CPSC Staff Statement on SEA, Ltd. Report "ATV Attribute Modification Study: Results of Baseline and Modified Vehicle Testing"[1]
April 2018

The report titled, "ATV Attribute Modification Study: Results of Baseline and Modified Vehicle Testing," presents the results of static and dynamic vehicle testing conducted by SEA, Ltd. (SEA) on three model year 2014-2015 adult single-rider all-terrain vehicles (ATVs). SEA conducted baseline testing of the three vehicles in their as-received condition, then made modifications to the vehicles (under direction from CPSC staff) to improve their lateral stability and/or handling characteristics, and conducted tests on the modified vehicles to study the effects on performance as compared to the vehicles in their baseline conditions. This work was conducted under Task Order 4 of contract HHSP233201400030I. This contract is funded by CPSC and is administered under an interagency agreement with the U.S. Department of Health and Human Services. The work represented by this report is part of a larger effort by CPSC staff to develop test methods, collect static and dynamic data, and identify opportunities for improvement regarding ATV performance characteristics related to vehicle stability and safety. The following reports have been published under this effort and are available at **https://www.cpsc.gov/Research--Statistics/Technical-Reports#atv-and-rovs**:

- Vehicle Characteristics Measurements of All-Terrain Vehicles
- Effects on Vehicle Characteristics of Two Persons Riding ATVs
- Effects on ATV Vehicle Characteristics of Rider Active Weight Shift
- Vehicle Characteristics Measurements of ATVs Tested on Groomed Dirt

Additionally, staff has previously identified a need for future testing, when resources are available, to include autonomous rollover testing and rollover simulation testing, with a goal to discover opportunities to reduce the likelihood and severity of injury.

[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.

ATV Attribute Modification Study:
Results of Baseline and Modified Vehicle Testing
Results from Tests on Three 2014-2015 Model Year Vehicles

for:
U.S. Consumer Product Safety Commission

February 2018

S-E-A ™

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."

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1. OVERVIEW

This report contains results from laboratory and dynamic (test track) tests made by SEA, Ltd. (SEA) on three 2014-2015 model year All-Terrain Vehicles (ATVs) for the U.S. Consumer Product Safety Commission (CPSC) under U.S. Department of Health and Human Services (HHS) contract HHSP233201400030I.

This report covers a portion of the work completed on Task Order 4 of the multi-task contract. The stated purpose and objective of this portion of Task Order 4 is:

> *The staff of the Consumer Product Safety Commission (CPSC) is evaluating various characteristics and features of All-Terrain Vehicles (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 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) condition, making modifications to the vehicles (under direction from CPSC staff) to improve their lateral stability (rollover resistance) and/or handling characteristics (yaw stability), and conducting tests on the modified vehicles to verify improvement in performance as compared to the vehicles in their baseline conditions.

Under a previous contract (CPSC contract CPSC-S-14-0047) three different vehicles from the three vehicles used in this study were tested in their baseline condition.[2] These tests were conducted with the intention of forming the baseline suite of tests that would be used in the ATV attribute modification study. However, between the time the baseline testing was completed and the time funding was available to complete the vehicle modification study, several other ATV test programs were conducted by SEA for CPSC, under Task Orders 1-4 of contract HHSP233201400030I. Highlights and references for these programs are:

- Task Order 1 involved testing 12 ATVs in the Driver Plus Instrumentation (DPI) loading condition (representing a nominal 215 lb driver) and in the Gross Vehicle Weight (GVW) loading condition using human test drivers. Laboratory and dynamic tests were performed under this task. The laboratory tests included making center-of-gravity (CG) location and inertia measurements on the vehicles as well as tilt table tests. The dynamic tests included Circle (Constant Radius) tests, J-Turn tests, and Yaw Rate Ratio (Constant Steer) tests. The SEA report to CPSC on these measurements is titled *Vehicle Characteristics Measurements of All-Terrain Vehicles – Results from Tests on Twelve 2014-2015 Model Year Vehicles*.[3]

- Task Order 2 involved autonomously testing the same 12 vehicles in a two-person (driver and passenger) loading condition. For the two-person loading condition, the vehicles were

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[2] *All-Terrain Vehicle (ATV) Attribute Modification Study – Results of Baseline Vehicle Testing*, CPSC Contract CPSC-14-0047, SEA, Ltd. Report to CPSC, January 2016. **https://www.cpsc.gov/s3fs-public/Final%20Report%20-%20ATV%20Attribute%20Modification%20Study%20-%20Baseline%20Testing%20-%20Janaury%2024%202016_0_0.pdf**

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

each tested at a total test weight nominally 430 lb (representing two 215 lb riders) above the curb weight for each vehicle. This task involved doing only dynamic tests, namely: Circle tests, J-Turn tests, and Yaw Rate Ratio tests. The SEA report to CPSC on these measurements is titled *Effects on Vehicle Characteristics of Two Persons Riding ATVs – Results from Tests on Twelve 2014-2015 Model Year Vehicles*.[4]

- Task Order 3 involved autonomously testing the same 12 vehicles to evaluate the effects on rollover resistance and vehicle handling characteristics when rider active weight shift is employed. For this rider weight shift study, the vehicles were each tested at a total test weight nominally 215 lb (representing a 215 lb rider) above the curb weight for each vehicle. Three different rider lateral lean angles were evaluated, one representing an upright rider (0° lateral lean angle), one representing a rider with a 20° lateral lean angle, and one representing a rider with a 40° lateral lean angle. This task also involved doing only dynamic tests, namely: Circle tests, J-Turn tests, and Yaw Rate Ratio tests. The tests were only conducted in the counterclockwise (CCW) and Left Turn directions to measure the effects of rider lean. The SEA report to CPSC on these measurements is titled *Effects on ATV Vehicle Characteristics of Rider Active Weight Shift – Results from Tests on Twelve 2014-2015 Model Year Vehicles*.[5]

- The other portion of the Task Order 4 work involved autonomously testing the same 12 vehicles on a groomed dirt surface. This groomed dirt study was conducted concurrently with the attribute modification study, so complete results from the groomed dirt study were not available at the start of the attribute modification study. The same loading condition that was used to represent an upright rider (0° lateral lean angle) in the Task Order 3 study was used for the groomed dirt study, and the same dynamic tests were performed. The SEA report to CPSC on these measurements is titled *Vehicle Characteristics Measurements of ATVs Tested on Groomed Dirt Results from Tests on Twelve 2014-2015 Model Year Vehicles.*[6]

Based on the results from testing done on all 12 vehicles (Vehicles A – L), the decision was made by CPSC staff to not use the three vehicles (Vehicles B, E and L) that were selected for the previous attribute modification study.[7] Vehicles B, E and L were originally selected by CPSC staff because they were among the most popular vehicles based on sales. However, after the various test programs involving all 12 vehicles were completed, results indicated that they were not the best subject vehicles for the attribute modification study. Vehicles B, E and L were three of the five vehicles with the highest Threshold Ay values measured during J-Turn tests, indicating that they

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[4] *Effects on Vehicle Characteristics of Two Persons Riding ATVs – Results from Tests on Twelve 2014-2015 Model Year Vehicles*, HHS Contract HHSP233201400030I, SEA, Ltd. Report to CPSC, September 2017. **https://www.cpsc.gov/s3fs-public/SEA-Final-Report-to-CPSC-2-Rider-ATV-Study.pdf?V0ixJO3o_kbtsmIBeKUInRAFx6hVocs5**

[5] *Effects on ATV Vehicle Characteristics of Rider Active Weight Shift – Results from Tests on Twelve 2014-2015 Model Year Vehicles*, HHS Contract HHSP233201400030I, SEA, Ltd. Report to CPSC, January 2018. **https://www.cpsc.gov/s3fs-public/SEA-Report-to-CPSC-Rider-Active-ATV-Study-December-2017.pdf?1nQBCXYgr.fkZoAR3axu7hkJ9l7mbSUl**

[6] *Vehicle Characteristics Measurements of ATVs Tested on Groomed Dirt Results from Tests on Twelve 2014-2015 Model Year Vehicles*, HHS Contract HHSP233201400030I, SEA, Ltd. Report to CPSC, In Review.

[7] *All-Terrain Vehicle (ATV) Attribute Modification Study – Results of Baseline Vehicle Testing*, CPSC Contract CPSC-14-0047, SEA, Ltd. Report to CPSC, January 2016. **https://www.cpsc.gov/s3fs-public/Final%20Report%20-%20ATV%20Attribute%20Modification%20Study%20-%20Baseline%20Testing%20-%20Janaury%2024%202016_0_0.pdf**

had relatively high rollover resistance among the 12 vehicles tested. Also, Vehicles B, E and L had relatively low Yaw Rate Ratio values when conducted on asphalt with human drivers and autonomously (in the upright driver loading condition); indicating that these three vehicles were not as prone to yaw instabilities as some of the other vehicles tested.

Ultimately, CPSC selected Vehicles F, G and K for the vehicle attribute modification study, which is the subject of this report; for the following reasons:

- Vehicle F was selected to study changes in attributes that would primarily improve its rollover resistance. Vehicle F has Threshold Ay values among the lowest of the vehicles tested, and it is one of the lightest automatic transmission vehicles with a solid rear axle suspension.

- Vehicle G was selected to study changes in attributes that would improve its handling (yaw stability) and rollover resistance. Vehicle G has Threshold Ay values among the lowest of the vehicles tested, and it has relatively high Yaw Rate Ratio values, above 6.9 in DPI tests conducted on asphalt with human drivers and autonomously (in the upright rider loading condition). Vehicle G has an independent rear suspension.

- Vehicle K was selected because it has available commercial hardware for converting its locked rear differential to an open rear differential. CPSC staff was interested in learning if testing an ATV with an open differential would cause any significant changes in the results of the Circle, J-Turn or Yaw Rate Ratio tests conducted. Vehicle K ranks near the middle of the 12 vehicles tested for its Threshold Ay values and it has relatively low Yaw Rate Ratio values, below 2.3 in DPI tests conducted on asphalt with human drivers and autonomously (in the upright rider loading condition). Vehicle K also has an independent rear suspension.

The Task Order 3 rider weight shift study was conducted in 2016 on the asphalt test pad at SEA. The tests conducted for this study were conducted autonomously using SEA's ATV Robotic Test Driver (ATV RTD). Conducting the tests autonomously provided a means to use ballast fixed rigidly to the vehicle to represent the driver mass. Conducting the tests without a human driver mitigated the potential for having the test results influenced by human drivers shifting their weight to secure themselves to the vehicles during the tests and it eliminated the need to have the drivers attempt to lean to specific lateral lean angles. For these reasons, the decision was made to conduct the attribute modification study tests autonomously. Furthermore, the decision was made to use the upright rider loading condition as the baseline for the modification study tests. Accordingly, tests conducted in 2016 as part of the driver weight shift study served as the baseline tests for the vehicle attribute modification study.

Table 1 contains a list of assorted vehicle information and tire specifications for the three vehicles. The measured curb weights and maximum speeds are listed. Table 1 also lists the front and rear tire make, tire size, and tire pressure for each vehicle.

The dynamic tests on the modified vehicles were performed by SEA on numerous dates between May 9, 2017 and July 26, 2017. All of the modified vehicles were tested on SEA's asphalt test pad, and Vehicle K was also tested on SEA's groomed dirt test pad. All vehicles were tested in two-wheel drive mode, and in their most open driveline configurations. Vehicle K was also modified for testing in two-wheel drive mode with an open rear differential.

The following suite of dynamic tests was performed for each vehicle:

- **Constant Radius (50 ft) (Circle) Tests**
- **Dropped Throttle J-Turn (Step Steer) Tests (Initial Speed of 20 mph)**
- **Constant Steer Tests (Yaw Rate Ratio Tests)**

This report contains six main sections: Overview, Vehicle Attributes Modified, Laboratory Testing, Dynamic Testing, Discussion of Test Results, and Comparison of Results from Vehicles with Modified Attributes. There are also three appendices containing test results.

Table 1: Test Vehicle Information and Tire Specifications

Vehicle F **Curb Weight: 526.2 lb** **Maximum Speed: 53.5 mph**	**Automatic Transmission** **Solid Rear Axle** **2WD**	
	Front Tires	Rear Tires
Tire Make	Kenda Pathfinder	Kenda Pathfinder
Tire Size	AT22X7-10 4 Ply	AT22X10-10 4 Ply
Tire Pressure (psi)	4	3.5
Vehicle G **Curb Weight: 694.0 lb** **Maximum Speed: 69.0 mph**	**Automatic Transmission** **Independent Rear Suspension** **2WD or 4WD**	
	Front Tires	Rear Tires
Tire Make	Duro DI-K911	Duro DI-K911
Tire Size	AT25X8-12 4 Ply	AT25X10-12 4 Ply
Tire Pressure (psi)	5	5
Vehicle K **Curb Weight: 832.0 lb** **Maximum Speed: 74.0 mph**	**Automatic Transmission** **Independent Rear Suspension** **2x4, 4x4, or 4x4 Lock**	
	Front Tires	Rear Tires
Tire Make	Carlisle AT489 II	Carlisle AT489 II
Tire Size	AT 26X8-14 6 Ply	AT 26X10-14 6 Ply
Tire Pressure (psi)	7	7

2. VEHICLE ATTRIBUTES MODIFIED

As mentioned, all tests were conducted in the representative 215 lb driver-only loading condition with 0° rider (driver) lean angle. Also, all baseline tests were conducted as part of the previous rider weight shift study.[8] The baseline tests, and all modification tests on Vehicle F and Vehicle G were conducted in the CCW and Left turn directions only. All modification tests on Vehicle K were conducted in both the CCW and CW directions, and in both the Left and Right turn directions.

The following lists the attribute modifications made for each vehicle:

- Vehicle F Modifications:

  1: Added 2-inch-thick wheel spacers on all four wheels to increase track width

  2: Lowered Driver-Lean Ballast to reduce vehicle CG height

  3: Moved Driver-Lean Ballast and other ballast forward to move vehicle CG forward (to match CG longitudinal position used for tests with human driver)

- Vehicle G Modifications:

  1: Replaced front springs to increase front (roll) stiffness

  2: Replaced front springs to increase front (roll) stiffness, and disconnected rear anti-roll bar to decrease rear roll stiffness

  3: Replaced front springs to increase front (roll) stiffness, disconnected rear anti-roll bar to decrease rear roll stiffness, and modified steering geometry to reduce roll oversteer

- Vehicle K Modifications:

  1: Tested on asphalt with locked rear differential

  2: Tested on asphalt with open rear differential

  3: Tested on groomed dirt with locked rear differential

  4: Tested on groomed dirt with open rear differential

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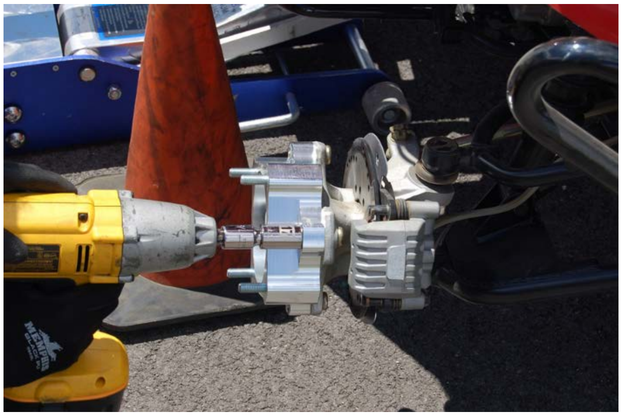
[8] *Effects on ATV Vehicle Characteristics of Rider Active Weight Shift – Results from Tests on Twelve 2014-2015 Model Year Vehicles*, HHS Contract HHSP233201400030I, SEA, Ltd. Report to CPSC, January 2018. **https://www.cpsc.gov/s3fs-public/SEA-Report-to-CPSC-Rider-Active-ATV-Study-December-2017.pdf?1nQBCXYgr.fkZoAR3axu7hkJ9l7mbSUl**

2.1 Details of Vehicle F Modifications

Modification 1 on Vehicle F involved adding two-inch-thick wheel spacers on all four wheels to increase the track width. Figure 1 shows the wheel spacers being added to the vehicle. Table 2 lists values for key attributes for Vehicle F in the Baseline and Modification 1 conditions. Adding the wheel spacers increased the vehicle track widths by 4.0 inches, and increased the Static Stability Factor (SSF) by 0.079.



2" Wheel Spacer on Front

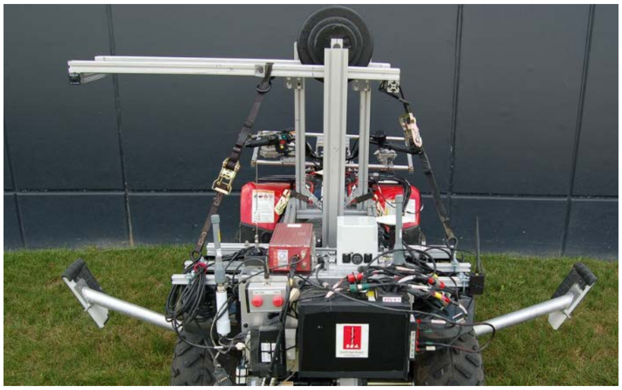
2" Wheel Spacer on Rear

Figure 1: Wheel Spacers Used on Vehicle F

Table 2: Key Attribute Changes for Modification 1 on Vehicle F

Attribute	Baseline	Modification 1
Vehicle Weight as Tested (lb)	740.0	753.0
Front Track Width (in)	32.55	36.55
Rear Track Width (in)	30.95	34.95
Average Track Width (in)	31.75	35.75
Measured CG Height (in)	23.15	23.37
Static Stability Factor (SSF)	0.686	0.765
Tilt Table Ratio (TTR)	0.471	0.538

Modification 2 on Vehicle F involved lowering the ballast used during the Rider Active study to represent different rider lean angles to reduce the vehicle CG height. Figure 2 shows the height of the rider-lean ballast in the Baseline and Modification 2 conditions, and Table 3 lists values for key attributes for Vehicle F in both conditions. Lowering the rider-lean ballast reduced the vehicle CG height by 1.44 inches, and increased the SSF by 0.045.



Normal Height of Rider-Lean Ballast
Baseline

Lowered Rider-Lean Ballast
Modification 2

Figure 2: Baseline and Lowered CG Height Conditions on Vehicle F

Table 3: Key Attribute Changes for Modification 2 on Vehicle F

Attribute	Baseline	Modification 2
Vehicle Weight as Tested (lb)	740.0	740.5
Front Track Width (in)	32.55	32.55
Rear Track Width (in)	30.95	30.95
Average Track Width (in)	31.75	31.75
Measured CG Height (in)	23.15	21.71
Static Stability Factor (SSF)	0.686	0.731
Tilt Table Ratio (TTR)	0.471	0.522

Modification 3 on Vehicle F involved moving the rider-lean ballast and other ballast forward to move the vehicle CG forward (to match the longitudinal CG position used for tests with a human driver). Figure 3 shows the rider-lean ballast moved forward on Vehicle 3. Also, the 24-volt battery was moved from the rear rack to the front rack, to move the overall vehicle longitudinal CG to the desired position. Table 4 lists values for key attributes for Vehicle F in its Baseline and Modification 3 conditions. The longitudinal distance from the front axle to the vehicle CG was 23.74 inches for Modification 3, and it was 23.76 inches in the human driver DPI loading condition.

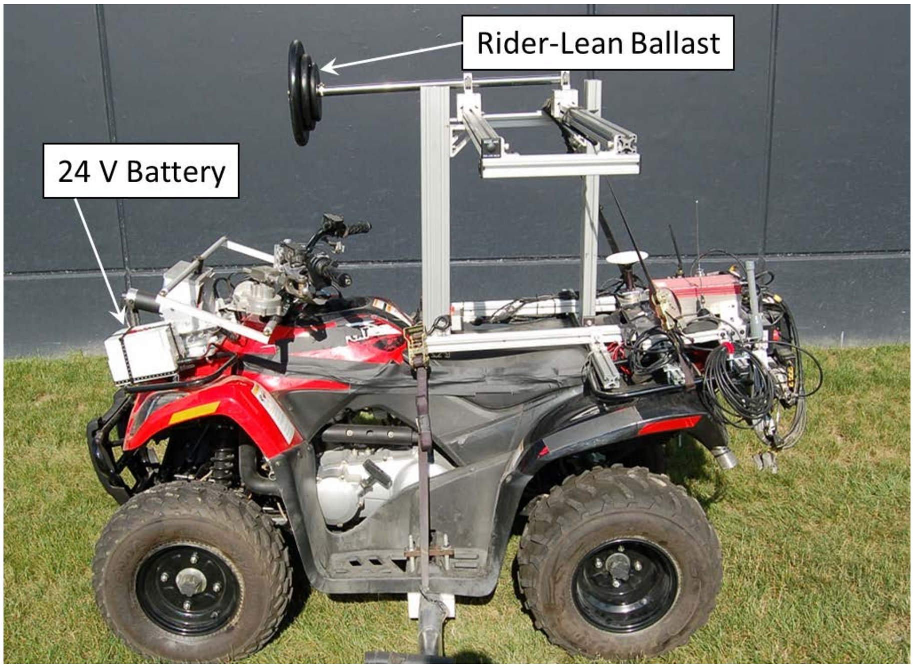


Figure 3: Forward Biased CG Condition on Vehicle F

Table 4: Key Attribute Changes for Modification 3 on Vehicle F

Attribute	Baseline	Modification 3
Vehicle Weight as Tested (lb)	740.0	749.2
Front Track Width (in)	32.55	32.55
Rear Track Width (in)	30.95	30.95
Average Track Width (in)	31.75	31.75
Longitudinal CG Position (in)	26.06	23.74
Measured CG Height (in)	23.15	23.39
Static Stability Factor (SSF)	0.686	0.679
Tilt Table Ratio (TTR)	0.471	0.469

2.2 Details of Vehicle G Modifications

Modification 1 on Vehicle G involved replacing the Original Equipment Manufacturer (OEM) front springs with springs with greater stiffness. Doing so increased the front vertical (bounce) stiffness and front roll stiffness of the vehicle. Figure 4 shows the replacement springs used on Vehicle G. Table 5 lists values for key attributes for Vehicle G in the Baseline and Modification 1 conditions. Replacing the front springs increased the vehicle CG height slightly, and slightly reduced the SSF. However, the TTR increased by 0.025 when the stiffer front springs were added to the vehicle.

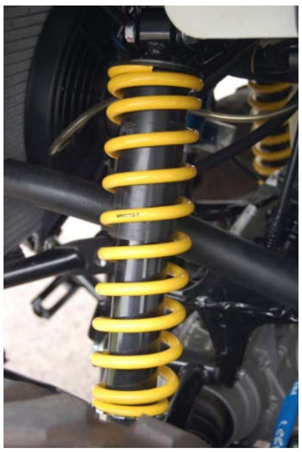
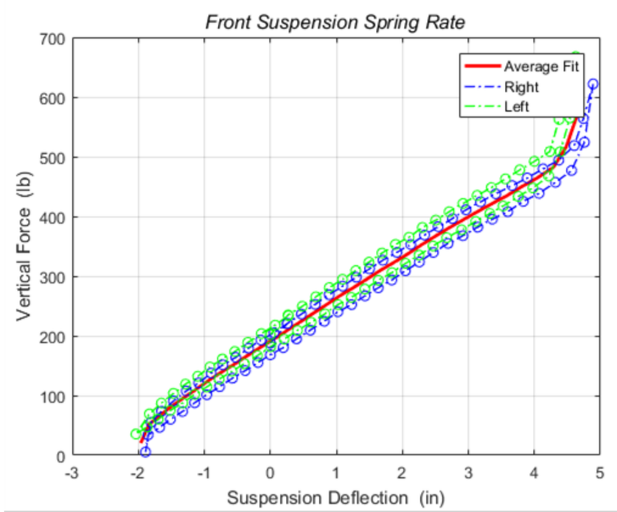


Figure 4: Replacement Front Springs Used to Increase Front Stiffness of Vehicle G

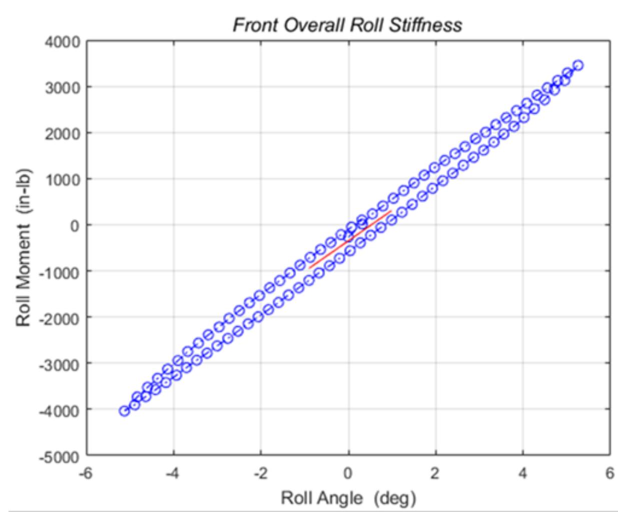
Table 5: Key Attribute Changes for Modification 1 on Vehicle G

Attribute	Baseline	Modification 1
Vehicle Weight as Tested (lb)	914.5	916.0
Measured CG Height (in)	24.85	25.14
Static Stability Factor (SSF)	0.730	0.722
Tilt Table Ratio (TTR)	0.538	0.563
Front Vertical Stiffness (lb/in)	74.5	106.0
Front Roll Stiffness (in-lb/deg)	662	911
Rear Roll Stiffness (in-lb/deg)	933	933
Total Roll Stiffness (in-lb/deg)	1,595	1,844
Percent Front Roll Stiffness (%)	41.5	49.4

The front suspension vertical and roll stiffnesses listed in Table 5 were measured using SEA's in-house Suspension Parameter Measurement Device (SPMD). Figure 5 contains graphs showing the vertical and bounce stiffness measurements made on Vehicle G in its Baseline condition. The rear suspension roll stiffness and total roll stiffness (overall vehicle roll stiffness) are also listed in Table 5. The percentage of total vehicle roll stiffness on the front suspension is also listed for both configurations.



