CPSC Staff Statement on SEA, Ltd. Report "All-Terrain Vehicle (ATV) Attribute Modification Study Results of Baseline Vehicle Testing"[1]
January 2016

The report titled, "All-Terrain Vehicle (ATV) Attribute Modification Study Results of Baseline Vehicle Testing," presents results for vehicle testing conducted by SEA Limited (SEA) on three 2014-2015 model year ATVs under contract CPSC-S-14-0047. The baseline testing results documented in the report includes static and dynamic characteristics data for the vehicles in their "as-received" configuration.

[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.

All-Terrain Vehicle (ATV)
Attribute Modification Study
Results of Baseline Vehicle Testing

for:
Consumer Product Safety Commission

June 2016

Vehicle Dynamics Division
7001 Buffalo Parkway
Columbus, Ohio 43229

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

Report prepared by Gary J. Heydinger, Ph.D., P.E.

Vehicle Dynamics Division
7001 Buffalo Parkway
Columbus, Ohio 43229

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1. OVERVIEW

This report contains results from laboratory and dynamic (test track) tests made by SEA on three 2014-2015 model year All-Terrain Vehicles (ATVs) for the Consumer Product Safety Commission (CPSC) under contract CPSC-S-14-0047.

The stated purpose and objective of the contract is:

> *The staff of the Consumer Product Safety Commission (CPSC) is evaluating various characteristics and features of ATVs. CPSC mechanical Engineering staff is focused on the stability and handling characteristics of the vehicles. This contract is to study modifications that can be made to all-terrain vehicles (ATVs) and how those modifications affect vehicle stability and handling.*

The contract includes overall tasks for: conducting baseline tests on the three vehicles in their as-received (baseline) conduction, making modifications to the vehicles (under direction from CPSC staff) to improve their lateral stability and/or handling characteristics, and conducting tests on the modified vehicles to verify improvement in performance as compared to the vehicles in their baseline conditions. This report contains results from the first overall task, making measurements on the baseline vehicles. The vehicles are designated Vehicle B2, Vehicle E2 and Vehicle L2.

The laboratory testing included measuring each vehicle's center-of-gravity (CG) location, inertia properties, front and rear track widths, wheelbase, and front and rear overall suspension roll stiffness. From these measurements, calculations were made to compute static stability factor (SSF) and lateral stability coefficient (KST). The dynamic tests included circle tests, J-turn tests, and sinusoidal sweep steering tests. Results from these were used to quantify each vehicle's lateral stability performance and handling characteristics.

This report has four main sections (Overview, Laboratory Testing, Dynamic Testing, and Discussion of Test Results) and two appendices (Appendix A: Results from Laboratory Tests and Appendix B: Results from Dynamic Tests).

2. LABORATORY TESTING

This section describes the laboratory measurements as well as computations made to compute various rollover resistance metrics and other vehicle characteristics. This section is divided into two parts, one covering the vehicle characteristics and metrics determined from Vehicle Inertia Measurement Facility (VIMF) testing and one covering the other laboratory measurement made, overall suspension roll stiffness. Tabular results from all of the measurements and metrics discussed in this section are contained in Appendix A.

2.1 Vehicle Characteristics and Metrics Determined from VIMF Testing

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)[1]. Measurements of front track width, rear track width, and wheelbase were also made. SEA conducts measurements of vehicle CG height, average track width, and Static Stability Factor (SSF) for the National Highway Traffic Safety Administration (NHTSA) New Car Assessment Program (NCAP). Where applicable, the same protocols and equipment used for the NCAP testing were used during this CPSC testing.

The VIMF tests were conducted in one loading condition:

Operator, Instrumentation, and Outriggers Loading Condition
This loading condition was specified to be the vehicle curb condition plus the weight of the actual test driver, test instrumentation (including measurement transducers, data acquisition computer, and SEA's All-Terrain Vehicle Automated Steering Controller (ATV ASC)), and ATV safety outriggers. The total nominal weight of the instrumentation, driver and outriggers is 254 lb. Table 1 provides a listing of the component weights.

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

SSF is a fundamental rollover resistance metric which equals the lateral acceleration in g's 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.

KST is similar to SSF in that it represents the acceleration in g's at which rollover begins in the

[1] *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.

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, KST and SSF are equal. KST is given by:

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

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

2.2 Overall Suspension Roll Stiffness Measurements

Figure 1 is a diagram of the setup used to measure the overall suspension roll stiffnesses. Upward and downward forces were applied to the ends of a bar (actually the main component of the ATV outriggers) attached to the underside of the test vehicle to impose a roll moment on to the chassis of the vehicle. Vertical force detecting scales were positioned under each of the four tires, and these provided measurements for computing the front and rear suspension roll moments. The chassis roll angle was also measured during the tests. The linear slopes of the graphs of suspension front and rear roll moments versus roll angle were computed, and these are the overall front and rear roll stiffnesses.

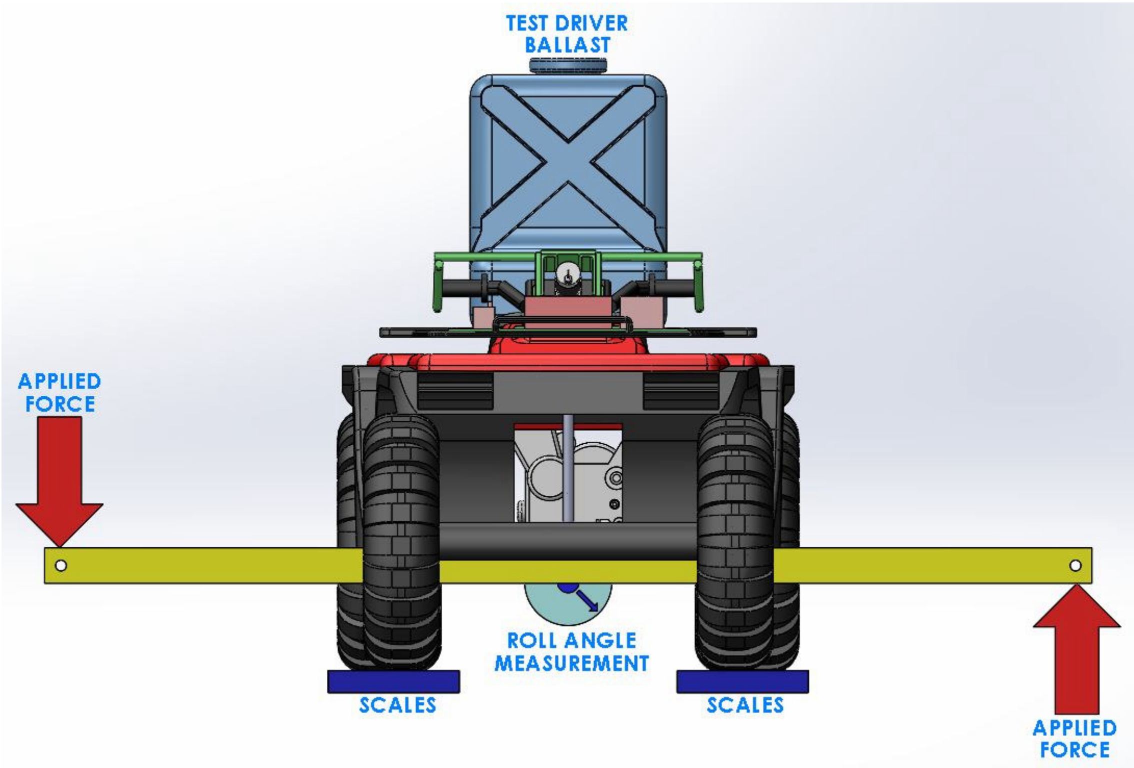

Figure 1: Diagram of Front and Rear Suspension Roll Stiffness Measurements

3. DYNAMIC TESTING

This section describes the dynamic testing conducted at the North Carolina Center for Automotive Research (NCCAR) between March 16 and March 19, 2015. The dynamic test evaluations included steering maneuvers on the flat dry asphalt surface of NCCAR's vehicle dynamics area.

All of the dynamic tests were performed in one loading configuration, namely:

Operator, Instrumentation, and Outriggers
This loading condition was specified to be the vehicle curb condition plus the weight of the actual test driver, test instrumentation (including measurement transducers, data acquisition computer, and SEA's All-Terrain Vehicle Automated Steering Controller (ATV ASC)), and ATV safety outriggers. The total nominal weight of the instrumentation, driver and outriggers is 254 lb. Table 1 provides a listing of the component weights.

Table 1: Weights of Instrumentation, Driver and Outriggers

Object	Weight (lb)
ATV ASC: Motor/Controller/Enclosures/Fasteners/Wires	34
RT3002 GPS/IMU, Antenna, and Cables	7
Auxiliary Batteries: Two 12V 5Ah Batteries	7
Test Driver	177
ATV Aluminum Underbody Outriggers	29
Total Nominal Weight	**254**

Table 2 lists the instrumentation used during the dynamic testing.

The RT3002 was mounted at the front of each vehicle; on a custom perforated steel plate that also supported the ATV ASC motor and electronics. For each vehicle, the longitudinal, lateral, and vertical offsets from the center of the RT3002 to the actual vehicle CG location were measured and entered into the RT3002 system software. This information was used to translate the measured quantities to those at the CG of the loaded vehicle. The lateral accelerations measured and reported herein are accelerations parallel to the road plane, as opposed to vehicle body-fixed accelerations.

Table 2: Instrumentation Used During Dynamic Testing			
Transducer	**Measurement**	**Range**	**Accuracy**
Oxford Technical Solutions RT3002 Inertial and GPS Navigation System	Longitudinal, Lateral, and Vertical Accelerations	± 100 m/s^2 (± 10 g)	0.01 m/s^2 (0.001 g)
	Roll, Pitch, and Yaw Rates	± 100 deg/s	0.01 deg/s
	Speed	No Limit Specified	0.05 km/h (0.03 mph)
	Roll and Pitch Angles	-180 to +180 deg	0.03 deg
	Vehicle Heading	0 to 360 deg	0.1 deg
Encoder on SEA ATV ASC	Handbar Steering Angle	No Limit Specified	± 0.1 deg

The following suite of three different types of dynamic tests was performed using each test vehicle:

- **Constant Radius (70 ft) Circle Tests**
- **Dropped-Throttle J-Turn (Step Steer) Tests (Initial Speed of 30 mph)**
- **Sinusoidal Sweep Steering Tests (Nominal Speed of 20 mph)**

Results from all of the dynamic tests (as well as plots of the roll stiffness measurements) are contained in Appendix B.

3.1 Constant Radius (70 ft) Circle Tests

Constant radius circle tests were used to evaluate the vehicles' understeer characteristics[1]. A constant radius circle test involves driving a vehicle on a circular path of constant radius (70 ft in this case). The test vehicles were driven in the clockwise and counterclockwise directions. For this testing, each vehicle was driven from a very low speed up to the speed that caused the vehicle to tip-up onto its safety outriggers.

The slowly increasing speed method as opposed to a discrete speed method was used for these tests. It is more efficient to conduct slowly increasing speed circle tests than discrete speed circle tests, and the data reduction process is more straightforward.

The constant radius circle tests were used to determine handlebar steer angle gradients. The

[1] SAE Surface Vehicle Recommended Practice - Steady-State Directional Control Test Procedures For Passenger Cars and Light Trucks, SAE J266, 1996.

handlebar steer angle gradients are the slopes of the characteristic curves of handlebar steer angle versus lateral acceleration. The circle tests were also used to determine if the vehicles transitioned from understeer to oversteer during the tests. Finally, roll gradients, vehicle roll angle response as a function of lateral acceleration, were computed from these tests.

3.2 Dropped-Throttle J-Turn (Step Steer) Tests (Initial Speed of 30 mph)

J-turn tests, often referred to as step steer tests, involve imparting a rapid steering input up to a fixed magnitude while the vehicle is traveling along a straight path. For the dropped-throttle J-Turn tests, the test driver drove each vehicle along a straight-line path at a speed slightly above 30 mph. He then dropped the throttle and triggered the ASC to initiate the steering input precisely when the vehicle speed reached 30 mph.

The test procedure used to determine threshold lateral acceleration (Threshold Ay) for these ATV tests is similar to that used for CPSC ROV tests to determine Threshold Ay. Basically, the steering input used for the J-Turn is increased until the test run results in two-wheel lift. For all of these ATV J-Turn tests, the handlebar steering rate used was 30 deg/sec.

Tests were run in two opposite heading directions, and both right turn and left turn tests were run in both heading directions. Several (from two to five) runs were conducted in each heading and steer direction.

For this testing, tip-up events were considered those that produced visual two-wheel lift. These tests provided a measure of the minimum peak lateral acceleration (Threshold Ay) required to cause two-wheel lifts during the tests.

3.3 Sinusoidal Sweep Steering (Frequency Response) Tests (20 mph)

Sinusoidal sweep steering input tests were conducted at 20 mph. The sinusoidal sweep steering maneuvers involved driving the vehicles at a nominal constant speed of 20 mph along an essentially straight-line path while steering in a sinusoidal manner with steering amplitude necessary to generate nominally 0.1-0.3 g of lateral acceleration. For the ATVs, handlebar steering amplitudes of 5.0 degrees were used for these tests. The ATV ASC was used for these tests, and it was commanded to sweep the steering input frequencies from 0.5 to 3.5 Hz over the course of 40 cycles. The total duration of the ASC steering input to complete the frequency sweep during these tests is close to 24 seconds.

The sinusoidal sweep steering tests were done to investigate any issues that might result from exciting a resonant frequency in the vehicles' responses. The sinusoidal sweep steering maneuvers were also used to generate the lateral acceleration, roll angle, roll rate, and yaw rate frequency responses to steering inputs.

4. DISCUSSION OF TEST RESULTS

4.1 Discussion of Appendix A: Laboratory Test Results

Appendix A contains tabular results of laboratory measurements made by SEA. There are three pages of results, one page for each vehicle. The first 19 rows of each table contain quantities related to the mass (weight), center-of-gravity location, and inertia measurements, as well as static rollover propensity calculations, based on measurements made using the VIMF. The final two rows contain measured values for the front and rear suspension overall roll stiffness.

VIMF tests were conducted on all vehicles in their Operator, Instrumentation and Outriggers configurations. For the Curb configurations only the vehicle weight was measured (i.e. no VIMF tests were conducted for this loading configuration).

4.2 Discussion of Appendix B: Results from Dynamic Tests

All of the results from the dynamic tests are contained in Appendix B. Appendix B has 39 pages, 13 pages for each vehicle. Pages 1-13 contain results for Vehicle B2, Pages 14-26 contain results for Vehicle E2, and Pages 27-39 contain results for Vehicle L2.

4.2.1 Discussion of Constant Radius (70 ft) Circle Test Results

Constant radius circle test results are contained in the first four pages for each vehicle, showing results from both the clockwise (CW) and counterclockwise (CCW) circle tests. The first page shows time domain plots of Steer Angle, Lateral Acceleration, Speed, Roll Angle, and Yaw Rate. All of the dynamic test data is sampled at 200 Hz. For the circle test results, the data shown was digitally low-pass filtered to 1.0 Hz using a phaseless, eighth-order, Butterworth filter. The circle tests conducted are quasi steady-state tests, so using a 1.0 Hz low-pass filter on the vehicle response data is appropriate and typical. The time domain data shown for each vehicle contains all of the data from the time the test driver started the data acquisition (prior to starting to move on the circle) to the time the test driver ended the data acquisition at the end of the test. The thin black lines for the CW and CCW tests show this full range of data. The thicker lines (red for CW and blue for CCW) indicate the range of data from the time the vehicle attained a speed of 3.2 mph, which is a lateral acceleration of 0.01 g on a 70 ft radius circle, until the vehicle attained a speed of 20.5 mph, which is a lateral acceleration of 0.40 g on a 70 ft radius circle. This range of data, from 0.01 g to 0.40 g, was selected because it provided a consistent range of lateral accelerations over which meaningful curve fits of the data could be made without weighting the spurious data that can occur at the beginning and end of a circle test taken to the limits of a vehicle’s response.

The speed plots show that the circle tests were conducted using a very slow rate of increase in speed during the tests. Regarding conducting circle tests for passenger vehicles, SAE J266[1] states: “If speed is steadily increased, the rate of increase shall not exceed 1.5 km/h per second (0.93 mph per second), and data shall be recorded continuously, so long as the vehicle remains on radius.” The rates of speed increase during the circle tests conducted are many times less than the J266 recommended maximum rate.

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[1] SAE Surface Vehicle Recommended Practice - Steady-State Directional Control Test Procedures For Passenger Cars and Light Trucks, SAE J266, 1996.

The second page for each vehicle shows graphs of Handlebar Steer Angle (δ_{SW}) versus Ay (lateral acceleration). The CW test results are in the upper right quadrants of the graphs and the CCW test results are in the lower left quadrants of the graphs. The thin red and blue lines show data in the range of vehicle speeds from 3.2 mph to full speed achieved during each test. For both the CW and CCW data, there are two thicker lines for indicating second-order polynomial curve fits to two different ranges of the data. The thick black lines are curve fits of the data in the range of vehicle speeds from 3.2 mph to maximum speed achieved during each test. The thick blue lines are curve fits of the data in the range of vehicle speeds from 3.2 mph (0.01 g) to 20.5 mph (0.40 g). The red circles on these graphs are the geometric Ackermann (handlebar) steer angles, a function of the wheelbase (L) divided by the circle radius (R), given by:

$$\delta_{SW\,(Geometric)} = \frac{(180/\pi)\times L}{R}$$

The geometric Ackermann steer angles are not the same as the actual steer angles required to negotiate the circles at very low speed, with Ay close to zero. The actual steer angles, which can be referred to as the measured Ackermann steer angles, are generally greater than the geometric Ackermann steer angles due primarily to compliance and lash in the steering system, and compliance in the suspension systems and tires.

The third page for each vehicle shows graphs of Handlebar Steer Angle minus (measured) Ackermann Angle versus Ay (lateral acceleration). For these graphs, the signs of the CCW data are reversed so that the CW and CCW results can be directly compared. The thin lines show data in the range of vehicle speeds from 3.2 mph (0.01 g) to 20.5 mph (0.40 g). The thick lines are the second-order polynomial curve fits to the data. Notice that the measured Ackermann steer angles are the abscissae of the curve fits taken at Ay equal to zero, so the curve fits tend to zero as Ay goes to zero. For a circle test: understeer can be defined as the condition when the handlebar steer input required to maintain the circular path increases as the vehicle speed increases, neutral steer can be defined as the condition when the handlebar steer input required to maintain the circular path does not change as the vehicle speed increases, and oversteer can be defined as the condition when the handlebar steer input required to maintain the circular path decreases as the vehicle speed increases. The second-order polynomial curve fits do a good job of representing the underlying data whether the particular test vehicle exhibits understeer, neutral steer, or oversteer characteristics during the circle tests.

Vehicle B2 is relatively close to neutral steer at all lateral acceleration levels, but it does transition from understeer to oversteer at 0.31 g in the CW direction and at 0.23 g in the CCW direction (Appendix B Pages 2 and 3). Vehicle E2 exhibits understeer at all levels of lateral acceleration (Appendix B Pages 15 and 16). The handlebar gradient for Vehicle L2 exhibits understeer up to 0.4 g (Appendix B Page 29), but it does transition to oversteer at higher lateral acceleration levels (Appendix B Page 28).

The fourth page for each vehicle shows a graph of Roll Angle versus Ay (lateral acceleration). The CW test results are in the lower right quadrants of the graphs and the CCW test results are in the upper left quadrants of the graphs. The thin lines show data in the range of vehicle speeds from 3.2 mph to full speed achieved during each test. The thick lines are linear curve fits to the

CW and CCW data in the range of vehicle speeds from 3.2 mph (0.01 g) to 20.5 mph (0.40 g). For each vehicle configuration, the average of the CW and CCW curve fit slopes are listed on the graphs as the Roll Gradient.

4.2.2 Discussion of 30 mph Dropped-Throttle J-Turn (Step Steer) Test Results

The fifth through ninth pages for each vehicle contain results from the dropped-throttle J-Turn tests. The first four pages show time domain plots for the tests. As mentioned previously, from two to five good test runs that resulted in minor to moderate two-wheel lift outcomes in each heading and steer direction were conducted; and the results for these tests are shown in Appendix B. The first and third pages for each vehicle show plots of (Handlebar) Steer Angle, Lateral Acceleration, Speed, Roll Angle, and Yaw Rate; for the good Northbound and Southbound runs, respectively. The second and forth pages for each vehicle show larger plots of Lateral Acceleration; for the Northbound and Southbound runs, respectively. For the J-turn test results, the data shown was digitally low-pass filtered to 2.0 Hz using a phaseless, eighth-order, Butterworth filter. Previous in-depth analyses of data from tests conducted on recreational off-highway vehicles revealed that low-pass filtering the vehicle response data to 2.0 Hz provided a reliable and repeatable method for selecting peak lateral acceleration levels during J-turn tests.[1]. The time domain data shown for each vehicle contains data from 0.5 seconds before the ATV ASC steering input was applied until 5.0 seconds after it was applied.

For each vehicle, the plots contain results from the Northbound right steer J-turns, Northbound left steer J-turns, Southbound right steer J-turns, and Southbound left steer J-turns. In all cases, the plots contain results for tests that resulted in visual two-wheel lift. An SAE standard sign convention is used, with Steer Angle, Lateral Acceleration, and Yaw Rate being positive and Roll Angle being negative for right turns.

The fifth page shown for each vehicle contains a summary of the peak lateral accelerations measured in each test. These values are the maximum values of lateral acceleration shown on the plots, which contain data that has been filtered to 2.0 Hz.

The summary pages show the peak lateral accelerations for the runs conducted in the Northbound right steer direction, Northbound left steer direction, Southbound right steer direction, and Southbound left steer direction. The mean values and standard deviations from each of the two to five sample runs are shown on the summary pages. Also, the average of the Northbound and Southbound runs is shown, as is the average of all runs, which is the Threshold Ay value.

