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CPSC Staff's[1] Statement on SEA Ltd.'s Report, "Vehicle Characteristics Measurements of Riding Mowers"

February 2023

The following contractor report titled, "Vehicle Characteristics Measurements of Riding Mowers," presents the results of research and testing conducted by SEA, Ltd. (SEA), under a CPSC contract.

SEA staff tested four residential riding mowers, comprising two tractor-style mowers and two zero-turn-style mowers. SEA took laboratory measurements using its Vehicle Inertia Measurement Facility (VIMF) and Tilt Table to find static properties, center of gravity, moments of inertia, and static roll-over resistance characteristics. SEA also tested the dynamic characteristics of the mowers with human drivers, starting with the ANSI/OPEI B71.1-2017 voluntary standard tests for dynamic turn stability and sudden traction control. These tests, conducted on a level asphalt surface, are designed to evaluate lateral roll-over resistance and rearward pitch-over resistance. In addition, SEA performed dynamic test maneuvers on the four riding mowers on sloped grass surfaces to evaluate lateral and rearward tip overs. The maneuvers developed by SEA may be useful for evaluating the feasibility and effectiveness of using roll-over protective structures (ROPS) on residential riding mowers.

This report will assist CPSC staff as they continue to work on potential standards for reducing the severity of roll-over and pitch-over hazards associated with residential riding lawn mowers.

Attachment

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

Vehicle Characteristics Measurements of Riding Mowers

Results from Tests on Four 2021 Model Year Vehicles

for:
Consumer Product Safety Commission

February 2023

S·E·A

Vehicle Dynamics Division
7001 Buffalo Parkway
Columbus, Ohio 43229

Vehicle Characteristics Measurements of Riding Mowers

Results from Tests on Four 2021 Model Year Vehicles

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

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1. OVERVIEW

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

This report covers work completed under Task Order 1 of contract 61320621D0001. Specific tasks for Task Order 1 include:

1. Review In-Depth Investigation (IDI) reports supplied by CPSC staff to determine scenarios involving mower overturn events.

2. Obtain and test four residential riding mowers, two tractor style mowers and two zero-turn style mowers.

3. Measure static metrics and properties (center-of-gravity height tests and tilt table tests) in two loading conditions for each test vehicle. The two loading conditions are:
    a. Curb weight
    b. Curb weight plus 95th percentile male

4. Design and construct safety outriggers for use in dynamic testing.

5. Conduct dynamic tests with a human driver to evaluate rollover resistance and vehicle handling. The load condition for the testing is the representative Curb weight plus 95th percentile male condition.

6. Conduct dynamic tests with a human test driver for each test vehicle.
    a. Recreate rollovers during turns and on sloped surfaces.
    b. Contractor recommended test maneuvers for the evaluation of rollover resistance.
    c. Develop other dynamic test maneuvers as required to achieve the objectives of the vehicle evaluation project.

The vehicles were evaluated using both laboratory measurements and dynamic tests. The laboratory measurements were made by SEA using their Vehicle Inertia Measurement Facility (VIMF) and Tilt Table. The dynamic tests were also performed by SEA, and they included maneuvers on SEA's asphalt vehicle dynamics test pads and grass-covered test areas.

American National Standard ANSI/OPEI B71.1[1] is a voluntary standard dealing with safety of pedestrian-controlled and ride-on mowers. This standard contains requirements for dynamic turn stability and sudden traction control tests for some versions of riding mowers. These tests are designed to evaluate the lateral tip-up resistance (rollover resistance) and rearward tip-up resistance (pitchover resistance) of vehicles. Therefore, versions of full speed, full steering input tests and sudden traction control tests on an asphalt test pad were performed on all four mowers.

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

In addition to the tests conducted on the flat asphalt test surface, tests were conducted on sloped grass surfaces. Test maneuvers to intentionally overturn the mowers were designed and conducted. The goal of these tests was to find a maneuver that would result in lateral tip-up (rollover) of the mowers and a different maneuver that would result in rearward tip-up (pitchover) of the mowers.

The mowers selected were not outfitted with ROPS, and ROPS were not offered as original equipment options for these mowers. The mowers selected included tractor and zero-turn models at both the small and large weight ranges of commercially available mowers. Table 1 contains the measured curb weights, measured maximum speeds, and tire specifications for the four mowers.

This report contains four main sections: Overview, Review of CPSC Mower Incidents, Laboratory Testing, and Dynamic Testing. There are also two appendices containing test results and one appendix containing photographs of test equipment.

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 Make	Deli Tire	Deli Tire
Tire Size	13X5.00-6 2 Ply	16X6.50-8 2 Ply
Tire Pressure (psi)	20	14
Vehicle B Large Tractor Mower	Curb Weight: 838.0 lb Maximum Speed: 5.96 mph	
	Front Tires	Rear Tires
Tire Make	Deli Tire	Deli Tire
Tire Size	16X6.5-3	23X10.5-12
Tire Pressure (psi)	14	10
Vehicle C Small Zero-Turn Mower	Curb Weight: 458.4 lb Maximum Speed: 6.75 mph	
	Front Tires	Rear Tires
Tire Make	Kenda	Kenda Super Turf
Tire Size	11X4-5	18X6.5-8
Tire Pressure (psi)	46	11
Vehicle D Large Zero-Turn Mower	Curb Weight: 582.2 lb Maximum Speed: 6.56 mph	
	Front Tires	Rear Tires
Tire Make	Kenda	Kenda Super Turf
Tire Size	13X5.00-6	20X9.00-10
Tire Pressure (psi)	15	10

2. REVIEW OF CPSC MOWER INCIDENTS

CPSC provided a list of about 600 mower incidents, most of them overturn events. In this list about 110 incidents had some data on mower types. The following review is based on 55 of these incidents that had some level of detail in what happened in the incident. These included In-Depth Incident reports from CPSC, medical examiners' reports (always fatalities), news reports, and consumer reports. There were 14 In-Depth Incident reports that contain considerable detail, including photographs. While the data reviewed was only a small subset of all the incidents involving mowers, there were a considerable number of accidents reviewed, and a considerable number of fatalities.

No statistical analysis was done, but trends were observed. Demographically, it was noted that a high proportion of reported incidents happened in the southeast quadrant of the US, and that a high proportional of accidents involved men over age 60. Other than these demographic trends, the following observations were made.

Many incidents involved mechanical issues, including broken welds, other broken parts, loose seats, and linkages not working properly. These were often related to aggressive accelerations, which caused the front wheels to lift and sometimes involved the mower tipping over backwards while on an upslope. A backward tip was involved in many of the incidents. Based on this, the current study included exploring maneuvers that would induce both rollovers (to the side) and pitchovers/tip overs (to the rear).

Some of the incidents reviewed involved operator error, such as when a foot slipped off the brake and engaged the accelerator. In some cases (including the small tractor that was tested by SEA) engine speed is set by a hand lever, then the forward motion of the tractor is controlled by a single foot lever. With the foot lever pushed down the brake is applied, with the pedal partially released the brake is released and the clutch is not engaged, and with the pedal fully released the clutch is engaged and forward motion begins. If the operator's foot slips off the pedal the vehicle goes from full braking to full forward immediately. Note that a mower is not like a highway vehicle, the engine is meant to run at constant speed for a long time, while the speed of the mower is controlled independently of the engine speed.

Some of the accidents involved the mower getting too close to a very steep slope or losing control near a very steep slope, such that once the mower went past a certain point, rollover was unavoidable. Often these incidents were near water, near the edge of a pond or a stream embankment. With or without water, fatalities occurred in these incidents. When water is involved, the operator is sometimes pinned by the weight of the vehicle under the water. A Roll-Over Protective Structure (ROPS) could provide survival space in incidents like this.

It was observed that 11 of the In-Depth Incident reports involved overturn events, and 10 of these 11 either had no ROPS or a ROPS that was folded down. Seven of these 10 involved fatalities. The one incident with a ROPS that was upright was also a fatality, when the unbelted operator was pinned under water by the ROPS. Without a ROPS, he might have been pinned instead by the weight of the vehicle.

None of the incidents studied, including the larger set of 55 incidents, involved contact with the blades of the mower. Mowers typically have a shut off switch such that when the operator leaves the seat the blades stop spinning, but in several incidents the operator was pinned against the seat, preventing the blades from stopping. The operator did not contact the blades in these incidents.

Many of the accidents involved a combination of factors, such as hitting holes or bumps, hitting obstacles, and going downhill and turning at the same time (possibly while also hitting items). Many of the incidents that included photographs appeared to have happened on slopes that were not very steep.

3. LABORATORY TESTING

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

3.1 Vehicle Loading Conditions

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

1. **Curb (Curb Weight)**
   This loading condition is the curb weight of the vehicle, the as-received vehicle with no driver or ballast load and with full fuel and fluids.

2. **Driver (Curb Weight plus 95th Percentile Male)**
   This loading condition is specified to be the vehicle curb condition plus a Hybrid III, 95th percentile, anthropometric test device (ATD) driver. The nominal weight of a 95th percentile ATD is 100 kg (220 lb). For tests conducted in this loading condition, the ATD was seated on each vehicle with its feet on the footrests and its hands attached to the steering wheel (for the tractor style mowers) or the hand tillers (for the zero-turn mowers). The vehicle weight for this loading is nominally 100 kg more than the vehicle curb weight.

The VIMF and Tilt Table tests were conducted in both loading conditions. The dynamic tests were conducted in the Driver plus Instrumentation Loading condition, which is described in the next section.

3.2 Vehicle Inertia Measurement Facility (VIMF) Tests

Laboratory measurements of vehicle weight (including the four corner weights); vehicle center-of-gravity (CG) position (longitudinal, lateral, and vertical (CG height)); vehicle pitch, roll, and yaw moments of inertia; and roll/yaw product of inertia were made by SEA using their Vehicle Inertia Measurement Facility (VIMF).[2] Measurements of front track width, rear track width, and wheelbase were also made.

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.

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

[2] *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.

In addition to the direct measurements provided by the VIMF, two other metrics that are used to characterize vehicle lateral rollover resistance were computed, namely, the Static Stability Factor (SSF) and the lateral stability coefficient (K_{ST}).

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

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

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

K_{ST} is similar to SSF in that it represents the acceleration in g's at which rollover begins in the most simplified rollover analysis of a vehicle with different front and rear track widths represented by a rigid body without suspension movement or tire deflections. For vehicles with equal front and rear track widths, K_{ST} and SSF are equal. K_{ST} is given by:

$$K_{ST} = \frac{L \times T_R + L_{CG-REAR} \times (T_F - T_R)}{2 \times L \times H_{CG}}$$

where: L is the Vehicle Wheelbase,
T_F is the Front Track Width,
T_R is the Rear Track Width, and
$L_{CG\text{-}REAR}$ is the Longitudinal Distance from the Rear Axle to the CG, and
H_{CG} is the Vehicle CG Height.

Two other metrics that are used to characterize vehicle longitudinal tip-up resistance were also computed, namely, the Forward SSF and the Rearward SSF.

$$Forward\ SSF = \frac{L_{CG-FRONT}}{H_{CG}}$$

$$Rearward\ SSF = \frac{L_{CG-REAR}}{H_{CG}}$$

where: $L_{CG\text{-}FRONT}$ is the Longitudinal Distance from the Front Axle to the CG,
$L_{CG\text{-}REAR}$ is the Longitudinal Distance from the Rear Axle to the CG, and
H_{CG} is the Vehicle CG Height.

Appendix A contains results from all the VIMF tests conducted on all four vehicles in both loading conditions.

3.3 Tilt Table Tests

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

Tilt Table tests were conducted in both loading conditions for all four vehicles, and tilts were conducted in four directions: left-side leading, right-side leading, front-end leading, and rear-end leading. Page 1 of Appendix C shows photographs of the small zero-turn mower in a lateral, left-side leading tilt and the large zero-turn mower in a longitudinal, rear-end leading tilt.

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

The front wheels of the zero-turn mowers are on casters that rotate freely when the wheels are exposed to lateral forces. This is a design feature of most, if not all, zero-turn mowers with tiller steering controls. To facilitate conducting the lateral tilt table tests on the two zero-turn mowers, a single span of all-thread rod was inserted as replacements for the front wheel axles (this can be seen on the photo of the small zero-turn mower on the left side of Page 1 of Appendix C). Inserting the all-thread rod prevented the front wheels from steering during the tilt table tests conducted on the zero-turn mowers.

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

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

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

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

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

$$\text{TTR} = \tan\left(\text{TTA}\right)$$

The small tractor mower (Vehicle A) was the first vehicle tested on the tilt table. In the Curb loading condition, Vehicle A did not experience a two wheel lift in front end leading longitudinal tilts even at the extreme angle range of the SEA tilt table, which is 60°. In the Curb plus 95% Male loading condition, the forward TTA for Vehicle A was over 56°. The Forward SSFs of all three of the other mowers in both loading conditions are significantly greater than the Forward SSF of Vehicle A in the Curb plus 95% Male loading condition. Given this information, no front end leading tilt table tests were performed on Vehicles B, C, and D in either loading condition, since these tests would not have resulted in two wheel lift even at 60° of tilt angle.

For rear end leading tilts, the angle at which two-wheel lift occurs is referred to here as Rearward Tilt Table Angle (RTTA). In addition to measuring RTTA, these tilt table test results provide measures of a vehicle's rearward pitch-over resistance, a metric referred to here as Rearward Tilt Table Ratio (RTTR). RTTR is computed using:

$$\text{RTTR} = \tan\left(\text{RTTA}\right)$$

Appendix A contains results from all tilt table tests conducted on all four vehicles in both loading conditions.

3.4 Discussion of Laboratory Test Results

Appendix A contains tabular results of the laboratory measurements. There are eight pages of results, two pages for each vehicle. The first page for each vehicle contains a table of results from the VIMF tests and the second page for each vehicle contains a table of results from the Tilt Table tests.

The first page for each vehicle contains measurements for both laboratory loading conditions related to the mass (weight), track width, wheelbase, center-of-gravity location, inertia properties, and static rollover/ pitch-over propensity metrics, based on measurements made using the VIMF. The first page for each vehicle also contains a column listing the weight properties of the vehicle in the Driver plus Instrumentation loading condition (the loading condition used during dynamic testing).

The second page of tabular results for each vehicle lists the tilt table angles and tilt table ratios for the lateral and longitudinal rear Tilt Table tests conducted. These tables also list which wheel lifted first for each Tilt Table test; either Front or Rear for the lateral tilts and either Right, Left, or Equal (indicating simultaneous right and left wheel lift) for the longitudinal rear tilts.

Lateral and rearward bar graphs of SSF, TTR, and TTA are shown in Figure 1, Figure 2, and Figure 3, respectively. These figures contain results from tests done in the driver loading condition. In general, the lateral and rearward SSF, TTR, and TTA values are higher for the large tractor and zero-turn large mowers than for the small tractor and zero-turn small mowers.

American National Standard ANSI/OPEI B71.1[3] is a voluntary standard dealing with safety of pedestrian-controlled and ride-on mowers. The mowers tested in this study fall under the purview of portions of this standard. For lateral tilt table tests, the standard has a test acceptance criterion stating, "The machine wheels shall not lift off before 25° is reached." In this study, which used a 220 lb 95% male driver, the measured Lateral TTA for the Small Tractor (Vehicle A) is 24.8°. Had a lighter driver ballast of 200 lb been used (the driver ballast specified in ANSI/OPEI B71.1) the measured Lateral TTA for Vehicle A would likely be at or above 25°. The Large Tractor (Vehicle B), the Small Zero-Turn (Vehicle C), and the Large Zero-Turn (Vehicle D) all had measured Lateral TTAs of over 30°.

For rearward tilt table tests, the standard has a test acceptance criterion stating, "The machine wheels shall not lift off before 30° is reached." In this study, all four mowers had measured Rearward TTAs of over 30°.

Unlike passenger vehicles and off-road vehicles like All-Terrain Vehicles (ATVs) and Recreational Off-Highway Vehicles (ROVs), the riding mowers tested do not have compliant suspensions with springs and shock absorbers. Since the mowers have relatively rigid suspensions, their measured Lateral and Rearward TTAs are good indicators of their fundamental tip-up resistance. As such, knowledge of these values helped guide the design of the dynamic tests developed to intentionally overturn the mowers.

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

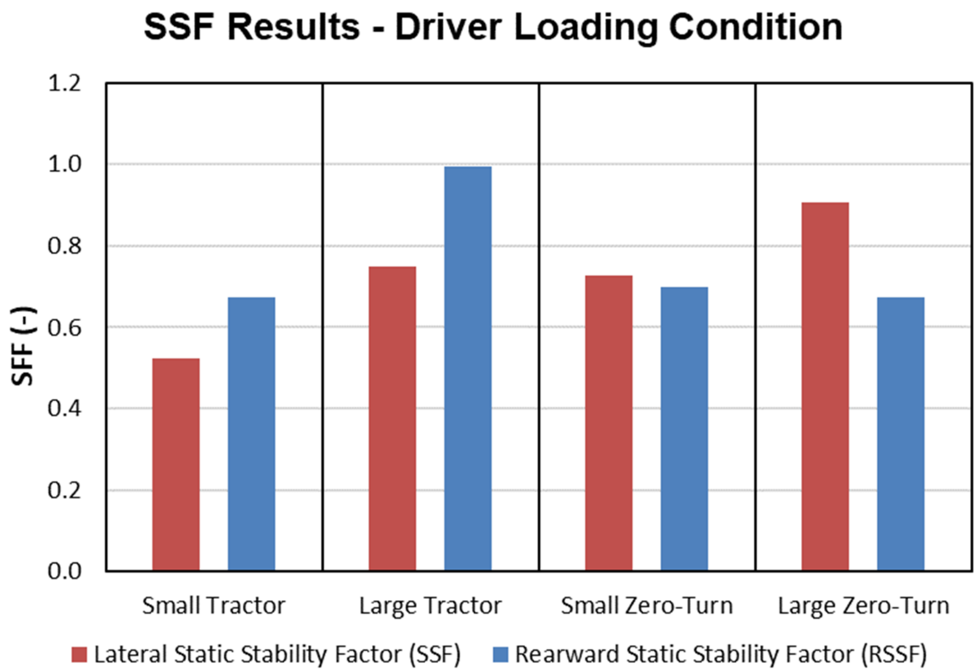


Figure 1. Lateral SSF and Rearward SSF in 95th% Male Driver Loading Condition

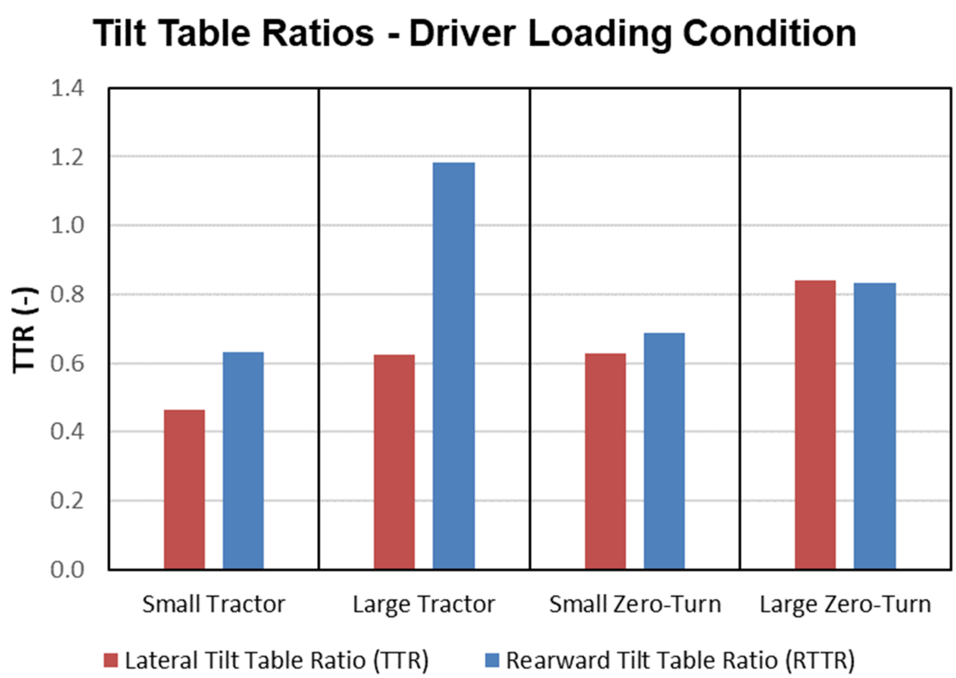


Figure 2. Lateral TTR and Rearward TTR in 95th% Male Driver Loading Condition

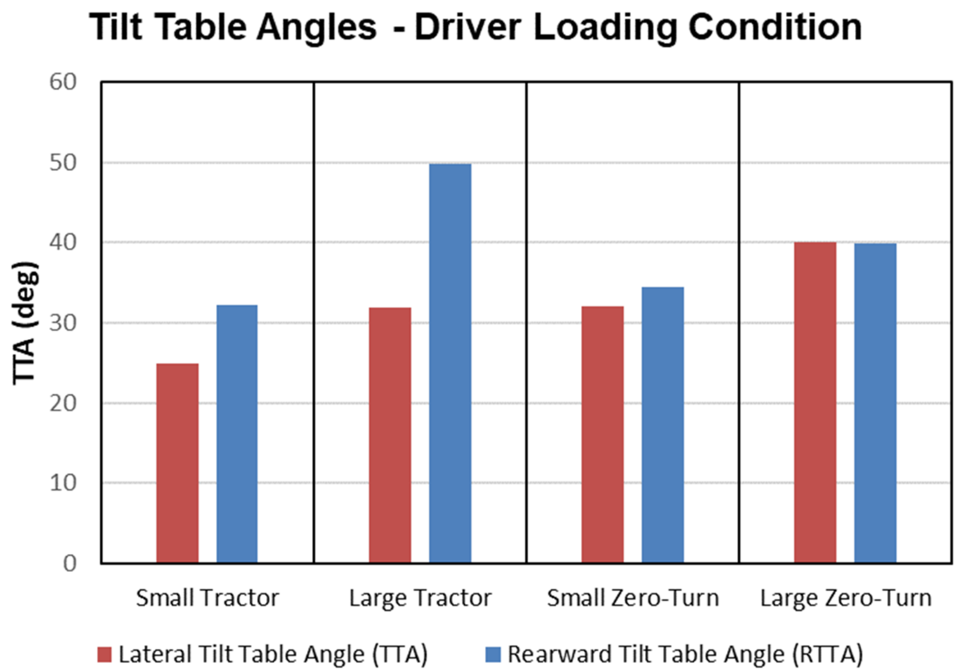


Figure 3. Lateral TTA and Rearward TTA in 95th% Male Driver Loading Condition

4. DYNAMIC TESTING

This section describes the dynamic tests conducted on numerous dates between May 26, 2022 and July 20, 2022. All four mowers were tested on SEA's asphalt vehicle dynamics test pad and grass-covered sloped areas. One of the sloped areas is a dedicated grass-covered test hill comprised of four sides with nominal slopes of 15°, 20°, 25°, and 30°. The grass areas contain mostly fescue grass mowed weekly to about three inches in height.

This section is divided into four parts: one covering the vehicle loading condition used for the dynamic tests, one covering the instrumentation used during the dynamic tests, one covering the dynamic tests and test results, and a summary.

4.1 Vehicle Loading Condition

The loading condition used for the dynamic testing is the Driver plus Instrumentation Loading condition. This loading condition is intended to represent the loading of a 95% male driver (weighing nominally 220 lb). Pages 2-5 of Appendix C contain front view and side view photographs of the four mowers in their as-tested configurations.

Driver plus Instrumentation Loading is the vehicle curb weight plus the weight of the test driver, test instrumentation and equipment, and safety outriggers. Table 2 lists the nominal weights for these items. The total nominal weight of the Driver plus Instrumentation, 258.9 lb, exceeds the target weight of 220 lb. If only one set of outriggers (either the rear outriggers or the lateral outriggers) had been used the Driver plus Instrumentation weight would have been kept below 220 lb. However, both sets of outriggers were used for all dynamic tests to protect the human driver.

Page 6 of Appendix C shows the electronics box containing the data acquisition system mounted on top of the aluminum framework that supports the adjustable height, rear safety outriggers (designed to prevent rearward pitchovers). The electronics box and rear outrigger assembly can be seen mounted on all four mowers on Pages 2-5 of Appendix C.

The lateral outriggers can also be seen mounted on all four mowers on Pages 2-5 of Appendix C. The lateral outriggers are constructed of aluminum tubes and plates, and they have the same size wheels and tires as the rear outriggers. The lateral outriggers have features for adjusting their height and width (length). For all four mowers, the lateral outriggers were mounted to the floorboard/footwell area of each vehicle directly in front of the driver's seat.

The position of 12V battery used to power the electronics box and the RT1003 GPS/IMU (Global Positioning System/Inertia Measurement Unit) can be seen on Page 7 of Appendix C. The photograph on Page 7 shows the equipment mounted on the large zero-turn mower. These items were placed generally in the same locations on the other three mowers tested, in the footwell areas of the vehicles. A thin sheet-metal guard (painted black) was installed over the red RT1003 to protect it from getting struck by the driver's feet.

4.2 Test Instrumentation

The on-vehicle instrumentation used during the dynamic testing is listed in Table 3. As mentioned, the GPS/IMU RT1003 was mounted in the footwell area of each vehicle. For all four vehicles tested, the longitudinal, lateral, and vertical offsets from the center of the RT1003 to the actual vehicle CG location were measured and entered into the RT1003 system software. This information was used to translate the measured quantities to those at the CG of the vehicle.