Vertical Stiffness: 74.5 lb/in



Roll Stiffness: 662 (in-lb)/deg

Figure 5: Front Suspension Vertical (Bounce) and Roll Stiffness Measurements Made on Vehicle G in its Baseline Condition

Modification 2 on Vehicle G involved replacing the OEM front springs with springs with greater stiffness to increase front (roll) stiffness, and disconnecting the rear anti-roll bar to decrease rear roll stiffness (see Figure 6). Table 6 lists values for key attributes for Vehicle G in the Baseline, Modification 1 and Modification 2 conditions. Disconnecting the rear anti-roll bar does not change the weight, track width, CG height or SSF, when compared to the Modification 1 conditions. However, disconnecting the rear anti-roll bar does reduces the rear suspension roll stiffness and decreases the TTR by 0.022.

The front suspension, rear suspension and total roll stiffnesses are listed in Table 6. About forty percent of the total roll stiffness was at the front of vehicle in the Baseline configuration, and it was about 50% for Modification 1 and about 60% for Modification 2.

Figure 6: Photo Showing One Side of Outbound Connection of Rear Anti-Roll Bar on Vehicle G

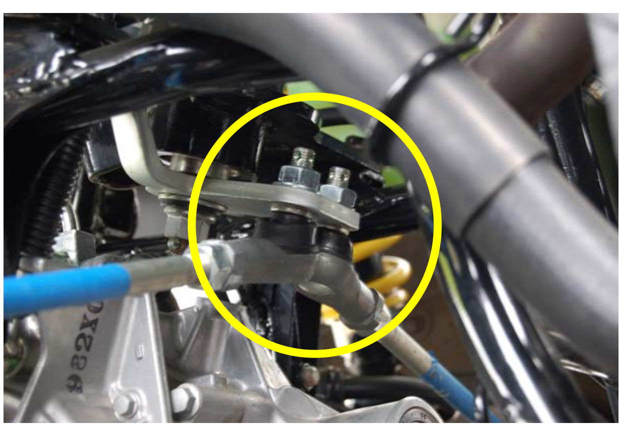
The nut in the center of the photo was removed to disconnect the Anti-Roll Bar.

Table 6: Key Attribute Changes for Modification 2 on Vehicle G			
Attribute	**Baseline**	**Mod 1**	**Mod 2**
Vehicle Weight as Tested (lb)	**914.5**	**916.0**	**916.0**
Measured CG Height (in)	**24.85**	**25.14**	**25.14**
Static Stability Factor (SSF)	**0.730**	**0.722**	**0.722**
Tilt Table Ratio (TTR)	**0.538**	**0.563**	**0.541**
Front Roll Stiffness (in-lb/deg)	**662**	**911**	**911**
Rear Roll Stiffness (in-lb/deg)	**933**	**933**	**609**
Total Roll Stiffness (in-lb/deg)	**1,595**	**1,844**	**1,520**
Percent Front Roll Stiffness (%)	**41.5**	**49.4**	**59.9**

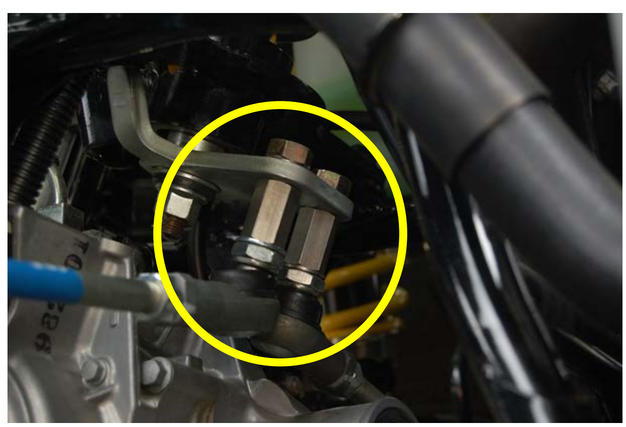
Modification 3 on Vehicle G involved replacing the OEM front springs with springs with greater stiffness to increase front (roll) stiffness, disconnecting the rear anti-roll bar to decrease rear roll stiffness, and modifying the steering geometry to reduce roll oversteer. Figure 7 shows the change made to the steering geometry. Spacers were inserted at the inboard connections of the steering tie rods. The tie rod lengths were adjusted after inserting the spacers so that static toe (steer) angles of the front wheels were not changed from their Baseline conditions.

Inserting the spacers changed the steering geometry to reduce the front bounce steer and roll steer of the vehicle. Figure 8 shows the front suspension bounce steer characteristic curves made before and after making the steering geometry changes. Figure 9 is a schematic showing front wheel steer when the suspension is compressed with the Baseline and Modification 3 steering tie rod connections.

Making the Modification 3 steering geometry changes did not significantly change any of the attributes listed for Modification 2 on Table 6.



Baseline Steering Tie Rod Connections



Modification 3 Steering Tie Rod Connections

Figure 7: Baseline and Modification 3 Steering Tie Rod Connections on Vehicle G

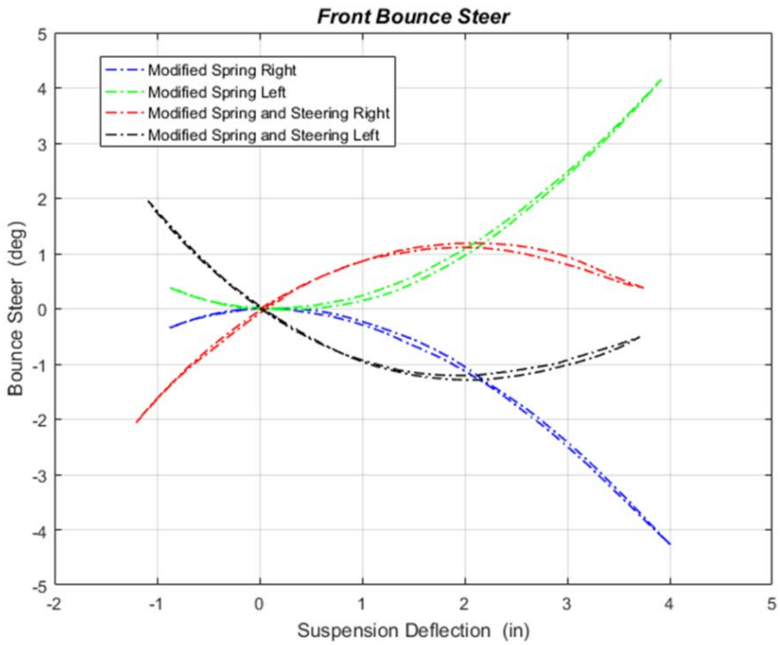


Figure 8: Front Suspension Bounce Steer Measurements Made on Vehicle G Before and After Making the Steering Geometry Changes

**Green and Blue Lines:
Pre Modification 3 Showing Roll Oversteer Characteristics**

**Red and Black Lines:
Post Modification 3 Showing Less Roll Oversteer Characteristics**

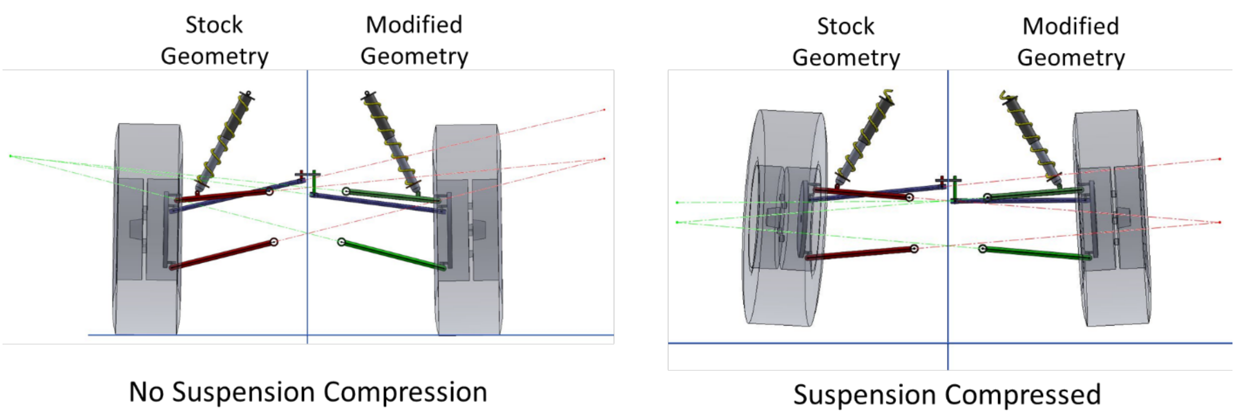
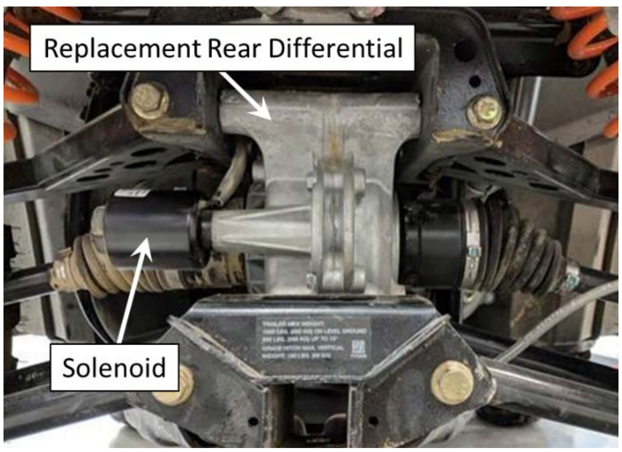


Figure 9: Schematic Showing Wheel Steer When Suspension is Compressed with Baseline (Stock) and Modification 3 Steering Tie Rod Connections on Vehicle G (Modification 3 Steering Geometry Reduces Roll Oversteer)

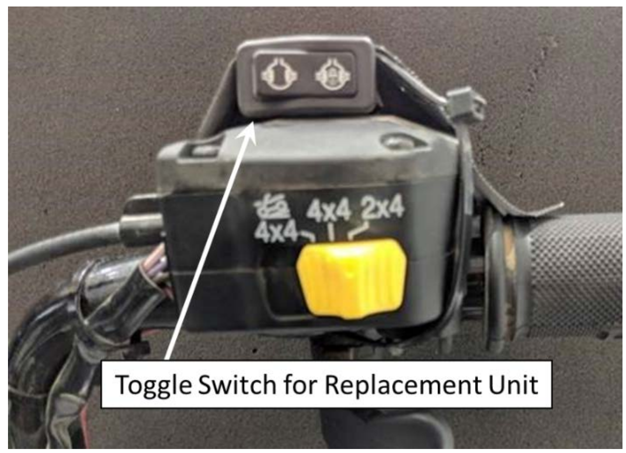
2.3 Details of Vehicle K Modifications

As mentioned, Vehicle K was selected because it has available commercial hardware for converting its locked rear differential to an open rear differential. Vehicle K was tested in both locked and open rear differential configurations to learn if testing an ATV with an open differential would cause any significant changes in the results of the Circle, J-Turn, or Yaw Rate Ratio tests conducted.

The replacement hardware included a differential unit with a solenoid that could electronically engage or disengage the open differential feature. The left side of Figure 10 shows the replacement rear differential with the solenoid. The replacement unit included a toggle switch for selecting either the open differential or locked differential setting. The toggle switch was mounted to the right side of the handlebar, as shown on the right side of Figure 10.



Replacement Rear Differential



Toggle Switch for Replacement Rear Differential

Figure 10: Replacement Rear Differential and Toggle Switch Used on Vehicle K

Vehicle K was tested in both locked and open rear differential configurations on both the asphalt and groomed dirt surfaces. As mentioned, the baseline tests on Vehicle K were conducted in the CCW and Left turn directions only during the Task Order 3 effort to study the effects of rider lean. Modification 1 involved expanding the baseline suite of tests on asphalt to include clockwise (CW) and Right turns. Similarly, the Modification 2-4 tests included conducting tests in both the CCW and CW directions.

The summary of modification tests conducted on Vehicle K is repeated below:

1: Tested on asphalt with locked rear differential

2: Tested on asphalt with open rear differential

3: Tested on groomed dirt with locked rear differential

4: Tested on groomed dirt with open rear differential

3. LABORATORY TESTING

The laboratory tests conducted on the baseline and modified vehicles included Vehicle Inertia Measurement Facility (VIMF) tests and Tilt Table tests. Details of the VIMF and Tilt Table tests are contained in the report covering the original tests conducted on these vehicles.[9] All of the measurements and computed metrics from the VIMF and Tilt Table tests are contained in Appendix A. In addition to the measurements made in the baseline and modification configurations as part of this study, results are included in Appendix A for previous measurements made on these vehicles in the Curb, Driver Only, and Driver Plus Instrumentation (DPI) configurations.

The loading conditions used for the baseline and modified vehicle configurations have been described in the previous sections. The weights of the test equipment and ballast used for the dynamic and laboratory tests are contained in the following section, and all measurements of overall vehicle weight, corner weight, CG location, track width, wheelbase and inertia properties are contained in Appendix A.

Two key metrics determined from the VIMF tests are Static Stability Factor (SSF) and lateral stability coefficient (K_{ST}); and they are defined as:

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

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

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

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.

The Tilt Table tests were conducted in four different tilt orientations: lateral right tilt, lateral left tilt, longitudinal front tilt and longitudinal rear tilt. For left side leaning and right side leaning 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. During tilt table tests, the load

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

perpendicular to the road plane decreases causing the CG to rise, which also contributes to TTR being less than SSF.

TTR is computed mathematically using:

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

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

$$\mathrm{FTTR} = tan\left(\mathrm{FTTA}\right)$$

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

For Vehicle F, VIMF and Tilt Table tests were conducted in the Baseline and Modification 1-3 configurations.

For Vehicle G, VIMF tests were conducted in the Baseline and only one other configuration. There are no significant differences in the weight, CG location, or inertia properties of Vehicle G in all three modification configurations. The single VIMF test done on modified Vehicle G represents Modification 1-3 configurations. However, for Vehicle G, Tilt Table tests were conducted in the Baseline and Modification 1-3 configurations. Modification 2 (disconnecting the rear anti-roll bar) does influence the roll stiffness, so lateral Tilt Table test results are not affected by this modification. Modification 3 (changing the steering geometry) does not have a significant effect on the Tilt Table test results, but nevertheless Tilt Table tests were also conducted in this configuration.

For Vehicle K, VIMF and Tilt Table tests were conducted in two configurations. The first configuration was with the vehicle equipped with the OEM locked rear differential, and this configuration was used for the Baseline dynamic tests. The second configuration was with the vehicle equipped with the replacement, open/locked selectable rear differential, and this configuration was used for the Modification 1-4 dynamic tests.

4. DYNAMIC TESTING

The dynamic tests on the modified vehicles were performed by SEA on numerous dates between May 9, 2017 and July 26, 2017. All of the modified vehicles were tested on SEA's asphalt test pad, and Vehicle K was also tested on SEA's groomed dirt test pad. All vehicles were tested in two-wheel drive mode, and in their most open driveline configurations. Vehicle K was also modified for testing in two-wheel drive mode with an open rear differential.

4.1 Test Equipment and Instrumentation

As mentioned, the representative 215 lb upright driver loading condition was used for all of the baseline and vehicle modification tests. This loading condition was specified to be the vehicle curb condition plus the weight (nominally 215 lb) of the test equipment and instrumentation that included: measurement transducers, SEA's ATV RTD,[10] SEA's ATV safety outriggers,[11] an auxiliary 24V battery, and the ballast weight frame. Table 7 lists the nominal weights of the components that comprise the driver only loading condition.

Table 7: Driver Only Loading

Component	Nominal Weight (lb)
Components Mounted at Front of Each Vehicle Base Plate, Steer Motor, Throttle Motor, Brake Motor, Steering Column Transducer, and Associated Linkages	37.2
Components Mounted at Rear of Each Vehicle Base Frame, Electronics Box, GPS/IMU, 24V Battery, and Antennas	57.6
Standard ATV Outriggers	29.0
Weight Frame and Miscellaneous Ballast (Includes 45 lb Laterally-Adjustable Steel Weights Used for Rider-Active Study)	91.2
Total Nominal Driver Only Weight	**215.0**

[10] SEA designed and fabricated the ATV RTD. The ATV RTD consists of a computer-controlled 24V electric motor that mounts to the front rack of an ATV for steering control. A four-bar linkage arrangement is used to connect the motor drive gear to an aluminum rod that is connected to the ATV steering column beneath the ATV handlebars. The ATV RTD also includes up to three other computer-controlled 24V electric motors that mount to the aluminum rod inserted beneath the ATV handlebars. One motor is used to control the throttle, one is used to apply the right hand brake, and in the case of the manual transmission vehicles, one is used to control the clutch on the left side of the handlebar. The ATV RTD also includes a GPS/IMU (OxTS RT3002 or RT4002), an electronics box (with a National Instruments (NI) cRIO, the on-vehicle computer with the motor controllers and data acquisition software), and antennas for wireless communication.

[11] SEA designed ATV-specific safety outriggers consisting of a single aluminum tubular beam structure that mounts to the underside of the ATVs. Adjustable height nylon pads are mounted to the ends of the outrigger beam, and these interact with the test surface to prevent the vehicles from tipping over.

The instrumentation used during the dynamic testing is listed in Table 8. The GPS/IMU (RT3002 or RT4002) was mounted on the rear base frame of each vehicle. The base frames were constructed using 80/20 T-slot aluminum bars and aluminum plates. For each vehicle, the longitudinal, lateral, and vertical offsets from the center of the GPS/IMU to the actual vehicle CG location were measured and entered into the GPS/IMU system software. This information was used to translate the measured quantities to those at the CG of the vehicle. The lateral accelerations measured and reported herein are accelerations parallel to the road plane, as opposed to vehicle body-fixed accelerations. Steering column angle (handlebar steering angle) was measured using an analog string potentiometer.

Table 8: Instrumentation Used During Dynamic Testing

Transducer	Measurement	Range	Accuracy
Oxford Technical Solutions (OxTS) RT3002 or RT4002 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
Steering Column Potentiometer	Steering Column Angle (Handlebar Angle)	No Limit Specified	± 0.25 deg

4.2 Constant Radius (50 ft) (Circle) Tests

Constant Radius or Circle tests were used to evaluate the vehicles' understeer characteristics.[12] A Constant Radius test involves driving a vehicle on a circular path of constant radius (50 ft in this case). The test vehicles were autonomously driven on the circular path using the ATV RTD. The ATV RTD was used to steer the vehicles and control the vehicle throttle (speed) during these tests.

A circular path with a 50 ft radius was generated in GPS coordinates, and the "path-following" feature of the RTD was used to control the steering input during these tests. The path-following algorithm has a collection of parameters used to model driver look-ahead distance, vehicle steering properties, and other steering-related control gains that were adjusted to provide good path following behavior for each vehicle tested. The throttle input was increased in piecewise linear steps to generate speed profiles from a very low speed up to a speed where the lateral acceleration reached 0.4 g.

Constant Radius tests were used to determine if the vehicles transitioned from understeer to oversteer during the tests. Roll gradients and vehicle roll angle response, as a function of lateral acceleration, were also computed from these tests.

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

4.3 Dropped Throttle J-Turn (Step Steer) Tests (Initial Speed of 20 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 RTD drove each vehicle along a straight-line path (defined by GPS coordinates) from low speed up to a speed of 21 mph. The RTD throttle inputs were programmed to generate the appropriate speed profiles so that the J-Turn maneuvers would take place near the center of the test pad. Once 21 mph was achieved, the RTD then dropped the throttle and triggered the steering input precisely when the vehicle speed reached 20 mph. The handlebar (motor) steering input rates used were 40 deg/sec, and the steering dwell or hold time used was 10.0 seconds, at which time the steering angle was programmed to return to 0 deg.

The J-Turn test procedure involved initially running tests with steering magnitudes less than the steering required to produce tip-up events, events that have visual two-wheel lift outcomes. The handlebar steering input magnitude was gradually increased in 1.0 degree increments to the point where a test run resulted in a two-wheel lift event. Then another test run using 0.5 degrees less steering input was used to refine the steering required for two-wheel lift. Once the steering input magnitude required for visual two-wheel lift was determined, repeat test runs using this steering input were conducted. Enough tests were conducted until three visual two-wheels lifts were achieved in each heading direction.

These tests provided a measure of the minimum peak lateral acceleration (Threshold Ay) required to cause visual two-wheel lifts during the tests.

4.4 Constant Steer Tests (Yaw Rate Ratio Tests)

Constant Steer tests are yet another well-established method used to evaluate a vehicle's understeer characteristics.[13] The recreational off-highway vehicle (ROV) industry groups Recreational Off-Highway Vehicle Association (ROHVA) and Outdoor Power Equipment Institute (OPEI), as well as CPSC staff, have used Constant Steer tests to evaluate vehicle yaw rate divergence. The industry groups have developed protocols for computing the ratio of yaw rate gain at a high lateral acceleration range (0.4 to 0.5 g) divided by the yaw rate gain at a low lateral acceleration range (0.1 to 0.2 g), and this ratio is referred to here as Yaw Rate Ratio. Both ROHVA and OPEI have industry voluntary standards that describe similar test and data reduction protocols for computing Yaw Rate Ratio for ROVs.[14,15] The same test and data reduction protocols were used for the current ATV testing. The only significant difference is that for the ATV testing, the high range of lateral accelerations was reduced to a range of 0.3 to 0.4 g because the ATVs tested exhibit rollover at a lower lateral acceleration range (from 0.38 g to 0.50 g) than ROVs.

For each vehicle, the steering magnitudes used for the baseline tests were also used for the tests on the modified-vehicle tests. Vehicles F and K used steering magnitudes based on using a 25 ft radius circle to establish the magnitude, and Vehicle G used a steering magnitude based on a 50 ft radius circle. The smaller path radius of 25 ft was used on the vehicles that exhibited enough understeer (radius of circle path increases) to potentially run off of the available test surface when

[13] Ibid

[14] American National Standard for Recreational Off-Highway Vehicles, ANSI/ROHVA 1-2016, May 2016.

[15] American National Standard for Multipurpose Off-Highway Utility Vehicles, ANSI/OPEI B71.9-2016, August 2016.

they were tested on asphalt. The test procedure used for the Yaw Rate Ratio tests was the same that used in the previous ATV test programs conducted for CPSC.

5. DISCUSSION OF TEST RESULTS

Appendix B contains a collection of tables and bar charts summarizing selected results from the laboratory and dynamic testing. Detailed graphical results from all of the dynamic testing conducted are contained in Appendix C. This section of the report contains discussion of the results presented in Appendices B and C.

5.1 Discussion of Appendix B: Summary Tables and Bar Charts

Page 1 of Appendix B contains summary tables of laboratory measurements SSF and TTR, and of the Roll Gradients, the amount of roll angle in degrees per "g" of lateral acceleration measured during the Circle tests.[16] Results in these tables, as well as for all the tables and charts in Appendix B, include values for all three vehicles in their baseline and all modified configurations.

Page 2 of Appendix B also contains three tables: Transition Lateral Acceleration levels at which the vehicles transitioned from understeer to oversteer during Circle tests ("NA" in the table indicates that no transition to oversteer occurred), Threshold Lateral Acceleration measured during 20 mph dropped throttle J-Turn tests, and Yaw Rate Ratio measured during Constant Steer tests.

Bar charts of individual metrics are contained on Pages 3-8 of Appendix B. In order, the bar charts show: SSF, TTR, Roll Gradient, Transition Lateral Acceleration, Threshold Lateral Acceleration, and Yaw Rate Ratio.

In the bottom table of Page 2, for Vehicle F in its Modification 3 configuration, there are two values listed for Yaw Rate Ratio. For Modification 3, ballast was moved forward on the vehicle so that its overall longitudinal CG location would match the longitudinal CG location when it was tested using a human driver.[17] When tests were conducted with human drivers, Vehicle F was one of two vehicles that transitioned from an oversteering condition to an understeering condition during the Yaw Rate Ratio tests. This phenomenon also occurred when Vehicle F was tested autonomously in its Modification 3 configuration, indicating that vehicle longitudinal loading is the reason why this phenomenon occurs. One of the Yaw Rate Ratio values listed uses the typical final slope range of 0.3 to 0.4 g, while the other value uses a final slope range of 0.27 to 0.32 g (with 0.32 g being the lateral acceleration level at which the vehicle response begins to transition to understeer behavior).

[16] "g" is the gravitational constant defined as 9.8 m/s^2 or 32.2 ft/s^2.

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

5.2 Discussion of Appendix C: Results from Dynamic Tests

Appendix C contains the graphical test results for all three vehicles tested, in the following order:

- Constant Radius (50 ft) (Circle) Tests
- Dropped Throttle J-Turn (Step Steer) Tests (Initial Speed of 20 mph)
- Constant Steer Tests (Yaw Rate Ratio Tests)

Table 9 lists the pages in Appendix C containing results for each vehicle.

Table 9: Appendix C Table of Contents	
Vehicle	**Page Numbers**
F	1-39
G	40-73
K	74-146

The following discussion will cover each test in the order listed above. A couple of general comments regarding the graphs presented for all test types are:

- The lateral accelerations shown on the graphs are the lateral accelerations parallel to the road plane, not the vehicle body-fixed lateral accelerations.
- The steering angles shown on the graphs are roadwheel steer angles, which are the measured steering column angles divided by the measured steering ratios. (The measured steering ratios between the steering columns and roadwheels are 1.21:1 for Vehicle F, 1.41:1 for Vehicle G and 1.43:1 for Vehicle K.)
- The ATV RTD was used for all of the Circle, J-Turn, and Yaw Rate Ratio tests. For tests using the ATV RTD, the commanded steering input is the input to the ATV RTD steering motor. The ATV RTD steering angle and the steering column angle are not exactly one-to-one, due to compliance in the ATV RTD four-bar linkage arrangement, its motor base mounting to the vehicles, and the handlebars.

