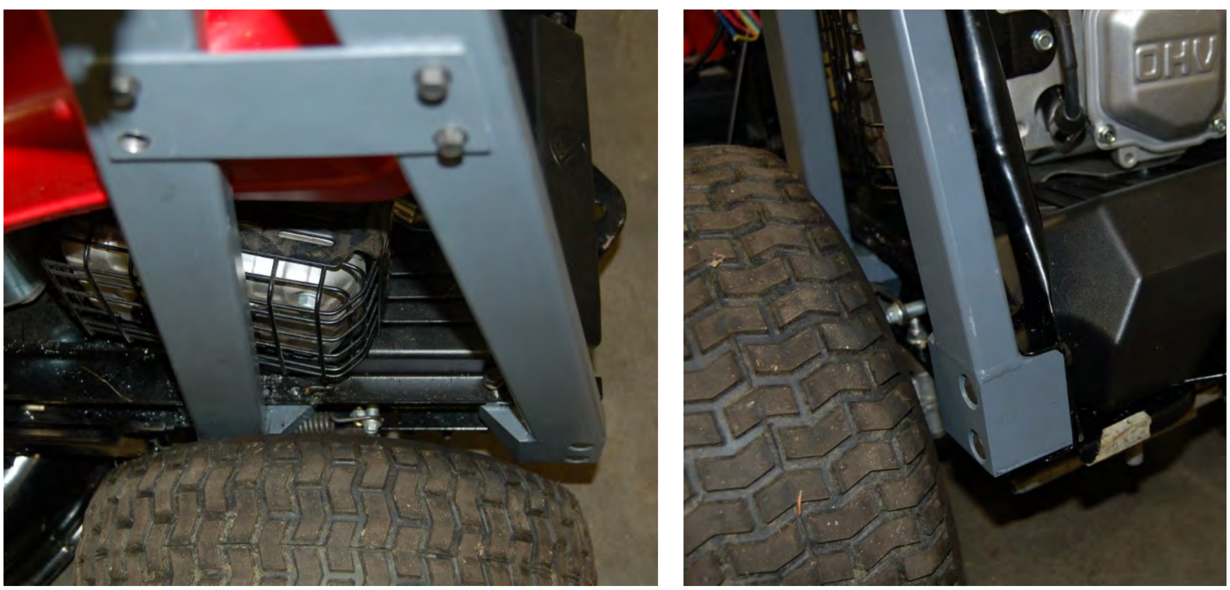

Figure 8: Left Photo: Side View of the Lower Section of ROPS for the Tractor Mower
Right Photo: Oblique View of the Lower Section of ROPS for the Tractor Mower
(As with the zero-turn mower, the lower ROPS pieces act as reinforcements
for the mower frame, which was not designed for use with ROPS.)

A few additional factors would need to be considered in the design of a production ROPS. These include getting the proper amount of strength with a lighter weight. A hinge to enable the ROPS to fold down could be added, as has been discussed. There are also potential issues around having the rider's head hit the ROPS in a back tilt, so parts of the ROPS could be padded.

Figure 9: Rear and Side Views of Tractor Mower with ROPS

Figure 10: Rear and Side Views of Zero-Turn Mower with ROPS

Complete rollover protection systems like those using the mower ROPS hardware described above are designed to have the driver always wear a seat belt (typically a lap seat belt only). Figure 11 shows the commercially available two-point lap seat belt purchased and used on both mowers. Figure 12 shows the belt installed on the tractor mower, with its bases bolted to the ROPS structure. Figure 13 shows the belt installed on the zero-turn mower, with its bases bolted to rigid metal standoffs attached to the frame of the vehicle. For both mowers, the belt was installed to cross the pelvis of the seated ATD, in an orientation typical of those used for occupants seated in vehicles with bucket seats.

Manufacture's Description of Seat Belt:

Heavy duty retractable seat belt specifically designed for use in trucks, campers, motor homes, buses, & off-road vehicles. Push-button buckle & standard hardware included. Meets FMVSS 209. Length: 54 inches. Color: Black

Figure 11: Lap Seat Belt used for Tractor Mower and Zero-Turn Mower

Seat Belt with Anchors Installed on ROPS Frame

Seat Belt Connected over ATD Lap

Figure 12: Lap Seat Belt Installed on Tractor Mower (Belt Bases Mounted to ROPS)

Seat Belt – Right Side View

Seat Belt – Left Side View

Figure 13: Lap Seat Belt Installed on Zero-Turn Mower (Belt Bases Mounted to Vehicle)

3. DESCRIPTION OF TESTING

3.1 Introduction

This section describes the setup of the dynamic tip-over tests conducted on numerous dates in May 2023. Both mowers were tested on SEA's grass-covered test hill comprised of four sides with nominal slopes of 15°, 20°, 25°, and 30°. Only the 20° and 25° slopes were used for the mower tip-over tests.

This section is divided into three parts: one covering the vehicle loading conditions used for the dynamic tests, one covering the instrumentation used during the dynamic tests, and one covering the autonomous control systems and test setups.

3.2 Vehicle Loading Conditions

The loading condition used for the mower dynamic tests included the test instrumentation and an instrumented Hybrid III 50th percentile male Anthropomorphic Test Device (ATD) used as the surrogate driver. Tests using ROPS also included the ROPS structure and a seat belt. Table 2 lists the nominal weight added to both mowers. A description of the ROPS is contained in the previous chapter and descriptions of the other components listed in Table 2 are described in this chapter.

For the previous FY2022 study, measurements were made of the weights, center-of-gravity locations, and inertia properties of the mowers in the Curb, Curb plus 95th% (95th percentile) male Driver, and Human Driver plus Instrumentation and Outriggers loading conditions. Weight, center-of-gravity location, and inertia properties of the mowers were also measured for the current study in the Autonomous Test Load with ATD and ROPS loading condition using SEA's Vehicle Inertia Measurement Facility (VIMF).[6]

Appendix A contains all the VIMF laboratory measurements made for both mowers. The VIMF measurements include vehicle weight (including the four corner weights); vehicle center-of-gravity (CG) location (longitudinal, lateral, and vertical (CG height)); vehicle pitch, roll, and yaw moments of inertia; and roll/yaw product of inertia. The vehicle CG longitudinal position is expressed as a distance from the front axle. The vehicle 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. Measurements of front track width, rear track width, and wheelbase were also made and are included in the tables in Appendix A. The last four rows in the tables in Appendix A contain fundamental rollover and pitchover resistance metrics of SSF (Static Stability Factor), KST (lateral stability coefficient), Forward SSF, and Rearward SSF. Descriptions of these metrics and how they are computed is provided in the previous FY2022 report.[7]

Table 2 shows that the total weight added for the tests conducted with POC ROPS installed on the

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[6] *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.

[7] *Vehicle Characteristics Measurements of Riding Mowers – Results from Tests on Four 2021 Model Year Vehicles*, CPSC Contract 61320621D000, SEA, Ltd. Report to CPSC, February 2023. https://www.cpsc.gov/s3fs-public/Vehicle-Characteristics-Measurements-of-Riding-Mowers-February-8-2023.pdf?VersionId=PNB0vjeBAWrGS11zq9yQ7xOr00iQ7kJz

mowers exceeded the weight of the 95th% male driver (test dummy weighing nominally 220 lb) used in the previous VIMF tests. The instrumented tractor mower with POC ROPS installed weighed nominally 46 lb more and the zero-turn mower 44 lb more than each mower weighed with a 95th% male driver. Comparing the "Autonomous Test Load with ATD & ROPS" columns to the "Curb plus 95th% Male" columns in Appendix A shows that the tests with POC ROPS had more rearward CG longitudinal locations (0.24" for the tractor and 1.03" for the zero-turn) and had lower CG heights (1.65" for the tractor and 0.48" for the zero-turn). The autonomous test loading condition used a lighter 50th %tile ATD and included both test instrumentation and the heaviest ROPS parts mounted below the CG height of the vehicle. This explains why the CG height is lower in the autonomous loading condition. Changes to the CG location of any vehicle affects its rollover resistance and pitchover resistance. The tests conducted for this study were designed to deliberately overturn the mowers, and these measurements are provided simply to detail the loading conditions used for the autonomous tip over tests.

Table 2: Autonomous Test Load with ATD and ROPS

Component	Component Weight Added To Tractor Style Mower (lb)	Component Weight Added To Zero-Turn Mower (lb)
Instrumented ATD	172	172
ROPS Structure and Seat Belt	62	52
Instrumentation: RT1003 GPS/IMU, Safety Circuit Box, On-Vehicle Computer, Freewave Radio, Antennas, 12V Battery, Cables, and Mounts	22	22
Tractor Style: Clutch-Brake Pedal and Dummy Release Electromagnets, and Wooden Mounting Board	12	NA
Zero-Turn: Lever Control Actuators including 24V Battery	NA	20
Total Weight Added with ATD and ROPS	**268**	**266**

3.3 Test Instrumentation

A description of the ATD, ATD instrumentation, and the ATD secure and release system is provided in Appendix D. The ATD and its instrumentation are CPSC-owned equipment that has been used in previous studies involving rollovers of All-Terrain Vehicles (ATVs). [8,9,10]

[8] *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

[9] *Rollover Tests of ATVs Outfitted with Occupant Protection Devices (OPDs)*, 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

[10] *Rollover Tests of ATVs Outfitted with Proof-of-Concept Occupant Protection Devices (OPDs)*, CPSC Contract

The on-vehicle instrumentation used during the dynamic testing was an OxTS GPS/IMU RT1003, and Table 3 lists the specifications for this unit. The on-vehicle computer used for controlling the actuators for the autonomous driving systems, for wireless communication, and for data acquisition was an NVIDIA Jetson. The Jetson and its peripheral electronics were mounted inside a rectangular plastic on-vehicle computer box, with plugs mounted on one side for connecting the electronic components. The left photo on Page 1 of Appendix C shows the red RT1003, the yellow safety circuit box (component of the wireless engine-kill circuit), and a white bullet antenna (used for wireless communication) mounted in the footwell area of the tractor mower. The right photo on this page shows the on-vehicle computer box, 12V battery, and Freewave Radio (used for GPS corrections from a fixed base station) mounted on a wooden board that was fixed beneath the mower deck during testing. The left photo on Page 2 of Appendix C shows the on-vehicle computer box, the yellow safety circuit box, and 12V battery mounted in the footwell area of the zero-turn mower. The right-side photos on this page show the red RT1003 and the Freewave Radio mounted beneath the seat of the zero-turn mower.

Table 3: Instrumentation Specifications

Transducer	Measurement	Range	Accuracy
Oxford Technical Solutions (OxTS) RT1003 GPS/IMU	Longitudinal, Lateral, and Vertical Accelerations	± 8 g	0.006 g
	Roll, Pitch, and Yaw Rates	± 480 deg/s	0.1 deg/s
	Speed	No Limit Specified	0.1 km/h (0.06 mph)
	Roll and Pitch Angles	-180 to +180 deg	0.05 deg
	Vehicle Heading	0 to 360 deg	0.1 deg

3.4 Autonomous Control Systems and Test Setup

As mentioned, for this current study the test maneuvers used to intentionally overturn the mowers were those established during the previous FY2022 study. For the tractor mower, the lateral rollover maneuver and rearward pitchover maneuver both involved having the vehicle drive straight, without any steering input. Therefore, at the beginning of these maneuvers, the vehicle was positioned at its start position and the steering linkages were locked using a small pin so the front wheels would not turn during the tip-over events.

The tractor mower has a clutch-brake foot pedal. Fully depressing the clutch-brake pedal disengages the clutch and engages the disc brake. Releasing the clutch-brake pedal disengages the disc brake and engages the clutch. To autonomously control the mower's forward motion, a system to hold the depressed clutch-brake pedal and rapidly release it was designed. Mechanically, the system used a 12V DC powered electromagnet with a 2" OD and with 180 lb of pull force to

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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 hold and release a metal plate attached to the pedal. Page 3 of Appendix C contains photos of this plate connected to and released from the electromagnet. The electromagnet was remotely controlled by the automated test driver program, the program that controls the specific autonomous test actuators and collects the test data.

Front and side view photos showing the test setup for the lateral rollover tests of the tractor mower are on Page 4 of Appendix C. For these tests, a natural, wedge-shaped rock was used as the tripping feature (replacing the wooden ramp used in the previous tests conducted with a human driver). The rock measured about 6" wide, 6" tall, and 16" long at its base. As shown, the mower was lined up with its front right (uphill) tire aligned with the rock on the 20° grass-covered slope.

The ATD secure and release system used for the mowers was designed to hold and support the ATD at the beginning of the tip over events, and then allow the ATD to release from the mower during tip over events. Conceptually the ATD secure and release system used for the mower tip over tests is like the ATD secure and release system used previously for ATV rollover tests. The ATD secure and release system held the ATD in an uphill-leaning posture at the beginning of the tests. The throttle was set using the vehicle's speed control level. For the lateral rollover tests, the speed control was set to its mid-range. To start the tests, the electromagnet was programmatically released, and the mower drove onto the tripping feature, causing it to laterally rollover.

Page 5 of Appendix C shows rear and oblique views of the tractor mower setup for rearward pitchover tests. The rearward pitchovers involved applying sudden traction control from a stopped condition with the mowers facing up and driving straight up the 25° grass-covered slope. For these tests, the speed control was set to its maximum. Again, to start the tests, the electromagnet was programmatically released, and the mower drove somewhat forward and ultimately pitched over in the rearward direction.

For the zero-turn mower, the autonomous control system hardware consisted of two electric linear actuators, one used to control the fore-aft motion of the right steering lever and one to control the left lever. The actuators, 24V DC electric servo cylinders with nominal force capacity of 100 lb under continuous operation and 3.75 inches of stroke, are shown in the photographs on Page 6 of Appendix C. These actuators were remotely controlled via a safe remote control, a wireless handheld joystick device that was interfaced to the automated test driver program to send separate move commands to the right and left lever actuators. (The safe remote control was also used as the remote engine kill-switch for both mowers.) The zero-turn mower could be driven straight forward by applying equal forward actuator/lever motions, driven straight in reverse by applying equal rearward actuator/lever motions, or steered left and/or right by applying different left and right actuator/lever motions.

Front and side view photos showing the test setup for the quasi-lateral rollover tests of the zero-turn mower are on Page 7 of Appendix C. This maneuver starts with the mower stopped facing up a 20° grass-covered slope with a steep ramp (Figure 14) close behind the mower's right rear tire. The maneuver involves backing rearward down the ramp, which serves as the overturn-causing obstacle. The park brake hand lever was manually set to prevent the vehicle from rolling rearward prior to the start of the tests. To start this maneuver, the throttle speed control was manually set to near its maximum and simultaneously the park brake lever was manually released (via a strap tied to the lever) and both driver-control levers were programmatically pulled to their full stroke in the rearward direction.

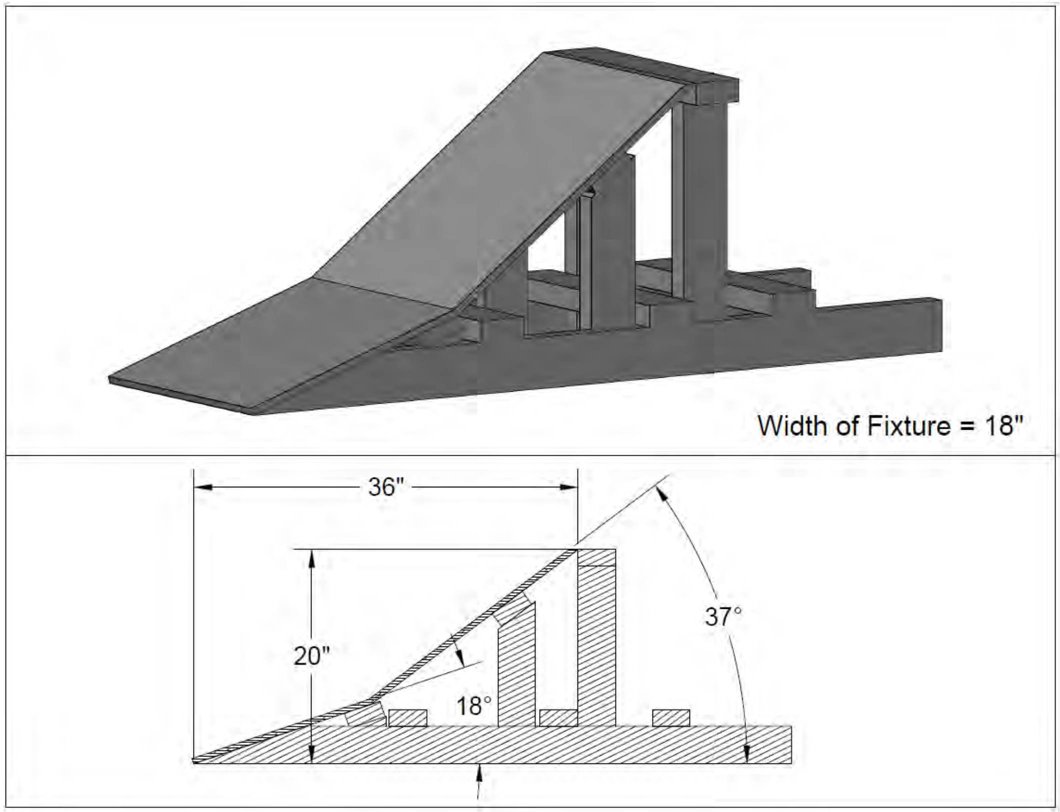

Figure 14: Ramp Used for Zero-Turn Mower Quasi-Lateral Rollover Maneuver on 20° Upslope

Page 8 of Appendix C shows rear and side views of the zero-turn mower setup for rearward pitchover tests. Sections of angle iron were placed behind the rear tires of the mower to prevent it from rolling rearward before the tests. The rearward pitchovers involved applying sudden traction control from a stopped condition with the mowers facing up and driving straight up the 25° grass-covered slope. To start the tests, the throttle speed control was manually set to its maximum setting and both driver-control levers were programmatically pushed to their full stroke in the forward direction. This caused the mower to drive somewhat forward and ultimately pitch over in the rearward direction.

4. DESCRIPTION OF TEST RESULTS

4.1 Introduction

The results from the dynamic tests are contained in Appendix B. The following sections describe the results for both mowers.

Table 4 contains a list of pages of results in Appendix B for each of the eight tip-over tests conducted. For each tip-over run, the first 6 to 14 pages of results (depending on the duration of the tip-over event) contain composite images taken from four different video cameras. The pages of camera images are followed by five pages of graphs containing data from the ATD: ATD Head Accelerations, ATD Head Angular Rates, ATD Chest Accelerations, ATD Neck Forces, and ATD Neck Moments. These are followed by three pages of graphs containing data from the vehicle: Vehicle Body Fixed Accelerations, Vehicle Angular Rates, and Vehicle Angles.

The vehicle body fixed coordinate system is an orthogonal coordinate system with its origin at the center of gravity of the vehicle. For this coordinate system, the X-axis is in the longitudinal direction toward the front of the vehicle, the Y-axis is in the lateral direction with positive to the right, and the Z-axes is down. This coordinate system is fixed to the vehicle, and rotates with the vehicle as it pitches, rolls, and yaws.

The ATD head, chest, and upper neck coordinate systems are orthogonal coordinate systems with their origins near the center of the head, chest, and upper neck, respectively. These are ATD fixed coordinate systems, each with its X-axis directed toward the front of the ATD, its Y-axis directed to the right, and its Z-axis directed down. The polarities of the head and chest accelerations, the head rotational rates, and the upper neck forces and moments are consistent with SAE standard sign conventions for ATD measurements.[11]

Table 4: Arrangement and Pagination of Appendix B

Vehicle	Test Condition	Pages
Vehicle A Small Tractor Mower	Lateral Rollover without ROPS	1 – 16
	Lateral Rollover with ROPS	17 – 31
	Rearward Pitchover without ROPS	32 – 53
	Rearward Pitchover with ROPS	54 – 69
Vehicle C Small Zero-Turn Mower	Quasi-Lateral Rollover without ROPS	70 – 89
	Quasi-Lateral Rollover with ROPS	90 – 107
	Rearward Pitchover without ROPS	108 – 129
	Rearward Pitchover with ROPS	130 – 145

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

4.1.1 Video Image Results

Four digital video cameras were used to videotape the tests. Each camera was set to capture images at 240 frames per second, and they were synchronized to start at the same time using a remote trigger. Sequences taken from the videos are used to generate the composite images contained in Appendix B. The video cameras were mounted on tripods, and arranged to capture front, rear, right side, and left side views of the tip-over events.

The number of video images presented in each section of Appendix B depends on the duration of the tip-over test. The first composite image for each test shows the start of each test (Time = 0.0 sec), a time determined when the vehicle first starts to move. Subsequent images were selected to show the progression of the tip-up over event up to the end of the run when the vehicle and ATD stopped moving. Depending on the type and duration of the tip-up event, the images are spaced in increments of 30 degrees of roll angle or 30 degrees of pitch angle, or increments of 0.25 sec or 0.50 sec. There are also images showing the peak roll angle or peak pitch angle, and images showing when the head of ATD first strikes the ground. The final image for each event is the end-of-run image.

4.1.2 ATD Results

A description of ATD, the ATD sensors and data collection system, and the system used to secure and release the ATD during the rollover events is contained in Appendix D.

As mentioned earlier, each section in Appendix B contains five pages of ATD results. The first page contains Head Accelerations in the head fixed X, Y, and Z directions; the second page contains Head Angular Rates about the head roll, pitch, and yaw axes; the third page contains Chest Accelerations in the chest fixed X, Y, and Z directions[12]; the fourth page contains Upper Neck Forces in the neck fixed X, Y, and Z directions; and the fifth page contains Upper Neck Moments about the roll, pitch, and yaw axes. All the ATD data was zeroed prior to the time the vehicle started moving, so the data presented shows the changes in accelerations, rates, forces, and moments that occurred throughout the rollover event. All the ATD data shown has been filtered using a 1,000 Hz low pass, Butterworth filter. Depending on the maneuver type, the ATD data was time synchronized to the vehicle data by matching either the ATD and vehicle roll rates or the ATD and vehicle pitch rates at the beginning of each test.

All the graphs containing ATD data include a vertical band (about 0.2 seconds wide) centered around the time of peak ATD head accelerations. The peaks in the ATD chest accelerations, head angular rates, neck forces, and neck moments are also generally all within this band.

4.1.3 Vehicle Results

The ATD results in each vehicle section in Appendix B are followed by three pages of vehicle results. The first page contains Vehicle Body Fixed Accelerations in the vehicle body fixed X, Y, and Z directions; the second page contains Vehicle Angular Rates about the vehicle's roll, pitch, and yaw axes; and the third page contains Vehicle Angles about the vehicle's roll, pitch, and yaw axes. The angle graphs show Heading Change (the change in angle about the yaw axis) and this

[12] For three of the tests conducted using the zero-turn mower, the ATD chest acceleration signal in the Y-axis direction, Chest Ay, was corrupted and it fluctuated around zero, as shown in the plots of Appendix B Pages 84, 102, and 124.

is the change from the initial angle the vehicle was headed at the start of each test. All the vehicle data is unfiltered.

4.2 Results for Tractor Style Mower

4.2.1 Lateral Rollover without ROPS

At the beginning of this test the right front tire of the mower drove onto the trip-hazard rock, and then the vehicle travelled rearward when the right rear tire lifted off the ground. Nonetheless, the mower rolled over as intended, but it took over two seconds for the roll angle to reach 30°. Note that the roll angles listed above the images are roll angle magnitudes (mower roll angles to the left are negative). The images in Appendix B show that the ATD roll angle lagged the mower roll angle during the initial part of the rollover. At 45° of mower roll angle, the ATD neck and hip cables were released, allowing the ATD roll angle to catch up with the vehicle roll angle by about 90° of roll angles. The ATD head first impacted the ground when the mower roll angle was close to 120°. After 120° of mower roll angle, the mower continued to roll about 10 more degrees, until its roll motion was stopped by the steering wheel and other parts of the mower hitting the ground. The cable ties holding the ATD's hands to the steering broke during this final phase, and both the ATD and mower slid slightly down the slope. However, the ATD did not displace much from the mower, it landed and ended with its buttocks within a foot of the seat of the mower. The mower did not roll on top of or over the ATD during this lateral rollover event.

4.2.2 Lateral Rollover with ROPS

The mower throttle was set higher for this test and the mower did not travel rearward during this test. Throughout this event, the motion of the ATD and mower were similar to the test without ROPS. As before, the ATD roll angle lagged the mower roll angle during the initial part of the rollover. At 45° of mower roll angle, the ATD neck and hip cables were released allowing the ATD roll angle to catch up with the vehicle roll angle by about 90° of roll angles. With the ROPS, the maximum mower roll angle was 115.6°, and this was the time when the head of the ATD first hit the ground. The seat belt kept the ATD connected to the seat of the mower, and this held the ATD inside the lateral deflection-limiting volume of the ROPS. The cable ties holding the ATD's hands to the steering wheel did not break during this lateral rollover event. The ROPS limited the roll motion of the mower and prevented the steering wheel from contacting the ground.

4.2.3 Rearward Pitchover without ROPS

The results provided in Appendix A show that the instrumented tractor mower with ROPS had a lower CG height and greater rearward static stability factor than when it was loaded with a 95th% male driver. The CG height of the instrumented tractor mower without ROPS is even lower. During the FY2022 tests with a human driver, the tractor mower tipped rearward when the clutch-brake pedal was rapidly released while the mower was facing up the 25° grass slope. In the autonomous test load condition without ROPS, the mower did not tip-over in the rearward direction on the uphill 25° slope; rather it just traveled forward up the hill. To intentionally cause a rearward pitchover, wooden blocks of approximately 4" height were placed under the front tires of the mower. With the blocks in place, the initial pitch angle was 34.6°. Rapidly releasing the clutch-brake pedal using this starting condition did cause the mower to tip-over in the rearward direction.

For this rearward pitchover test, the only added restraint to hold the ATD to the mower were cable ties holding the ATD's hands to the steering wheel. The back of the mower's seat prevented the ATD from sliding rearward off the mower through 120° of pitch angle, about the time when the ATD's head first contacted the ground. The cable ties were apparently not broken at this point, but they were by the time the mower pitch angle reached 180°.

Pages 38, 39, and 40 of Appendix B, with the mower pitched at 180°, 210°, and 240° respectively, show the mower landing on and pitching over the ATD. By the time the mower pitch angle was 270° through the end of the event the ATD was essentially separated from the mower.

4.2.4 Rearward Pitchover with ROPS

As mentioned, the CG height of the instrumented mower with ROPS is higher than that of the instrumented mower without ROPS. Also, the longitudinal CG location is more rearward with ROPS. Therefore, no blocks were needed under the front tires during the rearward pitchover test with ROPS. For this test, the initial mower pitch angle was close to 25°, the angle of the uphill slope.

For this rearward pitchover test, the seat belt served to hold the ATD to the mower in addition to the cable ties holding the ATD's hands to the steering wheel. The back of the mower's seat prevented the ATD from sliding rearward and the seat belt kept the ATD's pelvis held down in the seat. However, like the test without ROPS, the ATD's head first contacted the ground when the mower pitch angle was close to 120°, as was first contact of the ROPS with the ground. The ROPS limited the pitch motion of the mower, and the maximum pitch angle was 132.9°. The mower did not roll sideways during this event, it ended resting on the back of the ROPS. The cable ties securing the ATD's hands to the steering wheel remained intact during this pitchover event.

During this test, the open space in the vertical portion of the ROPS allowed the ATD's shoulders head and shoulders to travel slightly rearward beyond the back of the ROPS. To prevent this from happening during the subsequent tests using the zero-turn mower, a 1"x1" metal bar was installed to laterally span the opening in the ROPS at about mid-back height.

4.3 Results for Zero-Turn Mower

4.3.1 Quasi-Lateral Rollover without ROPS

For this quasi-lateral rollover test of the zero-turn mower, the uphill-facing mower was driven rearward with its right rear tire traveling onto the rollover-inducing ramp. By the time the right rear tire was about two thirds up the ramp, the mower rolled about 45° to the left, and soon after this it rolled off the ramp. Page 74 of Appendix B shows the time when the ATD's head first contacted the ground was when the mower roll angle was less than 90°. For this test without ROPS or seat belt, the right-hand cable tie broke before this time, which allowed the ATD's roll motion to lead the roll motion of the mower. Page 75 shows that the ATD tumbled downhill and landed free of the mower. However, Pages 76-78 show that the mower continued to roll on top of the ATD. After rolling over the ATD, the mower continued to roll, and slid to rest in an upright orientation.

4.3.2 Quasi-Lateral Rollover with ROPS

For the quasi-lateral rollover with ROPS, at the point where the right rear tire was about two thirds up the ramp, the mower rolled about 45° to the left, with the motion of the mower and ATD similar to the test without ROPS. However, the test outcome after this point was much different for this test with ROPS and seat belt. The seat belt held the ATD's pelvis to the seat of the mower, and this held the ATD inside the lateral deflection-limiting volume of the ROPS. Page 97 of Appendix B shows the initial contact of the ROPS with the ground. The mower did not move significantly after this. A short time after initial ROPS contact with ground, the ATD's left shoulder and head struck the ground. The seat belt kept the ATD coupled to the mower, and the handhold cable ties did not break during this event.

4.3.3 Rearward Pitchover without ROPS

The results provided in Appendix A show that the instrumented zero-turn mower with ROPS had a lower CG height than when it was loaded with a 95th% male driver. The CG height of the instrumented zero-turn mower without ROPS is even lower. Durning the FY2022 tests with a human driver, the zero-turn mower tipped rearward when the driver pushed rapidly forward on the driver control levers while the mower was facing up the 25° grass slope. In the autonomous test load condition without ROPS, the mower did not tip-over in the rearward direction on the uphill 25° slope; rather it just continued to travel forward up the hill. To intentionally cause a rearward pitchover, steel blocks of approximately 4" height were placed under the front tires of the mower. With the ramps in place the initial pitch angle was 33.1°. Rapidly pushing forward on the control levers using this starting condition did cause the mower to tip-over in the rearward direction.

For this rearward pitchover test, the only added restraint to hold the ATD to the mower were the cable ties holding the ATD's hands to the control levers. The back of the mower's seat prevented the ATD from sliding rearward off the mower through 120° of mower pitch angle. Soon after 120° of pitch angle, the ATD's head first contacted the ground.

The four sequence images after the ATD head strike, Pages 113-116 of Appendix B show the mower landing on and pitching and rolling over the ATD.

By the time the mower reached its maximum pitch angle, Page 117, the bulk of the weight of the mower had pitched and rolled off the ATD. The control levers of the zero-turn mower held the legs of the ATD close to the mower, and the ATD never fully disengaged from the mower throughout the entire rearward pitchover event. The handhold cable ties did not break during this event.

4.3.4 Rearward Pitchover with ROPS

As mentioned, the CG height of the instrumented mower with ROPS is higher than that of the instrumented mower without ROPS. Also, the longitudinal CG location is more rearward with ROPS. Therefore, no ramps were needed under the front tires during the rearward pitchover test with ROPS. For this test, the initial mower pitch angle was close to 25°, the angle of the uphill slope.

For this rearward pitchover test, the seat belt served to hold the ATD to the mower in addition to the cable ties holding the ATD's hands to the steering wheel. The back of the mower's seat prevented the ATD from sliding rearward and the seat belt kept the ATD's pelvis held down in the seat. Nonetheless, like the test without ROPS, the ATD's head first contacted the ground when the mower pitch angle was slightly above 120°, and the first contact of the ROPS with the ground was also at this time. The ROPS limited the pitch motion of the mower, and the maximum pitch angle was 160.1°. The mower did not roll sideways during this event, rather it ended resting on the back of the ROPS. The right-hand cable tie remained intact during the entire pitchover event, but the left-hand cable tie broke before the mower reached its maximum pitch angle.

4.4 HIC Values for Tests of Both Mowers

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 mower rollovers and pitchovers to assess potential head injury levels.

As described in detail in Appendix D, HIC values were computed as a measure of head impact severity using time duration ranges of 15 milliseconds and 36 milliseconds. These time duration ranges are commonly used, and they are denoted as HIC_{15} and HIC_{36}, respectively. The HIC value is the maximum of an integration involving the resultant head accelerations and time duration range, as the calculation is swept across the entire time span of the event (for this study, from five seconds before the trigger to fifteen seconds after the trigger). For all the tests conducted, the peak HIC values occurred around the time when the ATD's head first struck the ground.

Figure 15 contains graphs showing the HIC_{15} and HIC_{36} values for all the tractor mower tests (top graph) and zero-turn mower tests (bottom graph). The HIC_{15} values are generally greater than the HIC_{36} values. Having HIC_{15} values greater than HIC_{36} values means that the 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[13]) specifies that maximum calculated HIC_{15} values shall not exceed 700 and that the HIC_{36} values shall not exceed 1,000. A review of technical literature indicates that HIC values of 1,000 have over a 50% probability of serious head injury and 90% probability of moderate head injury. In a study involving professional athletes, HIC values of 250 were likely to result in concussions.[14]

All the HIC_{15} values computed are below 120 and all the HIC_{36} values are below 70. These low values suggest that moderate or severe head injuries, or even concussions, are not likely to occur during these types of mower overturn events, with or without a ROPS. The values also show that there is no substantial trend differences between tests with or without ROPS, or between tests of the tractor mower and zero-turn mower.

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[13] *FMVSS 208, Occupant Crash Protection*, NHTSA, Federal Register 49 CFR 571.208, 2011. https://www.govinfo.gov/content/pkg/CFR-2011-title49-vol6/pdf/CFR-2011-title49-vol6-sec571-208.pdf

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

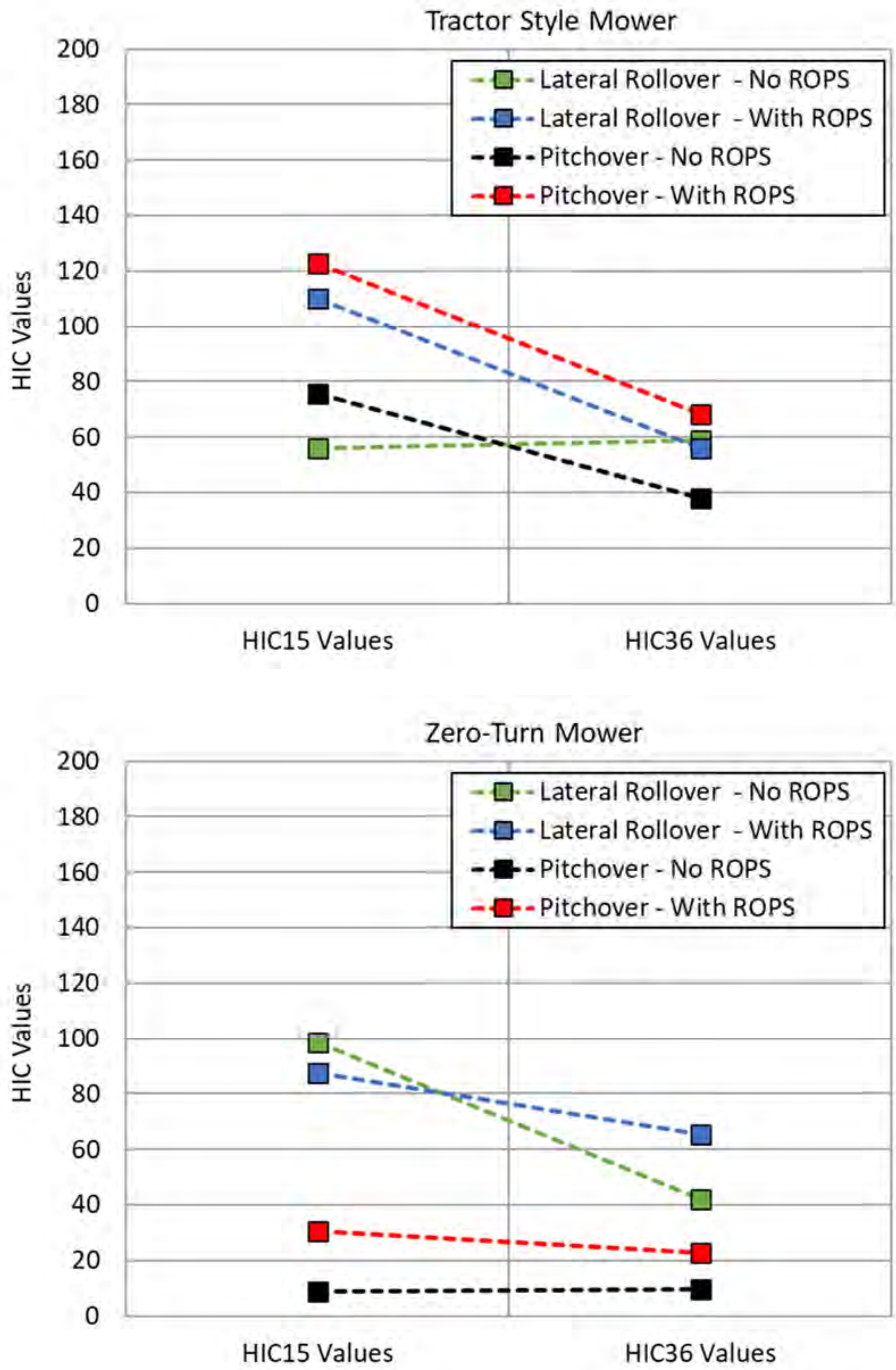


Figure 15: HIC Values Computed During Tests on
Tractor Mower (TOP) and Zero-Turn Mower (BOTTOM)

4.5 Summary

Two autonomous vehicle control systems, one for steering-wheel-controlled (tractor style) riding mowers and one for lever-controlled (zero-turn) riding mowers were designed and built. The autonomous control systems were used to conduct tests designed to deliberately overturn the two mowers tested. An anthropomorphic test dummy (ATD) secure-and-release system was designed and built, so an instrumented ATD could be used as a surrogate driver during the overturn tests.

Neither of the mowers tested was designed for use with ROPS. Therefore, Proof-of-Concept (POC) Rollover Protection Systems (ROPS) were designed and fabricated for each of the mowers for use in testing. Intentional rollover and pitchover tests were conducted with and without the POC ROPS to evaluate the potential feasibility and effectiveness of using these devices on riding mowers.

In all tests using ROPS, the ROPS prevented the mowers from rolling or pitching completely over. The upper structures of the ROPS remained flat against the ground, after the roll angle or pitch angle was limited by the ROPS in these tests. None of the tests with ROPS resulted in the mower landing on or overturning onto the ATD, the ATD generally remained in the lateral deflection-limiting volume of the ROPS.

The lateral rollover of the tractor mower without ROPS also resulted in a test outcome similar to those tested with ROPS. In this specific rollover scenario, the mower without ROPS did not roll completely over, as the roll motion was halted by the steering wheel and side structures of the mower.