Table 3 contains a summary of lateral stability metrics, and roll stiffness and roll gradient measurements for each vehicle. SSF, KST, Threshold Ay, Front and Rear Overall Roll Stiffness, Percent Front Roll Stiffness, and Roll Gradient are given in the table. Percent Front Roll Stiffness is simply the Front Roll Stiffness divided by the total roll stiffness (the sum of the Front and Rear Roll Stiffnesses).

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[1] *Repeatability of J-Turn Testing of Four Recreational Off-Highway Vehicles*, CPSC Contract CPSC-D-11-0003, S-E-A, Ltd. Report to CPSC, September 2013.
http://www.cpsc.gov//Global/Research-and-Statistics/Injury-Statistics/Sports-and-Recreation/ATVs/SEAReporttoCPSCRepeatabilityTestingSeptember%202013.pdf

Vehicle L2 has the highest SSF, KST and Threshold Ay values; and Vehicle B2 has the lowest SSF, KST, and Threshold Ay values.

Vehicle B2, the vehicle that transitioned from Understeer to Oversteer in the Circle Test, has a small percent front suspension roll stiffness. The trailing arm geometry of the solid axle rear suspension of this vehicle prevents the solid rear axle from rolling relative to the chassis; thus the high rear roll stiffness for this vehicle. The roll gradient of this vehicle is also much less than the other two vehicles.

The percent front roll stiffness for Vehicle E2 is greater than 50%. This is the vehicle that exhibited the greatest understeer characteristics in the circle tests. The percent front roll stiffness for Vehicle B2 is the lowest of the three vehicles (15%), and this is the vehicle that transitioned from understeer to oversteer during its circle tests.

Table 3: Summary of Lateral Stability Metrics, and Roll Stiffness and Roll Gradient Measurements

	Vehicle B2	Vehicle E2	Vehicle L2
SSF	0.800	0.827	0.849
KST	0.801	0.827	0.850
Threshold Ay (g) (from J-Turn Tests)	0.546	0.552	0.590
Front Roll Stiffness (in-lb/deg)	538	935	887
Rear Roll Stiffness (in-lb/deg)	3049	752	1911
Percent Front Stiffness (%)	15.0%	55.4%	31.7%
Roll Gradient (deg/g) (from Circle Tests)	5.4	17.4	10.4

4.2.3 Discussion of 20 mph Sinusoidal Sweep Steering (Frequency Response) Test Results

For each vehicle there are three pages of results from the sinusoidal sweep steering tests. The first page of results for each vehicle contains representative time domain plots for one of the sinusoidal sweep tests conducted. Each of these pages shows time domain plots of Steer Angle, Lateral Acceleration (Ay), Roll Angle, Roll Rate, and Yaw Rate. The data shown was digitally low-pass filtered to 10.0 Hz using a phaseless, eighth-order, Butterworth filter.

The steering inputs used during the sinusoidal sweeps provided for meaningful frequency response computations in the range of about 0.6 to 2.6 Hz. The frequency responses were computed using the transfer function estimator routine in Matlab. The second page of graphs for each vehicle contains frequency response plots of amplitude ratio and phase angle for lateral acceleration and roll angle frequency responses to steering input. The third page of graphs for each vehicle contains frequency response plots for roll rate and yaw rate. On each of the frequency response plots, results from two tests are shown.

Based on linear vehicle response theory, the low frequency values of the amplitude ratios (magnitudes) for lateral acceleration, roll angle, and yaw rate represent the steady state gains that a vehicle would have achieved if it was driven at a low (linear range) lateral acceleration steady state condition (The steady state gain for roll rate is zero.). The lateral acceleration and yaw rate frequency responses exhibited underdamped behavior; that is, the amplitude ratios (magnitudes) are greater at some higher frequencies than they are at low frequency (i.e. their steady state gain values). This behavior is not unusual for automotive passenger vehicles, and it is generally not indicative of any problem unless the amplitude ratios are considerably higher at some frequencies than they are at steady state. Based on the frequency responses generated from this testing, this does not appear to be an issue for any of the vehicles tested. The roll angle frequency responses are somewhat overdamped. This too is not an issue for these vehicles, and the roll damping at higher frequencies is likely partially a consequence of the damping that comes from the ATV tires.

Overall, the time domain and frequency response curves generated did not indicate any anomalous vehicle behavior. For all of the tests conducted, the vehicles were responsive to the steering inputs and remained stable for the sweep of steering inputs applied.

Vehicle B2

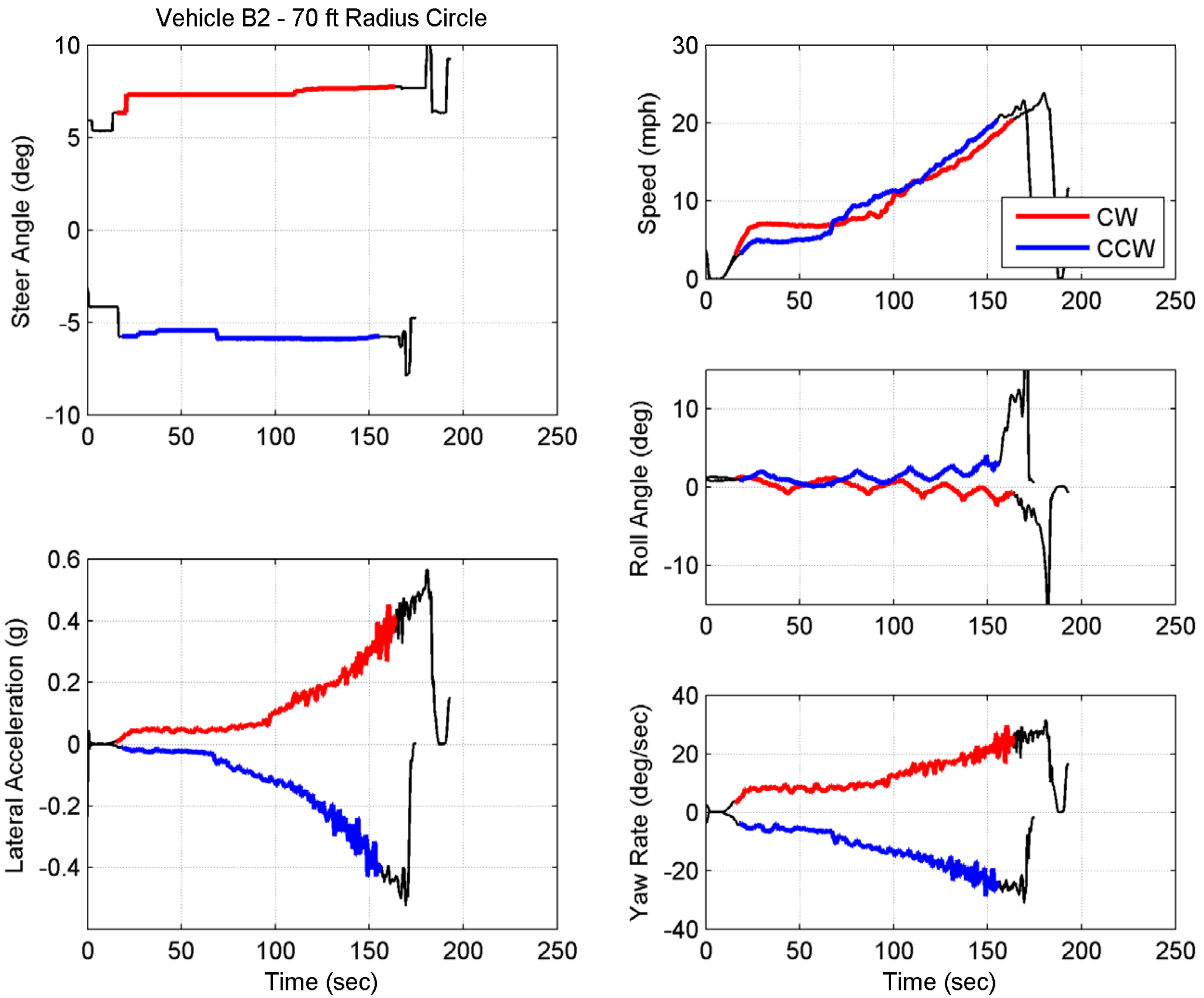
	Curb	Operator, Instrumentation & Outriggers
VIMF Test Number		5623
Total Vehicle Weight (lb)	432.7	686.0
Left Front Weight (lb)	113.9	178.6
Right Front Weight (lb)	105.4	161.8
Left Rear Weight (lb)	104.9	170.3
Right Rear Weight (lb)	108.5	175.3
Front Track Width (in)	37.78	37.88
Rear Track Width (in)	35.58	35.35
Average Track Width (in)	36.68	36.61
Wheelbase (in)	50.30	51.00
CG Longitudinal (in)	24.81	25.69
CG Lateral (in)	-0.22	-0.33
CG Height (in)		22.87
Roll Inertia - I_{XX} (ft-lb-s^2)		49
Pitch Inertia - I_{YY} (ft-lb-s^2)		70
Yaw Inertia - I_{ZZ} (ft-lb-s^2)		56
Roll/Yaw - I_{XZ} (ft-lb-s^2)		0
SSF		0.800
KST		0.801
Front Suspension Overall Roll Stiffness (in-lb/deg)		538
Rear Suspension Overall Roll Stiffness (in-lb/deg)		3049

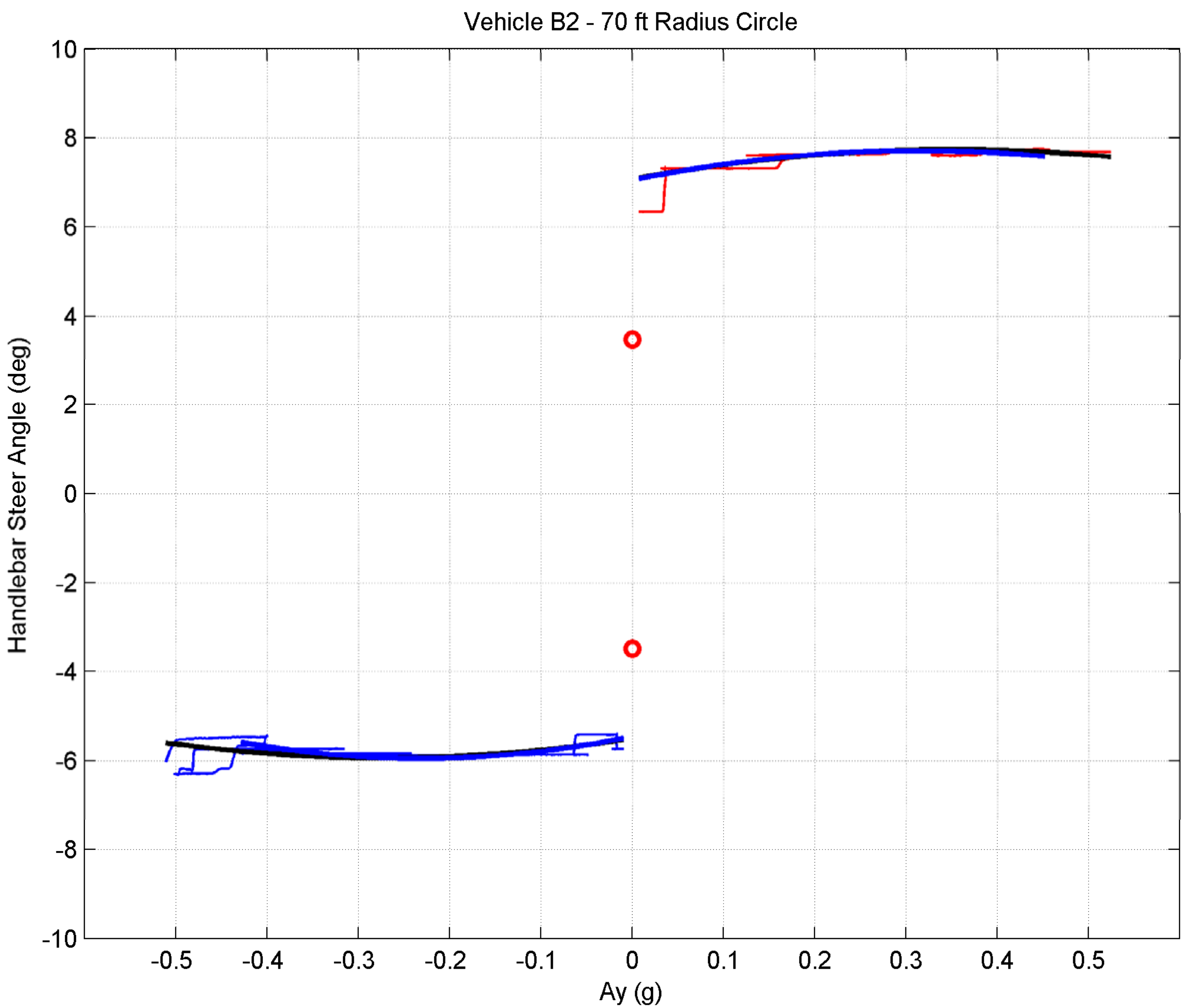
Vehicle B2

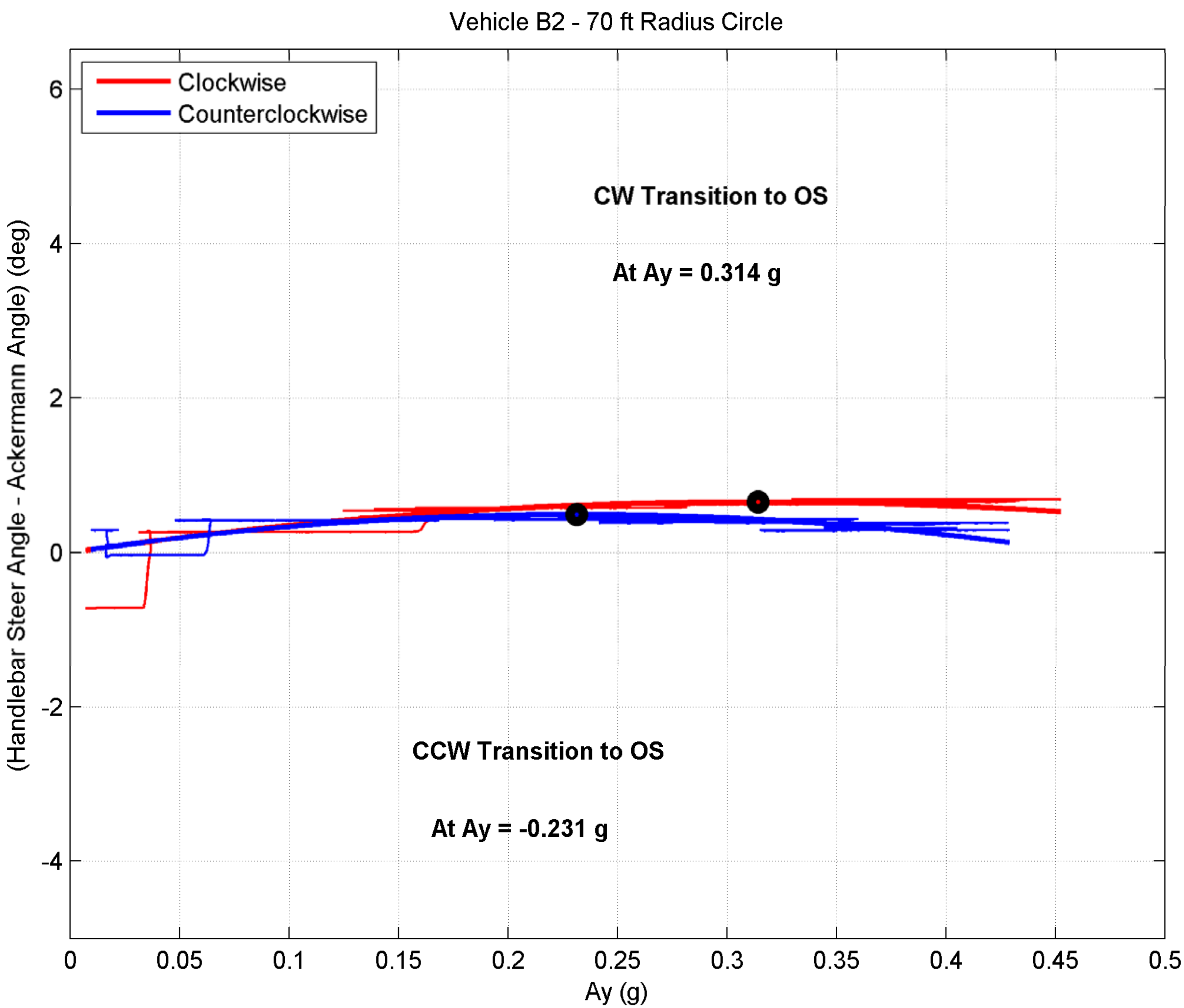
	Curb	Operator, Instrumentation & Outriggers
VIMF Test Number		5619
Total Vehicle Weight (lb)	731.2	985.4
Left Front Weight (lb)	179.6	240.9
Right Front Weight (lb)	177.0	236.7
Left Rear Weight (lb)	193.6	257.4
Right Rear Weight (lb)	181.0	250.4
Front Track Width (in)	39.38	40.23
Rear Track Width (in)	39.00	38.93
Average Track Width (in)	39.19	39.58
Wheelbase (in)	49.88	50.00
CG Longitudinal (in)	25.55	25.77
CG Lateral (in)	-0.41	-0.22
CG Height (in)		23.93
Roll Inertia - I_{XX} (ft-lb-s^2)		76
Pitch Inertia - I_{YY} (ft-lb-s^2)		122
Yaw Inertia - I_{ZZ} (ft-lb-s^2)		109
Roll/Yaw - I_{XZ} (ft-lb-s^2)		2
SSF		0.827
KST		0.827
Front Suspension Overall Roll Stiffness (in-lb/deg)		935
Rear Suspension Overall Roll Stiffness (in-lb/deg)		752