5.2.1 Constant Radius (50 ft) (Circle) Tests

For Vehicles F and G, the first four pages for both vehicles show results from the CCW Circle tests. Results from the baseline and modified vehicle tests are all contained on the same graphs. For Vehicle K the first four pages show results from the CCW Circle tests conducted in the baseline configuration. There are four additional sets of four pages for Vehicle K, one for each vehicle modification; and these include results from the CCW and CW Circle tests conducted.

The first page of each set shows time domain plots of Roadwheel Steer Angle, Lateral Acceleration, Speed, Roll Angle, and Yaw Rate. All of the dynamic test data is sampled at 100 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 are quasi-steady state tests, and it is common to use a low pass filter on data from these tests. The time domain data shown for each vehicle contains all of the data from the time the test engineer started the ATV RTD data acquisition (prior to when the vehicle started to move forward on the circle) to the time when the ATV RTD stopped collecting data (after at least 0.4 g lateral acceleration was achieved and the test was ended).

On the first page of Circle test graphs for each vehicle, the thin black lines show the full range of data collected. The thicker lines indicate the range of data used to fit the subsequent understeer and roll gradient characteristic curves. These ranges start from the time the vehicle attained a speed of 5.5 mph, which is a lateral acceleration of 0.04 g on a 50 ft radius circle. The range of data used for the curve fits was ended when the vehicle attained a lateral acceleration of 0.40 g. The speed plots show that the Circle tests were conducted using a very slow rate of increase in speed during the circle tests. Regarding conducting circle tests for passenger vehicles, SAE J266[18] 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 overall rates of speed increase during the Circle tests conducted are less than the J266 recommended maximum allowable rate.

The second page for each vehicle shows graphs of Roadwheel Steer Angle versus Ay (lateral acceleration). The thin lines show data in the selected ranges, as described above. The thicker lines are second-order polynomial curve fits to the range of data selected. The red circles on these graphs are the geometric Ackermann steer angles, a function of the steering ratio (K) times the wheelbase (L) divided by the circle radius (R), given by:

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

The geometric Ackermann steer angles are not the same as the actual roadwheel steer angles required to negotiate the circles at very low speed, with Ay close to zero. The actual roadwheel 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 contains a graph of Roadwheel Steer Angle minus (measured) Ackermann Angle versus Ay (lateral acceleration). For the modified vehicle configuration tests conducted on Vehicle K, which included both CW and CCW Circle tests, the signs of the CCW data are reversed so that the CW and CCW results can be directly compared on these graphs. Again, the thin lines show data in the range of data selected for each vehicle as described above, and 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 steering input required to maintain the circular path increases as the vehicle speed increases, neutral steer can be defined as the condition when the steering 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 steering 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

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

underlying data whether the particular test vehicle exhibits understeer, neutral steer, or oversteer characteristics during the Circle tests.

All of the baseline and modified vehicles exhibit understeer at low levels of lateral acceleration, and in their baseline configurations and some of their modified vehicle configurations they transition to oversteer at higher levels of lateral acceleration. The points of transition from understeer to oversteer are indicated on the graphs by black circles, and they are mathematically the points where the slopes of the curve fits change from being positive to negative. For Circle tests where the vehicles exhibited a transition from understeer to oversteer, the values of the lateral acceleration at the points of transition are indicated on the graphs.

The fourth page for each set of Circle test data contains a graph of Roll Angle versus Ay (lateral acceleration). The thin lines show data in the range of vehicle speeds selected for each test, and the thick lines are linear curve fits to the data over the selected ranges. The curve fit slopes are listed on the graphs as the Roll Gradients.

Summary tables of the Roll Gradients and the Transition Lateral Accelerations (points of transition from understeer to oversteer) determined from Circle tests are contained on Pages 1 and 2 in Appendix B, respectively. Page 5 in Appendix B is a bar chart of the Roll Gradients and Page 6 a bar chart of the Transition Lateral Accelerations.

5.2.2 Dropped Throttle J-Turn (Step Steer) Tests (Initial Speed of 20 mph)

For all J-Turn tests conducted on Vehicle F and G, and for the baseline J-Turn tests conducted on Vehicle K, only left steer direction tests were conducted. For these cases, there are two pages of graphical J-Turn test results for each configuration. The first pages for each configuration show plots of Roadwheel Steer Angle, Lateral Acceleration, Speed, Roll Angle, and Yaw Rate; for six runs, three each in opposite heading directions. The second pages for each configuration show larger plots of Lateral Acceleration. The modified vehicle tests on Vehicle K were conducted in both the left and right steer directions. For these tests there are four pages of graphical J-Turn results, two each containing results from left and right steer tests done in two opposite heading directions.

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. For tests conducted by SEA for CPSC on Recreational Off-Highway Vehicles (ROVs), the same 2.0 Hz. filter was used to filter all J-Turn test data used to select peak lateral acceleration values (Threshold Ay values) during J-Turn tests that resulted in two-wheel lift outcomes. Justification for using a 2.0 Hz low pass filter for selecting peak lateral accelerations is presented in the SEA report to CPSC titled *Repeatability of J-Turn Testing of Four Recreational Off-Highway Vehicles*.[19] The time domain data shown for each vehicle contains data from 0.5 seconds before the ATV RTD steering input was applied until 5.0 seconds after it was applied.

[19] *Repeatability of J-Turn Testing of Four Recreational Off-Highway Vehicles*, CPSC Contract CPSC-D-11-0003, SEA, Ltd. Report to CPSC, September 2013.
https://www.cpsc.gov/s3fs-public/SEAReporttoCPSCRepeatabilityTestingSeptember%202013.pdf

For each vehicle, the final page of J-Turn test results contains tables summarizing 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 mean values from runs conducted in each heading direction are provided, as are the overall averages for all runs conducted for each configuration, which are the Threshold Ay values.

Page 2 in Appendix B contains a summary table, and Page 7 a bar chart, of the Threshold Lateral Accelerations determined from J-Turn tests.

5.2.3 Constant Steer Tests (Yaw Rate Ratio Tests)

For all Constant Steer tests conducted on Vehicle F and G, and for the baseline J-Turn tests conducted on Vehicle K, only CCW steer direction tests were conducted. For these cases, there are five pages of graphical Constant Steer test results for each configuration. For the modified vehicle tests on Vehicle K, CCW and CW tests were conducted; and for these cases there are seven pages of graphical Constant Steer test results for each configuration.

The first page for each case shows time domain plots of Roadwheel Steer Angle, Estimated Ay (Estimated Lateral Acceleration), Speed, Roll Angle, and Yaw Rate. For all of the graphs from the Constant Steer tests, the Roadwheel Steer Angle, Speed, Roll Angle and Yaw Rate data shown is unfiltered. Per the OPEI and ROHVA ANSI protocols, the Estimated Ay data shown is computed by multiplying the Yaw Rate (filtered using a low-pass Butterworth filter with a cut-off frequency of 1.0 Hz) and Speed (filtered using a low-pass Butterworth filter with a cut-off frequency of 1.0 Hz).

The second page of results from the Constant Steer tests contains the plots of Estimated Ay versus Speed. The data is plotted up to the point of maximum Estimated Ay. The maximum Estimated Ay levels shown on these graphs are greater than 0.4 g, the selected end-point lateral acceleration level for data processing. For all of the Yaw Rate Ratio tests, the tests were not stopped before the Estimated Ay reached at least 0.4 g. At the end of the tests, the lateral accelerations increase as soon as the throttle (and vehicle speed) is dropped. When the vehicle speed drops, weight is shifted to the front axle and the vehicles tend to turn in, generally increasing lateral acceleration, roll angle and yaw rate. However, data after the speed was dropped at the ends of the tests was not used in the analyses to compute Yaw Rate Ratios.

The third page of results contains the plot of Yaw Rate versus Speed, and this is the graph that also shows the slope values for the individual test run initial and final ranges (and their standard deviations), the individual test run CCW (and also CW for the Vehicle K modified vehicle tests) slope ratios (and their standard deviations), and the average CCW (and CW) slope ratios (the Yaw Rate Ratios). All of the linear curve fits in the initial and final ranges are shown, and the thick black lines indicate where combinations of yaw rate and speed equal 0.4 g of lateral acceleration.

The following steps were taken to compute the slopes and Yaw Rate Ratios contained on the third page graphs:

1. For each test run, to determine the data regions for analysis, the yaw rate and speed channels were filtered using a low-pass Butterworth filter with a cut-off frequency of 1 Hz. Then the estimated lateral acceleration in units of "g's" was computed using the following equation:

$$\text{Estimated } A_y = \frac{\pi}{180} \times \frac{\text{Yaw Rate} \times \text{Speed}}{32.2}$$

   where Yaw Rate is in deg/sec and Speed is in ft/sec.

   The protocol used to compute Estimated Ay is the same as the protocols contained in ANSI/ROHVA 1-2016 and ANSI/OPEI B71.9-2016.[20]

2. The estimated lateral acceleration, Estimated Ay, was used to determine the start and stop points for the following regions:

   a. The Initial Region is from 0.1 to 0.2 g.
   b. The Final Region is from 0.3 to 0.4 g.

3. For each test run, in both the initial and final regions, linear slopes of unfiltered yaw rate versus data index and linear slopes of unfiltered speed versus data index were computed.[21] The slopes can be classified as:

   a. Y1 = linear slope of the yaw rate versus index plot for Initial Region
   b. Y2 = linear slope of the yaw rate versus index plot for Final Region
   c. V1 = linear slope of the vehicle speed versus index plot for Initial Region
   d. V2 = linear slope of the vehicle speed versus index plot for Final Region

4. The Yaw Rate Ratio (R) for each run was then computed using the following equation:

$$\text{Yaw Rate Ratio (R)} = \frac{\left(\frac{Y2}{V2}\right)}{\left(\frac{Y1}{V1}\right)}$$

   Note: This value may be negative or positive.

5. Steps 1 through 4 were then repeated for all five test runs in the CCW direction (and for all five test runs in the CW direction when included).

6. The following final slope ratios were then computed:

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[20] The equations given in ANSI/ROHVA 1-2016 and ANSI/OPEI B71.9-2016 to compute Estimated Ay differ from the equation listed above because metric dimensions are used in the voluntary standards. However, all of the equations compute Estimated Ay in units of "g's", by dividing by the gravitational constant defined as 9.8 m/s^2 or 32.2 ft/s^2.

[21] The ANSI/ROHVA 1-2016 and ANSI/OPEI B71.9-2016 protocols specify computing slopes as versus *time*. Given the form of the final computation for Yaw Rate Ratio, computing the slopes versus *time* or versus *data index* result in the same answer for Yaw Rate Ratio.

a. Right Turn Yaw Rate Ratio (CW Average) = Average of the absolute values of the 5 right turn test runs (when included)
b. Left Turn Yaw Rate Ratio (CCW Average) = Average of the absolute values of the 5 left turn test runs
c. Average Yaw Rate Ratio (Average Ratio) = Average of the Right Turn and Left Turn Yaw Rate Ratios (when both CCW and CW were conducted)

The next pages of results from the Constant Steer tests contain magnified sections of the individual final slope regions for the CCW (and CW when conducted) runs. These graphs also contain black lines indicating where combinations of yaw rate and speed equal 0.4 g of lateral acceleration. A vehicle with severe oversteer in the final slope region will have a steep slope (high Final Slope value), and this will produce a high Yaw Rate Ratio. Steep final slopes are indicative of divergent vehicle behavior, a condition when the yaw rate and lateral acceleration gains are high and the vehicle is prone to yaw and/or tip-up instability.

The final pages of results from the Constant Steer tests show individual path plots for the CCW and (and CW when conducted) runs. As speed is increased during a Constant Steer test, an understeering vehicle will travel on a path of increasing radius, and an oversteering vehicle will travel on a path of decreasing radius. The path plot graphs have green, red, and black line portions, indicating ranges of lateral acceleration during the runs. The initial regions are shown with the green lines and the final regions are shown with the red lines.

As mentioned, for Modification 3 on Vehicle F, ballast was moved forward on the vehicle so that its overall longitudinal CG location would match the longitudinal CG location when it was tested using a human driver. As was the case when Vehicle F was tested with a human driver, when tested in the Modification 3 configuration, Vehicle F also transitioned from an oversteering condition to an understeering condition during the Yaw Rate Ratio tests. To evaluate the Yaw Rate Ratio prior to the point of transition to understeer, data from runs using this configuration were reprocessed using data up to 0.32 g, the lateral acceleration level at which the vehicle response begins to transition to understeer behavior. Therefore, for Modification 3 of Vehicles F, there are two sets of five-page results for the Constant Steer tests. The first set uses data for the typical final slope range of 0.3-0.4 g, and the second set uses truncated data with a final slope range of 0.27-0.32 g.

Page 2 in Appendix B contains a summary table of the Yaw Rate Ratios determined from CCW Constant Steer tests, and Page 8 in Appendix B is a bar chart of the Yaw Rate Ratio results.

The ANSI/ROHVA 1-2016 and ANSI/OPEI B71.9-2016 criteria for passing their constant steer handling test using an ROV is that neither the left turn (CCW) Yaw Rate Ratio nor the right turn (CW) Yaw Rate Ratio exceeds 4.5.

6.0 COMPARISON OF RESULTS FROM VEHICLES WITH MODIFIED ATTRIBUTES

This section of the report contains discussion of the results from making the vehicle attribute modifications. Results from the laboratory measurements and dynamic tests that highlight the effects of the particular modifications made on each vehicle are summarized below.

6.1 Results for Vehicle F

The three modifications made to Vehicle F were:

1: Added 2-inch-thick wheel spacers on all four wheels to increase track width

2: Lowered Driver-Lean Ballast to reduce vehicle CG height

3: Moved Driver-Lean Ballast and other ballast forward to move vehicle CG forward (to match CG longitudinal position used for tests with human driver)

Modifications 1 and 2 were made to evaluate how basic vehicle properties (track width and CG height) could be modified to improve the rollover resistance of the vehicle. Modification 3 was made to gain some understanding of the reason why Vehicle F exhibited a transition from oversteer response to understeer response during previously conducted Constant Steer tests with a human driver.

Figure 11 contains bar charts summarizing the rollover resistance metrics (SSF, TTR and Threshold Ay) for Vehicle F.

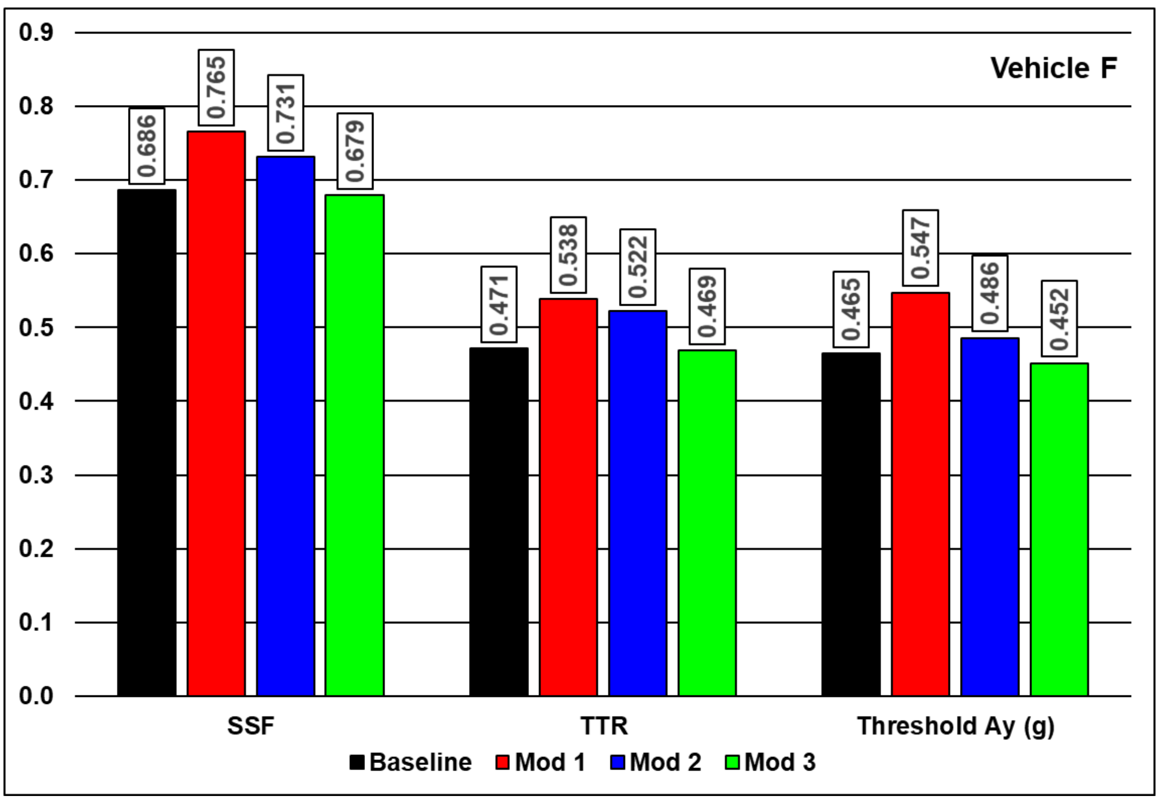


Figure 11: Rollover Resistance Metrics for Vehicle F

Modification 1 (increasing the track width by 4.00 inches) and Modification 2 (lowering the vehicle CG height by 1.44 inches) clearly increase SSF, TTR and Threshold Ay values over the Baseline values. The magnitude of the increase in track width and the magnitude of the reduction in CG height for Vehicle F are relatively large. Incorporating large changes to these intrinsic properties of a vehicle might change its overall intended design characteristics, including such things as its maneuverability and ground clearance. Nevertheless, these changes were made during this study to quantify their primary effects on rollover resistance.

Modification 3 (moving the CG of the vehicle forward by 2.32 inches) had little effect on the rollover resistance metrics. Moving the ballast forward slightly increased the CG height, which resulted in slightly reduced SSF, TTR and Threshold Ay compared to the Baseline configuration.

Graphical results from Circle tests conducted on Vehicle F are shown in Figure 12 (Understeer/Oversteer Characteristic Curves) and Figure 13 (Roll Gradient Characteristic Curves). Figure 12 shows that the modifications did not change the general understeer/oversteer trend of Vehicle F. In all configurations Vehicle F does exhibit a transition to oversteer, but it remains relatively neutral steer at all lateral acceleration levels. However, all three modifications did increase the lateral acceleration at which transition to oversteer occurred. Increasing the track width (Modification 1) and reducing the CG height (Modification 2) both reduced the Roll Gradients measured during the Circle tests (Figure 13). The measured Roll Gradient was also slightly less than the Baseline value when the longitudinal CG was moved forward on the vehicle (Modification 3).

A bar chart showing all of Yaw Rate Ratio values determined from CCW Constant Steer tests conducted on all three vehicles is shown in Figure 14. Modifications 1 and 2 on Vehicle F had little effect on the Yaw Rate Ratios. However, Modification 3 (moving the longitudinal CG of the vehicle forward by 2.32 inches to match its location during tests conducted with a human driver) significantly changed the Yaw Rate Ratio. When tested in the Modification 3 configuration, Vehicle F transitioned from an oversteering condition to an understeering condition during the Constant Steer tests. Figure 15 shows results from the Yaw Rate Ratio tests conducted on Vehicle F in its Baseline and Modification 3 configurations. For Modification 3, using the typical final slope range of 0.3-0.4 g, the Yaw Rate Ratio is well below 1.0, indicating a strong understeering response.

As mentioned previously, Vehicle F also exhibited the phenomenon of transitioning from oversteer to understeer behavior when it was tested with a human driver. Figures 16 and 17 contain results from tests autonomous conducted on Vehicle F in its Modification 3 configuration and from tests conducted using a human driver (results are from the previous report of tests conducted with human drivers[22]). Figure 16 uses data for the typical final slope ranges of 0.3-0.4 g, and Figure 17 uses truncated data with final slope ranges up to the lateral acceleration level at which the vehicle response begins to transition to understeer behavior. Both Modification 3 and human driver Yaw Rate Ratios are less than 1.0 using final slope ranges up to 0.4 g; and they are similar (CCW value of 2.19 for Modification 3 and CCW value of 2.64 with human driver) and greater than 1.0 (indicating oversteer behavior) using the truncated data up to the point of transition to understeer. These results indicate that vehicle longitudinal loading is the reason why the phenomenon of transition from oversteer to understeer occurs during the Constant Steer tests occurs for Vehicle F.