Page 8 of Appendix C shows a linear position transducer mounted to measure steering column rotation on the small tractor style mower. For both tractor style mowers (Vehicles A and B), the handwheel steering angle was calibrated to the position recorded by the linear transducer. This calibration provided the measurement of steering wheel angle (Steer Angle) used on some of the graphs of results for the tractor mowers.

Page 9 of Appendix C shows a linear position transducer mounted to measure steering tiller stroke (displacement) on the right side of the small zero-turn mower. Another linear position transducer was used to measure stroke on the left side tiller. For both zero-turn mowers (Vehicles C and D), the left side and right side tiller strokes were calibrated to the position recorded by the left side and right side linear transducers. The (Left and Right) Tiller Stroke plots shown in the graphical results are calibrated to be 100% when the tiller is pushed fully forward and 0% when the tiller is at its zero or released position.

Table 2: Driver Plus Instrumentation Loading	
Component	**Nominal Weight (lb)**
Weight of Test Driver	165.0
Rear Outrigger and Electronics Box Containing Data Acquisition System	37.7
Lateral Outrigger	38.1
12V Battery	6.5
RT1003 GPS/IMU and Protective Guard	2.9
Misc. Cabling, Sensors, and Antennae	8.7
Total Driver plus Instrumentation Weight	**258.9**

Table 3: Instrumentation Used During Dynamic Testing			
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
Unimeasure Linear Position Transducers LX-PA-20	String Transducers used to Measure Steering Column Rotation for Tractor Mowers and Tiller Displacement for Zero-Turn Mowers	20 in (500 mm)	0.1 in (2.5 mm)

4.3 Dynamic Tests and Test Results

The results from the dynamic tests are contained in Appendix B. The following sections describe the tests and results for each of the four mowers.

4.3.1 Vehicle A – Small Tractor Style Mower

Results from tests conducted on Vehicle A are on Pages 1-11 of Appendix B. As mentioned in the introduction, ANSI/OPEI B71.1 contains dynamic turn stability tests and sudden traction control tests that are applicable to some mowers (tiller-steer mowers are exempt from these two tests). The dynamic turn stability test is a full speed, full steering test designed to evaluate the tip-up resistance of the mower. The test procedure is to drive at full speed along a straight line and gradually turn the hand-operated steering controls to the extent of their travel. The tests are conducted in both the right and left turning directions. Test acceptance for the dynamic turn stability test is that lift-off of the wheels shall not exceed 5°.

Pages 1 and 2 of Appendix B contain results from the dynamic turn stability tests using gradual steering on Vehicle A. Page 1 shows graphs of Steer Angle, Lateral Acceleration (vehicle lateral acceleration in the road plane), Speed, Roll Angle, and Yaw Rate. For these time domain graphs, time equal to zero seconds is specified to be when the magnitude of the steering input is 40°. Page 2 shows the paths of the maneuvers. For these graphs, the origin of the plots shown (zero East and zero North) is specified to be one second before time equal to zero seconds. Vehicle A did not have any wheel lift during these dynamic turn stability tests, and the maximum roll angle magnitudes of the vehicle are only slightly above 2°. The mean value of the steady lateral acceleration magnitudes in both turn directions are close to 0.38 g. This lateral acceleration level is below Vehicle A's lateral Tilt Table Ratio of 0.46.

Since one of the objectives of this study was to investigate maneuvers that could lead to lateral tip-ups (rollovers), the dynamic turn stability tests were run using rapid steering input in an attempt to generate greater lateral acceleration. Pages 3 and 4 of Appendix B contain results from the dynamic turn stability tests using rapid steering. The rapid steering caused a brief drop in vehicle speed near 0.5 seconds, but otherwise the steady-state vehicle responses are similar to the tests conducted using gradual steering input.

The ANSI/OPEI B71.1 sudden traction control test (STCT) states: "The test shall be conducted with the machine set for maximum ground speed and shall be conducted in forward travel. With the machine positioned to travel in a straight line, the traction drive shall be engaged by suddenly releasing the foot operated clutch control. If possible, this should be done by sliding the foot sideways off of the foot operated clutch and allowing the clutch to engage quickly." This is the procedure that was used to conduct STCTs on Vehicle A. Test acceptance for the sudden traction control test is that lift-off of the wheels shall not exceed 10° or the vehicle has a positive stop that will prevent the vehicle from tipping more than 20°.

Page 5 of Appendix B contains results from the STCT conducted on Vehicle A on the SEA asphalt test pad. Graphs of Steer Angle, Body Ax (body fixed longitudinal acceleration), Body Az (body fixed vertical acceleration), Speed, Pitch Angle, and Pitch Rate are provided. For the STCT time domain graphs, time equal to zero seconds is specified to be when the vehicle speed reaches 0.5 mph. Vehicle A did not experience any wheel lift during the STCT conducted on the test pad. The peak pitch angle is less than 2°.

To find a maneuver that would result in a rearward tip up (pitchover), progressively more severe sudden traction control tests were conducted on the dedicated grass-covered test hill comprised of four sides with nominal slopes of 15°, 20°, 25°, and 30°. Page 6 of Appendix B shows the results for the Vehicle A STCT conducted on the 15° upslope. During this test, the vehicle drove forward, and the pitch angle increased less than a few degrees when sudden traction was engaged. Likewise, during the test conducted on the 20° upslope the pitch angle increased less than a few degrees, as shown on Page 7. When the STCT was conducted on the 25° upslope, Vehicle A did experience tip up onto the rear outriggers. Page 8 contains graphical results from this test and Page 9 contains a video frame showing the rear outrigger contact. The rearward Tilt Table Angle for Vehicle A is 32.3°. Once this angle was exceeded during the test on the 25° slope, the vehicle tipped up onto the outriggers and maintained a pitch angle near 38-40°. Without the rear outriggers this test would have likely resulted in a rearward pitchover of the vehicle.

To find a maneuver that would result in a lateral tip-up event (rollover), numerous maneuvers were evaluated by driving the tractor style mowers on various cross slopes and down slopes while steering rapidly. None of these maneuvers resulted in lateral tip-up event. During rapid turns on cross slopes and downslopes the steered front tires would plough out, and the vehicles would travel along relatively straight paths and not generate high lateral accelerations that would lead to tip-up events. During other non-rapid steering maneuvers on cross slopes, the high side rear wheel would lift and spin freely, and the vehicle speed would drop to zero because of the rear open differential, which limits power to the rear drive wheels based on the wheel with the lowest amount of grip.

Ultimately a maneuver that involved driving onto a ramp on a cross slope was deemed to be a good maneuver that would result in lateral tip up and that would be reproducible. The 20° grass-covered slope was used as the cross slope, and a 12-inch wide, 7-inch-tall wooden ramp topped with anti-slip tape (profile dimensions shown on Figure 4) was used. The graphical results from this test are shown on Page 10, and video images showing the approach to the ramp and the two-wheel lift outcome from this test are on Page 11.

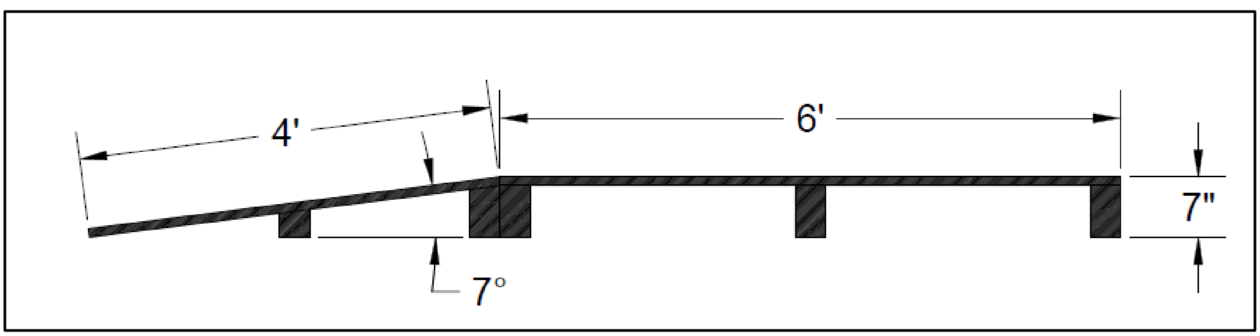


Figure 4: Ramp Used for Vehicle A Lateral Tip-up on 20° Cross Slope

This test started with the vehicle stopped off the cross slope (at the bottom of the hill). The driver drove the vehicle onto the cross slope and then drove the left side tires onto the ramp. Time zero is when the vehicle speed reached 0.5 mph. The engine speed was set to 75% full throttle for this test. The driver was driving on the cross slope and approaching the ramp between about 2.5 to 4.0 seconds, when the roll angle was near 20°. After 4.0 seconds the driver drove onto the ramp, the vehicle tipped up laterally onto the outriggers, and the vehicle came to a stop before 7.0 seconds with the rear left wheel spinning. The lateral TTA for Vehicle A is 24.8°, so after the roll angle exceeded this level, the tip up onto the outriggers occurred. Without the lateral outriggers this test would have likely resulted in a lateral rollover of the vehicle.

4.3.2 Vehicle B – Large Tractor Style Mower

Results from tests conducted on Vehicle B are on Pages 12-24 of Appendix B. Pages 12 and 13 contain results from the dynamic turn stability tests using gradual steering and Pages 14 and 15 for tests using rapid steering. No wheel lift occurred during any of the gradual or rapid steering tests, the maximum roll angle magnitudes are less than 2.5°, and the steady-state lateral acceleration peak magnitudes are in the range of 0.4 g. This lateral acceleration level is well below Vehicle B's lateral Tilt Table Ratio of 0.62.

Vehicle B has a hydrostatic transmission and requires that a foot pedal be depressed to engage the clutch and generate forward speed. Releasing the foot pedal releases the clutch and forward drive. Mowers with this type of transmission and pedal arrangement are exempt from the ANSI/OPEI B71.1 sudden traction control standard test, since sliding the foot sideways off of the foot operated clutch disables forward motion. For Vehicle B, a surrogate sudden traction control test (STCT) procedure was used. The STCTs for Vehicle B involved having the driver rapidly depress the forward foot pedal to generate sudden traction (and sudden forward motion).

Results from the surrogate STCT conducted on Vehicle B on the test pad are on Page 16. Vehicle B did not experience any wheel lift during the STCT conducted on the test pad. The peak pitch angle is less than 2°. Page 17 shows the results for the Vehicle B STCT conducted on the 15° upslope. During this test, the vehicle drove forward, and the pitch angle fluctuated about its starting value near 15°. STCTs conducted on the 20°, 25°, and 30° grass upslopes are shown on Pages 18, 19, and 20, respectively. In all three of these tests the drive torque on the rear wheels was high enough for the rear tires to lose traction resulting in the mower essentially staying in place (or sliding somewhat rearward) with the rear wheels spinning. The pitch angles did not vary much from their starting angles during these three tests.

Another STCT on the 30° grass upslope was conducted, this time with the rear wheels on high friction aluminum plates (with their top surface covered with marine grade safety walk paint). Graphical results from this test are on Page 21 and a video frame showing the vehicle near its highest pitch angle (near 40°) is shown on Page 22. On the high friction surface, the front wheels did lift, and a maximum pitch angle near 40° occurred about 1.5 seconds after the sudden traction was applied. Soon after the peak in pitch angle, the front of the vehicle dropped back to the sloped surface and the driver released the forward pedal. Vehicle B has a rearward TTA of 49.8°. Thus, even this STCT conducted on a high friction surface resulted in a pitch angle that is almost 10° below a pitch angle required to cause a rearward pitchover of this vehicle. Vehicle B has an extremely high rearward pitchover resistance, and no further attempts were made to demonstrate a situation that would result in rearward pitchover of this vehicle.

The lateral tip-up (rollover) maneuver for Vehicle B also used the 20° grass-covered slope as the cross slope, and in this case a 24-inch wide, 11½ inch-tall wooden ramp topped with anti-slip tape (profile dimensions shown on Figure 5) was used. The graphical results from this test are shown on Page 23, and video images showing the approach to the ramp and the two-wheel lift outcome from this test are on Page 24.

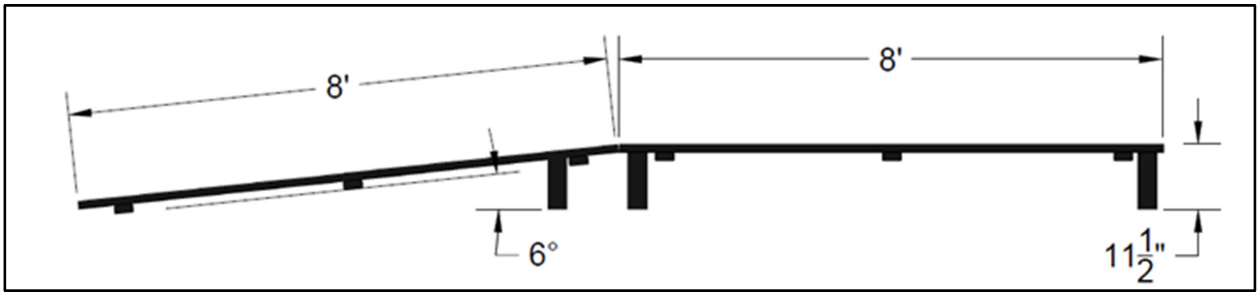


Figure 5: Ramp Used for Vehicle B Lateral Tip-up on 20° Cross Slope

This test started with the vehicle stopped off the cross slope (at the bottom of the hill). The driver drove the vehicle onto the cross slope and then drove the left side tires onto the ramp. Time zero is when the vehicle speed reached 0.5 mph. The engine speed was set to 75% full throttle for this test. The driver was driving on the cross slope and approaching the ramp between about 4.0 to 5.0 seconds, when the roll angle was near 20°. After 5.0 seconds the driver drove onto the ramp, the vehicle tipped up laterally and the mower deck acted like an outrigger by limiting further roll beyond about 40°. The vehicle came to a stop at 7.5 seconds with the rear left wheel spinning. The lateral TTA for Vehicle B is 32.0°, so after the roll angle exceeded this level, the tip up onto the mower deck occurred. Without the mower deck halting roll, this test would have likely resulted in a lateral rollover of the vehicle. However, with the deck in place Vehicle B has a high rollover resistance, and no further attempts were made to demonstrate a situation that would result in lateral rollover of this vehicle.

4.3.3 Vehicle C – Small Zero-Turn Mower

Forward motion of a zero-turn mower with tiller steering controls is achieved by pushing both the right and left tillers forward, and reverse motion is achieved pulling both tillers rearward. Zero-turn mowers with tillers are also turned using tillers. The position of right tiller controls the right rear motor drive the left tiller the left rear motor drive. Moving the tillers to different positions generates different rear wheel drive speeds, and this differential drive feature steers the mower. For example, if the left tiller is moved forward and the right tiller is moved less forward (or rearward), the mower will turn to the right.

Zero-turn mowers are exempt from both the ANSI/OPEI B71.1 dynamic turn stability standard test and the sudden traction control standard test. Maximum speed for zero-turn mowers with tiller controls is only sustained when both tillers are fully forward. Once a turn is made in either direction, the mower speed decreases. Nonetheless, numerous maximum initial speed maneuvers were conducted on the asphalt test pad using various tiller steering inputs to evaluate the level ground lateral tip-up resistance of these vehicles. None of these evaluation maneuvers resulted in any wheel lift.

A surrogate dynamic turn stability test was used to evaluate the lateral tip-up resistance of the two zero-turn mowers. The procedure used was to drive the mower at full speed along a straight path and then release the right tiller (so it would return to its neutral, zero drive position) causing the mower to turn to the right. This test was repeated in the left turn direction, by traveling at full speed and releasing the left tiller. Based on the above-mentioned exploratory maneuvers conducted, this surrogate dynamic turn stability maneuver is thought to be a good maneuver for generating maximum lateral acceleration of a zero-turn mower on flat ground. Turning by pulling one tiller full rearward generates a tighter turning path, but this further reduces the speed of the mower, and the lateral acceleration is not greater than in the surrogate maneuver. Turning by pulling a tiller back less than the full release position results in less speed decrease, but the turning path is larger, and the lateral acceleration is also not greater than in the surrogate maneuver.

Pages 25 and 26 of Appendix B contain results from the surrogate dynamic turn stability test for Vehicle C, the small zero-turn mower. Time zero on the time domain plots is when the yaw rate magnitude is 20 deg/sec. The plots on Page 25 are the same as the previous dynamic turn stability plots except that the previous Steer Angle plot is now replaced with two plots containing Left Tiller Stroke and Right Tiller Stroke. A 100% stroke is when the tiller is fully forward, and a stroke of 0% is when the tiller is in its neutral position. After a tiller is released, the vehicle speed drops from the maximum test speed. No wheel lift occurred during either of these tests, the maximum roll angle magnitudes are less than 2.5°, and the mean value of the peak lateral acceleration magnitude in both tests is in the range of 0.38 g. This level lateral acceleration is well below Vehicle C's lateral Tilt Table Ratio of 0.63.

The surrogate STCT maneuver used for the zero-turn mowers involved simultaneously and rapidly pushing both tillers forward. These surrogate tests were conducted to evaluate the rearward tip-up resistance of the mowers. Results from the surrogate STCT conducted on Vehicle C on the test pad are on Page 27. The front wheels lifted by nearly 12 inches during the STCT conducted on the test pad, when the peak pitch angle was close to 15°. However, the wheel lift was short lived as the pitch angle returned to zero within one second. Notice that the driver held both tillers fully forward for a full second, until the front wheels returned to the test pad. The peak pitch angle of 15° is well below Vehicle C's rearward TTA of 34.5°.

Page 28 shows the results for the STCT conducted on the 15° upslope. The front wheels lifted, and the vehicle pitched to 37° as the vehicle drove forward. Even though the pitch angle briefly exceeded the rearward TTA of the vehicle, there was no outrigger contact during this test. Rather the dynamics of the maneuver were such that the front wheels returned to the ground as the vehicle drove up the slope.

The next STCT test was conducted on the 25° upslope (because the drive-on lateral ramp was set up on the 20° slope). When tested on the 25° upslope, Vehicle C did experience tip up onto the rear outriggers. Page 29 contains graphical results from this test and Page 30 contains a video frame showing the rear outrigger contact. The outriggers hit down hard as the vehicle pitched to over 45°. When the outriggers hit, the driver released the tillers and the front wheels returned to the ground and the vehicle stopped on the hill. Without the rear outriggers this test would have likely resulted in a rearward pitchover of the vehicle.

Numerous attempts were made to cause an intentional pure lateral (sideways on to the lateral outriggers) tip-up of the zero-turn mowers. This included using the same maneuver that was used for the tractor style mowers, which is driving onto a ramp on a cross slope. When one of the zero-turn mower front wheels gets onto the ramp, the other front wheel is on the slope below the wheel on the ramp. Since the front wheels are on casters, there is a strong tendency for the front of the vehicle to turn down the hill. Despite his best efforts, the driver was not able to drive the zero turn mowers far enough onto the ramp to generate lateral tip up. As the driver attempted to stay on the ramp, either one or both rear wheels would lose grip (either spin or slide), as the friction capacity of the rear wheels on the grass hill was not enough to prevent the vehicle from yawing front first down the hill.

Other attempts to find a lateral tip-up maneuver for the zero-turn mowers involved driving them on various cross slopes and down slopes while steering rapidly. None of these maneuvers resulted in lateral tip-up. The zero-turn mowers' tendency to yaw front first down the slopes was greater than the capacity of the rear wheels to turn the vehicle and keep it on a cross-slope path.

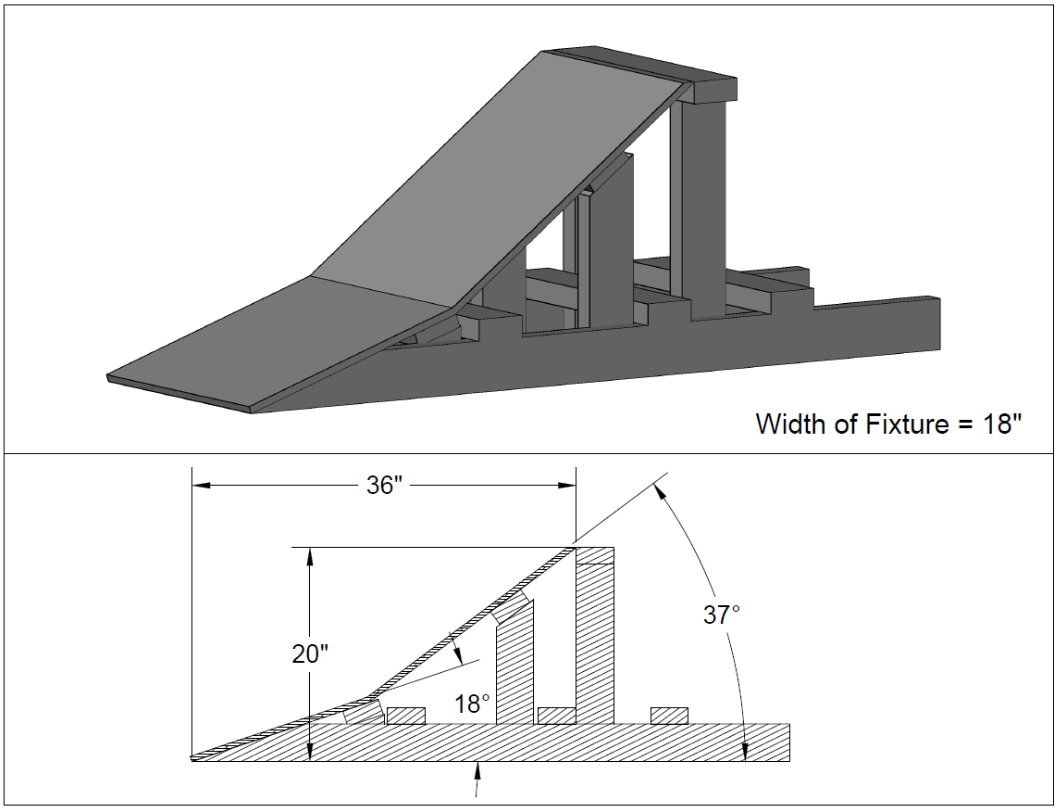


Figure 6: Ramp Used for Quasi-Lateral Tip-up Maneuver on 20° Upslope

The review of the CPSC incidents revealed that mower overturns sometime involve obstacles that contribute to or cause the overturn event. Obstacles that could potentially contribute to a mower overturn event include bumps or holes in the terrain, tree roots or stumps, culverts, or other obstructions that would cause one or more wheels of the mower to lift. A maneuver was devised that would result in a quasi-lateral tip up of the zero-turn mowers. The maneuver starts with the mower stopped facing up the 20° slope with a steep ramp close behind one of the rear wheels. Figure 6 contains drawings of the ramp used for this quasi-lateral tip-up maneuver. The maneuver involves backing rearward down the ramp, which serves as the overturn-causing obstacle. The tip-up caused by this maneuver is not purely lateral, rather the direction of the tip up is part lateral and part rearward. The overturn direction (orientation) and dynamics from this maneuver are different from the direction and dynamics of a pure lateral rollover or a pure rearward pitchover.

The initial run to check and practice the maneuver resulted in the mower overturning. The mower overturned generally about the downside left rear tire. The mower pivoted laterally and rearward about the left side lateral outrigger and the upside right rear tire on the ramp. The lateral outrigger provided space for the driver to exit from beneath the mower as it overturned.

Unfortunately, no data, video, or photographs were collected of this initial check-out run that resulted in an overturn event. For safety reasons, no additional runs of this quasi-lateral tip-up maneuver with a driver were conducted.

However, the quasi-lateral tip-up maneuver was demonstrated without using a human driver. Page 31 of Appendix B shows a sequence through portions of the quasi-lateral tip-up maneuver. Page 32 contains four photographs of the mower stopped with its upside tire near the top of ramp. Had the mower not been stopped, it could have overturned. It would have likely overturned if the lateral outriggers were not in place. There was no driver involved in recreating the conditions shown on Pages 31 and 32, rather the mower was manually slowly pushed into, and stopped at, the positions shown.

Using a driving robot, this maneuver can be conducted to intentionally overturn a mower. As mentioned, the procedure for this maneuver is to start with mower at rest facing up the 20° slope and with the ramp directly behind one of the rear wheels. The mower will then by driven in reverse (using a driving robot) straight onto the ramp. Once the high side rear tire gets high enough on the ramp. The mower will overturn in a quasi-lateral orientation.

4.3.4 Vehicle D – Large Zero-Turn Mower

Results from the surrogate dynamic turn stability tests on Vehicle D are contained on Pages 33 and 34 of Appendix B. No wheel lift occurred during either of these tests, the maximum roll angle magnitudes are less than 2.0°, and the mean value of the steady lateral acceleration magnitude in both tests is in the range of 0.34 g. This level lateral acceleration is well below Vehicle D's lateral Tilt Table Ratio of 0.84.

Page 35 contains results from the surrogate STCT conducted on Vehicle D on the test pad. The front wheels lifted about 5 inches during the STCT conducted on the test pad, when the peak pitch angle was close to 5.5°. However, the wheel lift was short lived as the pitch angle returned to zero within one second. The peak pitch angle of 5.5° is well below Vehicle D's rearward TTA of 39.8°.

Page 36 shows the results for the STCT conducted on the 15° upslope. The front wheels lifted, and the vehicle pitched to nearly 30° as the vehicle drove forward. The front wheels returned to the slope in just over one second. There was no outrigger contact during this test. Rather the dynamics of the maneuver were such that the front wheels returned to the ground as the vehicle drove up the slope.