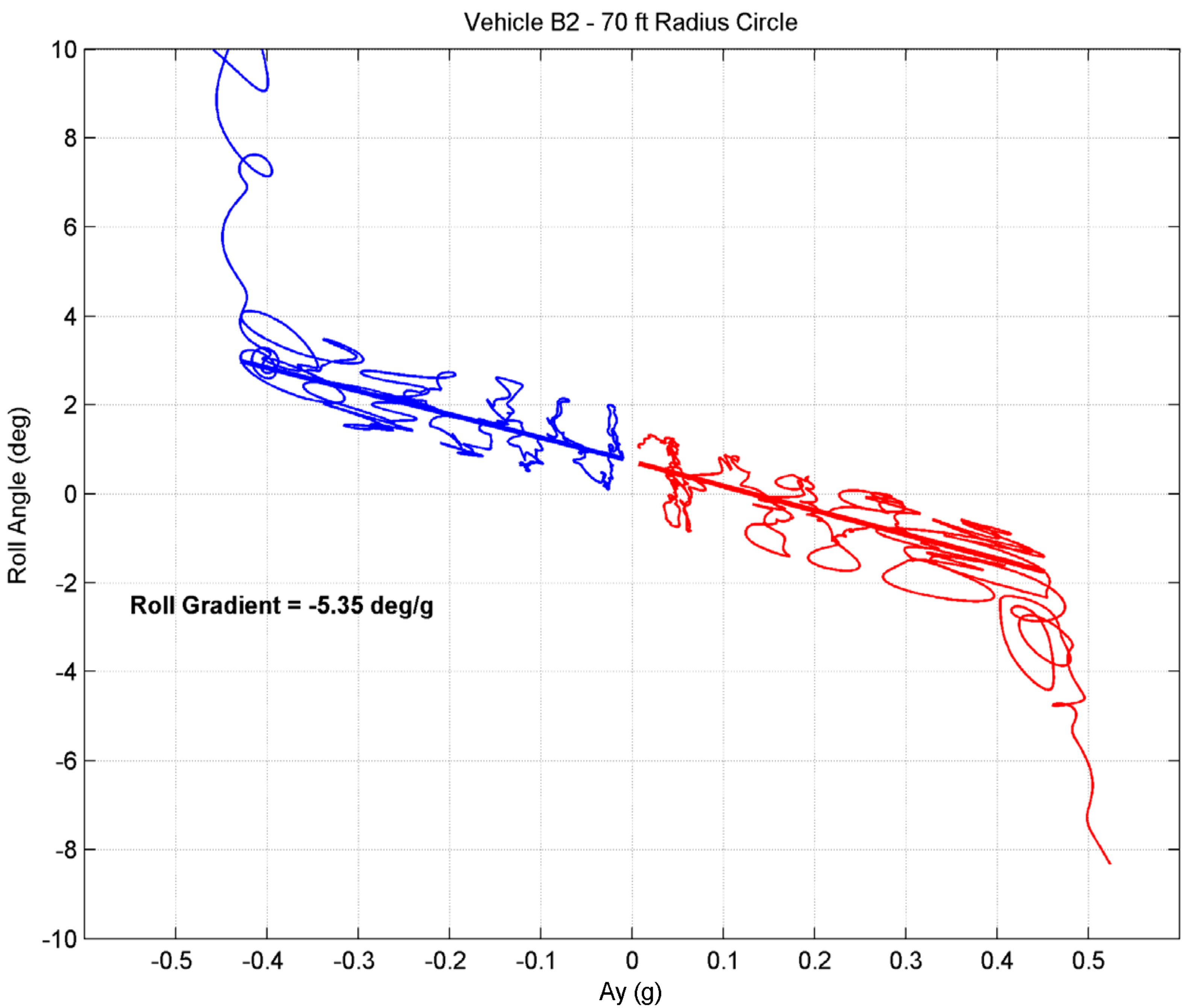
Vehicle B2

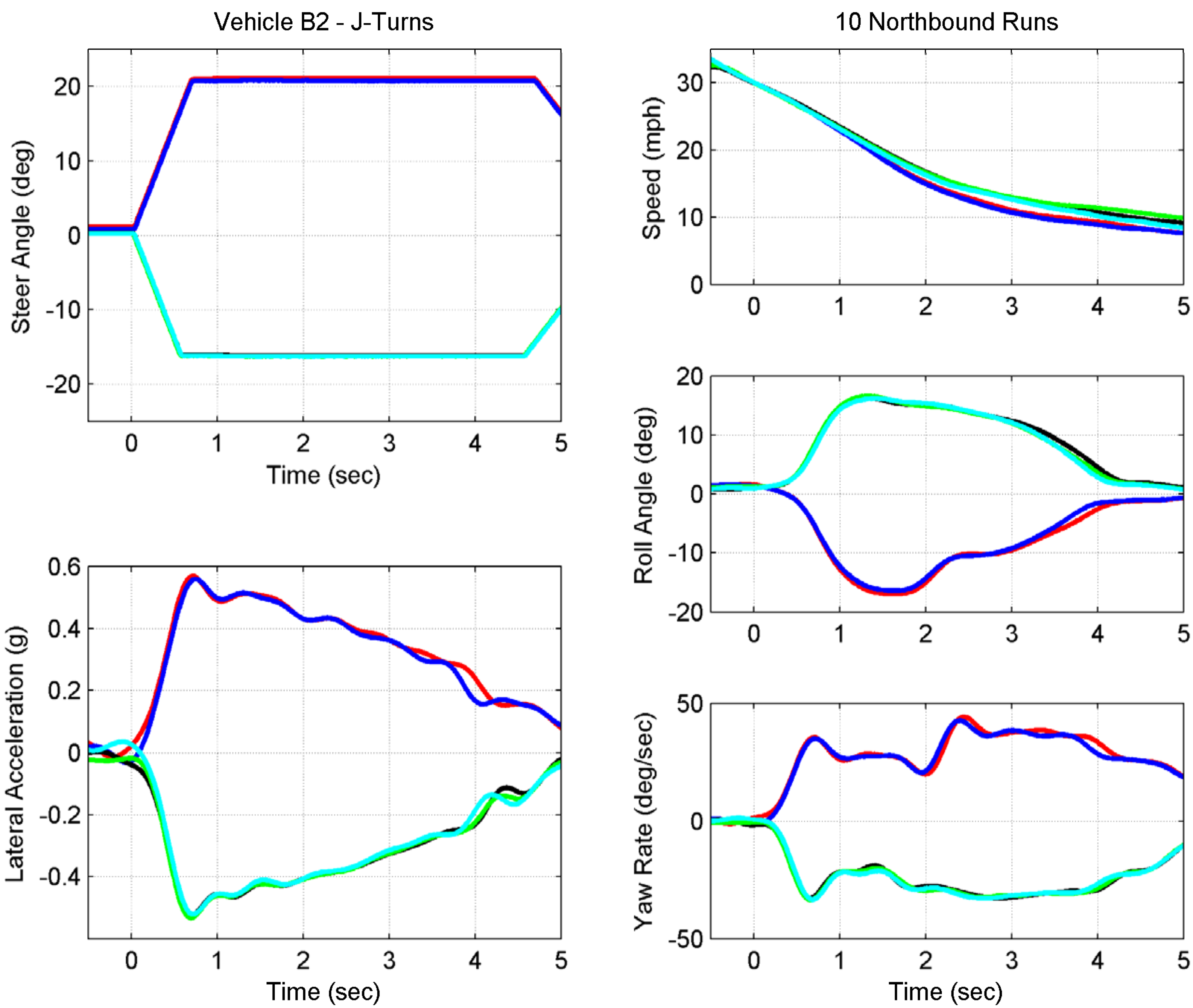
	Curb	Operator, Instrumentation & Outriggers
VIMF Test Number		5621
Total Vehicle Weight (lb)	712.1	966.5
Left Front Weight (lb)	183.1	246.0
Right Front Weight (lb)	160.9	218.0
Left Rear Weight (lb)	178.7	248.2
Right Rear Weight (lb)	189.4	254.3
Front Track Width (in)	39.40	39.80
Rear Track Width (in)	36.90	37.50
Average Track Width (in)	38.15	38.65
Wheelbase (in)	50.45	50.60
CG Longitudinal (in)	26.08	26.31
CG Lateral (in)	-0.34	-0.46
CG Height (in)		22.77
Roll Inertia - I_{XX} (ft-lb-s^2)		76
Pitch Inertia - I_{YY} (ft-lb-s^2)		124
Yaw Inertia - I_{ZZ} (ft-lb-s^2)		117
Roll/Yaw - I_{XZ} (ft-lb-s^2)		3
SSF		0.849
KST		0.850
Front Suspension Overall Roll Stiffness (in-lb/deg)		887
Rear Suspension Overall Roll Stiffness (in-lb/deg)		1911

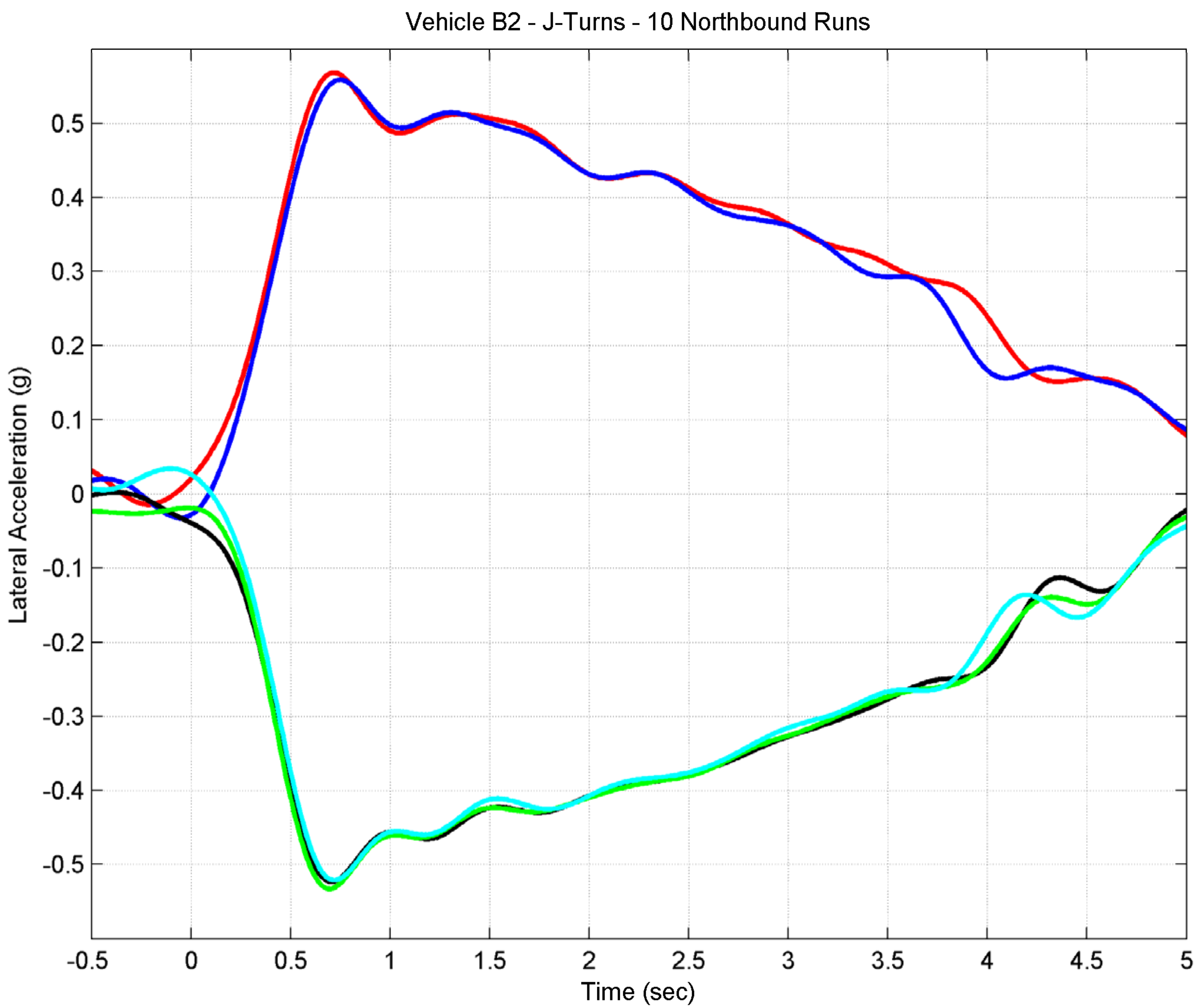

Vehicle B2 - 70 ft Radius Circle
Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)


Vehicle B2 - 70 ft Radius Circle
10
8
6
4
2
0
-2
-4
-6
-8
-10
Handlebar Steer Angle (deg)
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
Ay (g)

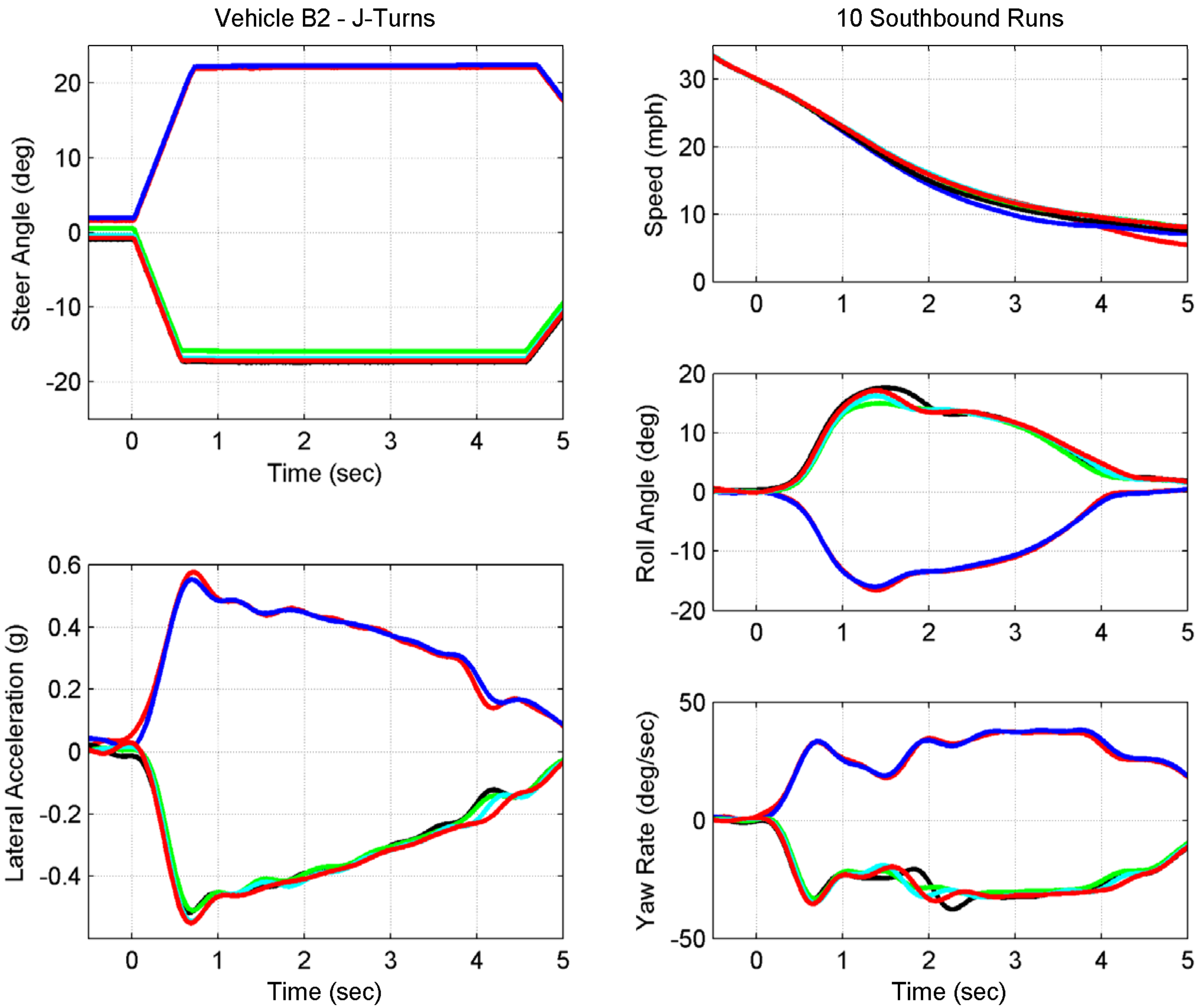

Vehicle B2 - 70 ft Radius Circle
Clockwise
Counterclockwise
CW Transition to OS
At Ay = 0.314 g
CCW Transition to OS
At Ay = -0.231 g
(Handlebar Steer Angle - Ackermann Angle) (deg)
Ay (g)
6
4
2
0
-2
-4
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5

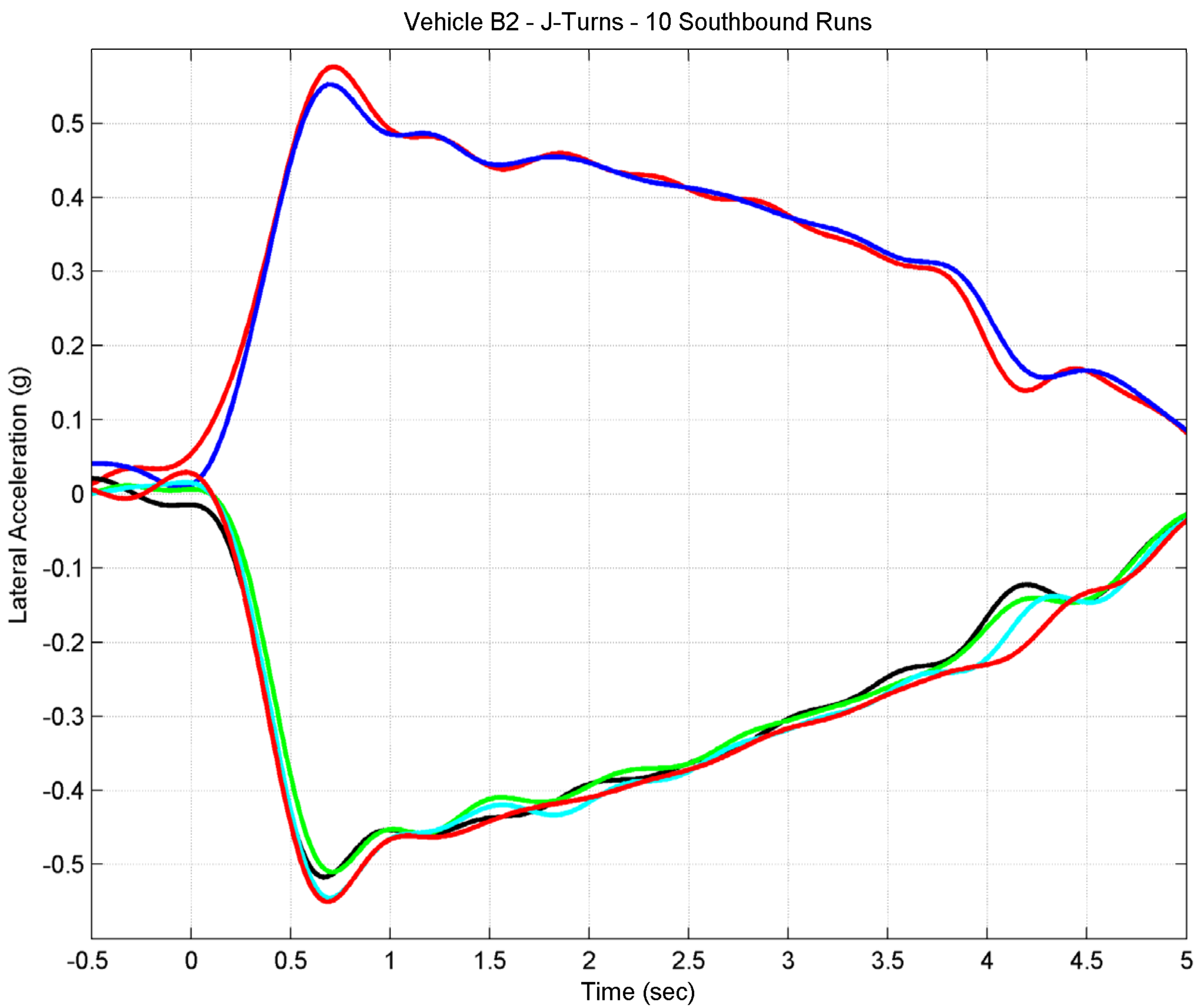

Vehicle B2 - 70 ft Radius Circle
Roll Angle (deg)
Ay (g)
Roll Gradient = -5.35 deg/g
10
8
6
4
2
0
-2
-4
-6
-8
-10
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5


Vehicle B2 - J-Turns
10 Northbound Runs
Steer Angle (deg)
20
10
0
-10
-20
Time (sec)
0
1
2
3
4
5
Speed (mph)
30
20
10
0
Roll Angle (deg)
20
10
0
-10
-20
Lateral Acceleration (g)
0.6
0.4
0.2
0
-0.2
-0.4
Yaw Rate (deg/sec)
50
0
-50



Vehicle B2 - J-Turns - 10 Northbound Runs
Lateral Acceleration (g)
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (sec)


Vehicle B2 - J-Turns
10 Southbound Runs
Steer Angle (deg)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)
Time (sec)



Vehicle B2 - J-Turns - 10 Southbound Runs
Lateral Acceleration (g)
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (sec)

Vehicle B2

Run Number	Northbound Right Turns	Northbound Left Turns
1	0.5680	-0.5234
2	0.5584	-0.5329
3		-0.5215
4		
5		
Mean Value of Runs	0.5632	-0.5259
Standard Deviation of Runs	0.007	0.006