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

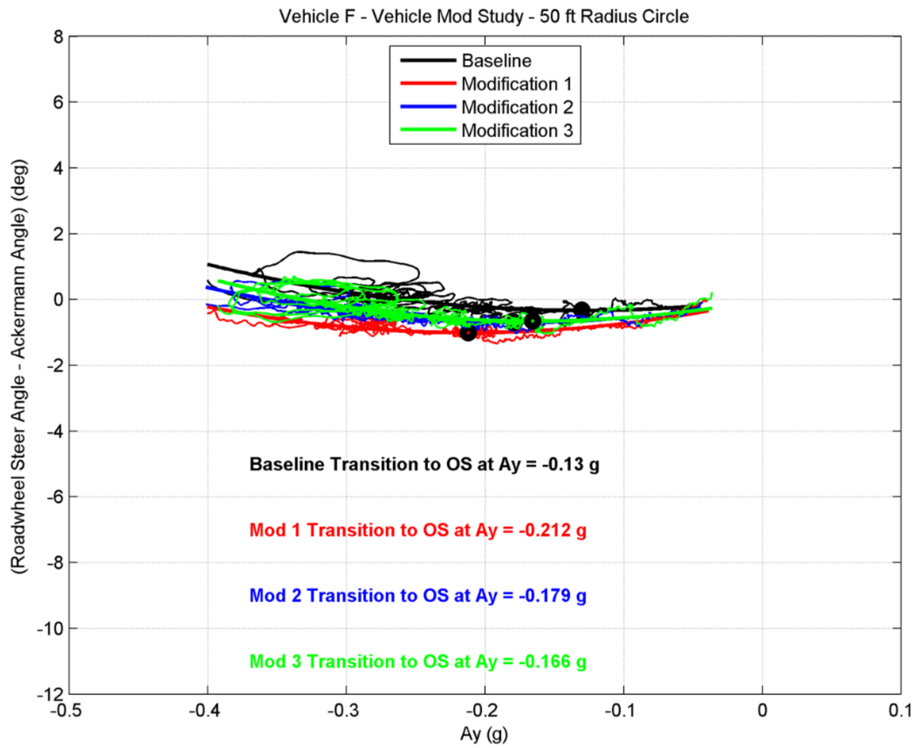


Figure 12: Understeer/Oversteer Characteristic Curves for Vehicle F

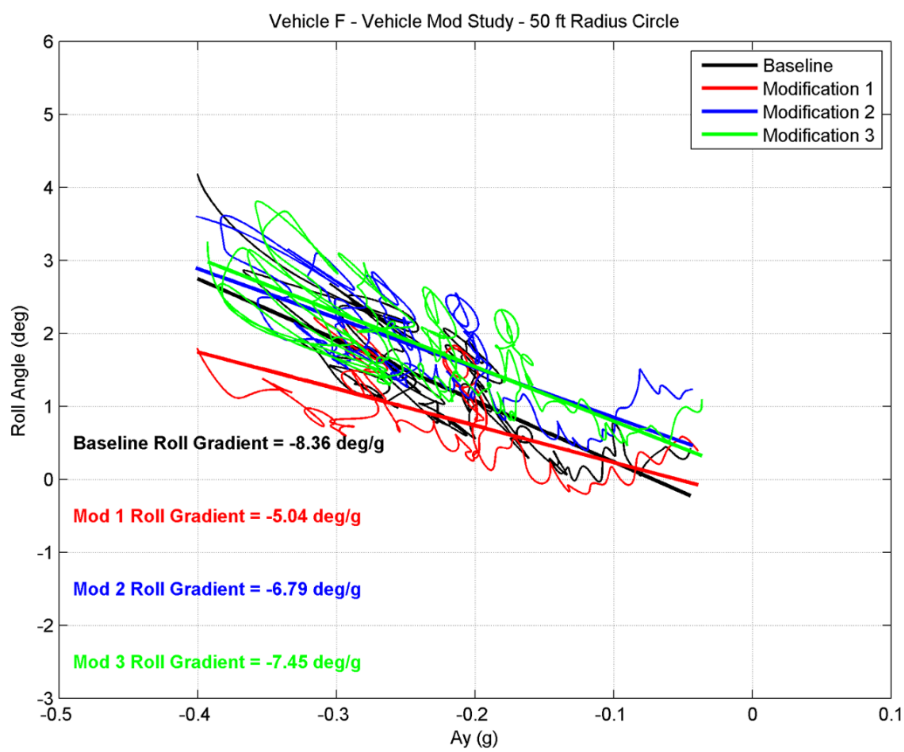


Figure 13: Roll Gradient Characteristic Curves for Vehicle F

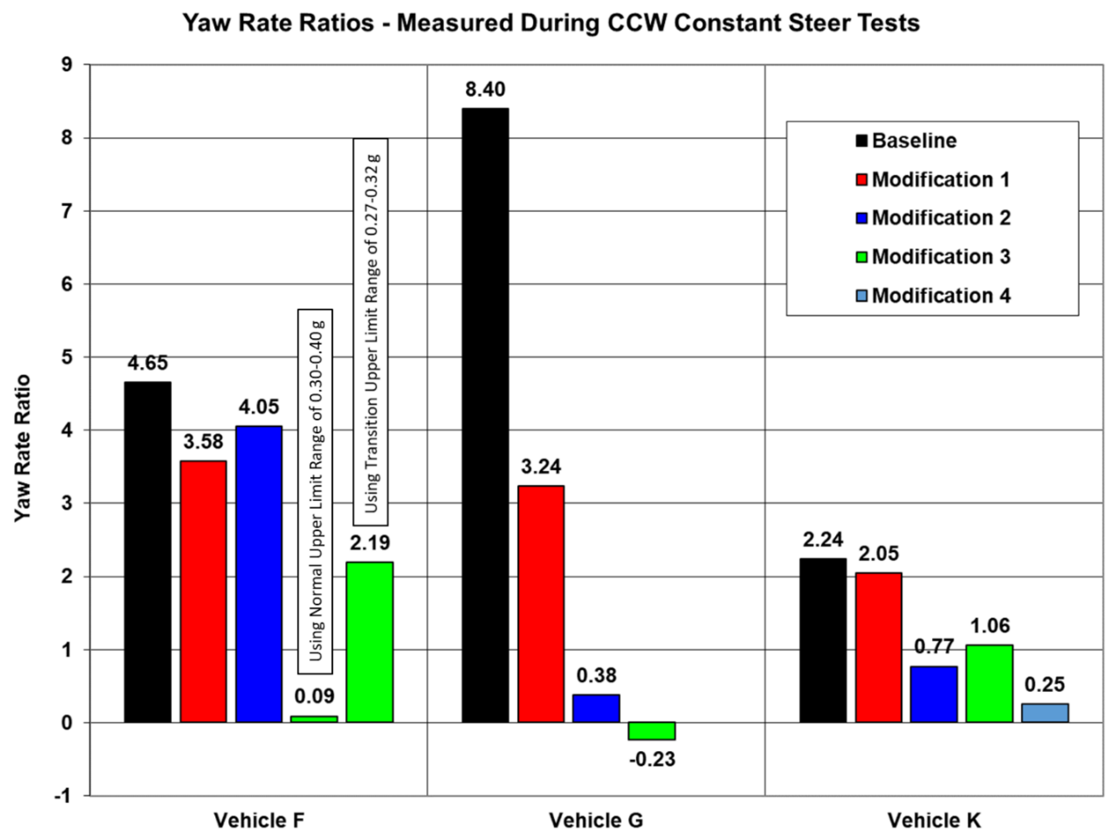
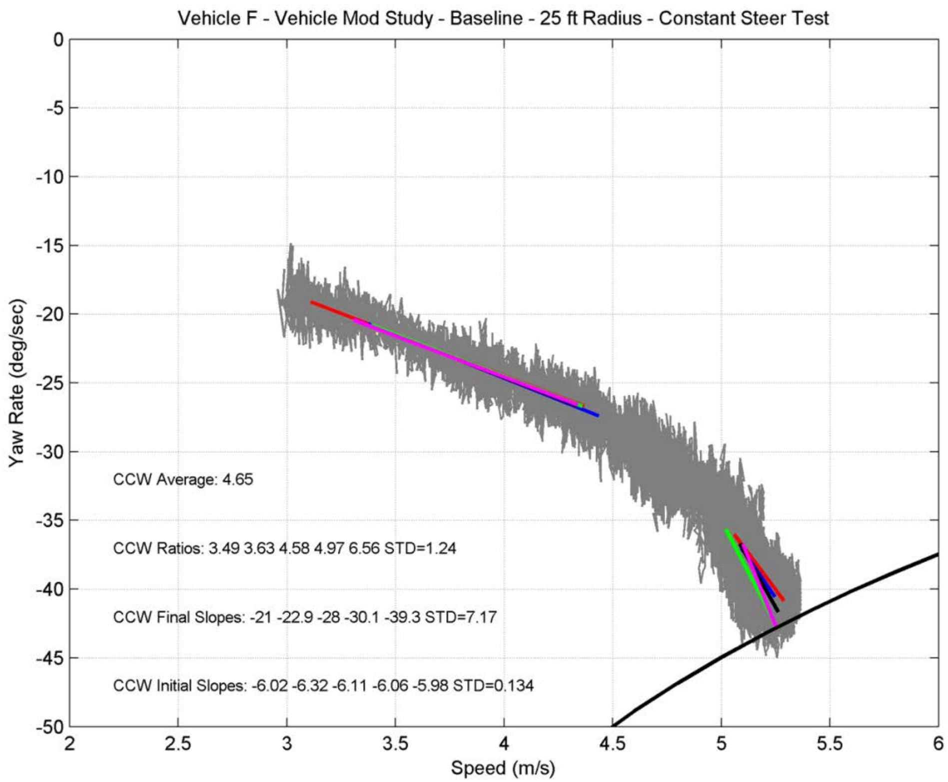
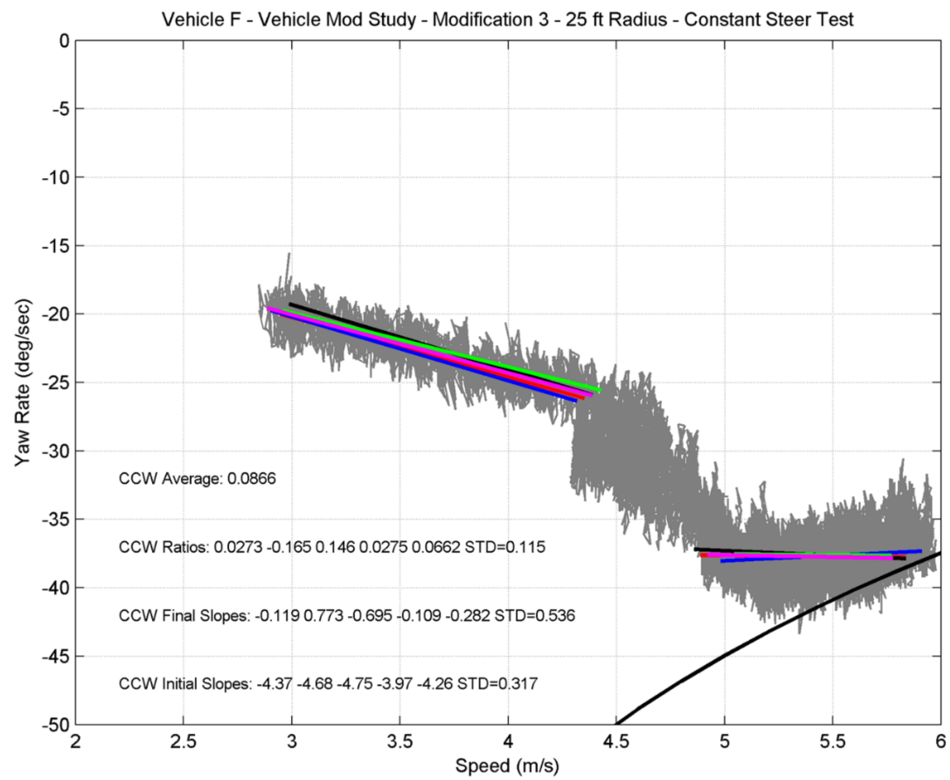


Figure 14: Yaw Rate Ratios for All Three Vehicles

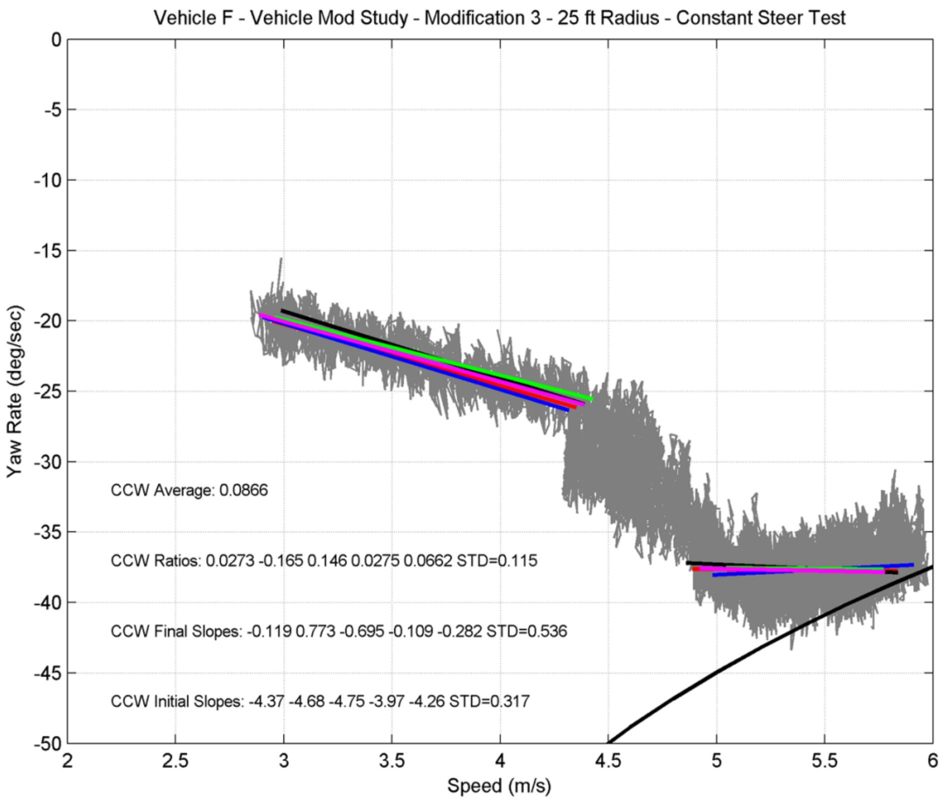


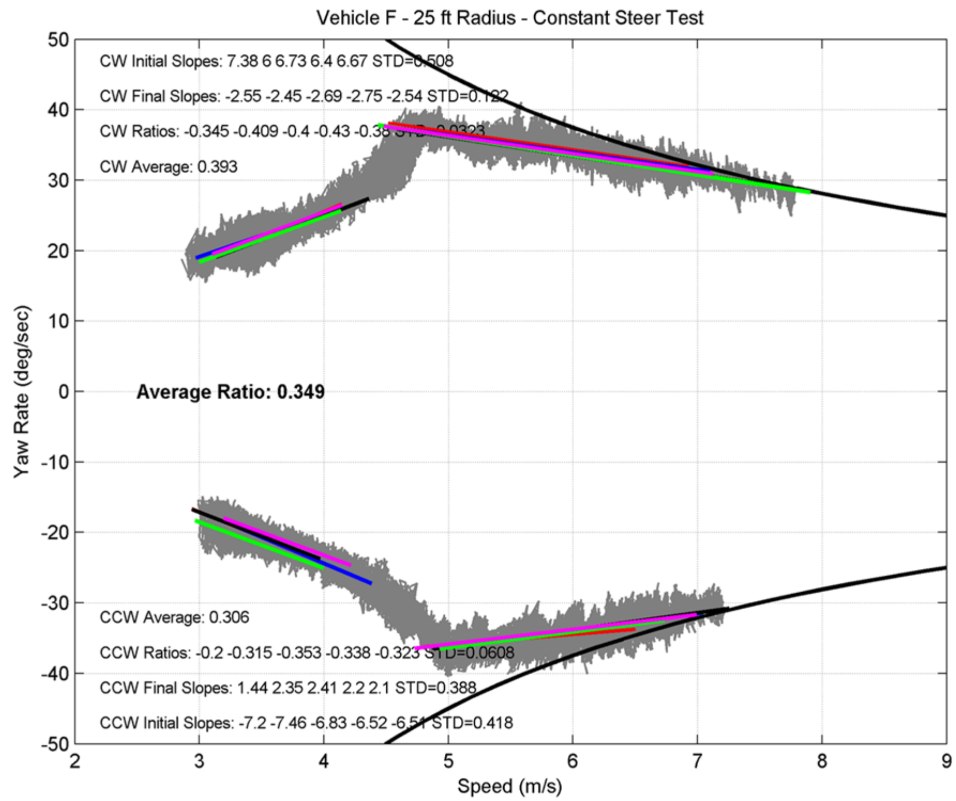
Vehicle F – Baseline



Vehicle F – Modification 3

Figure 15: Results from Vehicle F Yaw Rate Ratio Tests: Baseline (Left) and Modification 3 (Right)

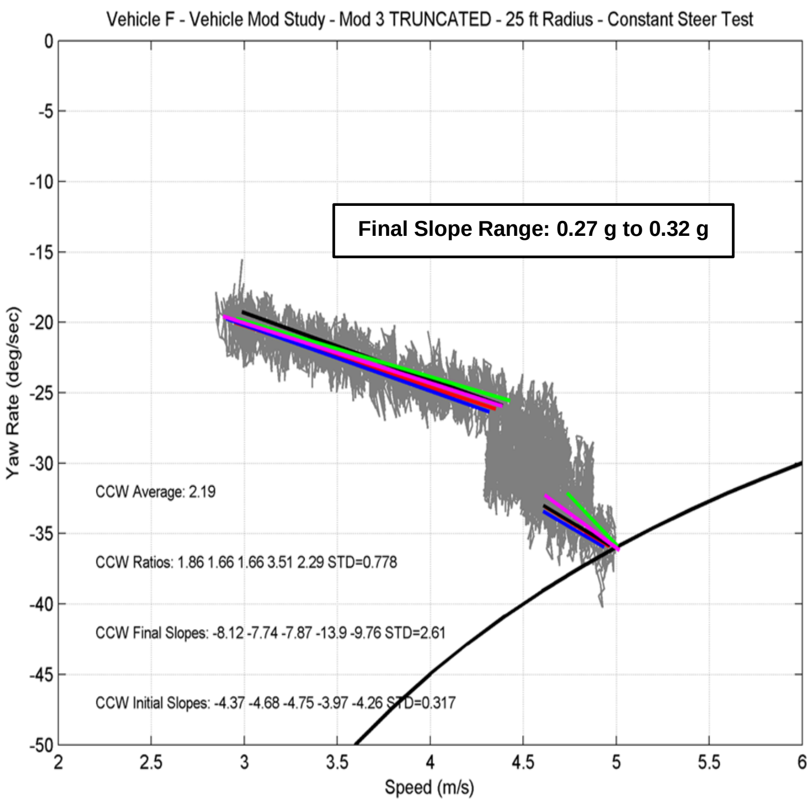




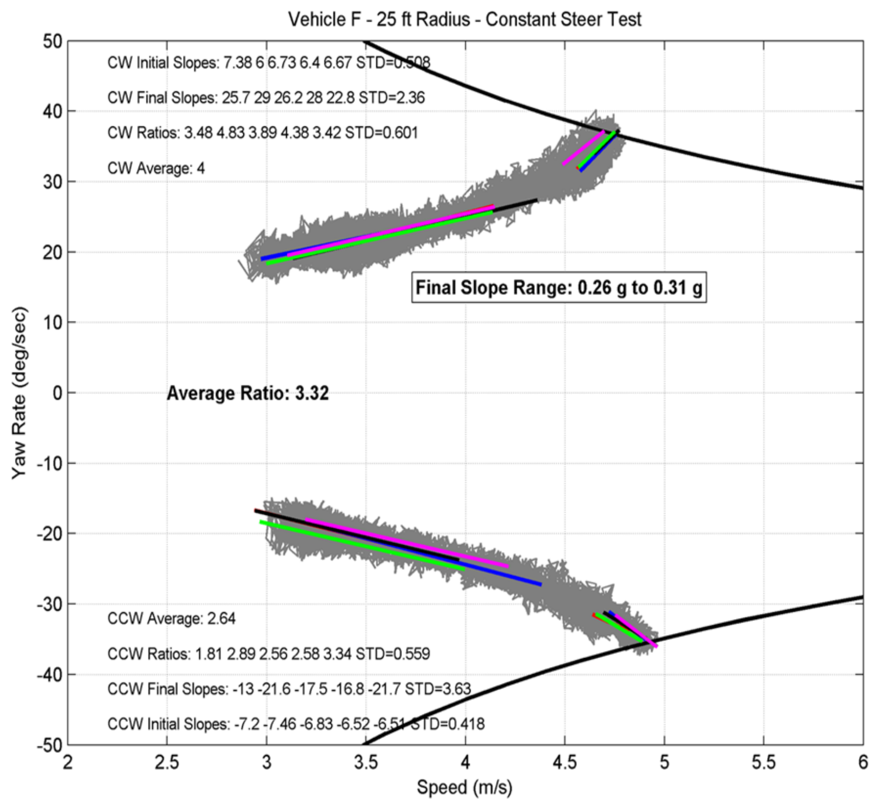
Vehicle F – Modification 3
Longitudinal CG Modified to Match Longitudinal CG of Vehicle F During Tests with Human Driver

Vehicle F – Results from Tests Conducted with Human Driver

Figure 16: Vehicle F Yaw Rate Ratio Tests: Results from Modification 3 Tests (Left) and Results from Tests Conducted with a Human Driver (Right)



Vehicle F – Modification 3
Longitudinal CG Modified to Match Longitudinal CG of Vehicle F During Tests with Human Driver



Vehicle F – Results from Tests Conducted with Human Driver

Figure 17: Vehicle F Yaw Rate Ratio Tests – Using Data Truncated up to the Lateral Acceleration Level When the Vehicle Response Begins to Transition to Understeer Behavior: Results from Modification 3 Tests (Left) and Results from Tests Conducted with a Human Driver (Right)

6.2 Results for Vehicle G

The three modifications made to Vehicle G were:

1: Replaced front springs to increase front (roll) stiffness

2: Replaced front springs to increase front (roll) stiffness, and disconnected rear anti-roll bar to decrease rear roll stiffness

3: Replaced front springs to increase front (roll) stiffness, disconnected rear anti-roll bar to decrease rear roll stiffness, and modified steering geometry to reduce roll oversteer

Figure 18 contains bar charts summarizing the rollover resistance metrics (SSF, TTR and Threshold Ay) for Vehicle F.

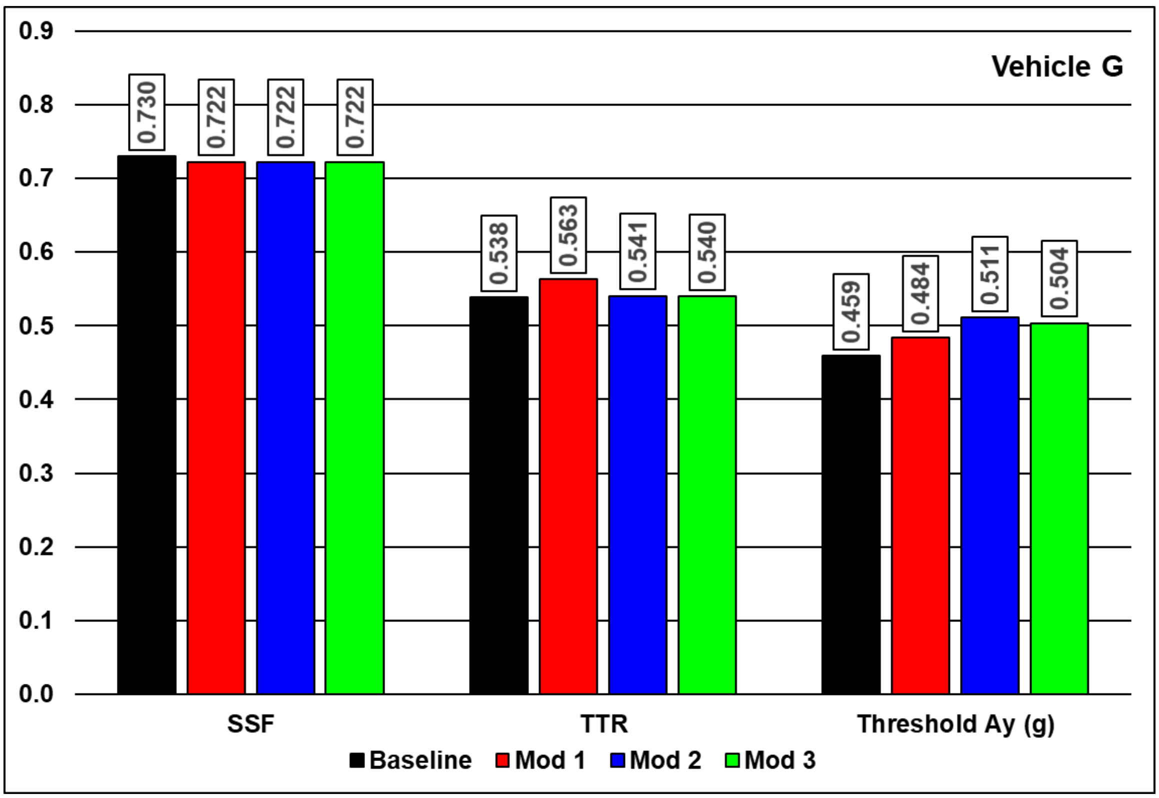


Figure 18: Rollover Resistance Metrics for Vehicle G

While Vehicle G was selected primarily to study changes in attributes that would improve its handling (yaw stability), the attribute changes made to Vehicle G also affected its rollover resistance. Modification 1 (replacing the front springs with stiffer ones) increased the vertical and roll stiffness of the front suspension. Replacing the front springs slightly increased the CG height, and slightly decreased the SSF. Modifications 2 (Modification 1 plus disconnecting the rear anti-roll bar) and Modification 3 (Modification 2 plus modifying the steer geometry) did not change the CG height or SSF. Modification 1 increased the front roll stiffness (and overall vehicle roll stiffness), which increased the TTR and Threshold Ay values over their Baseline values. The overall roll stiffness and TTR for Modification 2 were similar to those of the Baseline vehicle. While the net effects of Modification 2 changes (increasing front roll stiffness and decreasing rear roll stiffness) did not influence the SSF and TTR, they did result in a modest increase in measured

Threshold Ay. With the Modification 2 changes, the vehicle is more understeering and it has significantly more percent roll stiffness on the front (59.9%) compared to the Baseline vehicle (41.5%). During all the J-Turn tests for Vehicle G with two-wheel lift (2WL), the inside rear wheel lifts before the inside front wheel lifts. Increasing the percent front roll stiffness tends to lessen front wheel lift (relative to rear wheel lift) during a J-Turn maneuver, and this likely contributed to needing greater lateral acceleration to generate visual 2WL outcomes (i.e. greater Threshold Ay values).

As Figure 18 shows, Modification 3 changes (changes to the steering geometry) did not significantly change any of the rollover resistance metrics compared to the Modification 2 configuration.

Graphical results from Circle tests conducted on Vehicle F are shown in Figure 19 (Understeer/Oversteer Characteristic Curves) and Figure 20 (Roll Gradient Characteristic Curves). Figure 19 shows that the amount of increase in front roll stiffness from Modification 1 alone did not have a significant effect on the understeer/oversteer characteristics of Vehicle G, as measured during the Circle tests. However, when the rear anti-roll bar was also disconnected (Modification 2) Vehicle G did not transition to oversteer during the Circle test. Changing the steering geometry to intentionally reduce roll-steer oversteer (Modification 3) significantly further increased the understeer of Vehicle G.

Figure 20 shows that the Modification 1 increase in front roll stiffness (and total vehicle roll stiffness) decreases the roll gradient. Not surprising, the roll gradients for Modifications 2 and 3 are similar. While the total vehicle roll stiffness for the Baseline vehicle is only slightly greater than total roll stiffness of Modifications 2 and 3, the measured roll gradients for Modifications 2 and 3 were modestly greater than for the Baseline vehicle. This indicates that the combinations of front to rear roll stiffness and front to rear load allowed for the vehicle to roll more when configured like Modifications 2 and 3 than the Baseline configuration.

The bar chart in Figure 14 shows all of Yaw Rate Ratios determined from CCW Constant Steer tests conducted on Vehicle G. Unlike the results from the Circle tests, the Yaw Rate Ratio values measured during the CCW Constant Steer tests suggest that Modification 1 does have a significant effect on the understeer/oversteer response of Vehicle G. The Yaw Rate Ratio in the Baseline configuration is 8.40 and it is 3.24 in the Modification 1 configuration. However, the graphs on Pages 56 and 57 of Appendix C show that one of the five Constant Steer tests conducted in the Baseline configuration resulted in a much greater individual Yaw Rate Ratio (23.1) than the other four tests conducted (values of 5.96, 3.18, 6.13 and 3.61). This outcome – that the individual Yaw Rate Ratio values can vary significantly for an oversteering vehicle – has been observed in previous studies and it is not unique to Vehicle G.

The Yaw Rate Ratio values for Modifications 2 and 3 are consistent with the findings from the Circle tests. Modification 2 resulted in a Yaw Rate Ratio less than 1.0, indicating that it exhibits understeer response up to 0.4 g. The Yaw Rate Ratio value for Modification 3 is negative (detailed graphical results are shown on Pages 71 and 72 of Appendix C), which indicates that this configuration has significant understeer, and this finding was also indicated from Circle test results (Figure 19).