When the STCT was conducted on the 20° upslope, Vehicle D experienced tip up onto the rear outriggers. Page 37 contains graphical results from this test and Page 38 contains a video frame showing the rear outrigger contact. The outriggers made contact as the vehicle pitched to nearly 41°. After the outriggers hit, the pitch angle decreased and the vehicle drove forward with the rear outriggers and front wheels off the ground, until the driver released the tillers. The peak pitch angle only slightly exceeded Vehicle D's rearward TTA of 39.8°. Without the rear outriggers this test might have resulted in a rearward pitchover of the vehicle. A rearward pitchover of Vehicle D would more definitely occur if the 25° slope is used.

As mentioned in the previous section, numerous attempts were made to cause an intentional pure lateral tip-up of the zero-turn mowers, but none of these maneuvers resulted in lateral tip-up. Also mentioned is the fact that for safety reasons, no runs of the quasi-lateral tip-up maneuver were conducted using Vehicle D.

4.4 Summary

To evaluate the lateral tip-up resistance of the mowers on a flat surface, ANSI/OPEI B71.1 dynamic turn stability maneuvers and surrogates of this maneuver were conducted. None of the four mowers tested experienced any wheel lift in these initial full speed tests conducted on the flat asphalt test pad. Additional maneuvers were conducted on the asphalt test pad, including using multi-direction rapid steering inputs at full speed, in an attempt to cause lateral tip-up events. None of these other maneuvers resulted in wheel lift and nothing indicated that they were any more severe than the full speed, full steering dynamic turn stability tests reported. The asphalt test pad has significantly higher friction than grass, so the mowers are more rollover resistant on flat grass surfaces than on asphalt surfaces. Further, the mowers have relatively low maximum speeds, and this limits the amount of lateral acceleration that can be developed during turning maneuvers on flat ground.

Attempts to get the tractor style mowers and zero-turns mowers to tip up while turning on cross slopes and downslopes from 15° to 30° were unsuccessful. Therefore, tip-up causing features, to represent obstacles like terrain bumps, tree stumps, or concrete culverts, were added to the mix. Ultimately, lateral tip ups of the tractor style mowers were generated by driving onto a ramp positioned cross ways on the 20° sloped surface. This lateral tip-up maneuver is potentially useful for evaluating the feasibility and effectiveness of using ROPS on tractor style riding mowers.

For the zero-turn mowers, which could not be driven onto the ramp positioned cross ways on the slope, a different quasi-lateral tip-up maneuver was developed. This quasi-lateral maneuver involves driving rearward onto a steep ramp aligned with the 20° slope surface. The orientation and dynamics of the quasi-lateral tip-up event differ from a pure lateral rollover and a pure rearward pitchover; so, this quasi-lateral tip-up maneuver is potentially useful for evaluating the feasibility and effectiveness of using ROPS on zero-turn riding mowers.

To evaluate the rearward tip-up resistance of the mowers on a flat surface, ANSI/OPEI B71.1 Sudden Tractor Control Test (STCT) maneuvers and surrogates to the STCT maneuver were conducted. The tractor style mowers did not experience front wheel lift during STCTs on the asphalt test pad. The zero-turn mowers did experience front wheel lift during STCTs on the test pad, but the pitch angles were well below rearward TTAs for the two zero-turn mowers. The asphalt test pad has significantly higher friction than grass, so the mowers are more pitchover resistance on flat grass surfaces than on asphalt surfaces.

Vehicle B, the large tractor style mower, has a very high rearward TTA of 49.8°. Attempts to get this vehicle to pitch onto the rear outriggers during STCTs on upslopes were unsuccessful. Even the STCT on a high friction, 30° upslope surface did not result in outrigger contact. However, the other three mowers did experience rear outrigger contact during STCTs on upslopes. These maneuvers that resulted in rear outrigger contact outcomes would have likely resulted in rearward pitchovers had it not been for the outriggers; so, these rearward tip-up maneuvers are potentially useful for evaluating the feasibility and effectiveness of using ROPS on riding mowers.

Small Tractor

	Curb	Curb plus 95th% Male	Driver plus Instrumentation
VIMF Test Number	8060	8075	Weight Only
Total Vehicle Weight (lb)	271.5	494.5	531.4
Left Front Weight (lb)	51.4	93.9	77.1
Right Front Weight (lb)	40.7	78.4	69.9
Left Rear Weight (lb)	86.9	157.8	189.1
Right Rear Weight (lb)	92.5	164.4	195.3
Front Track (in)	26.00	26.00	26.00
Rear Track (in)	24.00	24.00	24.00
Average Track (in)	25.00	25.00	25.00
Wheelbase (in)	46.30	46.30	46.30
CG Longitudinal (in)	30.59	30.17	33.49
CG Lateral (in)	-0.26	-0.25	-0.04
CG Height (in)	12.86	23.95	
Roll Inertia - Ixx ($ft\text{-}lb\text{-}s^2$)	6	40	
Pitch Inertia - Iyy ($ft\text{-}lb\text{-}s^2$)	14	40	
Yaw Inertia - Izz ($ft\text{-}lb\text{-}s^2$)	9	15	
Roll/Yaw - Ixz ($ft\text{-}lb\text{-}s^2$)	1	4	
SSF	0.972	0.522	
KST	0.960	0.516	
Forward SSF	2.379	1.260	
Rearward SSF	1.221	0.674	

Small Tractor

		Curb	Curb plus 95th% Male
Lateral Direction: Right Tilt	Tilt Table: First Wheel Lift	Rear	Rear
	Tilt Table Angle (TTA) (deg)	41.6	24.7
	Tilt Table Ratio (TTR)	0.887	0.460
Lateral Direction: Left Tilt	Tilt Table: First Wheel Lift	Front	Rear
	Tilt Table Angle (TTA) (deg)	40.0	25.0
	Tilt Table Ratio (TTR)	0.839	0.466
	Average Lateral TTA (deg)	**40.8**	**24.8**
	Average Lateral TTR	**0.863**	**0.463**

Longitudinal Direction: Rear Tilt	Tilt Table: First Wheel Lift	Right	Left
	Rearward Tilt Table Angle (RTTA) (deg)	**54.9**	**32.2**
	Rearward Tilt Table Ratio (RTTR)	**1.424**	**0.631**

Large Tractor

	Curb	Curb plus 95^{th}% Male	Driver plus Instrumentation
VIMF Test Number	8078	8079	Weight Only
Total Vehicle Weight (lb)	838	1062.9	1101.7
Left Front Weight (lb)	199.7	213.1	202.9
Right Front Weight (lb)	199.1	215.2	203.5
Left Rear Weight (lb)	215.1	310.7	346.6
Right Rear Weight (lb)	224.1	323.9	348.7
Front Track (in)	31.30	31.30	31.30
Rear Track (in)	30.00	30.00	30.00
Average Track (in)	30.65	30.65	30.65
Wheelbase (in)	50.55	50.55	50.55
CG Longitudinal (in)	26.49	30.18	31.90
CG Lateral (in)	0.15	0.22	0.04
CG Height (in)	15.03	20.46	
Roll Inertia - Ixx ($ft\text{-}lb\text{-}s^2$)	37	68	
Pitch Inertia - Iyy ($ft\text{-}lb\text{-}s^2$)	91	132	
Yaw Inertia - Izz ($ft\text{-}lb\text{-}s^2$)	89	105	
Roll/Yaw - Ixz ($ft\text{-}lb\text{-}s^2$)	-6	22	
SSF	1.020	0.749	
KST	1.019	0.746	
Forward SSF	1.763	1.475	
Rearward SSF	1.601	0.996	

Large Tractor

		Curb	Curb plus 95^{th}% Male
Lateral Direction: Right Tilt	Tilt Table: First Wheel Lift	Rear	Rear
	Tilt Table Angle (TTA) (deg)	41.2	32.5
	Tilt Table Ratio (TTR)	0.875	0.638
Lateral Direction: Left Tilt	Tilt Table: First Wheel Lift	Rear	Rear
	Tilt Table Angle (TTA) (deg)	43.0	31.4
	Tilt Table Ratio (TTR)	0.933	0.610
	Average Lateral TTA (deg)	**42.1**	**32.0**
	Average Lateral TTR	**0.904**	**0.624**

Longitudinal Direction: Rear Tilt	Tilt Table: First Wheel Lift	Both	Both
	Rearward Tilt Table Angle (RTTA) (deg)	**60.0**	**49.8**
	Rearward Tilt Table Ratio (RTTR)	**1.732**	**1.184**

Small Zero-Turn

	Curb	Curb plus 95th% Male	Driver plus Instrumentation
VIMF Test Number	8082	8083	Weight Only
Total Vehicle Weight (lb)	458.4	681.7	716.8
Left Front Weight (lb)	60.8	105.7	105.0
Right Front Weight (lb)	65.0	101.2	97.6
Left Rear Weight (lb)	168.3	236.5	253.9
Right Rear Weight (lb)	164.3	238.3	260.4
Front Track (in)	27.95	27.95	27.95
Rear Track (in)	29.75	29.75	29.75
Average Track (in)	28.85	28.85	28.85
Wheelbase (in)	45.70	45.70	45.70
CG Longitudinal (in)	33.16	31.83	32.79
CG Lateral (in)	0.00	-0.05	-0.01
CG Height (in)	13.31	19.82	
Roll Inertia - Ixx (ft-lb-s^2)	13	35	
Pitch Inertia - Iyy (ft-lb-s^2)	30	51	
Yaw Inertia - Izz (ft-lb-s^2)	28	34	
Roll/Yaw - Ixz (ft-lb-s^2)	3	3	
SSF	1.084	0.728	
KST	1.099	0.737	
Forward SSF	2.491	1.606	
Rearward SSF	0.942	0.700	

Small Zero-Turn

		Curb	Curb plus 95th% Male
Lateral Direction: Right Tilt	**Tilt Table: First Wheel Lift**	Front	Front
	Tilt Table Angle (TTA) (deg)	44.1	32.1
	Tilt Table Ratio (TTR)	0.970	0.628
Lateral Direction: Left Tilt	**Tilt Table: First Wheel Lift**	Front	Front
	Tilt Table Angle (TTA) (deg)	44.6	32.1
	Tilt Table Ratio (TTR)	0.985	0.626
	Average Lateral TTA (deg)	**44.3**	**32.1**
	Average Lateral TTR	**0.977**	**0.627**

Longitudinal Direction: Rear Tilt	**Tilt Table: First Wheel Lift**	Both	Both
	Rearward Tilt Table Angle (RTTA) (deg)	**49.1**	**34.5**
	Rearward Tilt Table Ratio (RTTR)	**1.153**	**0.686**

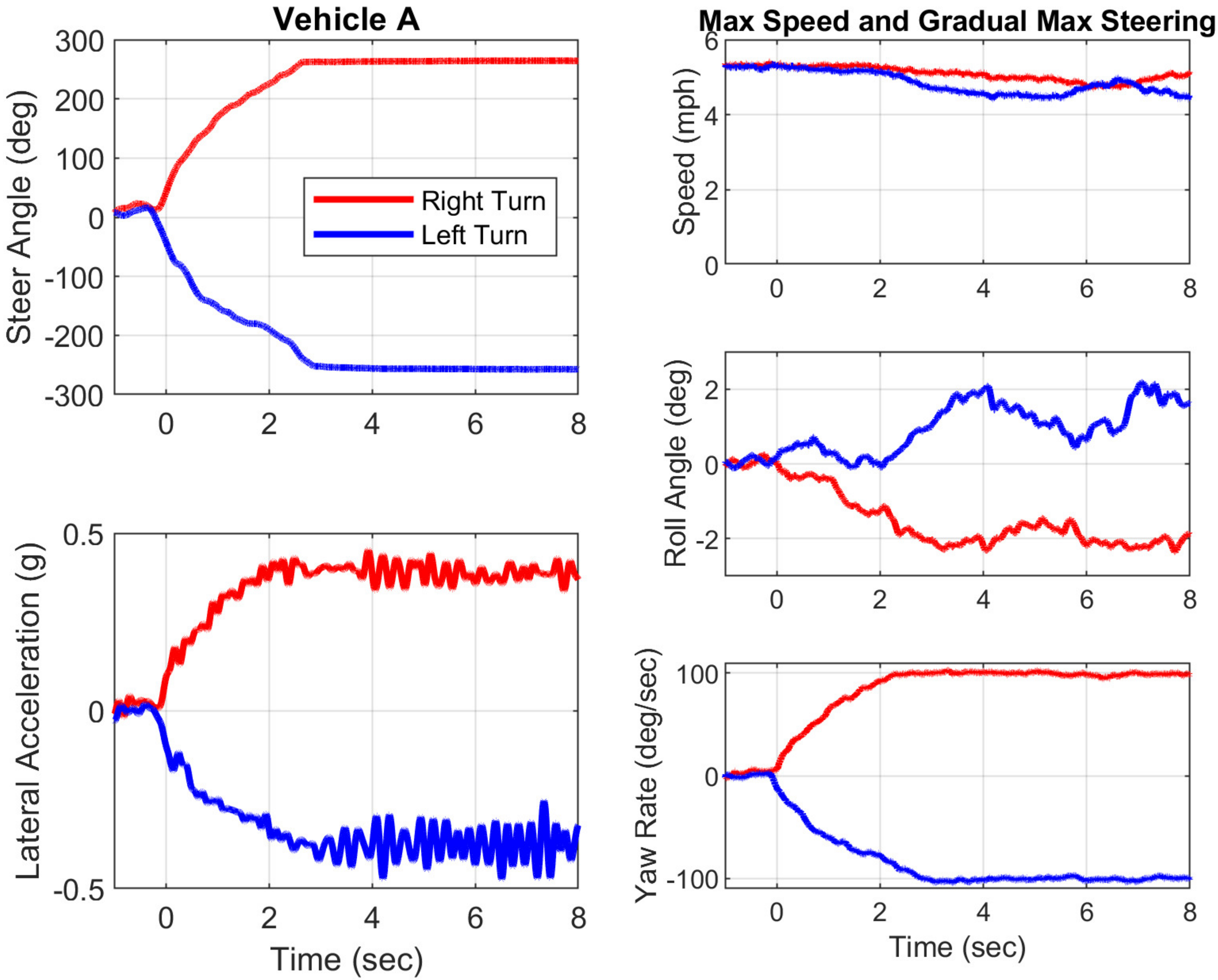
Large Zero-Turn

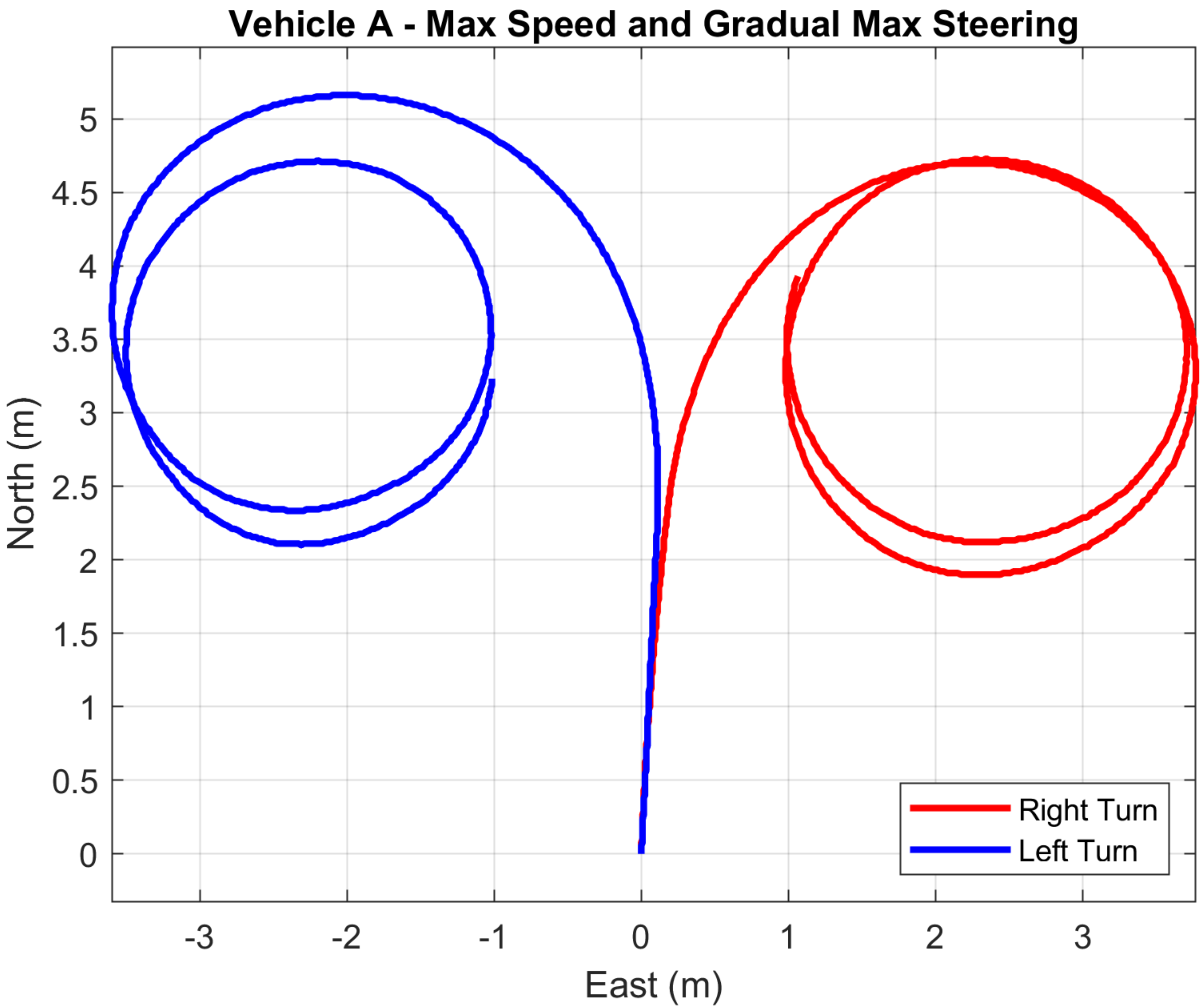
	Curb	Curb plus 95th% Male	Driver plus Instrumentation
VIMF Test Number	8080	8081	Weight Only
Total Vehicle Weight (lb)	582.2	804.9	834.6
Left Front Weight (lb)	64.8	99	109.3
Right Front Weight (lb)	76.5	109.9	92.7
Left Rear Weight (lb)	238.3	318.9	320.9
Right Rear Weight (lb)	202.6	277.1	311.7
Front Track (in)	32.80	32.90	32.90
Rear Track (in)	36.80	36.85	36.85
Average Track (in)	34.80	34.88	34.88
Wheelbase (in)	49.90	49.90	49.90
CG Longitudinal (in)	37.79	36.95	37.82
CG Lateral (in)	-0.80	-0.73	-0.53
CG Height (in)	13.28	19.26	
Roll Inertia - Ixx (ft-lb-s^2)	28	53	
Pitch Inertia - Iyy (ft-lb-s^2)	45	67	
Yaw Inertia - Izz (ft-lb-s^2)	55	56	
Roll/Yaw - Ixz (ft-lb-s^2)	6	8	
SSF	1.310	0.905	
KST	1.349	0.930	
Forward SSF	2.846	1.918	
Rearward SSF	0.912	0.672	

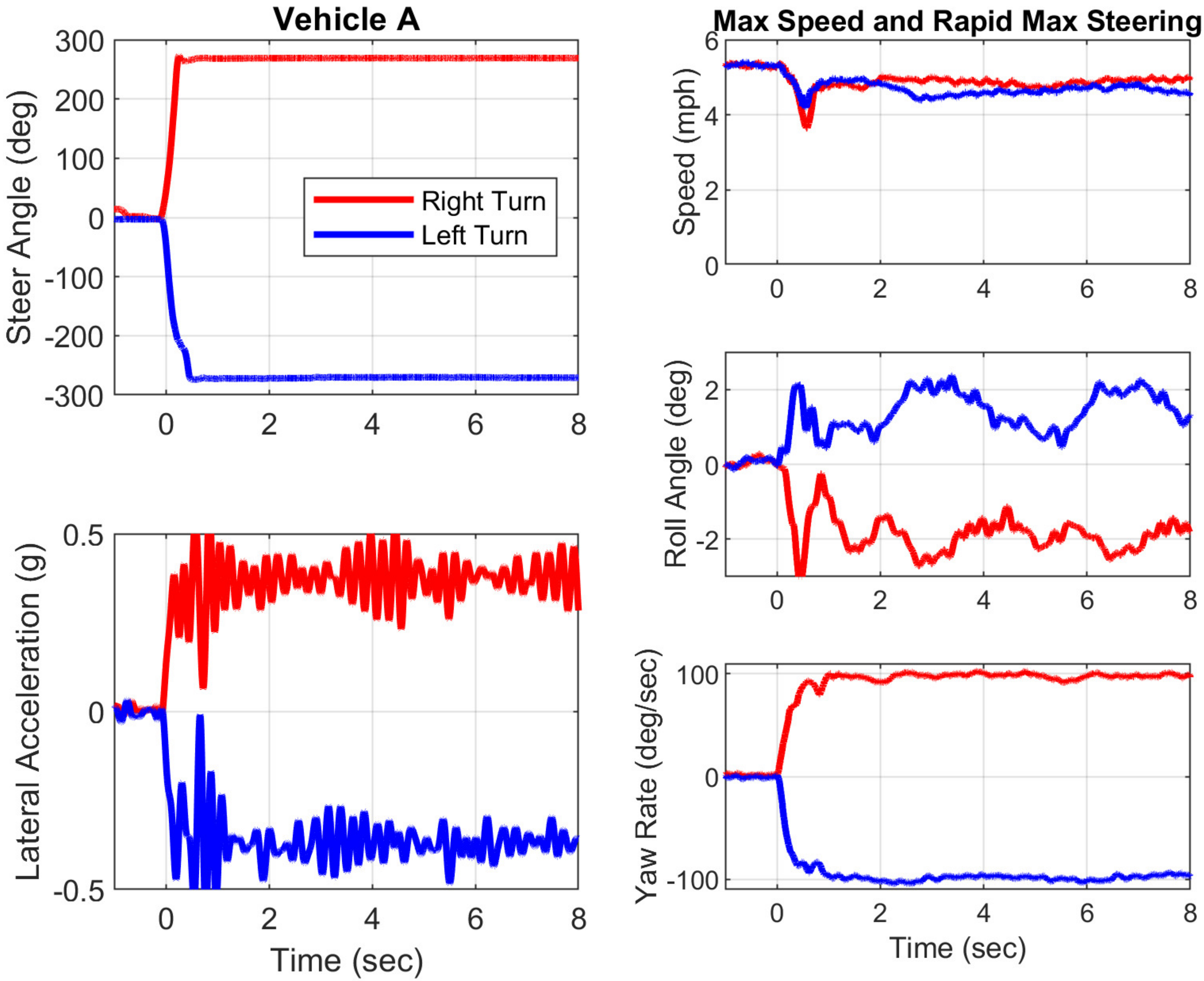
Large Zero-Turn

		Curb	Curb plus 95th% Male
Lateral Direction: Right Tilt	**Tilt Table: First Wheel Lift**	Front	Front
	Tilt Table Angle (TTA) (deg)	55.7	40.4
	Tilt Table Ratio (TTR)	1.465	0.850
Lateral Direction: Left Tilt	**Tilt Table: First Wheel Lift**	Both	Front
	Tilt Table Angle (TTA) (deg)	53.2	39.8
	Tilt Table Ratio (TTR)	1.335	0.832
	Average Lateral TTA (deg)	**54.4**	**40.1**
	Average Lateral TTR	**1.400**	**0.841**

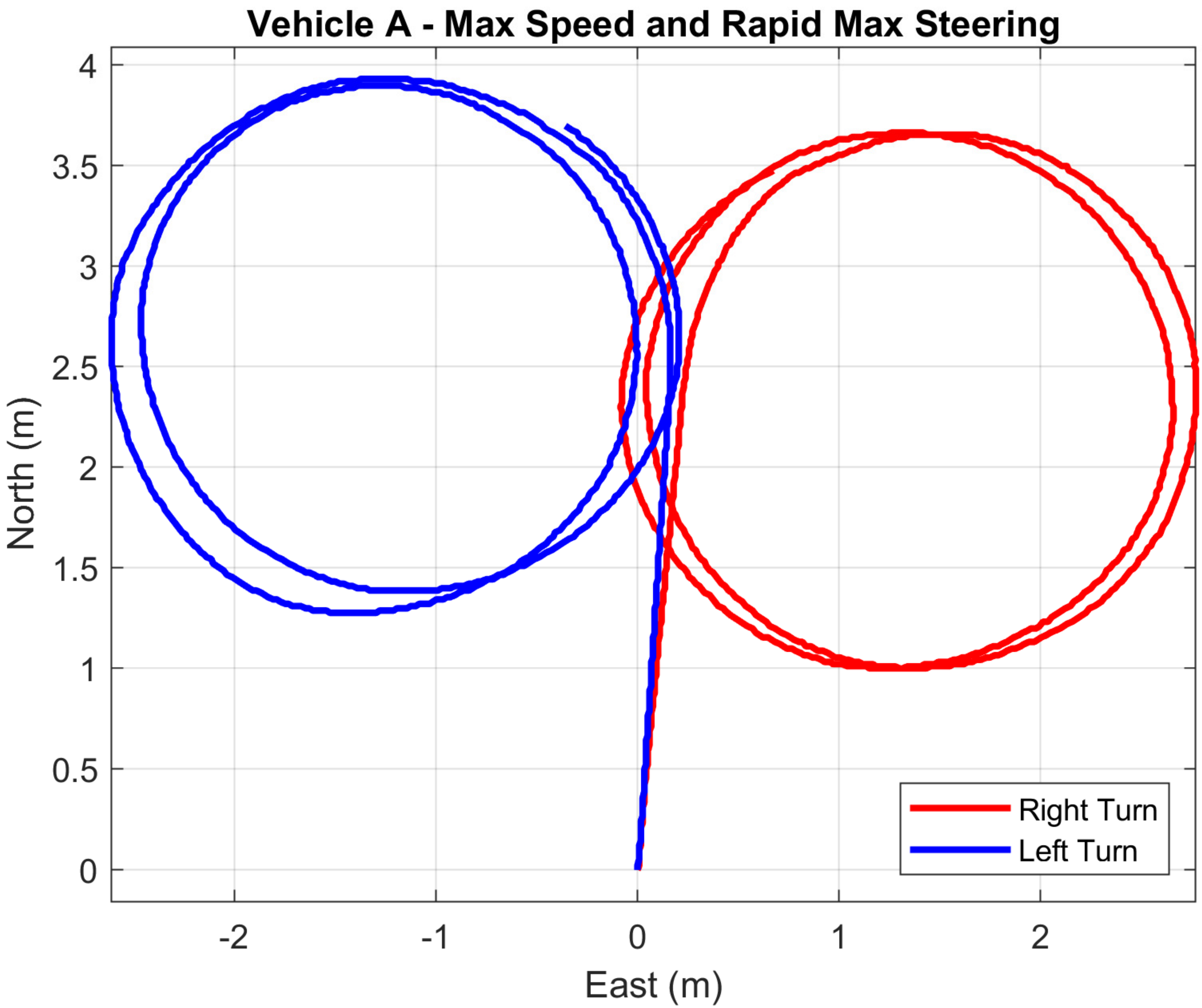
Longitudinal Direction: Rear Tilt	**Tilt Table: First Wheel Lift**	Left	Both
	Rearward Tilt Table Angle (RTTA) (deg)	**48.8**	**39.8**
	Rearward Tilt Table Ratio (RTTR)	**1.143**	**0.834**