Average of Northbound Runs

0.5445

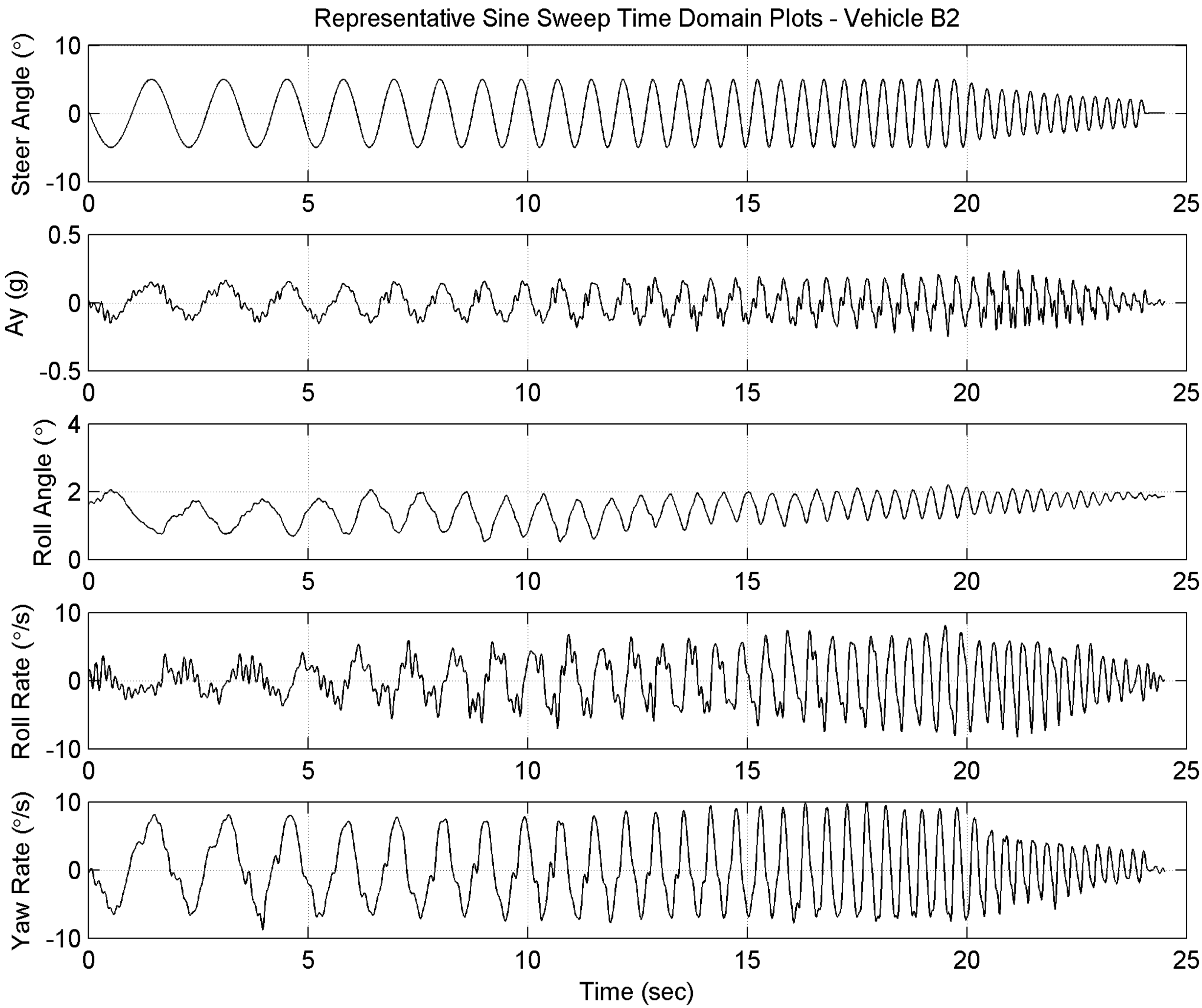
Average of All Runs

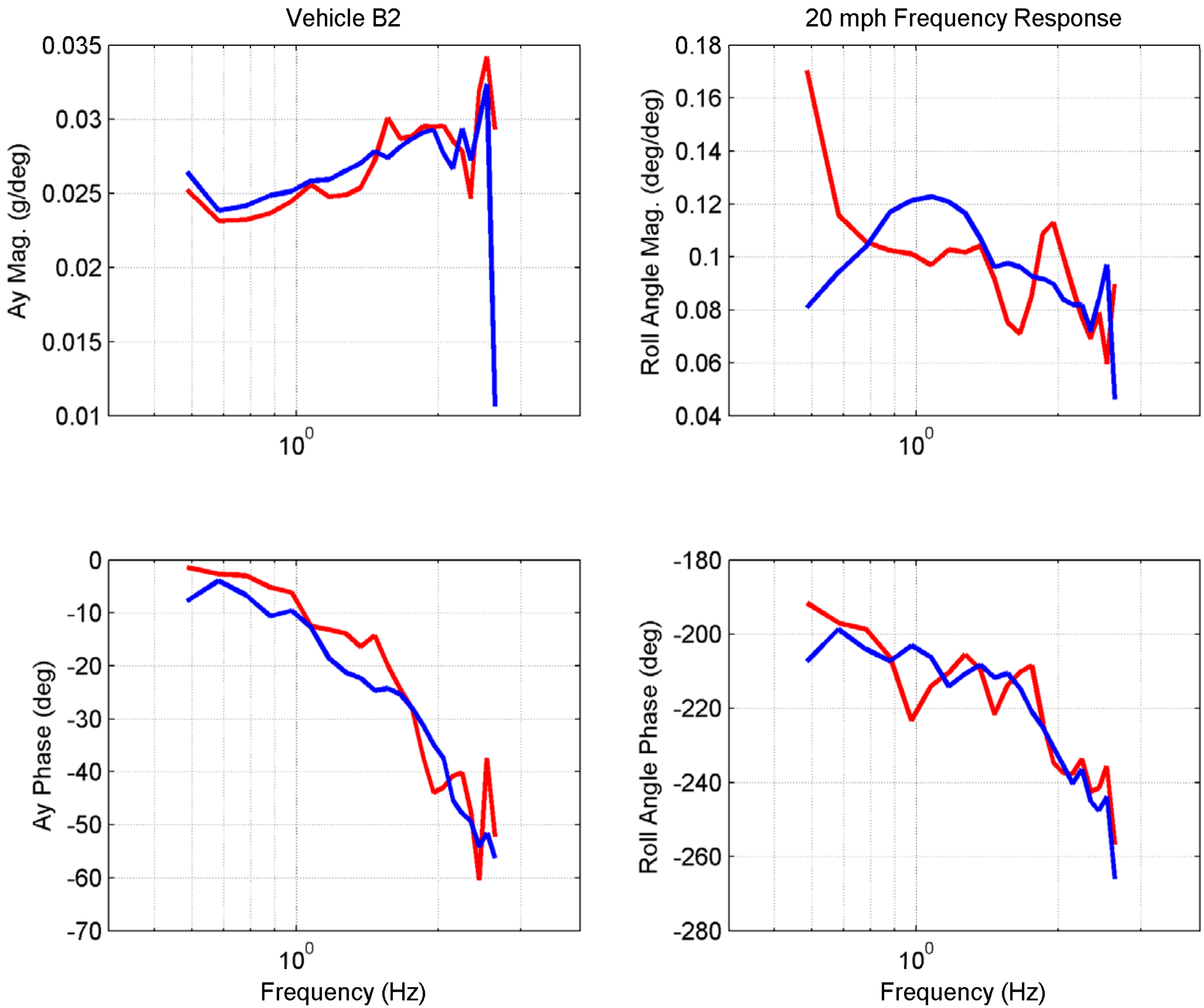
0.546

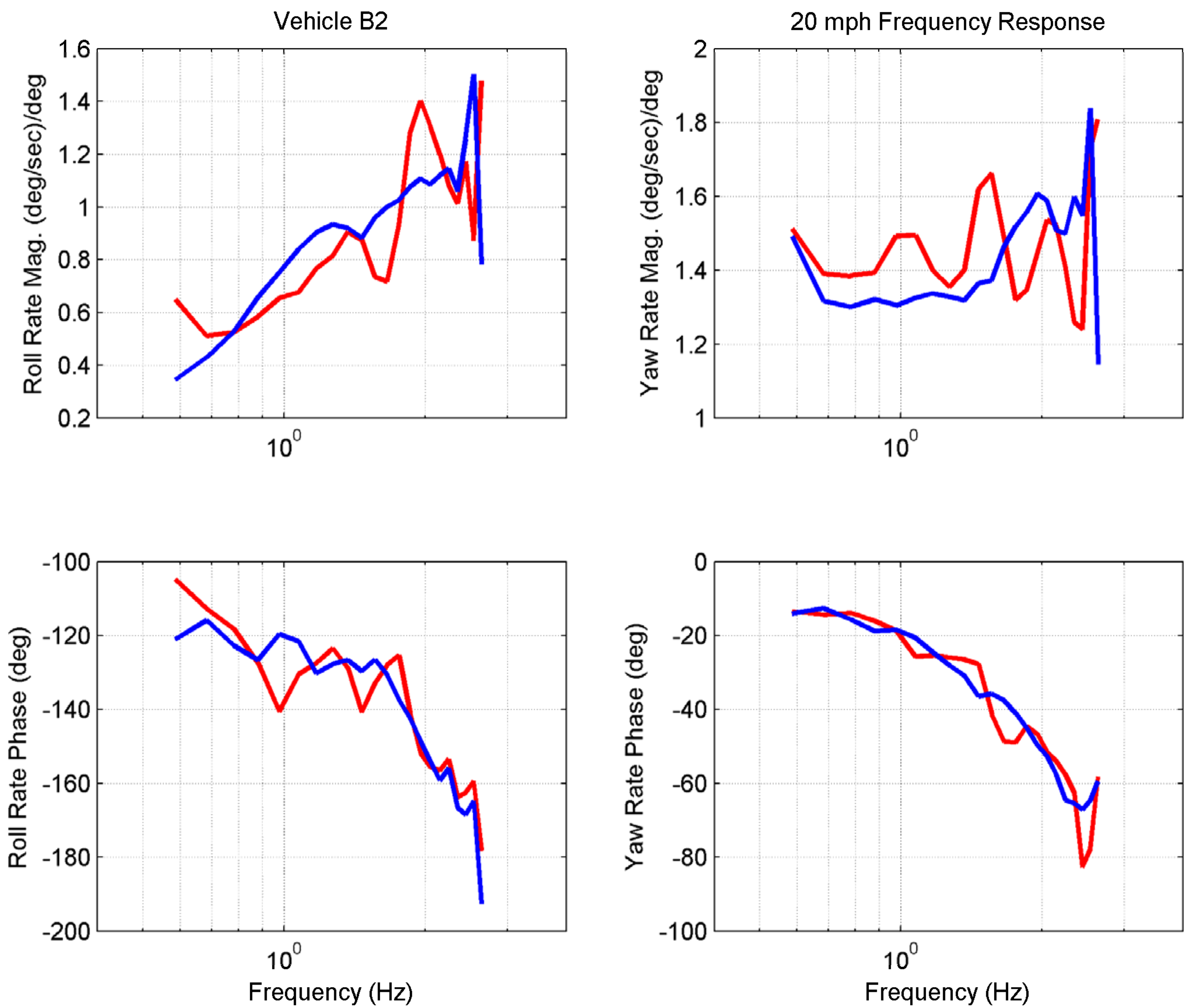
Run Number	Southbound Right Turns	Southbound Left Turns
1	0.5760	-0.5172
2	0.5521	-0.5104
3		-0.5454
4		-0.5503
5		
Mean Value of Runs	0.5641	-0.5308
Standard Deviation of Runs	0.017	0.020

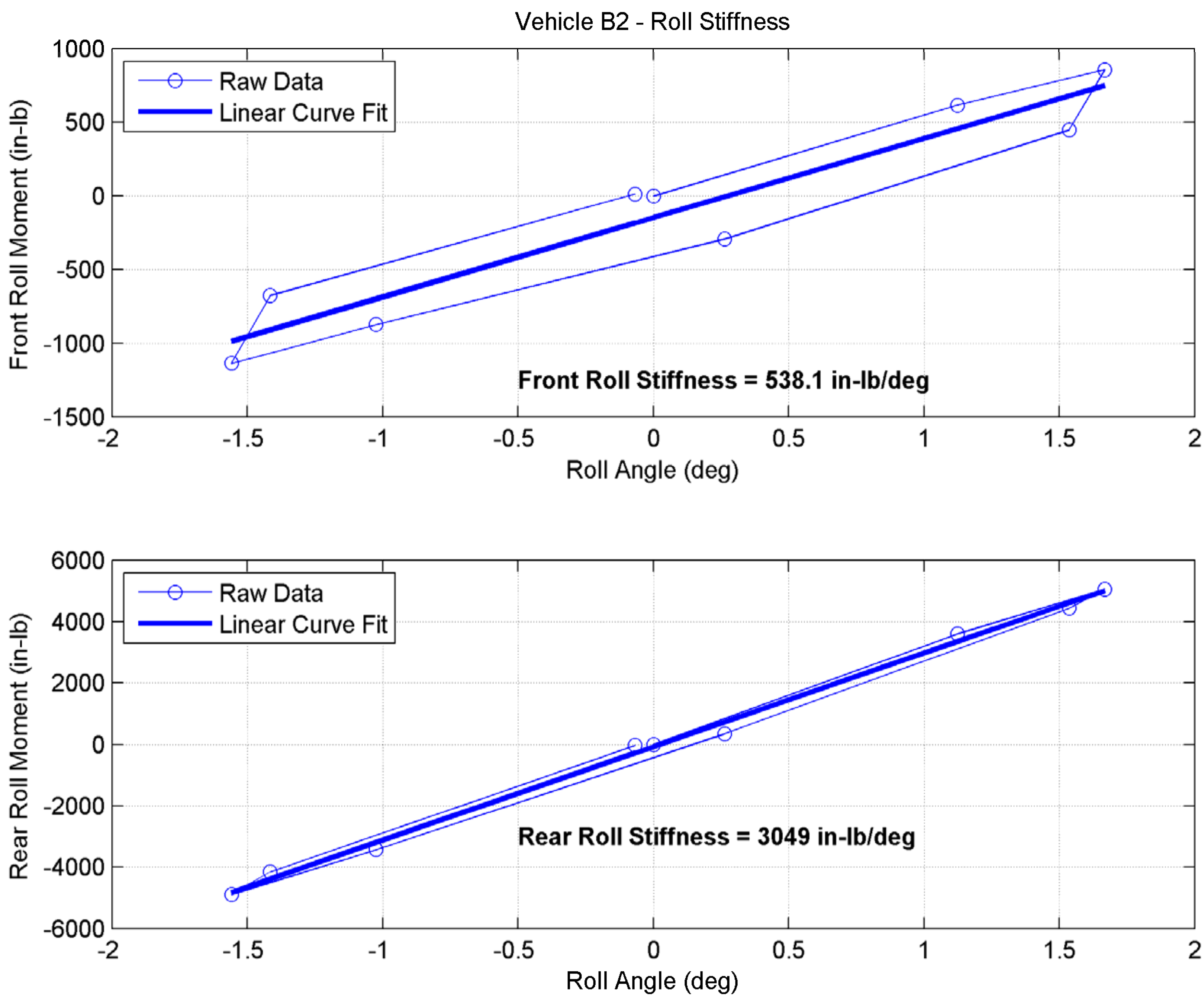
Average of Southbound Runs

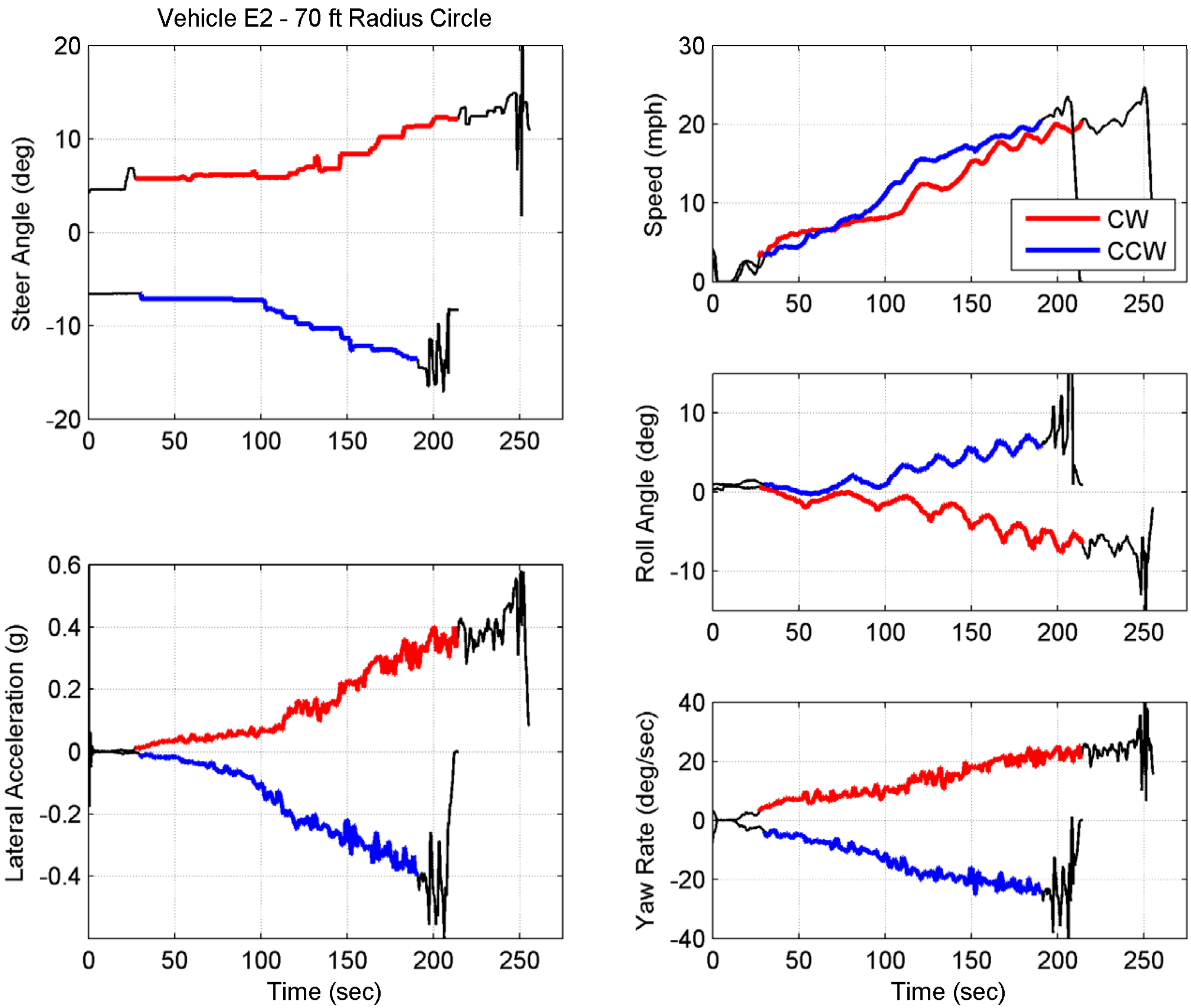
0.5474


Representative Sine Sweep Time Domain Plots - Vehicle B2
Steer Angle (°)
10
0
-10
Ay (g)
0.5
0
-0.5
Roll Angle (°)
4
2
0
Roll Rate (°/s)
10
0
-10
Yaw Rate (°/s)
10
0
-10
0
5
10
15
20
25
Time (sec)

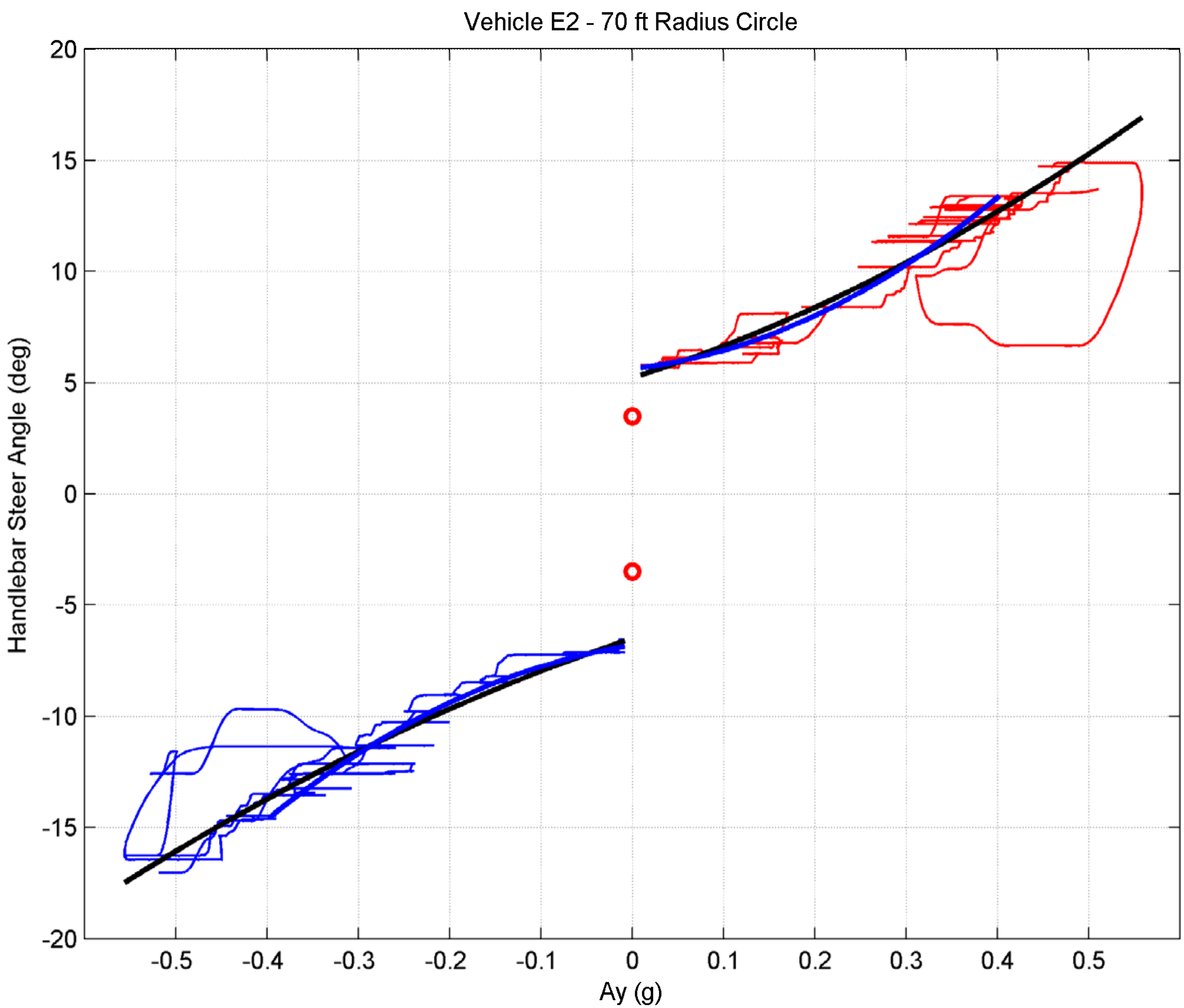

Vehicle B2
20 mph Frequency Response
Ay Mag. (g/deg)
0.035
0.03
0.025
0.02
0.015
0.01
Roll Angle Mag. (deg/deg)
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
10^0
Ay Phase (deg)
0
-10
-20
-30
-40
-50
-60
-70
Roll Angle Phase (deg)
-180
-200
-220
-240
-260
-280
Frequency (Hz)

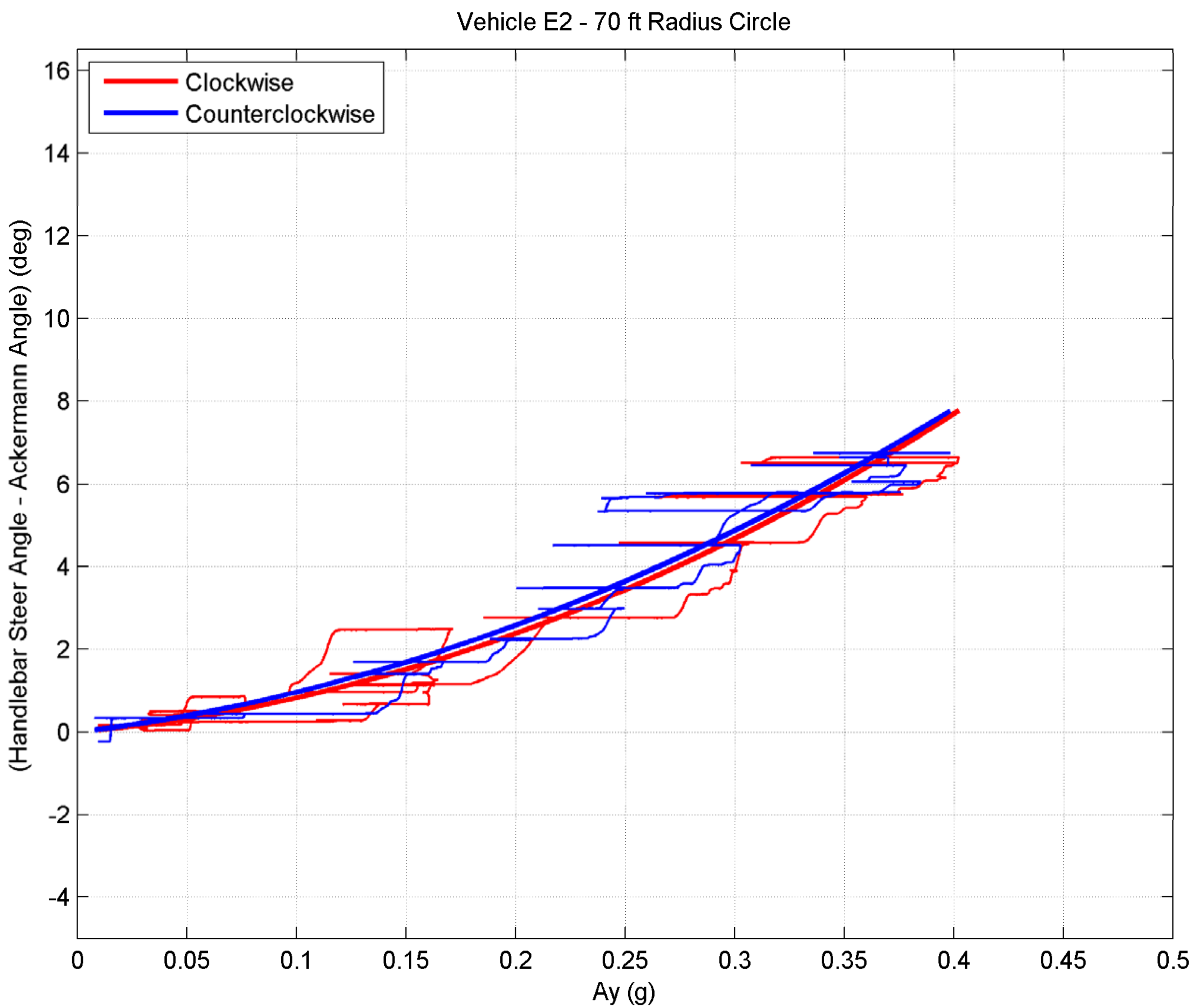

Vehicle B2
20 mph Frequency Response
Roll Rate Mag. (deg/sec)/deg
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
10^0
Yaw Rate Mag. (deg/sec)/deg
2
1.8
1.6
1.4
1.2
1
10^0
Roll Rate Phase (deg)
-100
-120
-140
-160
-180
-200
10^0
Frequency (Hz)
Yaw Rate Phase (deg)
0
-20
-40
-60
-80
-100
10^0
Frequency (Hz)