The other three tests conducted to deliberately overturn the mowers without ROPS, the quasi-lateral rollover of the zero-turn mower and rearward pitchovers of both mowers, each resulted in the bulk of the weight of the mower landing on and tumbling over the ATD.

Calculations of Head Injury Criterion (HIC) values obtained using the test data suggest that no moderate or greater head injuries or concussions were likely to occur during the specific mower overturn events conducted as part of this study, with or without a ROPS.

There are many types and severities of mower tip-over events. This study included a small sample of rollover and pitchover tests, conducted on sloped surfaces that exceed the recommended maximum angles for operating the two mowers. Nonetheless, test outcomes preliminarily demonstrate that it is achievable to use ROPS on riding mowers of the types and sizes tested to prevent the mowers from landing on and tumbling over belted operators of the mowers, in the tip-over events tested.

During all tests conducted using ROPS, the ATD was belted. Mower overturn event results will be different if the ATD (or consumer) is not belted.

On mowers that require ROPS, the ROPS typically include a feature to fold down for use when mowing under trees/bushes and for storage. This feature comes with the risk that consumers will use the mower with the ROPS folded down. During all tests conducted using (non-foldable) ROPS in this study, the ROPS were at their full upright position. Mower overturn event results will be different if the ROPS are folded down.

The POC ROPS used for this study were designed to be fixed to mowers that were not designed to have ROPS. Stronger and lighter ROPS with more optimal geometries could be designed if they were integral to the overall design of a mower. Likewise, the attachments and positions of the seat belts could potentially be improved if they were designed as an integral component of a mower. Finally, steps could be taken to potentially increase driver head space while entering or leaving the seat, to add padding around the upper portion of the ROPS, and to have ROPS that could be folded to allow access for mowing under things like low tree limbs.

The FY2022 review of mower incidents provided by CPSC found that the more severe mower accidents often involved vehicles losing directional control and then going down very steep slopes on which no reasonable mower could resist tipping. Further, it was noted that a significant number of fatalities involved mowers overturning into water, where the rider was trapped and killed. Whether the death was from crushing or drowning was usually unknown.

The maneuvers used in this study to deliberately overturn the mowers fall into the category of maneuvers with "no reasonable mower could resist tipping" outcomes, as the goal of testing was to evaluate the impact of overturn events on the ATD and vehicle, not to evaluate specific mowers or overturn conditions. Further consideration should be given to more severe maneuvers on steeper slopes and/or drop-offs, and other maneuvers involving forward pitchovers, maneuvers involving combined rollover/pitchover at oblique angles, and overturns into bodies of water.

Finally, while the specific events studied here suggest ROPS may prevent injuries in some circumstances, this study did not address the risk-benefit assessment of using ROPS on residential riding mowers. The FY2022 study demonstrated that the mowers evaluated were only likely to overturn if they were operated on surfaces with slopes that exceeded their recommended operating use case and, in some cases, also included a trip hazard. Considerations warranting further study of potential adverse effects of adding ROPS to residential riding mowers include: how changes to the CG height and CG longitudinal location with ROPS effects rollover and pitchover resistance, how having a ROPS on a lightweight vehicle like Vehicle A or Vehicle C could introduce the potential of rearward pitchovers happening if the vehicle is driven under low limbs or clotheslines, the potential for injuries from impacting the ROPS during both ingress/egress onto the mower and during more severe overturn events, what happens in situations when a ROPS structure is installed and the operator does not use their seat belt, and what happens in situations when a foldable ROPS is folded down.

Small Tractor Mower

	Curb	Curb plus 95^{th}% Male	Human Driver plus Instrumentation & Outriggers	Autonomous Test Load with ATD & ROPS
VIMF Test Number	8060	8075	Weight Only	8448
Total Vehicle Weight (lb)	271.5	494.5	531.4	537.1
Left Front Weight (lb)	51.4	93.9	77.1	90.9
Right Front Weight (lb)	40.7	78.4	69.9	93.4
Left Rear Weight (lb)	86.9	157.8	189.1	183.5
Right Rear Weight (lb)	92.5	164.4	195.3	169.3
Front Track (in)	26.00	26.00	26.00	26.00
Rear Track (in)	24.00	24.00	24.00	24.00
Average Track (in)	25.00	25.00	25.00	25.00
Wheelbase (in)	46.30	46.30	46.30	46.30
CG Longitudinal (in)	30.59	30.17	33.49	30.41
CG Lateral (in)	-0.26	-0.25	-0.04	-0.26
CG Height (in)	12.86	23.95		22.30
Roll Inertia - Ixx (ft-lb-s^2)	6	40		53
Pitch Inertia - Iyy (ft-lb-s^2)	14	40		57
Yaw Inertia - Izz (ft-lb-s^2)	9	15		31
Roll/Yaw - Ixz (ft-lb-s^2)	1	4		3
SSF	0.972	0.522		0.561
KST	0.960	0.516		0.554
Forward SSF	2.379	1.260		1.364
Rearward SSF	1.221	0.674		0.712

Small Zero-Turn Mower

	Curb	Curb plus 95th% Male	Human Driver plus Instrumentation & Outriggers	Autonomous Test Load with ATD & ROPS
VIMF Test Number	8082	8083	Weight Only	8466
Total Vehicle Weight (lb)	458.4	681.7	716.8	725.2
Left Front Weight (lb)	60.8	105.7	105.0	121.0
Right Front Weight (lb)	65.0	101.2	97.6	82.7
Left Rear Weight (lb)	168.3	236.5	253.9	235.0
Right Rear Weight (lb)	164.3	238.3	260.4	286.5
Front Track (in)	27.95	27.95	26.95	27.95
Rear Track (in)	29.75	29.75	28.75	29.75
Average Track (in)	28.85	28.85	27.85	28.85
Wheelbase (in)	45.70	45.70	44.70	45.70
CG Longitudinal (in)	33.16	31.83	32.07	32.86
CG Lateral (in)	0.00	-0.05	-0.01	0.32
CG Height (in)	13.31	19.82		19.34
Roll Inertia - Ixx (ft-lb-s^2)	13	35		41
Pitch Inertia - Iyy (ft-lb-s^2)	30	51		55
Yaw Inertia - Izz (ft-lb-s^2)	28	34		39
Roll/Yaw - Ixz (ft-lb-s^2)	3	3		5
SSF	1.084	0.728		0.746
KST	1.099	0.737		0.756
Forward SSF	2.491	1.606		1.699
Rearward SSF	0.942	0.700		0.664

Time of Start - Time = 0.0 sec

Tractor Style Mower – Lateral Rollover without ROPS

Roll Angle = 30° - Time = 2.22 sec

Tractor Style Mower – Lateral Rollover without ROPS

Roll Angle = 60° - Time = 4.02 sec

Tractor Style Mower – Lateral Rollover without ROPS

Roll Angle = 90° - Time = 4.28 sec

Tractor Style Mower – Lateral Rollover without ROPS

Roll Angle = 120° - Time = 4.42 sec

Tractor Style Mower – Lateral Rollover without ROPS

ATD Head Strike - Time = 4.42 sec

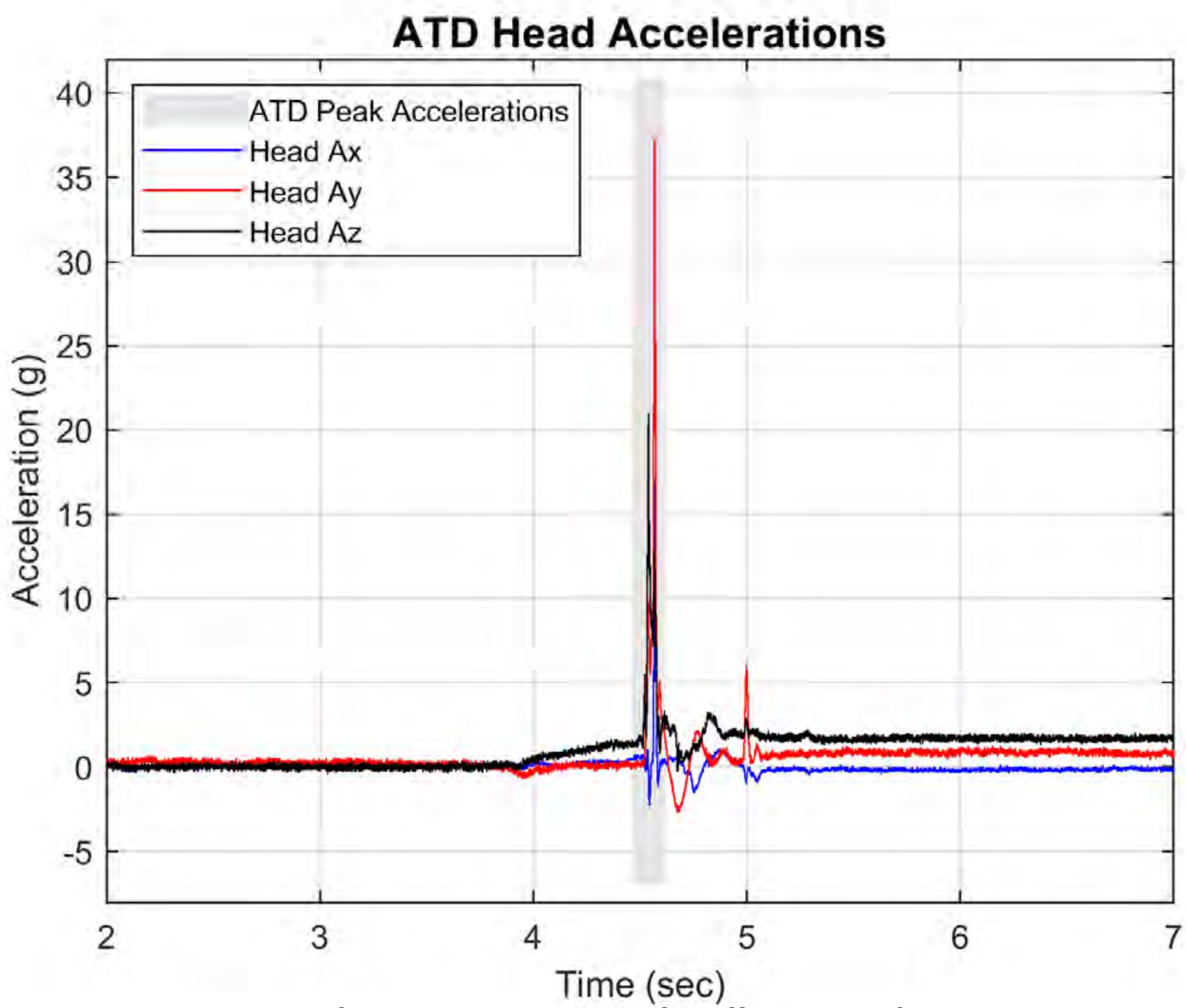
Tractor Style Mower – Lateral Rollover without ROPS

Max Roll Angle = 130.6° - Time = 4.92 sec

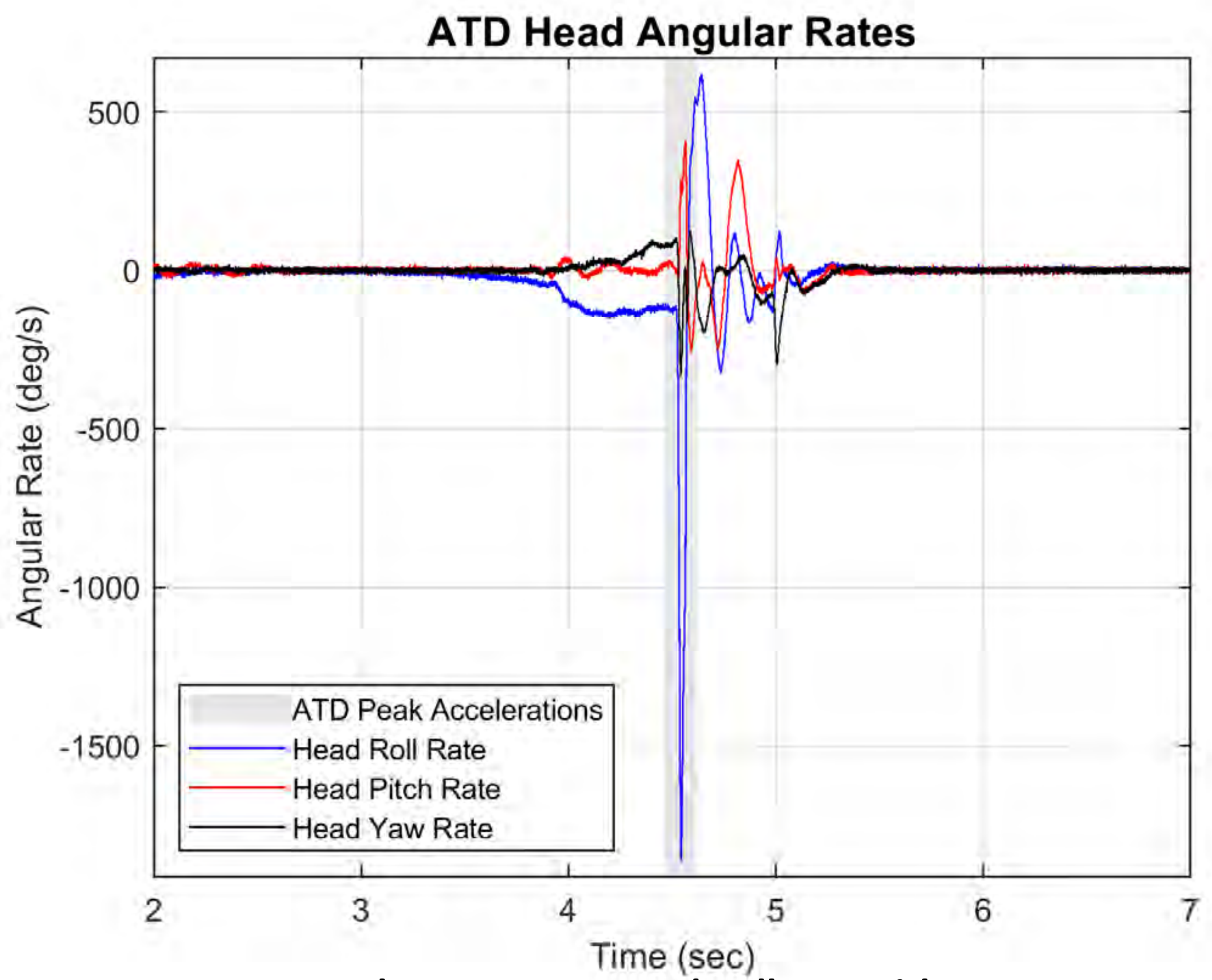
Tractor Style Mower – Lateral Rollover without ROPS

End of Run - Roll Angle = 127.0°

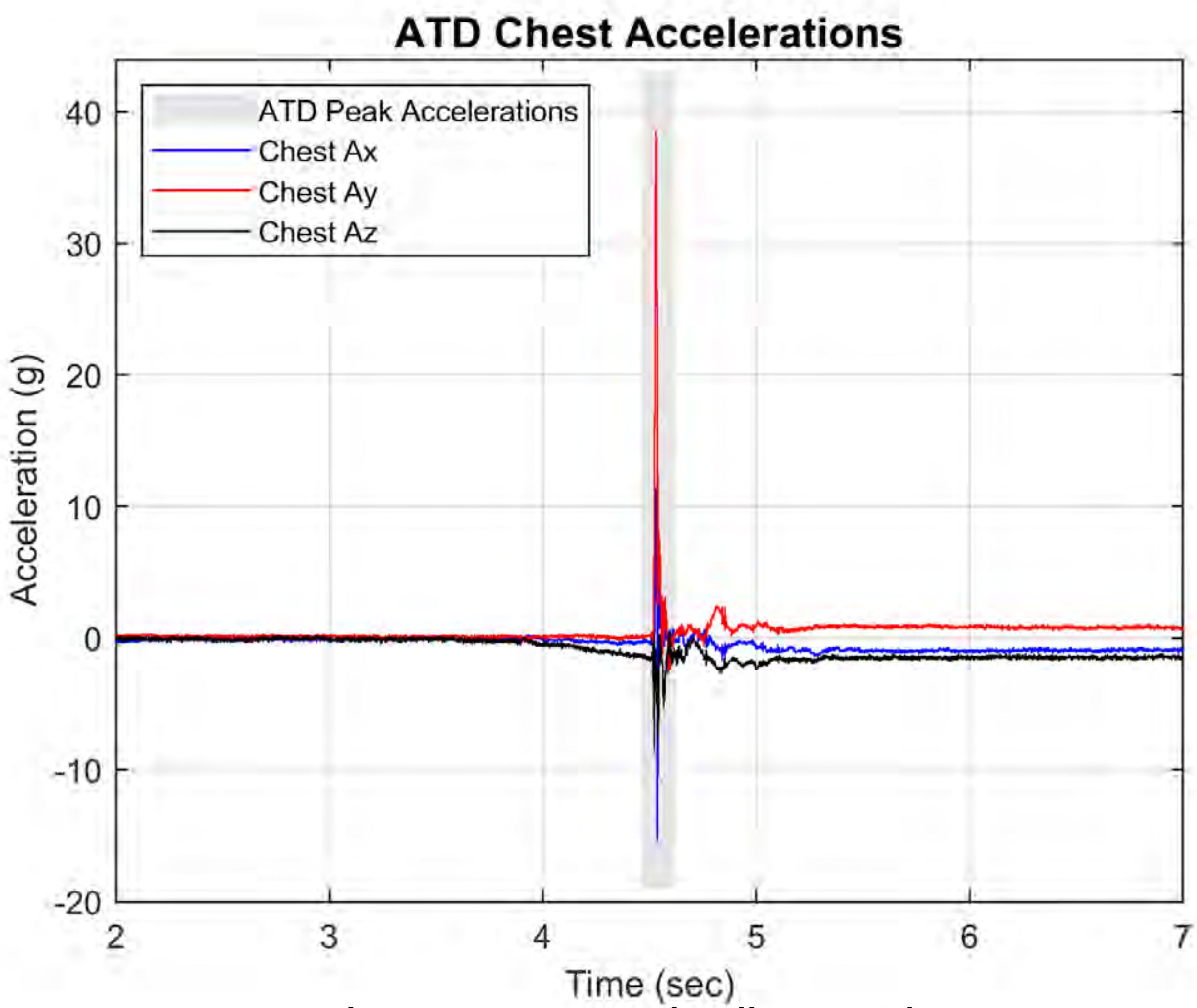
Tractor Style Mower – Lateral Rollover without ROPS



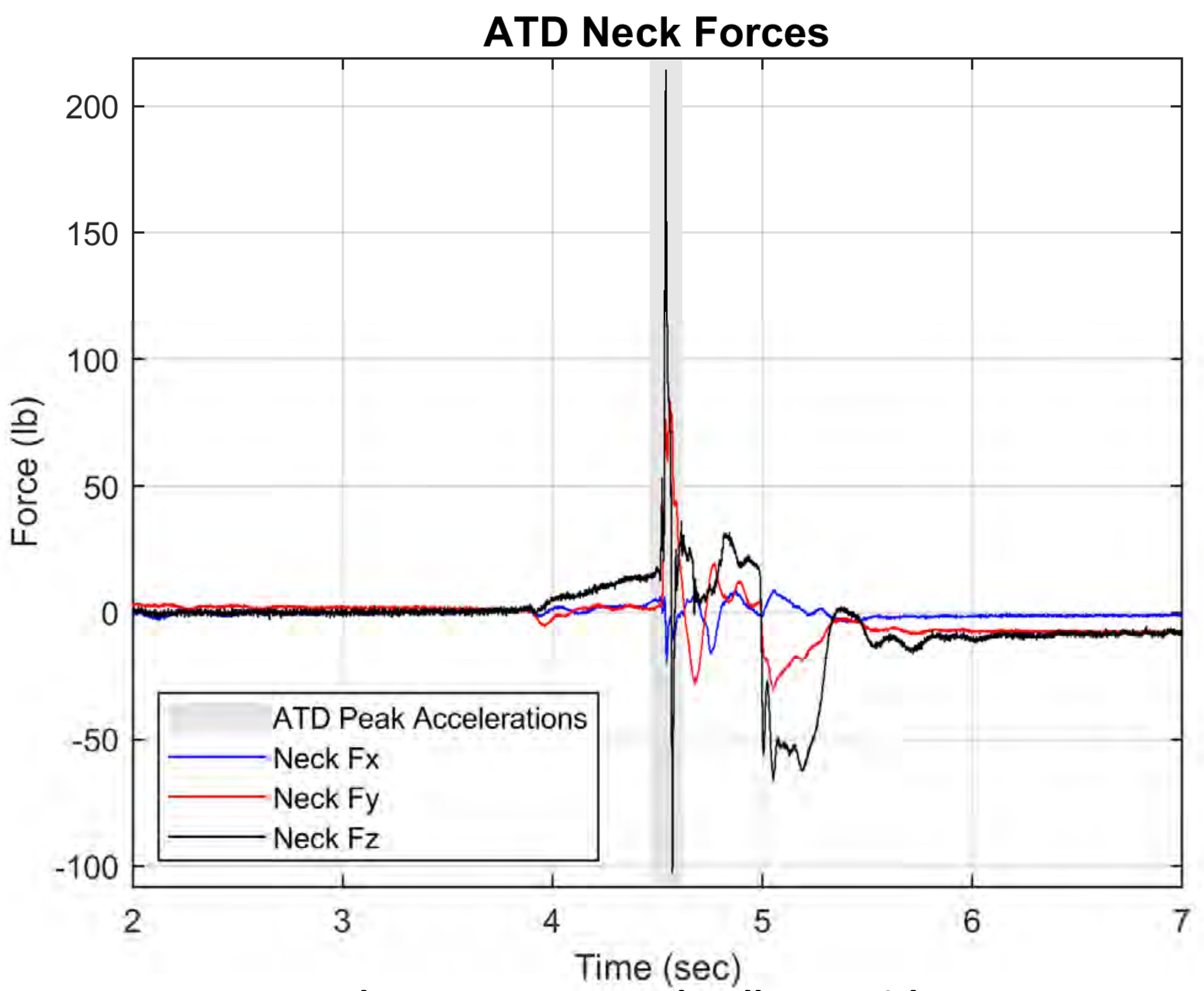
Tractor Style Mower – Lateral Rollover without ROPS



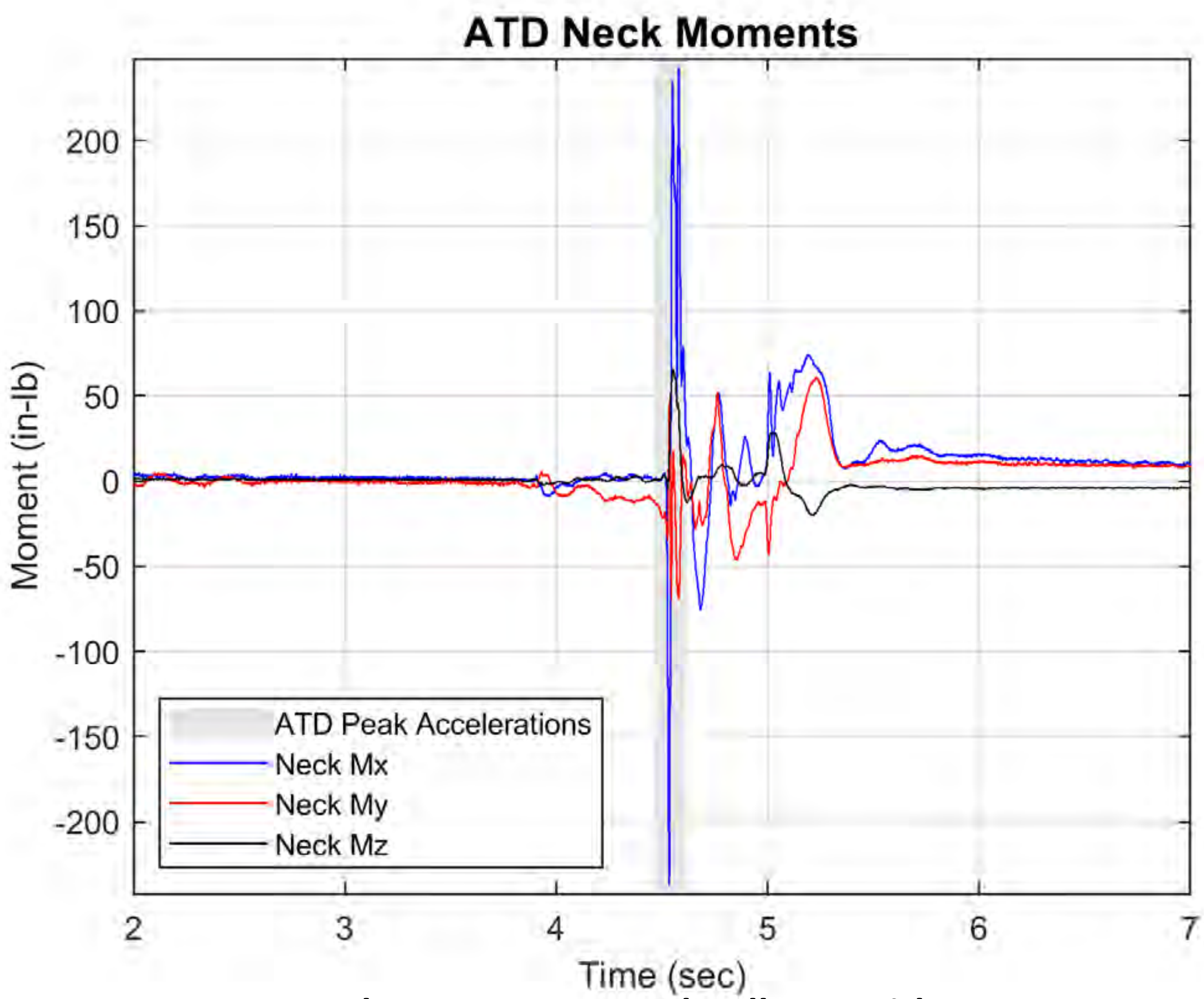
Tractor Style Mower – Lateral Rollover without ROPS



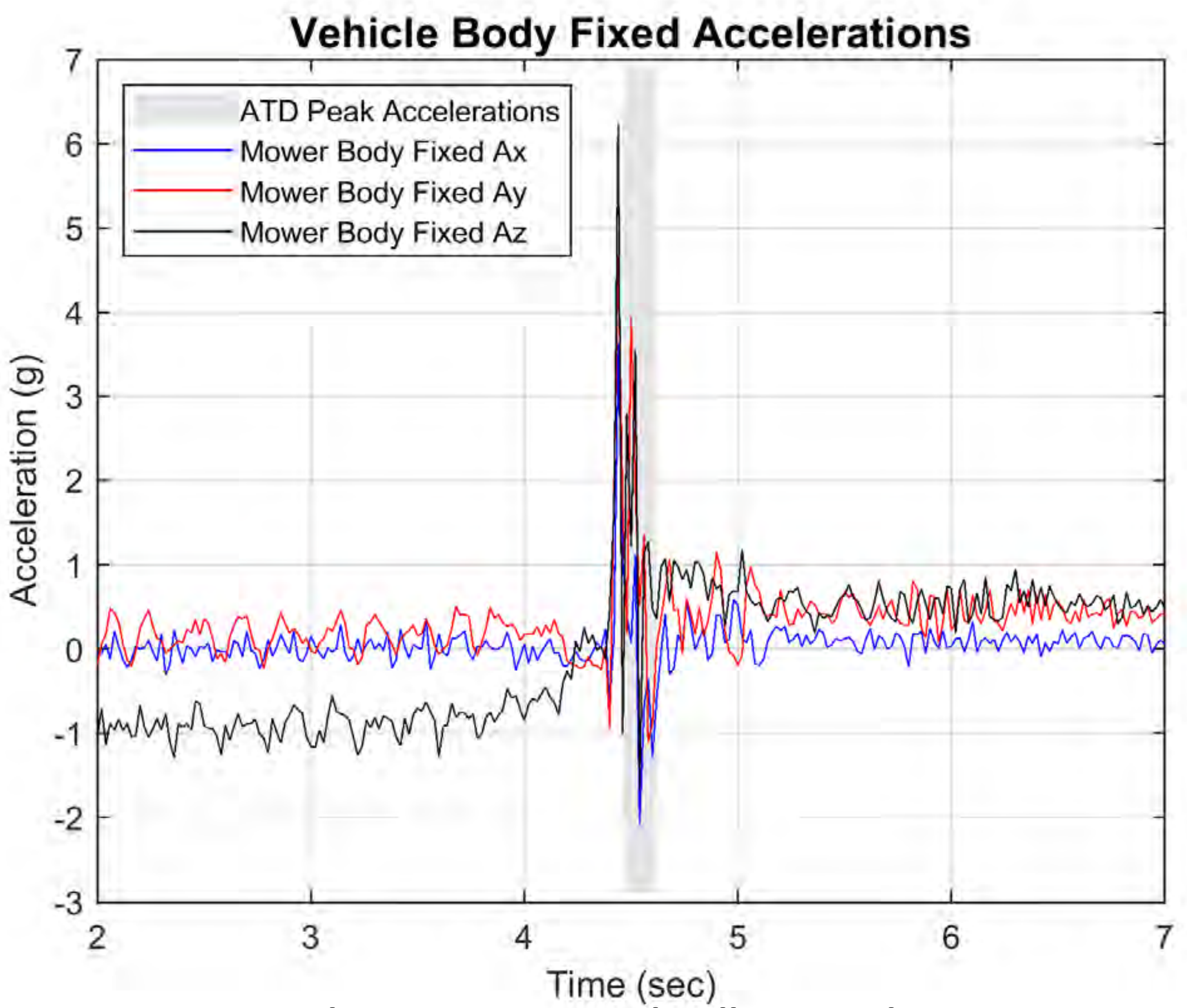
Tractor Style Mower – Lateral Rollover without ROPS



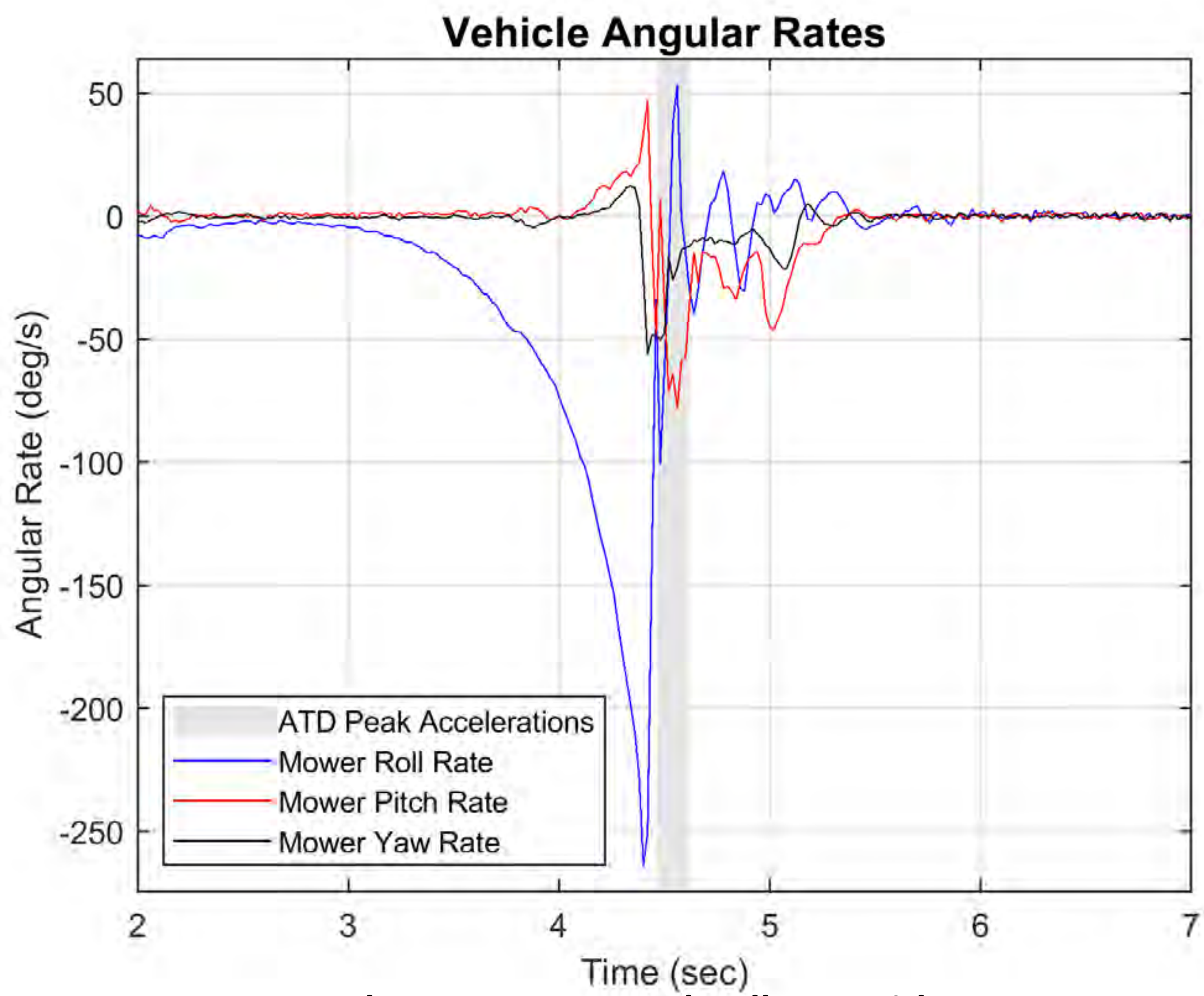
Tractor Style Mower – Lateral Rollover without ROPS



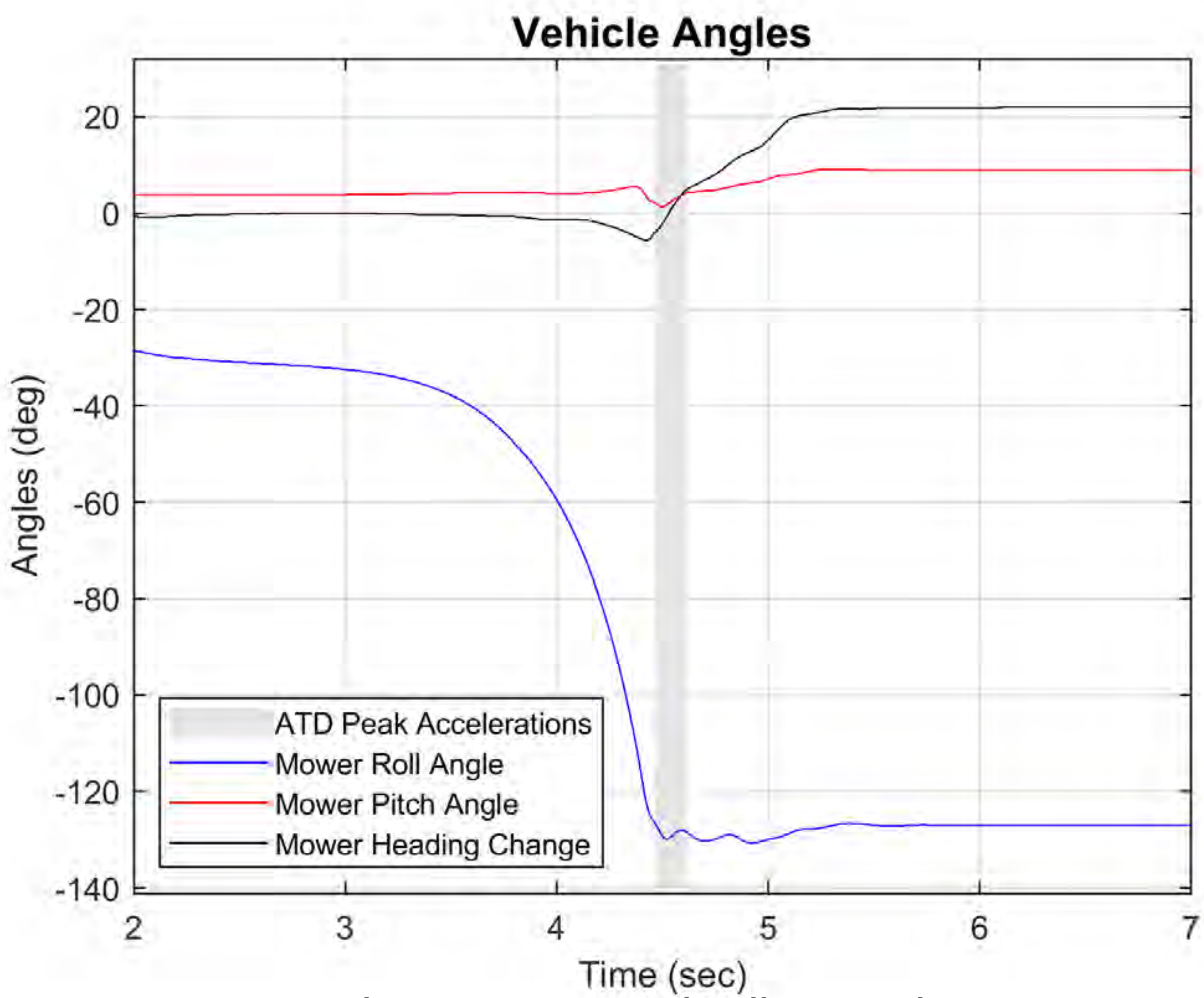
Tractor Style Mower – Lateral Rollover without ROPS