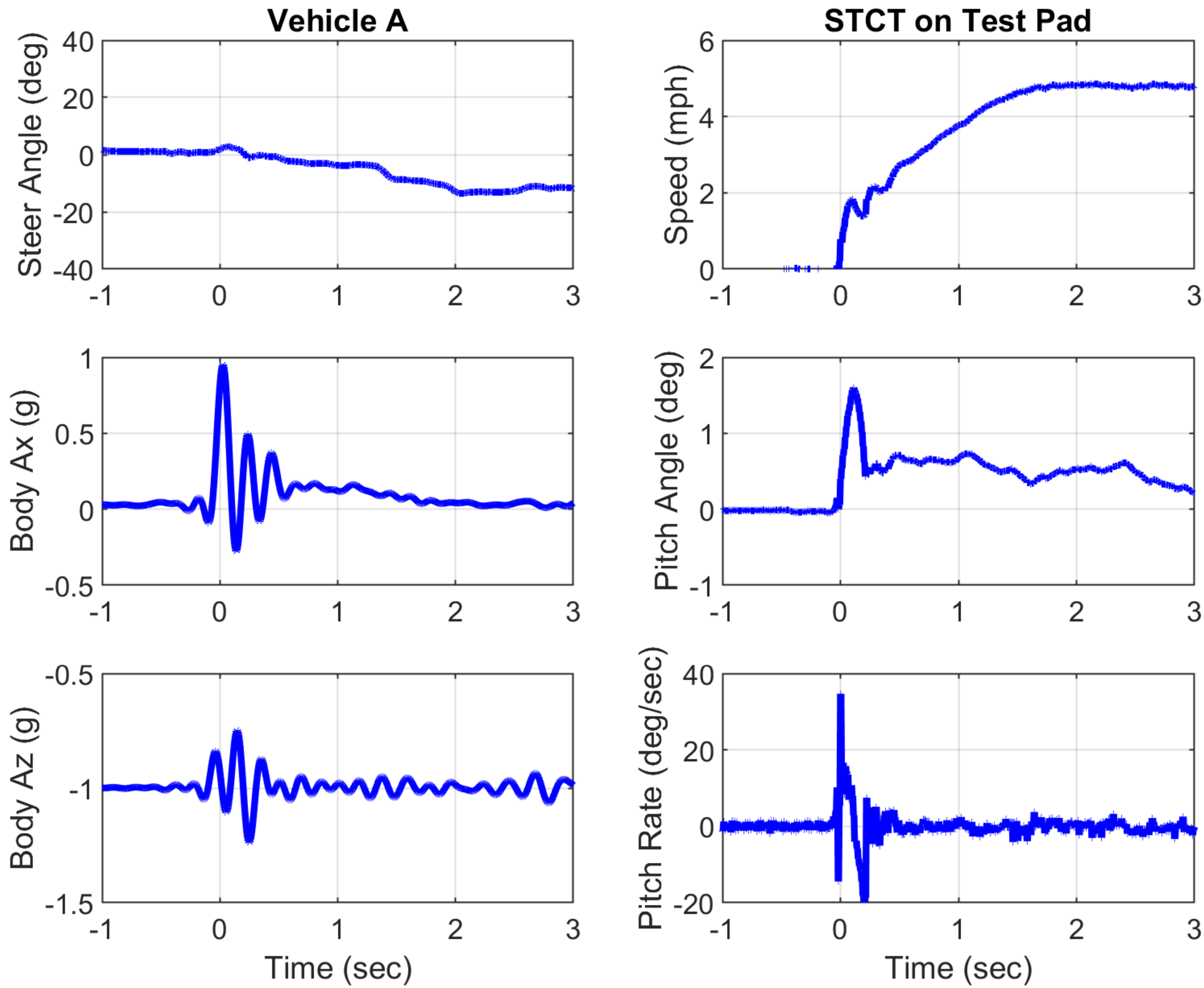

Vehicle A
Max Speed and Gradual Max Steering
Steer Angle (deg)
Right Turn
Left Turn
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

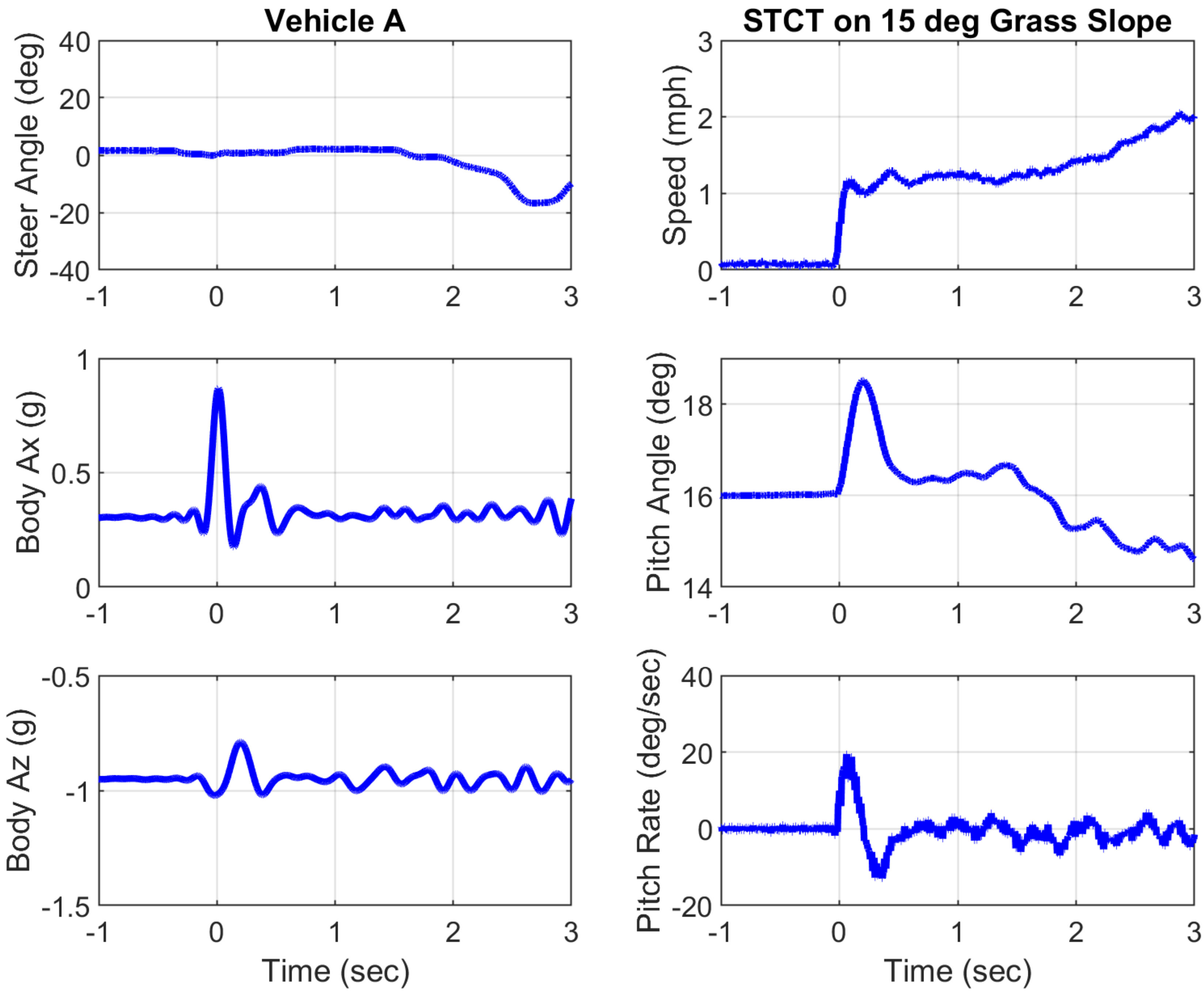

Vehicle A - Max Speed and Gradual Max Steering
North (m)
East (m)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-3
-2
-1
0
1
2
3
Right Turn
Left Turn

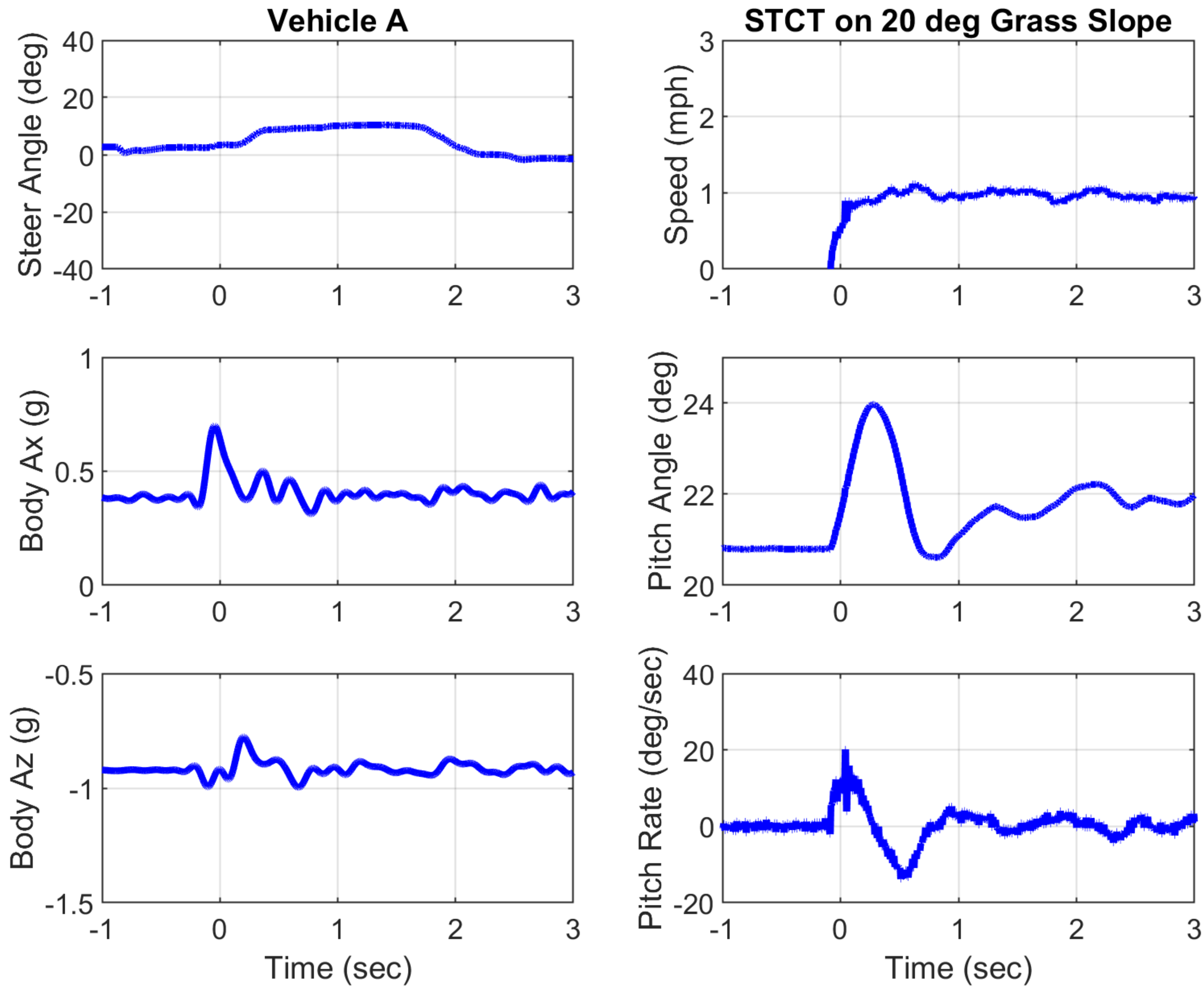


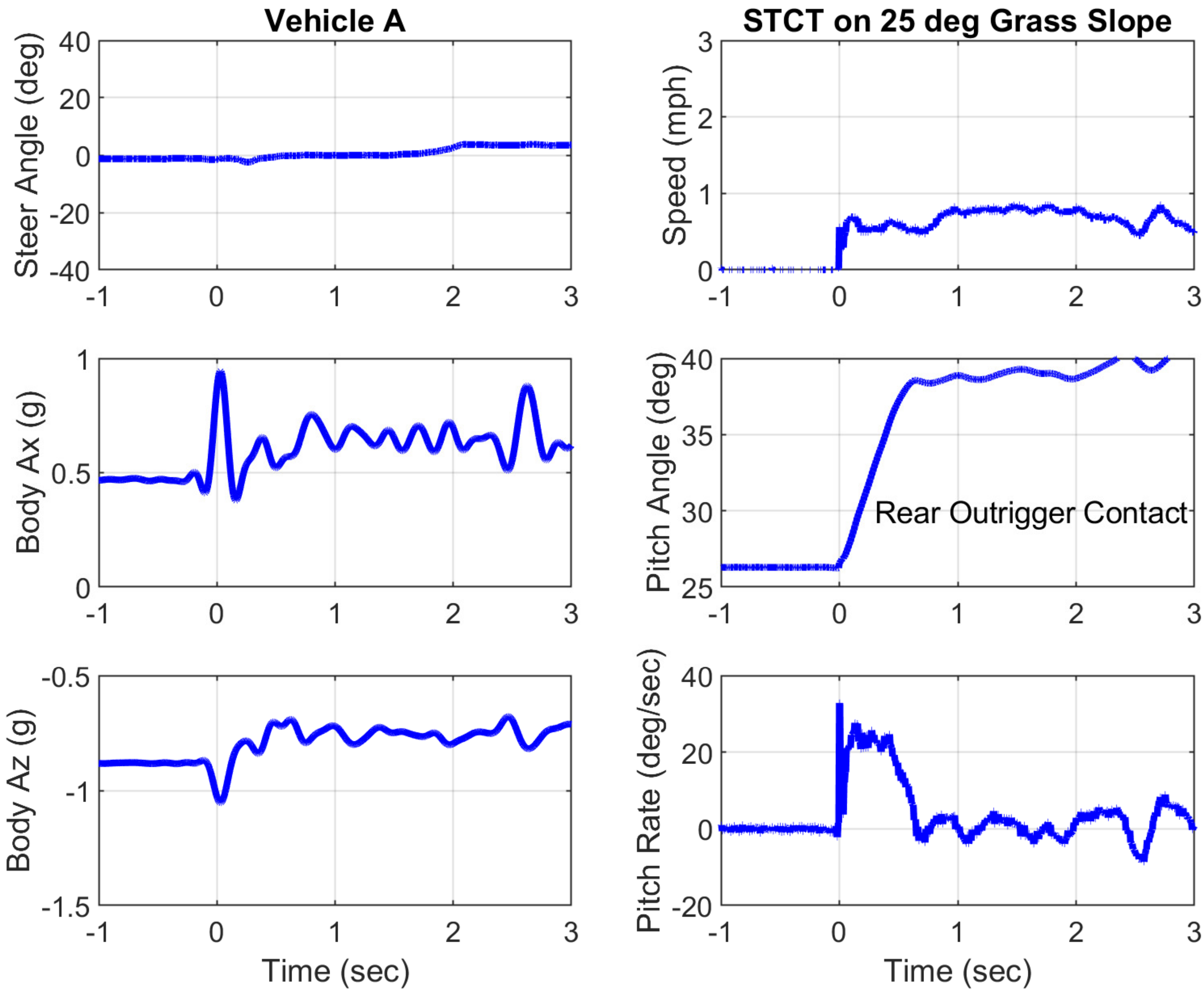
Vehicle A
Max Speed and Rapid Max Steering
Steer Angle (deg)
300
200
100
0
-100
-200
-300
Right Turn
Left Turn
0
2
4
6
8
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
0.5
-0.5
Yaw Rate (deg/sec)
-100
Time (sec)
Time (sec)


Vehicle A - Max Speed and Rapid Max Steering
North (m)
East (m)
Right Turn
Left Turn
4
3.5
3
2.5
2
1.5
1
0.5
0
-2
-1
0
1
2


Vehicle A
STCT on Test Pad
Steer Angle (deg)
Speed (mph)
Body Ax (g)
Pitch Angle (deg)
Body Az (g)
Pitch Rate (deg/sec)
Time (sec)
Time (sec)

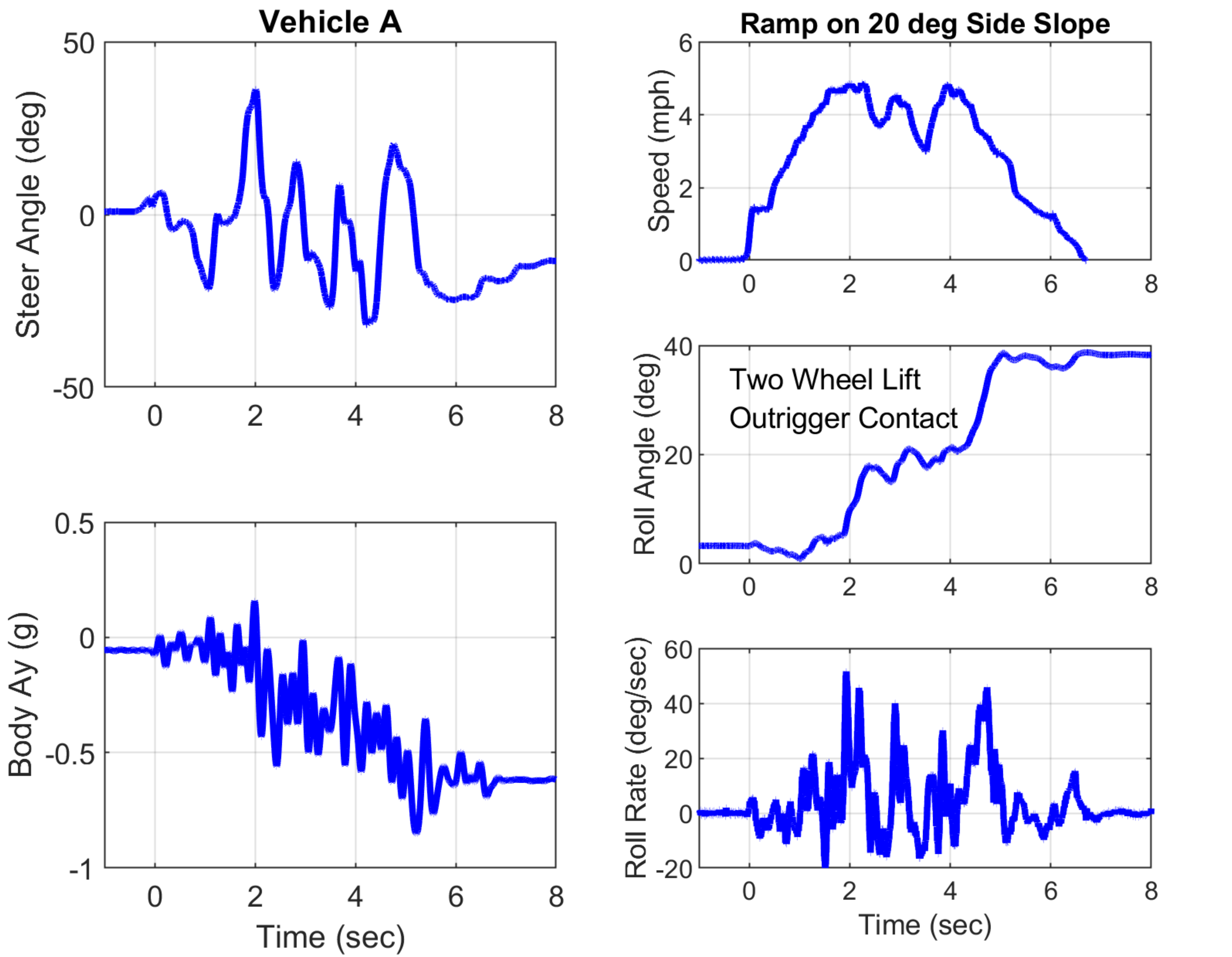

Vehicle A
STCT on 15 deg Grass Slope
Steer Angle (deg)
40
20
0
-20
-40
Speed (mph)
3
2
1
0
Body Ax (g)
1
0.5
0
Pitch Angle (deg)
18
16
14
Body Az (g)
-0.5
-1
-1.5
Pitch Rate (deg/sec)
40
20
0
-20
-1
0
1
2
3
Time (sec)
Time (sec)


Vehicle A
STCT on 20 deg Grass Slope
Steer Angle (deg)
Speed (mph)
Body Ax (g)
Pitch Angle (deg)
Body Az (g)
Pitch Rate (deg/sec)
Time (sec)
Time (sec)



Vehicle A
STCT on 25 deg Grass Slope
Steer Angle (deg)
Speed (mph)
Body Ax (g)
Pitch Angle (deg)
Rear Outrigger Contact
Body Az (g)
Pitch Rate (deg/sec)
Time (sec)
Time (sec)

Vehicle A – Rearward Tip-up on to Outriggers
(Sudden Acceleration on a 25 deg Grass Slope)



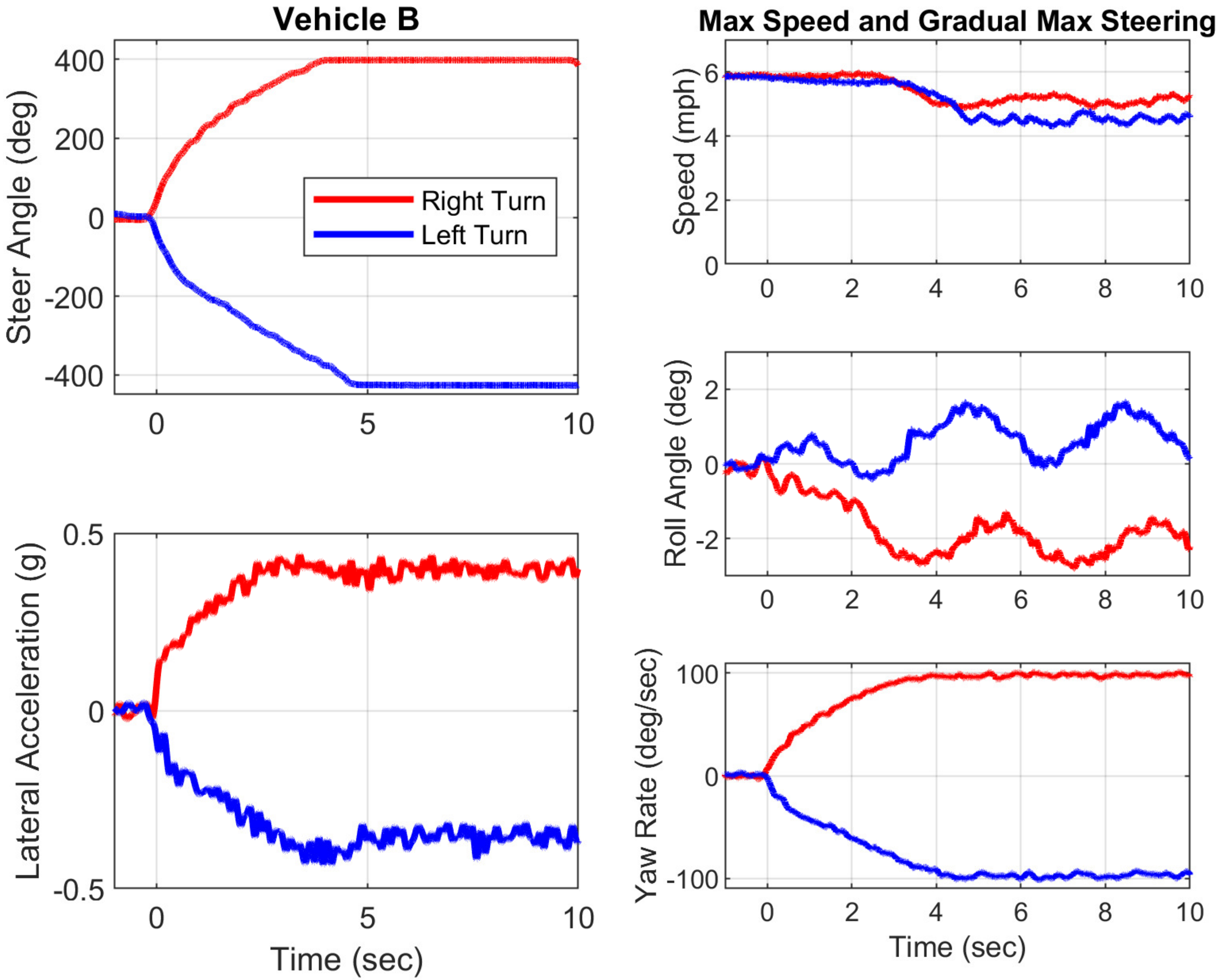
Vehicle A
Ramp on 20 deg Side Slope
Steer Angle (deg)
Body Ay (g)
Speed (mph)
Roll Angle (deg)
Roll Rate (deg/sec)
Time (sec)
Two Wheel Lift
Outrigger Contact