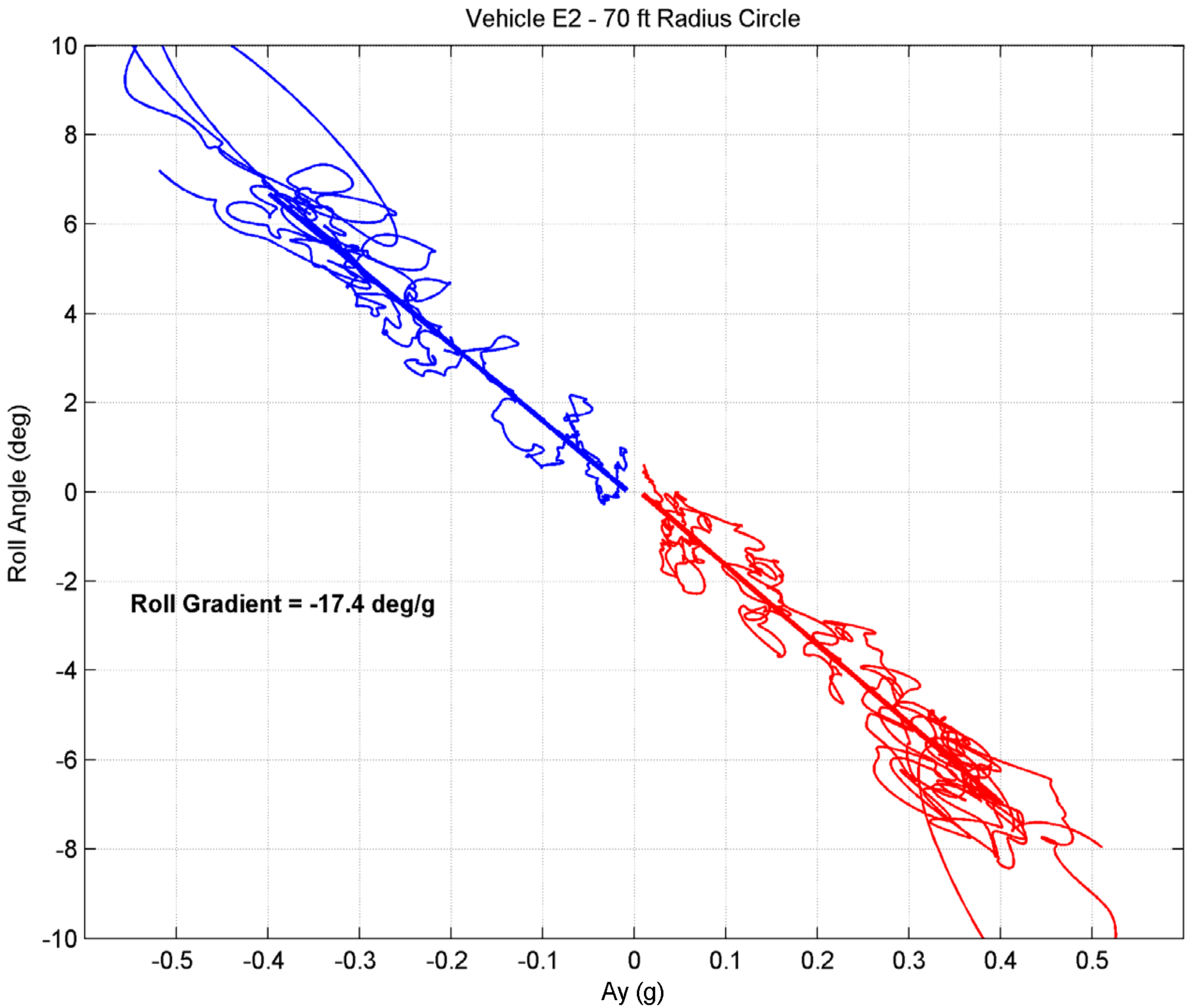

Vehicle B2 - Roll Stiffness
Raw Data
Linear Curve Fit
Front Roll Stiffness = 538.1 in-lb/deg
Front Roll Moment (in-lb)
Roll Angle (deg)
Raw Data
Linear Curve Fit
Rear Roll Stiffness = 3049 in-lb/deg
Rear Roll Moment (in-lb)
Roll Angle (deg)



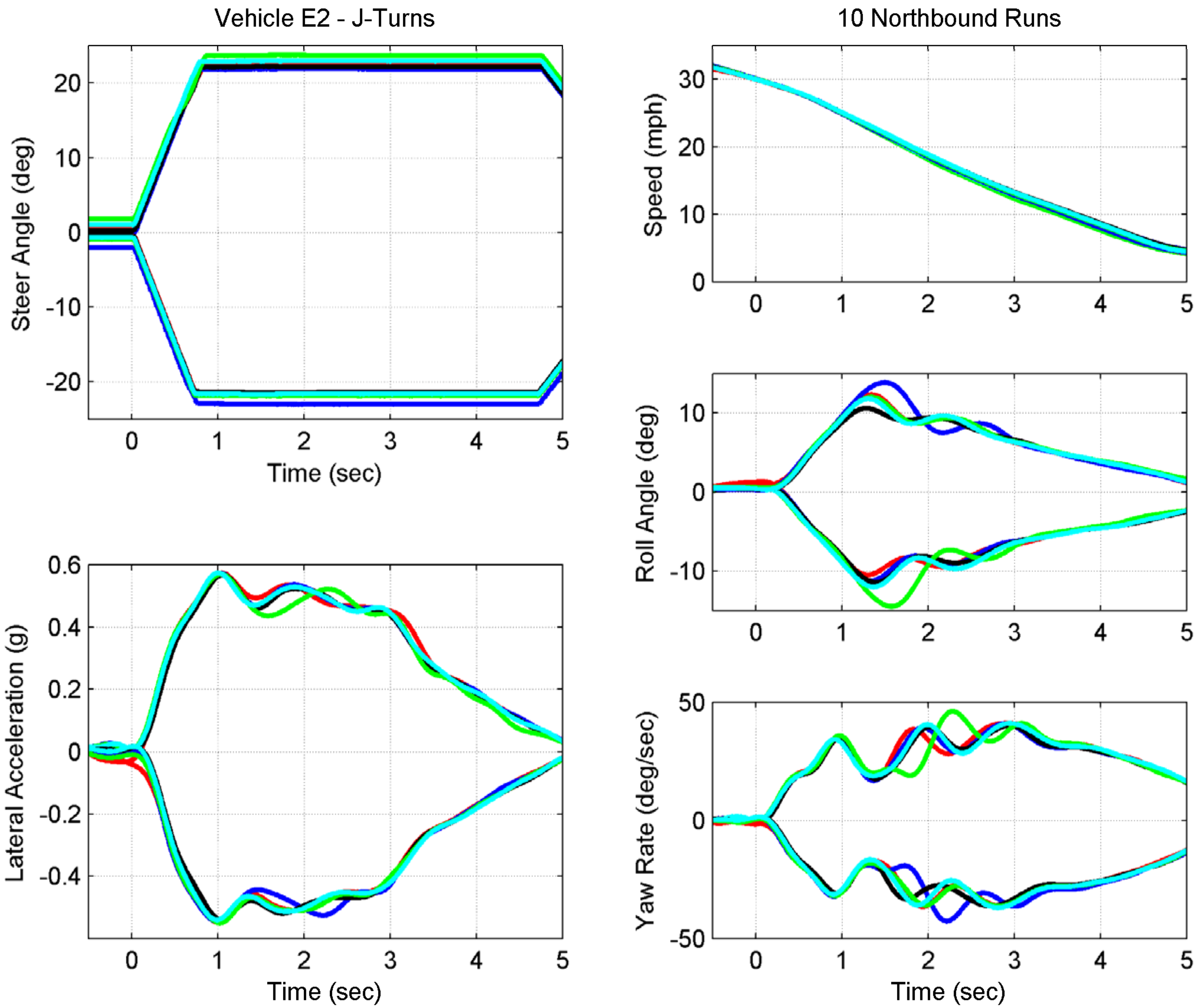
Vehicle E2 - 70 ft Radius Circle
Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

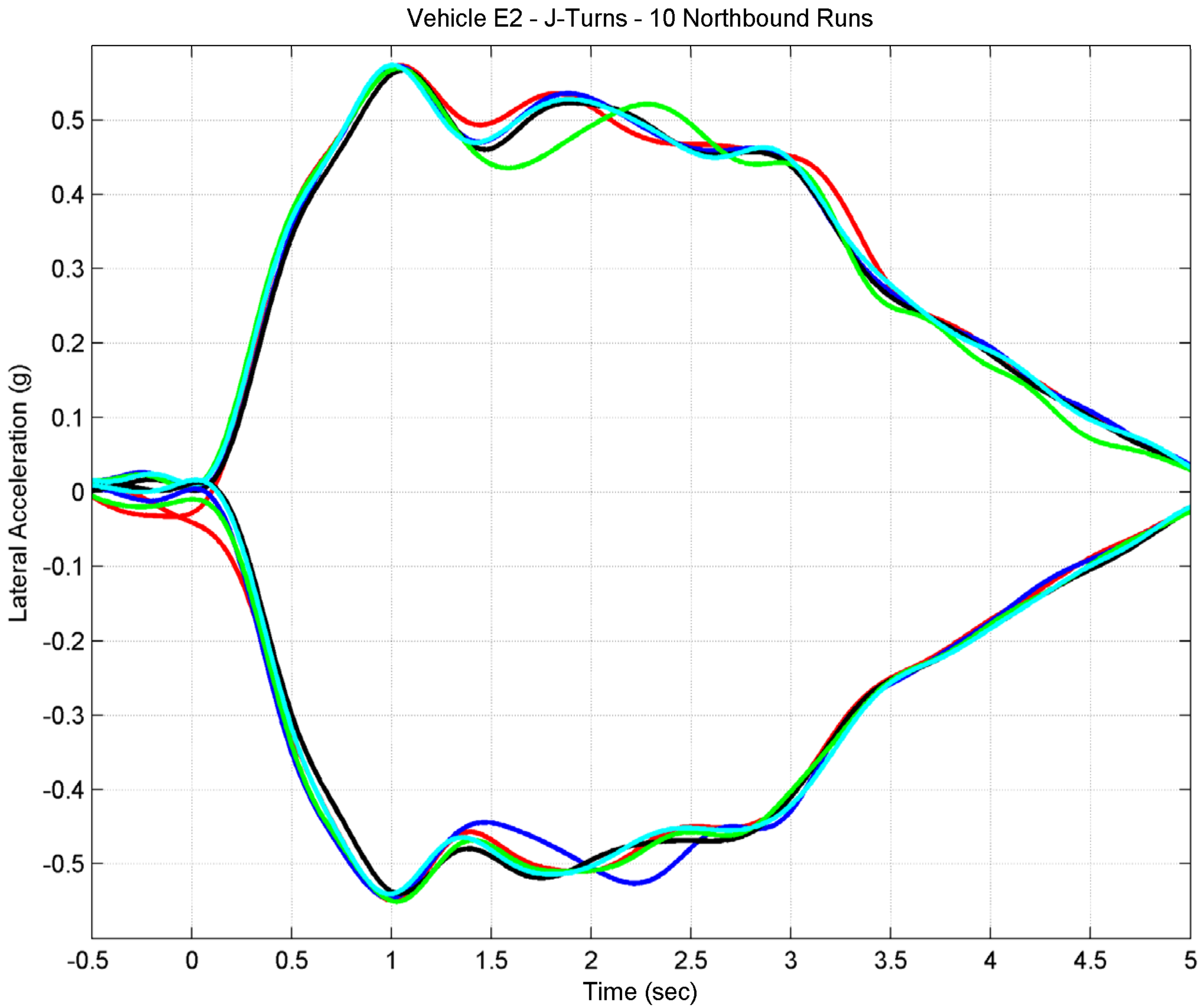

Vehicle E2 - 70 ft Radius Circle
Handlebar Steer Angle (deg)
20
15
10
5
0
-5
-10
-15
-20
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
Ay (g)

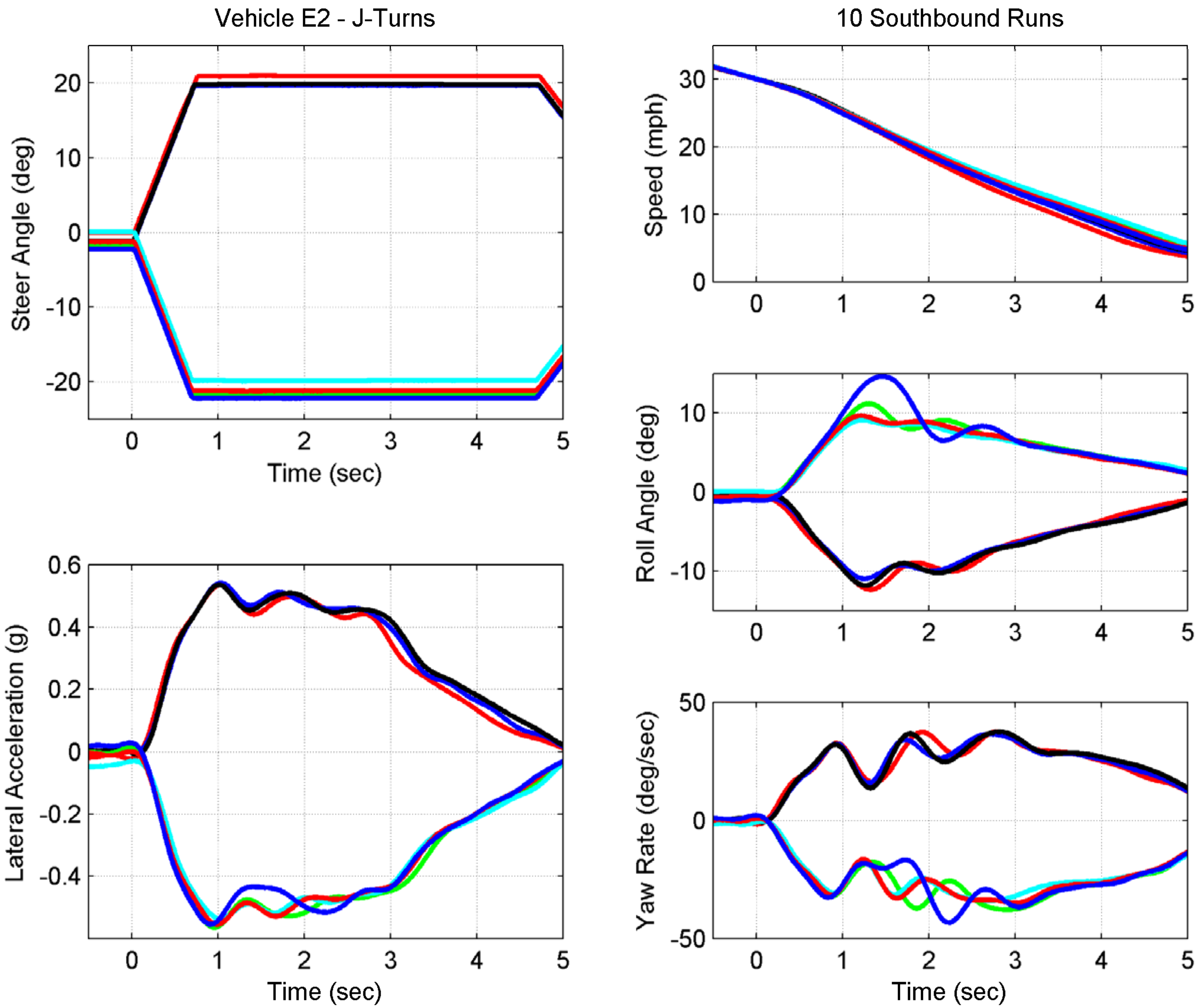

Vehicle E2 - 70 ft Radius Circle
Clockwise
Counterclockwise
(Handlebar Steer Angle - Ackermann Angle) (deg)
16
14
12
10
8
6
4
2
0
-2
-4
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Ay (g)

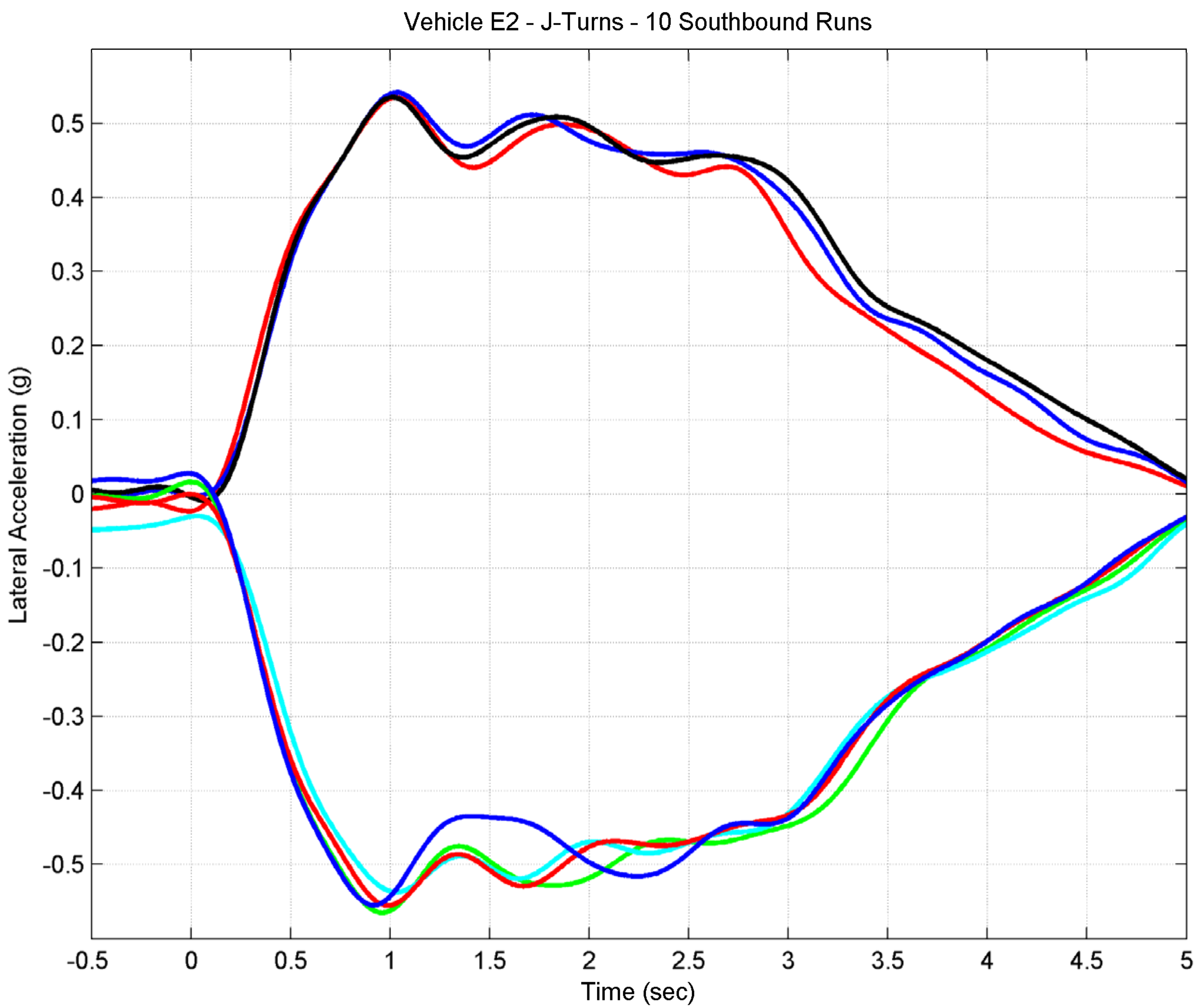


Vehicle E2 - 70 ft Radius Circle
Roll Angle (deg)
10
8
6
4
2
0
-2
-4
-6
-8
-10
Roll Gradient = -17.4 deg/g
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
Ay (g)


Vehicle E2 - J-Turns
10 Northbound Runs
Steer Angle (deg)
Time (sec)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)


Vehicle E2 - J-Turns - 10 Northbound Runs
Lateral Acceleration (g)
Time (sec)
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5


Vehicle E2 - J-Turns
10 Southbound Runs
Steer Angle (deg)
Time (sec)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)



Vehicle E2 - J-Turns - 10 Southbound Runs
Lateral Acceleration (g)
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (sec)

Vehicle E2

Run Number	Northbound Right Turns	Northbound Left Turns
1	0.5730	-0.5495
2	0.5723	-0.5458
3	0.5669	-0.5401
4	0.5692	-0.5505
5	0.5734	-0.5406
Mean Value of Runs	0.5709	-0.5453
Standard Deviation of Runs	0.003	0.005