Tractor Style Mower – Lateral Rollover without ROPS



Tractor Style Mower – Lateral Rollover without ROPS



Tractor Style Mower – Lateral Rollover without ROPS

Time of Start - Time = 0.0 sec

Tractor Style Mower – Lateral Rollover with ROPS

Roll Angle = 30° - Time = 1.04 sec

Tractor Style Mower – Lateral Rollover with ROPS

Roll Angle = 60° - Time = 1.66 sec

Tractor Style Mower – Lateral Rollover with ROPS

Roll Angle = 90° - Time = 1.88 sec

Tractor Style Mower – Lateral Rollover with ROPS

ATD Head Strike - Time = 2.10 sec

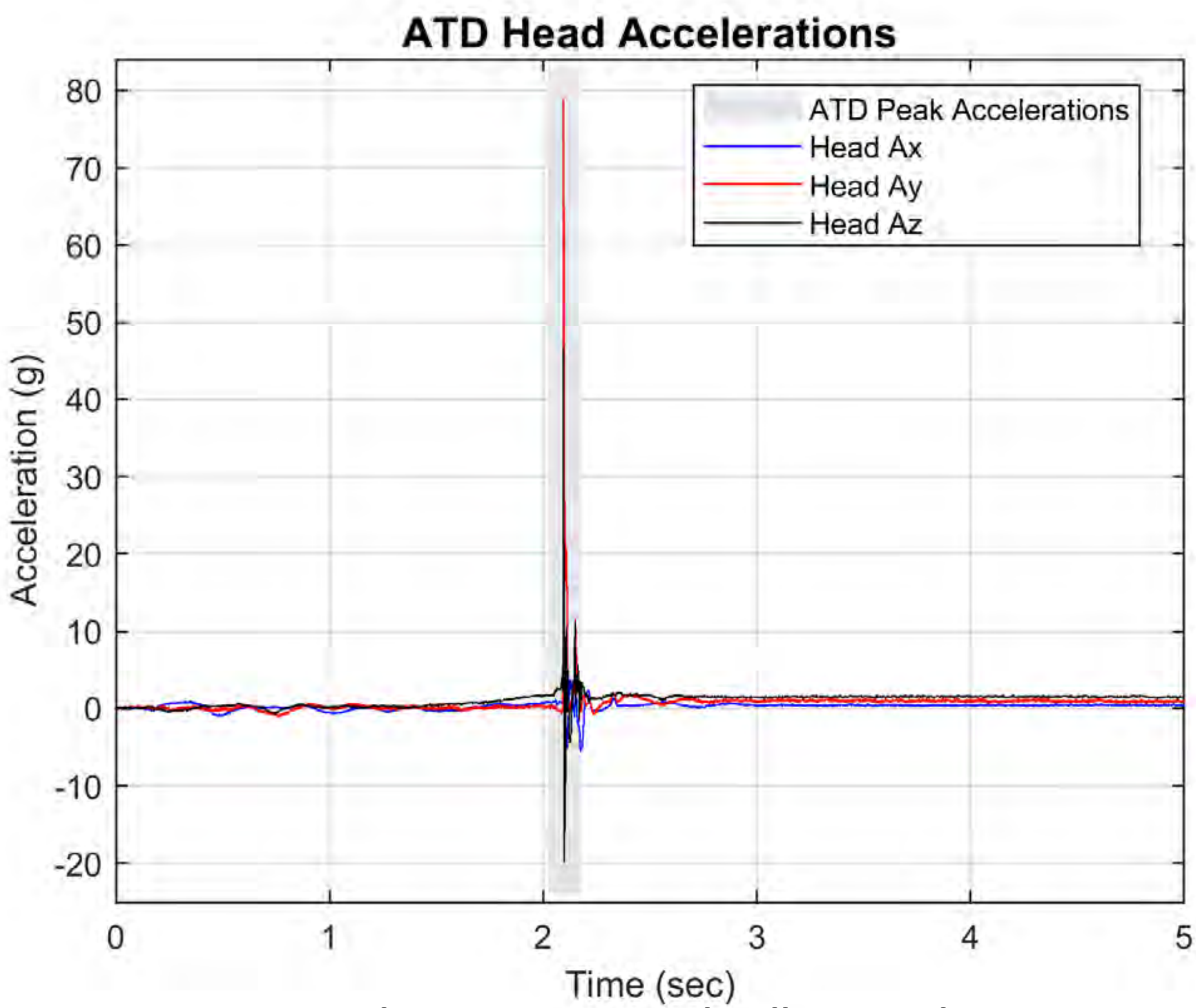
Tractor Style Mower – Lateral Rollover with ROPS

Max Roll Angle = 115.6° - Time = 2.10 sec

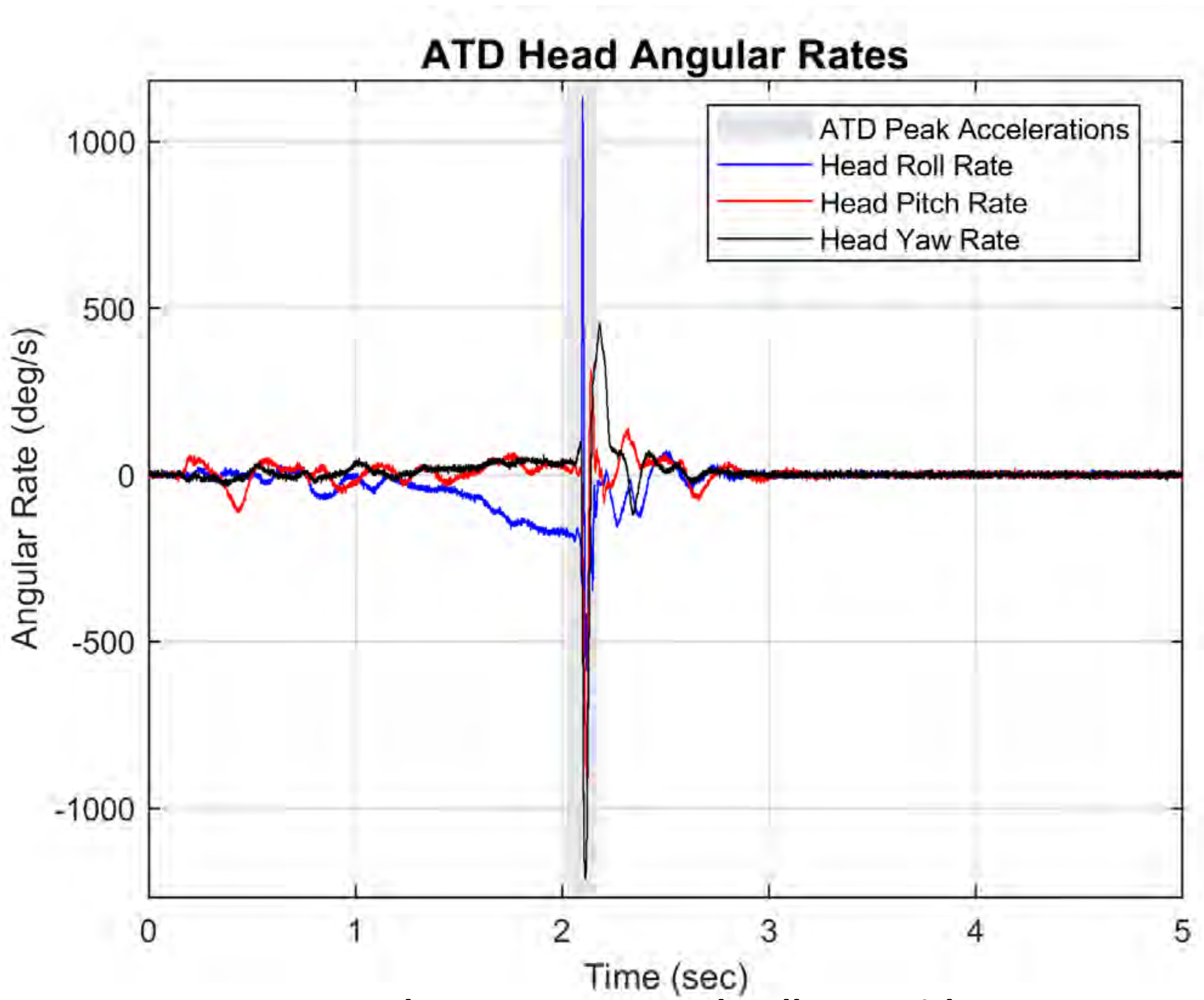
Tractor Style Mower – Lateral Rollover with ROPS

End of Run - Roll Angle = 112.6°

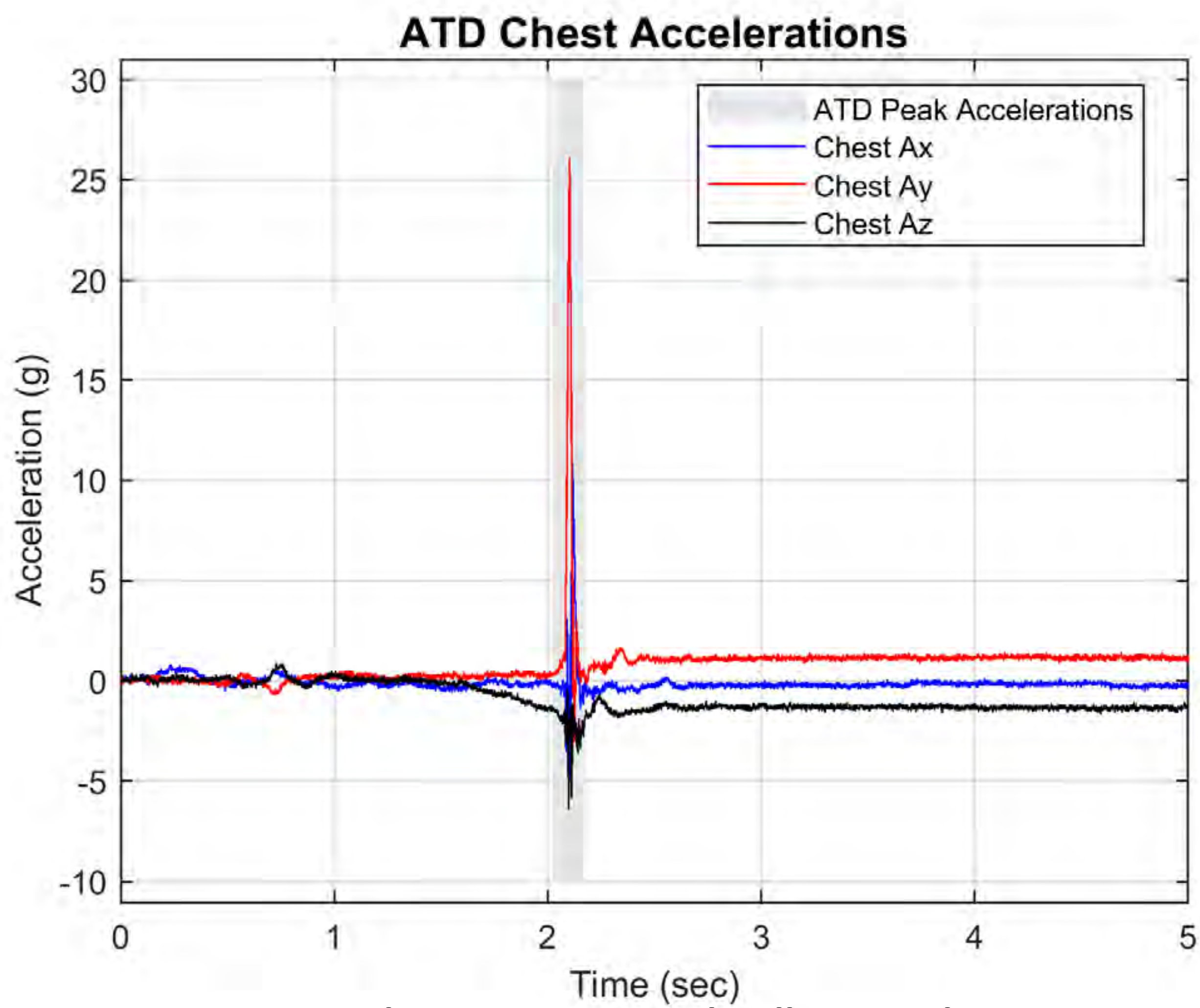
Tractor Style Mower – Lateral Rollover with ROPS



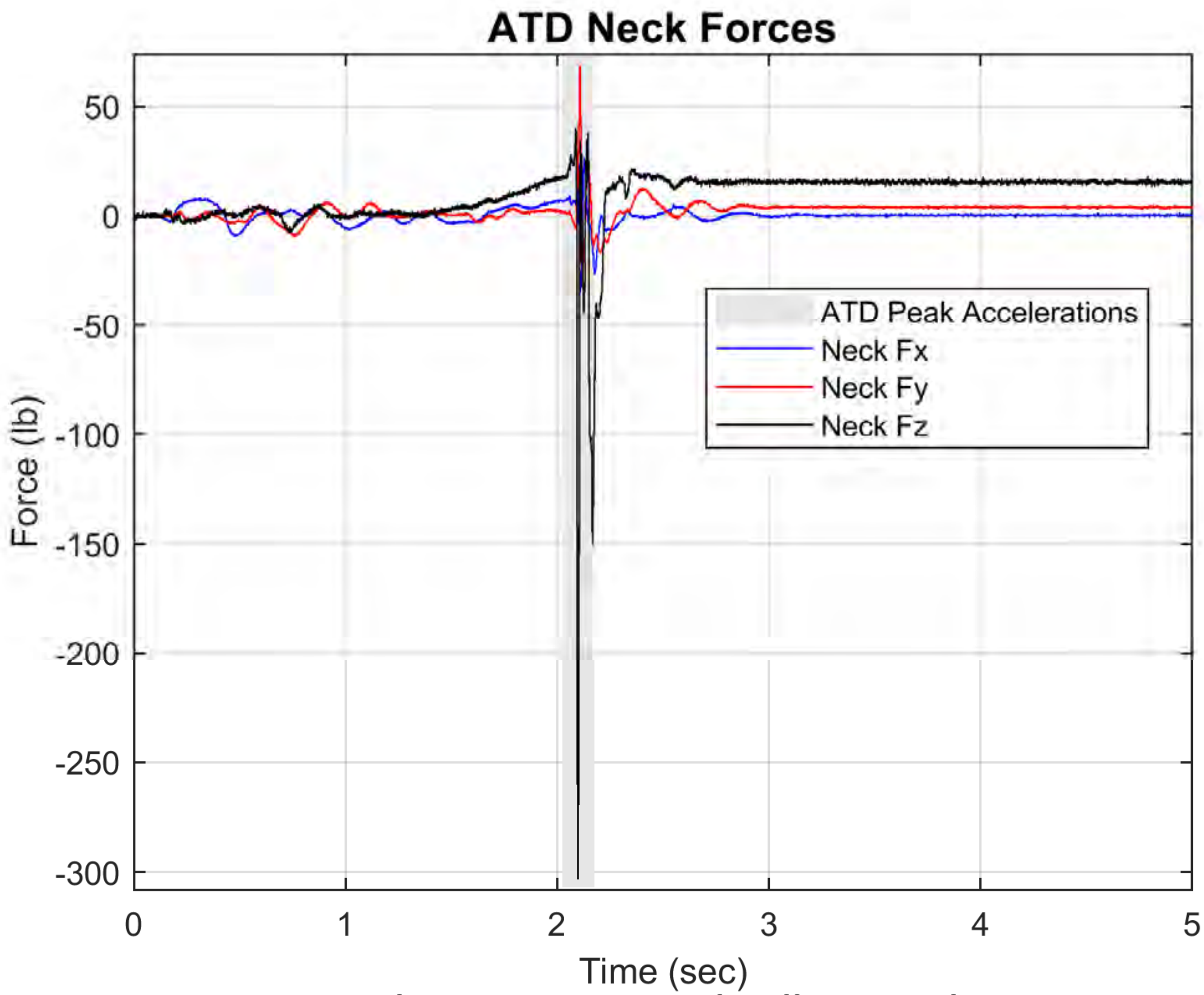
Tractor Style Mower – Lateral Rollover with ROPS



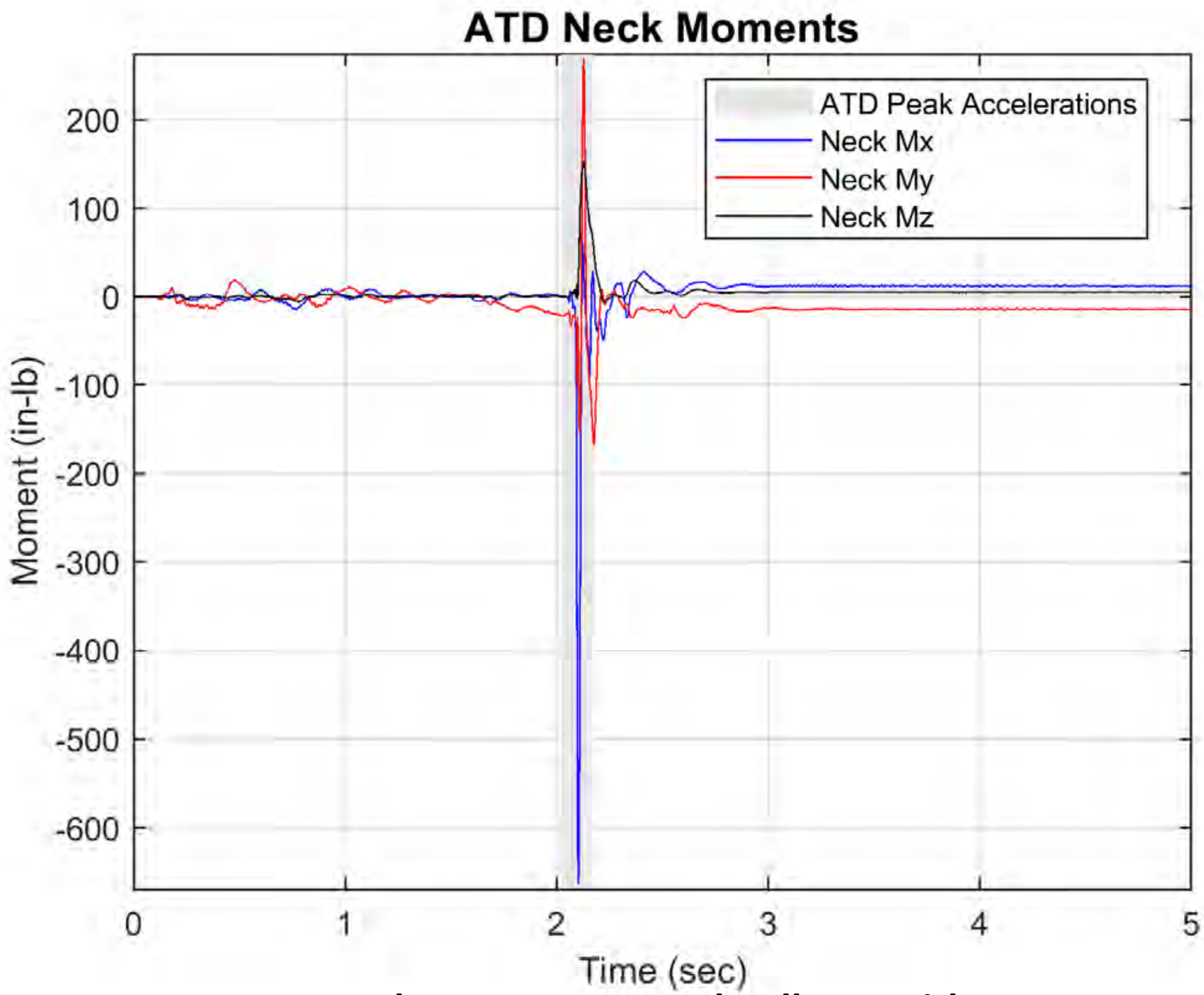
Tractor Style Mower – Lateral Rollover with ROPS



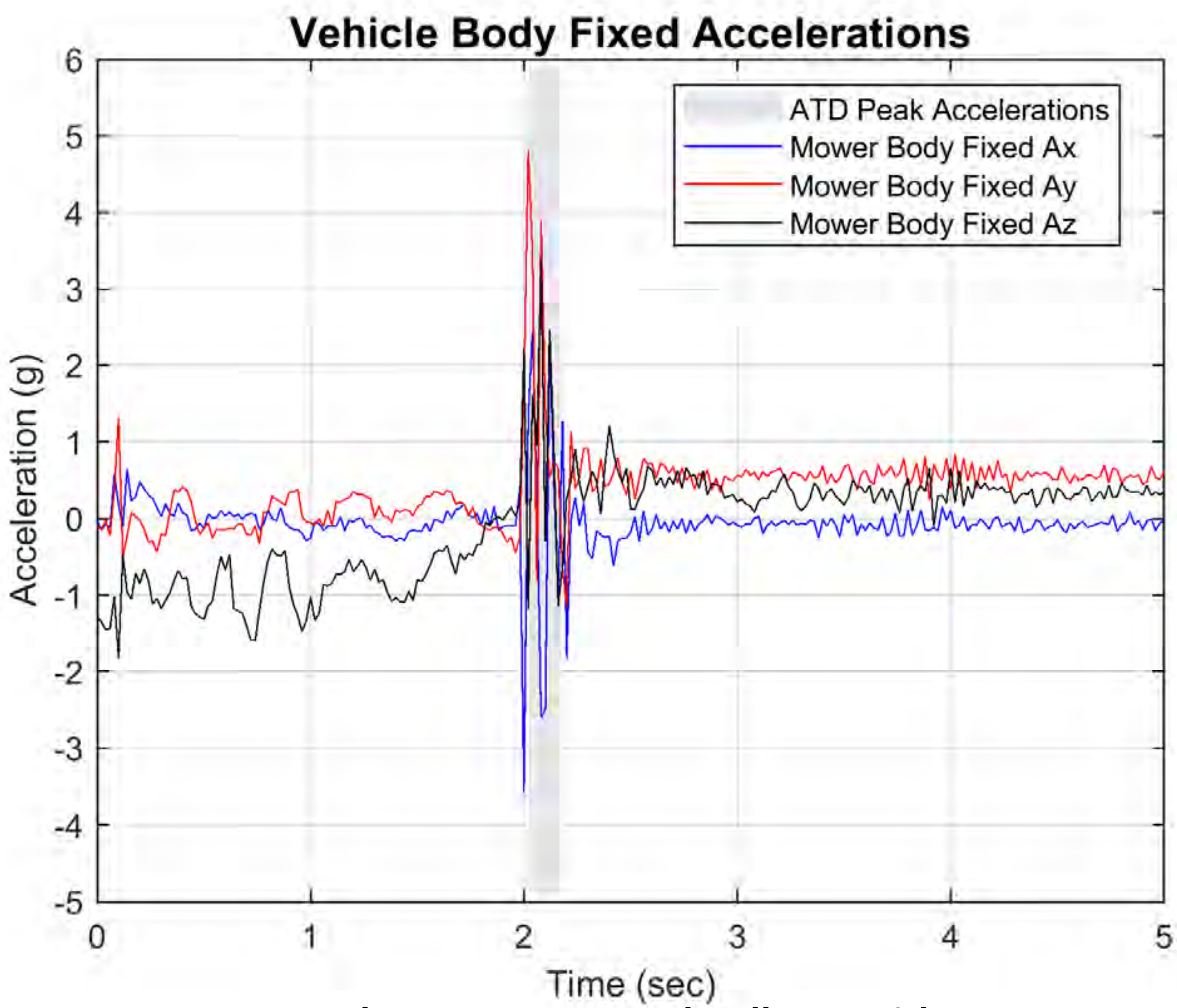
Tractor Style Mower – Lateral Rollover with ROPS



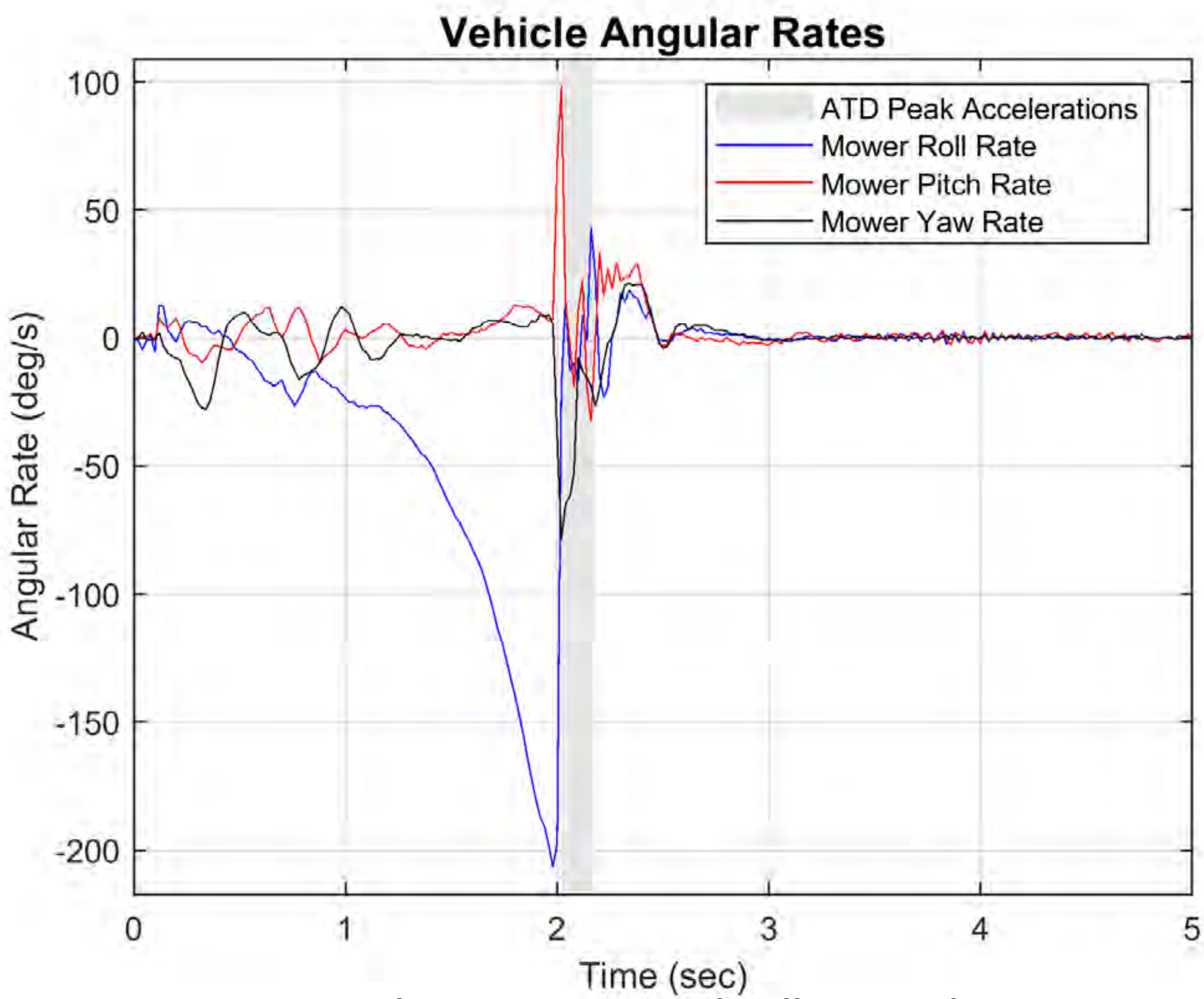
Tractor Style Mower – Lateral Rollover with ROPS



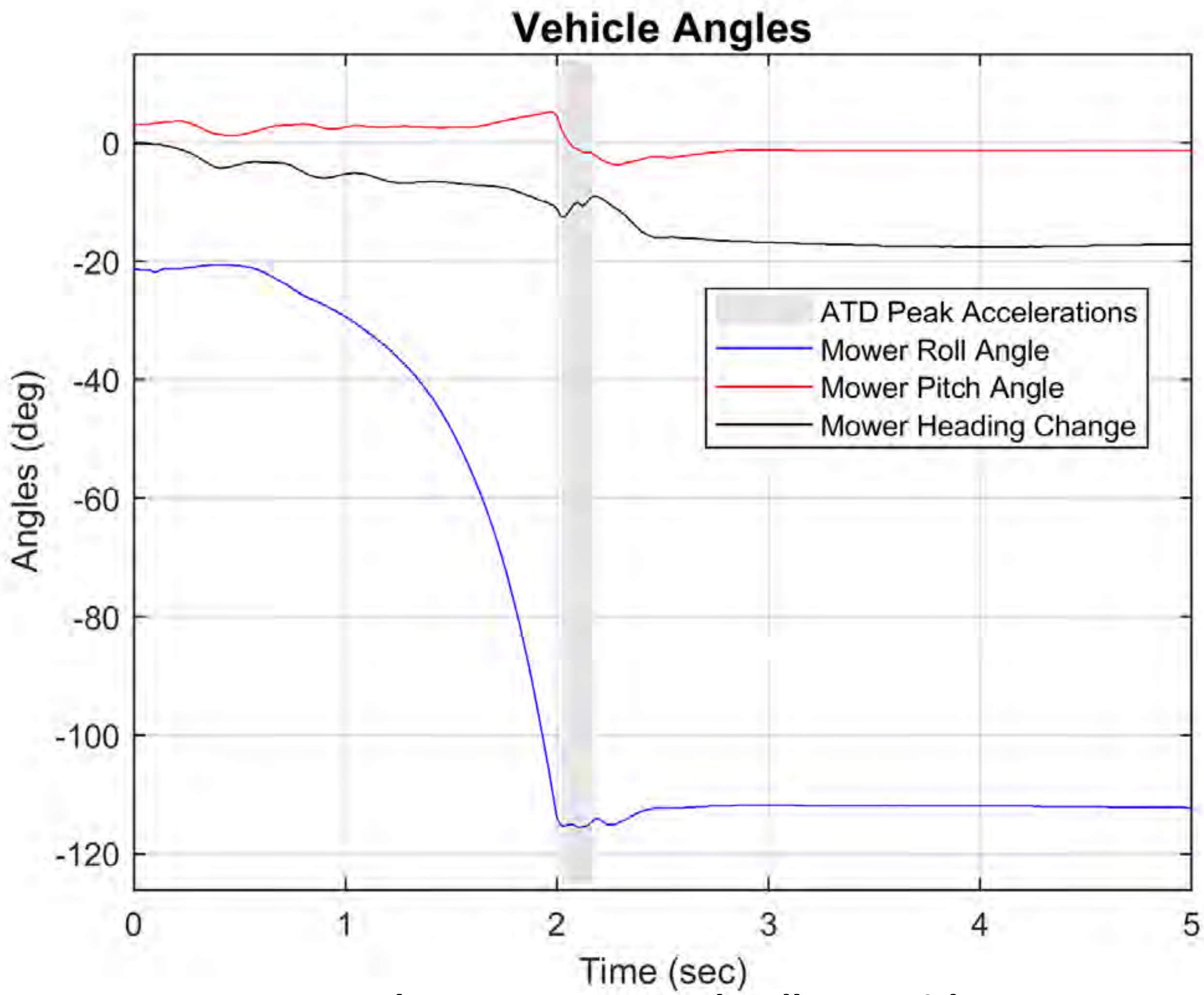
Tractor Style Mower – Lateral Rollover with ROPS



Tractor Style Mower – Lateral Rollover with ROPS



Tractor Style Mower – Lateral Rollover with ROPS



Tractor Style Mower – Lateral Rollover with ROPS

Time of Start - Time = 0.0 sec - Pitch Angle = 34.6°

Tractor Style Mower – Rearward Pitchover without ROPS

Pitch Angle = 60° - Time = 1.10 sec

Tractor Style Mower – Rearward Pitchover without ROPS

Pitch Angle = 90° - Time = 1.40 sec

Tractor Style Mower – Rearward Pitchover without ROPS

Pitch Angle = 120° - Time = 1.58 sec

Tractor Style Mower – Rearward Pitchover without ROPS

ATD Head Strike - Time = 1.60 sec

Tractor Style Mower – Rearward Pitchover without ROPS

Pitch Angle = 150° - Time = 1.74 sec

Tractor Style Mower – Rearward Pitchover without ROPS

Pitch Angle = 180° - Time = 2.04 sec

Tractor Style Mower – Rearward Pitchover without ROPS

Pitch Angle = 210° - Time = 2.34 sec

Tractor Style Mower – Rearward Pitchover without ROPS

Pitch Angle = 240° - Time = 2.50 sec

Tractor Style Mower – Rearward Pitchover without ROPS

Pitch Angle = 270° - Time = 2.80 sec

Tractor Style Mower – Rearward Pitchover without ROPS

Time = 3.30 sec

Tractor Style Mower – Rearward Pitchover without ROPS

Time = 3.80 sec

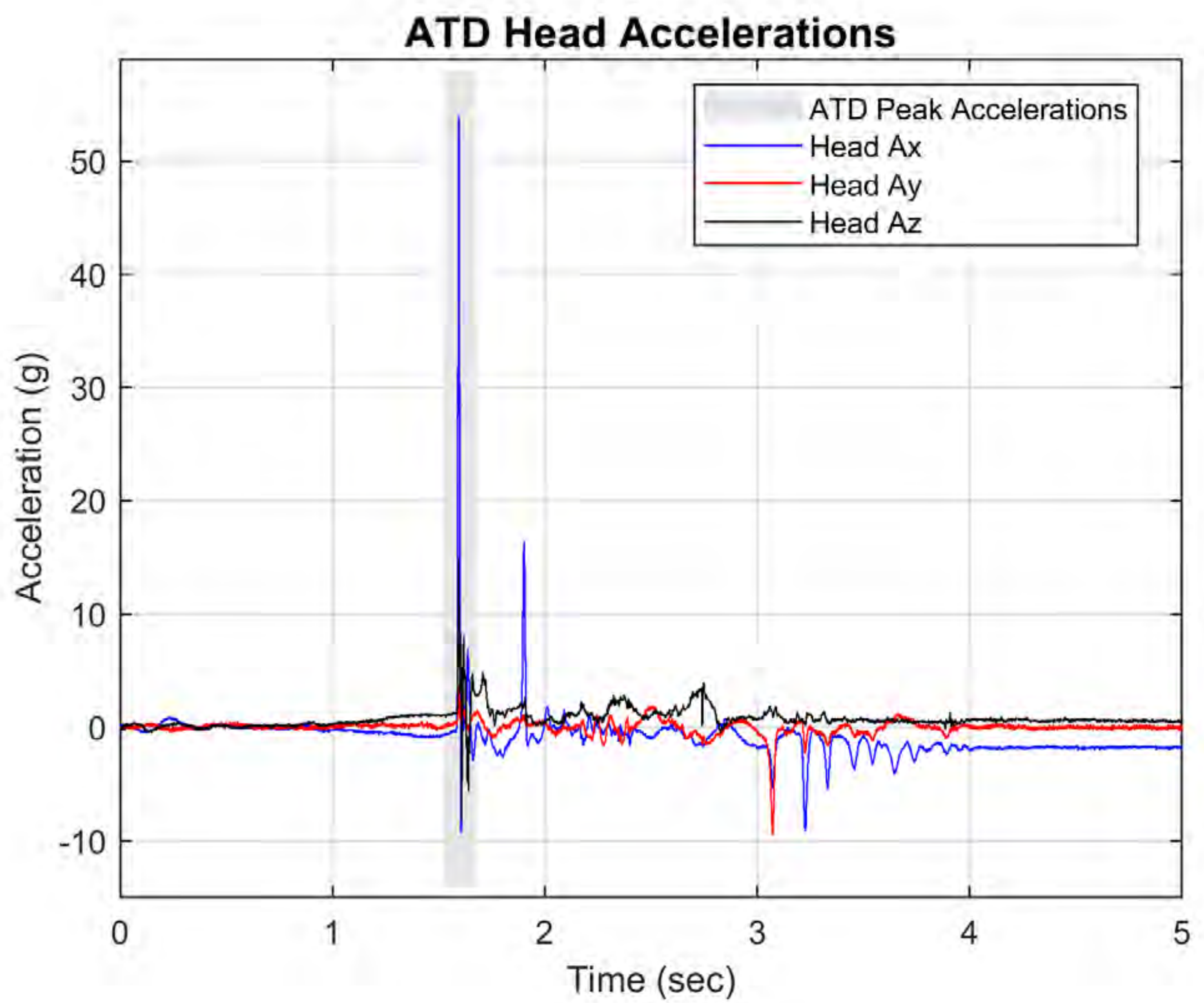
Tractor Style Mower – Rearward Pitchover without ROPS

Time = 4.30 sec

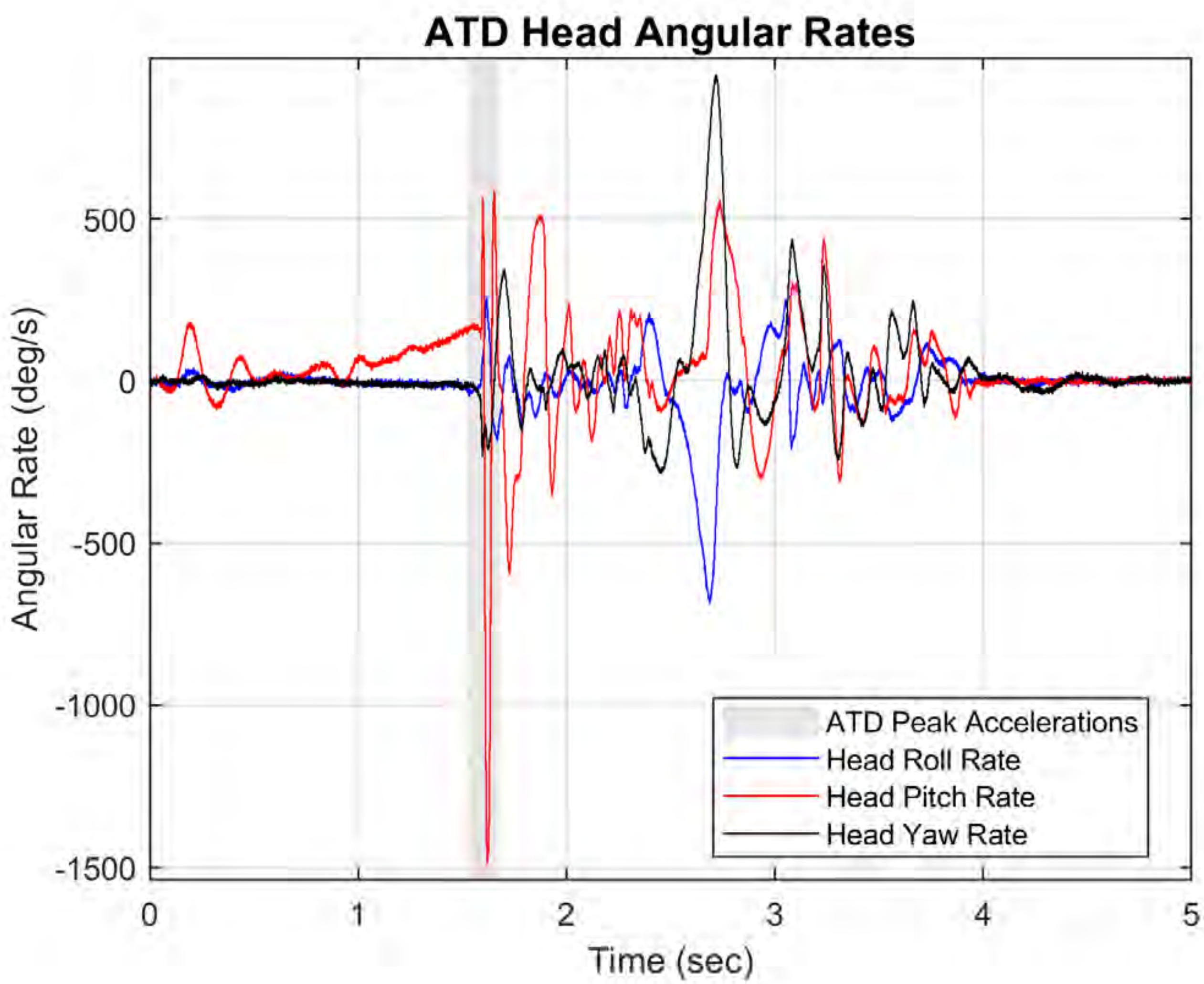
Tractor Style Mower – Rearward Pitchover without ROPS