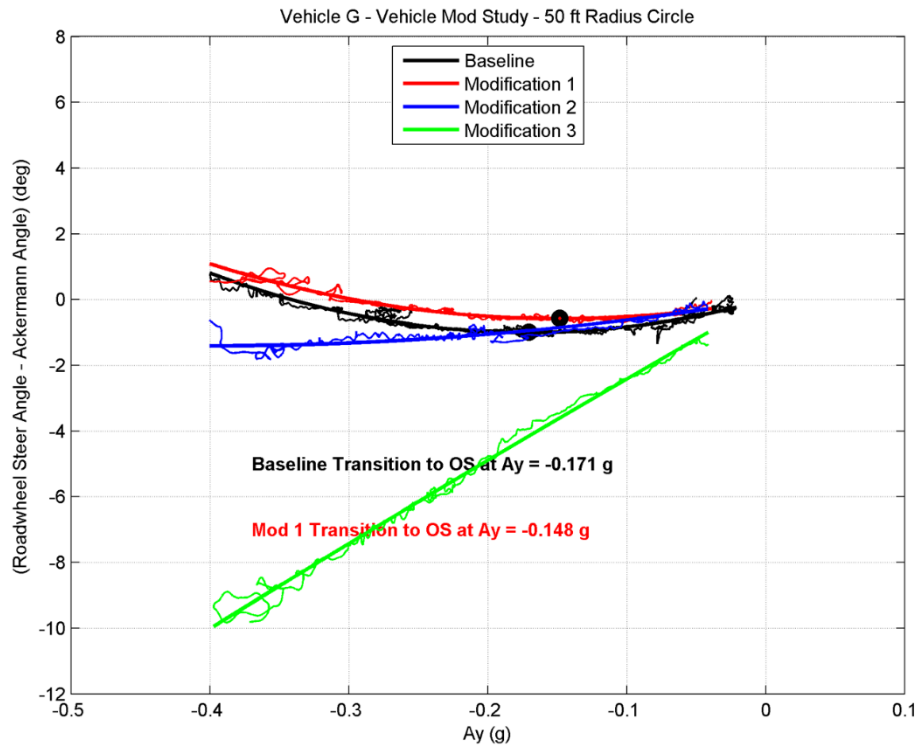


Figure 19: Understeer/Oversteer Characteristic Curves for Vehicle G

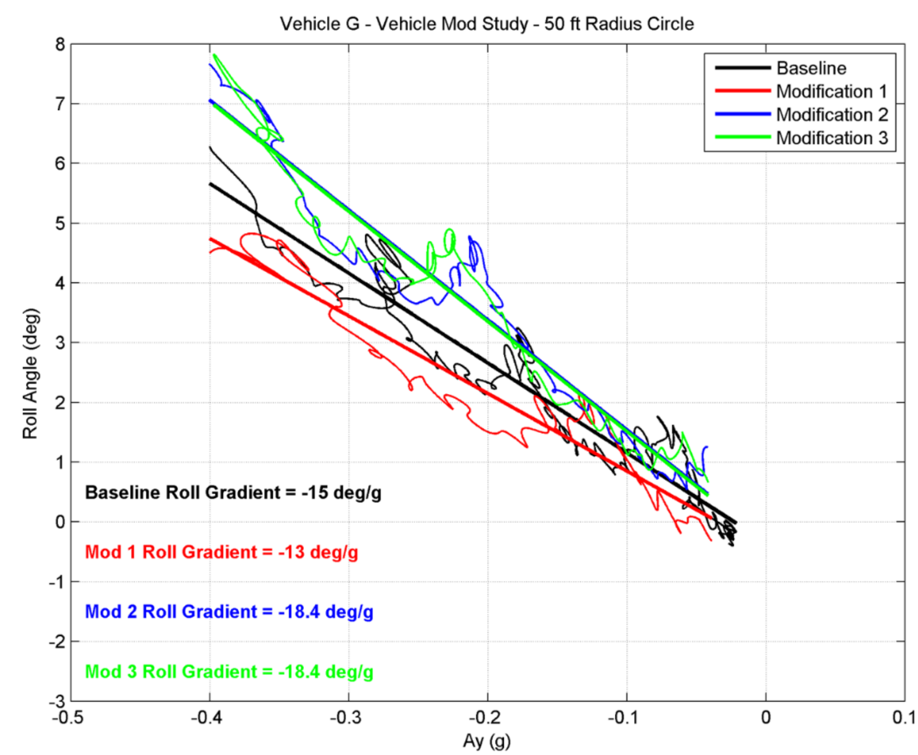


Figure 20: Roll Gradient Characteristic Curves for Vehicle G

6.3 Results for Vehicle K

The only physical change made to Vehicle K during this study was to replace its always locked rear differential with a rear differential that could be open or locked. The hardware includes electronics for engaging and disengaging the open differential feature.

Although only one physical modification was made to Vehicle K, the tests done to study the effects of operating the vehicle with a locked and open rear differential are described by the following "modification" tests:

1: Tested on asphalt with locked rear differential

2: Tested on asphalt with open rear differential

3: Tested on groomed dirt with locked rear differential

4: Tested on groomed dirt with open rear differential

As mentioned, the Baseline tests on Vehicle K were conducted in the CCW and Left turn directions only. Modification 1 involved expanding the Baseline suite of tests on asphalt to include CW and Right turns. Likewise, the Modification 2-4 tests included conducting tests in both steer directions.

Figure 21 contains bar charts summarizing the rollover resistance metrics (SSF, TTR and Threshold Ay) for Vehicle K.

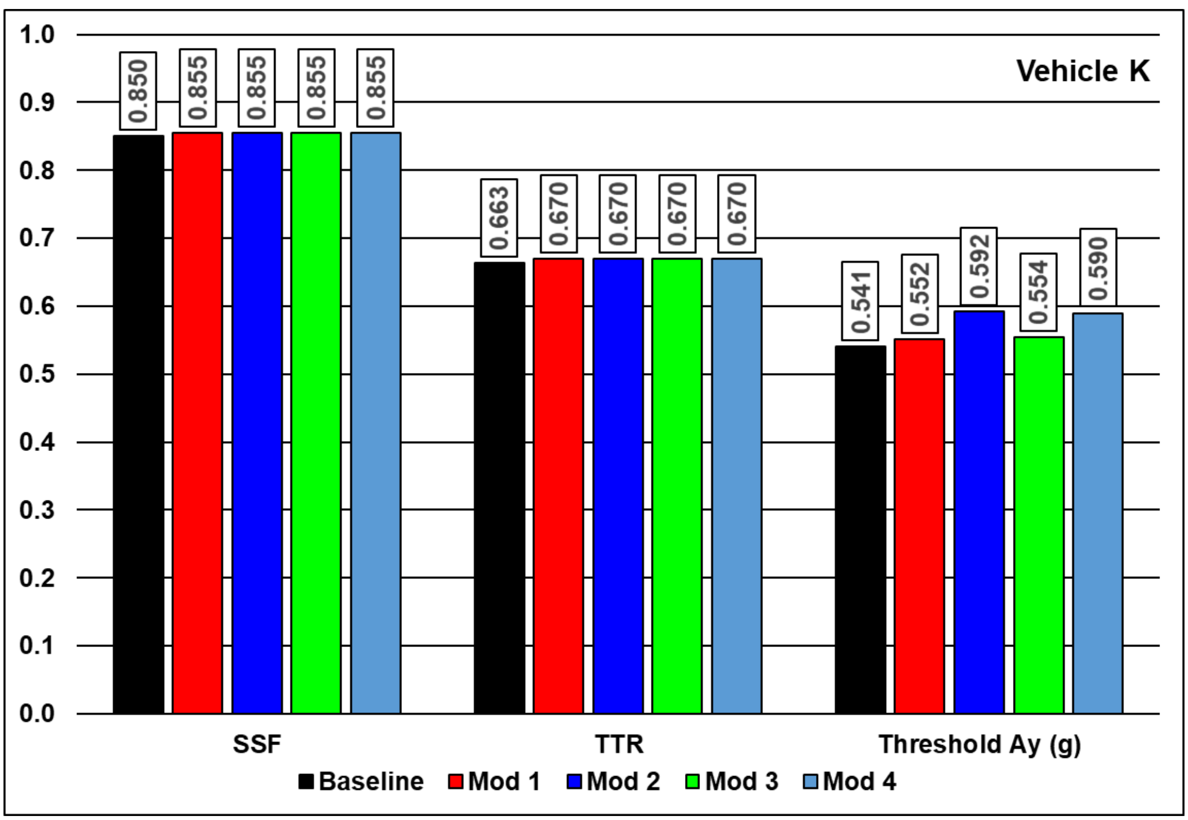


Figure 21: Rollover Resistance Metrics for Vehicle K

The replacement differential was slightly heavier than the always-locked differential, and this slightly reduced the CG height, which slightly increased the SSF and TTR (Modifications 1-4 are with the replacement rear differential).

The Threshold Ay value (based on left-turn and right-turn J-Turns tests) for Modification 1 configuration is slightly higher than the Baseline configuration value (based on only left-turn J-Turns), which is consistent with the slight increase in SSF. Similar Threshold Ay values were measured for Vehicle K with a locked differential on asphalt (Modification 1) and on groomed dirt (Modification 3). Likewise, similar Threshold Ay values were measured for Vehicle K with an open differential on asphalt (Modification 2) and on groomed dirt (Modification 4).

The measured Threshold Ay values with the open differential where modestly higher than the Threshold Ay values with the locked differential, on both asphalt and on groomed dirt (i.e. Modification 2 and 4 values are greater than Modification 1 and 3 values). With an open differential there is less tire scrub resistance on the rear axle during the J-Turns. This allows the vehicle with open differential to slightly develop more yaw rate more quickly through the turn. Vehicle speed decreases more during the J-Turns with a locked differential than with an open differential. On both asphalt and on groomed dirt, the steering magnitudes needed to generate two-wheel lift events were greater when the rear differential was locked. The tests conducted indicate that the combination of these differences cause Vehicle K to require higher lateral acceleration to generate two-wheel events (higher Threshold Ay) when tested with an open rear differential on both asphalt and groomed dirt.

Understeer/oversteer characteristic curves from Circle tests conducted on Vehicle K are shown in Figure 22. The graphs are for the four modification configurations. The locked differential tests are on the left side of Figure 22, and the open differential tests are on the right side. The top two graphs are for tests conducted on asphalt and the bottom two are for tests conducted on groomed dirt.

The understeer/oversteer characteristic curves are similar for the locked differential tests conducted on asphalt (Modification 1) and groomed dirt (Modification 3). These results are also similar to the CCW Circle test results conducted in the Baseline configuration (Page 77 of Appendix C). Likewise, the understeer/oversteer characteristic curves are similar for the open differential tests conducted on asphalt (Modification 2) and groomed dirt (Modification 4).

With a locked rear differential, Vehicle K, while close to neutral steer, does transition to oversteer in the range of 0.25 g on asphalt and on groomed dirt. With an open rear differential, Vehicle K does not transition to oversteer, rather it remains understeering through the range of 0.4 g lateral acceleration.

The Yaw Rate Ratio values determined from CCW Constant Steer tests conducted on Vehicle K are shown on the bar chart in Figure 14. The Yaw Rate Ratio results are consistent with the Circle test results. With a locked rear differential (Baseline, Modification 1 and Modification 3 configurations) Vehicle K has relatively low Yaw Rate Ratio values above 1.0 on asphalt and on groomed dirt, indicating near neutral steer characteristics with mild oversteer at the higher lateral accelerations tested. With an open rear differential (Modification 2 and Modification 4 configurations) Vehicle K has Yaw Rate Ratio values below 1.0 on asphalt and on groomed dirt, indicating understeer behavior through the range of 0.4 g lateral acceleration.

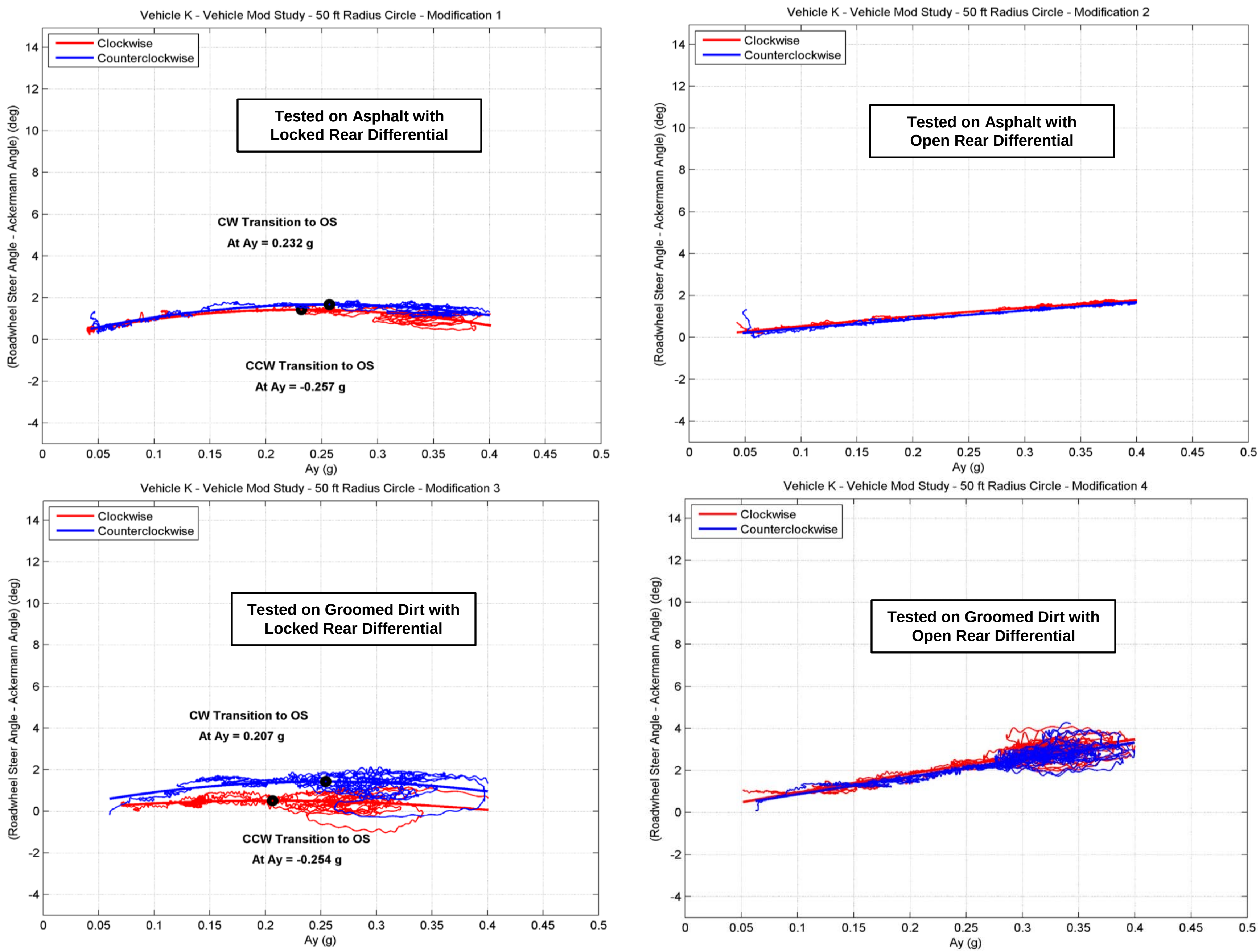


Figure 22: Understeer/Oversteer Characteristic Curves for Vehicle K

6.4 Summary

Results from attribute-modified tests conducted on Vehicle F showed that changing fundamental vehicle properties such as increasing track width and reducing CG height to increase SSF and TTR do improve rollover resistance as indicated by increased Threshold Ay values measured during J-Turn tests. Moving the longitudinal CG of Vehicle F forward, to where it was during tests conducted with a human driver, resulted in Constant Steer test results that showed Vehicle F transitioning from oversteer to understeer during Constant Steer tests. This phenomenon also occurred during the tests with a human driver, but it did not occur during the previous autonomous tests conducted on Vehicle F in the Rider Active and Groomed Dirt studies. During these studies, which also used representative DPI loading, Vehicle F was loaded such that the longitudinal CG was located more rearward (by about 2.0 to 3.3 inches). The fact that the transition phenomenon reoccurred during the autonomous tests conducted on Vehicle F when loaded like it was when tested with a human driver indicates that the effects of longitudinal CG location on the vehicle cause the transition to occur.

A series of successive vehicle attributes were made to Vehicle G with the intention of successively improving its handling (yaw response) based on increasing its understeer behavior. All three successive modifications made to Vehicle G – increasing the front suspension roll stiffness, decreasing the rear suspension roll stiffness and modifying the steering geometry to reduce roll oversteer – reduced Yaw Rate Ratio values measured during Constant Steer tests. Vehicle G transitioned to oversteer during Circle tests in its baseline configuration and when only the front roll stiffness was increased. Vehicle G remained understeering throughout Circle tests conducted when the rear roll stiffness was decreased, and it became more understeering when the steering geometry was included to the modifications. Increasing the front suspension roll stiffness of Vehicle G increased its TTR and Threshold Ay. When the rear roll stiffness was also decreased, the TTR decreased but the Threshold Ay, as indicated by onset of two-wheel lift, increased further. Modifying the steering geometry had no significant effect on SSF, TTR or Threshold Ay.

Vehicle K was tested on asphalt and on groomed dirt with a locked and open rear differential. The SSF and TTR values were the same whether the rear differential was locked or open, but the measured lateral acceleration required to generate two-wheel lift in J-Turn tests, the Threshold Ay, was greater with the open differential configuration. With a locked rear differential, Vehicle K exhibited transition to oversteer during Circle tests on asphalt and groomed dirt, and it also had Yaw Rate Ratio values greater than 1.0 measured during Constant Steer tests on both surfaces. With an open rear differential, and on both asphalt and groomed dirt, Vehicle K remained understeering during Circle tests and had Yaw Rate Ratio values less than 1.0 during Constant Steer tests.

The attribute modifications made to Vehicles F and G were made with the goal of improving rollover resistance as determined by increasing SSF, TTR and Threshold Ay and/or improving handling (yaw stability) as determined by increasing understeer trends in Circle tests and reduce Yaw Rate Ratio values in Constant Steer tests. Laboratory measurements and dynamic field test results showed that the modifications did improve rollover resistance and handling as intended.

However, it is important to point out that the attribute modifications made also influence other aspects of vehicle performance that were not evaluated as part of this study. Changing intrinsic properties of an ATV – such as track width, overall vehicle CG location, front and rear suspension stiffnesses, steering geometry and using an open or locked rear differential – might change its overall intended design characteristics. Important design characteristics for ATVs include geometric properties like overall width and ground clearance, and subjective and objective measures related to ride quality, maneuverability and overall function (utility or recreation). Certainly, aspects of overall vehicle performance not considered as part of this study warrant consideration when ultimately designing, specifying and modifying vehicle attributes.

Vehicle F

	Curb	Driver	Driver Plus Instrumentation (DPI)	Autonomous Ballast to Driver Loading (Baseline)	Modification #1: Wheel Spacers	Modification #2: Vertical CG Shift	Modification #3: Longitudinal CG Shift
VIMF Test Number		5780	5781	6587	6588	6590	6589
Total Vehicle Weight (lb)	526.2	739.8	761.4	740.0	753.0	740.5	749.2
Left Front Weight (lb)	149.1	166.1	190.7	159.7	163.7	156.9	177.6
Right Front Weight (lb)	122.7	172.1	179.2	162.9	165.9	165.9	186.7
Left Rear Weight (lb)	151.6	213.1	208.6	215.9	225.4	221.1	203.5
Right Rear Weight (lb)	102.8	188.5	182.9	201.5	198.0	196.6	181.4
Front Track Width (in)	32.14	32.55	32.45	32.55	36.55	32.55	32.55
Rear Track Width (in)	30.71	30.95	30.89	30.95	34.95	30.95	30.95
Average Track Width (in)	31.43	31.75	31.67	31.75	35.75	31.75	31.75
Wheelbase (in)	46.20	46.20	46.20	46.20	46.20	46.20	46.20
CG Longitudinal (in)	22.34	25.08	23.76	26.06	25.98	26.06	23.74
CG Lateral (in)	-2.23	-0.38	-0.77	-0.23	-0.58	-0.31	-0.26
CG Height (in)		23.45	22.38	23.15	23.37	21.71	23.39
Roll Inertia - I_{XX} (ft-lb-s^2)		53	60	67	74	49	73
Pitch Inertia - I_{YY} (ft-lb-s^2)		74	78	98	107	86	103
Yaw Inertia - I_{ZZ} (ft-lb-s^2)		52	60	83	84	79	82
Roll/Yaw - I_{XZ} (ft-lb-s^2)		6	4	3	5	2	-2
SSF		0.677	0.708	0.686	0.765	0.731	0.679
KST		0.678	0.708	0.688	0.767	0.734	0.679
Steering Ratio (deg/deg)			1.29				

Vehicle F

		Driver	Driver Plus Instrumentation (DPI)	Autonomous Ballast to Driver Loading (Baseline)	Modification #1: Wheel Spacers	Modification #2: Vertical CG Shift	Modification #3: Longitudinal CG Shift
Lateral Direction: Right Tilt	Tilt Table: First Wheel Lift	Rear	Rear	Rear	Rear	Rear	Rear
	Tilt Table Angle (TTA) (deg)	26.1	26.5	26.1	29.4	28.3	26.1
	Tilt Table Ratio (TTR)	0.490	0.498	0.490	0.562	0.539	0.490
Lateral Direction: Left Tilt	Tilt Table: First Wheel Lift	Rear	Rear	Rear	Rear	Rear	Rear
	Tilt Table Angle (TTA) (deg)	24.6	25.2	24.3	27.2	26.8	24.1
	Tilt Table Ratio (TTR)	0.457	0.470	0.452	0.514	0.505	0.447
	Average Lateral TTA (deg)	**25.3**	**25.8**	**25.2**	**28.3**	**27.6**	**25.1**
	Average Laleral TTR	**0.474**	**0.484**	**0.471**	**0.538**	**0.522**	**0.469**

Longitudinal Direction: Front Tilt	Tilt Table: First Wheel Lift	Right	Left	Right	Right	Right	Right
	Forward Tilt Table Angle (FTTA) (deg)	46.0	44.6	47.1	46.8	49.5	45.0
	Forward Tilt Table Ratio (FTTR)	1.036	0.987	1.078	1.064	1.169	1.000

Longitudinal Direction: Rear Tilt	Tilt Table: First Wheel Lift	Left	Left	Left	Left	Equal	Equal
	Rearward Tilt Table Angle (RTTA) (deg)	42.0	45.4	40.7	41.8	44.1	45.4
	Rearward Tilt Table Ratio (RTTR)	0.902	1.014	0.861	0.894	0.968	1.015

Vehicle G

	Curb	Driver	Driver Plus Instrumentation (DPI)	Autonomous Ballast to Driver Loading (Baseline)	Modification #1: Replaced OEM Front Springs	Modification #2: Mod 1 plus Disconnected Rear Anti-roll Bar	Modification #3: Mod 1 and Mod 2 plus Modified Steering Geometry
VIMF Test Number		5783	5784	6582	6585		
Total Vehicle Weight (lb)	694.0	909.4	928.6	914.5	916.0	916.0	916.0
Left Front Weight (lb)	174.2	215.4	223.9	197.3	191.0	191.0	191.0
Right Front Weight (lb)	168.1	199.1	219.4	198.5	200.9	200.9	200.9
Left Rear Weight (lb)	175.9	246.6	242.5	255.5	263.0	263.0	263.0
Right Rear Weight (lb)	175.8	248.3	242.8	263.2	261.1	261.1	261.1
Front Track Width (in)	36.35	36.45	36.50	36.45	36.28	36.28	36.28
Rear Track Width (in)	35.60	36.10	36.06	36.10	36.36	36.36	36.36
Average Track Width (in)	35.98	36.28	36.28	36.28	36.32	36.32	36.32
Wheelbase (in)	50.55	50.65	50.60	50.65	50.65	50.65	50.65
CG Longitudinal (in)	25.62	27.56	26.44	28.73	28.98	28.98	28.98
CG Lateral (in)	-0.16	-0.29	-0.08	0.18	0.16	0.16	0.16
CG Height (in)		24.07	23.34	24.85	25.14	25.14	25.14
Roll Inertia - I_{XX} (ft-lb-s^2)		79	75	85	83	83	83
Pitch Inertia - I_{YY} (ft-lb-s^2)		110	117	145	146	146	146
Yaw Inertia - I_{ZZ} (ft-lb-s^2)		88	96	133	132	132	132
Roll/Yaw - I_{XZ} (ft-lb-s^2)		5	5	9	7	7	7
SSF		0.753	0.777	0.730	0.722	0.722	0.722
KST		0.754	0.777	0.730	0.722	0.722	0.722
Steering Ratio (deg/deg)			1.41				

Vehicle G

		Driver	Driver Plus Instrumentation (DPI)	Autonomous Ballast to Driver Loading (Baseline)	Modification #1: Replaced OEM Front Springs	Modification #2: Mod 1 plus Disconnected Rear Anti-roll Bar	Modification #3: Mod 1 and Mod 2 plus Modified Steering Geometry
Lateral Direction: Right Tilt	**Tilt Table: First Wheel Lift**	Rear	Rear	Rear	Equal	Front	Front
	Tilt Table Angle (TTA) (deg)	28.2	28.4	27.8	29.0	28.1	28.2
	Tilt Table Ratio (TTR)	0.535	0.540	0.527	0.555	0.533	0.536
Lateral Direction: Left Tilt	**Tilt Table: First Wheel Lift**	Rear	Rear	Equal	Equal	Front	Front
	Tilt Table Angle (TTA) (deg)	28.8	28.8	28.8	29.7	28.7	28.5
	Tilt Table Ratio (TTR)	0.550	0.551	0.550	0.571	0.548	0.544
	Average Lateral TTA (deg)	**28.5**	**28.6**	**28.3**	**29.4**	**28.4**	**28.4**
	Average Laleral TTR	**0.542**	**0.545**	**0.538**	**0.563**	**0.541**	**0.540**
Longitudinal Direction: Front Tilt	**Tilt Table: First Wheel Lift**	Left	Left	Right	Equal	Right	Right
	Forward Tilt Table Angle (FTTA) (deg)	49.3	48.1	47.9	49.0	49.2	48.8
	Forward Tilt Table Ratio (FTTR)	1.163	1.114	1.105	1.152	1.156	1.144
Longitudinal Direction: Rear Tilt	**Tilt Table: First Wheel Lift**	Left	Right	Left	Left	Left	Left
	Rearward Tilt Table Angle (RTTA) (deg)	43.1	44.1	42.0	42.4	42.6	42.8
	Rearward Tilt Table Ratio (RTTR)	0.935	0.969	0.900	0.912	0.921	0.927

Vehicle K

	Curb	Driver	Driver Plus Instrumentation (DPI)	Autonomous Ballast to Driver Loading (Baseline)	Equipped with Selectable Rear Differential Mods 1-4
VIMF Test Number		5795	5796	6586	6591
Total Vehicle Weight (lb)	832.0	1044.8	1070.7	1044.6	1066.8
Left Front Weight (lb)	206.7	239.9	241.8	225.6	223.2
Right Front Weight (lb)	192.0	220.6	224.7	218.4	226.3
Left Rear Weight (lb)	227.2	295.8	303.9	302.0	313.3
Right Rear Weight (lb)	206.1	288.5	300.3	298.6	304.0
Front Track Width (in)	39.96	40.83	40.83	40.83	40.83
Rear Track Width (in)	38.20	39.24	39.16	39.24	39.24
Average Track Width (in)	39.08	40.03	39.99	40.03	40.03
Wheelbase (in)	53.15	53.15	53.20	53.15	53.15
CG Longitudinal (in)	27.68	29.72	30.02	30.56	30.76
CG Lateral (in)	-0.84	-0.51	-0.39	-0.20	-0.11
CG Height (in)		23.44	22.92	23.55	23.42
Roll Inertia - I_{XX} (ft-lb-s^2)		73	79	82	92
Pitch Inertia - I_{YY} (ft-lb-s^2)		130	138	160	160
Yaw Inertia - I_{ZZ} (ft-lb-s^2)		116	126	151	153
Roll/Yaw - I_{XZ} (ft-lb-s^2)		4	5	-1	2
SSF		0.854	0.873	0.850	0.855
KST		0.856	0.875	0.852	0.857
Steering Ratio (deg/deg)			1.43		