Average of Northbound Runs

0.5581

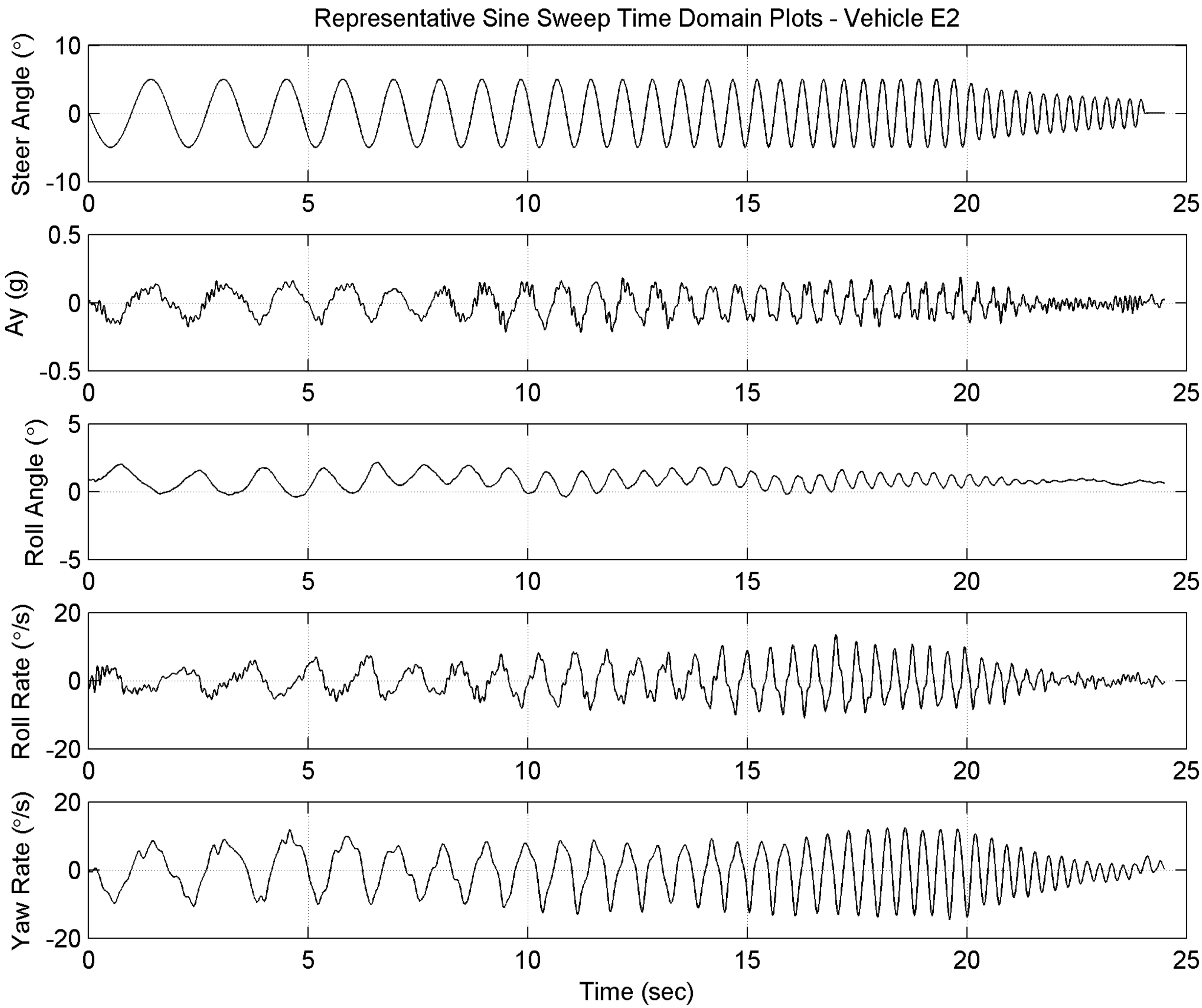
Average of All Runs

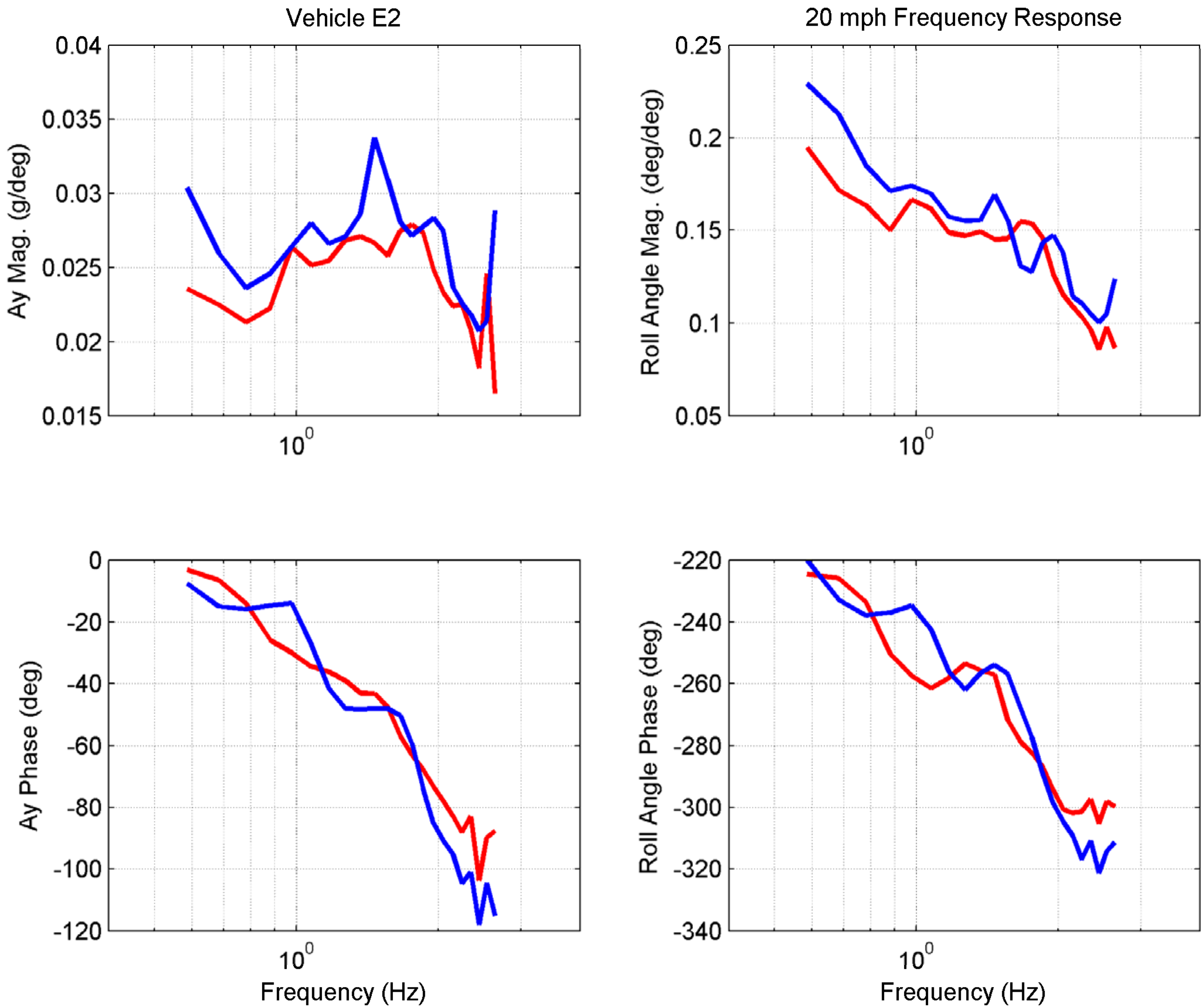
0.552

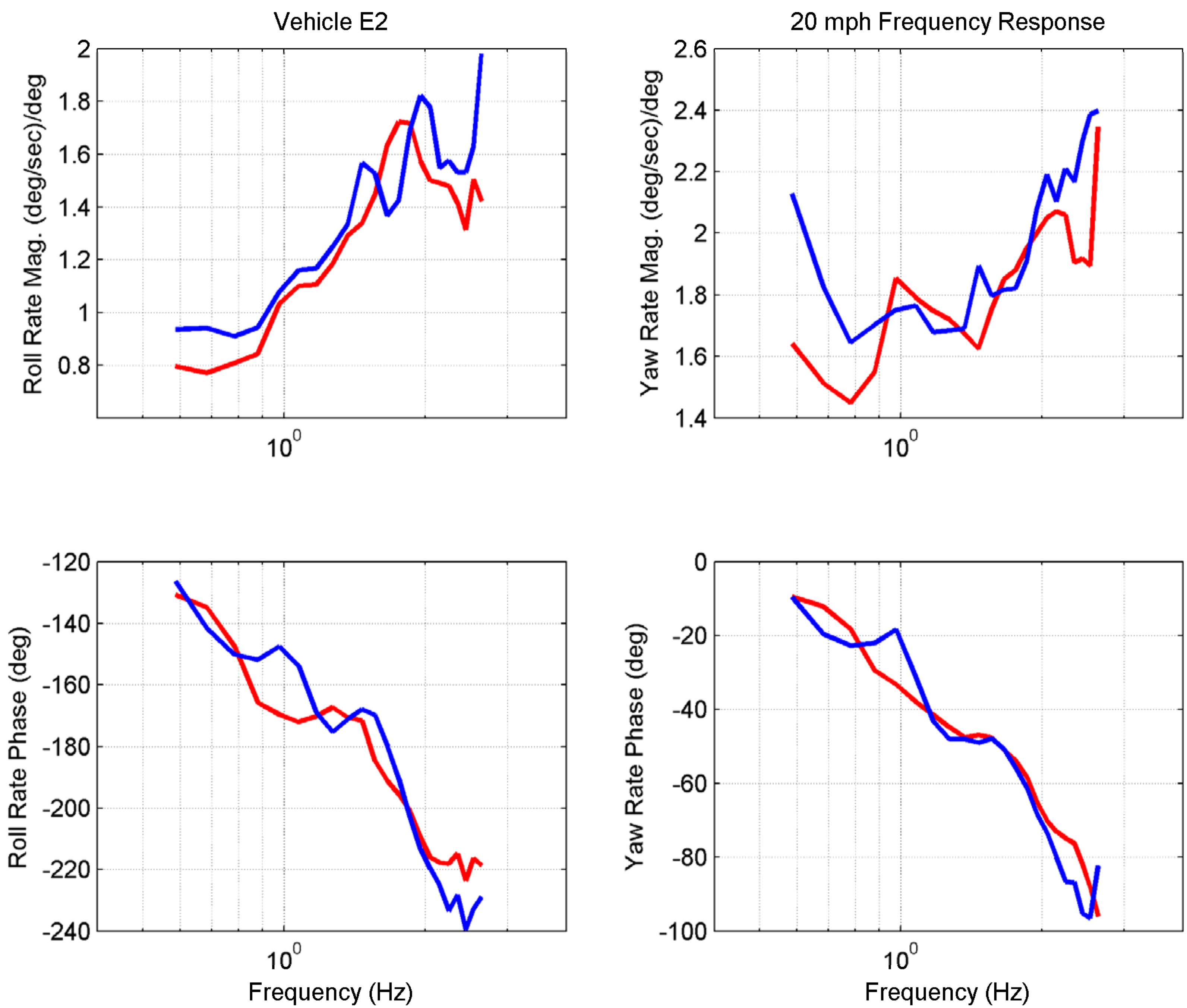
Run Number	Southbound Right Turns	Southbound Left Turns
1	0.5347	-0.5649
2	0.5412	-0.5373
3	0.5350	-0.5553
4		-0.5549
5		
Mean Value of Runs	0.5370	-0.5531
Standard Deviation of Runs	0.004	0.012

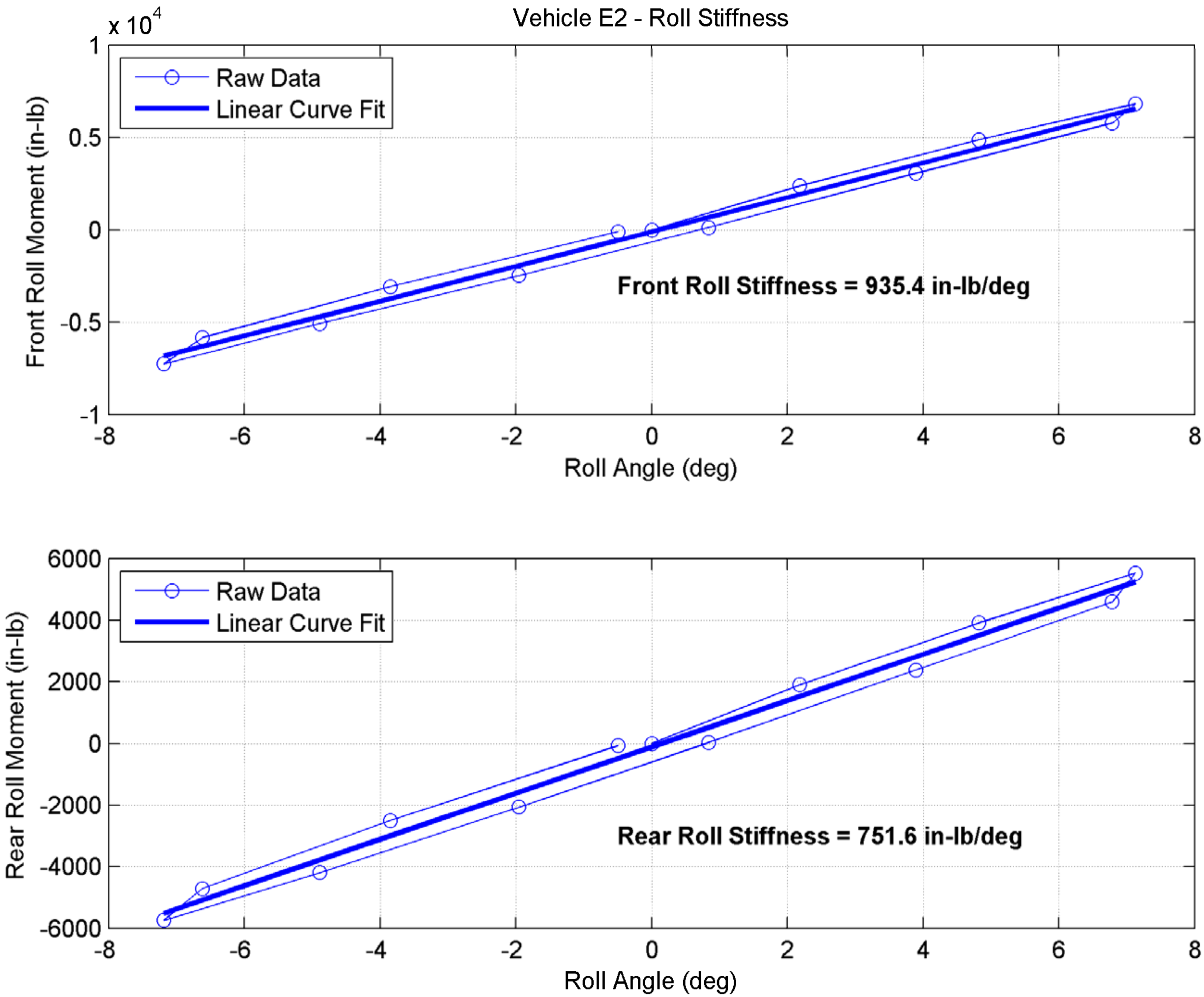
Average of Southbound Runs

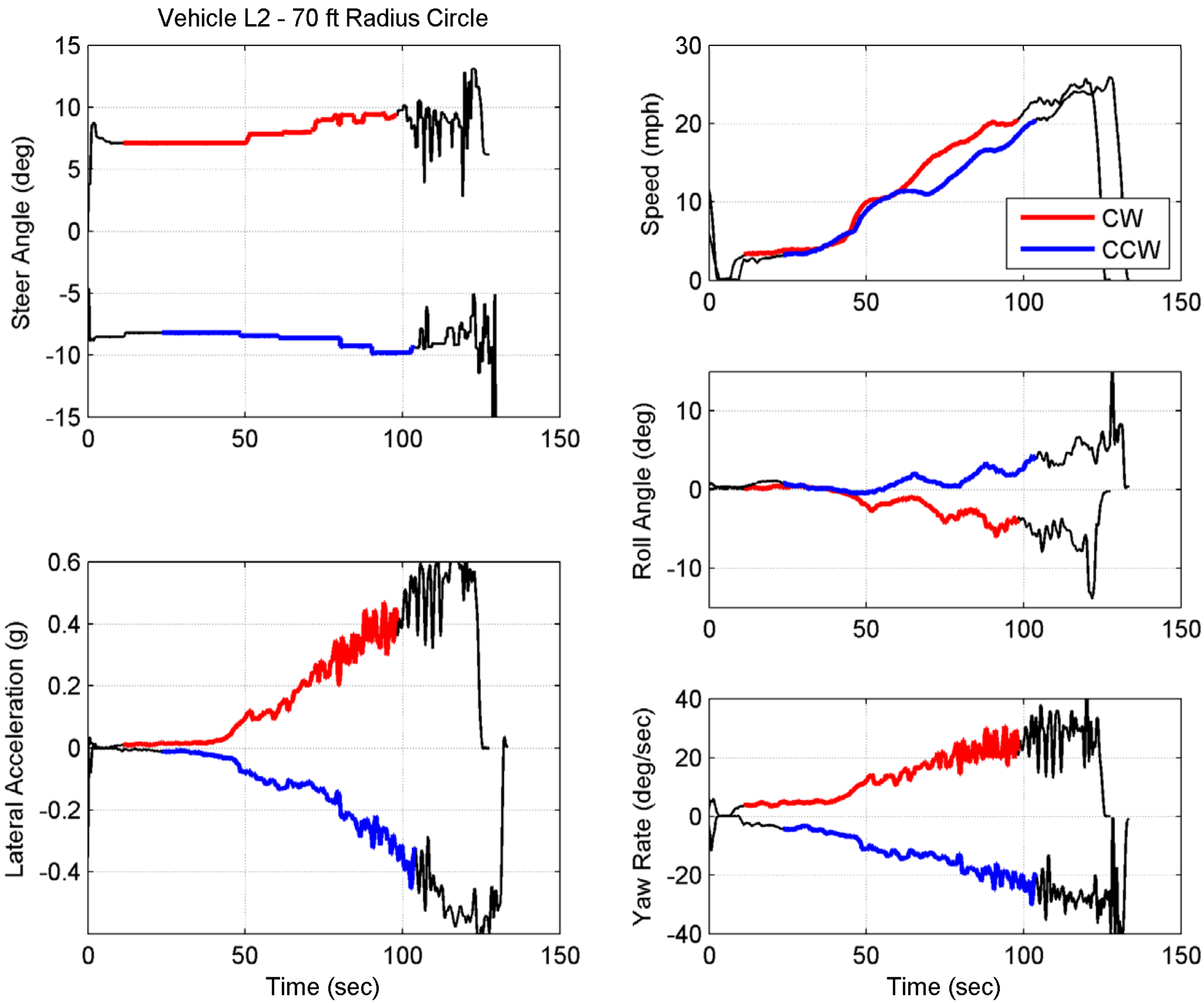
0.5450

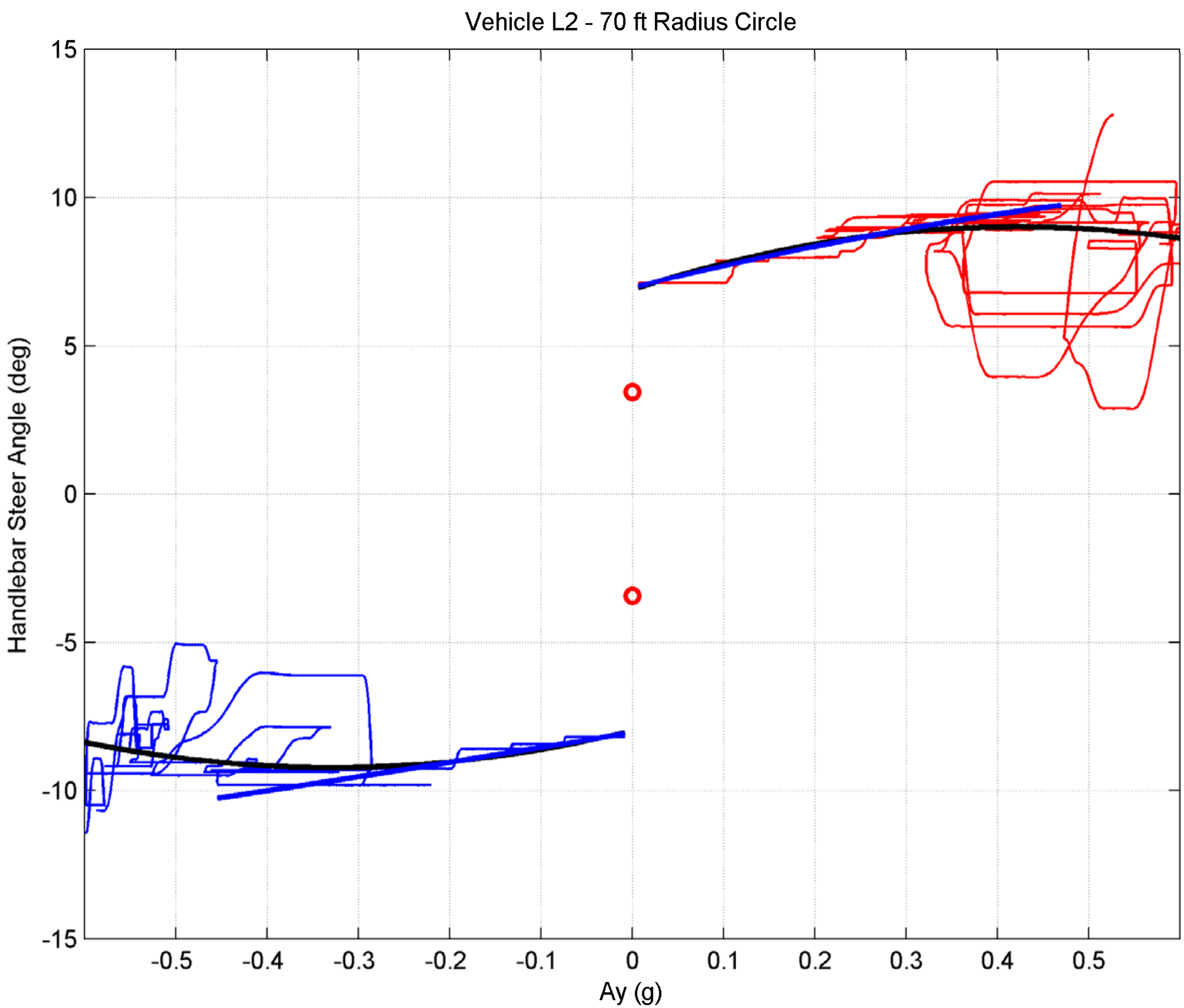

Representative Sine Sweep Time Domain Plots - Vehicle E2
Steer Angle (°)
10
0
-10
Ay (g)
0.5
0
-0.5
Roll Angle (°)
5
0
-5
Roll Rate (°/s)
20
0
-20
Yaw Rate (°/s)
20
0
-20
0
5
10
15
20
25
Time (sec)