End of Run - Pitch Angle = 283.1°

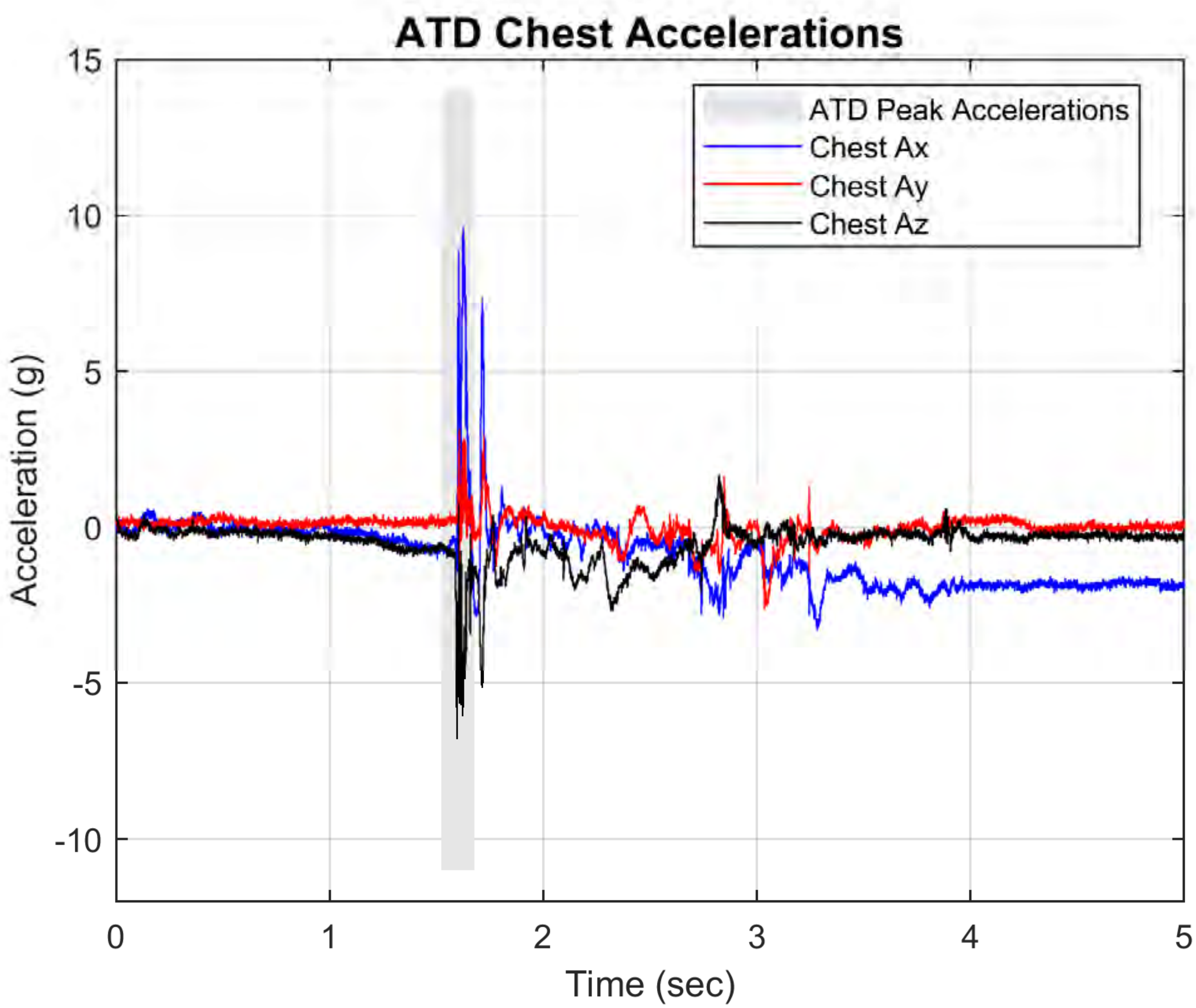
Tractor Style Mower – Rearward Pitchover without ROPS



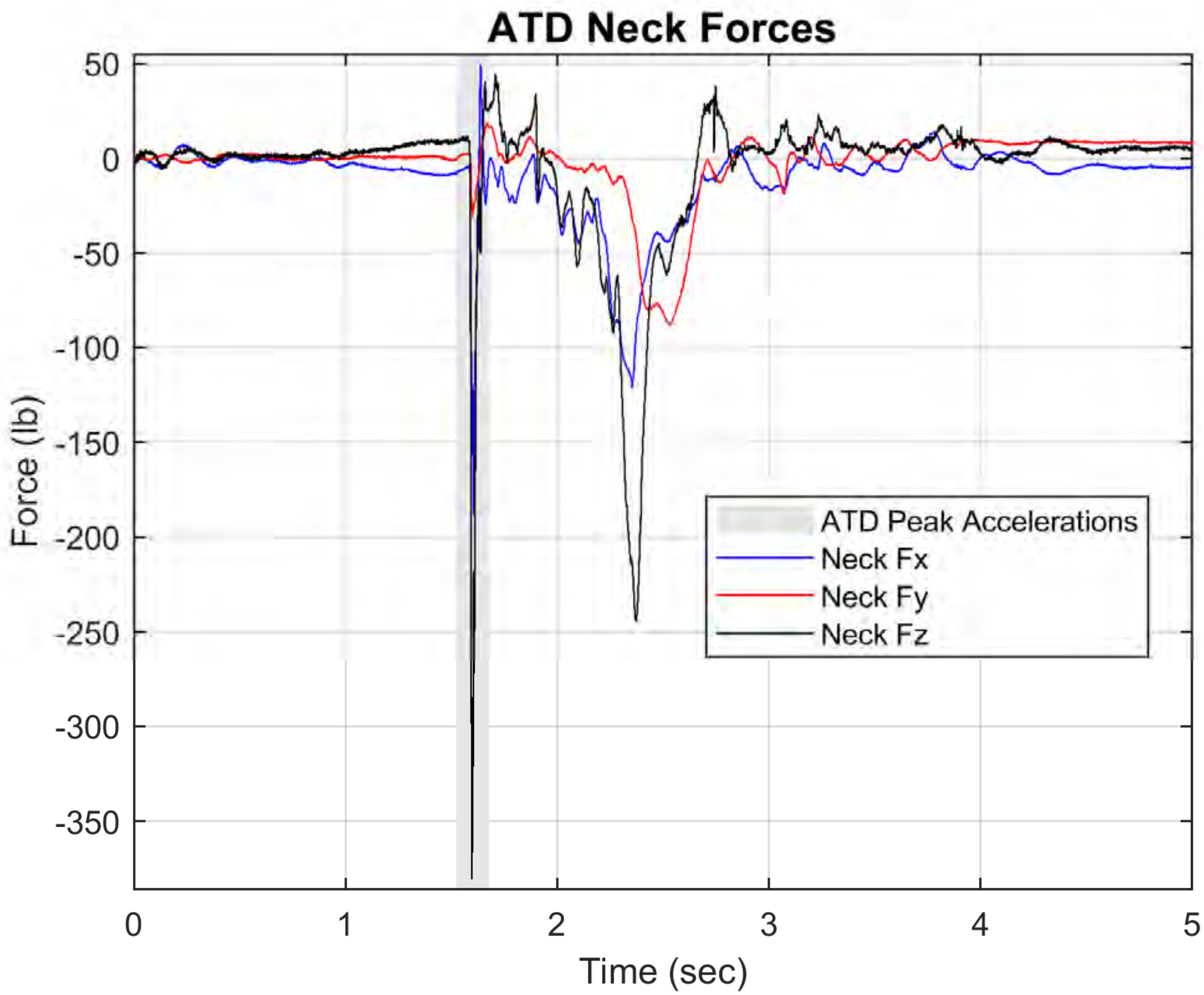
Tractor Style Mower – Rearward Pitchover without ROPS



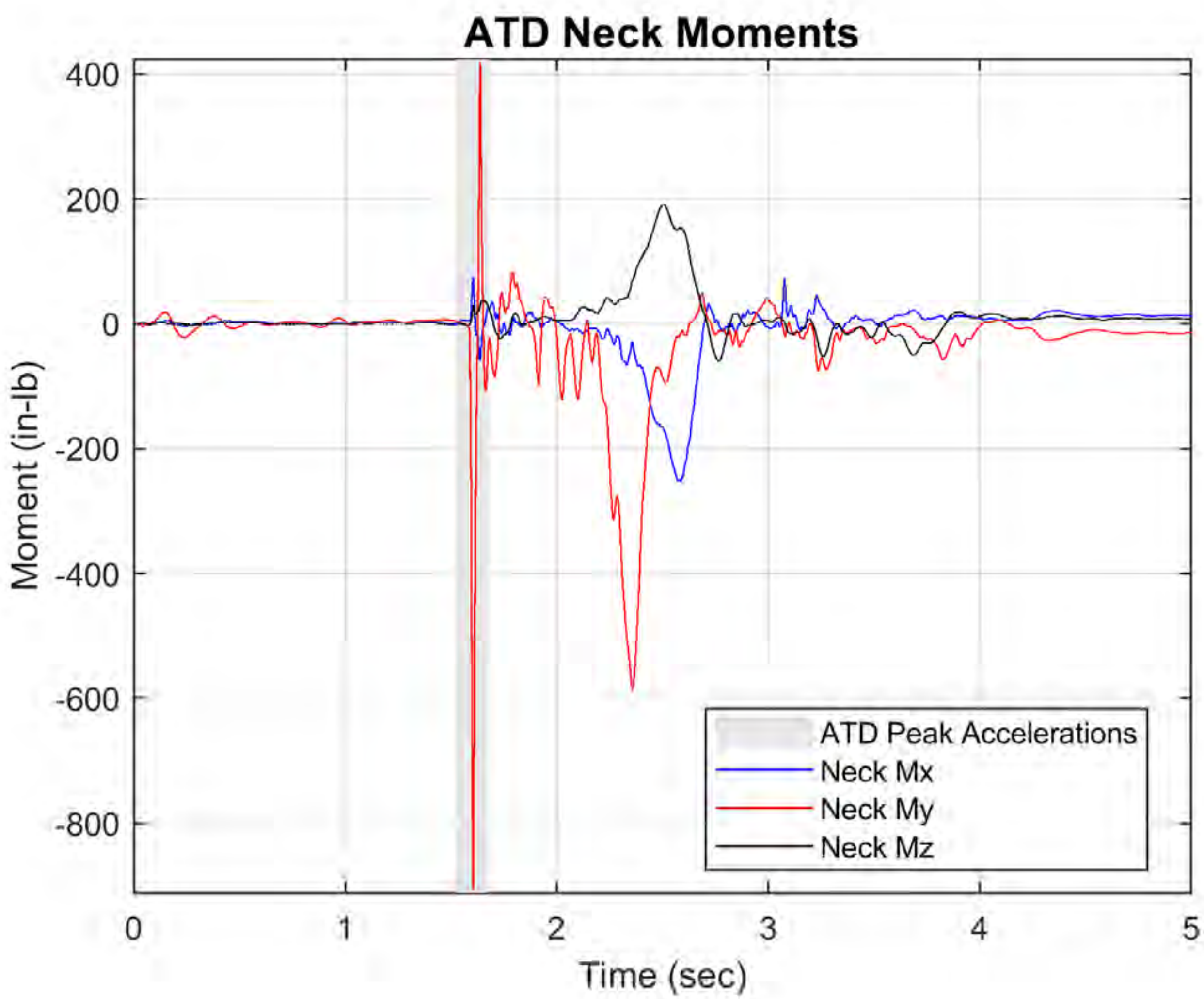
Tractor Style Mower – Rearward Pitchover without ROPS



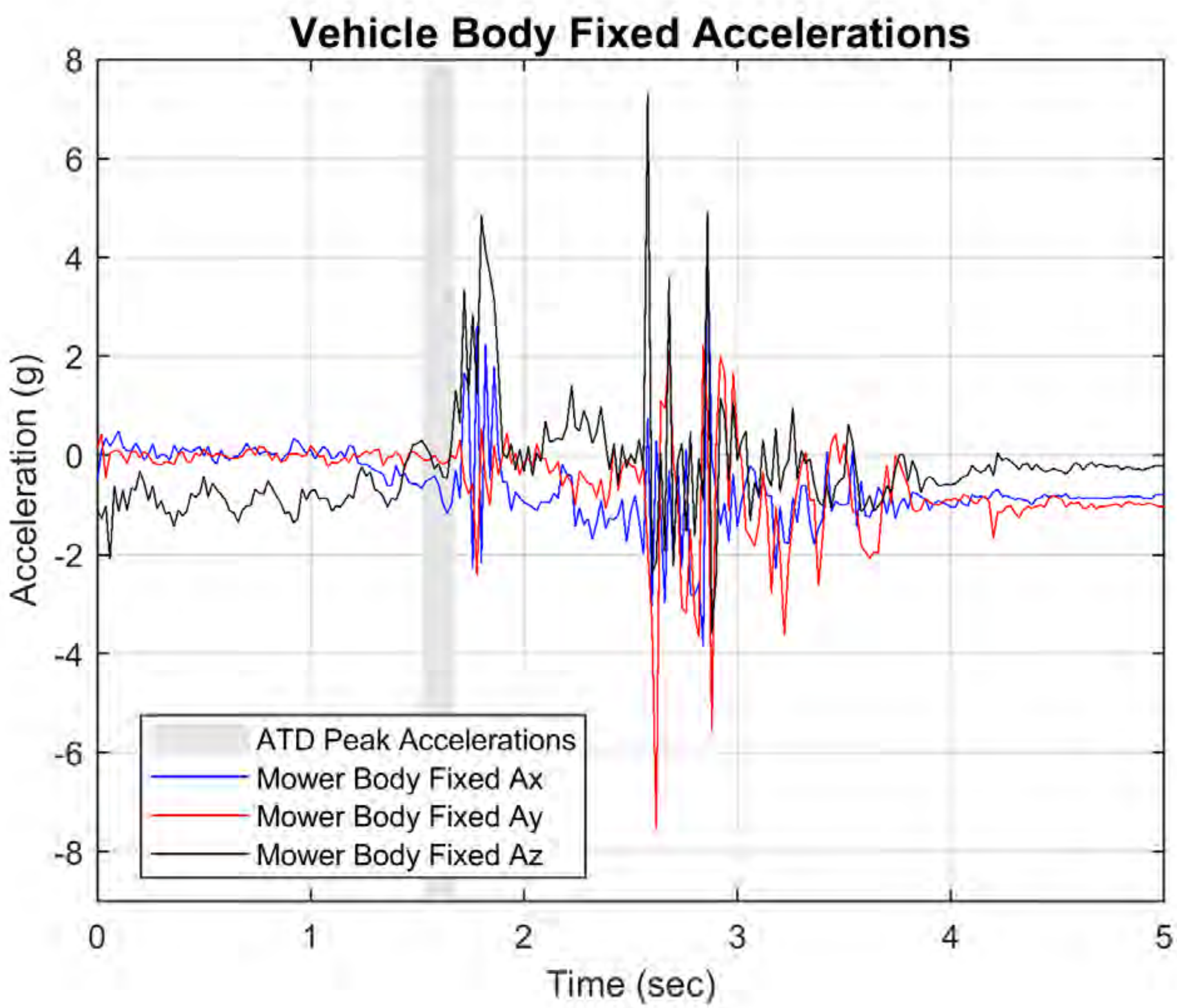
Tractor Style Mower – Rearward Pitchover without ROPS



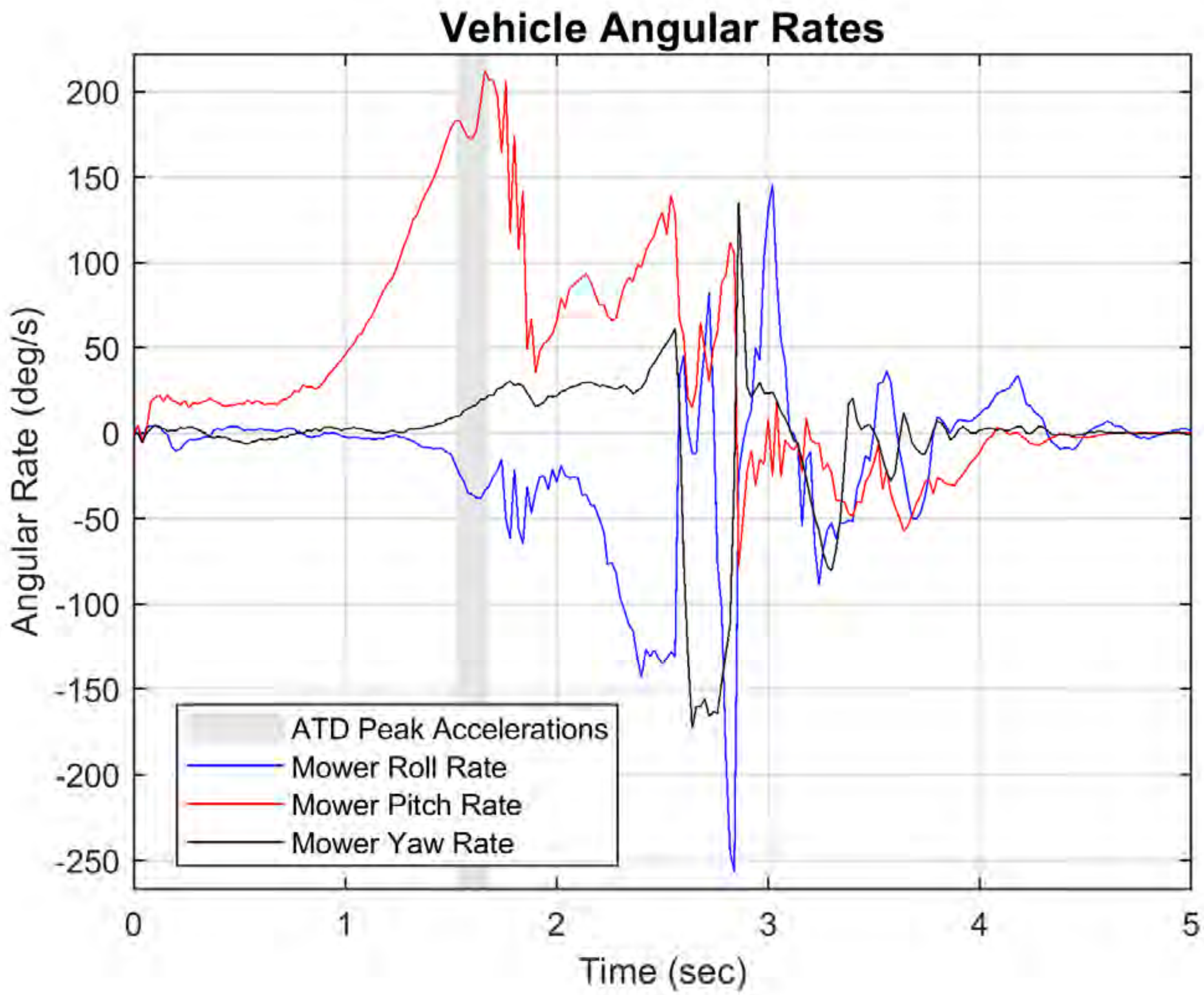
Tractor Style Mower – Rearward Pitchover without ROPS



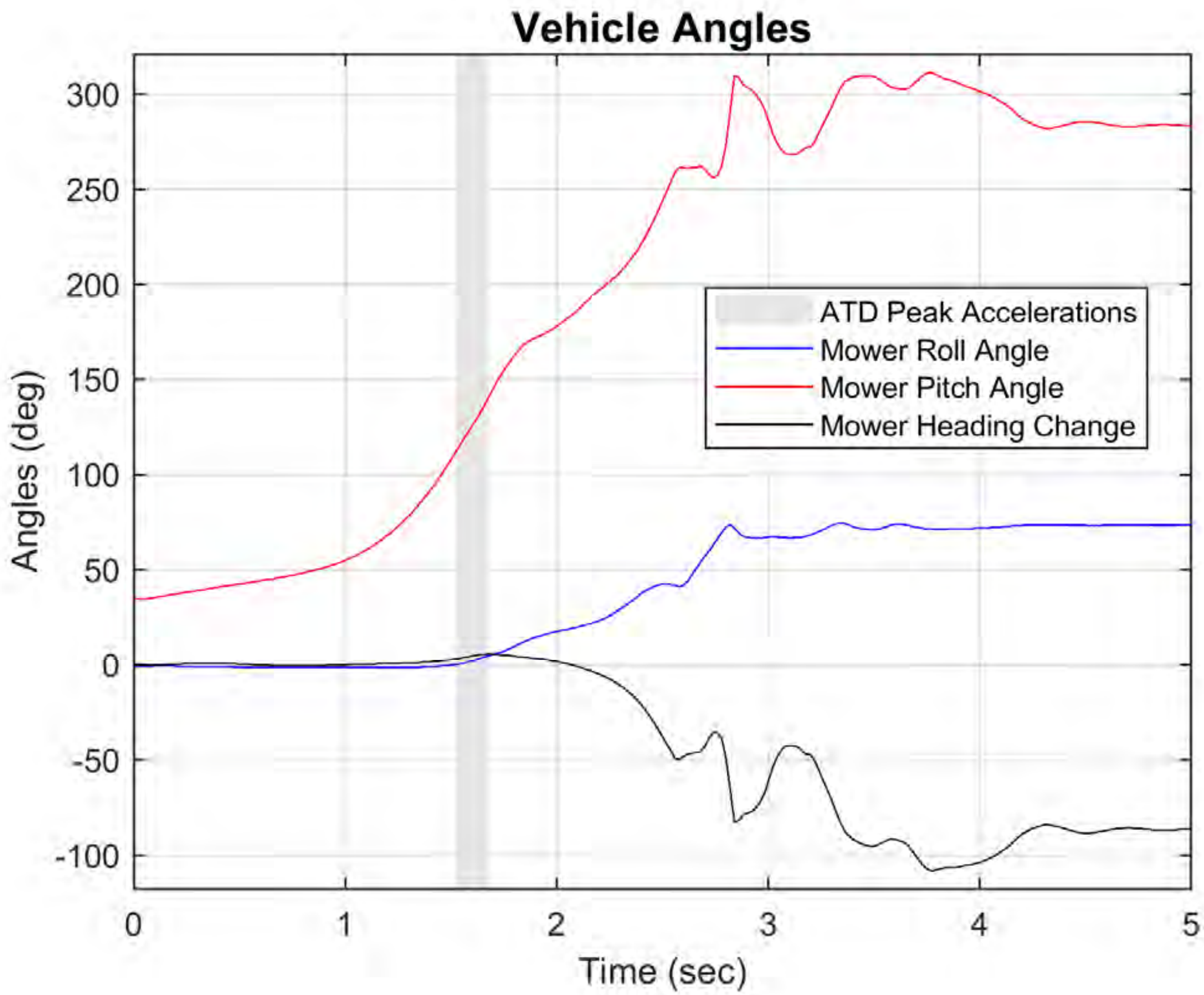
Tractor Style Mower – Rearward Pitchover without ROPS



Tractor Style Mower – Rearward Pitchover without ROPS



Tractor Style Mower – Rearward Pitchover without ROPS



Tractor Style Mower – Rearward Pitchover without ROPS

Time of Start - Time = 0.0 sec

Tractor Style Mower – Rearward Pitchover with ROPS

Pitch Angle = 30° - Time = 0.50 sec

Tractor Style Mower – Rearward Pitchover with ROPS

Pitch Angle = 60° - Time = 1.58 sec

Tractor Style Mower – Rearward Pitchover with ROPS

Pitch Angle = 90° - Time = 1.82 sec

Tractor Style Mower – Rearward Pitchover with ROPS

Pitch Angle = 120° - Time = 2.00 sec

Tractor Style Mower – Rearward Pitchover with ROPS

ATD Head Strike - Time = 2.02 sec

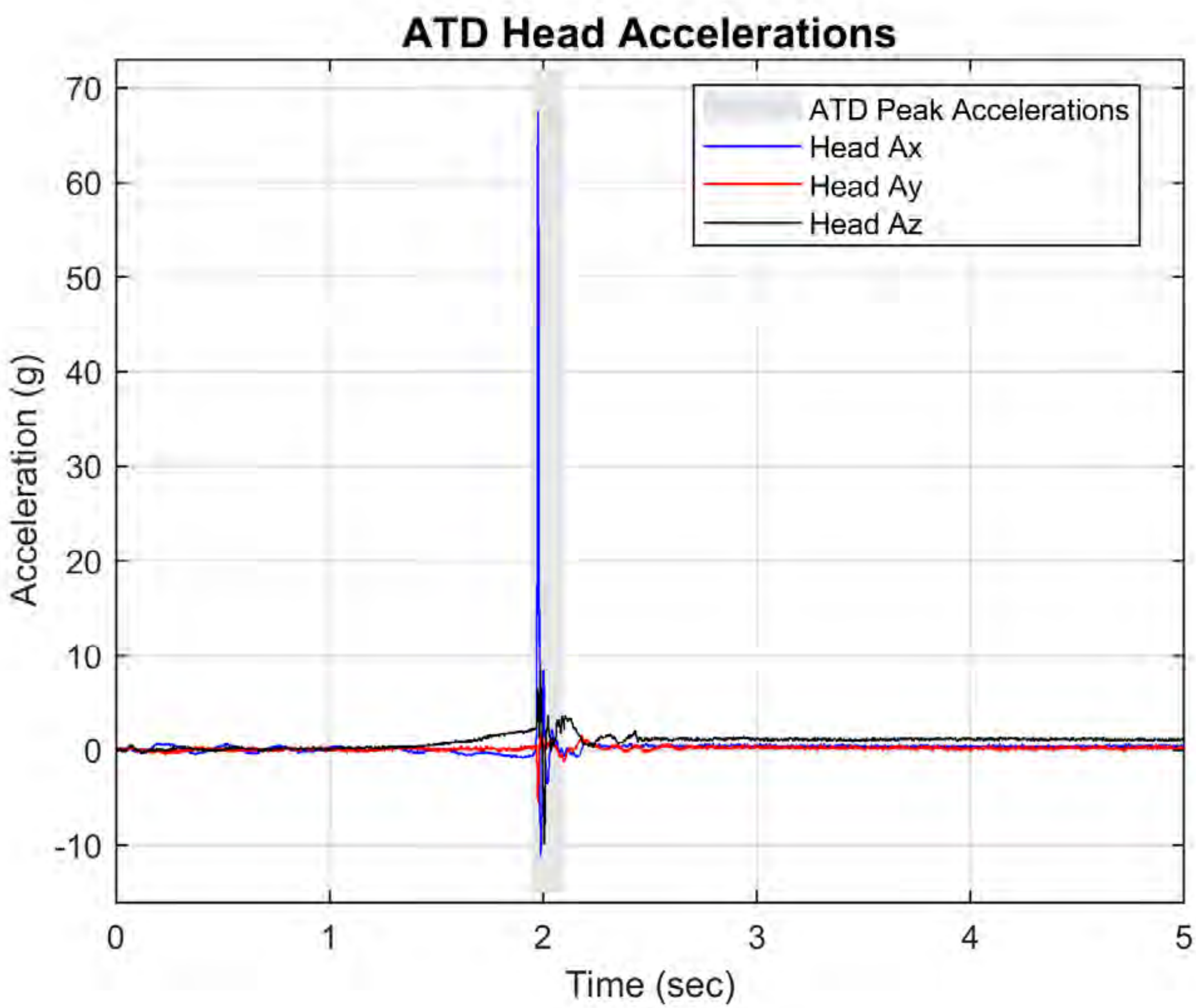
Tractor Style Mower – Rearward Pitchover with ROPS

Max Pitch Angle = 132.9° - Time = 2.08 sec

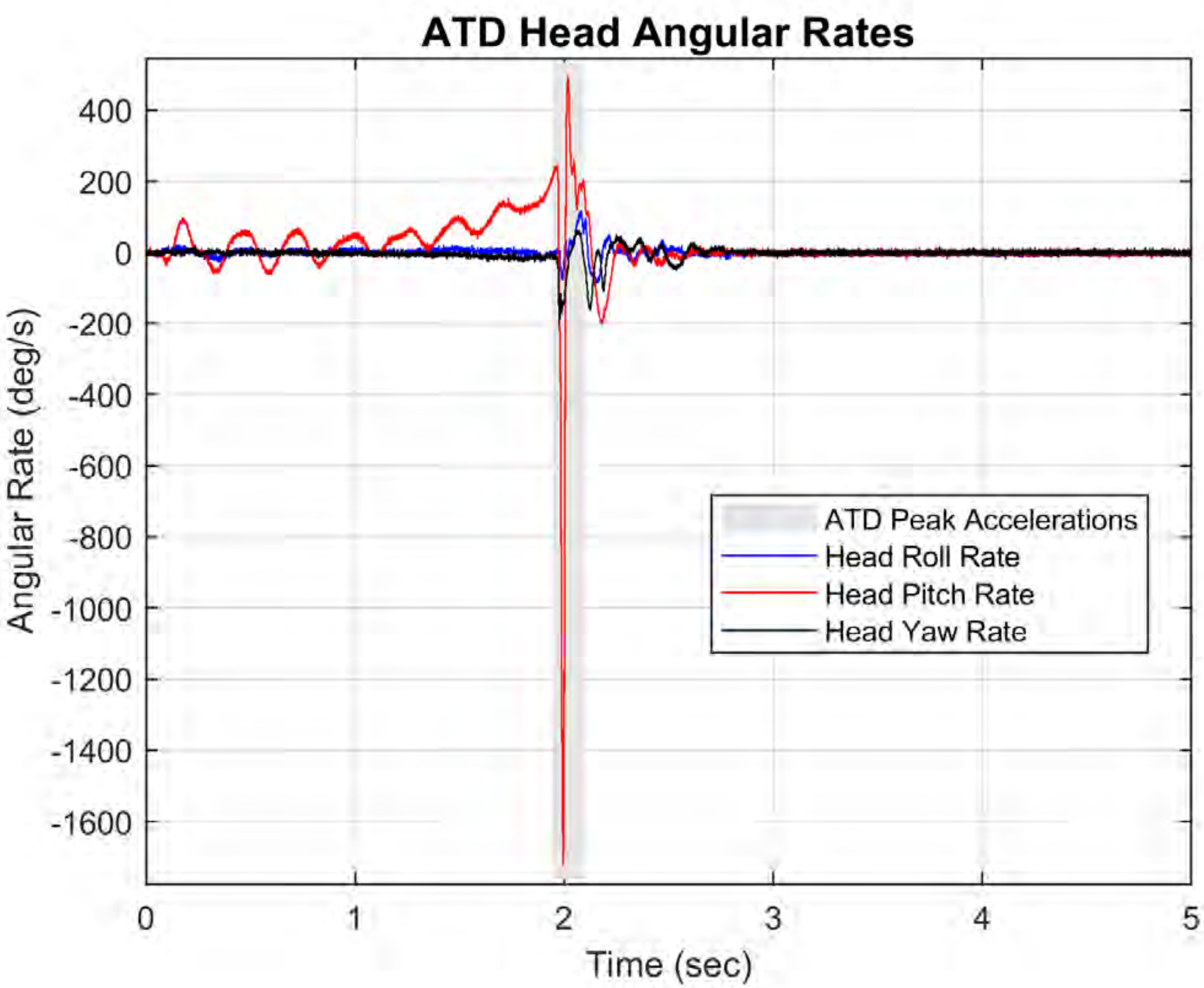
Tractor Style Mower – Rearward Pitchover with ROPS

End of Run - Pitch Angle = 129.7°

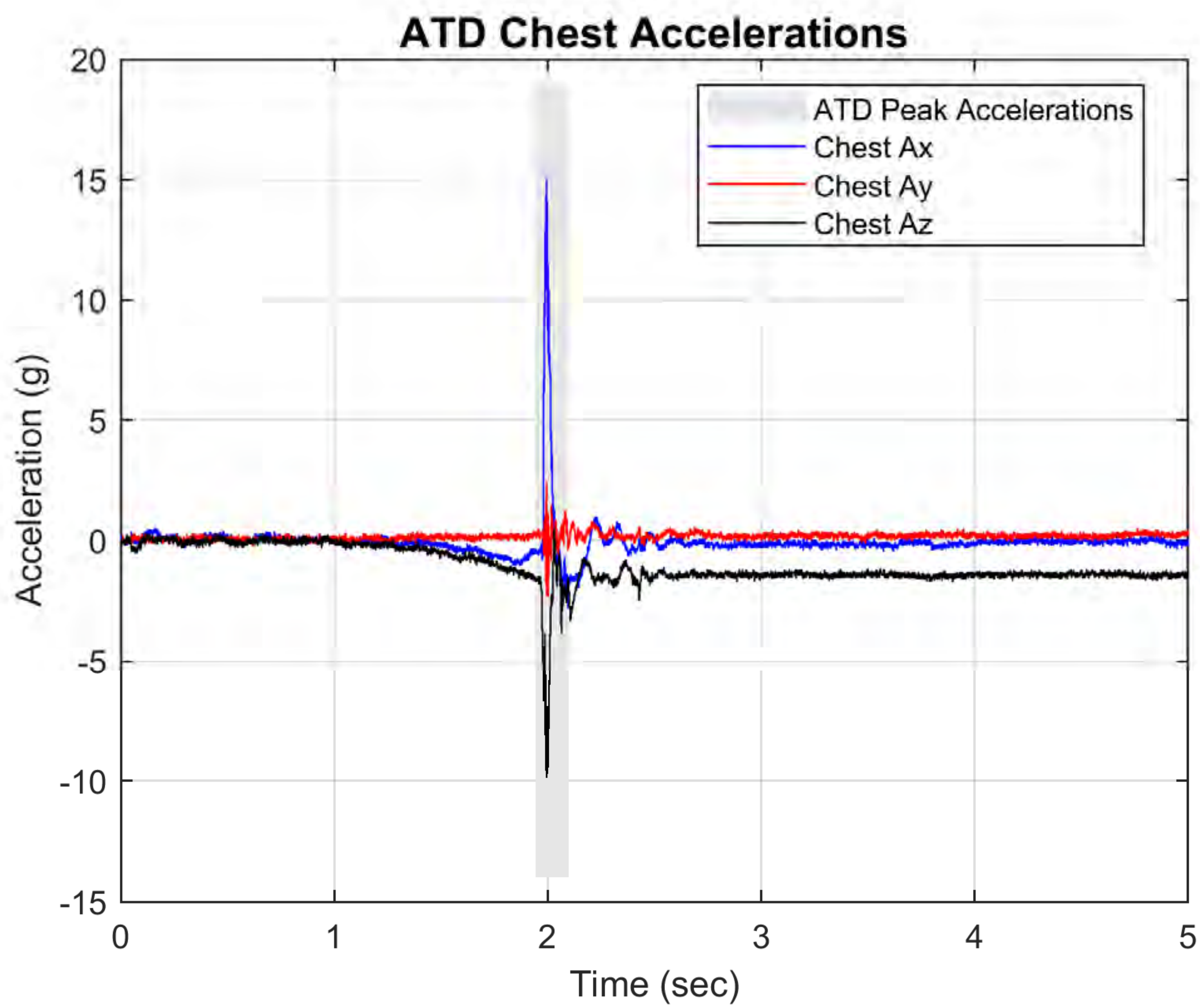
Tractor Style Mower – Rearward Pitchover with ROPS



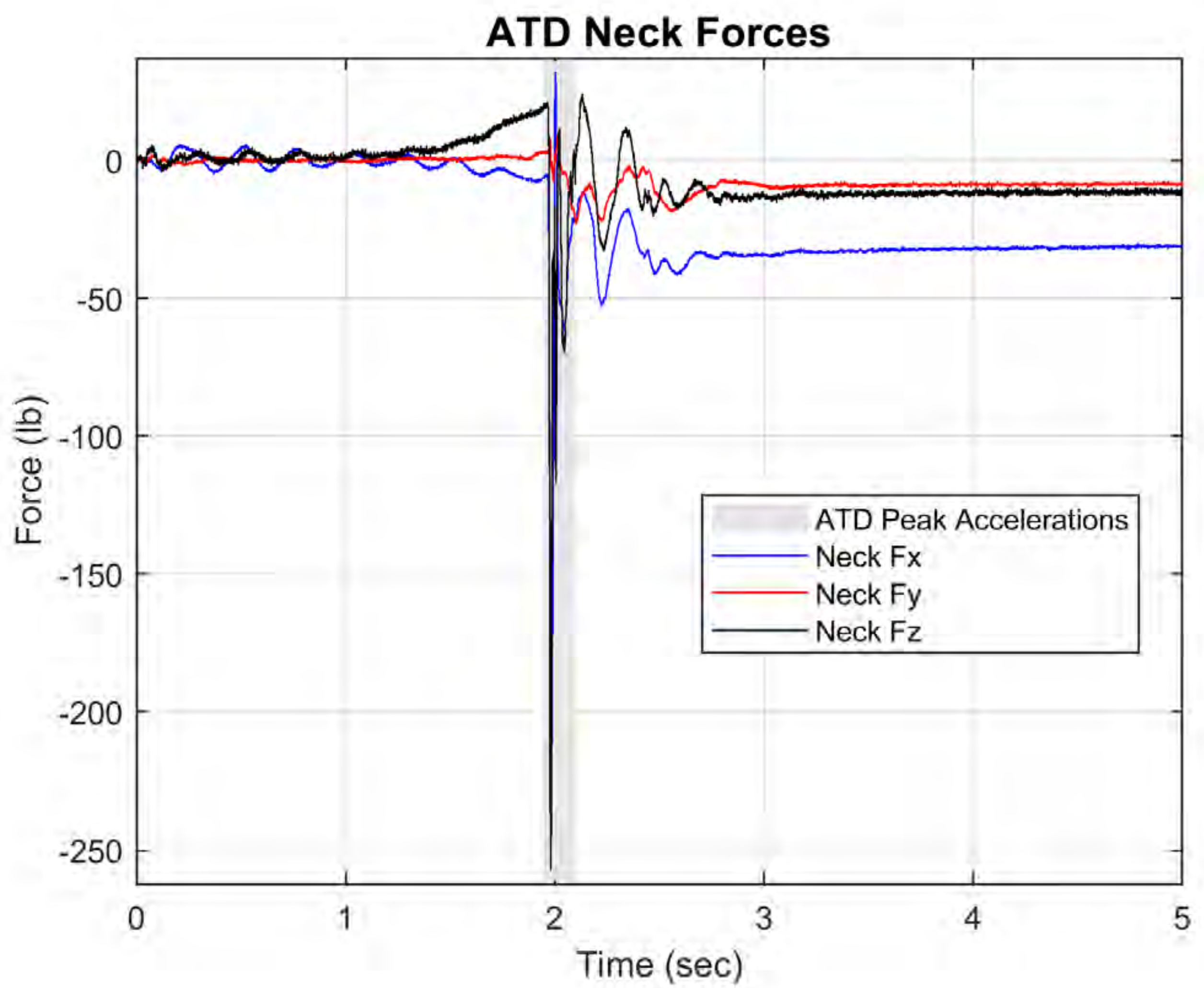
Tractor Style Mower – Rearward Pitchover with ROPS