Vehicle K

		Driver	Driver Plus Instrumentation (DPI)	Autonomous Ballast to Driver Loading (Baseline)	Equipped with Selectable Rear Differential Mods 1-4
Lateral Direction: Right Tilt	**Tilt Table: First Wheel Lift**	Rear	Rear	Rear	Rear
	Tilt Table Angle (TTA) (deg)	33.7	33.0	33.8	33.7
	Tilt Table Ratio (TTR)	0.668	0.649	0.669	0.667
Lateral Direction: Left Tilt	**Tilt Table: First Wheel Lift**	Rear	Rear	Rear	Rear
	Tilt Table Angle (TTA) (deg)	33.9	34.0	33.3	33.9
	Tilt Table Ratio (TTR)	0.672	0.675	0.657	0.672
	Average Lateral TTA (deg)	**33.8**	**33.5**	**33.5**	**33.8**
	Average Laleral TTR	**0.670**	**0.662**	**0.663**	**0.670**
Longitudinal Direction: Front Tilt	**Tilt Table: First Wheel Lift**	Equal	Right	Right	Right
	Forward Tilt Table Angle (FTTA) (deg)	53.8	51.3	52.2	53.6
	Forward Tilt Table Ratio (FTTR)	1.365	1.247	1.289	1.355
Longitudinal Direction: Rear Tilt	**Tilt Table: First Wheel Lift**	Left	Left	Equal	Equal
	Rearward Tilt Table Angle (RTTA) (deg)	42.7	46.2	45.7	44.0
	Rearward Tilt Table Ratio (RTTR)	0.924	1.044	1.023	0.966

Static Stability Factor (SSF)

	Baseline SSF	Mod 1 SSF	Mod 2 SSF	Mod 3 SSF	Mod 4 SSF
Vehicle F	0.686	0.765	0.731	0.679	
Vehicle G	0.730	0.722	0.722	0.722	
Vehicle K	0.850	0.855	0.855	0.855	0.855

Tilt Table Ratio (TTR)

Average of Left and Right Tilts

	Baseline TTR	Mod 1 TTR	Mod 2 TTR	Mod 3 TTR	Mod 4 TTR
Vehicle F	0.471	0.538	0.522	0.469	
Vehicle G	0.538	0.563	0.541	0.540	
Vehicle K	0.663	0.670	0.670	0.670	0.670

Constant Radius (50 ft) Circle Tests

Roll Gradients

CCW Tests
(Except Vehicle K Modifications were Run in Both CCW and CW Directions)

	Baseline Roll Gradient (deg/g)	Mod 1 Roll Gradient (deg/g)	Mod 2 Roll Gradient (deg/g)	Mod 3 Roll Gradient (deg/g)	Mod 4 Roll Gradient (deg/g)
Vehicle F	8.4	5.0	6.8	7.5	
Vehicle G	15.0	13.0	18.4	18.4	
Vehicle K	7.5	8.9	9.0	9.6	8.9

Constant Radius (50 ft) Circle Tests

Transition Lateral Acceleration

Lateral Acceleration Level at Point of Transition from Understeer to Oversteer

CCW Tests
(Except Vehicle K Modifications were Run in Both CCW and CW Directions)

	Baseline (g)	Mod 1 (g)	Mod 2 (g)	Mod 3 (g)	Mod 4 (g)
Vehicle F	0.13	0.21	0.18	0.17	
Vehicle G	0.17	0.15	NA	NA	
Vehicle K	0.25	0.24	NA	0.23	NA

20 mph Dropped Throttle J-Turn Tests

Threshold Lateral Acceleration

Left Turns
(Except Vehicle K Modifications were Run in Both Left and Right Turn Directions)

	Baseline (g)	Mod 1 (g)	Mod 2 (g)	Mod 3 (g)	Mod 4 (g)
Vehicle F	0.465	0.547	0.486	0.452	
Vehicle G	0.459	0.484	0.511	0.504	
Vehicle K	0.541	0.552	0.592	0.554	0.590

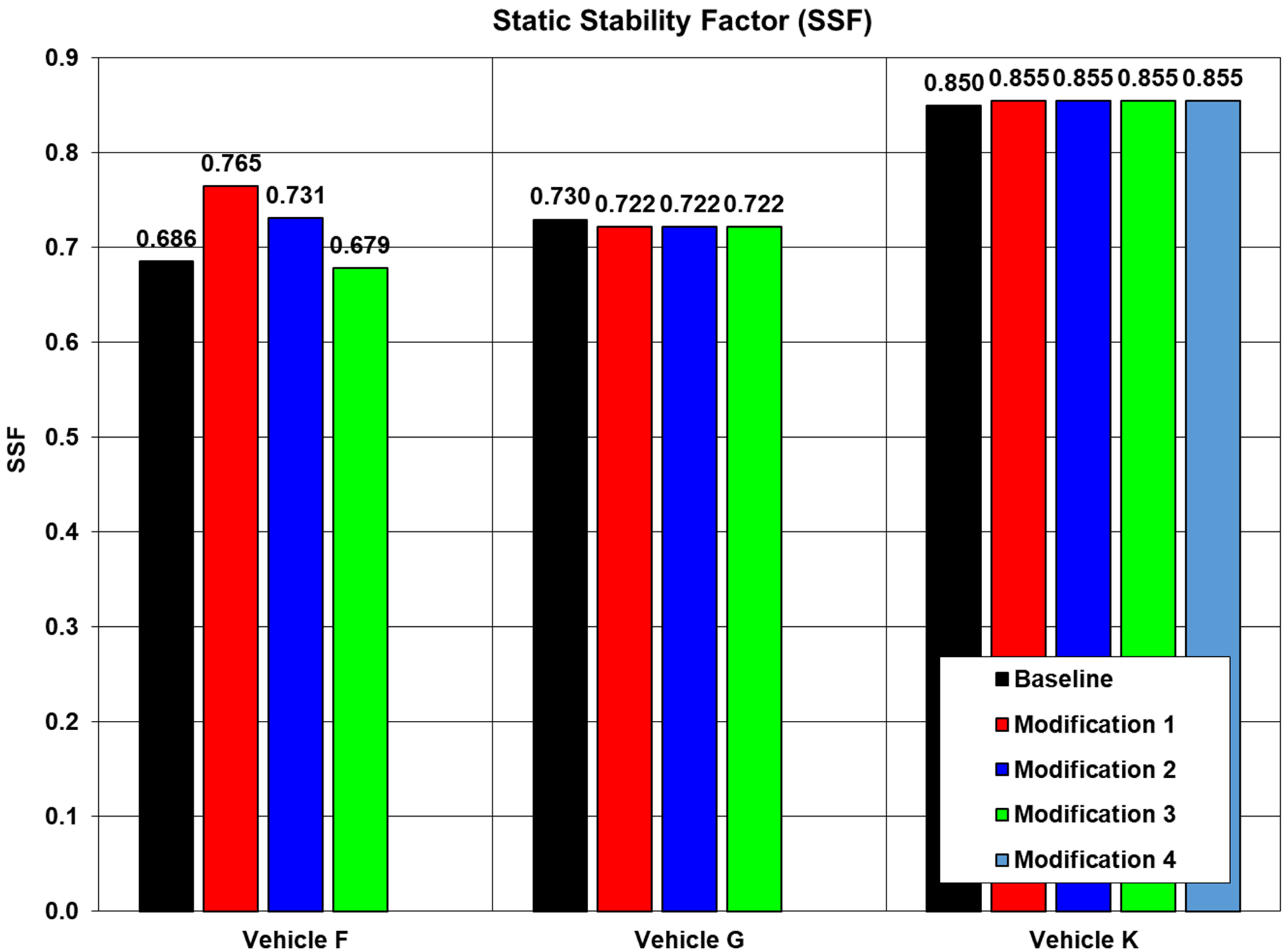
Constant Steer Tests

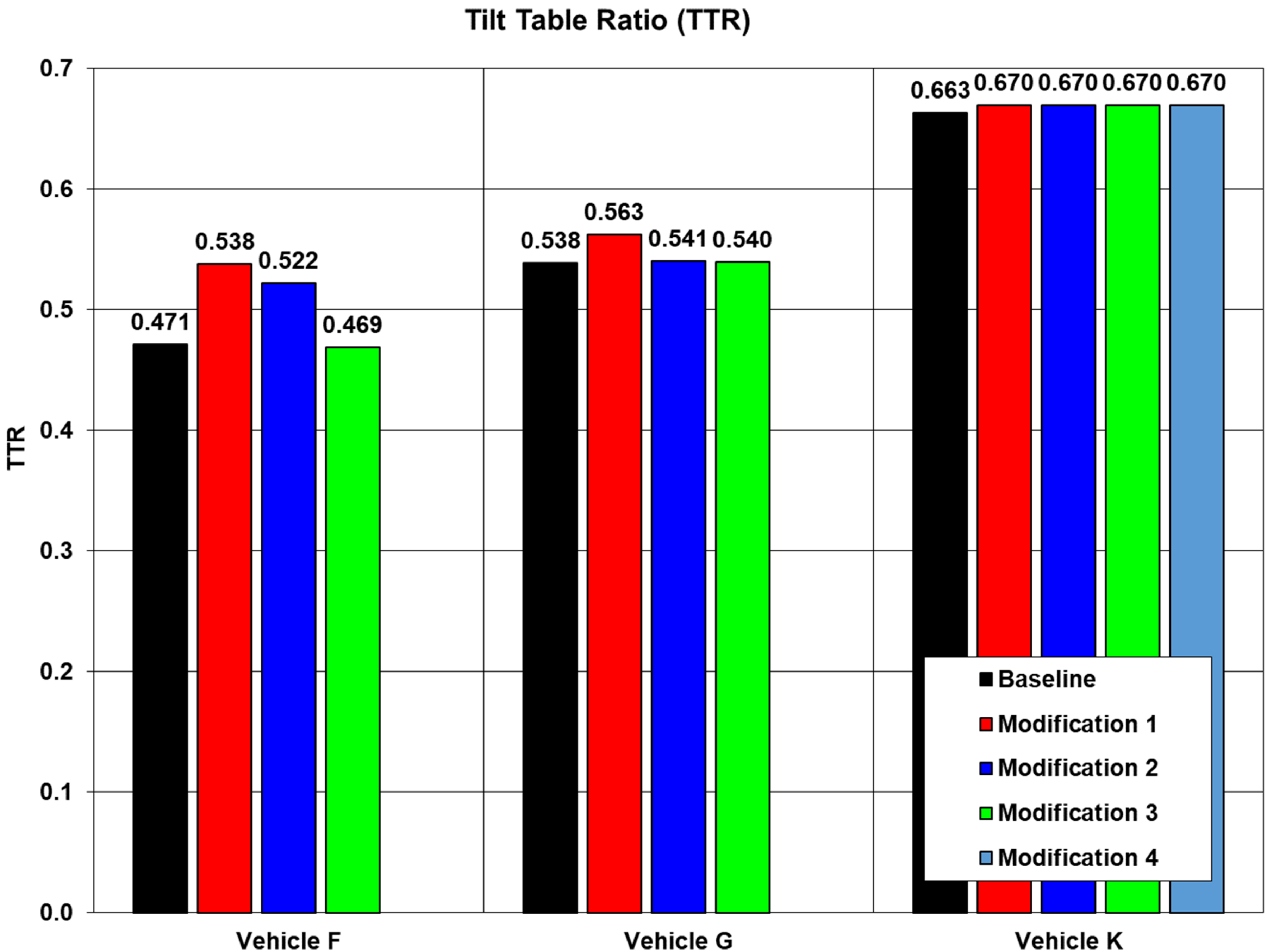
Yaw Rate Ratios

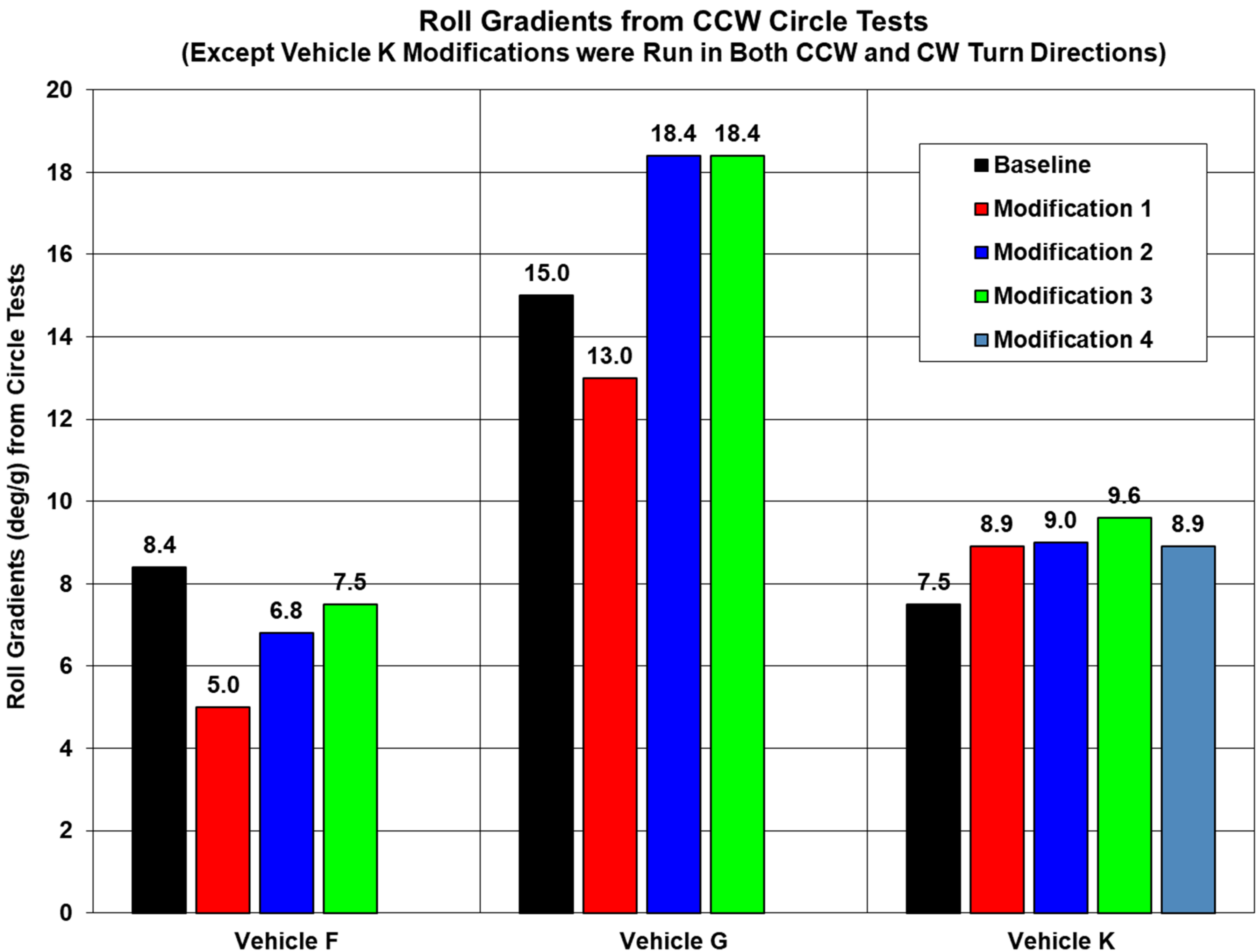
CCW Tests

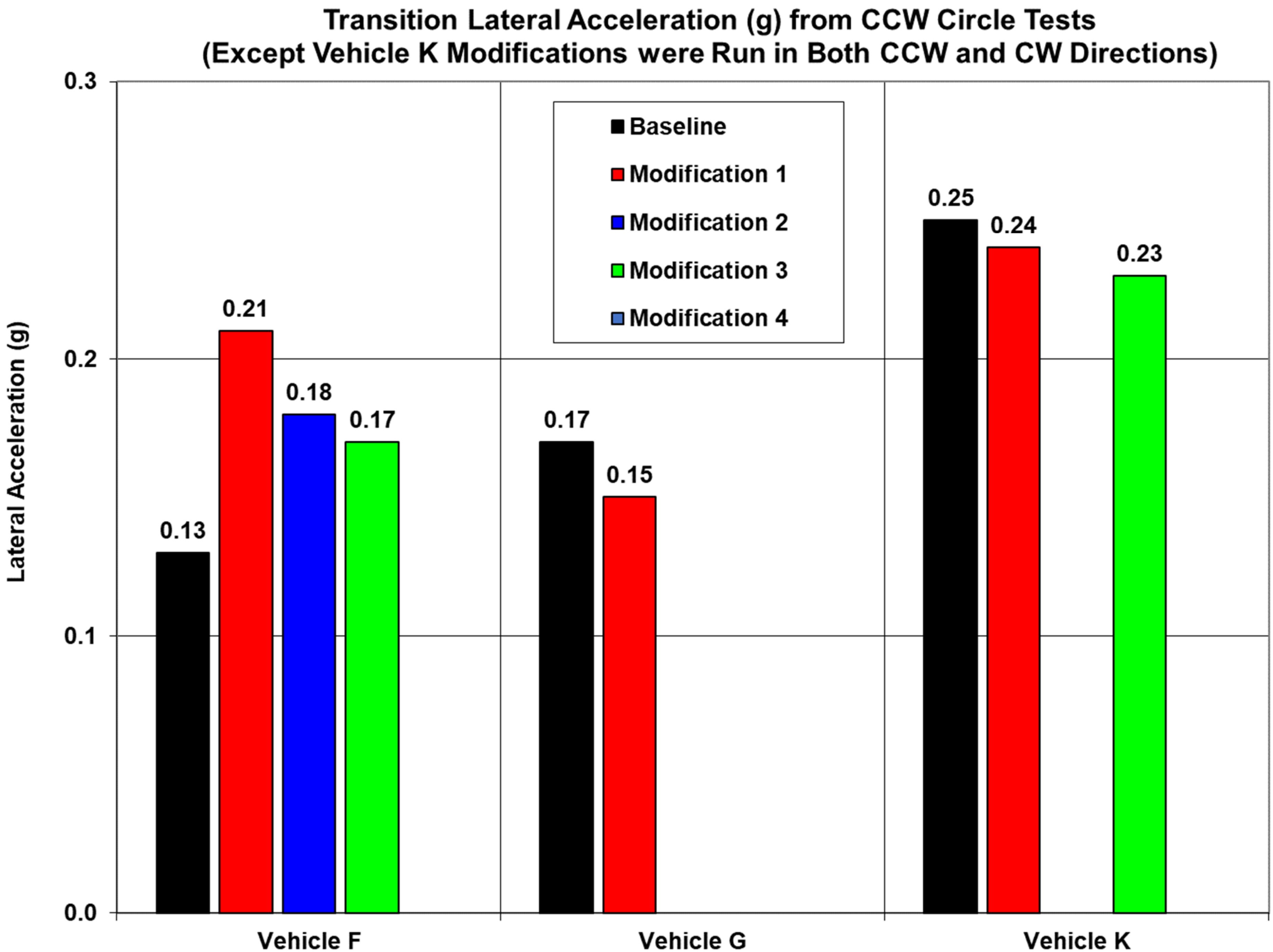
	Baseline Ratio	Mod 1 Ratio	Mod 2 Ratio	Mod 3 Ratio	Mod 4 Ratio
Vehicle F	4.65	3.58	4.05	0.09 / 2.19*	
Vehicle G	8.40	3.24	0.38	-0.23	
Vehicle K	2.24	2.05	0.77	1.06	0.25

* Value of 0.09 using normal upper limit range of 0.30-0.40 g
Value of 2.19 using transition upper limit range of 0.27-0.32 g

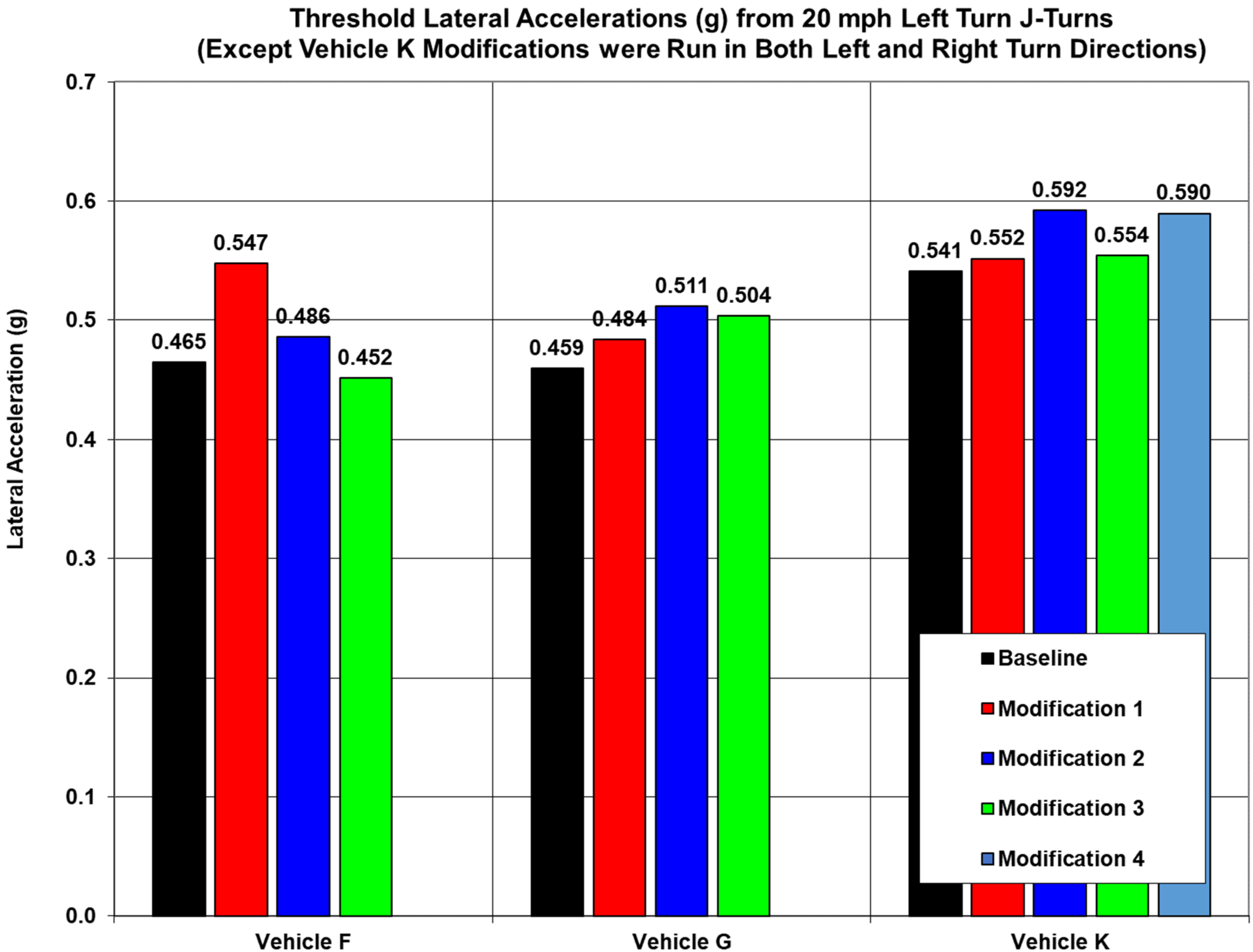

Static Stability Factor (SSF)
SSF
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.686
0.765
0.731
0.679
0.730
0.722
0.722
0.722
0.850
0.855
0.855
0.855
0.855
Baseline
Modification 1
Modification 2
Modification 3
Modification 4
Vehicle F
Vehicle G
Vehicle K