Vehicle A – Lateral Two Wheel Lift
(Driving On To 7" Tall Ramp on 20 deg Side Slope)

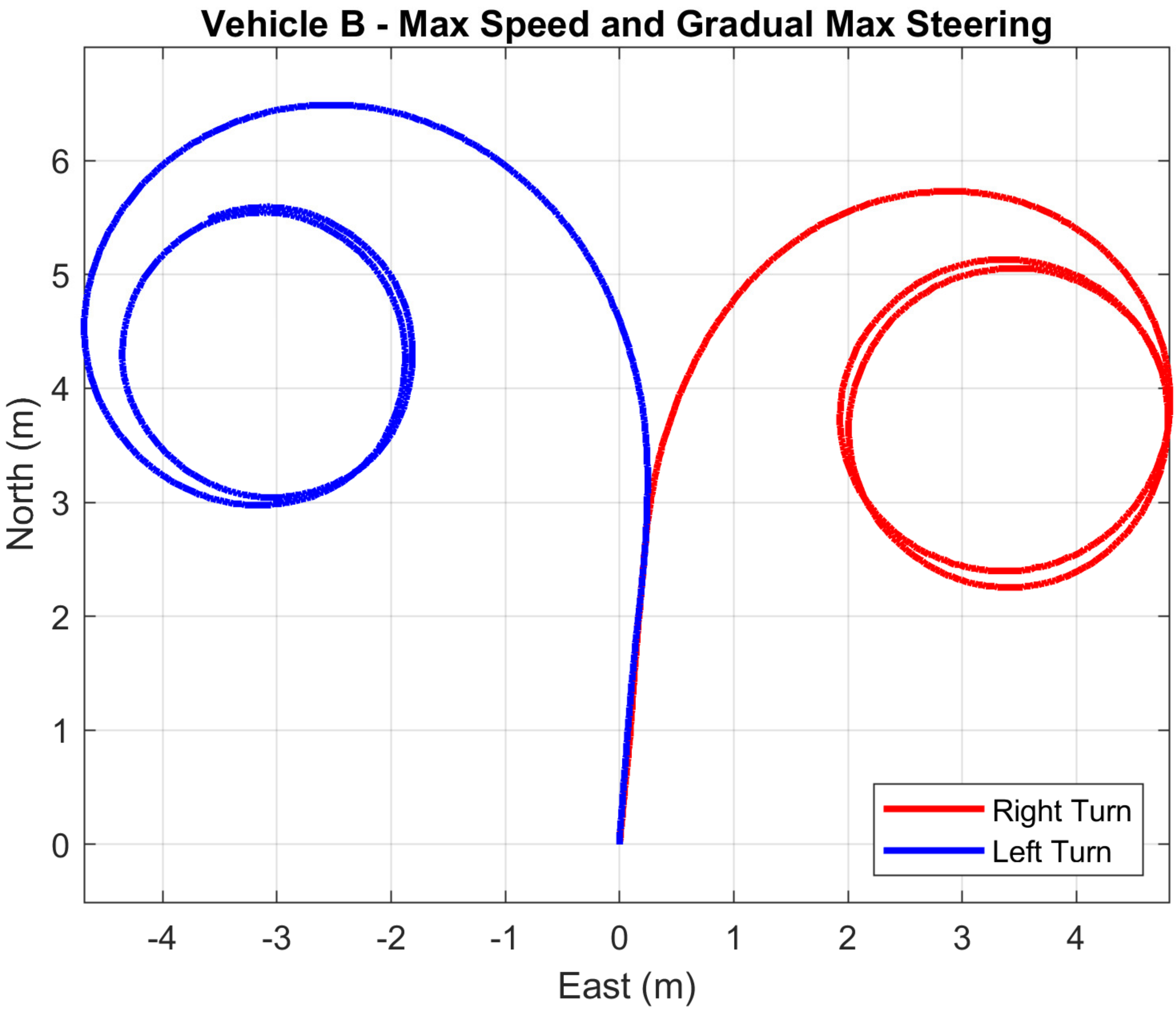
Vehicle On Approach To Ramp

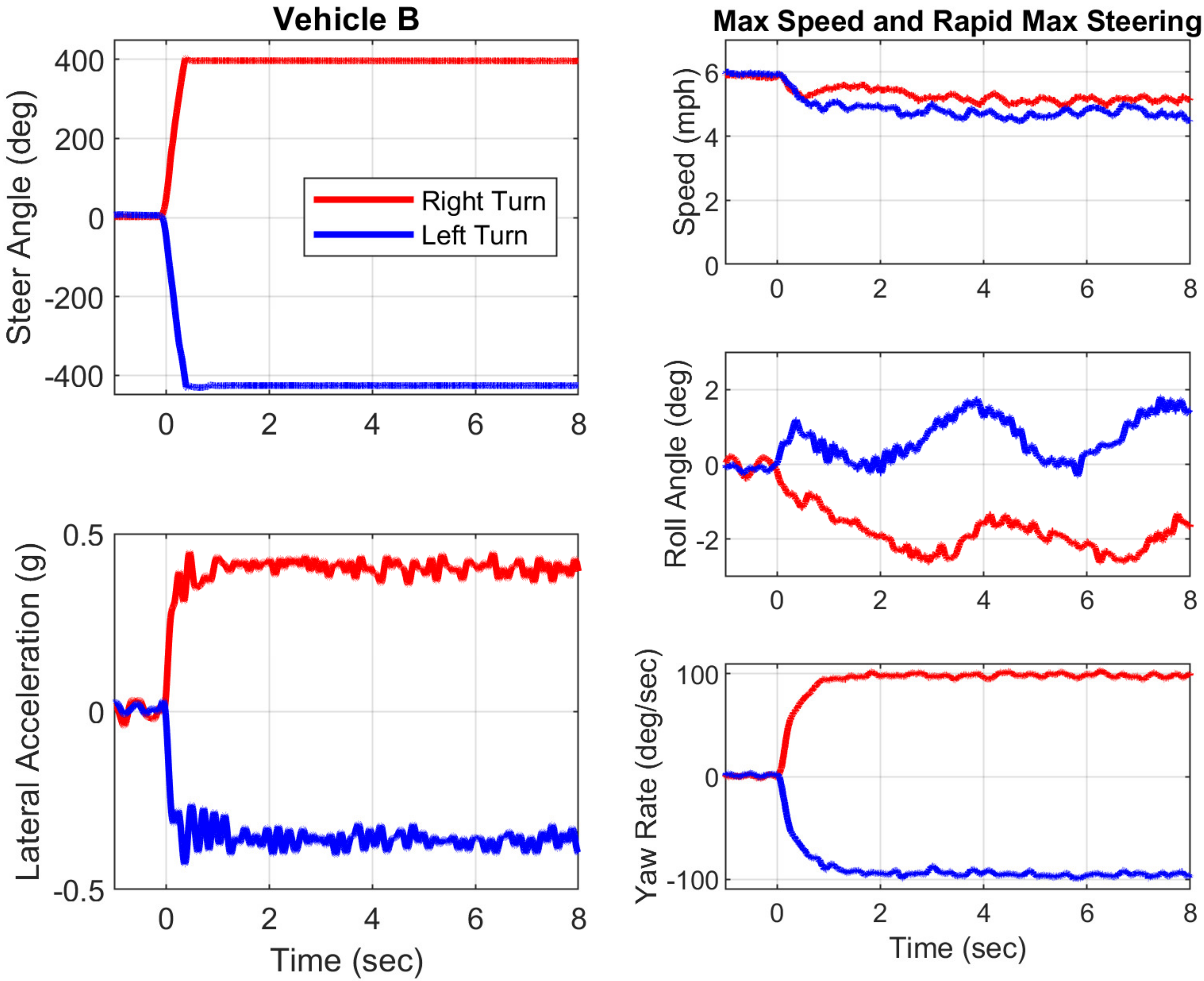
Two Wheel Lift

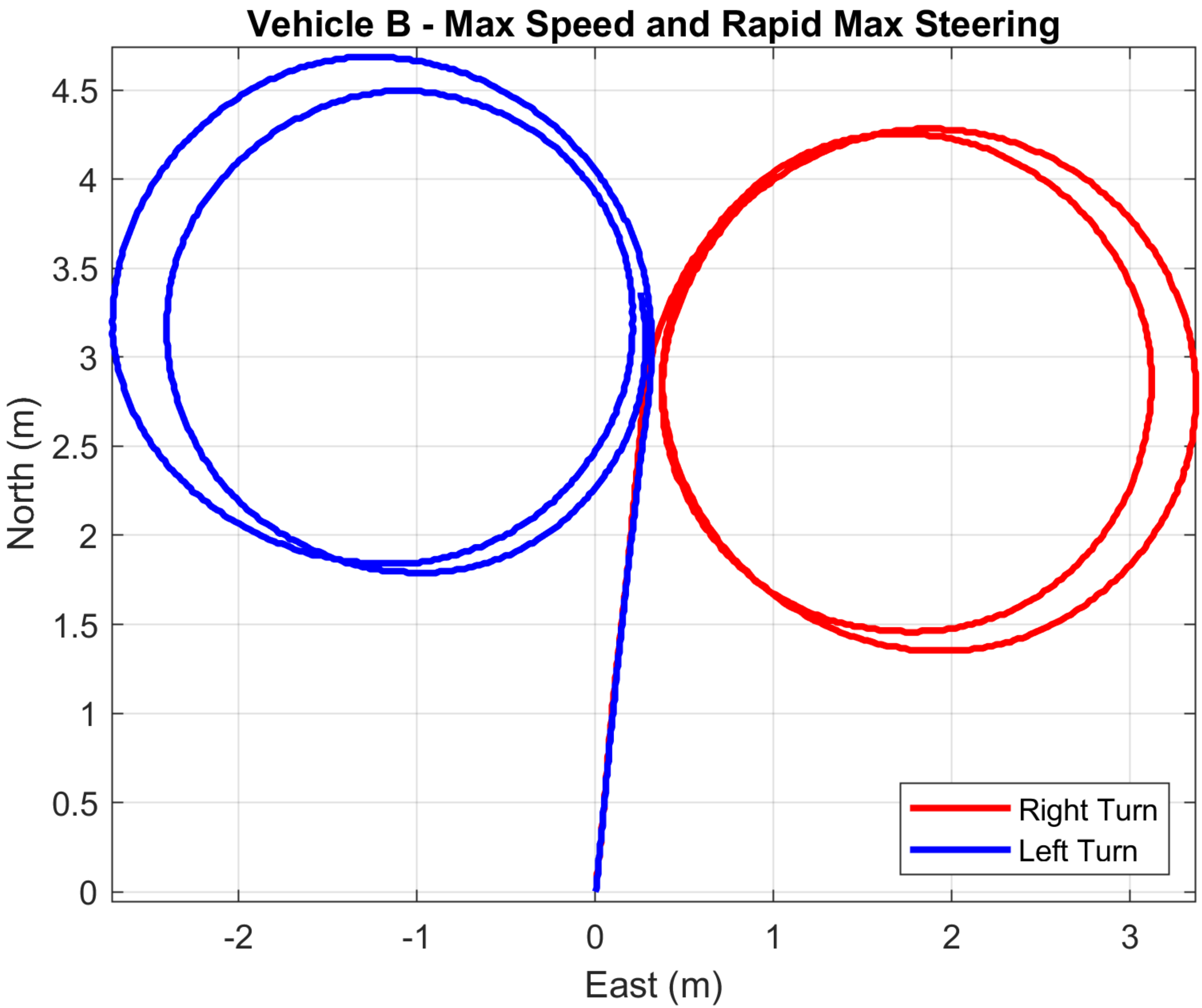
Vehicle Stopped and Resting on Outrigger

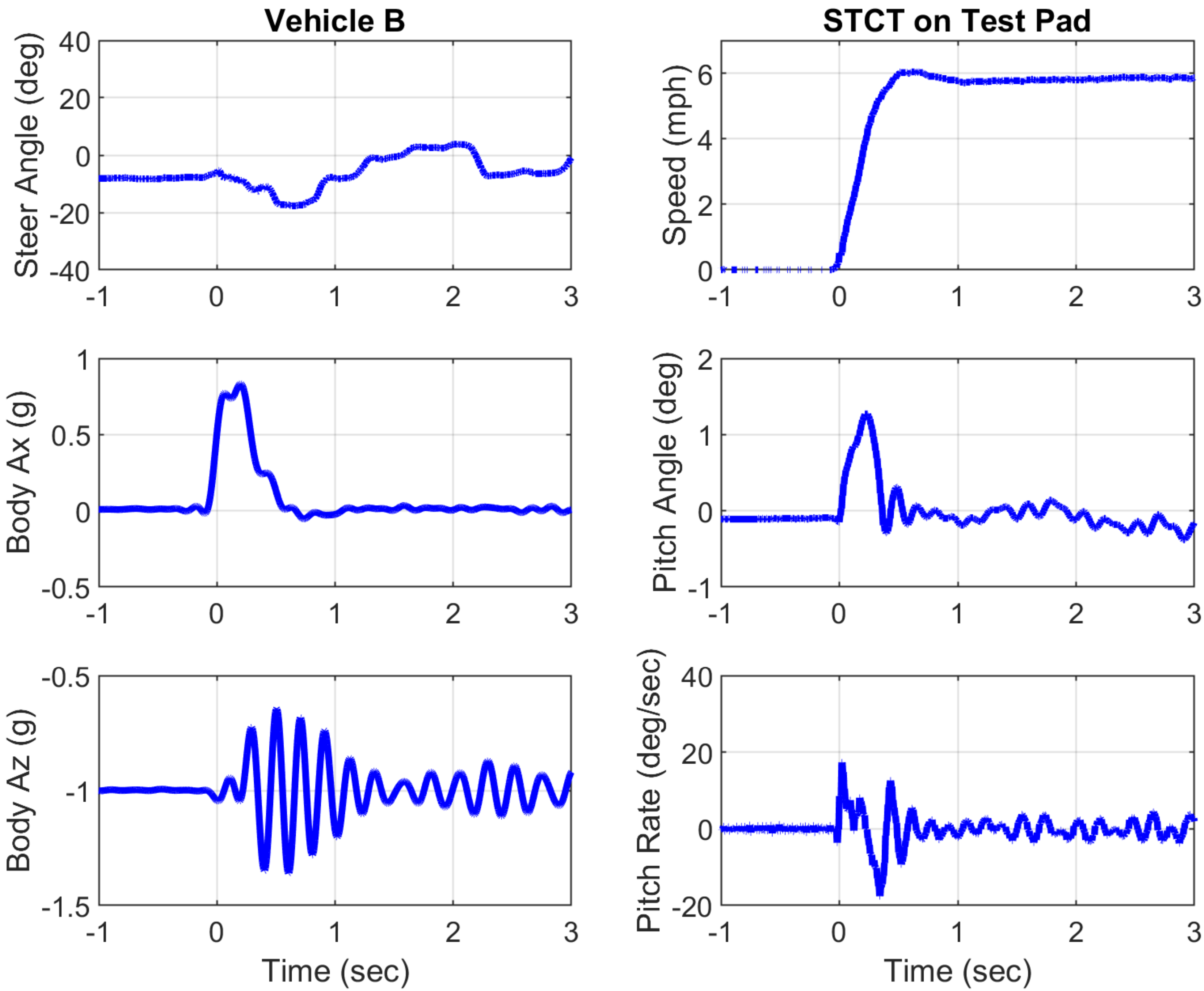


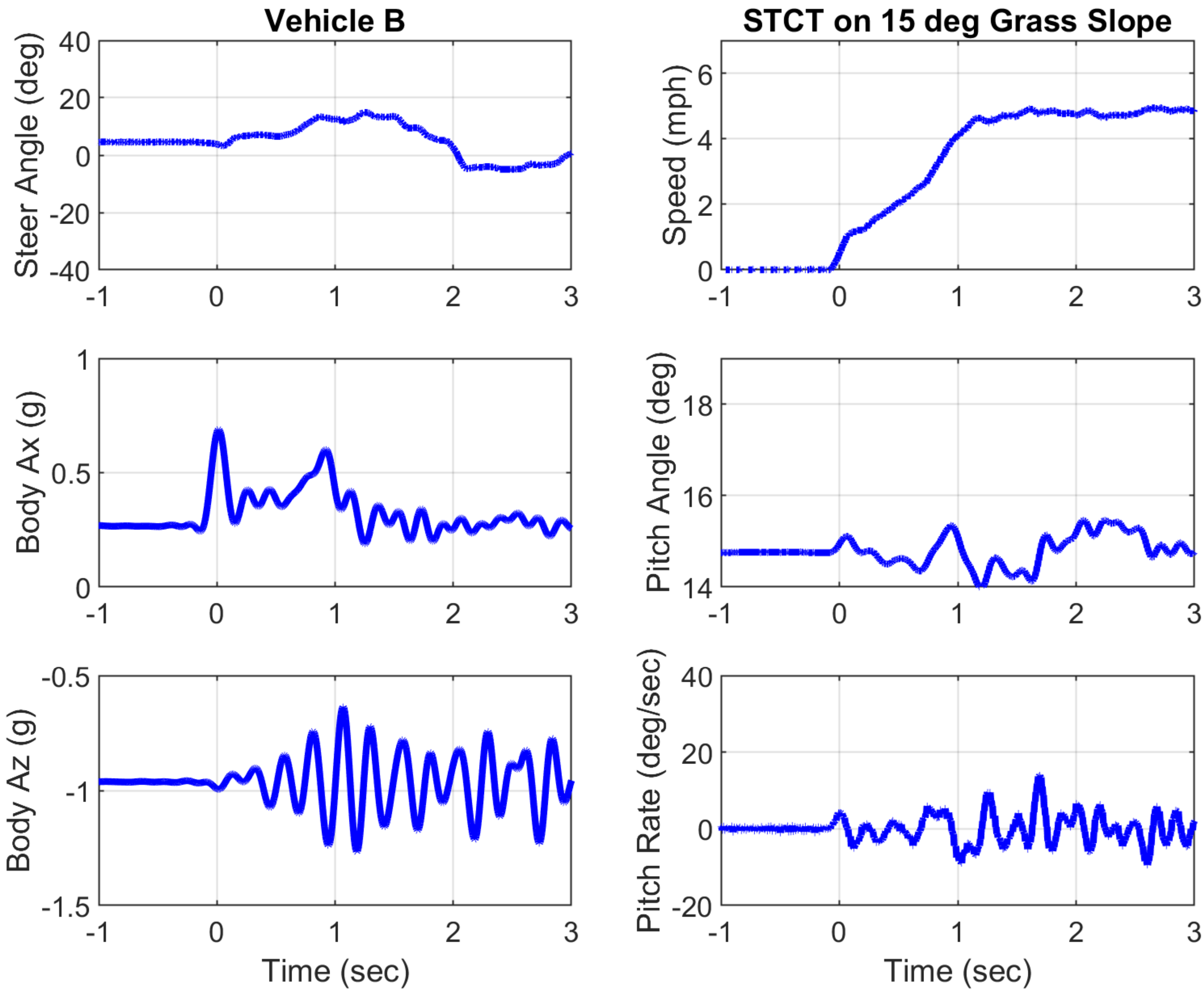
Vehicle B
Max Speed and Gradual Max Steering
Steer Angle (deg)
400
200
0
-200
-400
Right Turn
Left Turn
0
5
10
Speed (mph)
6
4
2
0
0
2
4
6
8
10
Roll Angle (deg)
2
0
-2
Lateral Acceleration (g)
0.5
0
-0.5
Time (sec)
Yaw Rate (deg/sec)
100
0
-100
Time (sec)

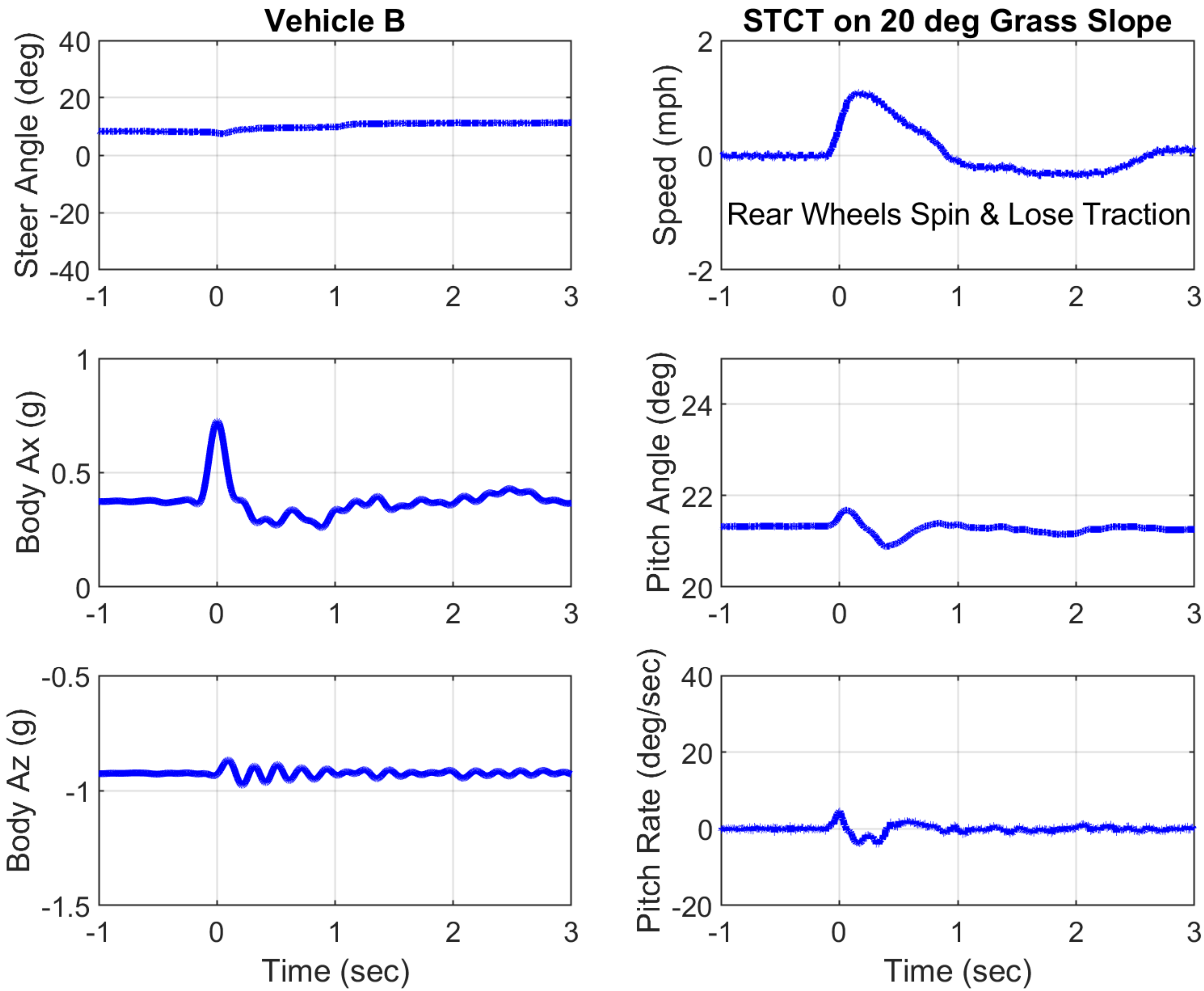

Vehicle B - Max Speed and Gradual Max Steering
North (m)
East (m)
Right Turn
Left Turn
0
1
2
3
4
5
6
-4
-3
-2
-1
0
1
2
3
4