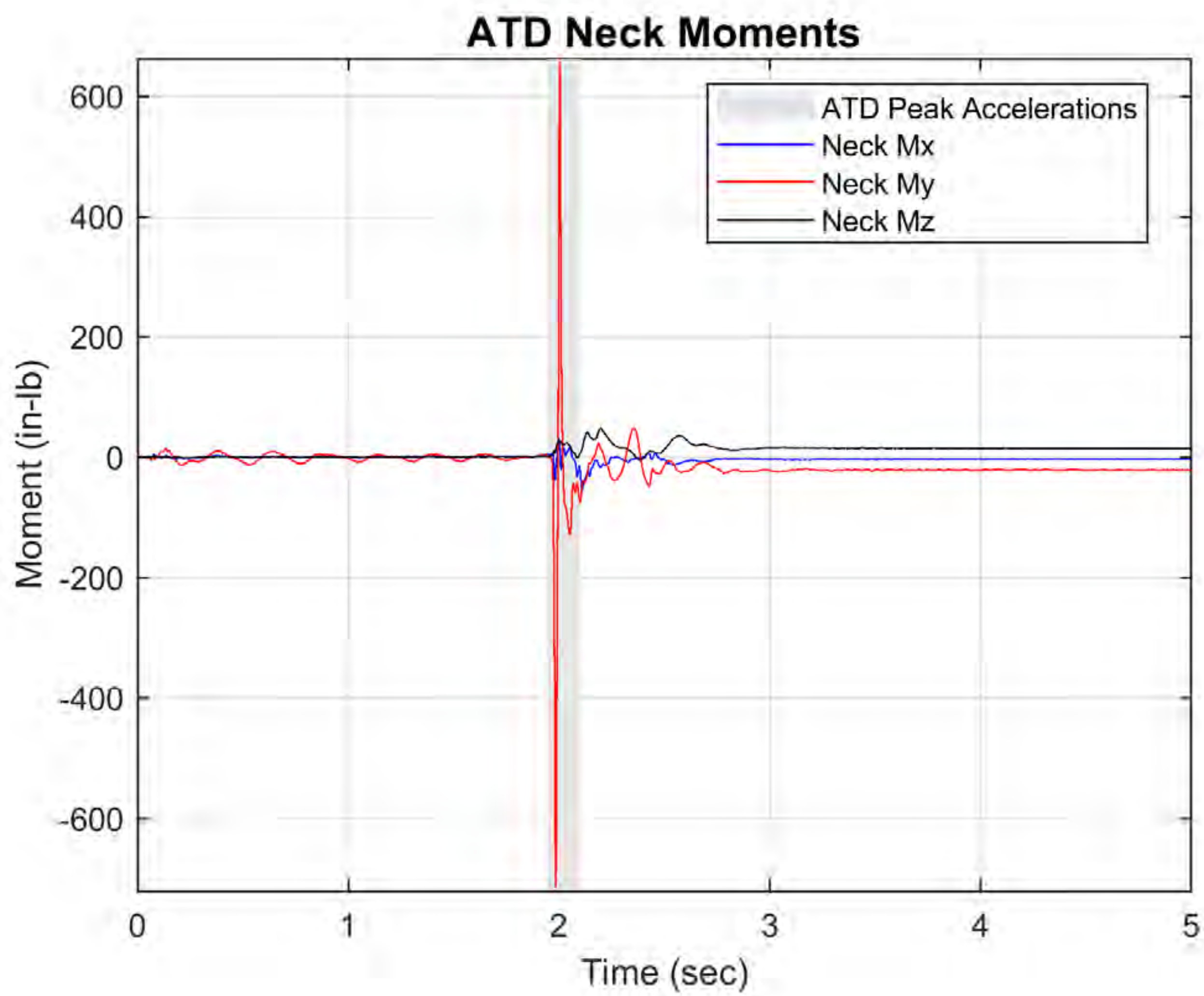
Tractor Style Mower – Rearward Pitchover with ROPS



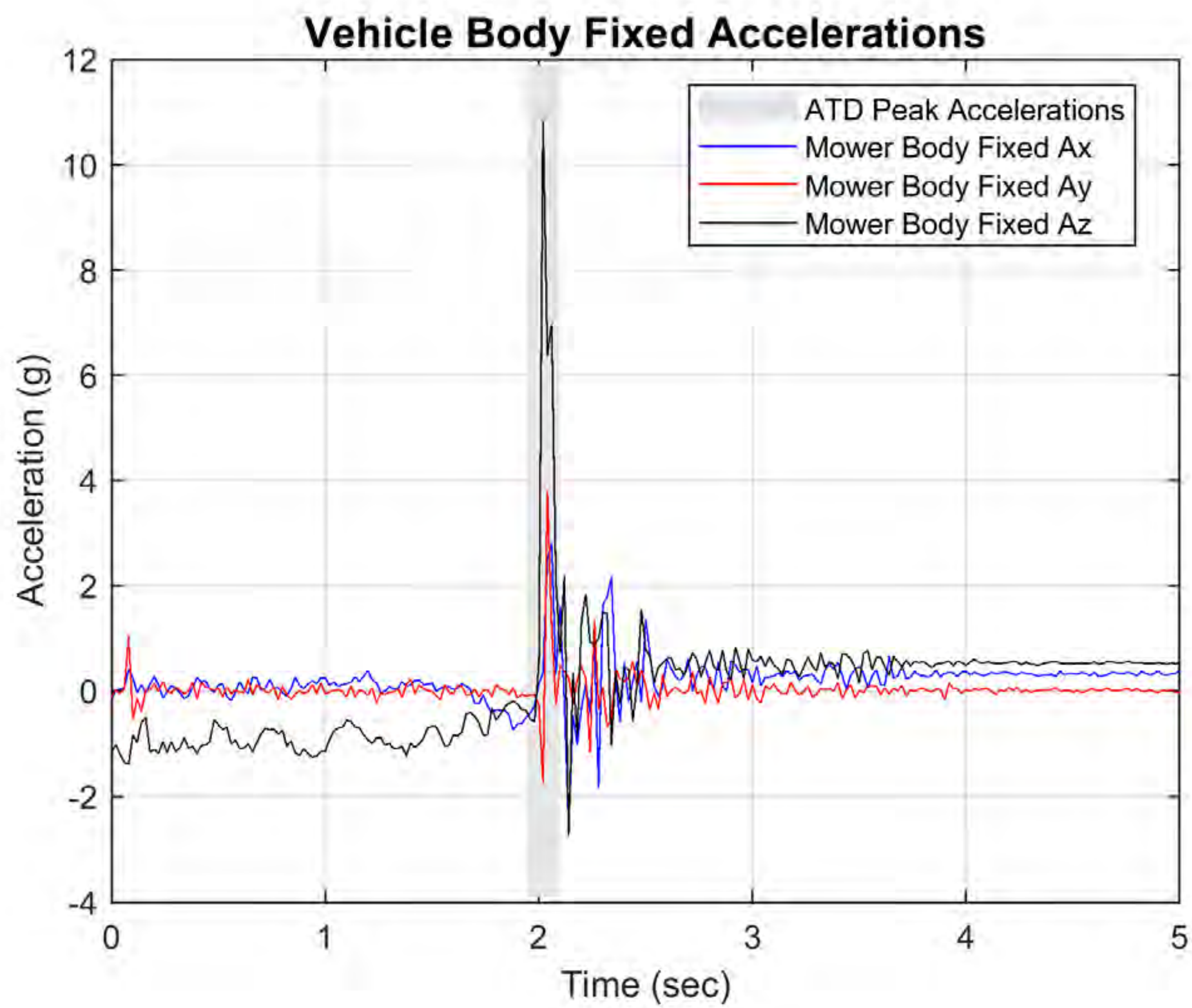
Tractor Style Mower – Rearward Pitchover with ROPS



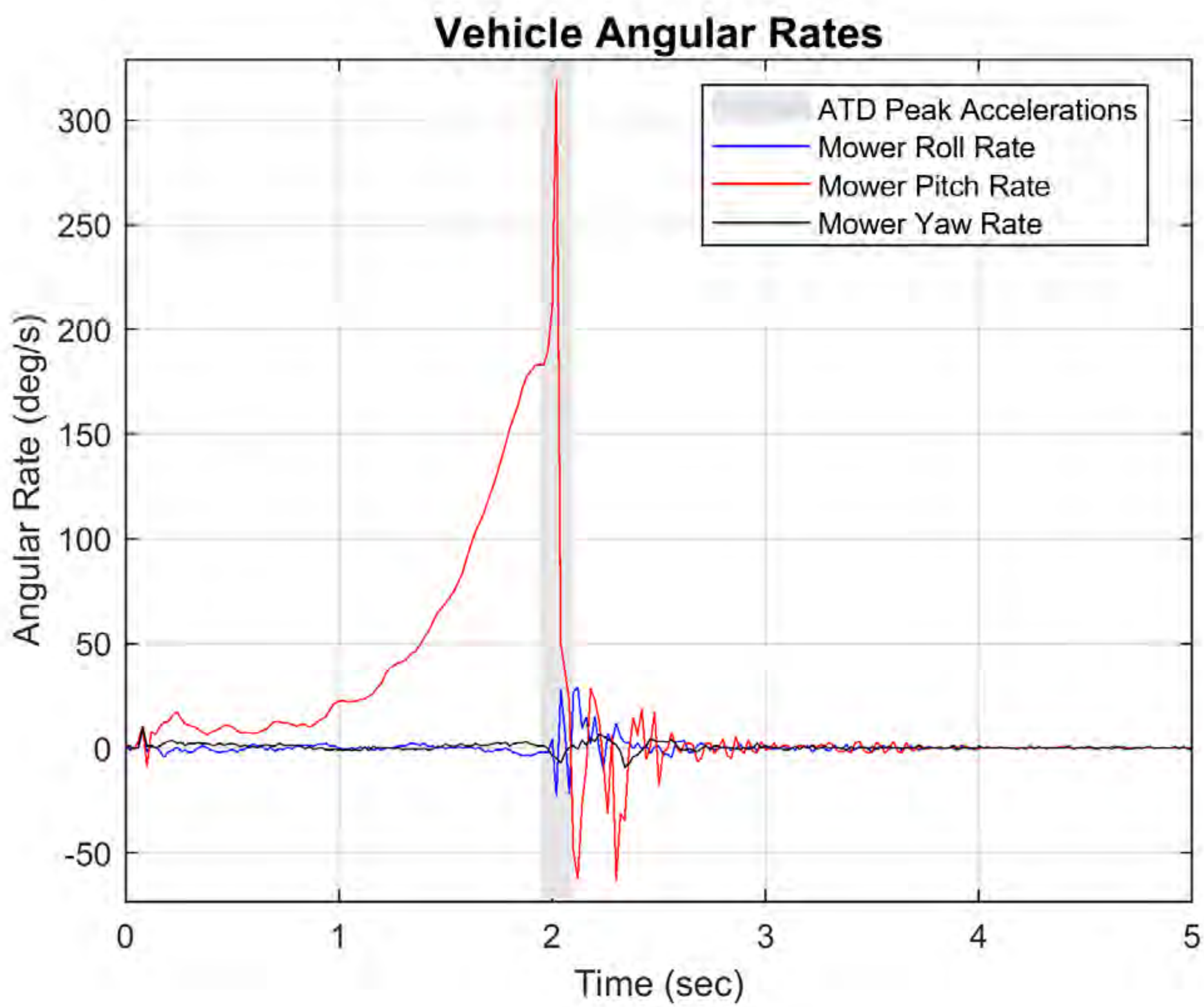
Tractor Style Mower – Rearward Pitchover with ROPS



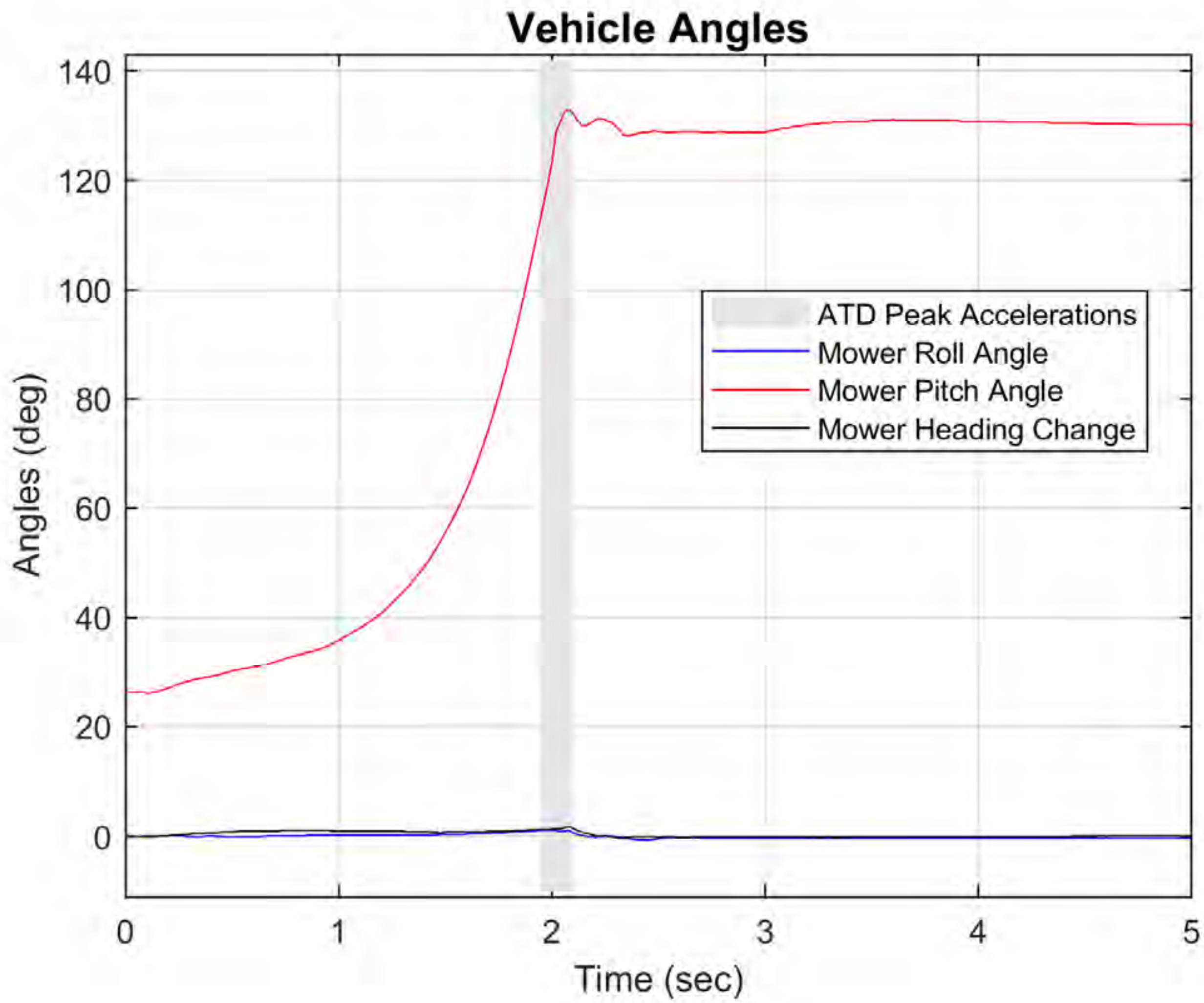
Tractor Style Mower – Rearward Pitchover with ROPS



Tractor Style Mower – Rearward Pitchover with ROPS



Tractor Style Mower – Rearward Pitchover with ROPS



Tractor Style Mower – Rearward Pitchover with ROPS

Time of Start - Time = 0.0 sec

Zero-Turn Mower – Quasi-Lateral Rollover without ROPS

Time = 0.50 sec

Zero-Turn Mower – Quasi-Lateral Rollover without ROPS

Time = 1.00 sec

Zero-Turn Mower – Quasi-Lateral Rollover without ROPS

Time = 1.50 sec

Zero-Turn Mower – Quasi-Lateral Rollover without ROPS

ATD Head Strike - Time = 1.85 sec

Zero-Turn Mower – Quasi-Lateral Rollover without ROPS

Time = 2.00 sec

Zero-Turn Mower – Quasi-Lateral Rollover without ROPS

Time = 2.50 sec

Zero-Turn Mower – Quasi-Lateral Rollover without ROPS

Time = 3.00 sec

Zero-Turn Mower – Quasi-Lateral Rollover without ROPS

Time = 3.50 sec

Zero-Turn Mower – Quasi-Lateral Rollover without ROPS

Time = 4.00 sec

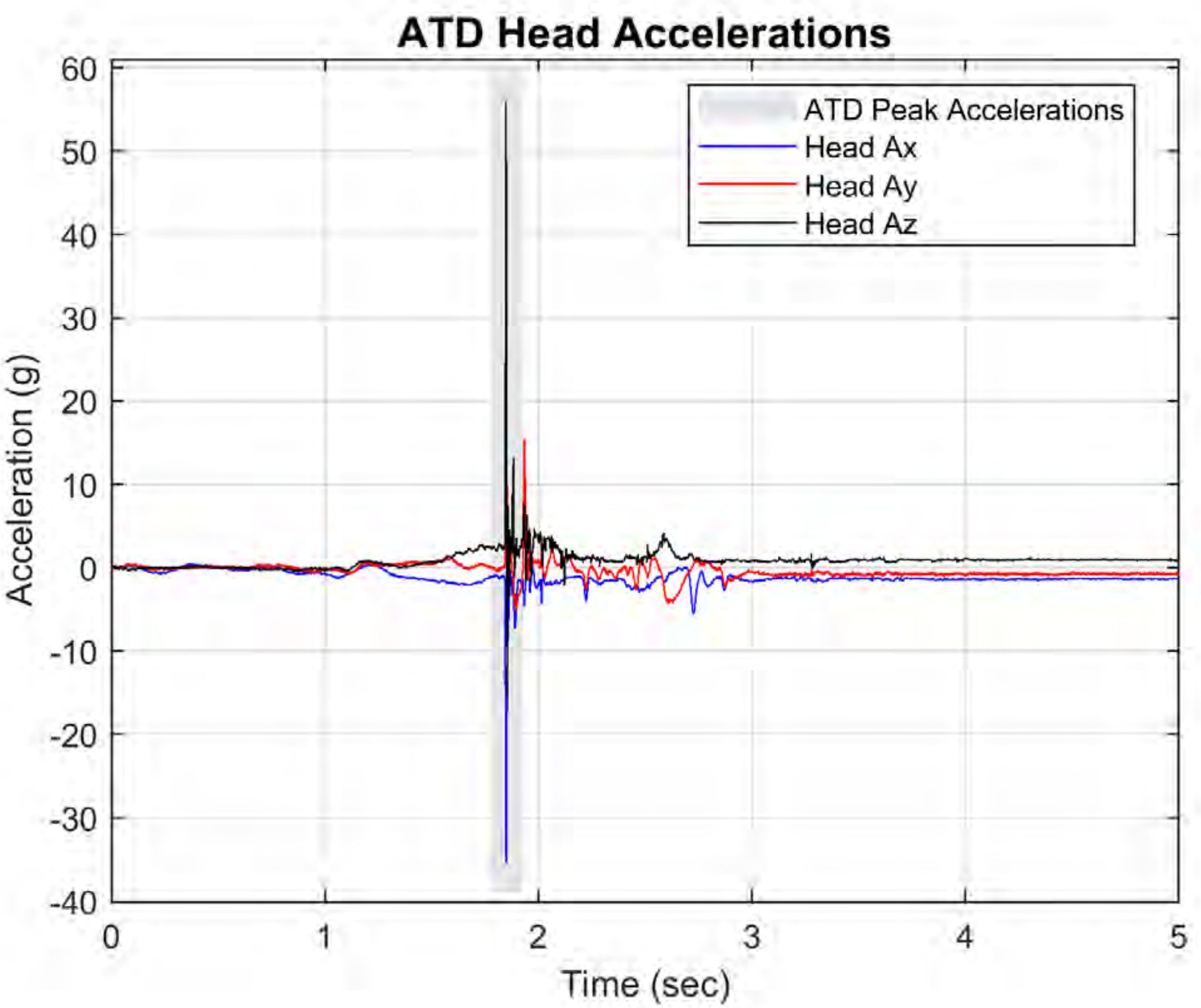
Zero-Turn Mower – Quasi-Lateral Rollover without ROPS

Time = 4.50 sec

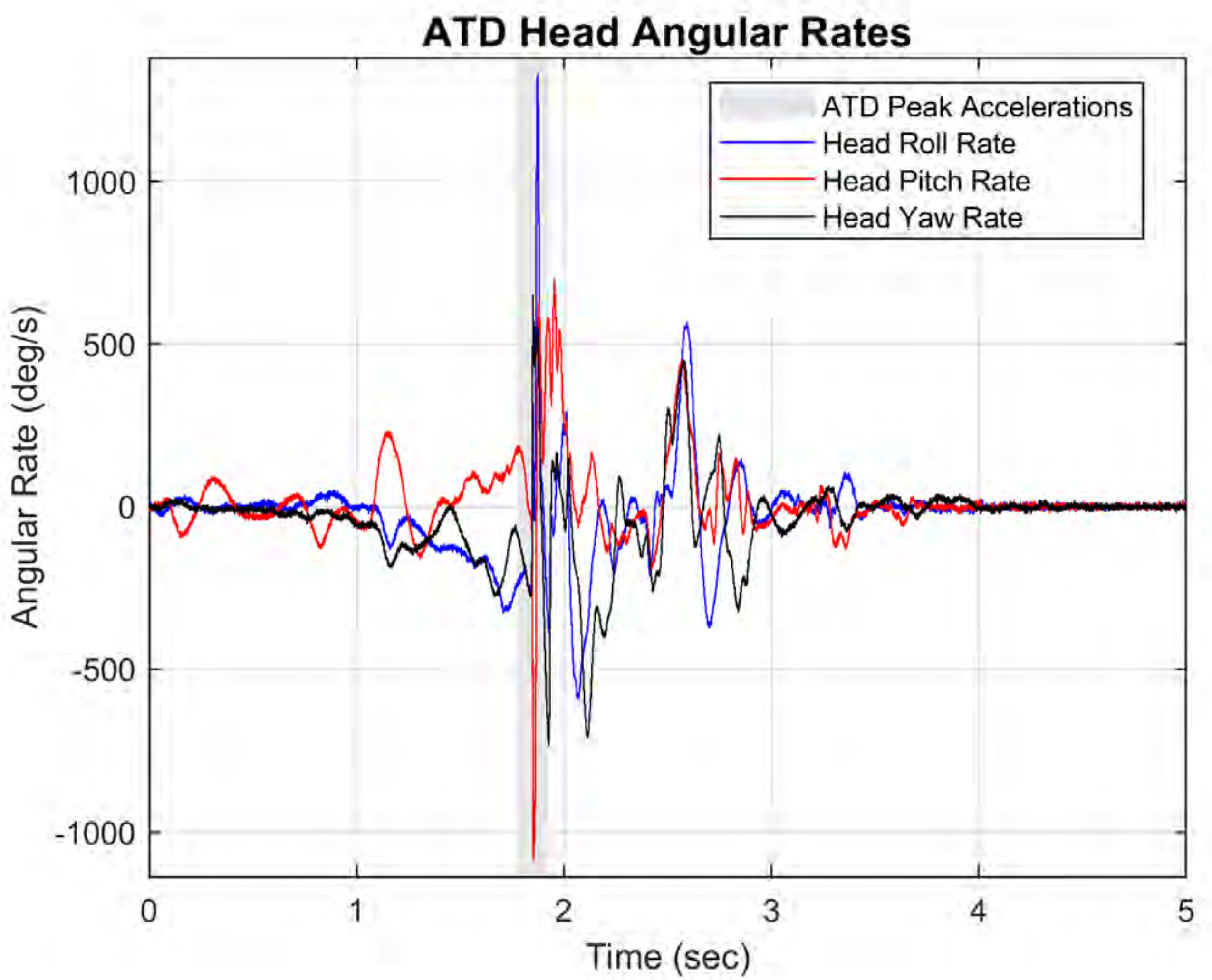
Zero-Turn Mower – Quasi-Lateral Rollover without ROPS

End of Run

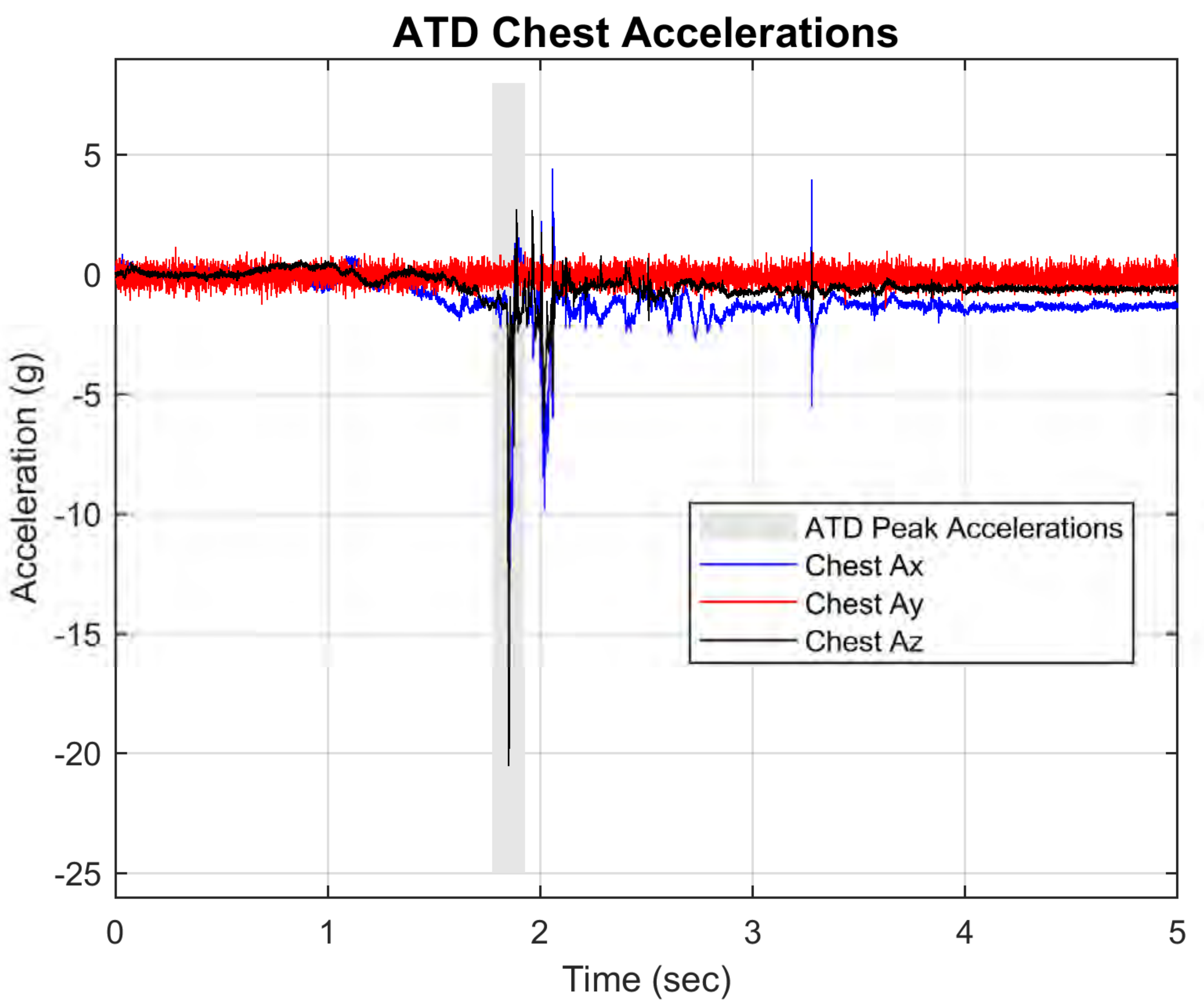
Zero-Turn Mower – Quasi-Lateral Rollover without ROPS



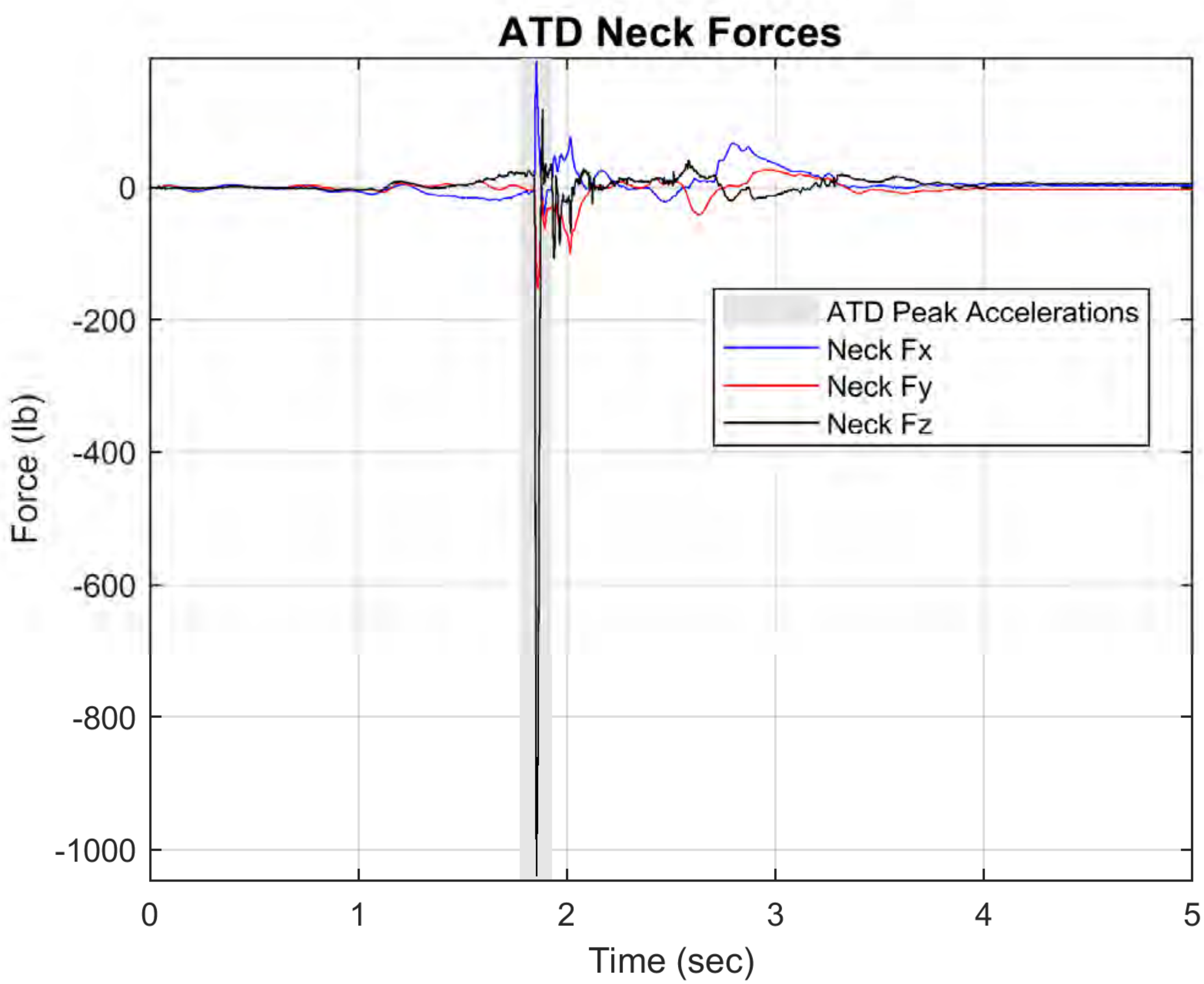
Zero-Turn Mower – Quasi-Lateral Rollover without ROPS



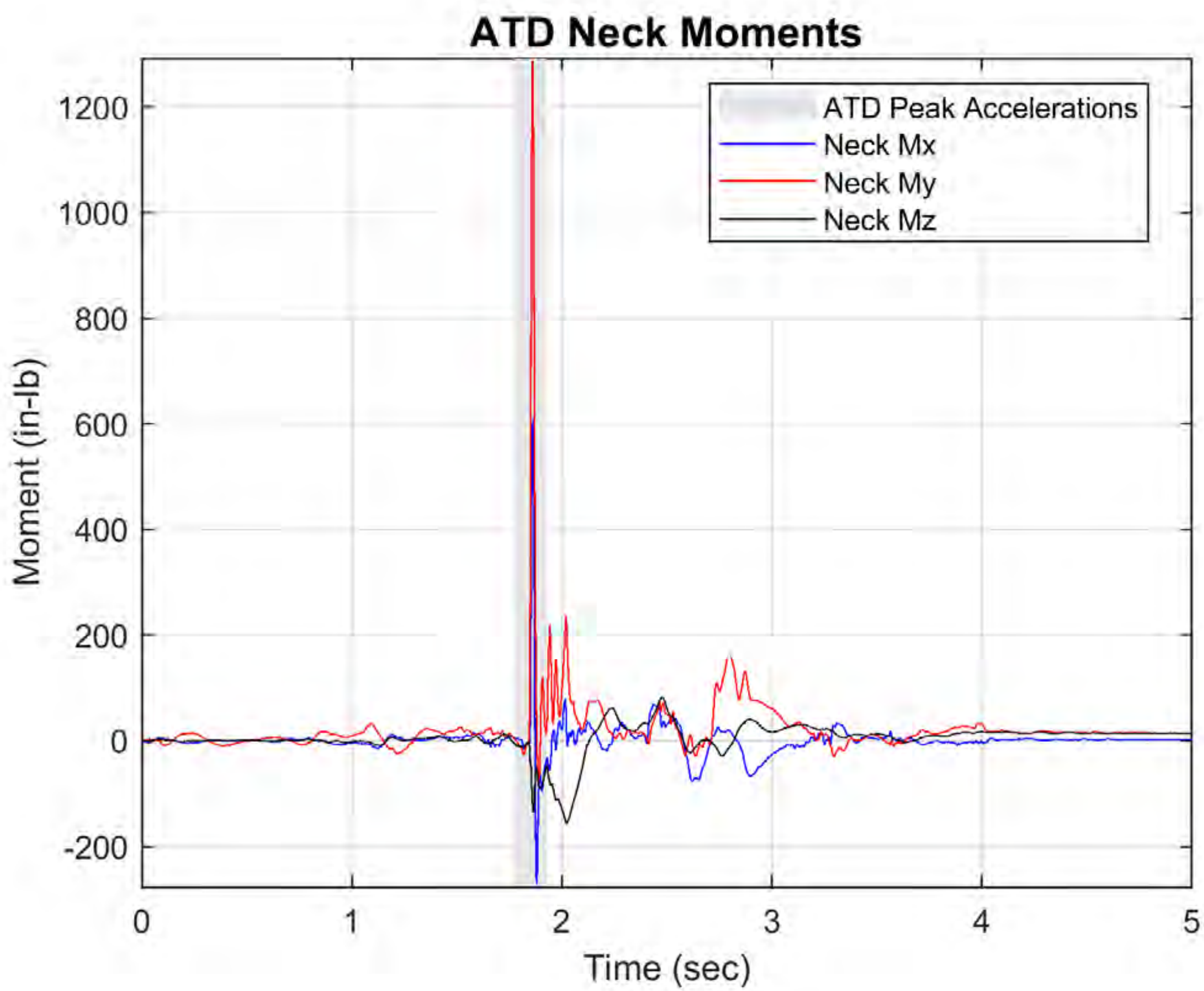
Zero-Turn Mower – Quasi-Lateral Rollover without ROPS



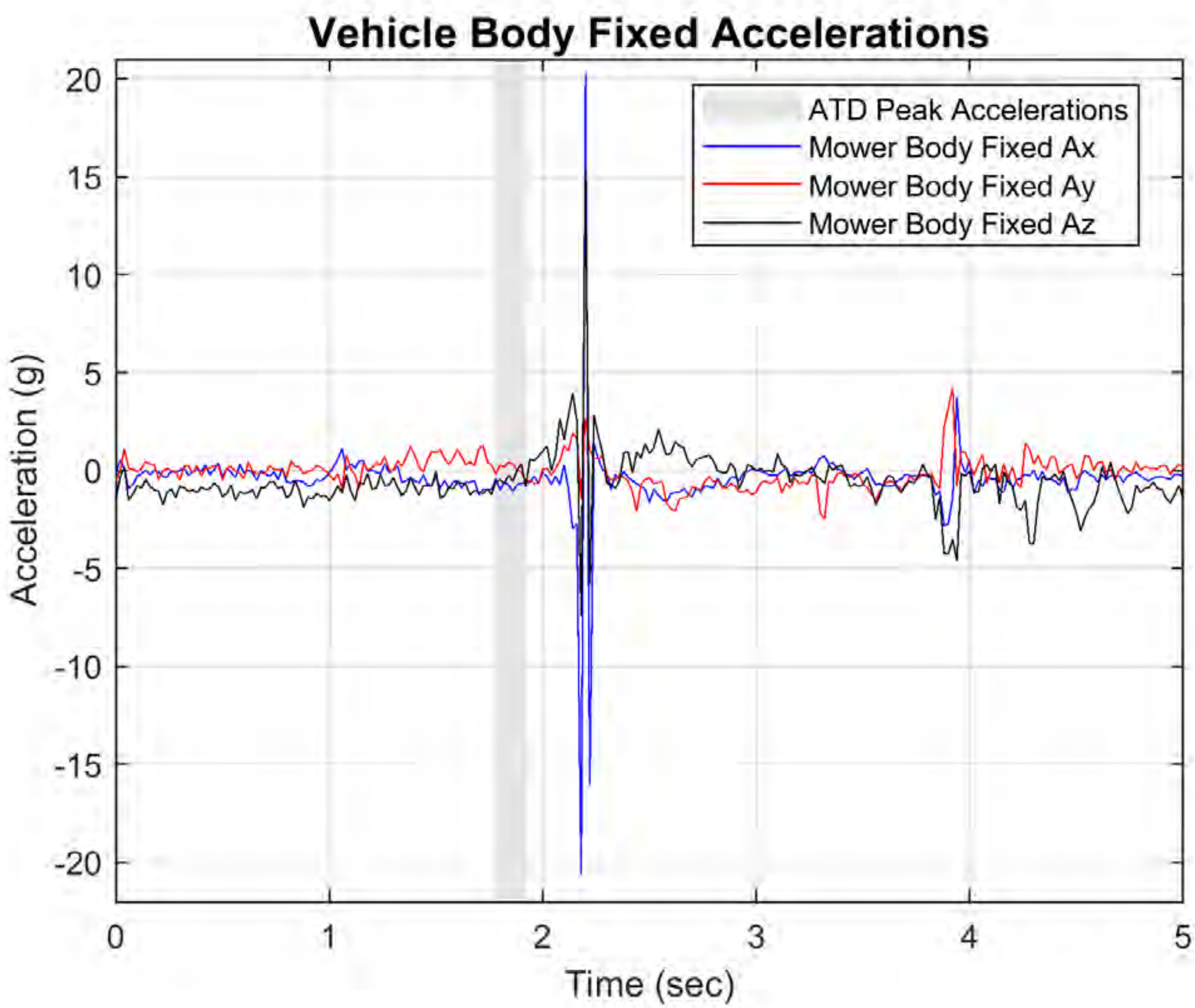
Zero-Turn Mower – Quasi-Lateral Rollover without ROPS