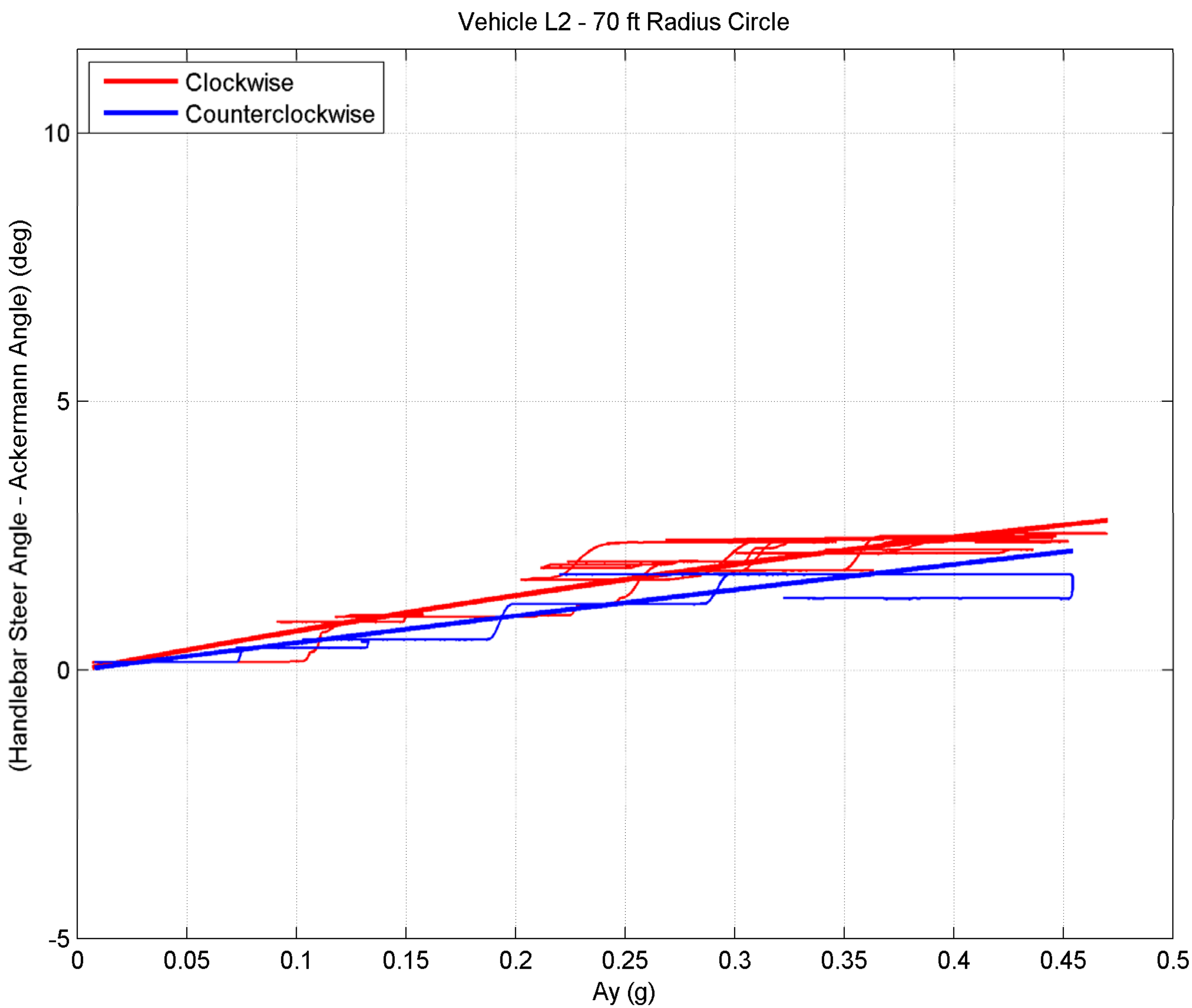

Vehicle E2
20 mph Frequency Response
Ay Mag. (g/deg)
0.04
0.035
0.03
0.025
0.02
0.015
Roll Angle Mag. (deg/deg)
0.25
0.2
0.15
0.1
0.05
Ay Phase (deg)
0
-20
-40
-60
-80
-100
-120
Roll Angle Phase (deg)
-220
-240
-260
-280
-300
-320
-340
10^0
Frequency (Hz)

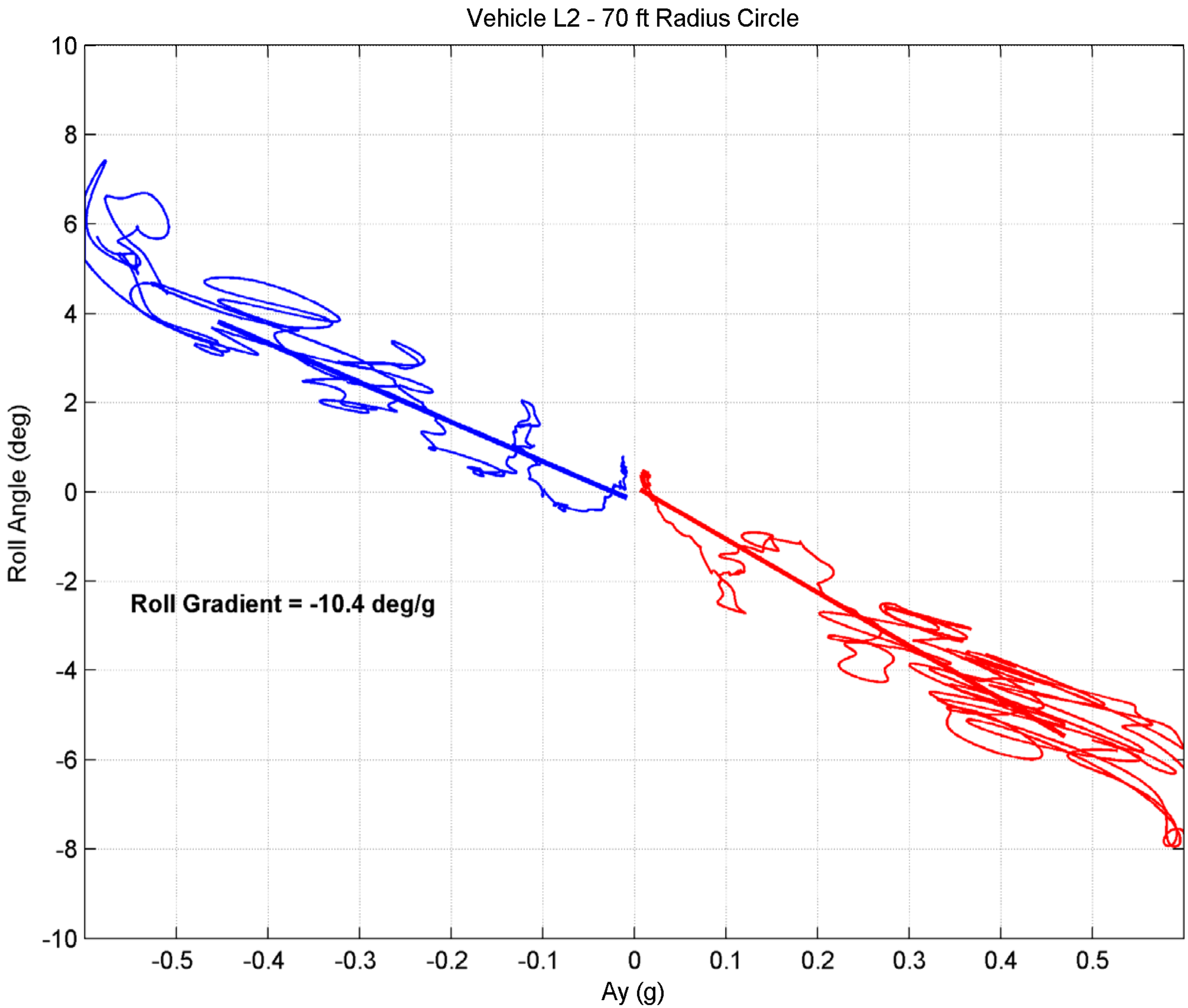

Vehicle E2
20 mph Frequency Response
Roll Rate Mag. (deg/sec)/deg
Yaw Rate Mag. (deg/sec)/deg
Roll Rate Phase (deg)
Yaw Rate Phase (deg)
Frequency (Hz)
Frequency (Hz)

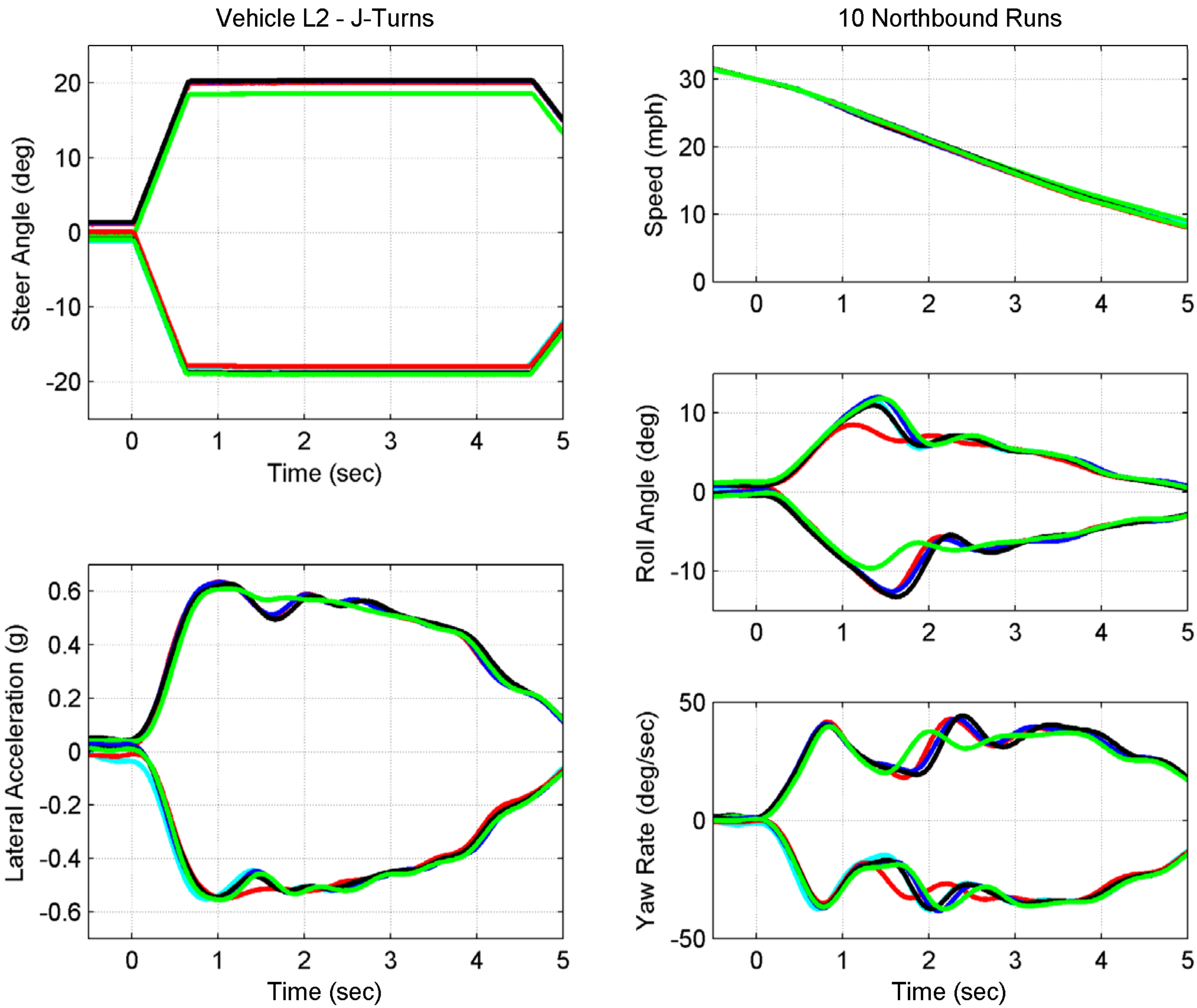

Vehicle E2 - Roll Stiffness
x 10^4
Raw Data
Linear Curve Fit
Front Roll Stiffness = 935.4 in-lb/deg
Front Roll Moment (in-lb)
Roll Angle (deg)
Raw Data
Linear Curve Fit
Rear Roll Stiffness = 751.6 in-lb/deg
Rear Roll Moment (in-lb)
Roll Angle (deg)


Vehicle L2 - 70 ft Radius Circle
Steer Angle (deg)
15
10
5
0
-5
-10
-15
0
50
100
150
Speed (mph)
30
20
10
0
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
0.6
0.4
0.2
0
-0.2
-0.4
Time (sec)
Yaw Rate (deg/sec)
40
20
-20
-40
Time (sec)

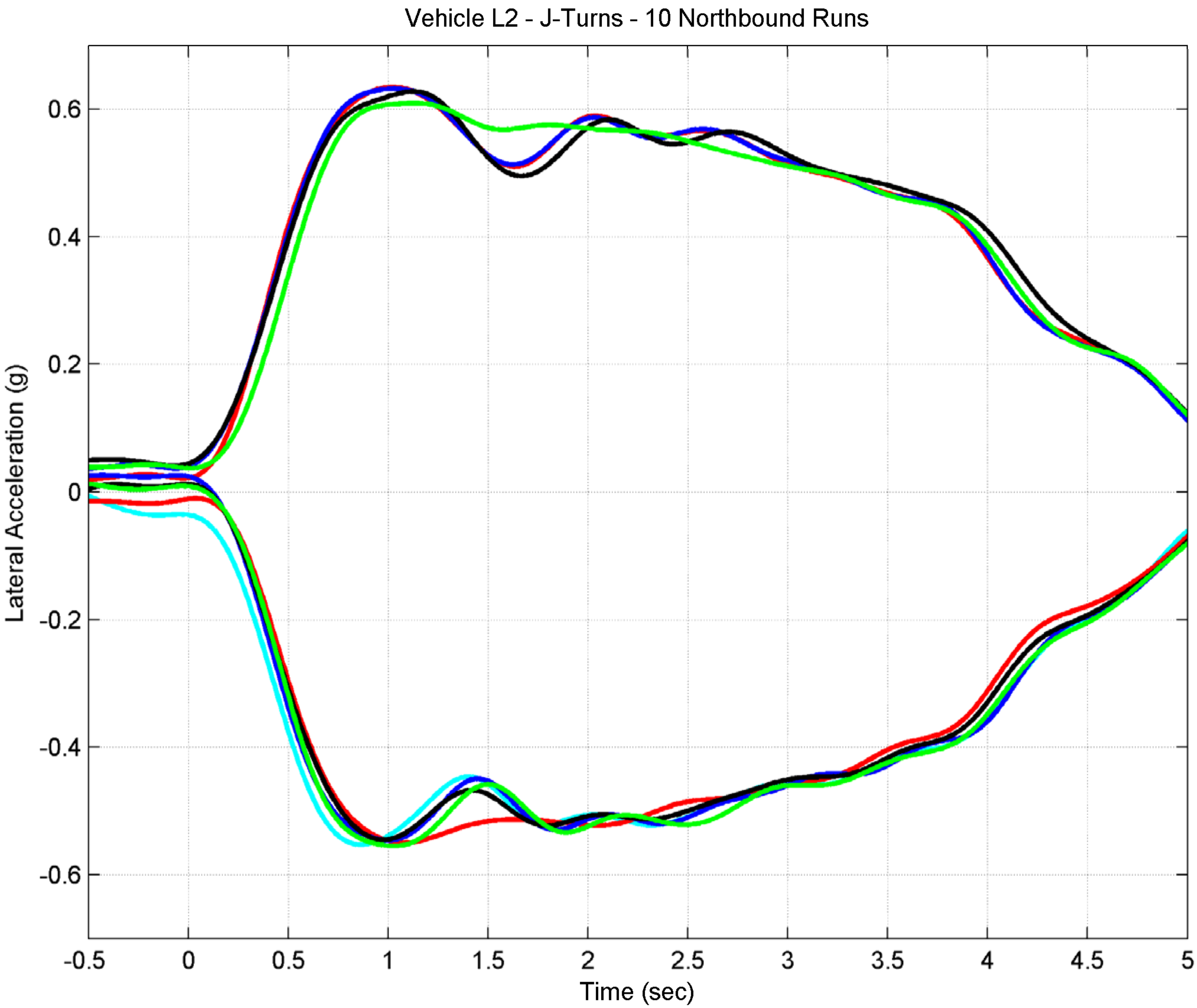

Vehicle L2 - 70 ft Radius Circle
Handlebar Steer Angle (deg)
15
10
5
0
-5
-10
-15
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
Ay (g)

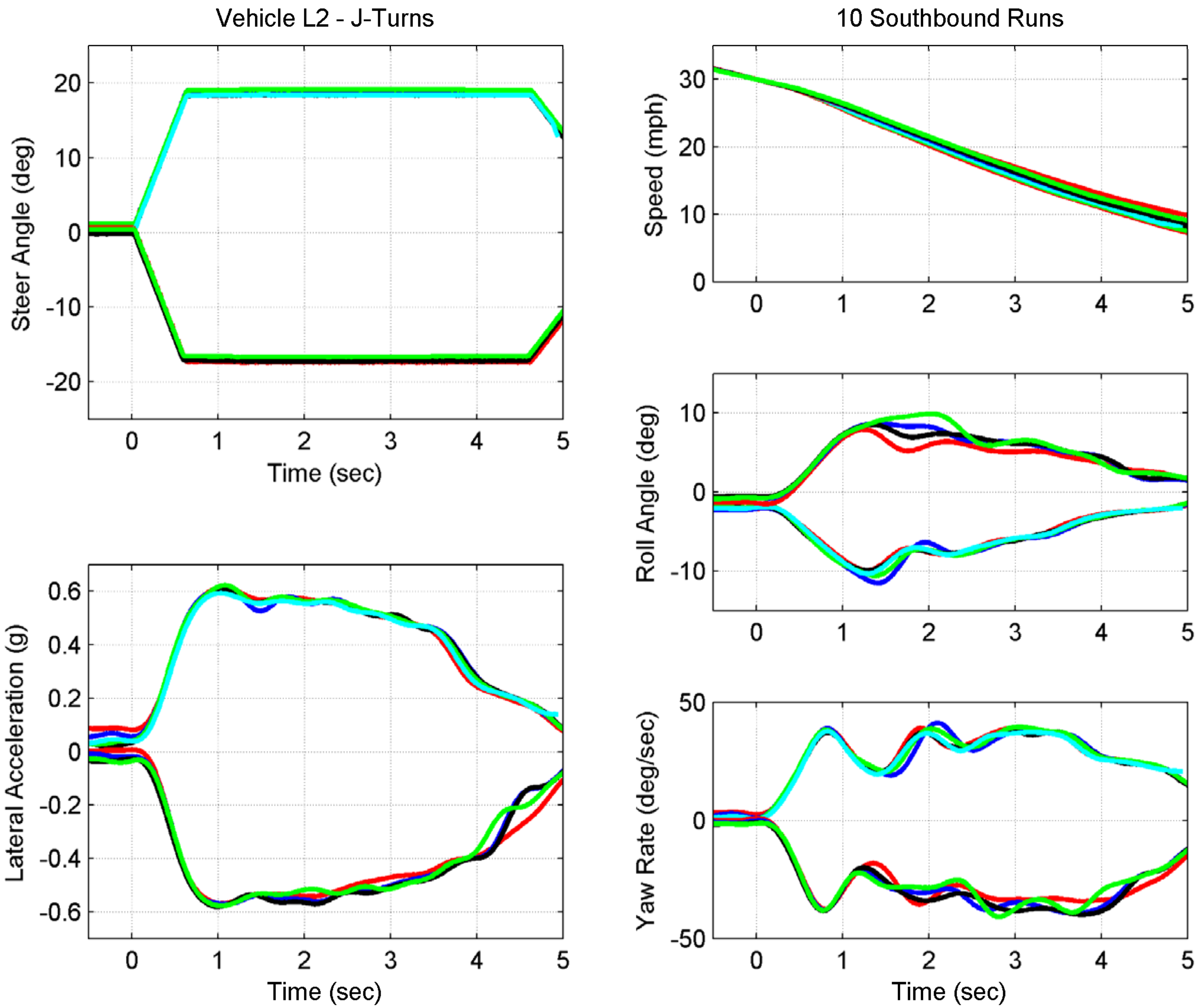

Vehicle L2 - 70 ft Radius Circle
Clockwise
Counterclockwise
10
5
0
-5
(Handlebar Steer Angle - Ackermann Angle) (deg)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Ay (g)