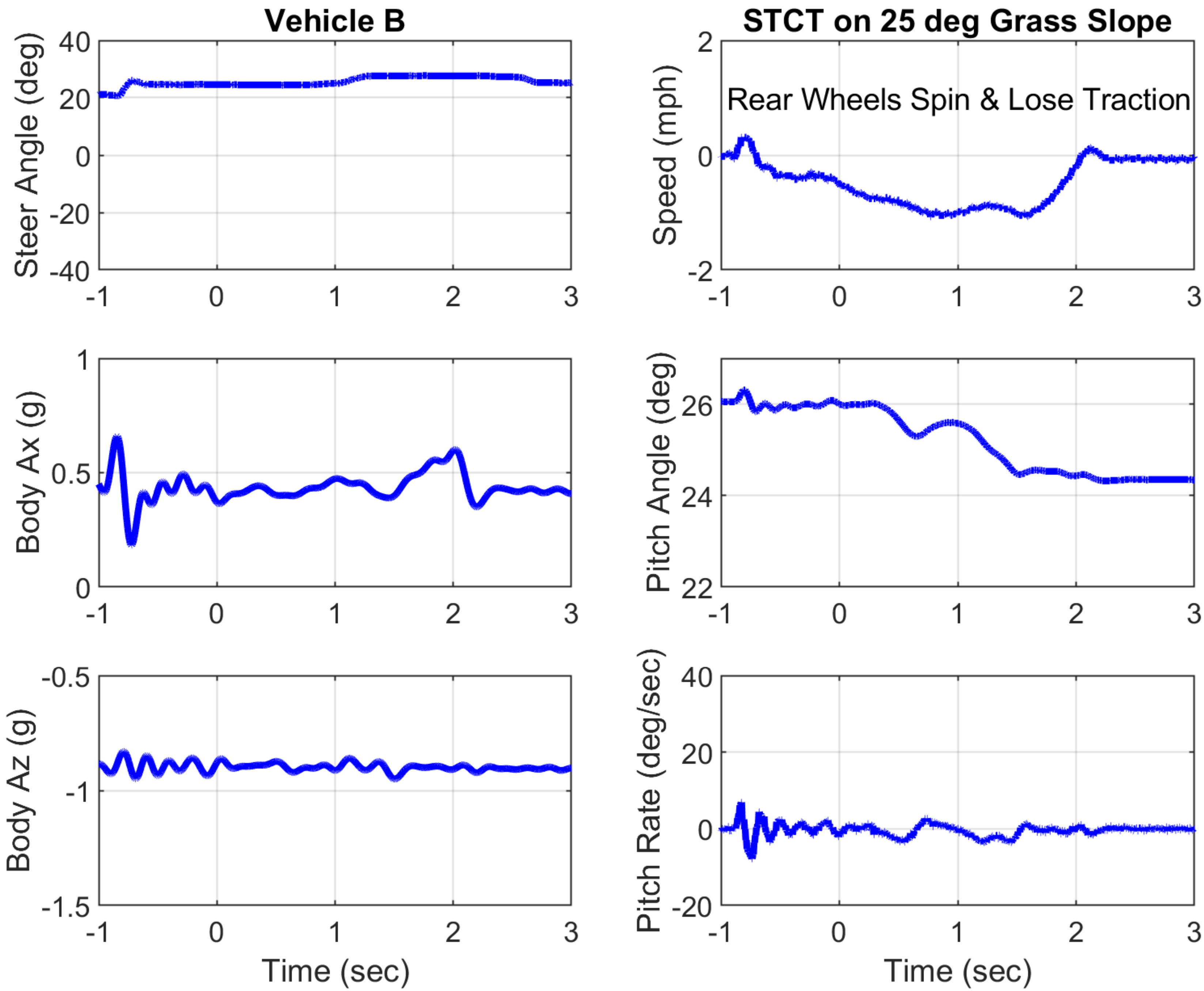

Vehicle B
Max Speed and Rapid Max Steering
Steer Angle (deg)
Right Turn
Left Turn
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

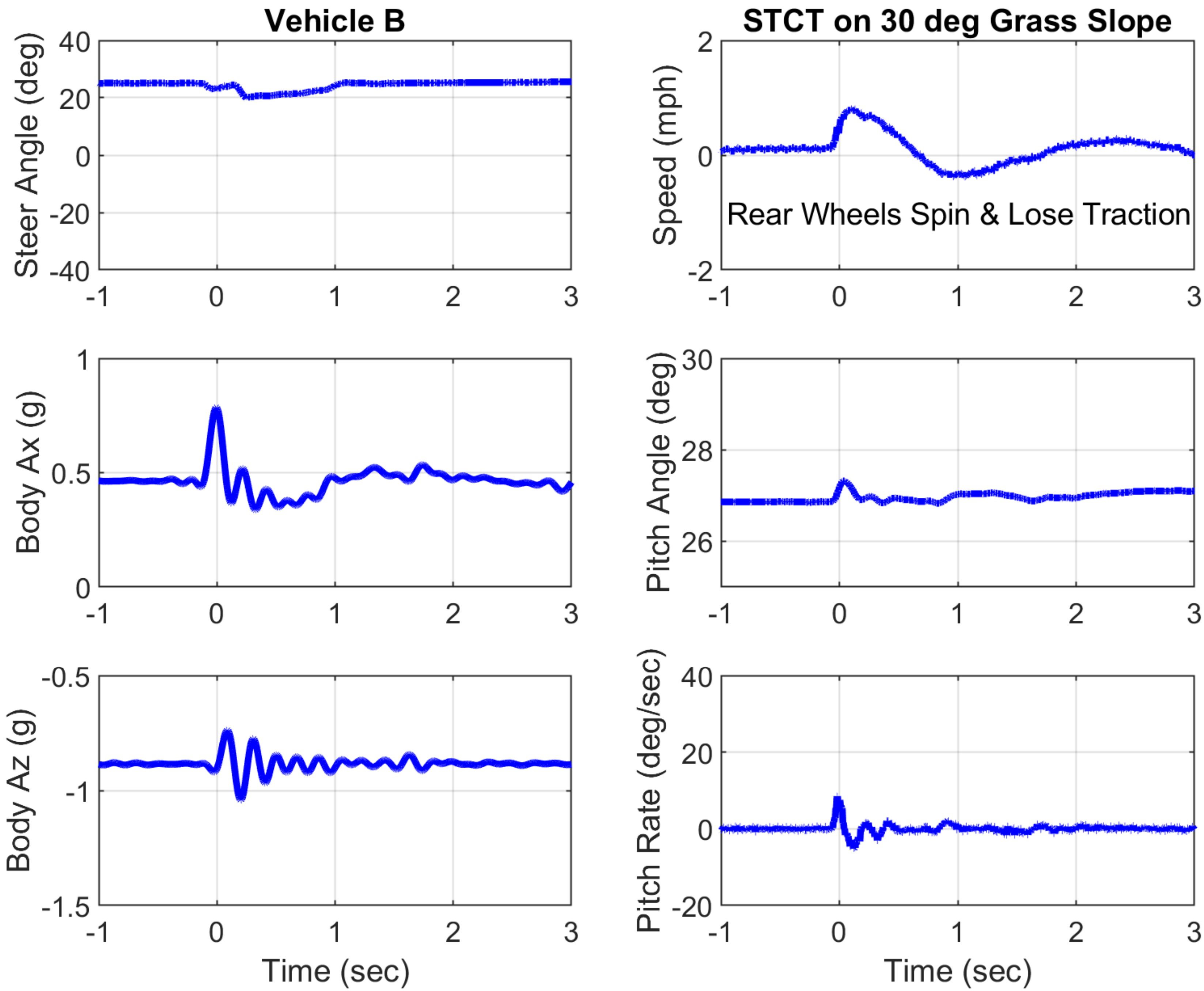

Vehicle B - Max Speed and Rapid Max Steering
North (m)
East (m)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-2
-1
0
1
2
3
Right Turn
Left Turn

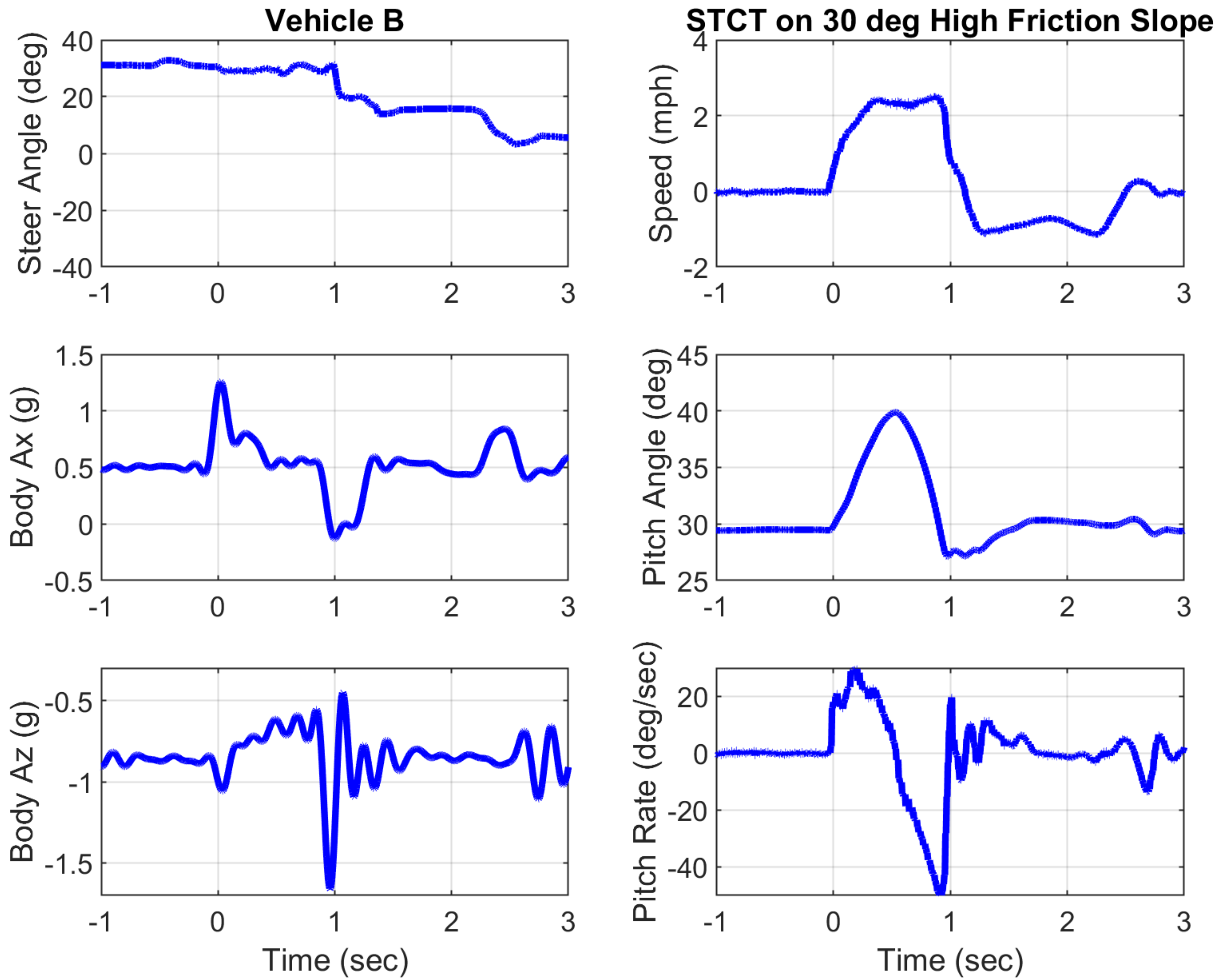

Vehicle B
STCT on Test Pad
Steer Angle (deg)
Speed (mph)
Body Ax (g)
Pitch Angle (deg)
Body Az (g)
Pitch Rate (deg/sec)
Time (sec)
Time (sec)


Vehicle B
STCT on 15 deg Grass Slope
Steer Angle (deg)
40
20
0
-20
-40
Speed (mph)
6
4
2
0
Body Ax (g)
1
0.5
0
Pitch Angle (deg)
18
16
14
Body Az (g)
-0.5
-1
-1.5
Pitch Rate (deg/sec)
40
20
0
-20
-1
0
1
2
3
Time (sec)
Time (sec)


Vehicle B
STCT on 20 deg Grass Slope
Steer Angle (deg)
40
20
0
-20
-40
-1
0
1
2
3
Speed (mph)
2
0
-2
Rear Wheels Spin & Lose Traction
Body Ax (g)
1
0.5
0
Pitch Angle (deg)
24
22
20
Body Az (g)
-0.5
-1
-1.5
Pitch Rate (deg/sec)
40
20
0
-20
Time (sec)
Time (sec)

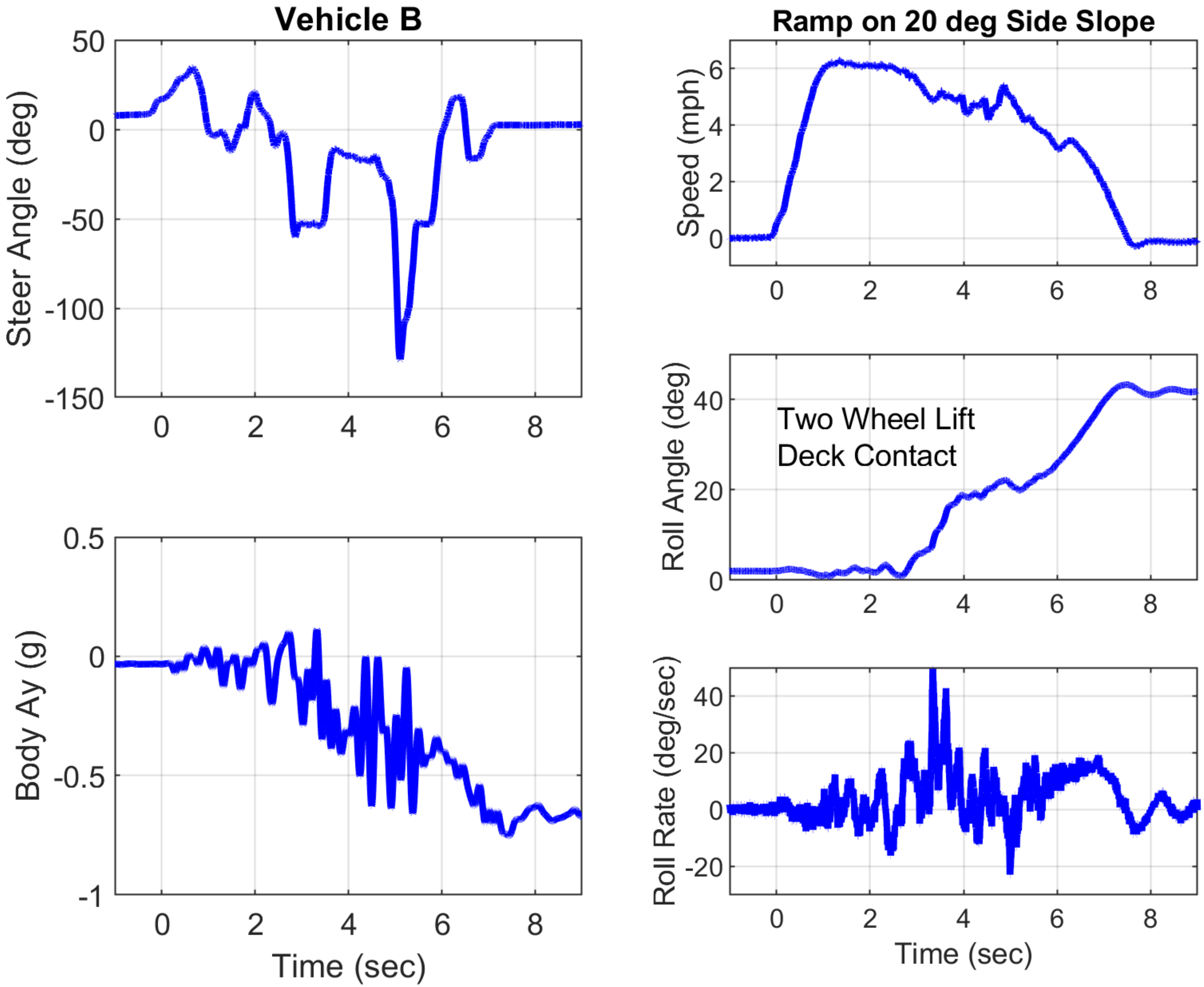

Vehicle B
STCT on 25 deg Grass Slope
Steer Angle (deg)
Speed (mph)
Rear Wheels Spin & Lose Traction
Body Ax (g)
Pitch Angle (deg)
Body Az (g)
Pitch Rate (deg/sec)
Time (sec)
Time (sec)


Vehicle B
STCT on 30 deg Grass Slope
Steer Angle (deg)
Speed (mph)
Rear Wheels Spin & Lose Traction
Body Ax (g)
Pitch Angle (deg)
Body Az (g)
Pitch Rate (deg/sec)
Time (sec)
Time (sec)



Vehicle B
STCT on 30 deg High Friction Slope
Steer Angle (deg)
40
20
0
-20
-40
-1
0
1
2
3
Speed (mph)
4
2
0
-2
Body Ax (g)
1.5
1
0.5
0
-0.5
Pitch Angle (deg)
45
40
35
30
25
Body Az (g)
-0.5
-1
-1.5
Time (sec)
Pitch Rate (deg/sec)
20
0
-20
-40
Time (sec)

Vehicle B – Rearward Tip-up to 40 deg Pitch Angle
(Sudden Acceleration on a 30 deg High Friction Slope)

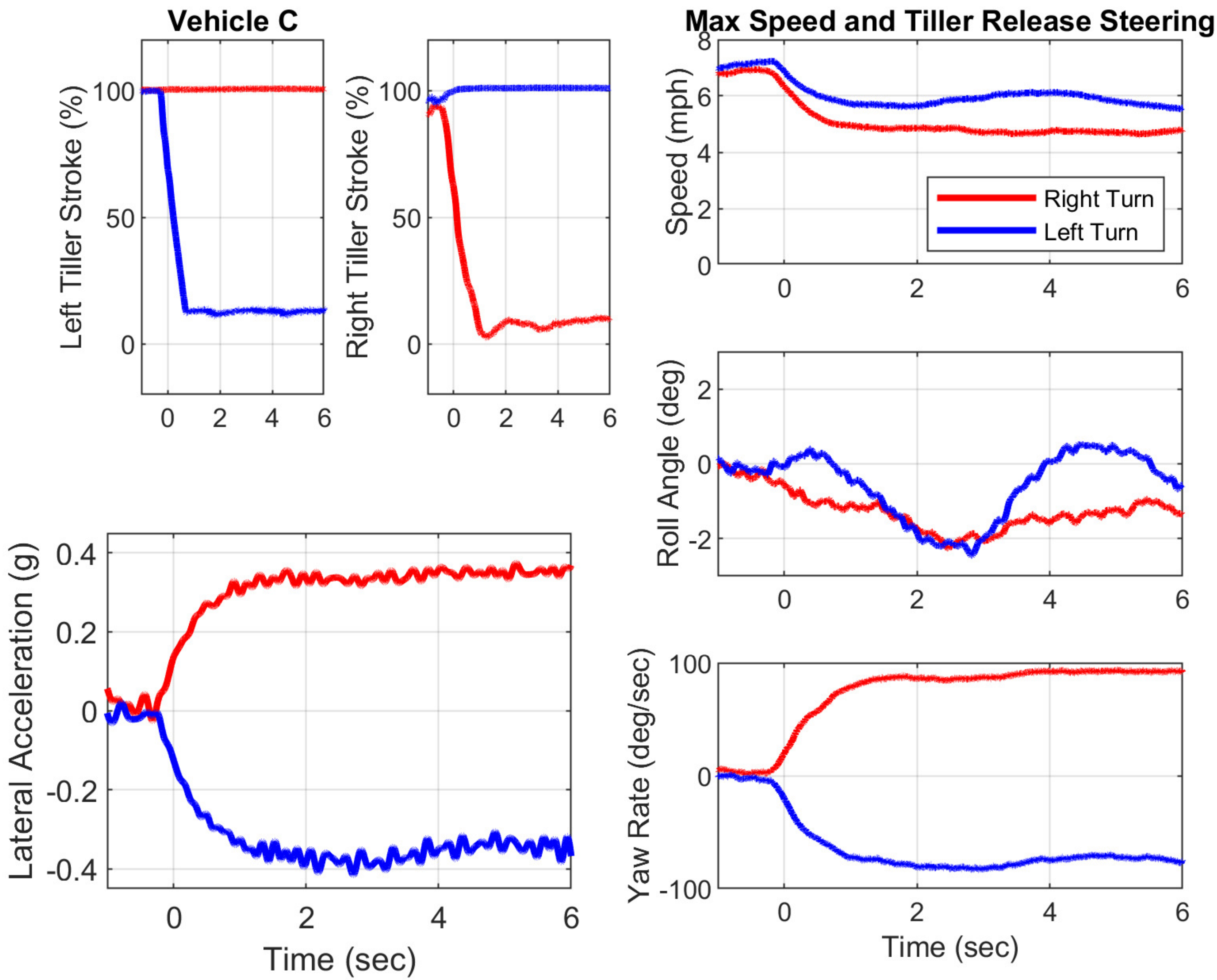

Vehicle B
Ramp on 20 deg Side Slope
Steer Angle (deg)
Speed (mph)
Roll Angle (deg)
Two Wheel Lift
Deck Contact
Body Ay (g)
Roll Rate (deg/sec)
Time (sec)
Time (sec)

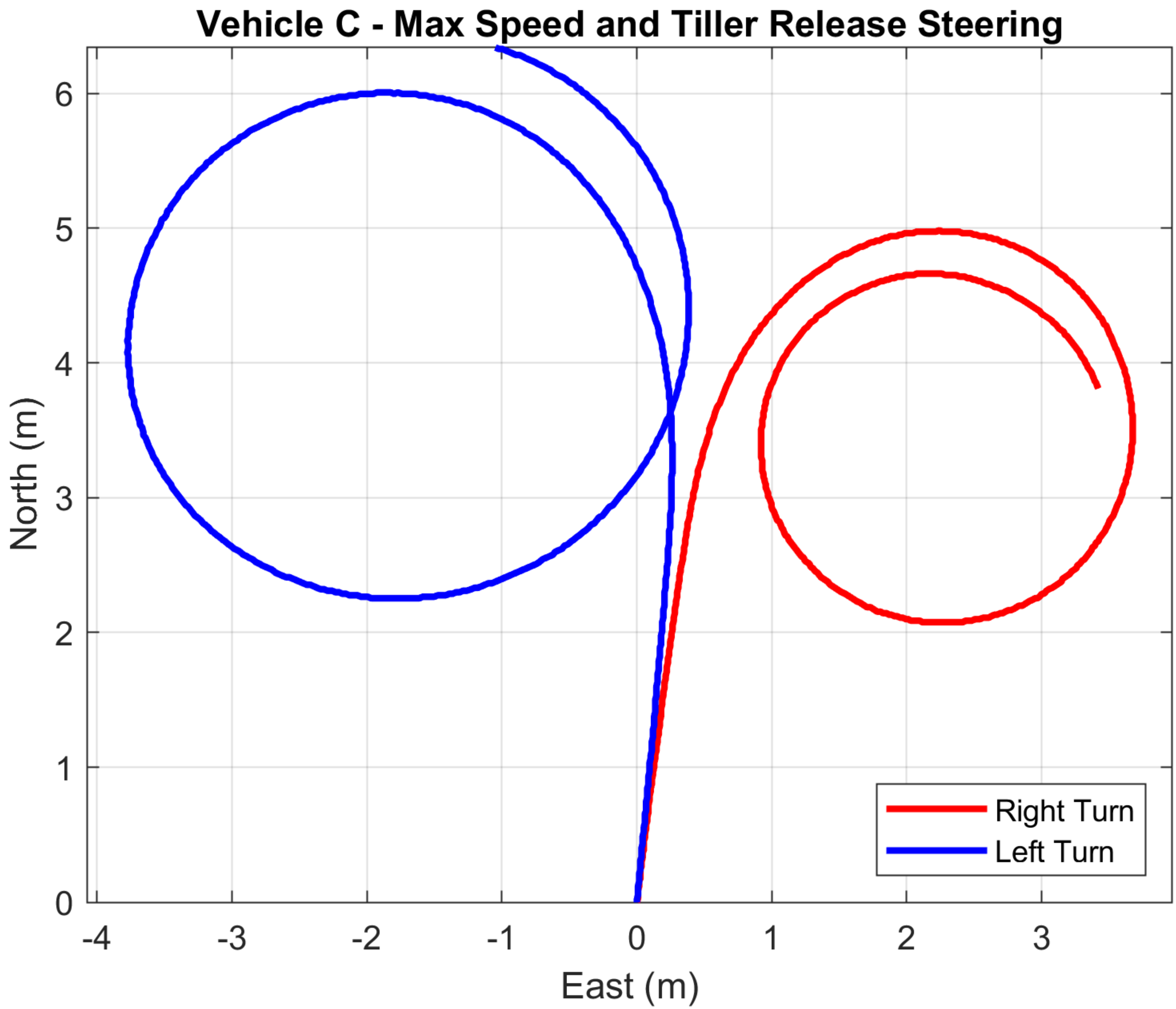
Vehicle B – Lateral Two Wheel Lift
(Driving On To 11½" Tall Ramp on 20 deg Side Slope)