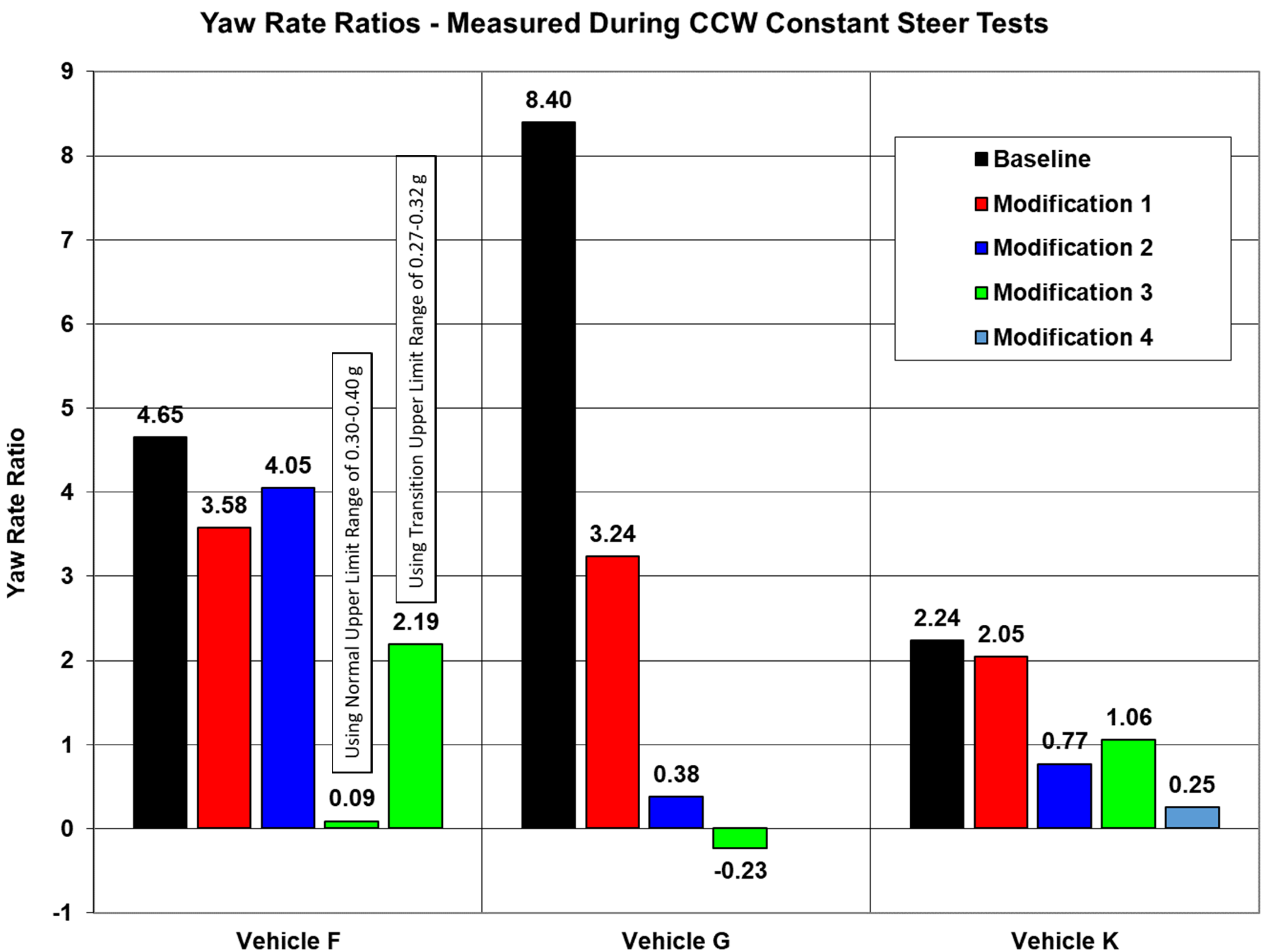

Tilt Table Ratio (TTR)
TTR
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.471
0.538
0.522
0.469
0.538
0.563
0.541
0.540
0.663
0.670
0.670
0.670
0.670
Baseline
Modification 1
Modification 2
Modification 3
Modification 4
Vehicle F
Vehicle G
Vehicle K


Roll Gradients from CCW Circle Tests
(Except Vehicle K Modifications were Run in Both CCW and CW Turn Directions)
Roll Gradients (deg/g) from Circle Tests
0
2
4
6
8
10
12
14
16
18
20
8.4
5.0
6.8
7.5
15.0
13.0
18.4
18.4
7.5
8.9
9.0
9.6
8.9
Baseline
Modification 1
Modification 2
Modification 3
Modification 4
Vehicle F
Vehicle G
Vehicle K



Transition Lateral Acceleration (g) from CCW Circle Tests
(Except Vehicle K Modifications were Run in Both CCW and CW Directions)
Lateral Acceleration (g)
0.3
0.2
0.1
0.0
Baseline
Modification 1
Modification 2
Modification 3
Modification 4
0.13
0.21
0.18
0.17
0.17
0.15
0.25
0.24
0.23
Vehicle F
Vehicle G
Vehicle K


Threshold Lateral Accelerations (g) from 20 mph Left Turn J-Turns
(Except Vehicle K Modifications were Run in Both Left and Right Turn Directions)
Lateral Acceleration (g)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.465
0.547
0.486
0.452
0.459
0.484
0.511
0.504
0.541
0.552
0.592
0.554
0.590
Baseline
Modification 1
Modification 2
Modification 3
Modification 4
Vehicle F
Vehicle G
Vehicle K


Yaw Rate Ratios - Measured During CCW Constant Steer Tests
Yaw Rate Ratio
9
8
7
6
5
4
3
2
1
0
-1
4.65
3.58
4.05
0.09
2.19
Using Normal Upper Limit Range of 0.30-0.40 g
Using Transition Upper Limit Range of 0.27-0.32 g
8.40
3.24
0.38
-0.23
2.24
2.05
0.77
1.06
0.25
Baseline
Modification 1
Modification 2
Modification 3
Modification 4
Vehicle F
Vehicle G
Vehicle K

Vehicle Modification Study

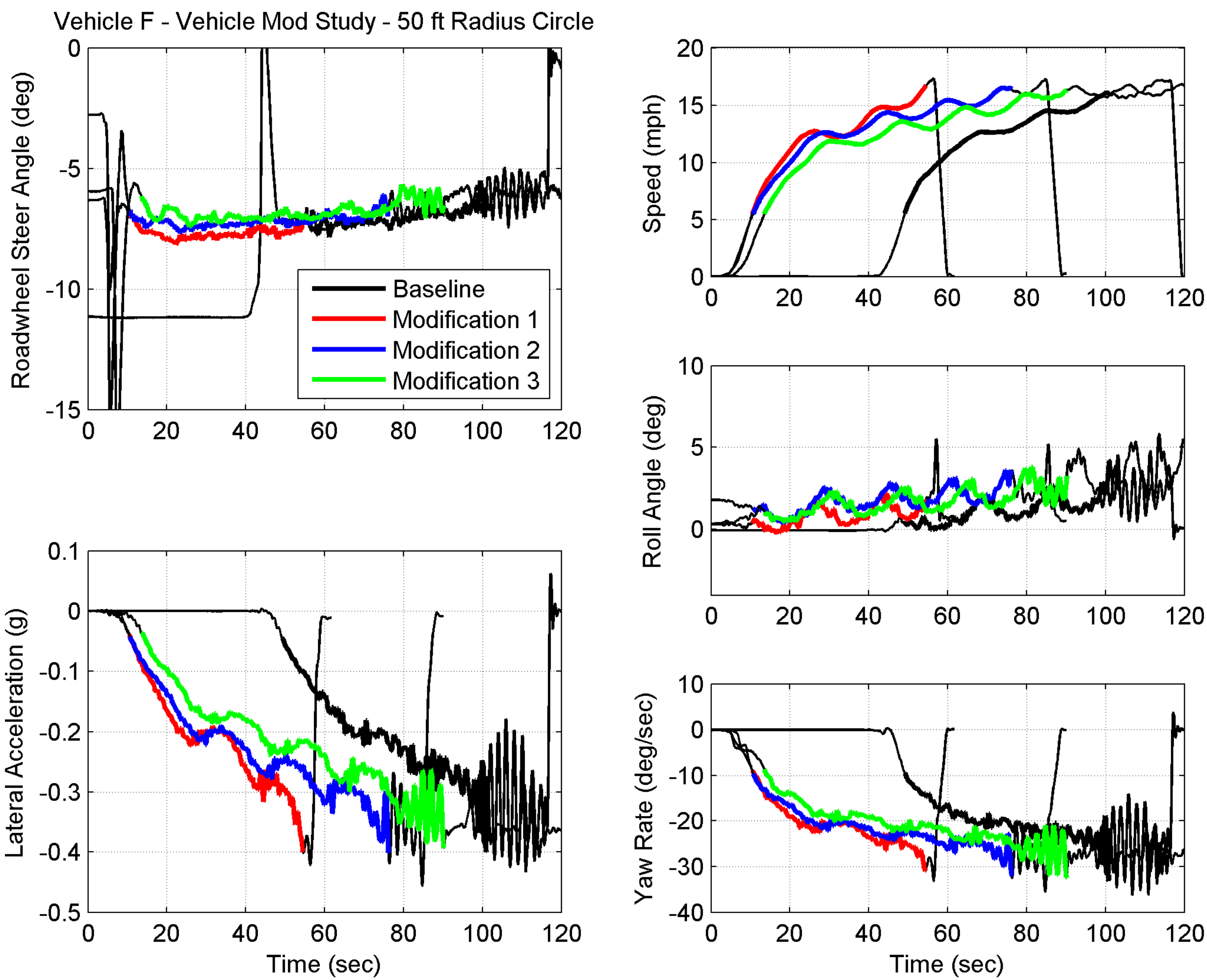
Results for Vehicle F

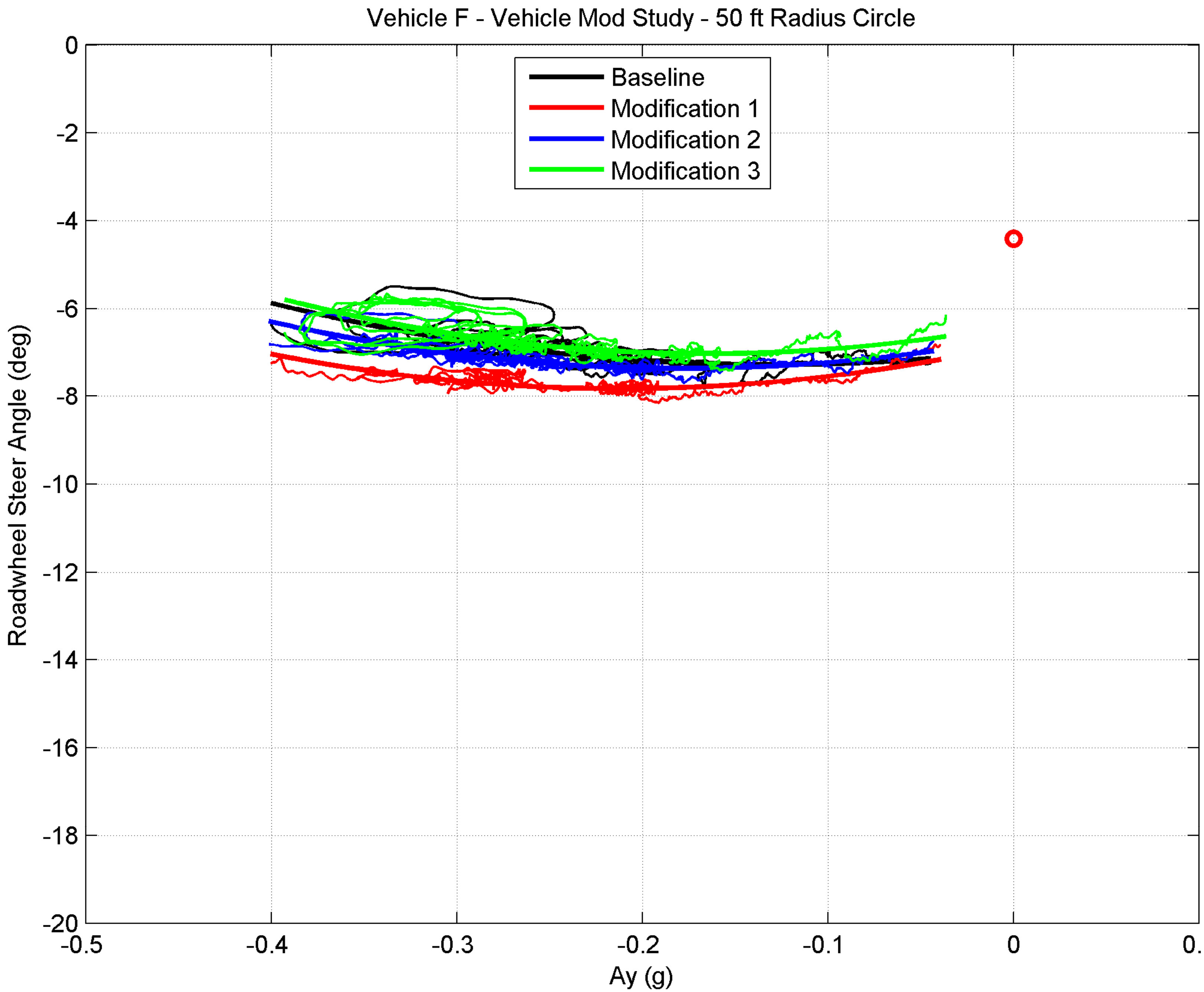
Baseline: Driver Plus Instrumentation (DPI) Loading 0° Rider (Driver) Lean

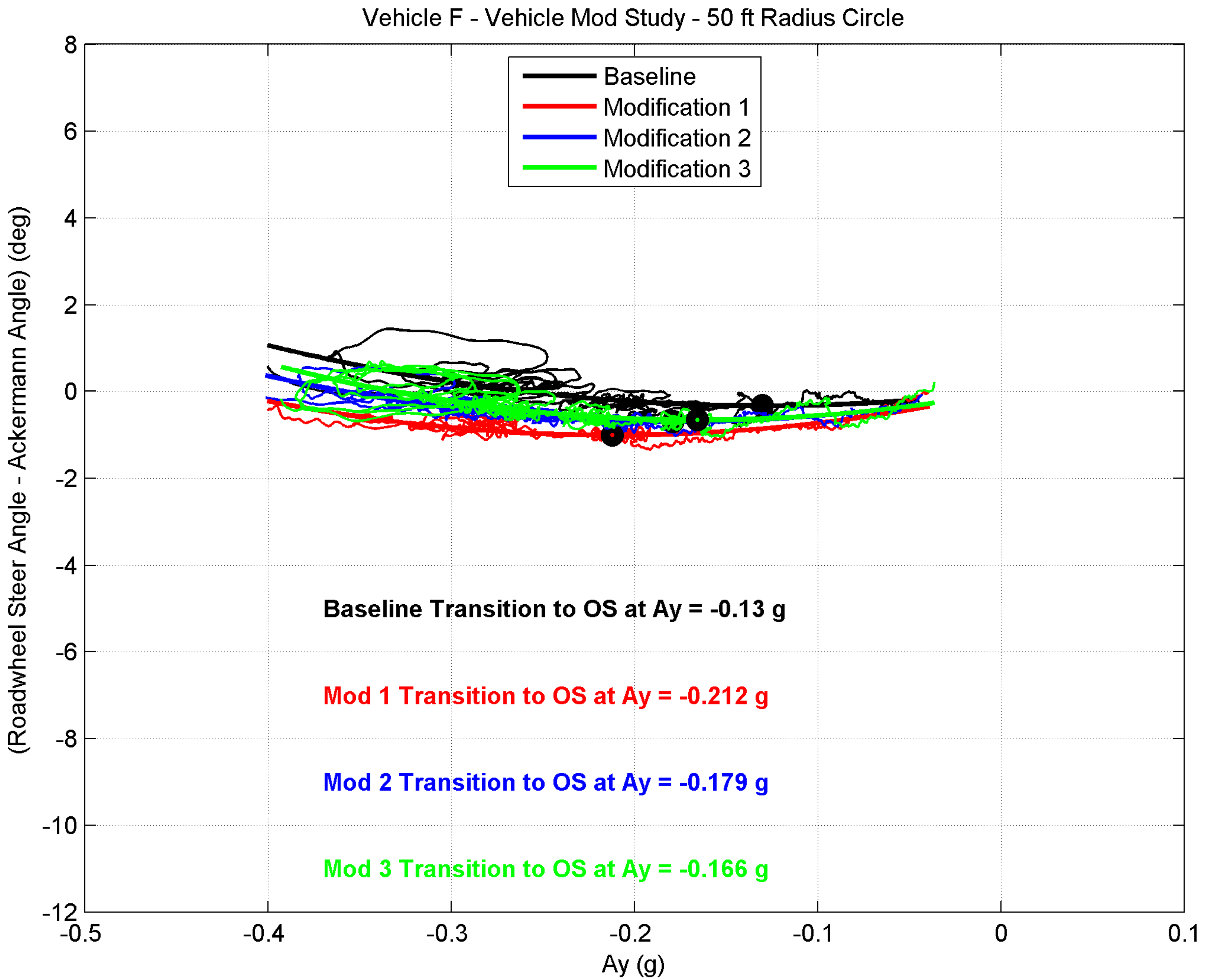
Mod 1: Driver Plus Instrumentation (DPI) Loading 0° Rider (Driver) Lean
Added 2-Inch-Thick Wheel Spacers to Increase Track Width

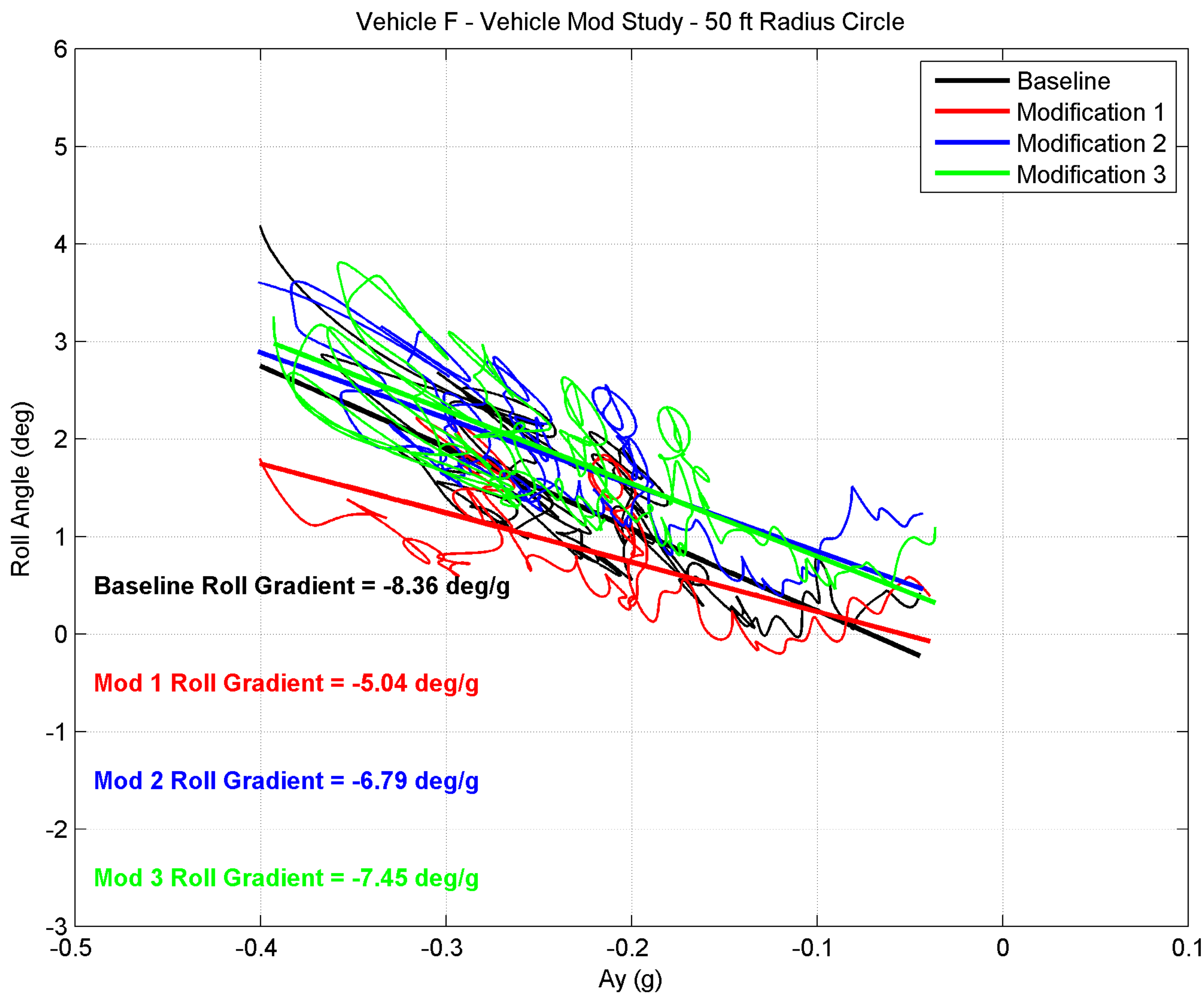
Mod 2: Driver Plus Instrumentation (DPI) Loading 0° Rider (Driver) Lean
Lowered Driver-Lean Ballast to Reduce Vehicle CG Height

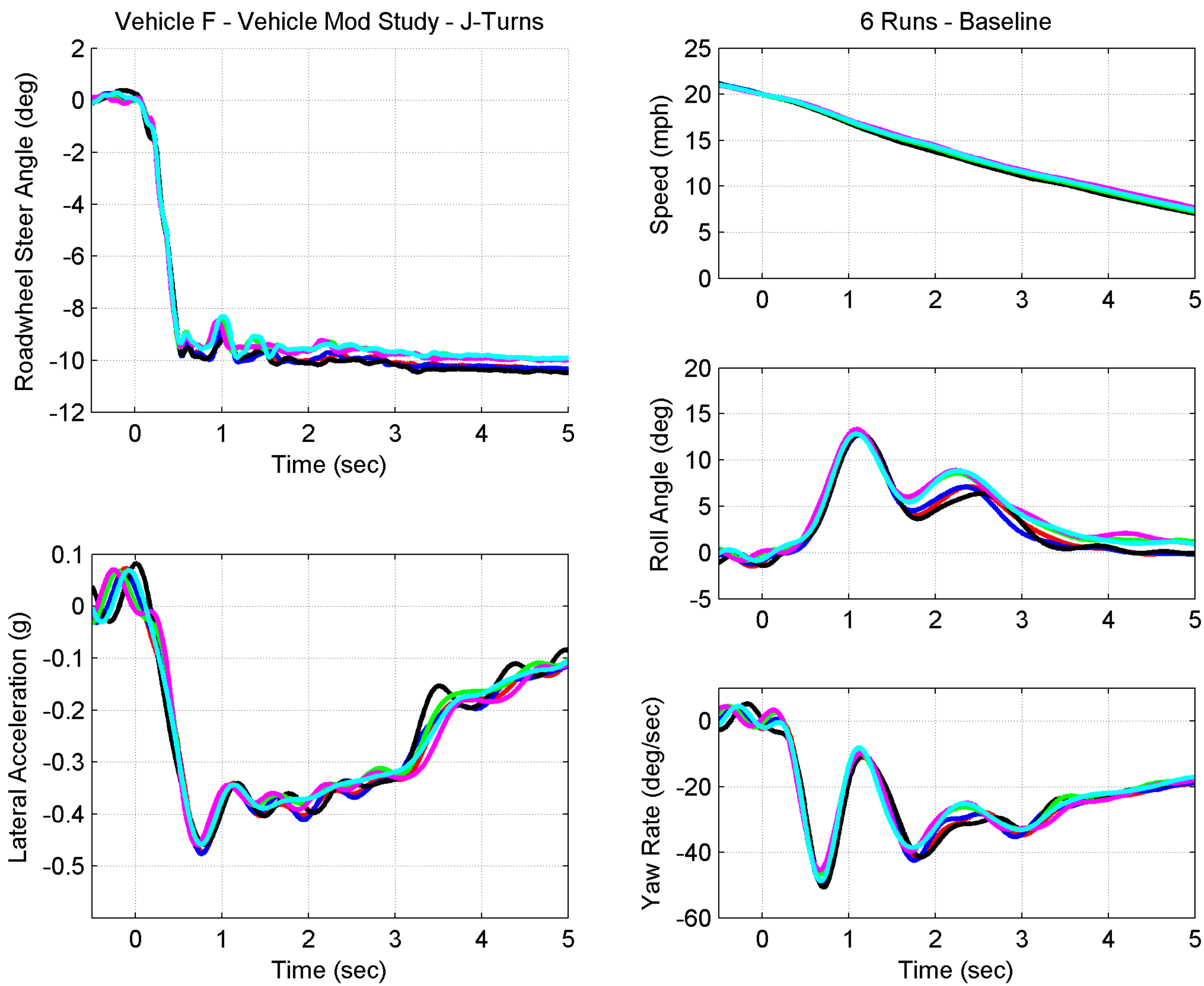
Mod 3: Driver Plus Instrumentation (DPI) Loading 0° Rider (Driver) Lean
Moved Driver-Lean-Ballast and Other Ballast Forward to Move Vehicle CG Forward (to Match CG Longitudinal Position Used for Tests With Human Driver)


Vehicle F - Vehicle Mod Study - 50 ft Radius Circle
Roadwheel Steer Angle (deg)
Baseline
Modification 1
Modification 2
Modification 3
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

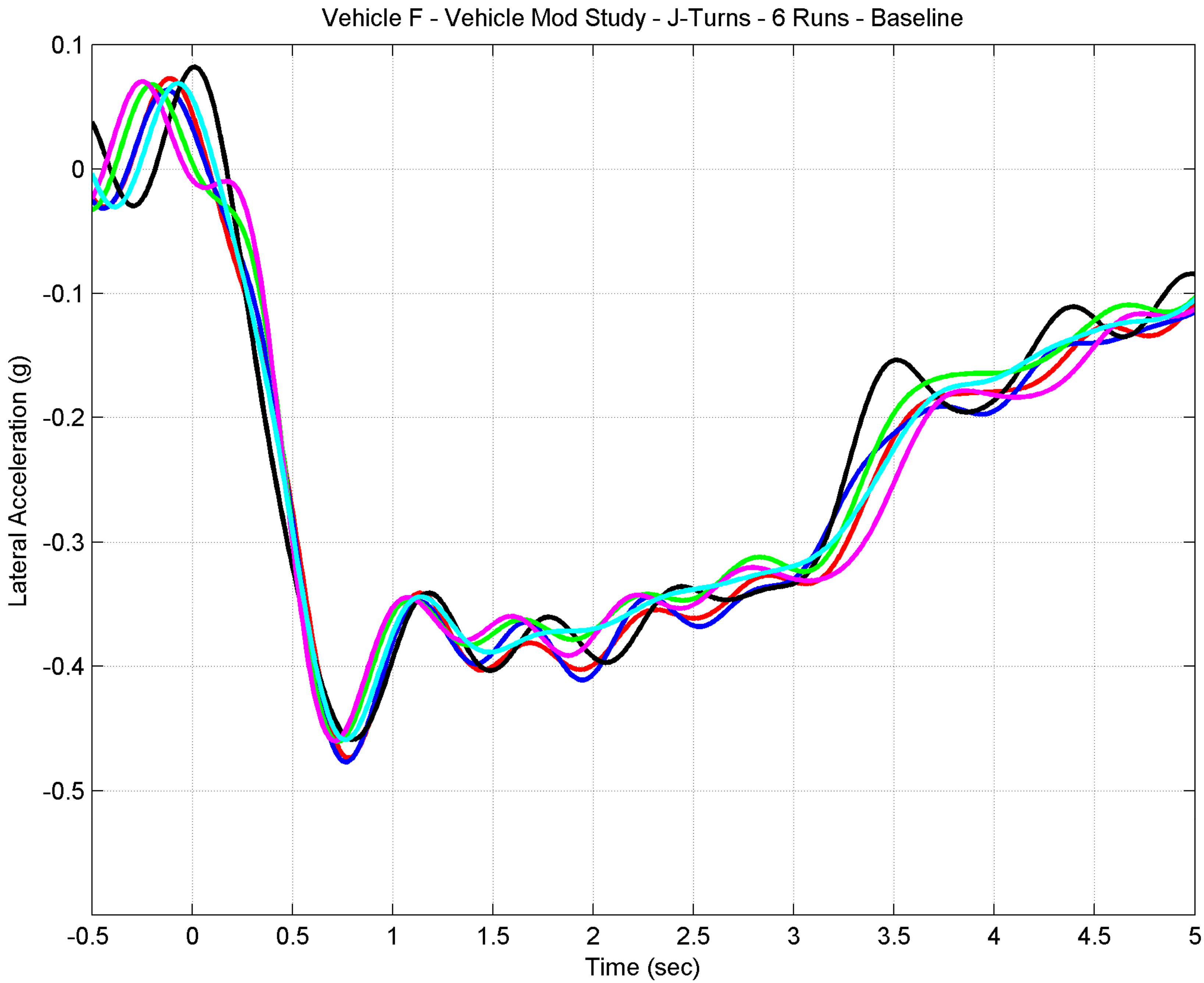

Vehicle F - Vehicle Mod Study - 50 ft Radius Circle
Baseline
Modification 1
Modification 2
Modification 3
Roadwheel Steer Angle (deg)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
Ay (g)