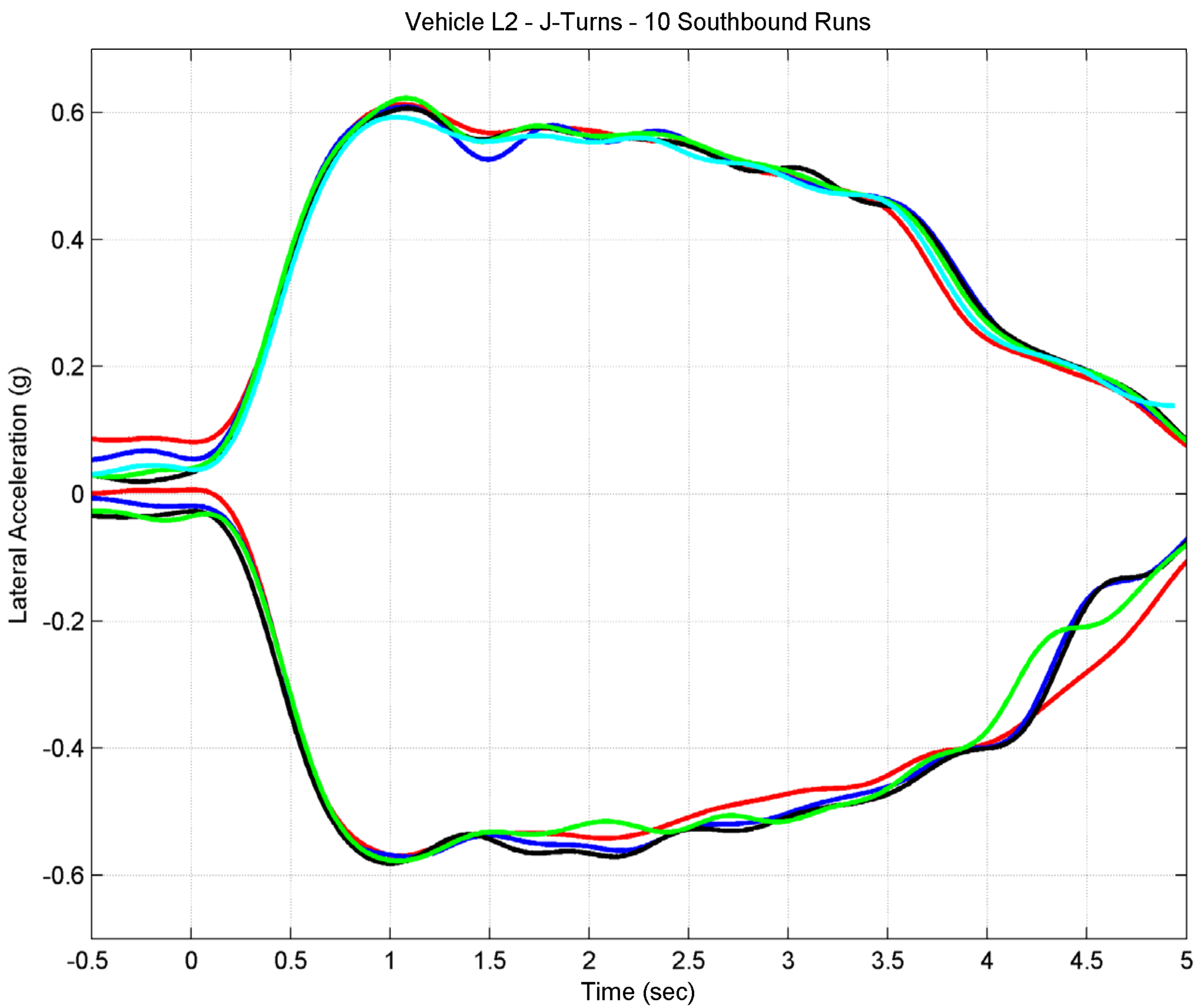

Vehicle L2 - 70 ft Radius Circle
Roll Angle (deg)
Ay (g)
Roll Gradient = -10.4 deg/g
10
8
6
4
2
0
-2
-4
-6
-8
-10
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5



Vehicle L2 - J-Turns
10 Northbound Runs
Steer Angle (deg)
Time (sec)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)


Vehicle L2 - J-Turns - 10 Northbound Runs
Lateral Acceleration (g)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (sec)


Vehicle L2 - J-Turns
10 Southbound Runs
Steer Angle (deg)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)
Time (sec)



Vehicle L2 - J-Turns - 10 Southbound Runs
Lateral Acceleration (g)
Time (sec)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

Vehicle L2

Run Number	Northbound Right Turns	Northbound Left Turns
1	0.6347	-0.5532
2	0.6323	-0.5502
3	0.6279	-0.5463
4	0.6096	-0.5457
5		-0.5554
Mean Value of Runs	0.6261	-0.5501
Standard Deviation of Runs	0.011	0.004

Average of Northbound Runs

0.5881

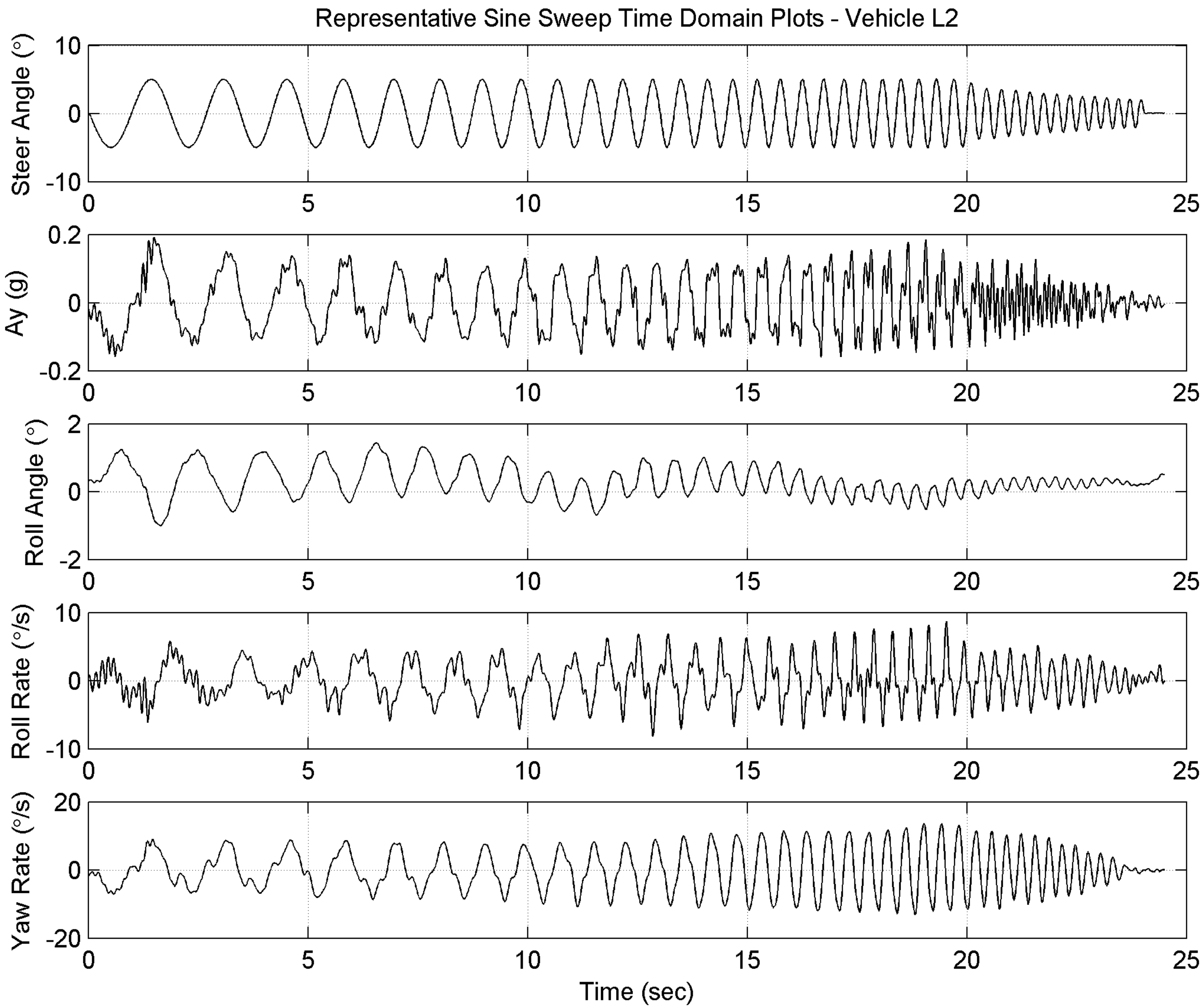
Average of All Runs

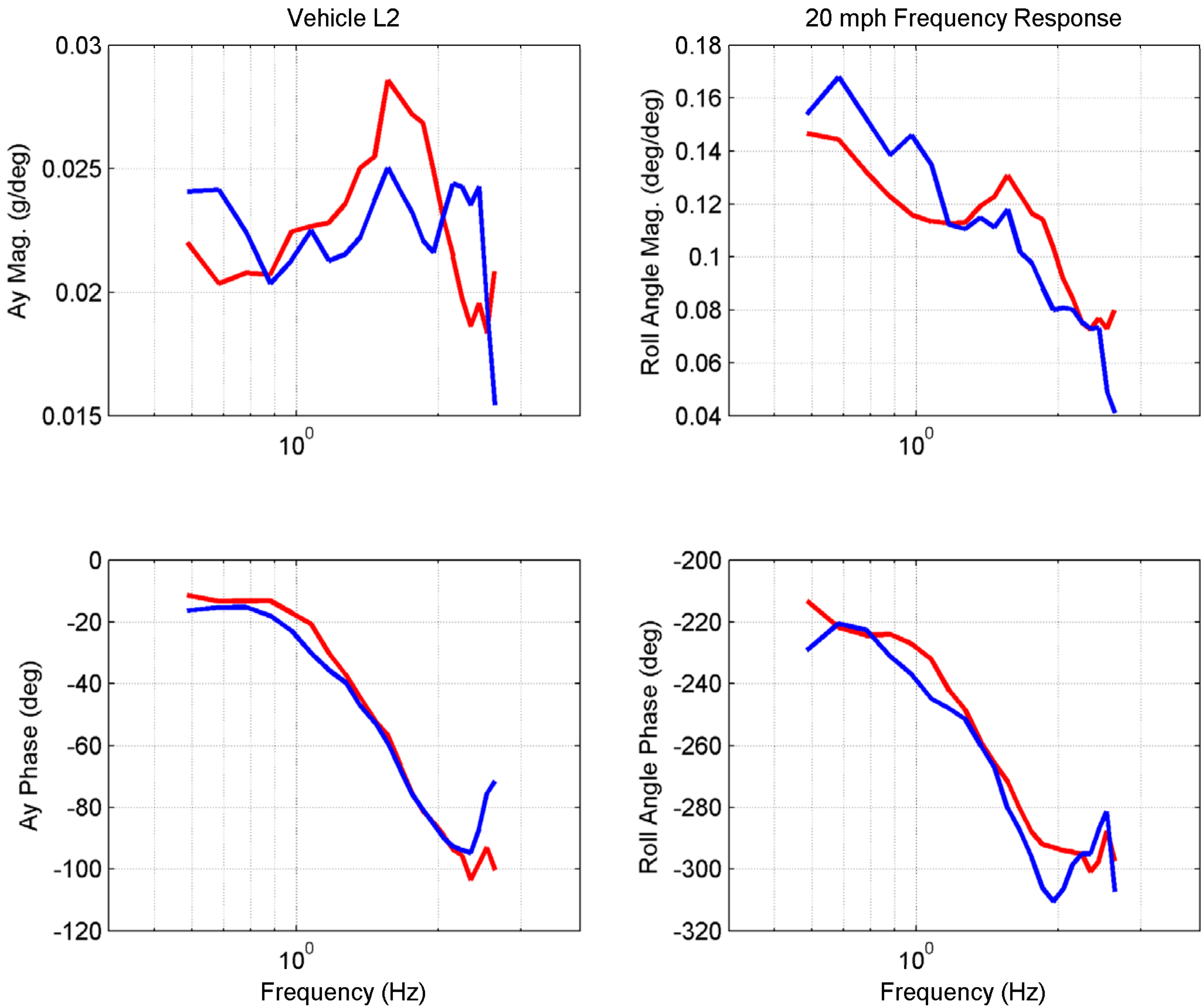
0.590

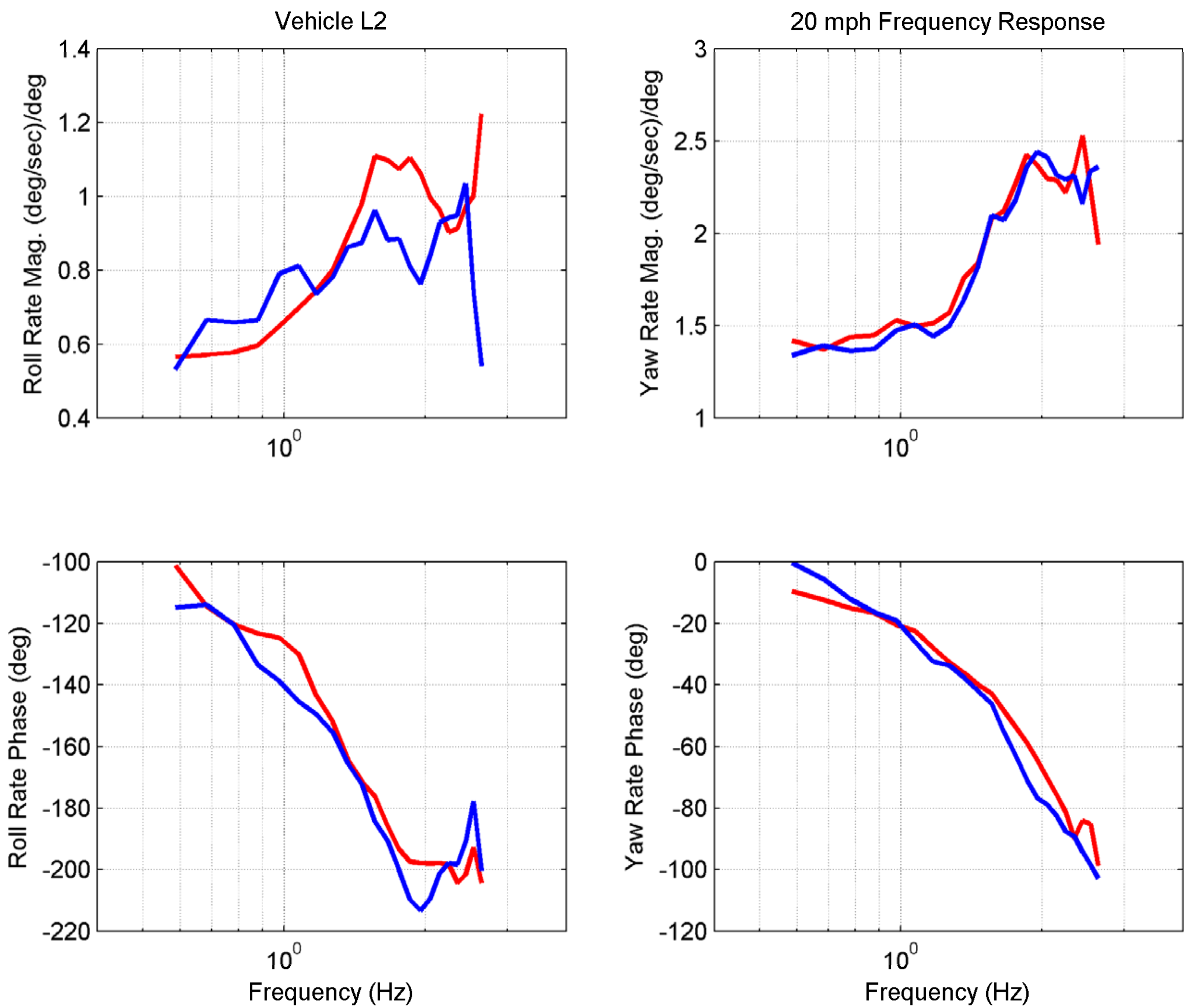
Run Number	Southbound Right Turns	Southbound Left Turns
1	0.6128	-0.5700
2	0.6091	-0.5713
3	0.6065	-0.5818
4	0.6229	-0.5778
5	0.5929	
Mean Value of Runs	0.6088	-0.5752
Standard Deviation of Runs	0.011	0.006

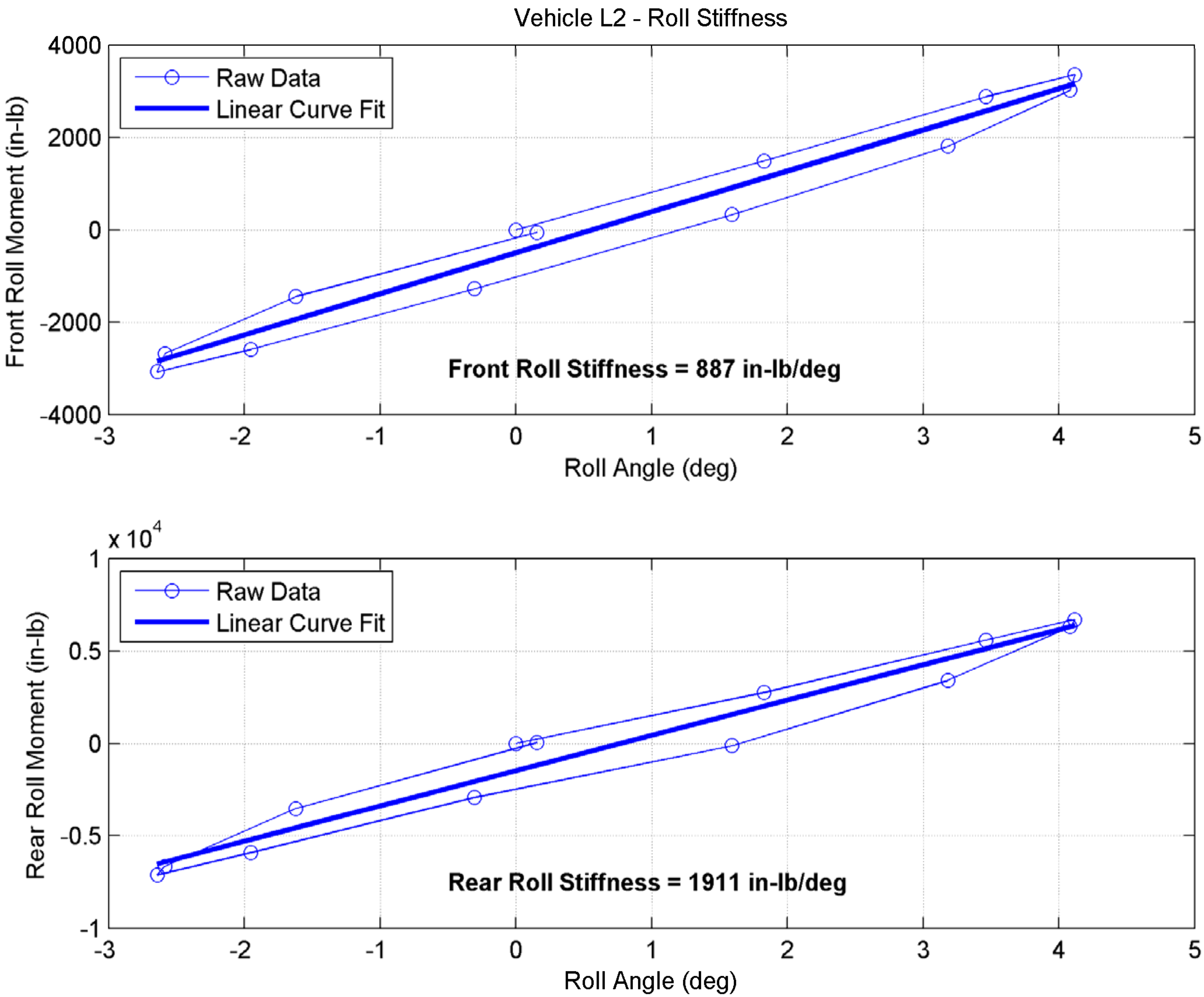
Average of Southbound Runs

0.5920


Representative Sine Sweep Time Domain Plots - Vehicle L2
Steer Angle (°)
Ay (g)
Roll Angle (°)
Roll Rate (°/s)
Yaw Rate (°/s)
Time (sec)
10
0
-10
0.2
0
-0.2
2
0
-2
10
0
-10
20
0
-20
0
5
10
15
20
25


Vehicle L2
20 mph Frequency Response
0.03
0.025
0.02
0.015
Ay Mag. (g/deg)
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
Roll Angle Mag. (deg/deg)
10^0
0
-20
-40
-60
-80
-100
-120
Ay Phase (deg)
-200
-220
-240
-260
-280
-300
-320
Roll Angle Phase (deg)
Frequency (Hz)


Vehicle L2
20 mph Frequency Response
Roll Rate Mag. (deg/sec)/deg
1.4
1.2
1
0.8
0.6
0.4
10^0
Yaw Rate Mag. (deg/sec)/deg
3
2.5
2
1.5
1
10^0
Roll Rate Phase (deg)
-100
-120
-140
-160
-180
-200
-220
10^0
Frequency (Hz)
Yaw Rate Phase (deg)
0
-20
-40
-60
-80
-100
-120
10^0
Frequency (Hz)


Vehicle L2 - Roll Stiffness
Raw Data
Linear Curve Fit
Front Roll Stiffness = 887 in-lb/deg
Front Roll Moment (in-lb)
Roll Angle (deg)
4000
2000
0
-2000
-4000
-3
-2
-1
0
1
2
3
4
5
x 10^4
Raw Data
Linear Curve Fit
Rear Roll Stiffness = 1911 in-lb/deg
Rear Roll Moment (in-lb)
Roll Angle (deg)
1
0.5
0
-0.5
-1
-3
-2
-1
0
1
2
3
4
5