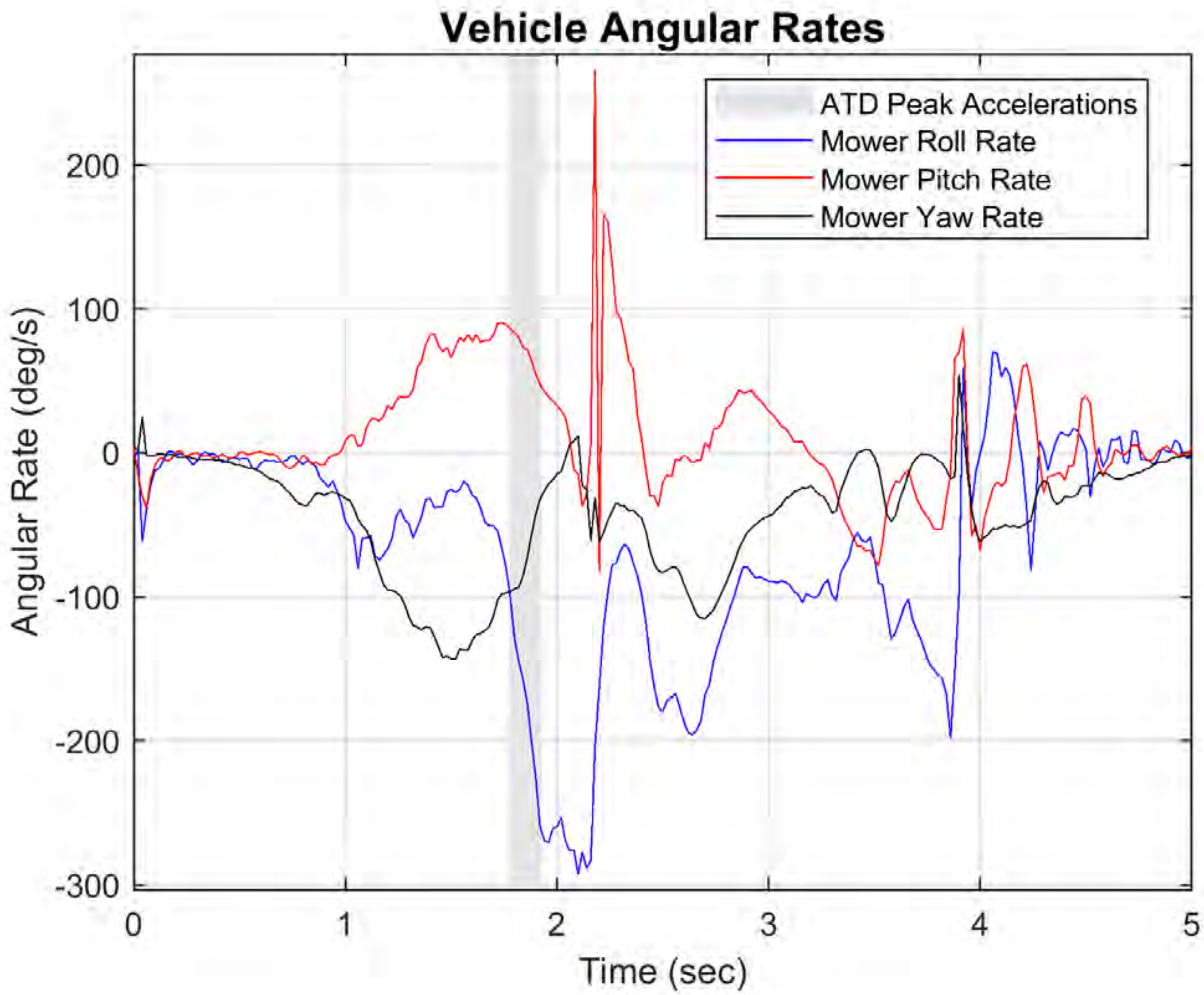
Zero-Turn Mower – Quasi-Lateral Rollover without ROPS



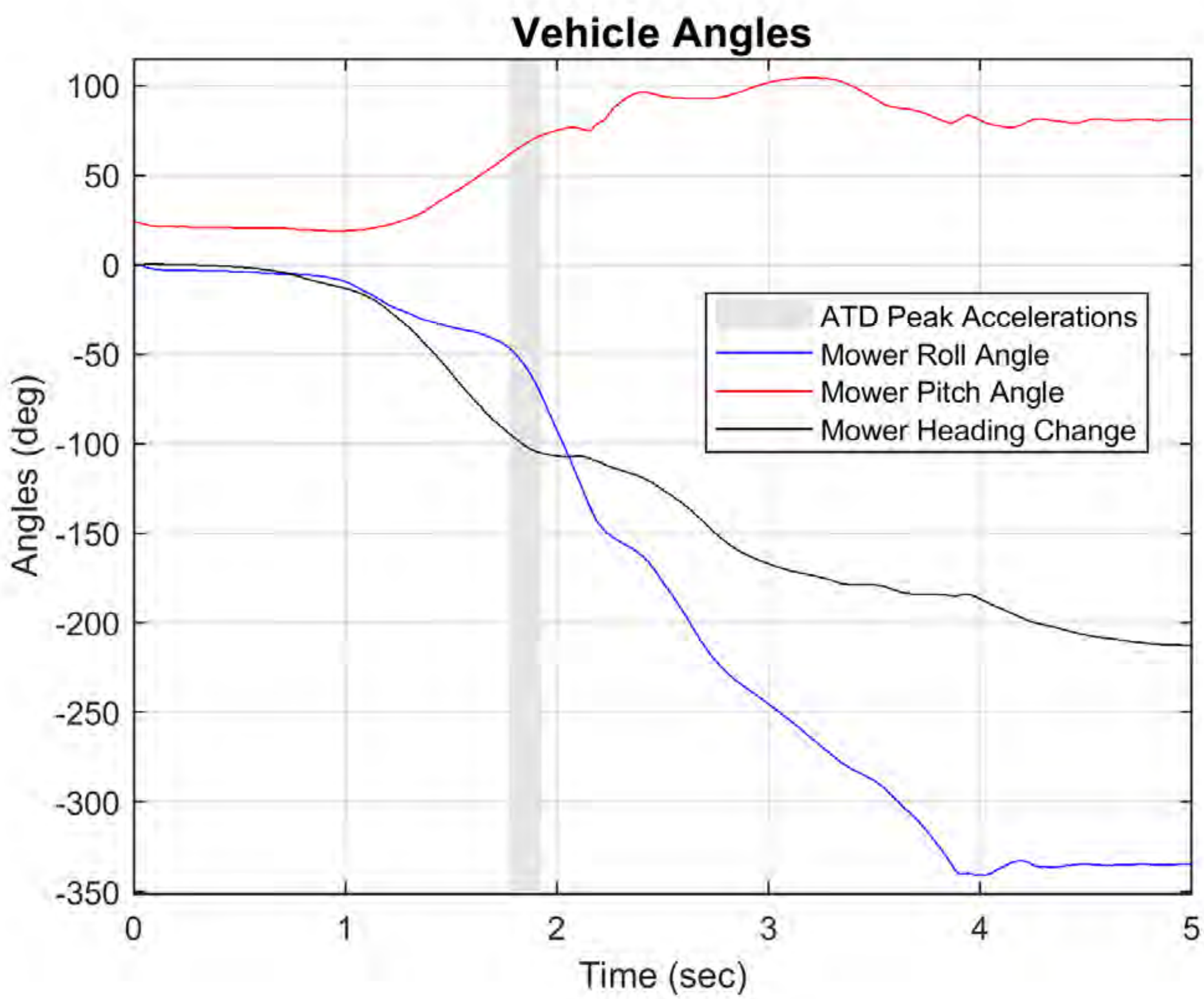
Zero-Turn Mower – Quasi-Lateral Rollover without ROPS



Zero-Turn Mower – Quasi-Lateral Rollover without ROPS



Zero-Turn Mower – Quasi-Lateral Rollover without ROPS



Zero-Turn Mower – Quasi-Lateral Rollover without ROPS

Time of Start - Time = 0.0 sec

Zero-Turn Mower – Quasi-Lateral Rollover with ROPS

Time = 0.25 sec

Zero-Turn Mower – Quasi-Lateral Rollover with ROPS

Time = 0.50 sec

Zero-Turn Mower – Quasi-Lateral Rollover with ROPS

Time = 0.75 sec

Zero-Turn Mower – Quasi-Lateral Rollover with ROPS

Time = 1.00 sec

Zero-Turn Mower – Quasi-Lateral Rollover with ROPS

Time = 1.25 sec

Zero-Turn Mower – Quasi-Lateral Rollover with ROPS

Time = 1.50 sec

Zero-Turn Mower – Quasi-Lateral Rollover with ROPS

Time = 1.75 sec

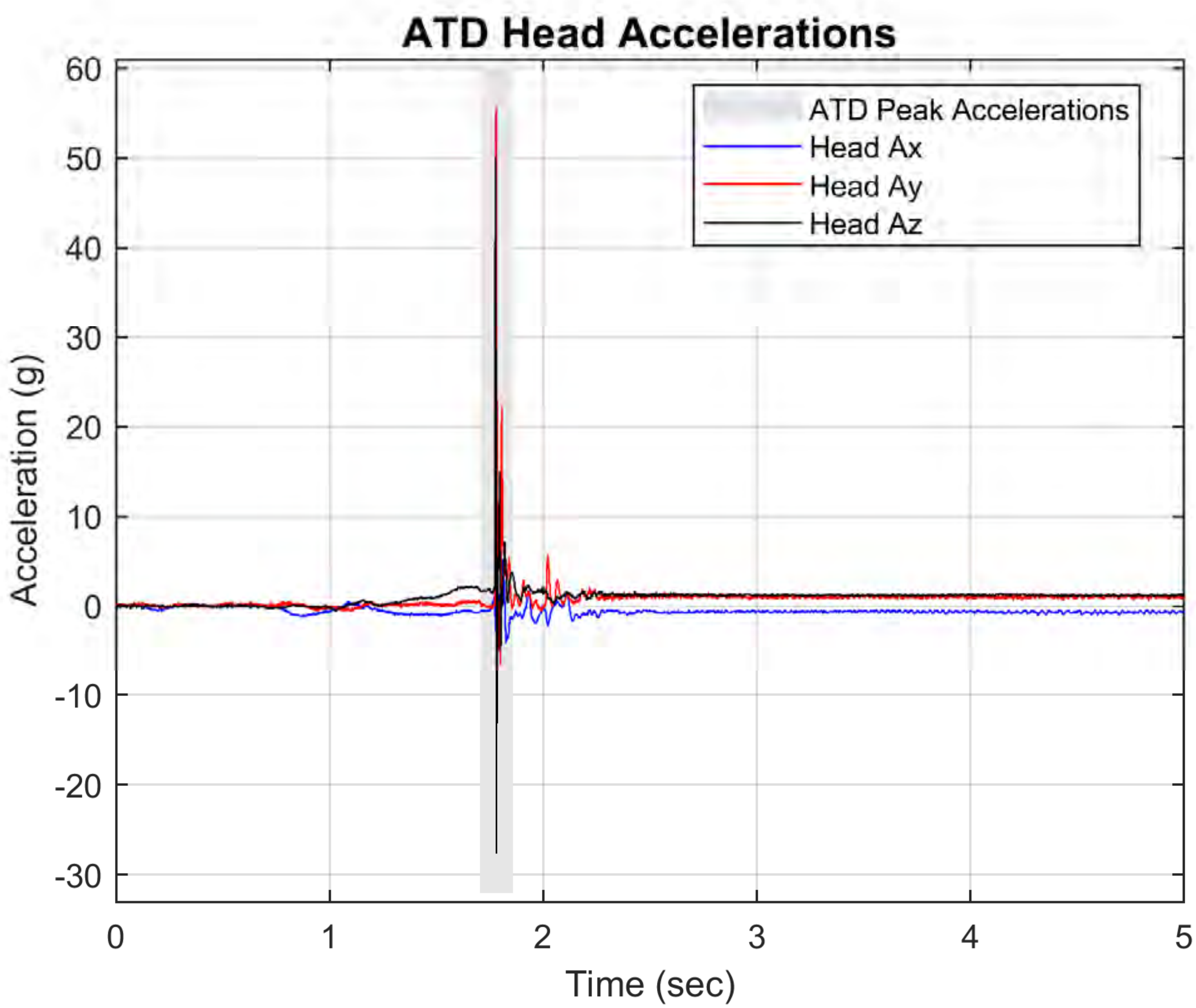
Zero-Turn Mower – Quasi-Lateral Rollover with ROPS

ATD Head Strike - Time = 1.78 sec

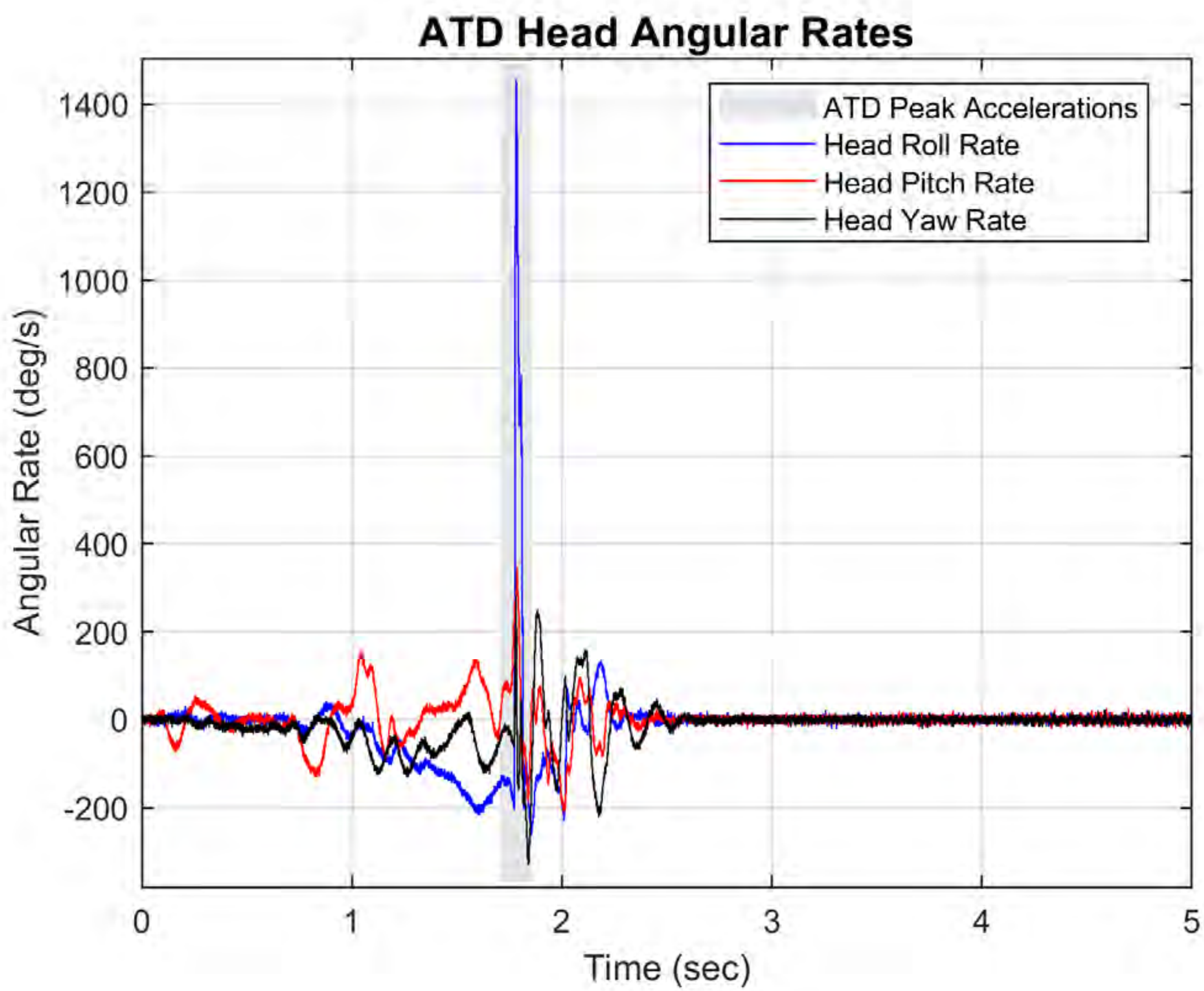
Zero-Turn Mower – Quasi-Lateral Rollover with ROPS

End of Run

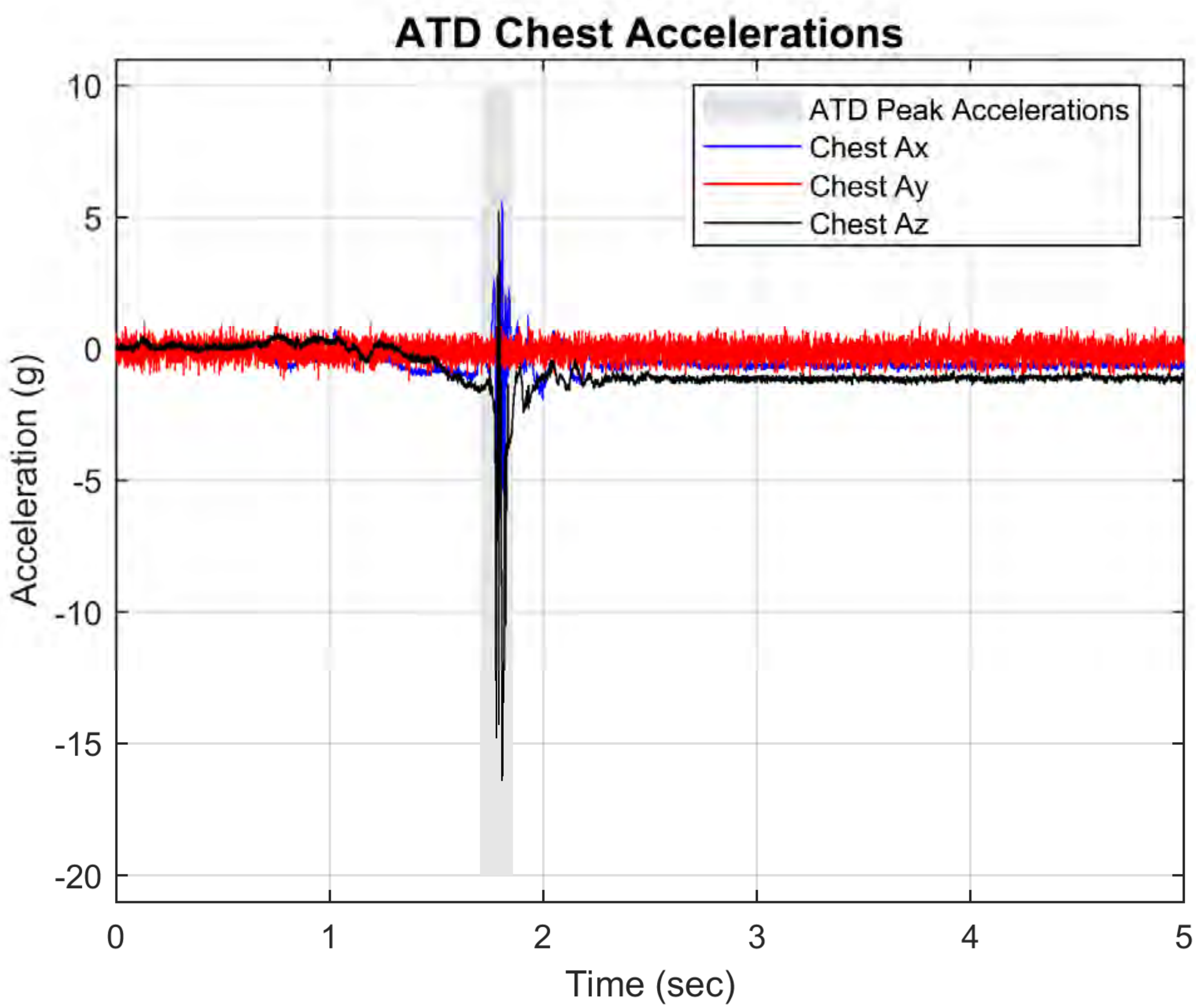
Zero-Turn Mower – Quasi-Lateral Rollover with ROPS



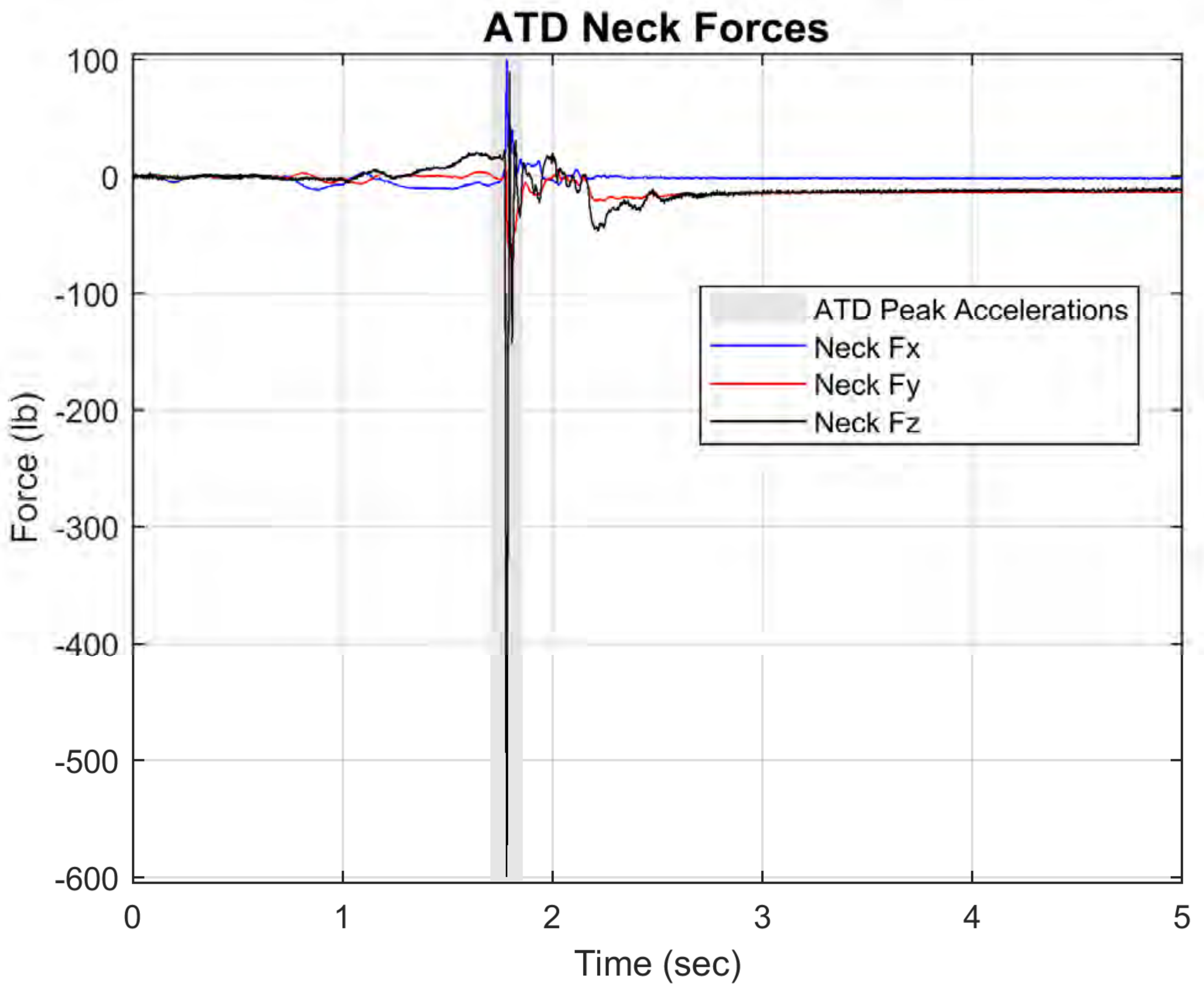
Zero-Turn Mower – Quasi-Lateral Rollover with ROPS



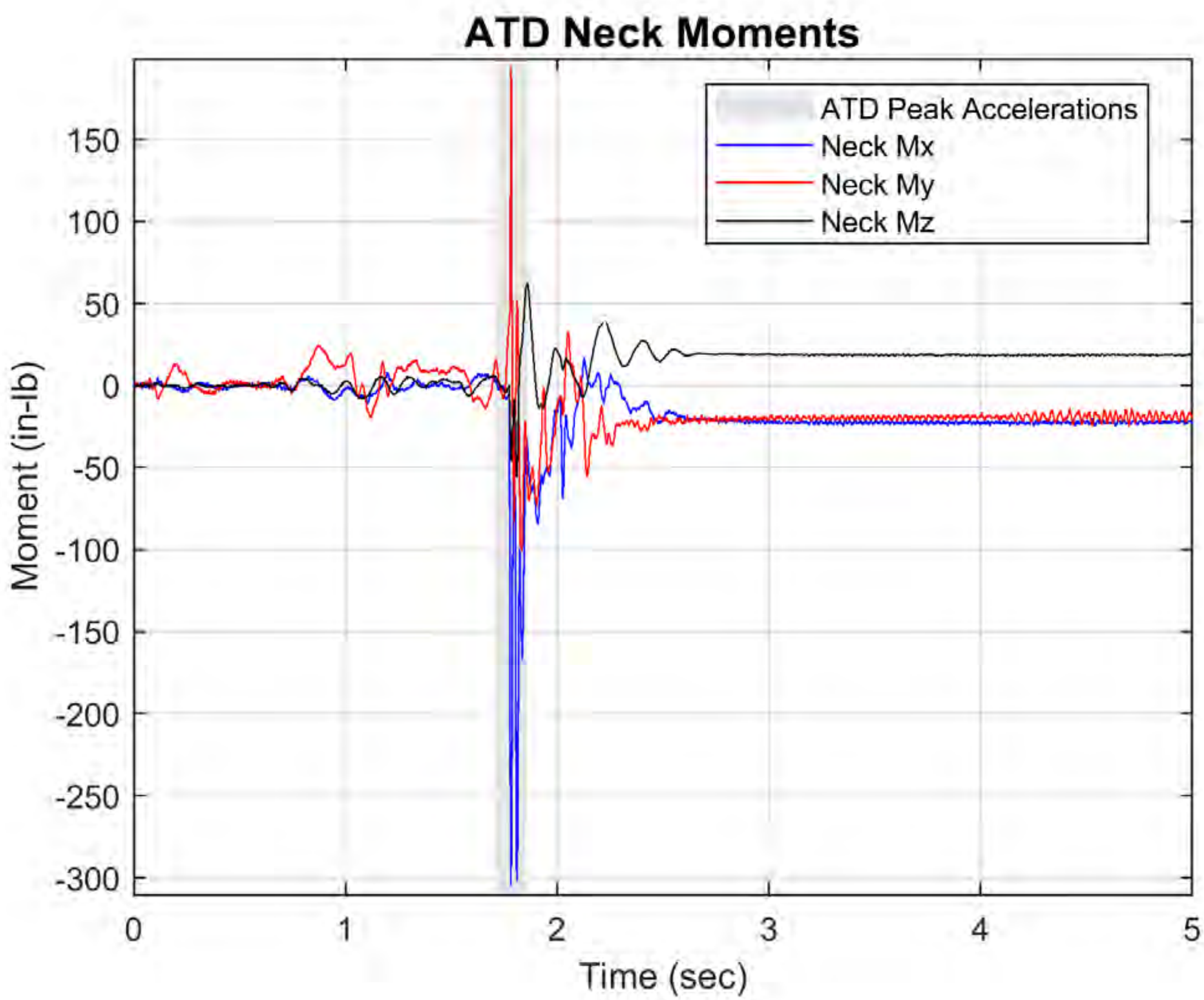
Zero-Turn Mower – Quasi-Lateral Rollover with ROPS



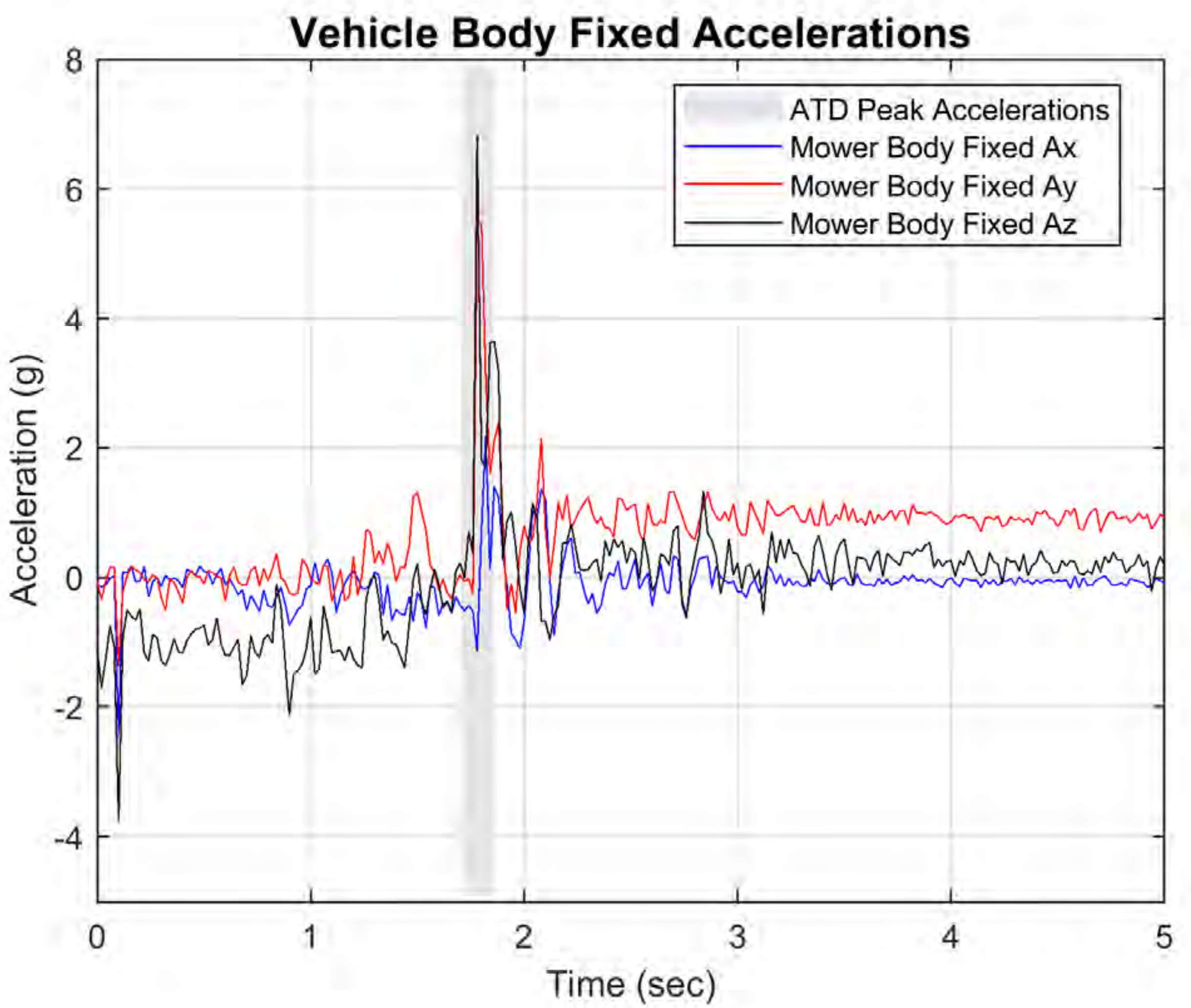
Zero-Turn Mower – Quasi-Lateral Rollover with ROPS



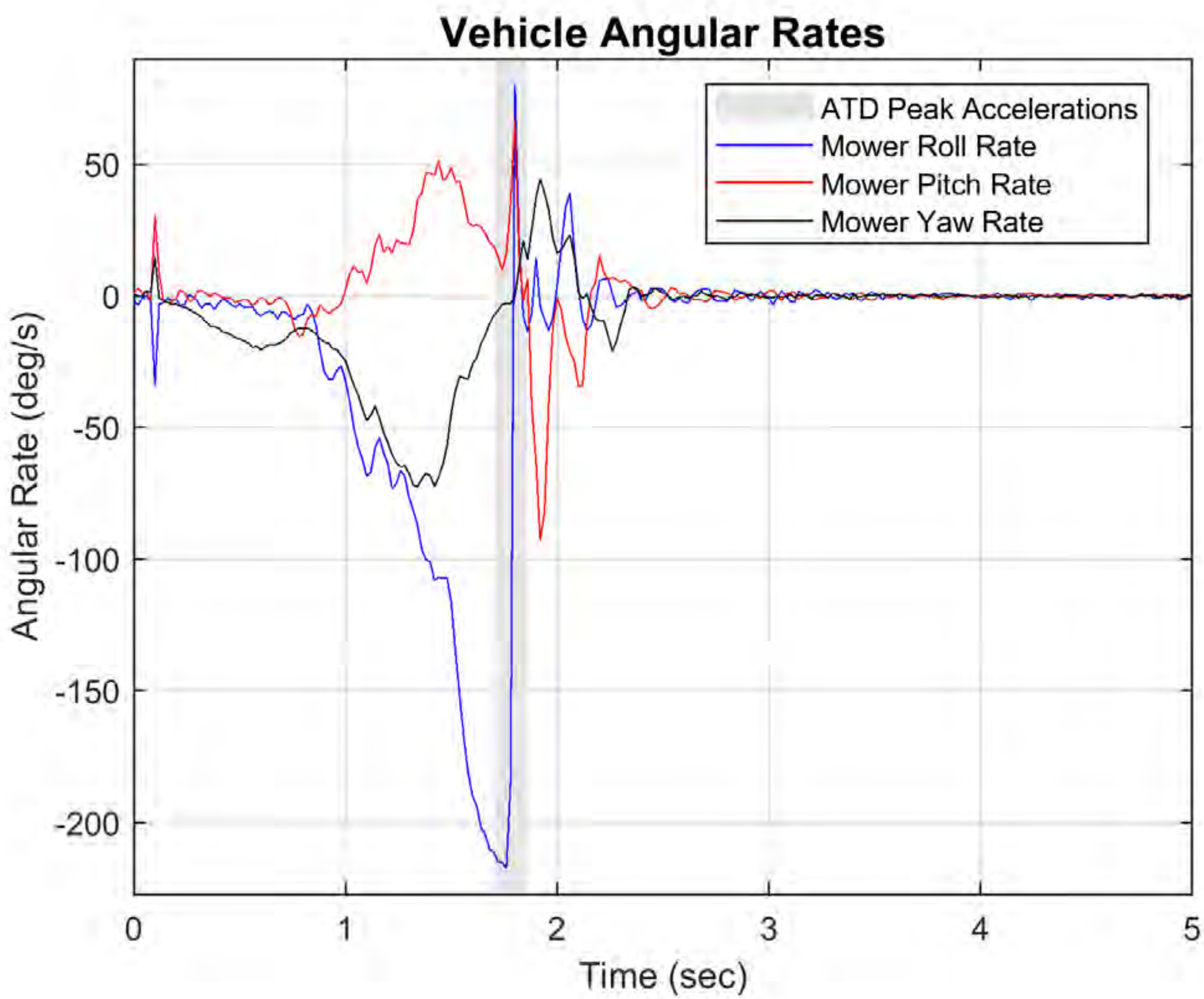
Zero-Turn Mower – Quasi-Lateral Rollover with ROPS