Vehicle Part Way Up Ramp

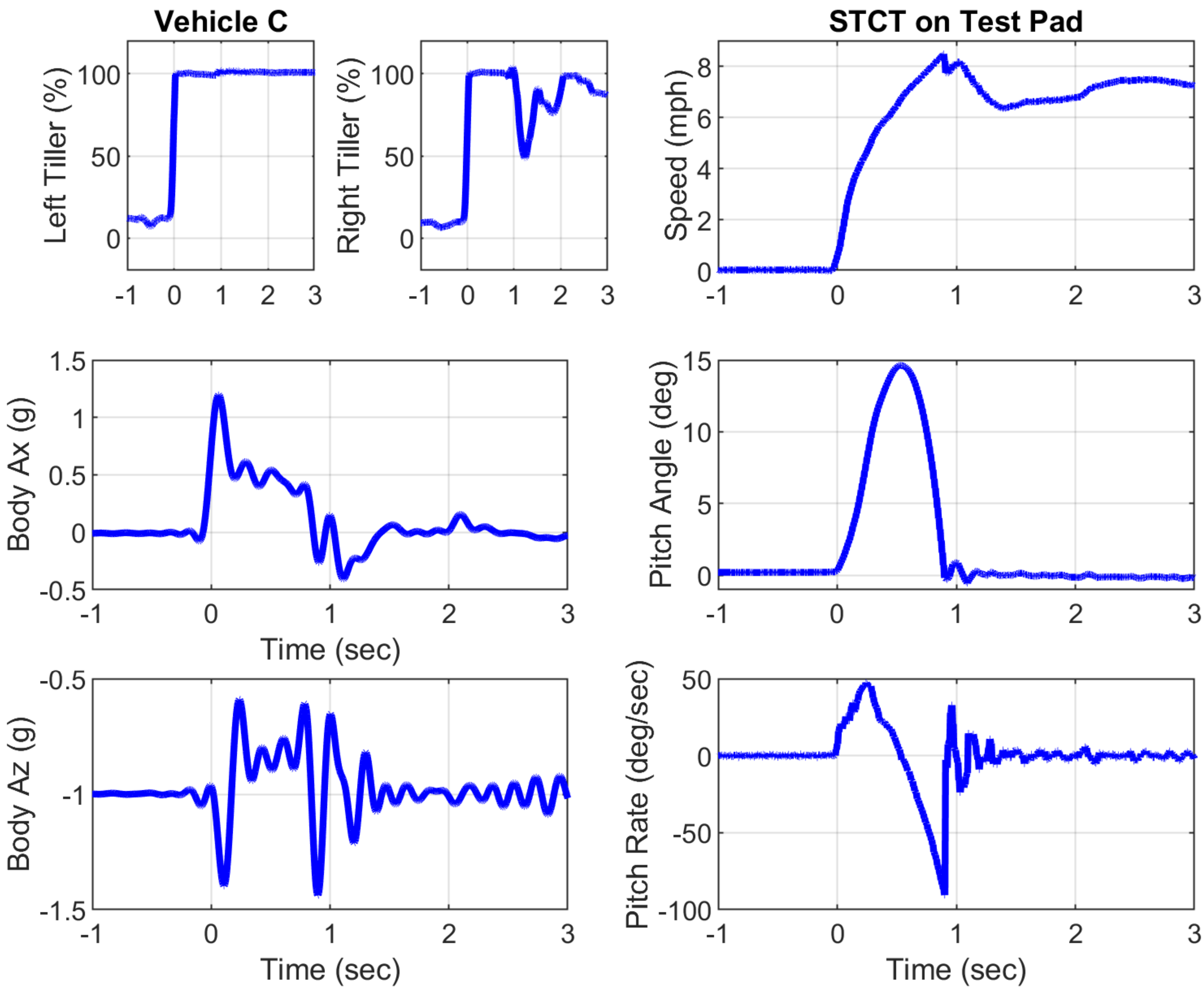
Two Wheel Lift

Vehicle Stopped and Resting
on Outer Edge of Mower Deck

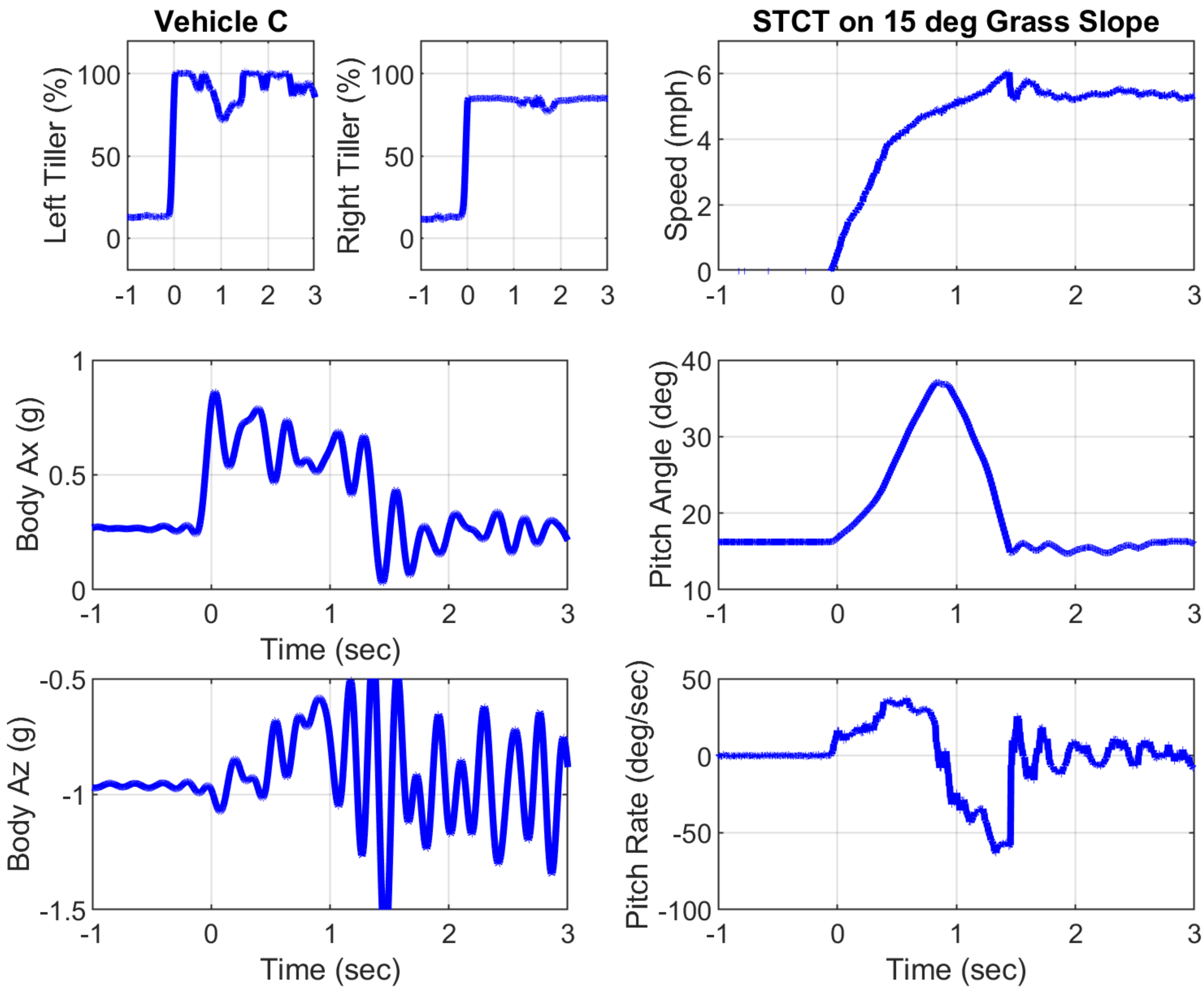

Vehicle C
Max Speed and Tiller Release Steering
Left Tiller Stroke (%)
Right Tiller Stroke (%)
Speed (mph)
Right Turn
Left Turn
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

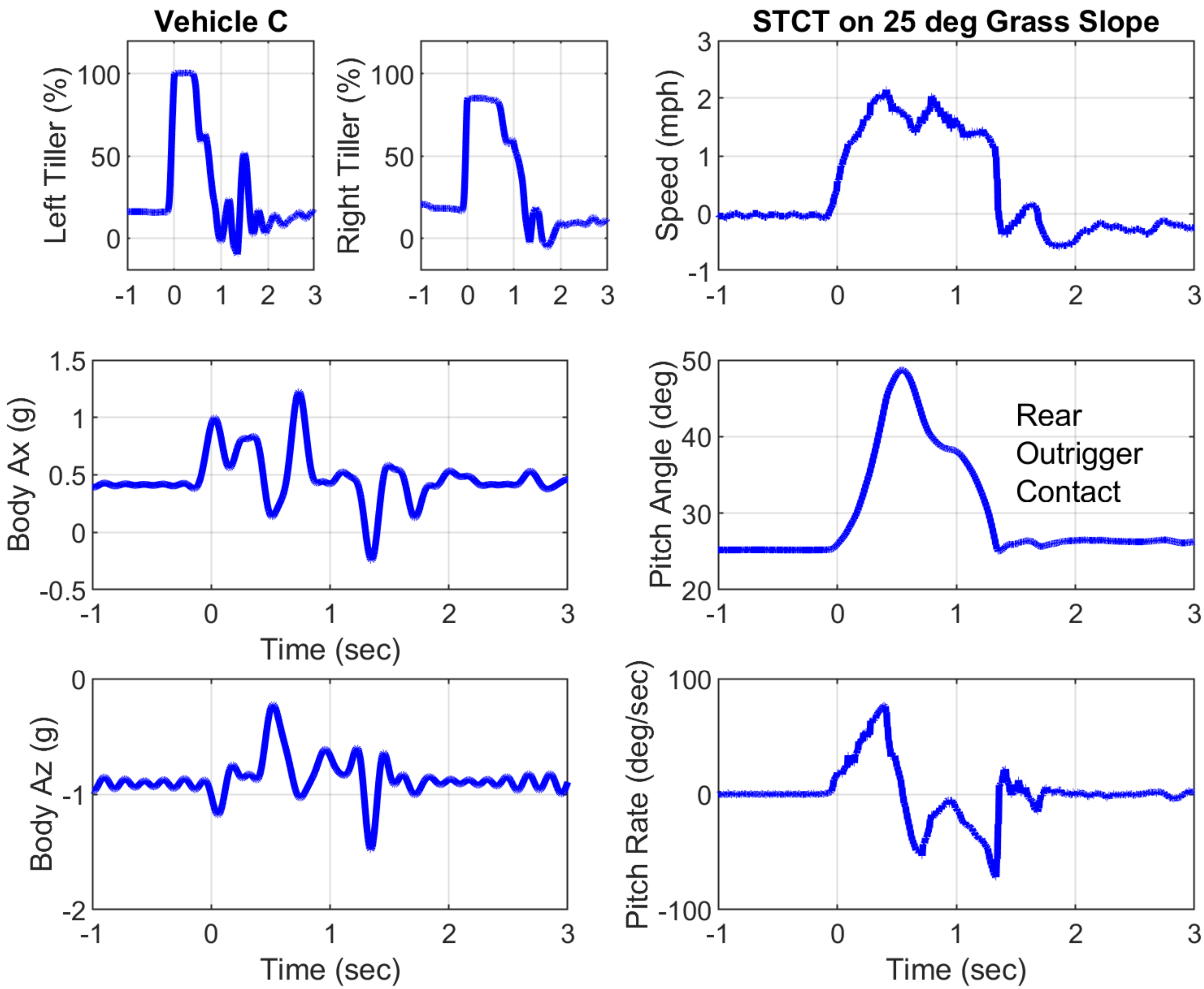


Vehicle C - Max Speed and Tiller Release Steering
North (m)
East (m)
0
1
2
3
4
5
6
-4
-3
-2
-1
0
1
2
3
Right Turn
Left Turn



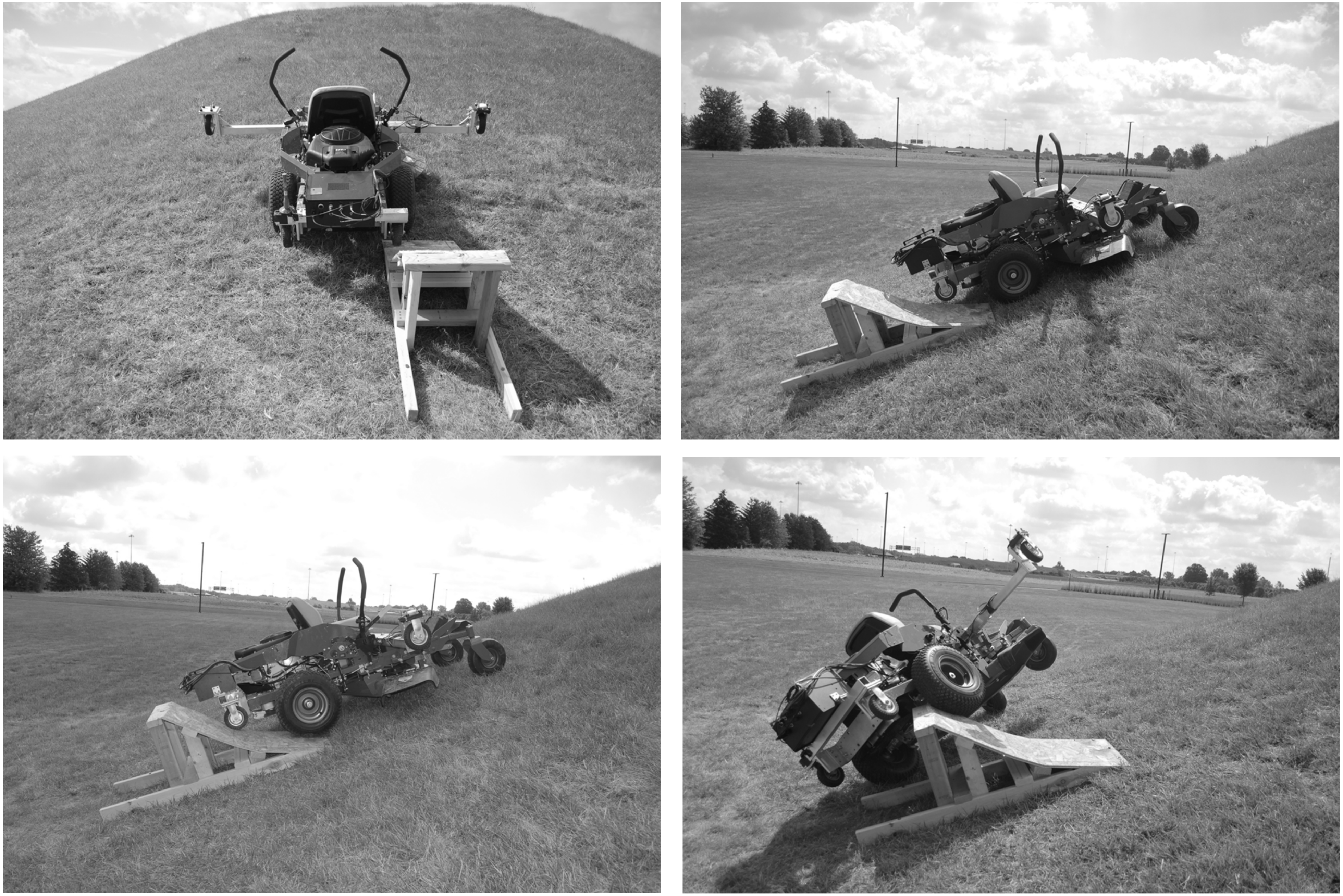
Vehicle C
STCT on Test Pad
Left Tiller (%)
Right Tiller (%)
Speed (mph)
Body Ax (g)
Pitch Angle (deg)
Body Az (g)
Pitch Rate (deg/sec)
Time (sec)
Time (sec)
Time (sec)


Vehicle C
STCT on 15 deg Grass Slope
Left Tiller (%)
Right Tiller (%)
Speed (mph)
Body Ax (g)
Pitch Angle (deg)
Body Az (g)
Pitch Rate (deg/sec)
Time (sec)
Time (sec)
Time (sec)

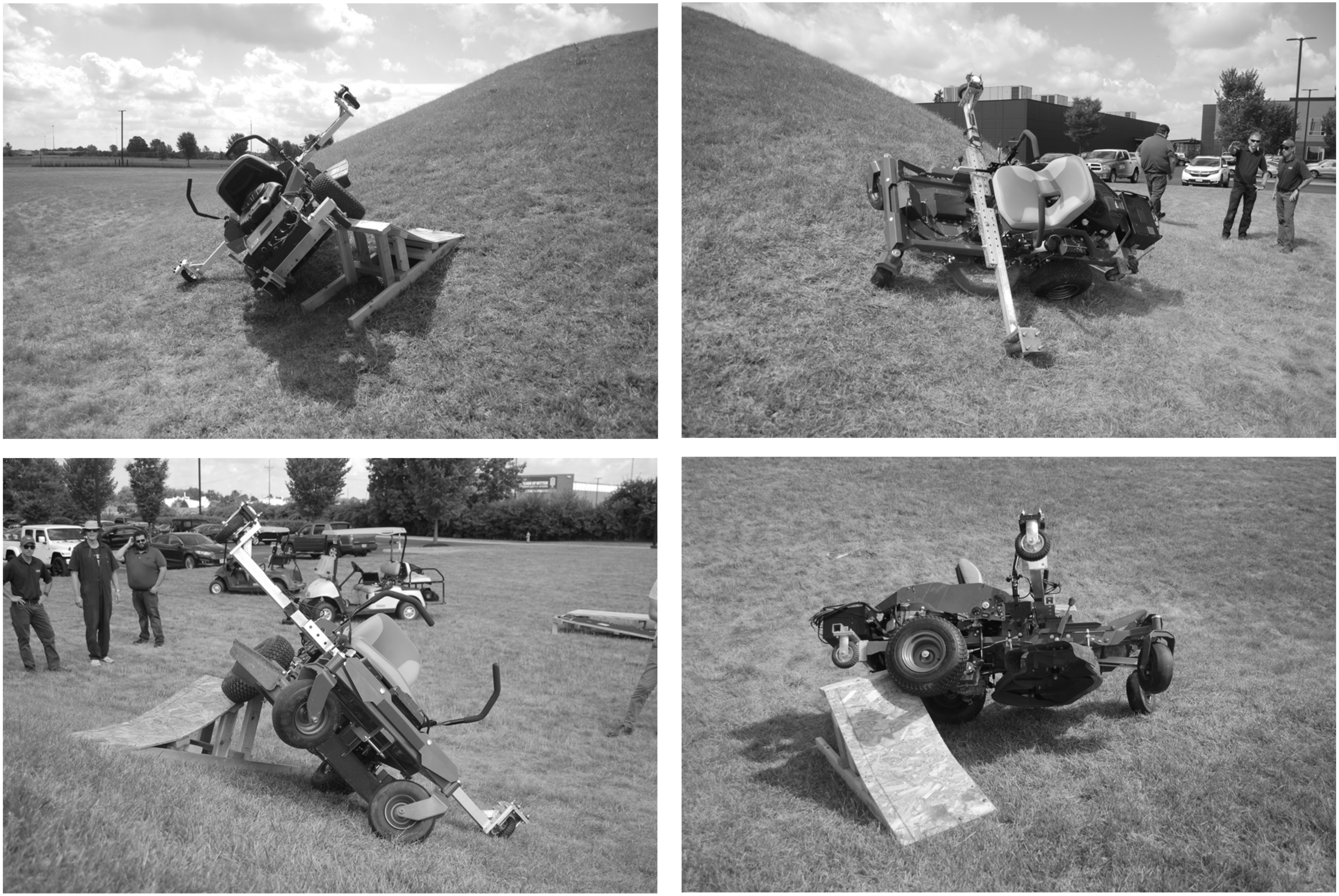


Vehicle C
STCT on 25 deg Grass Slope
Left Tiller (%)
Right Tiller (%)
Speed (mph)
Body Ax (g)
Pitch Angle (deg)
Rear
Outrigger
Contact
Body Az (g)
Pitch Rate (deg/sec)
Time (sec)

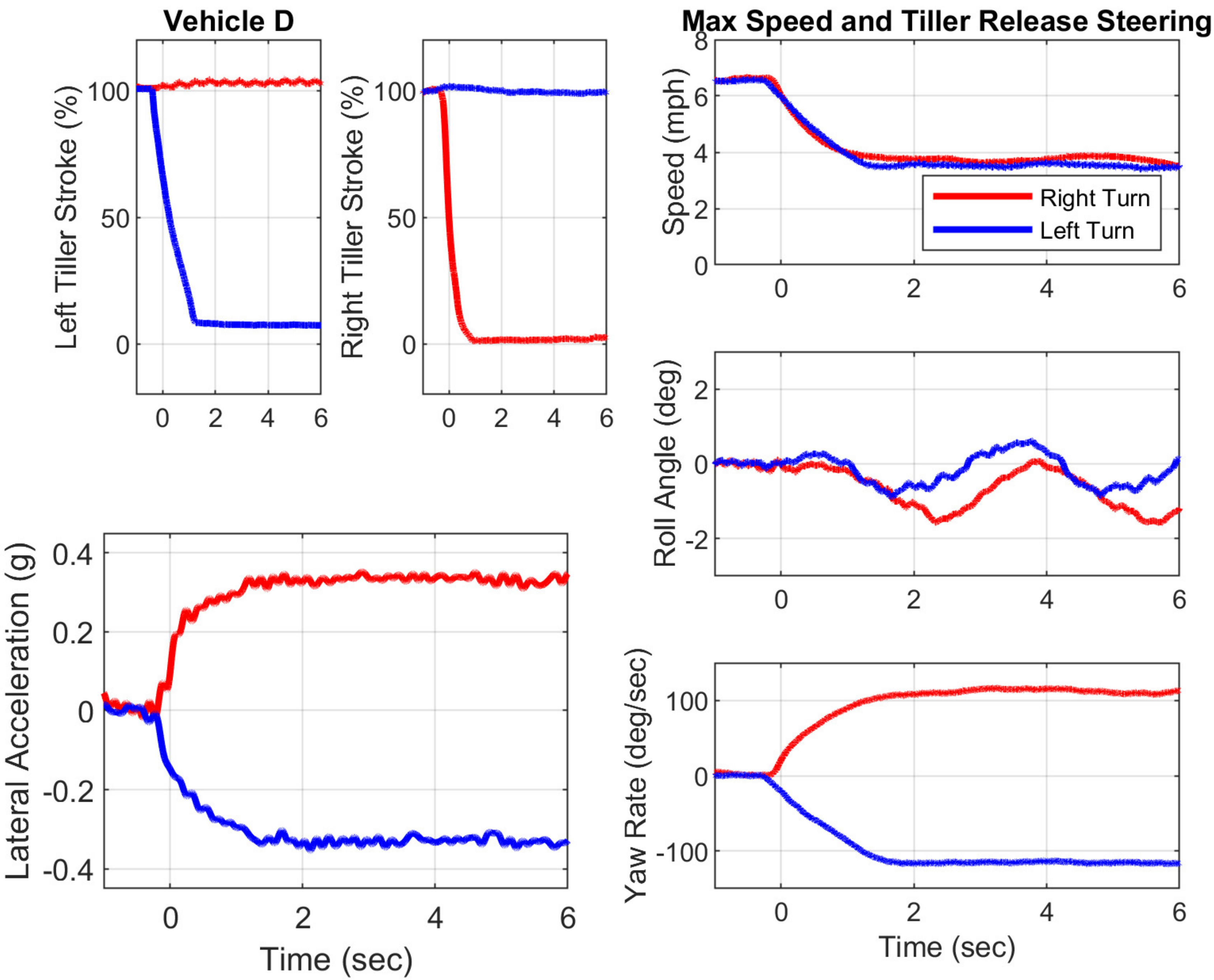
Vehicle C – Rearward Tip-up on to Outriggers
(Sudden Acceleration on a 25 deg Grass Slope)