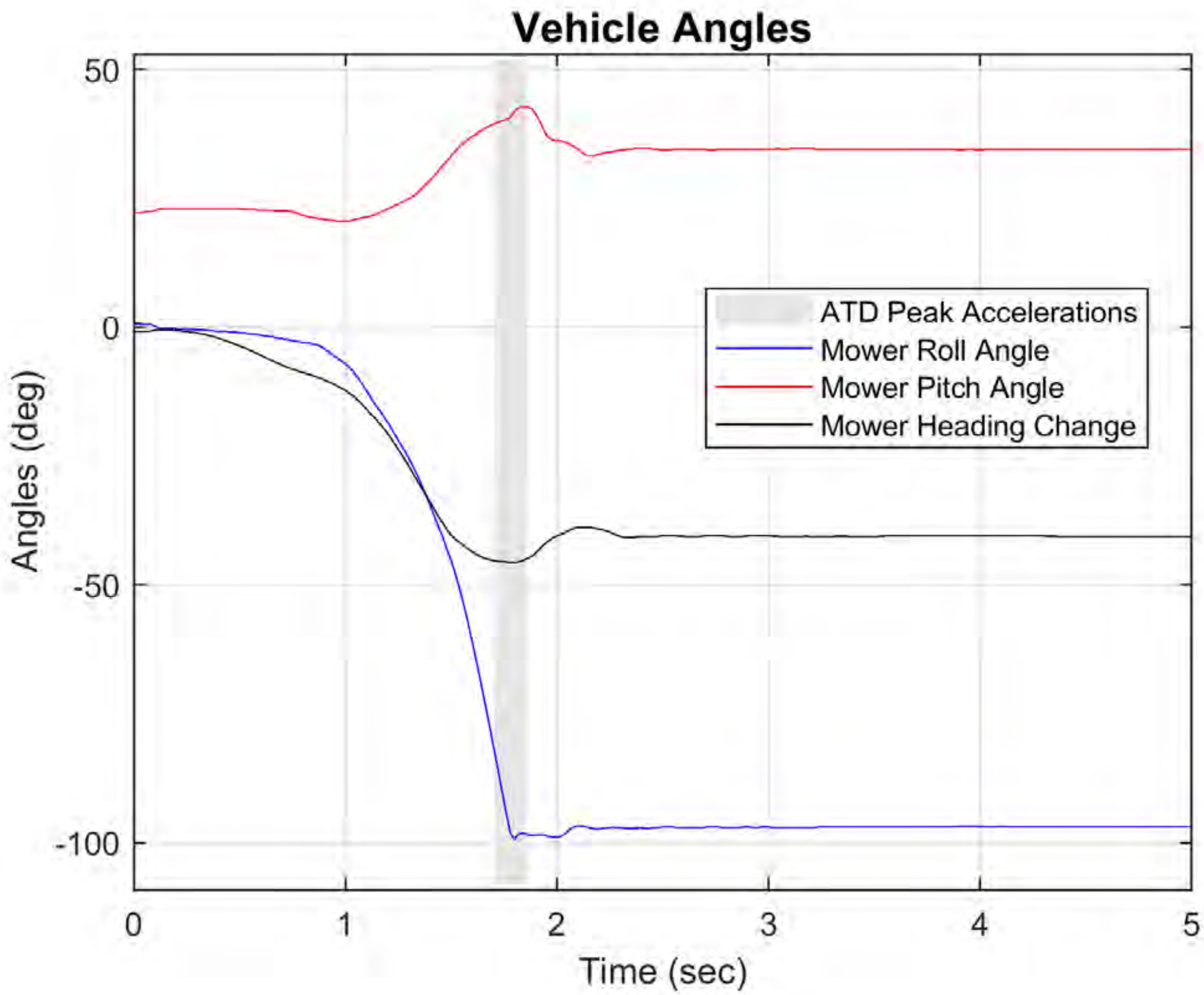
Zero-Turn Mower – Quasi-Lateral Rollover with ROPS



Zero-Turn Mower – Quasi-Lateral Rollover with ROPS



Zero-Turn Mower – Quasi-Lateral Rollover with ROPS



Zero-Turn Mower – Quasi-Lateral Rollover with ROPS

Time of Start - Time = 0.0 sec - Pitch Angle = 33.1°

Zero-Turn Mower – Rearward Pitchover without ROPS

Pitch Angle = 60° - Time = 1.22 sec

Zero-Turn Mower – Rearward Pitchover without ROPS

Pitch Angle = 90° - Time = 2.04 sec

Zero-Turn Mower – Rearward Pitchover without ROPS

Pitch Angle = 120° - Time = 2.38 sec

Zero-Turn Mower – Rearward Pitchover without ROPS

ATD Head Strike - Time = 2.50 sec

Zero-Turn Mower – Rearward Pitchover without ROPS

Pitch Angle = 150° - Time = 2.60 sec

Zero-Turn Mower – Rearward Pitchover without ROPS

Pitch Angle = 180° - Time = 2.76 sec

Zero-Turn Mower – Rearward Pitchover without ROPS

Pitch Angle = 210° - Time = 2.96 sec

Zero-Turn Mower – Rearward Pitchover without ROPS

Pitch Angle = 240° - Time = 3.16 sec

Zero-Turn Mower – Rearward Pitchover without ROPS

Max Pitch Angle = 261.1° - Time = 3.80 sec

Zero-Turn Mower – Rearward Pitchover without ROPS

Time = 4.30 sec

Zero-Turn Mower – Rearward Pitchover without ROPS

Time = 4.80 sec

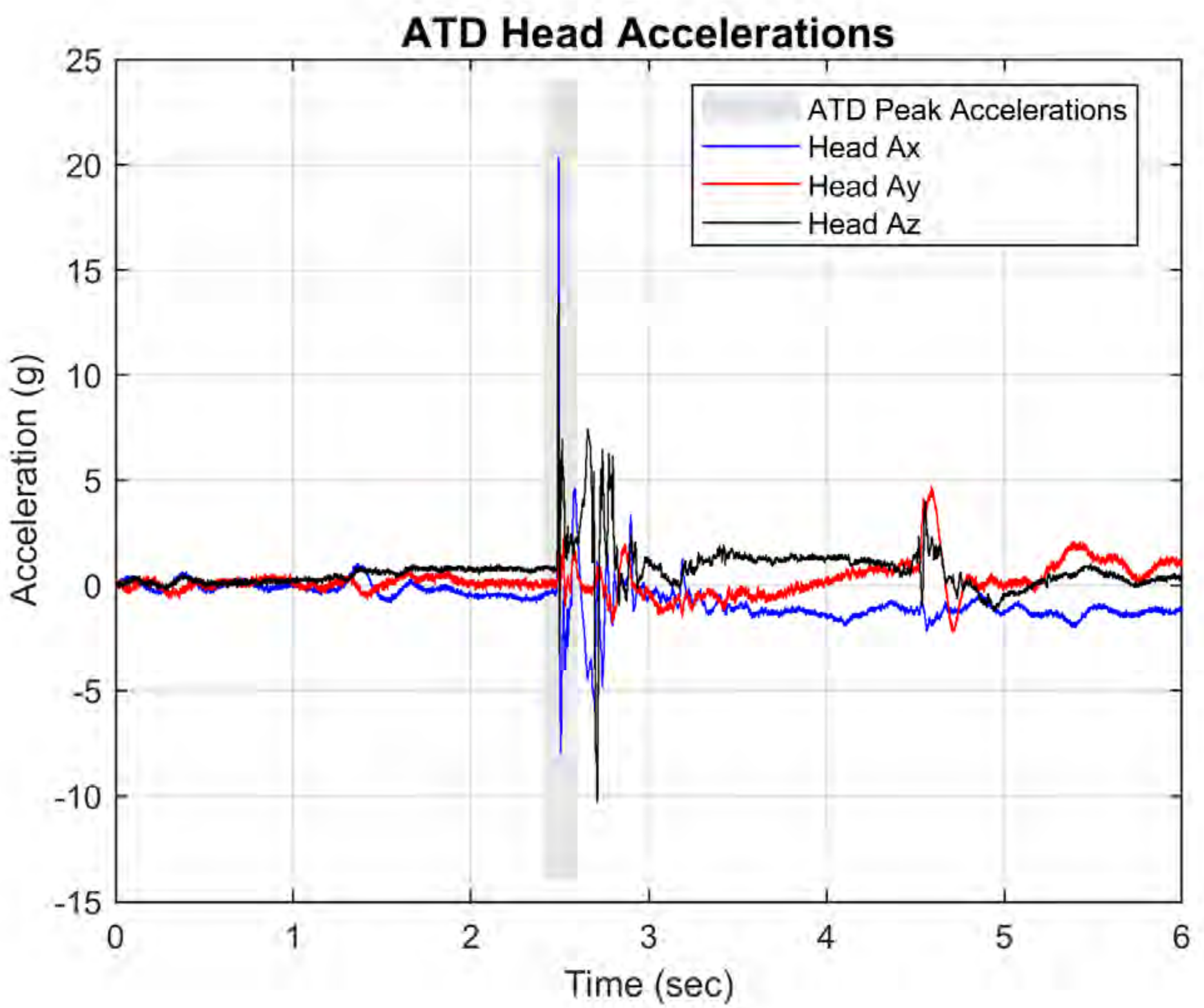
Zero-Turn Mower – Rearward Pitchover without ROPS

Time = 5.30 sec

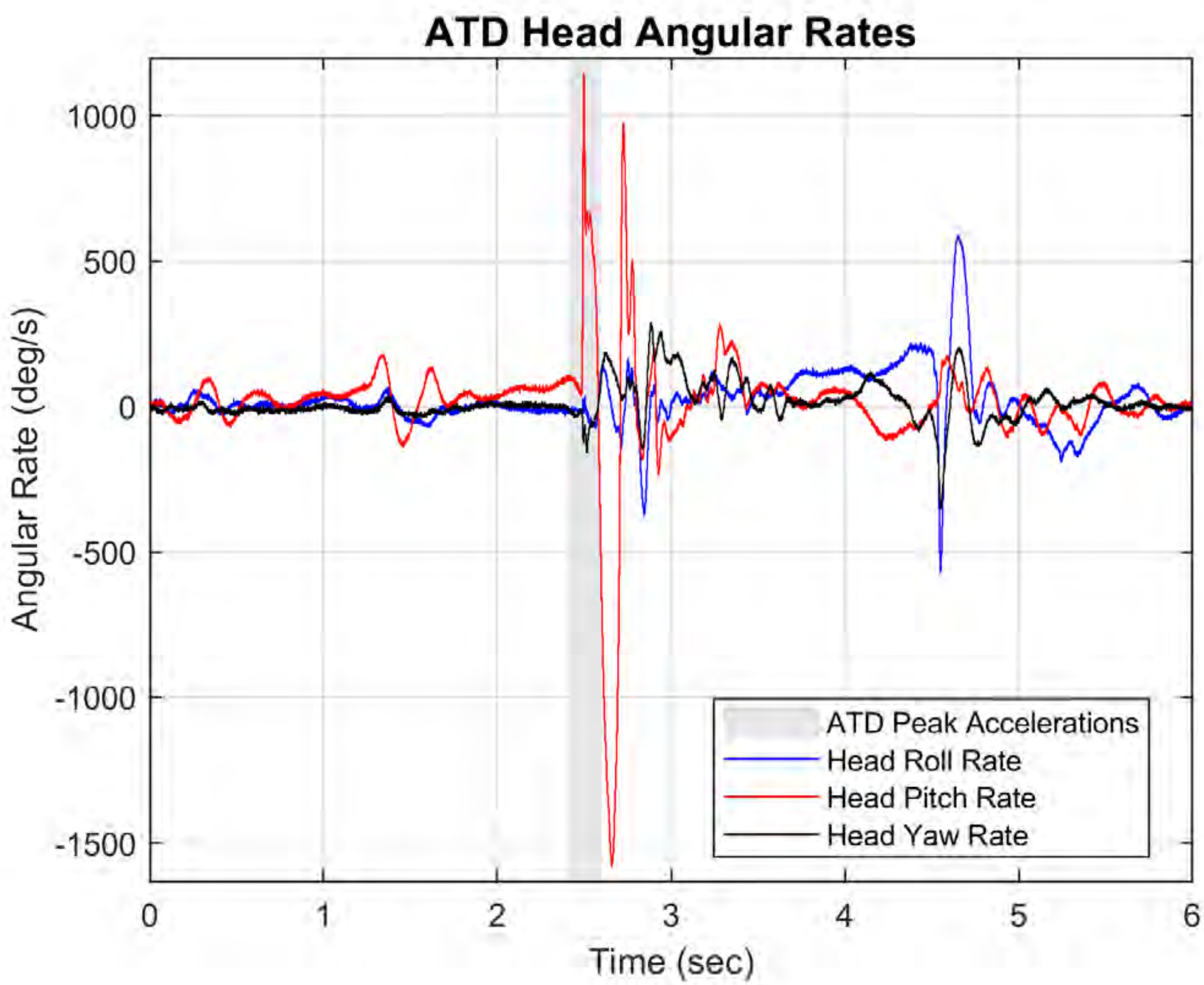
Zero-Turn Mower – Rearward Pitchover without ROPS

End of Run

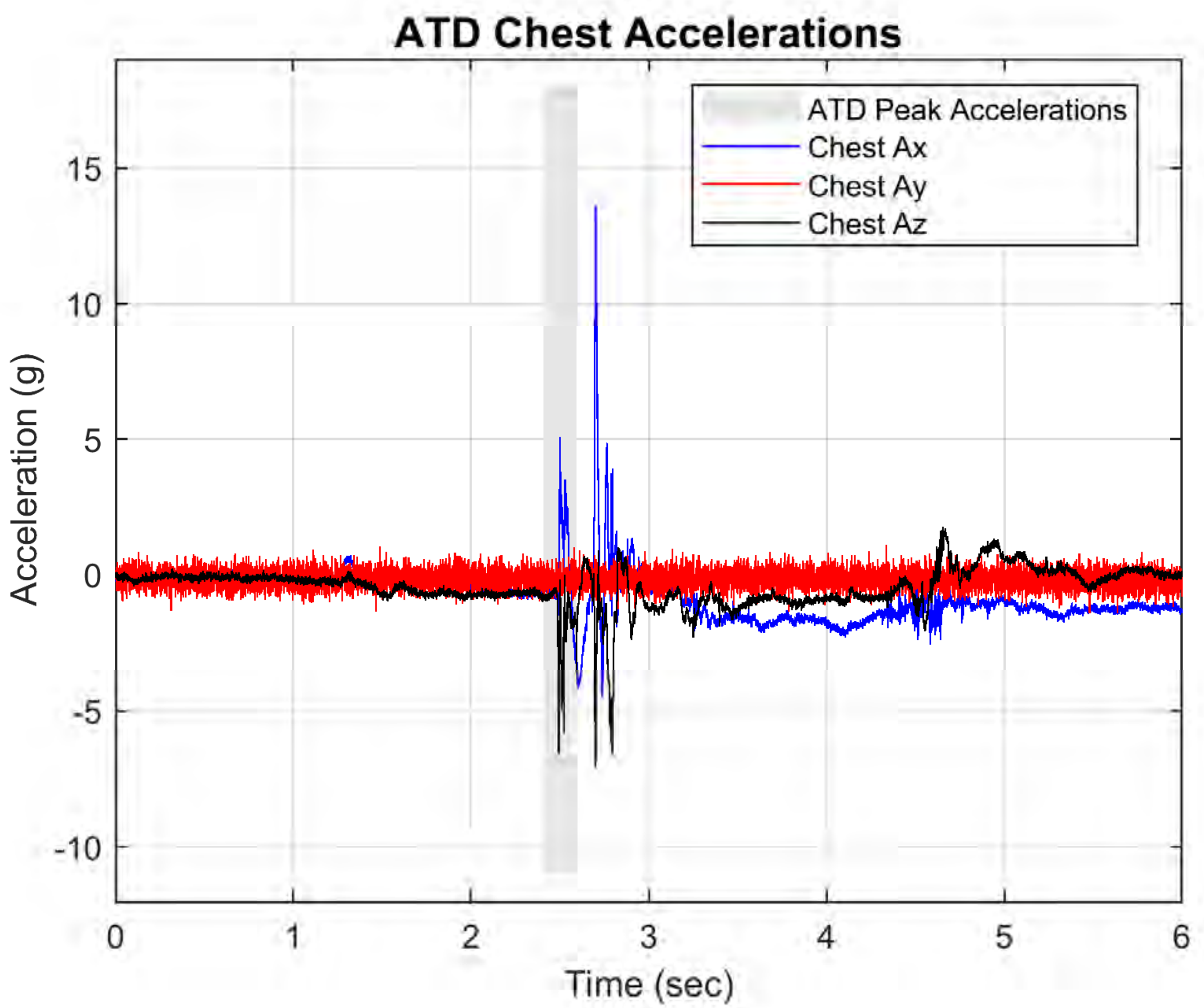
Zero-Turn Mower – Rearward Pitchover without ROPS



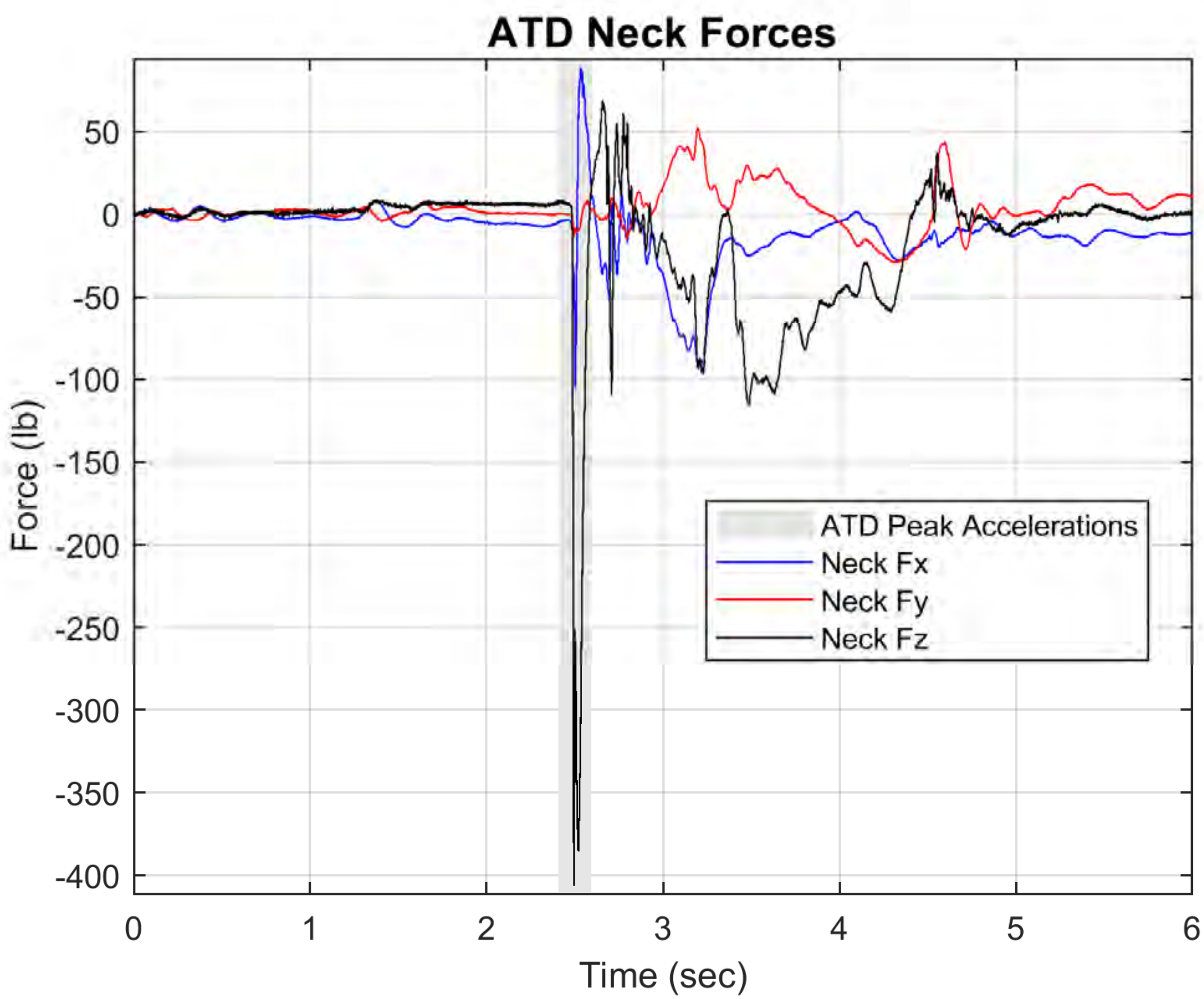
Zero-Turn Mower – Rearward Pitchover without ROPS



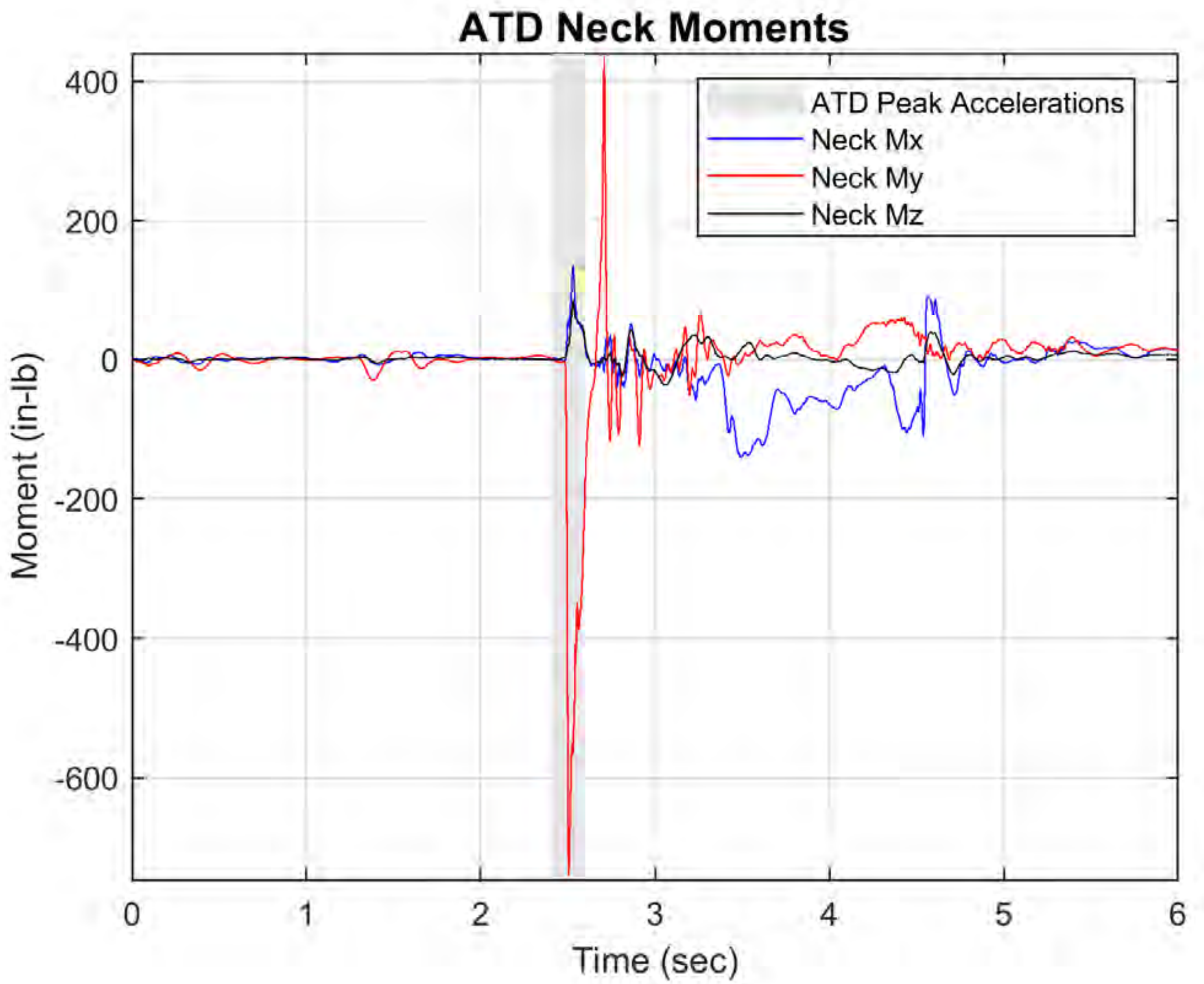
Zero-Turn Mower – Rearward Pitchover without ROPS



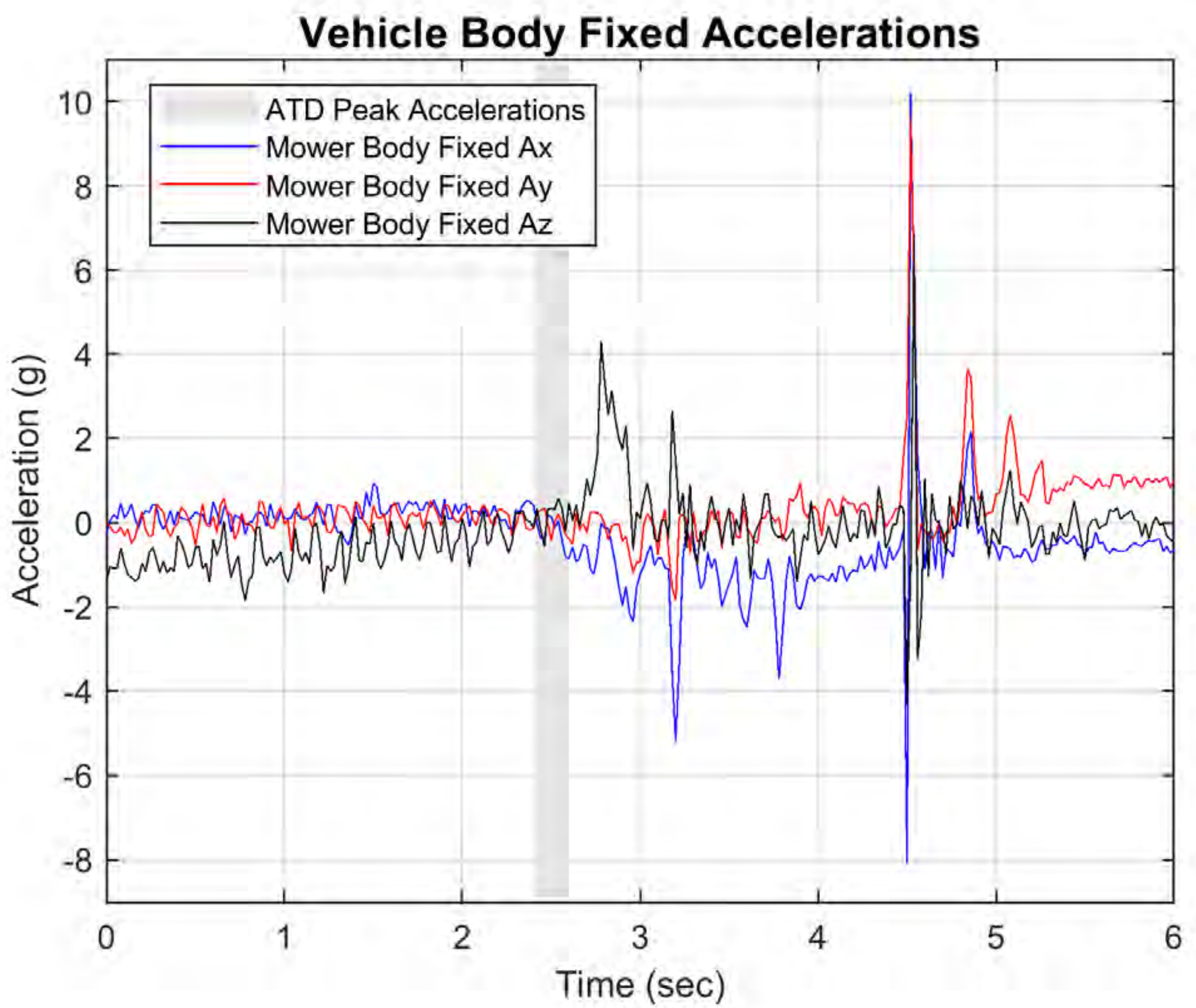
Zero-Turn Mower – Rearward Pitchover without ROPS



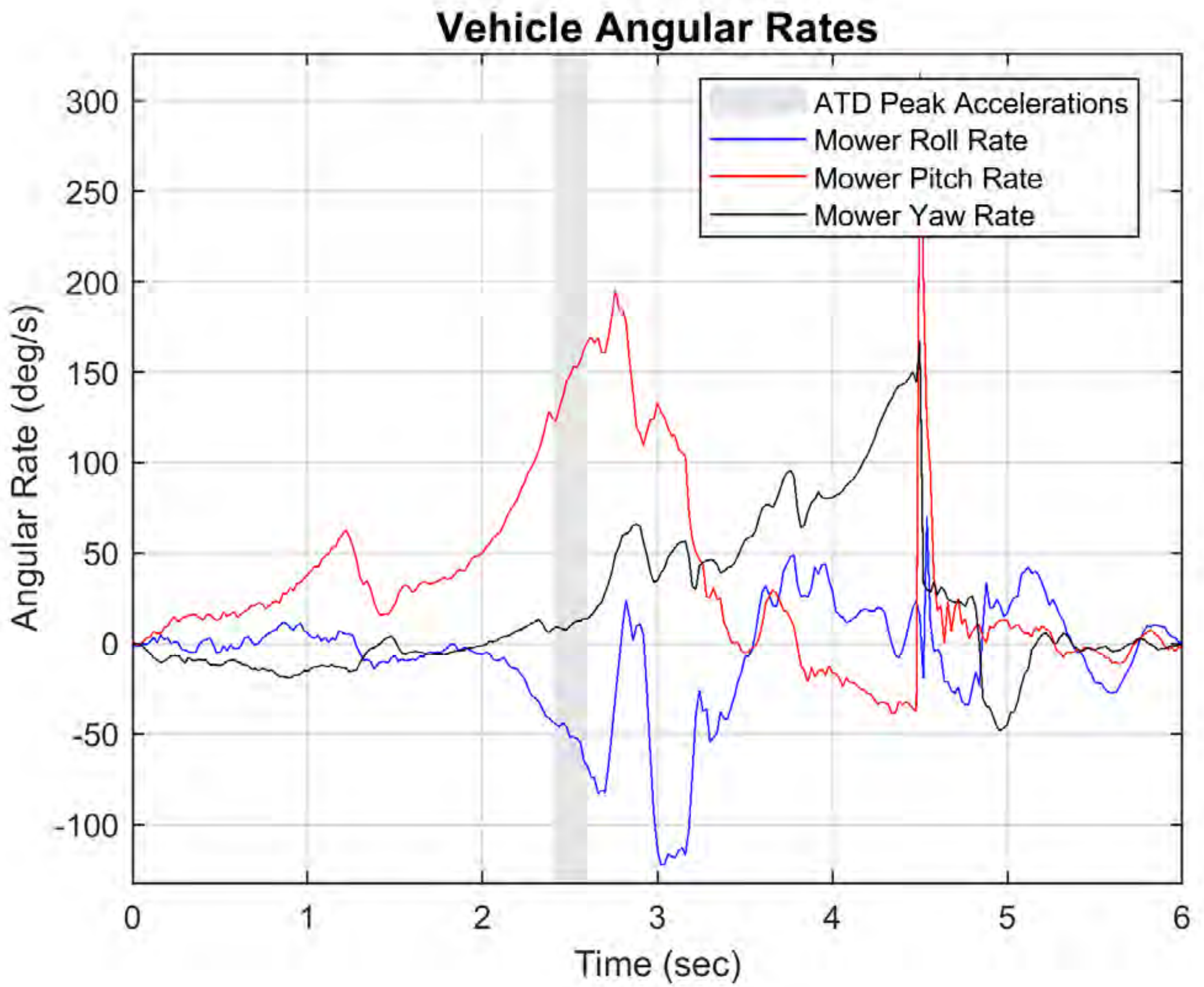
Zero-Turn Mower – Rearward Pitchover without ROPS



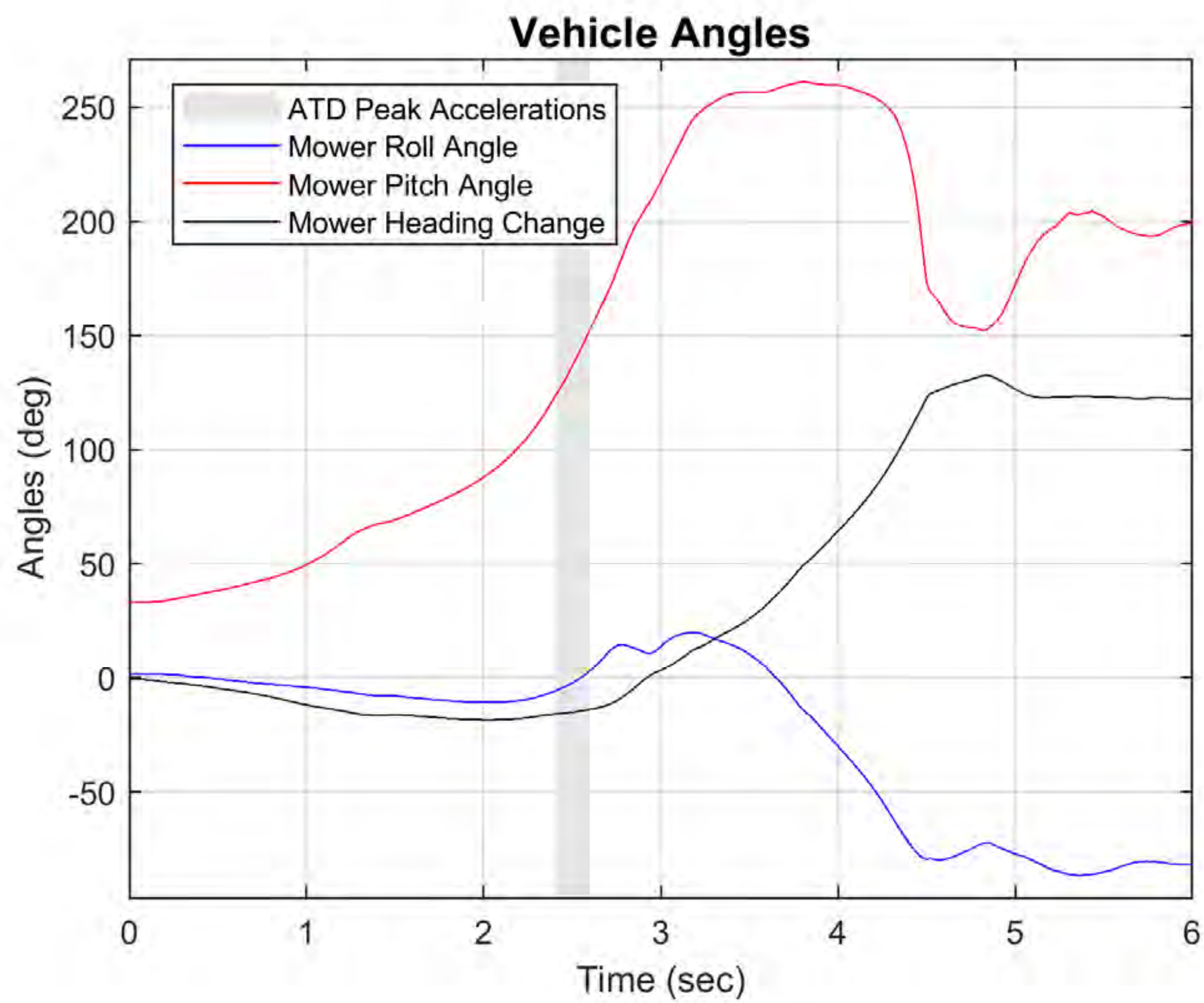
Zero-Turn Mower – Rearward Pitchover without ROPS



Zero-Turn Mower – Rearward Pitchover without ROPS



Zero-Turn Mower – Rearward Pitchover without ROPS



Zero-Turn Mower – Rearward Pitchover without ROPS

Time of Start - Time = 0.0 sec

Zero-Turn Mower – Rearward Pitchover with ROPS

Pitch Angle = 30° - Time = 0.30 sec

Zero-Turn Mower – Rearward Pitchover with ROPS

Pitch Angle = 60° - Time = 0.84 sec

Zero-Turn Mower – Rearward Pitchover with ROPS

Pitch Angle = 90° - Time = 1.76 sec

Zero-Turn Mower – Rearward Pitchover with ROPS

Pitch Angle = 120° - Time = 2.06 sec

Zero-Turn Mower – Rearward Pitchover with ROPS

ATD Head Strike - Time = 2.20 sec

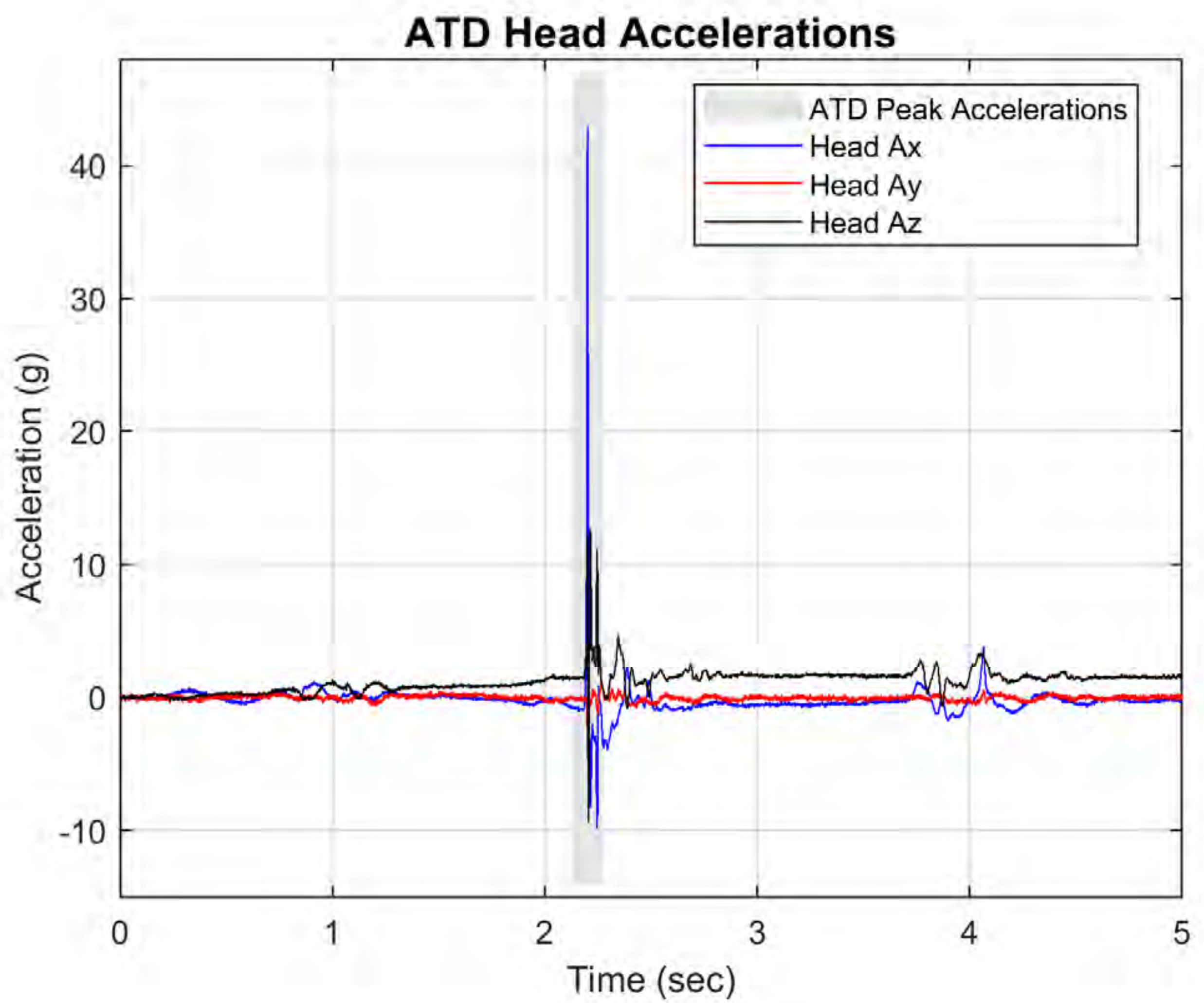
Zero-Turn Mower – Rearward Pitchover with ROPS