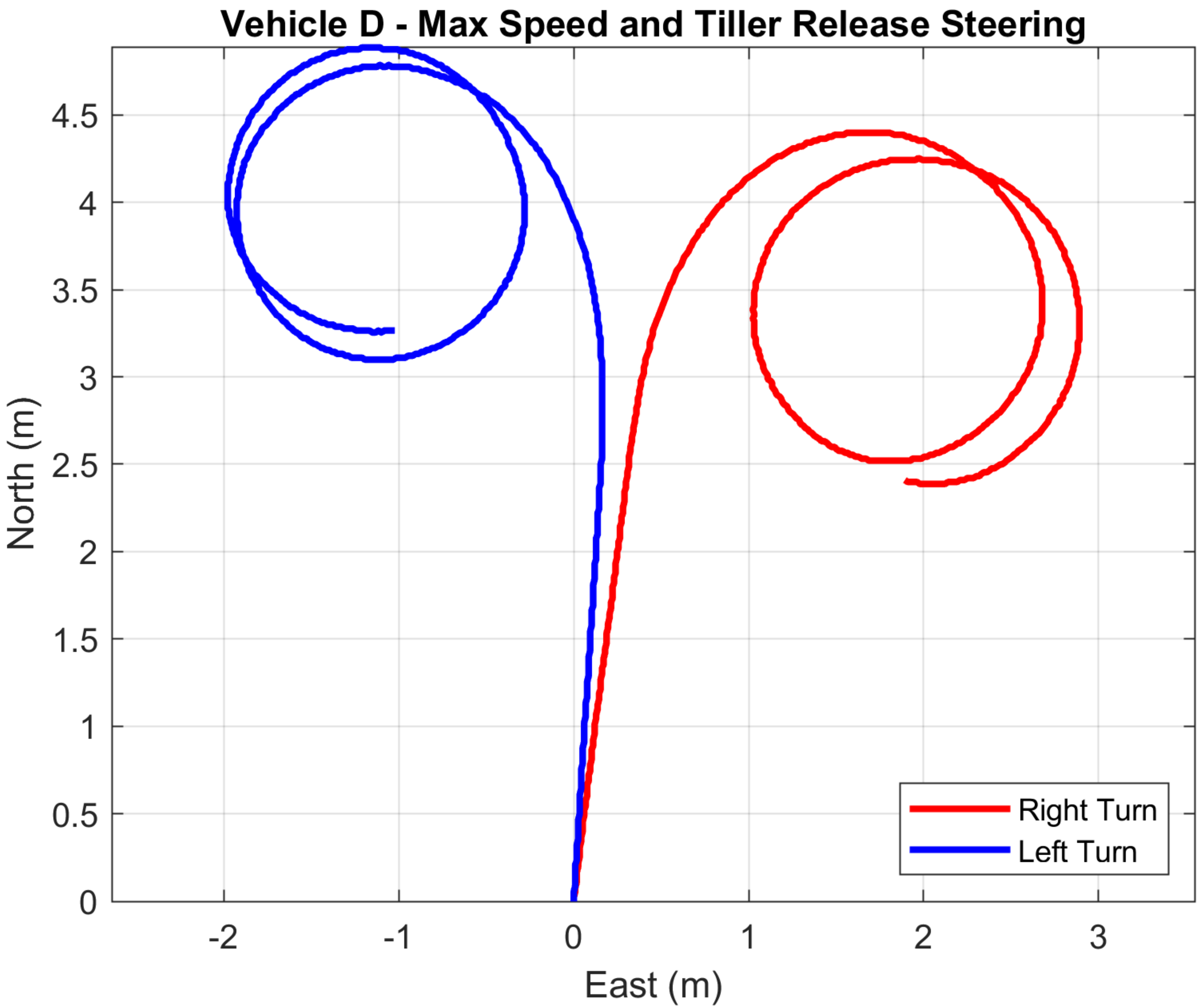


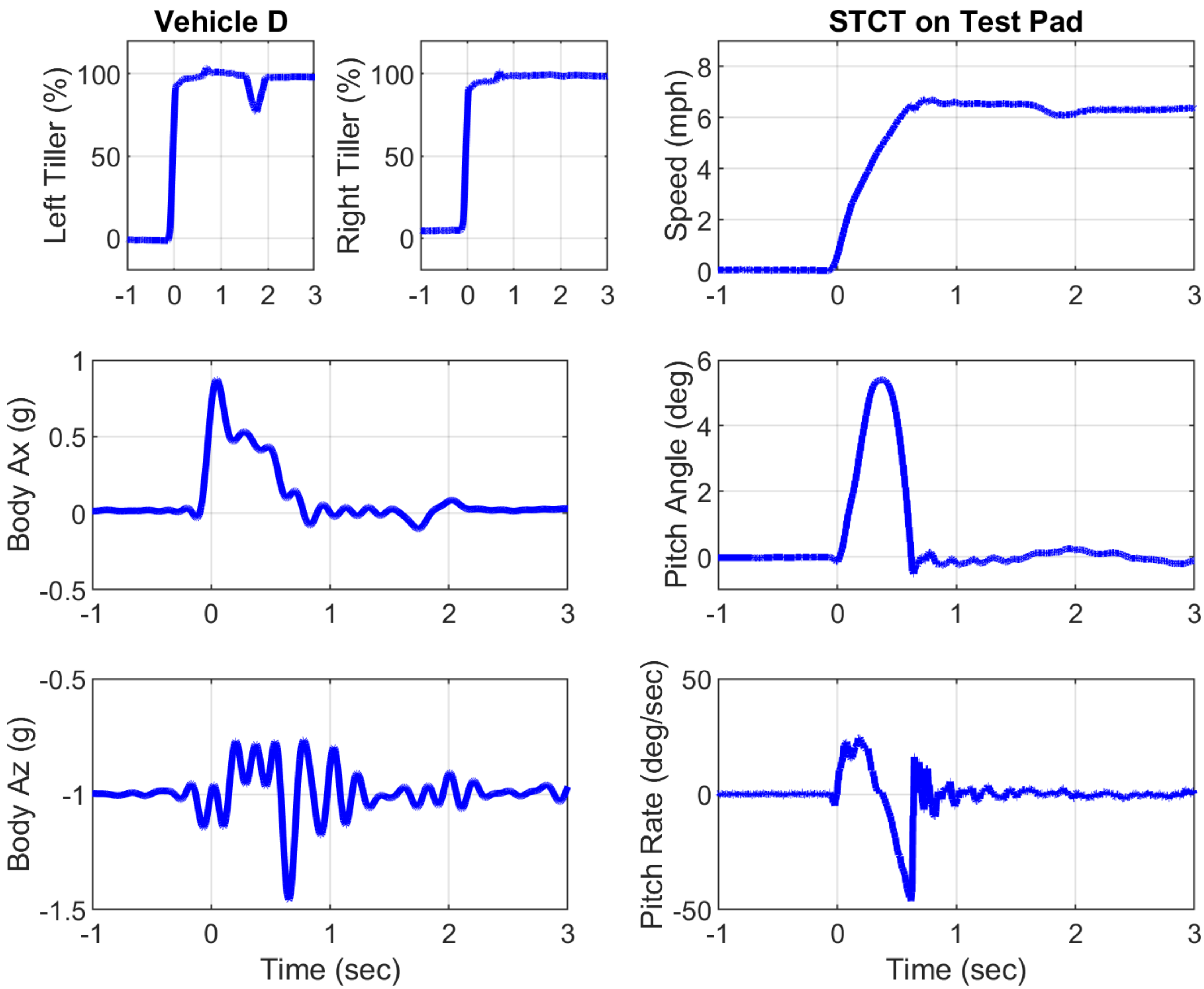
Vehicle C – Photo Sequence of Zero-Turn Mower Quasi-Lateral Tip-up

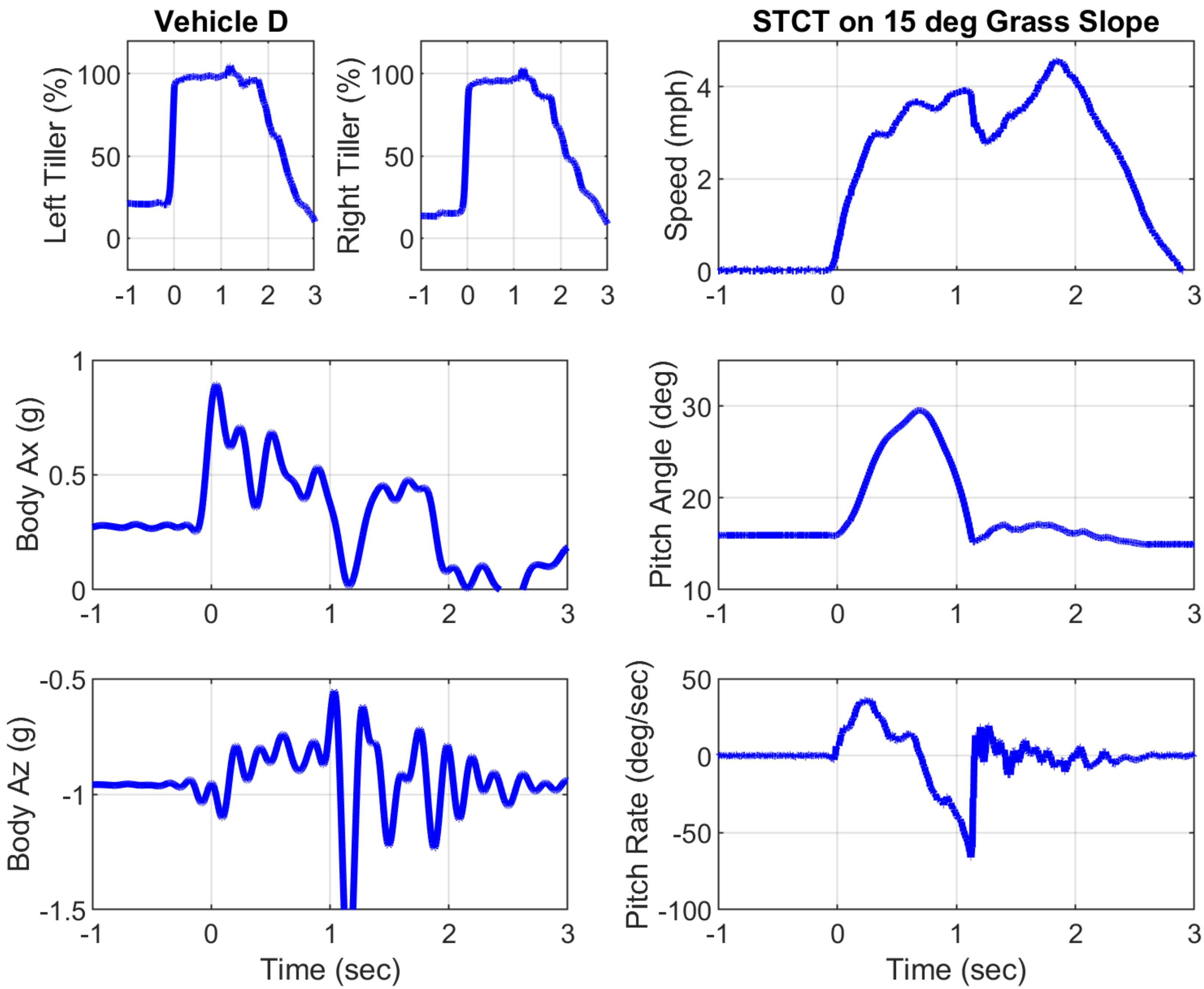


Vehicle C – Additional Photos of Zero-Turn Mower Quasi-Lateral Tip-up

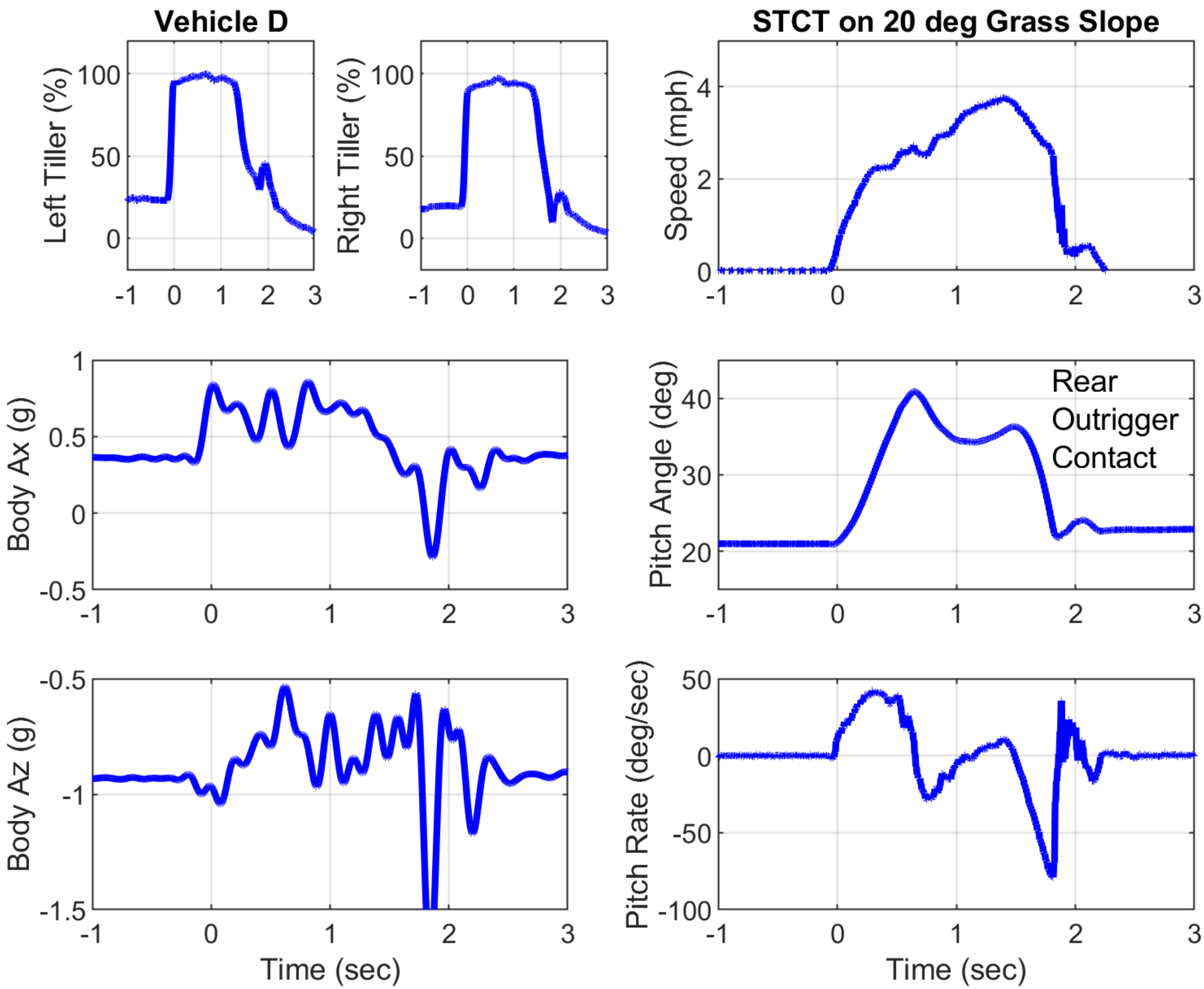

Vehicle D
Max Speed and Tiller Release Steering
Left Tiller Stroke (%)
Right Tiller Stroke (%)
Speed (mph)
Right Turn
Left Turn
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)


Vehicle D - Max Speed and Tiller Release Steering
North (m)
East (m)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
-2
-1
0
1
2
3
Right Turn
Left Turn


Vehicle D
STCT on Test Pad
Left Tiller (%)
Right Tiller (%)
Speed (mph)
Body Ax (g)
Pitch Angle (deg)
Body Az (g)
Pitch Rate (deg/sec)
Time (sec)
Time (sec)



Vehicle D
STCT on 15 deg Grass Slope
Left Tiller (%)
Right Tiller (%)
Speed (mph)
Body Ax (g)
Pitch Angle (deg)
Body Az (g)
Pitch Rate (deg/sec)
Time (sec)
Time (sec)



Vehicle D
STCT on 20 deg Grass Slope
Left Tiller (%)
Right Tiller (%)
Speed (mph)
Body Ax (g)
Pitch Angle (deg)
Rear
Outrigger
Contact
Body Az (g)
Pitch Rate (deg/sec)
Time (sec)
Time (sec)

Vehicle D – Rearward Tip-up on to Outriggers
(Sudden Acceleration on a 20 deg Grass Slope)

Photographs of Mowers on SEA Tilt Table

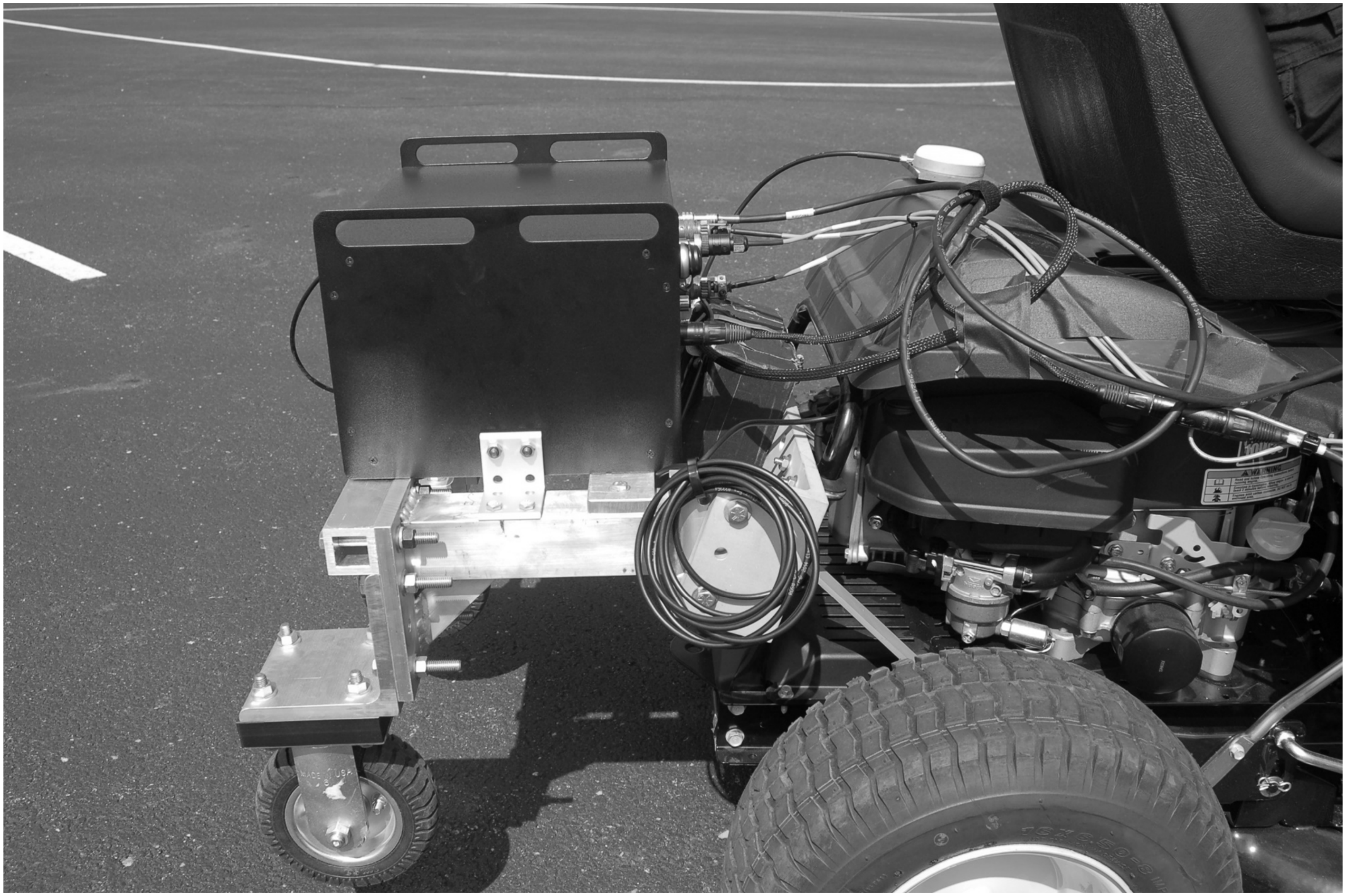
Front and Side Views of Small Tractor Mower

Front and Side Views of Large Tractor Mower

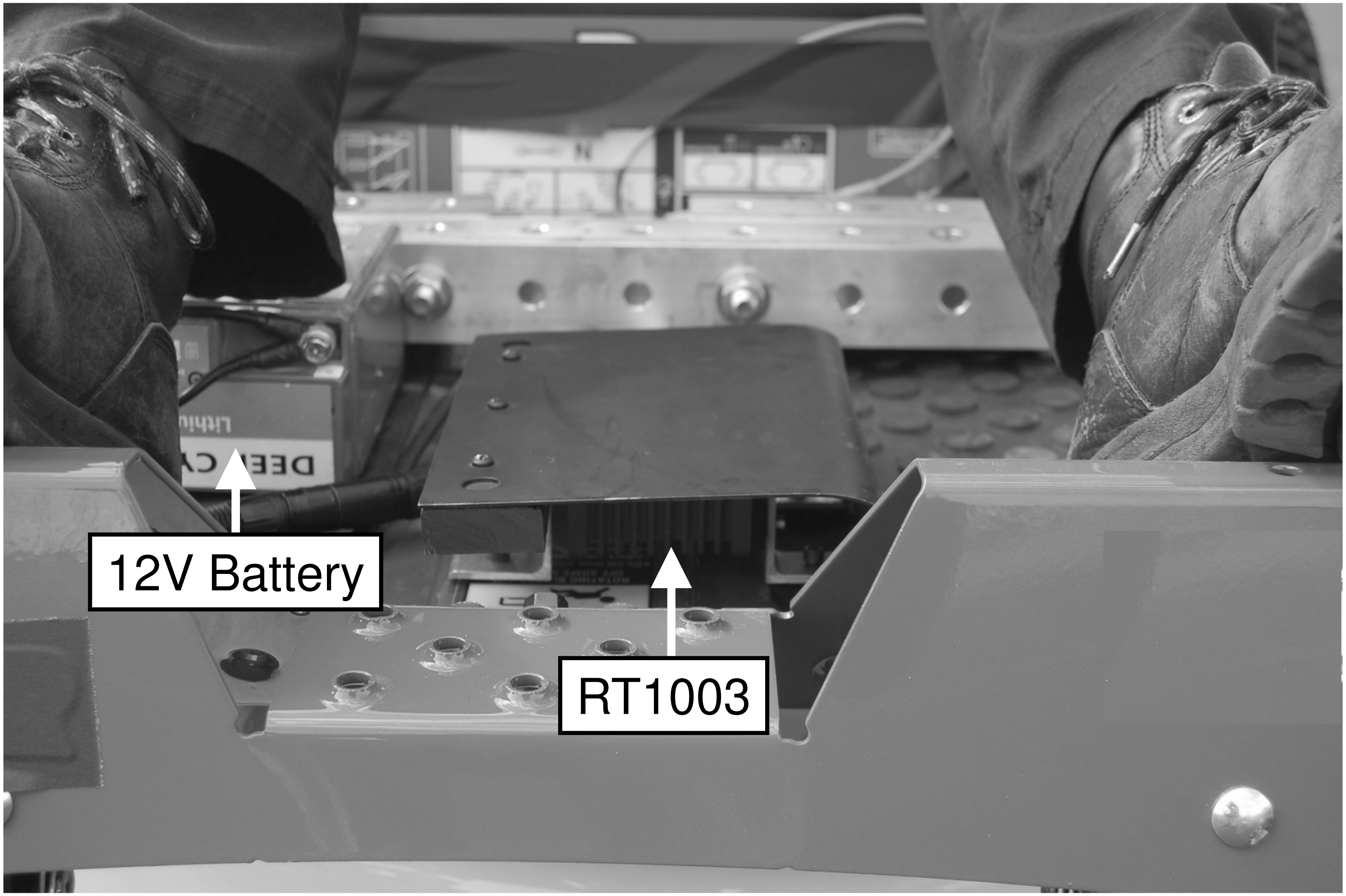
Front and Side Views of Small Zero-Turn Mower

Front and Side Views of Large Zero-Turn Mower

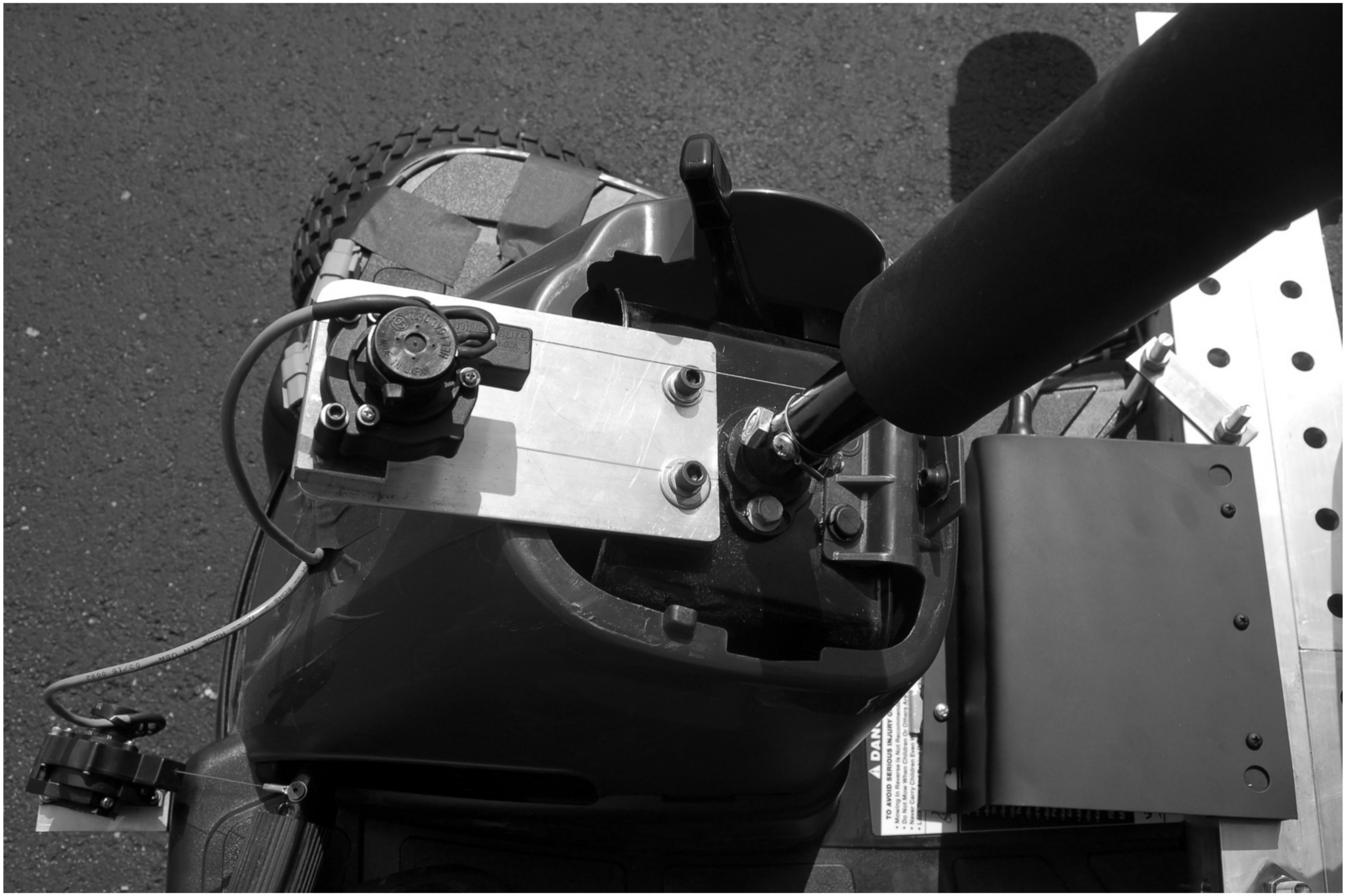
Rear Outrigger and Electronics Box Containing Data Acquisition System



Representative Locations of RT1003 GPS/IMU and 12V Battery in Footrest Area



Position Transducer Used to Measure Steering Angle on Tractor Mower



Position Transducer Used to Measure (Right Side) Tiller Stroke on Zero-Turn Mower