Max Pitch Angle = 160.1° - Time = 2.94 sec

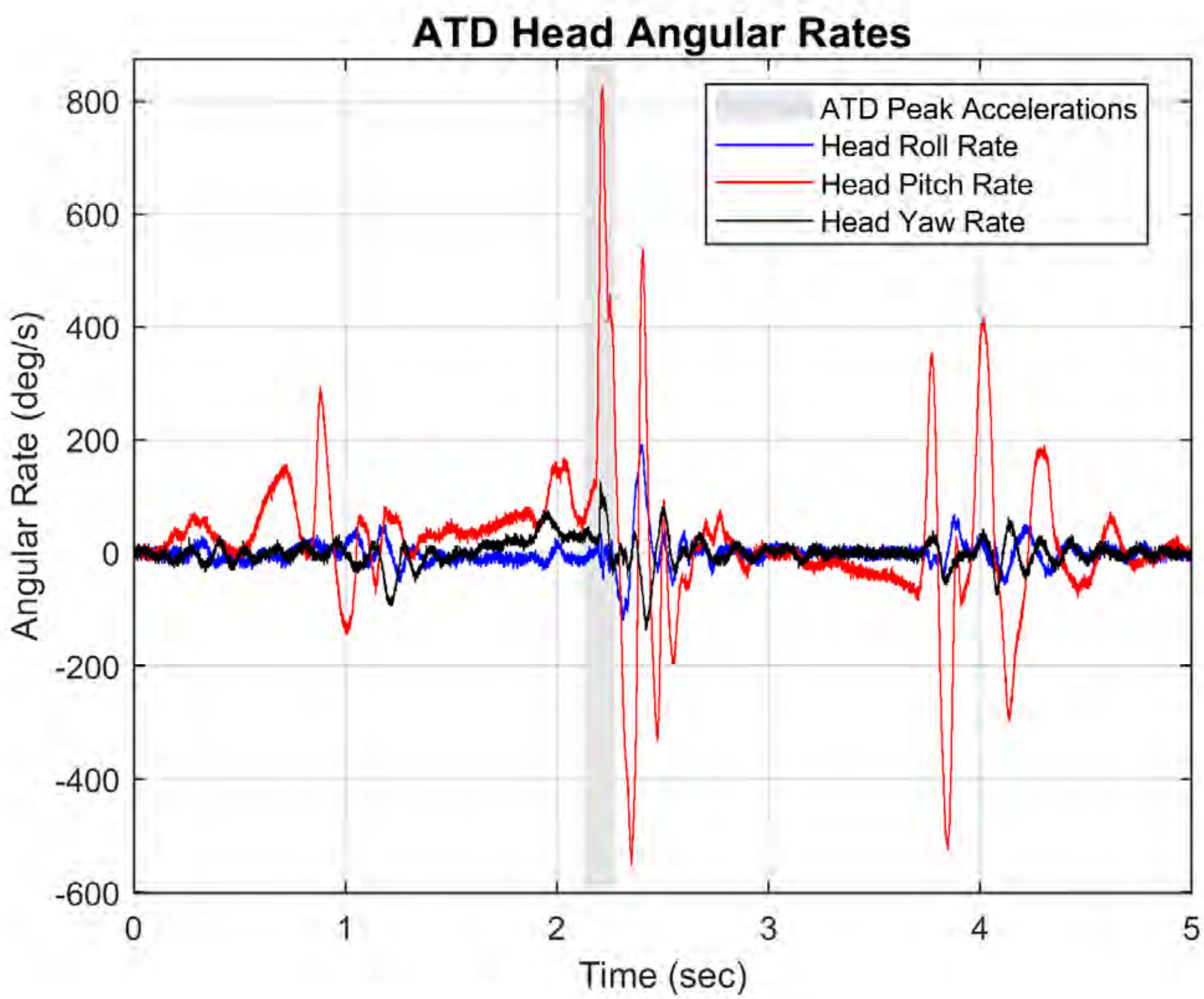
Zero-Turn Mower – Rearward Pitchover with ROPS

End of Run - Pitch Angle = 139.1°

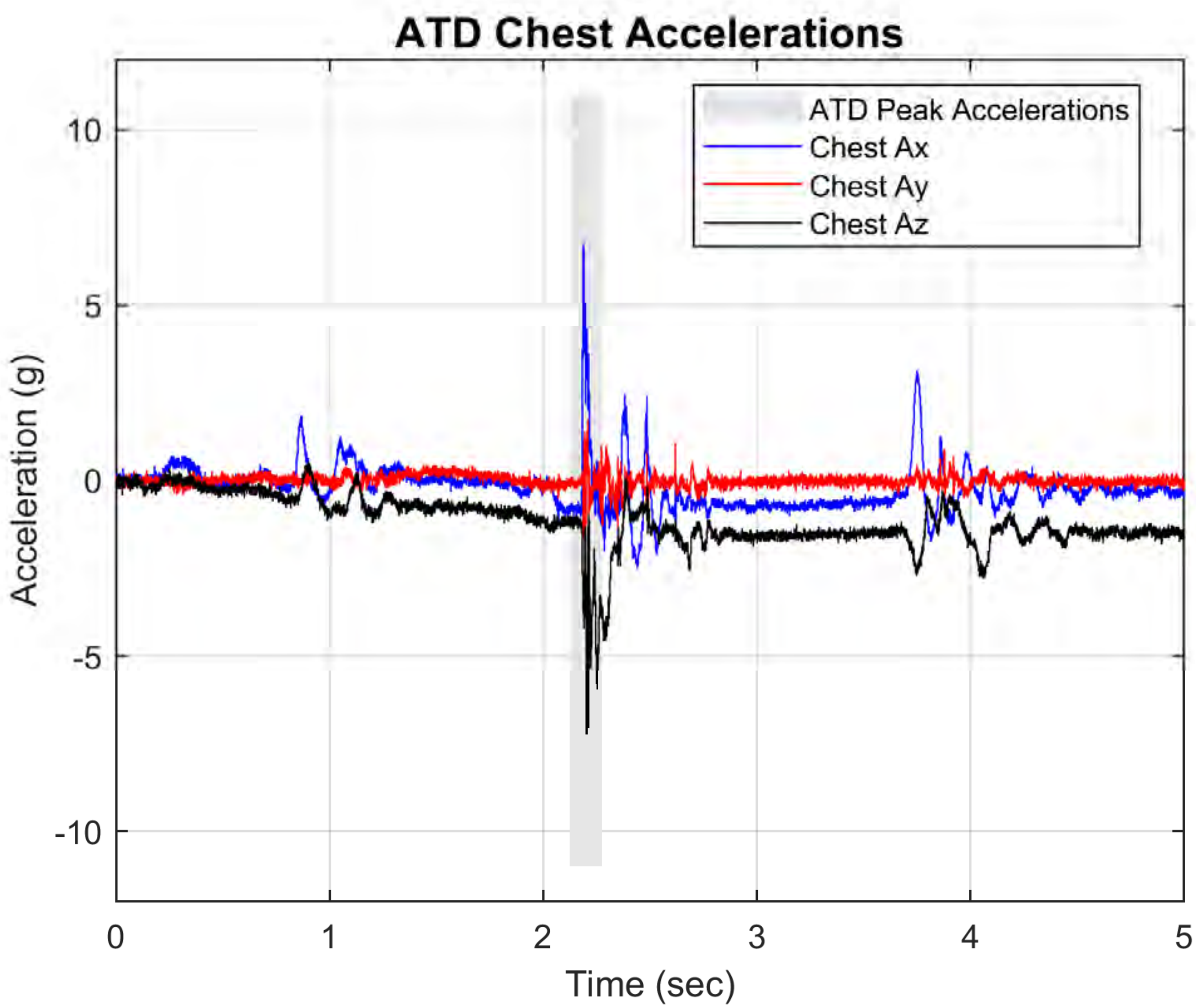
Zero-Turn Mower – Rearward Pitchover with ROPS



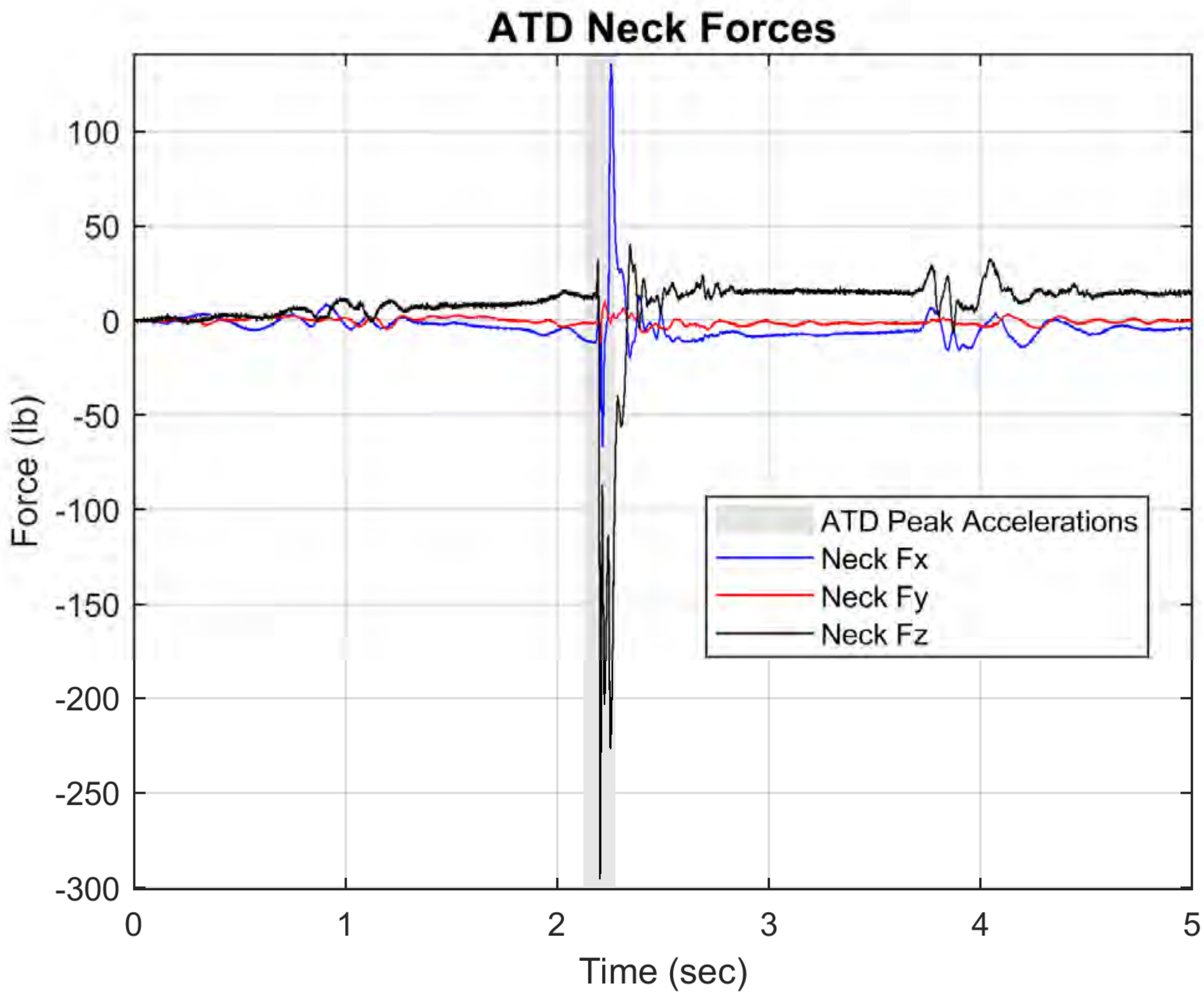
Zero-Turn Mower – Rearward Pitchover with ROPS



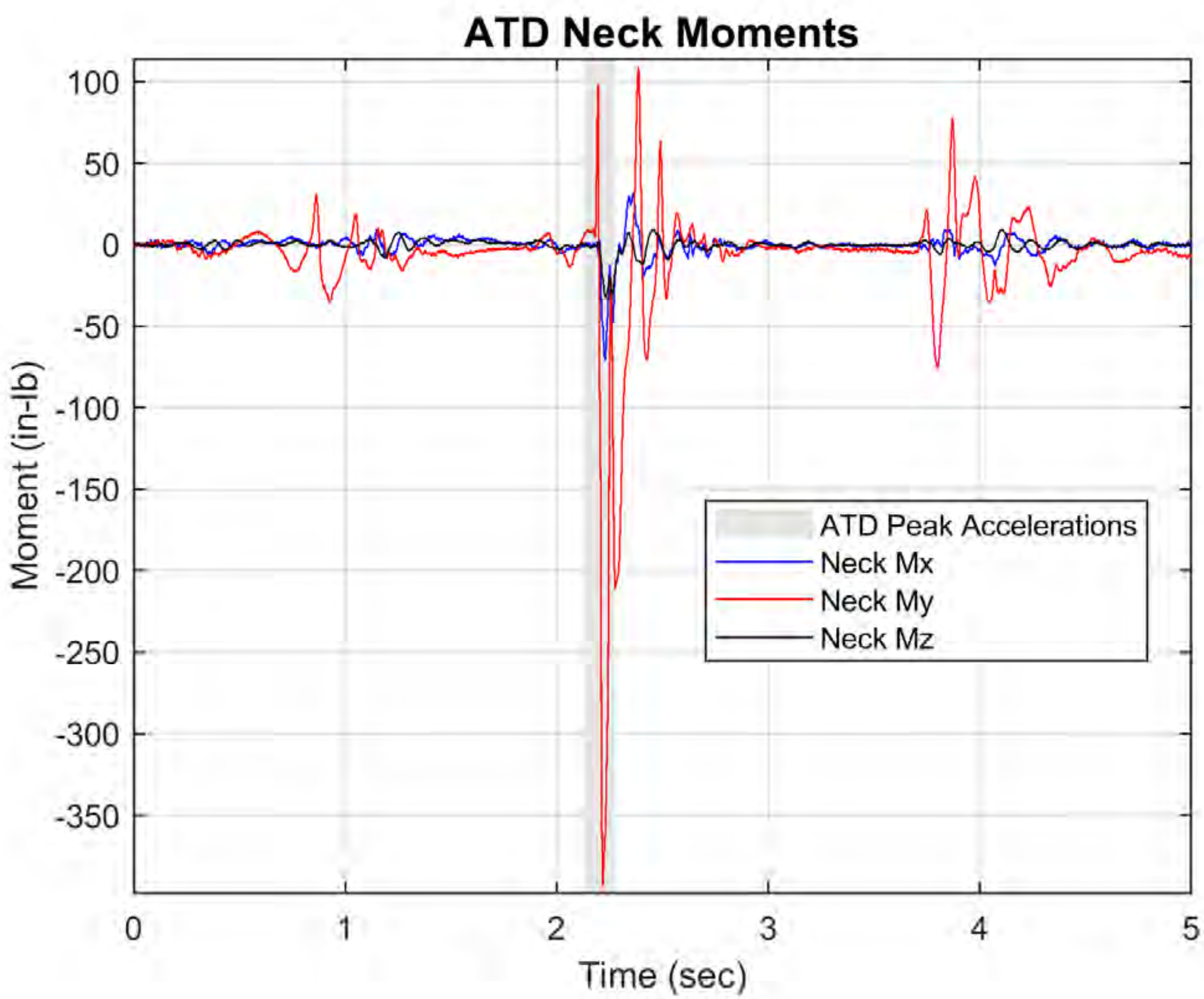
Zero-Turn Mower – Rearward Pitchover with ROPS



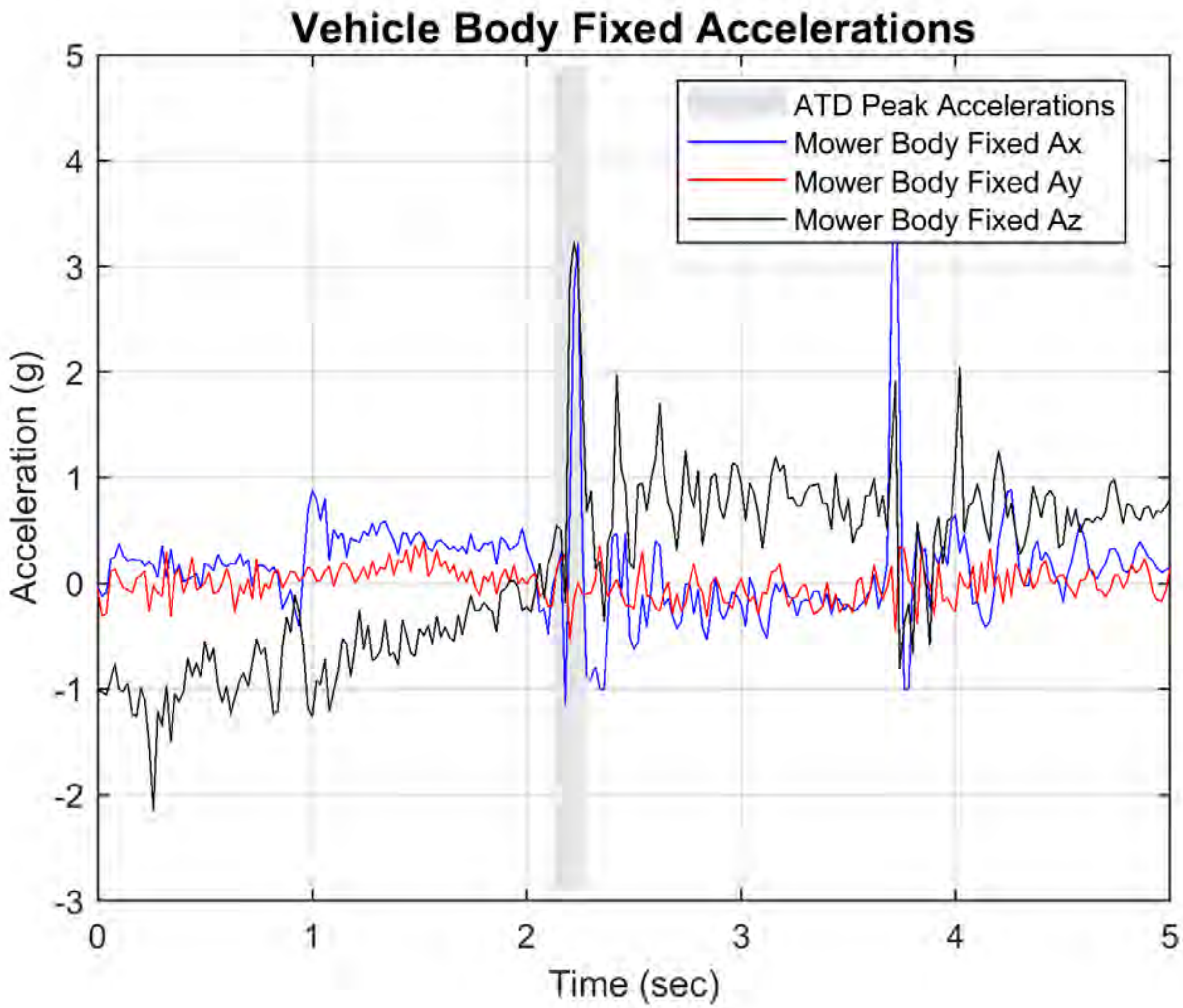
Zero-Turn Mower – Rearward Pitchover with ROPS



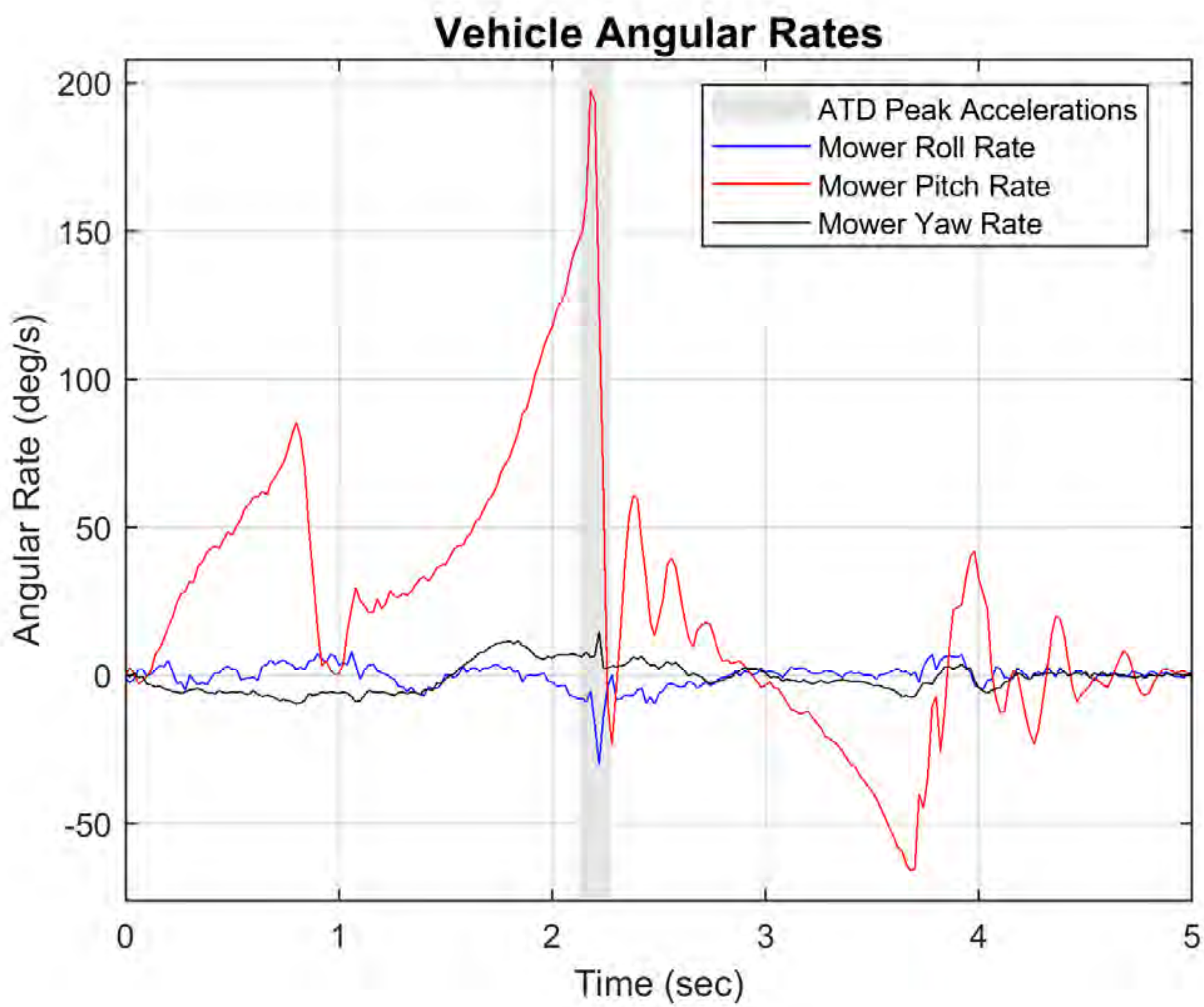
Zero-Turn Mower – Rearward Pitchover with ROPS



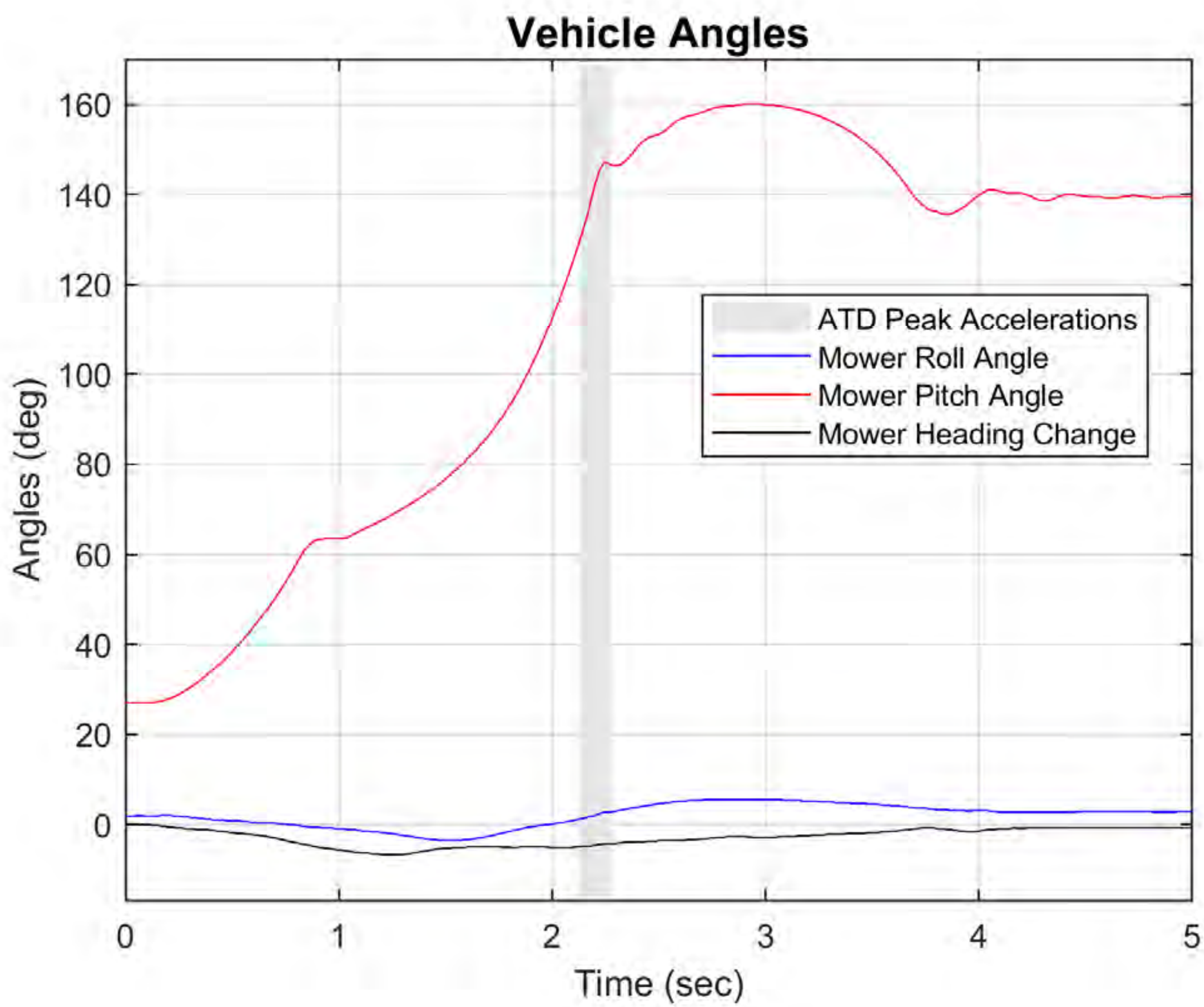
Zero-Turn Mower – Rearward Pitchover with ROPS



Zero-Turn Mower – Rearward Pitchover with ROPS



Zero-Turn Mower – Rearward Pitchover with ROPS



Zero-Turn Mower – Rearward Pitchover with ROPS

Test Instrumentation on Tractor Mower

RT1003 GPS/IMU and Safety Circuit Box
Mounted in Footwell of Vehicle

On-Vehicle Computer Box, 12V Battery, and Freewave Radio
Mounted on Board Fixed Beneath Mower Deck

Test Instrumentation on Zero-Turn Mower

On-Vehicle Computer Box, 12V Battery, and Safety Circuit Box Mounted in Footwell of Vehicle

RT1003 GPS/IMU (TOP) and Freewave Radio (BOTTOM) Mounted Beneath Mower Seat

Autonomous Control Component for Tractor Mower

Vehicle Brake On and Drive Disengaged
(Pedal Plate Connected to Electromagnet)

Vehicle Brake Off and Drive Engaged
(Pedal Plate Released from Electromagnet)

Test Setup for Tractor Mower

Front View for Lateral Rollover Test

Side View for Lateral Rollover Test

Test Setup for Tractor Mower

Rear View for Rearward Pitchover Test

Oblique View for Rearward Pitchover Test

Autonomous Control Components for Zero-Turn Mower

Right Side Lever Control Actuator

Left Side Lever Control Actuator

Test Setup for Zero Turn Mower

Front View for Quasi-Lateral Rollover Test

Side View for Quasi-Lateral Rollover Test

Test Setup for Zero-Turn Mower

Rear View for Rearward Pitchover Test

Side View for Rearward Pitchover Test

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

Table D.1: ATD Instrumentation

Transducer	Measurement	Range	Linearity
DTS 6DX Pro Sensor 2K-1500	Head X, Y and Z Accelerations	± 2,000 g	1% of Reading
	Head Roll, Pitch, and Yaw Rates	± 1,500 deg/s	1% of Reading
mg-sensor GmbH N6ALB11A	Upper Neck Forces F_x, F_y, and F_z	± 8.9 kN (± 2,000 lb)	0.5% FS
	Upper Neck Moments M_x, M_y, and M_z	± 283 Nm (± 209 ft-lb)	0.5% FS
Endevco 7264-2KTZ-2-360	Chest X, Y and Z Accelerations	± 2,000 g	1% of Reading

The ATD instrumentation package is self-contained inside the ATD. Prior to each use, the ATD instrumentation package was armed, readying it to start data collection as soon as one of two trigger levels was reached. For all 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:

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

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

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

Prior to computing the HIC values, the accelerations were filtered using a 1,000 Hz Butterworth low-pass filter. For each data run, HIC values were computed for time durations $(t_2 - t_1)$ of 15 milliseconds and 36 milliseconds. The HIC value is the maximum value of the calculation shown on the right side of Equation D.1, as the time range (with a duration of either 15 or 36 milliseconds) is swept across the entire time span of the event, from five seconds before the trigger to fifteen seconds after the trigger. These time range duration limits are commonly used, and they are denoted as HIC_{15} and HIC_{36}, respectively. For all of the 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 mowers 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

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

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

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

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 a mower 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.

Several methods for securing the hands of the ATD to the mower hand grips (steering wheel of the tractor mower and levers of the zero-turn mower) were considered, including using tape, Velcro, magnets, and cable ties. 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 mower 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 hand grip areas of the mowers. Figure D.3 shows the ATD hands secured to the steering wheel on the tractor mower and Figure D.4 shows the hands secured to the control levers on the zero-turn mower. These cable ties provide for a handhold strength of close to 80 lb. During the tip over events, the cable ties break when they experience enough force, and this is intended to represent when a human operator would release their handholds on the vehicle controls.

No information from actual mower tip over events with human drivers is available to indicate when a human driver might disengage or be thrown from the vehicle. During the rearward pitchover events for both vehicles, the rear of the ATD's buttocks maintained contact with the seat back to the point when the ATD's head struck the ground, even for the tests without ROPS structures or seat belts. Therefore, no other ATD secure system components were used during any of the rearward pitchover tests. However, during a preliminary rearward pitchover test, the lap seat belt rose above the ATD's pelvis and into the (non-human like) open area between the pelvis and lower abdomen of the ATD. To prevent this from happening in any of the official tests, a ½"

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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.

thick cable tie was loosely wrapped around one of the ATD's thighs and the seat belt (see Figure D.4). This cable tie did not interfere with how the ATD was secured to the mowers, it was installed simply to prevent the seat belt from rising into the open cavity between the ATV's pelvis and abdomen.

During the zero-turn mower quasi-lateral rollover event without ROPS structure or seat belt, the ATD's buttocks separated from the mower's seat when the mower roll angle was near 45 degrees. Also, the handhold cables broke near this time during the event. The ATD release from the mower seemed representative of how a human driver might release during this event, therefore no other ATD secure system components were used during the quasi-lateral rollovers of the zero-turn mower.

Additional ATD restraints were necessary to hold the ATD in place during the tractor style mower lateral rollover tests. During these tests the mower was driven on a side slope. To prevent the ATD from leaning too much toward the down-slope direction, a cable was connected between a Velcro loop around the ATD's neck to a release point, a hook attached to plate held by an electromagnet. Also, to keep the ATD from sliding sideways toward the downhill direction, a cable was connected between the left hip area of a climbing harness placed on the ATD to the same release point used for the neck cable. The neck cable and hip cable are both shown on Figure D.5. During tests with and without ROPS structure and seat belt, the electromagnet plate was programmatically released during the rollover event, when the mower roll angle reached 45 degrees. The left photo of Figure D.6 shows the plate connected to the electromagnet and the right photo shows the plate released. (The electromagnet used was the same model used the for clutch control of the tractor style mower, a 12V DC magnet with a pull force of 180 lb.)

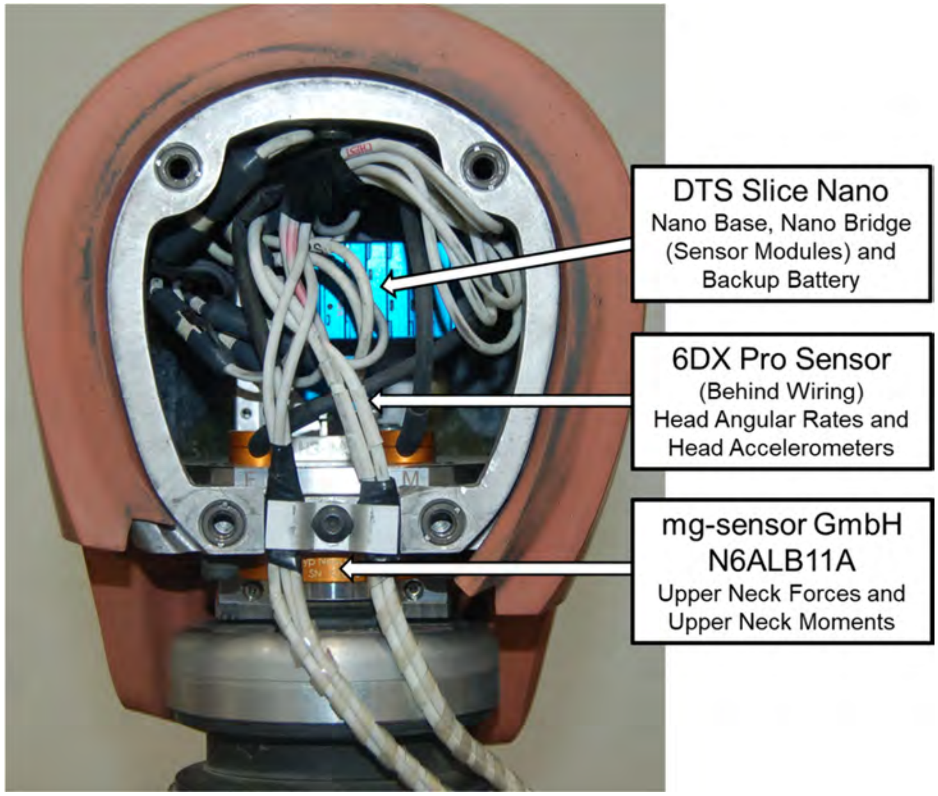

Figure D.1: Instrumentation in ATD Head

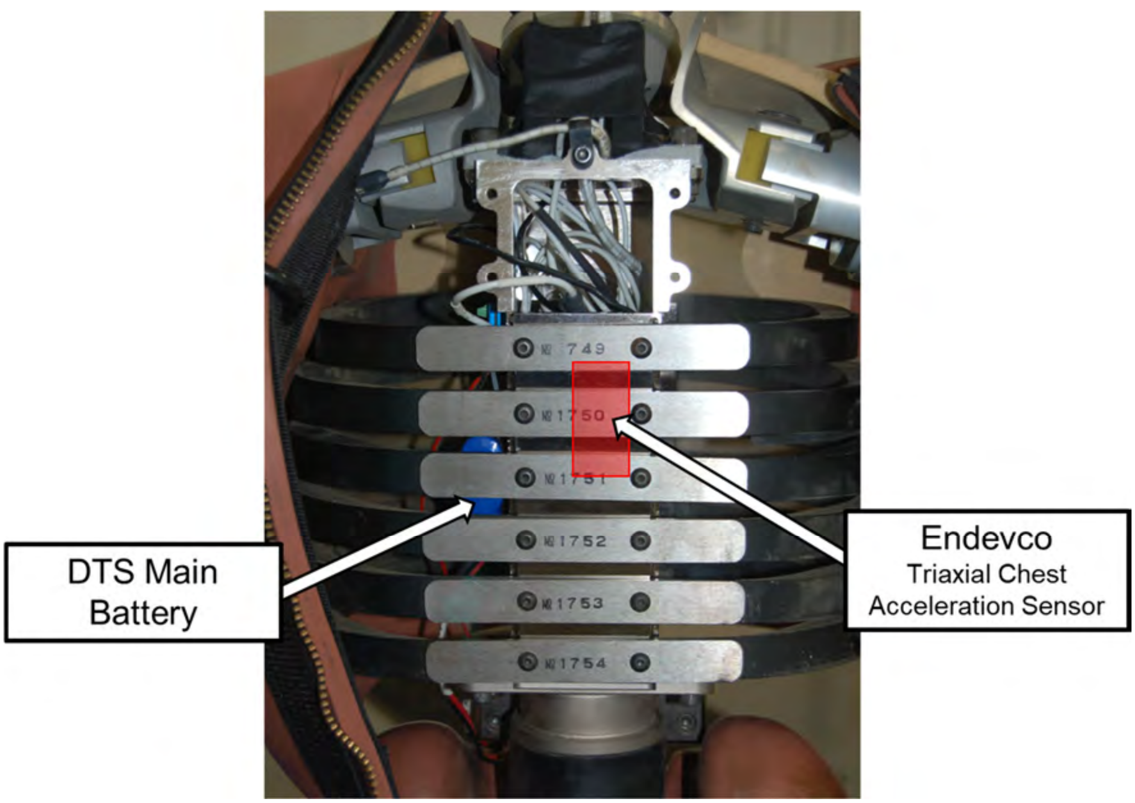

Figure D.2: Instrumentation in ATD Chest

ABOVE: Cable Ties for Handhold to Steering Wheel

RIGHT: Restraint System Securing ATD Position Prior to Lateral Rollover Test

Figure D.3: Handhold Cable Ties Used on Tractor Style Mower

Cable Ties for Handhold
to Control Levers

Cable Tie Loosely Connecting
ATD Thigh to Seat Belt
to Prevent Seat Belt from
Sliding into Cavity Between
ATD Pelvis and Chest

Figure D.4: Handhold and Thigh Cable Ties Used on Zero-Turn Mower

Restraint System
Secure Cable to ATD Neck

Restraint System
Secure Cable to ATD Left Hip (TOP)
and Across Lap (BOTTOM)

Figure D.5: Neck and Hip Restraint Cable Used on Tractor Style Mower

Restraint System Secure & Release Cables
Connected to Electromagnet Plate

Restraint System
Electromagnet Plate Released

Figure D.6: Electromagnet and Cable Release Plate Used on Tractor Style Mower