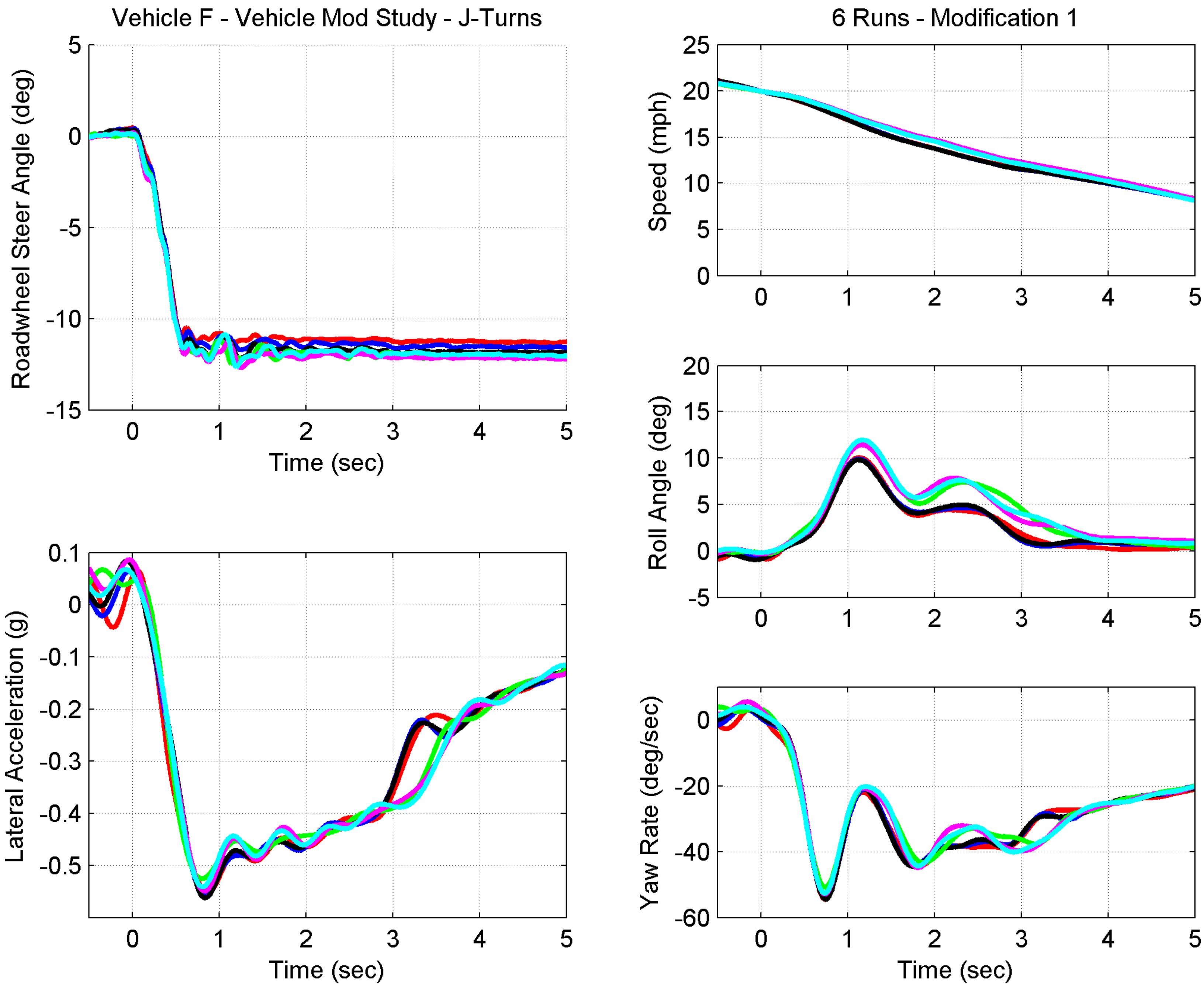

Vehicle F - Vehicle Mod Study - 50 ft Radius Circle
Baseline
Modification 1
Modification 2
Modification 3
Baseline Transition to OS at Ay = -0.13 g
Mod 1 Transition to OS at Ay = -0.212 g
Mod 2 Transition to OS at Ay = -0.179 g
Mod 3 Transition to OS at Ay = -0.166 g
(Roadwheel Steer Angle - Ackermann Angle) (deg)
Ay (g)
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1

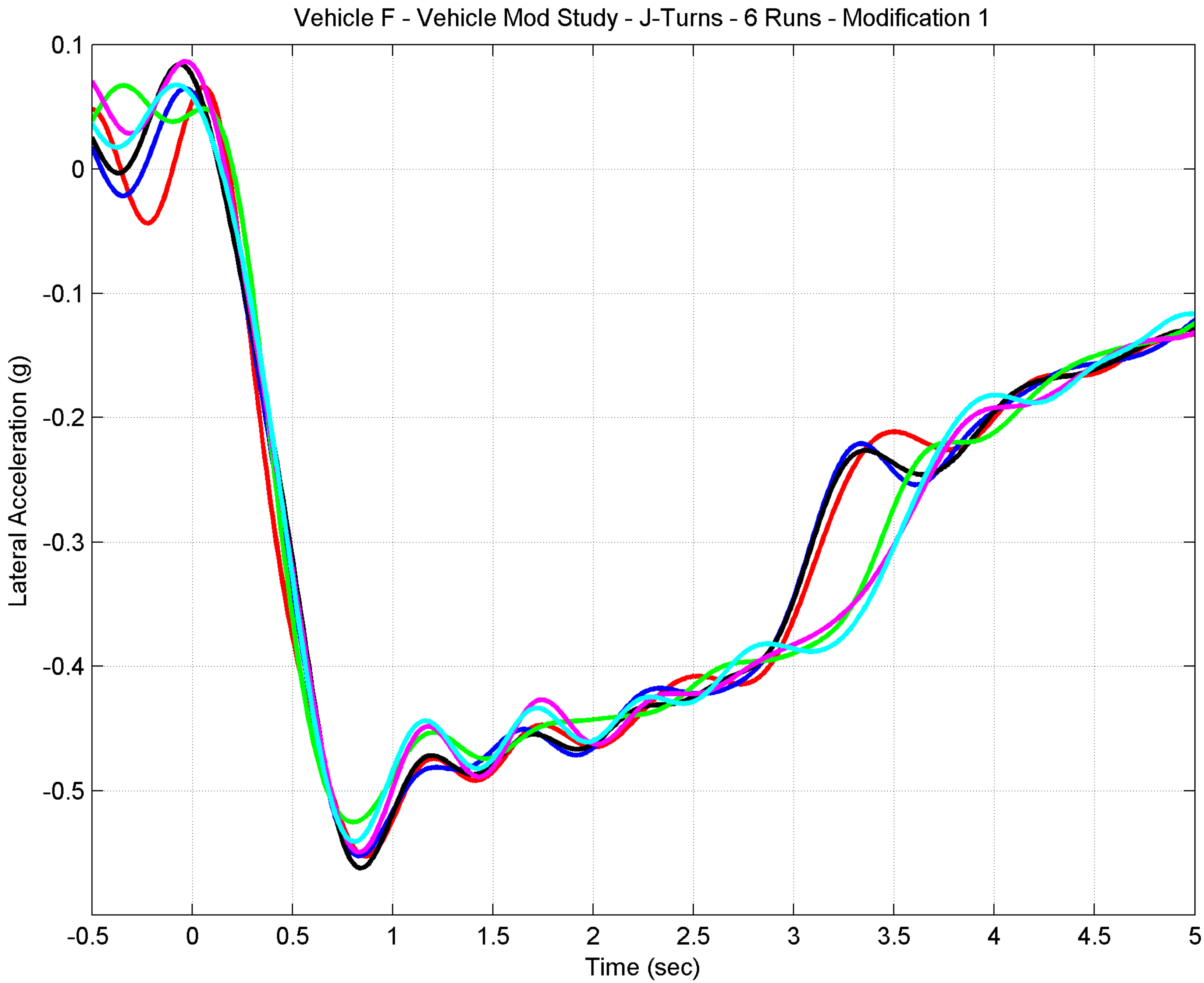

Vehicle F - Vehicle Mod Study - 50 ft Radius Circle
Baseline
Modification 1
Modification 2
Modification 3
Baseline Roll Gradient = -8.36 deg/g
Mod 1 Roll Gradient = -5.04 deg/g
Mod 2 Roll Gradient = -6.79 deg/g
Mod 3 Roll Gradient = -7.45 deg/g
Roll Angle (deg)
Ay (g)
6
5
4
3
2
1
0
-1
-2
-3
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1

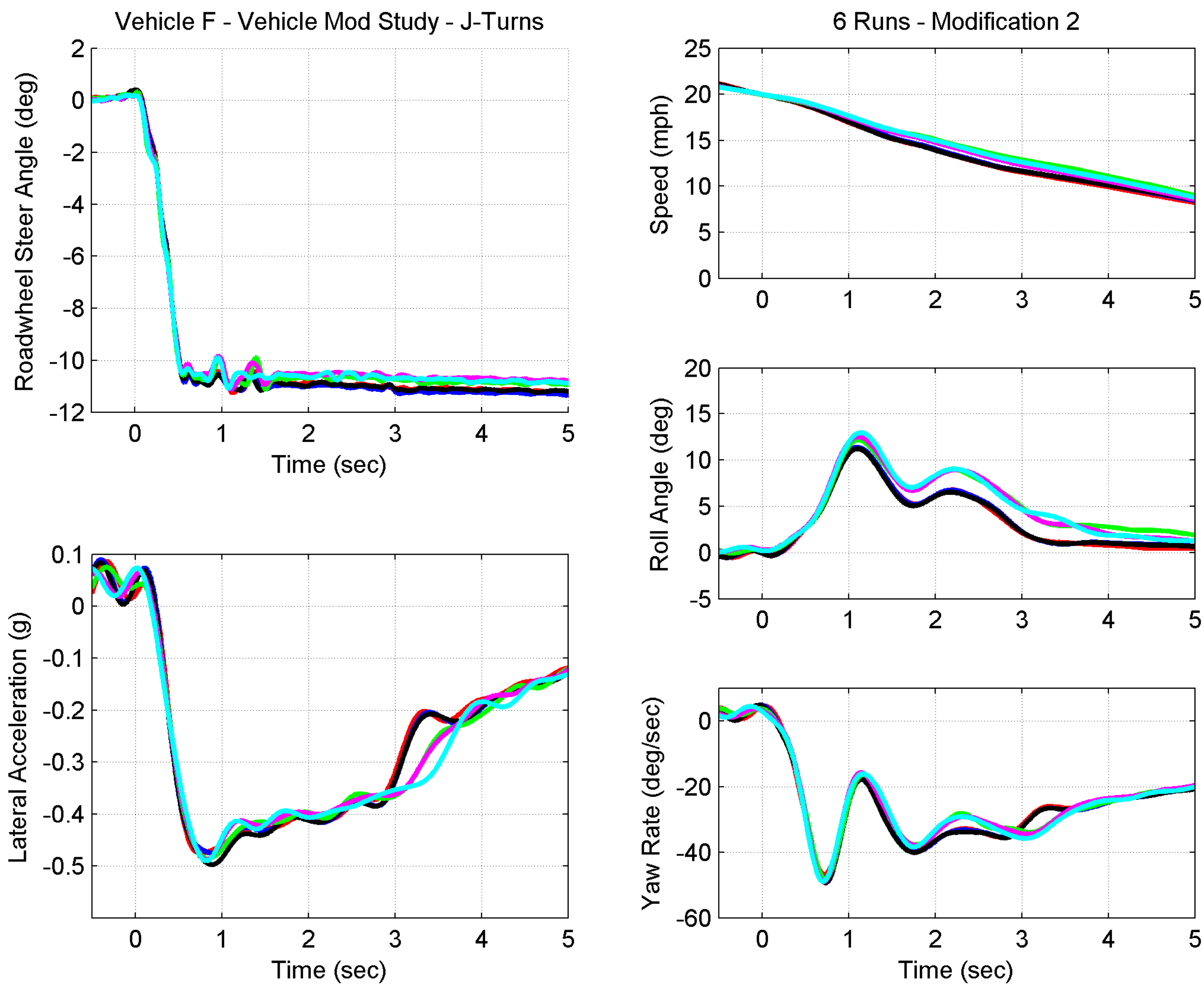


Vehicle F - Vehicle Mod Study - J-Turns
6 Runs - Baseline
Roadwheel Steer Angle (deg)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)
Time (sec)

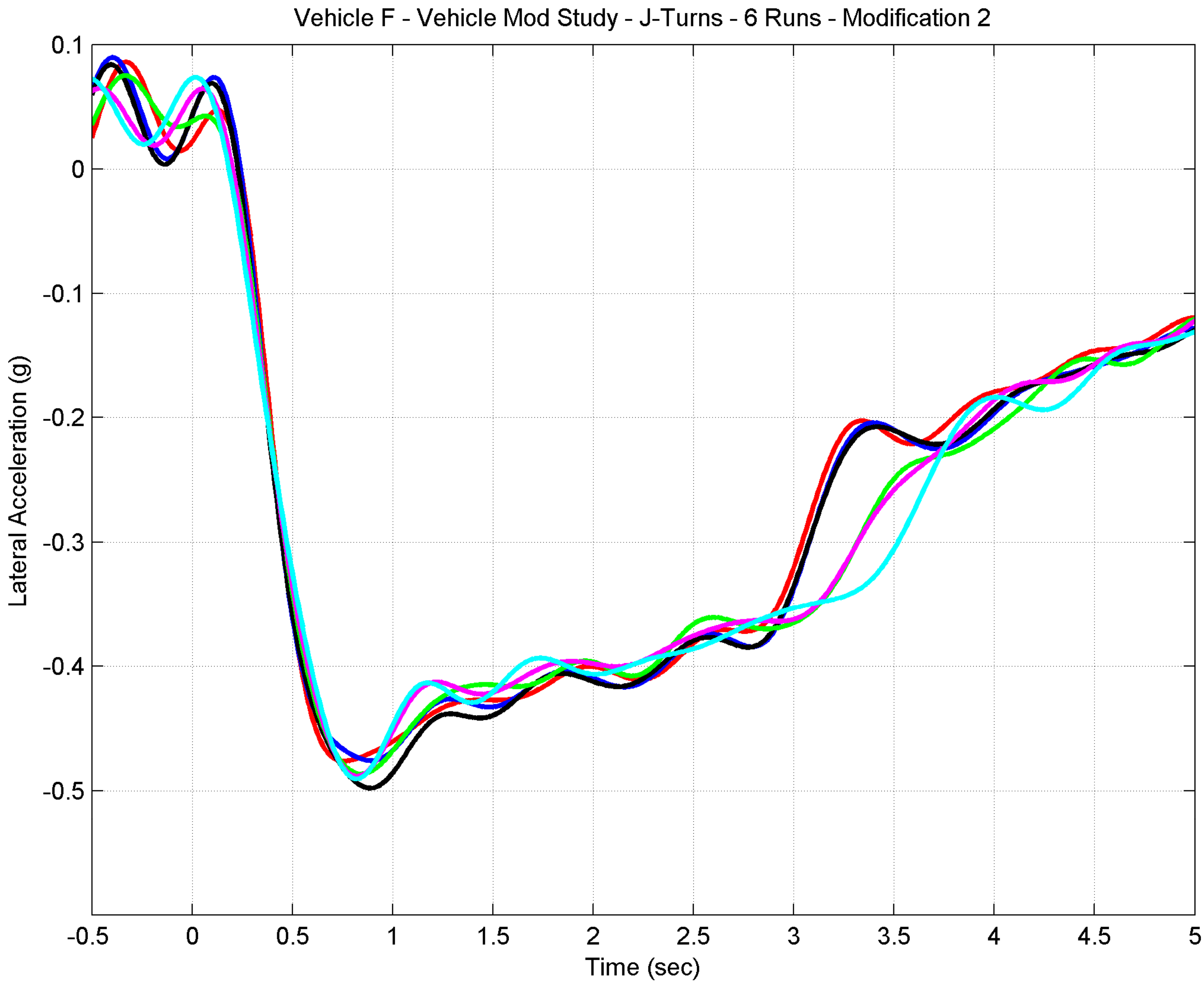

Vehicle F - Vehicle Mod Study - J-Turns - 6 Runs - Baseline
Lateral Acceleration (g)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
Time (sec)
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5


Vehicle F - Vehicle Mod Study - J-Turns
6 Runs - Modification 1
Roadwheel Steer Angle (deg)
Time (sec)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

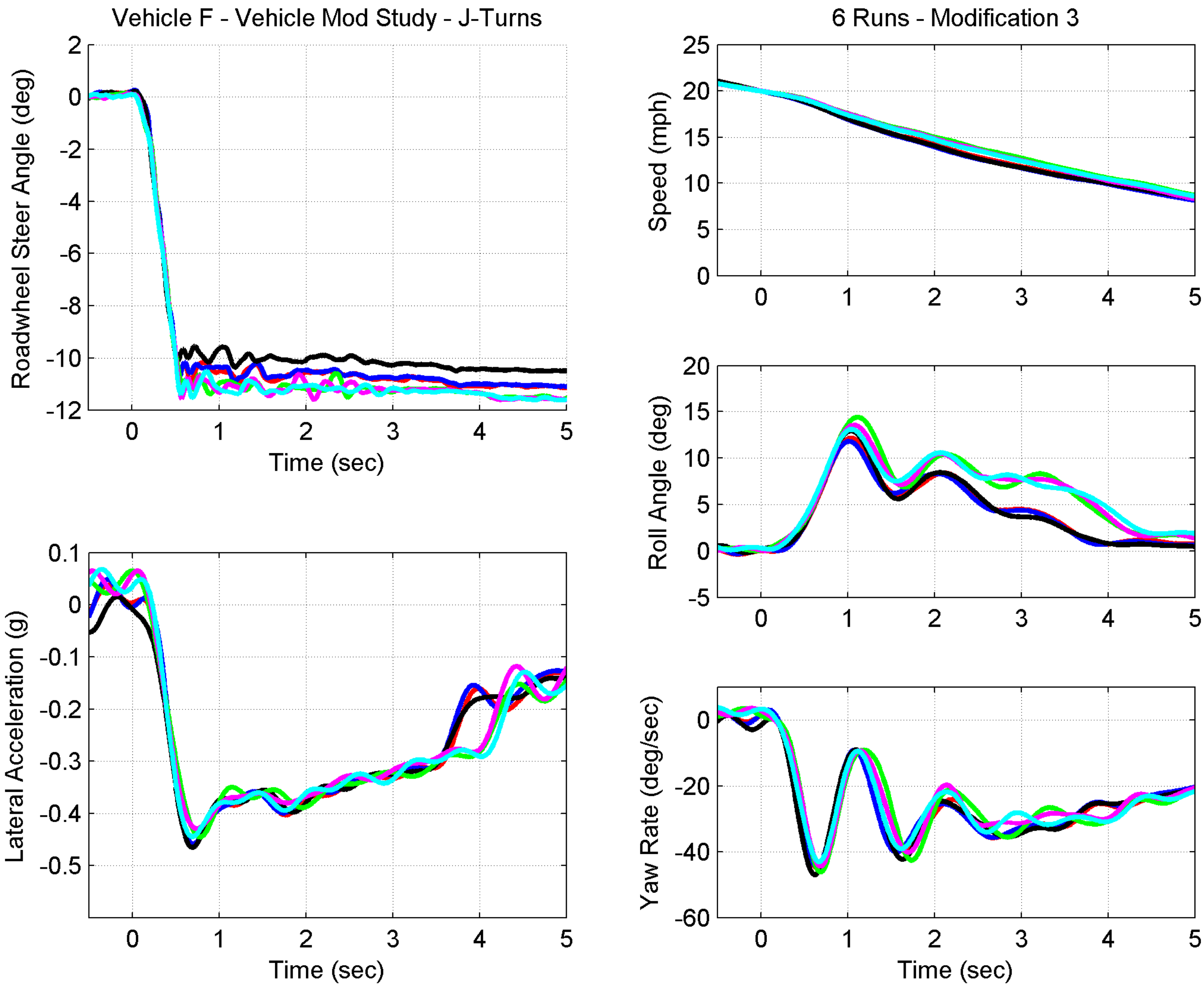

Vehicle F - Vehicle Mod Study - J-Turns - 6 Runs - Modification 1
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
Lateral Acceleration (g)
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (sec)

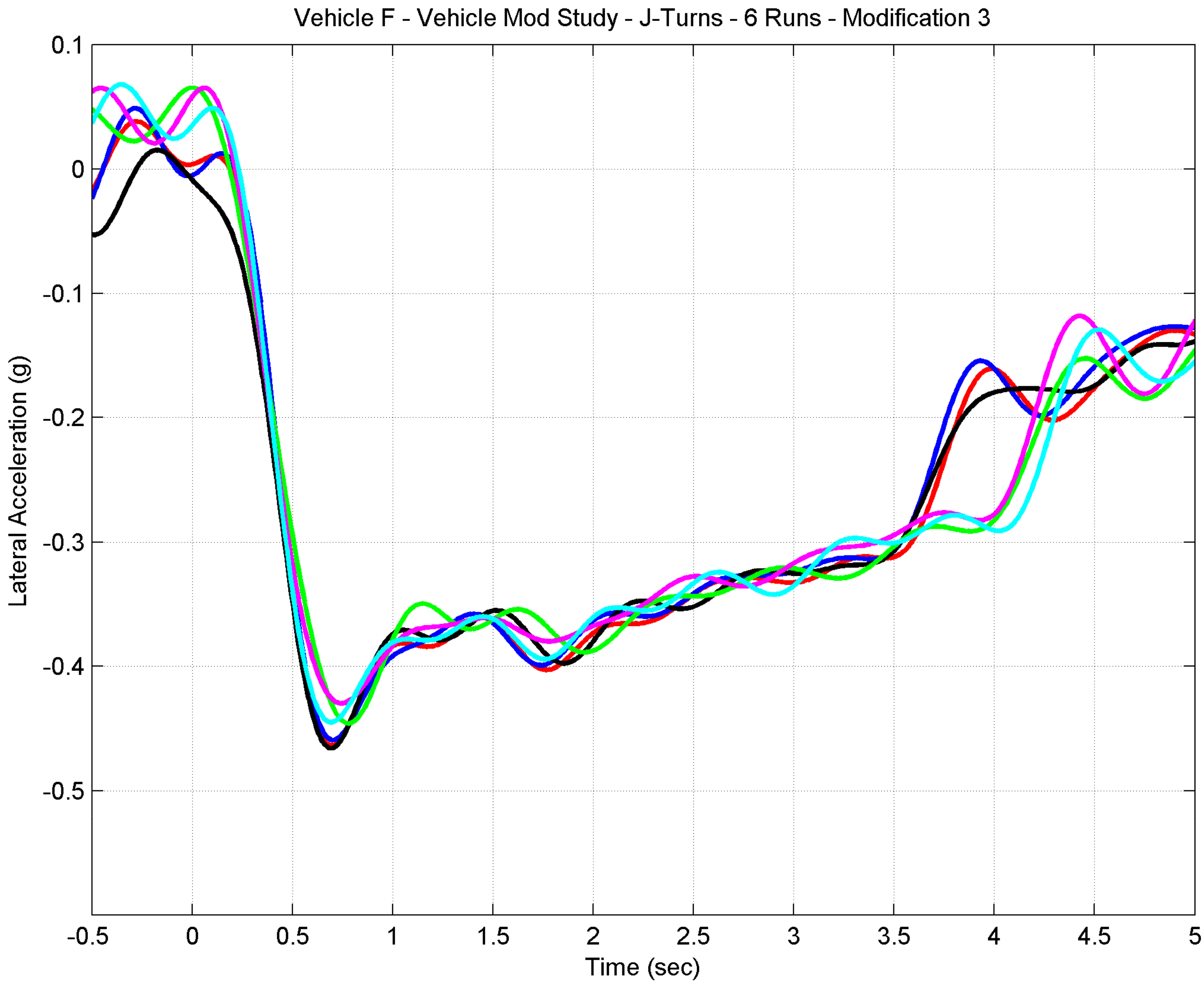


Vehicle F - Vehicle Mod Study - J-Turns
6 Runs - Modification 2
Roadwheel Steer Angle (deg)
Time (sec)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)



Vehicle F - Vehicle Mod Study - J-Turns - 6 Runs - Modification 2
Lateral Acceleration (g)
Time (sec)
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 F - Vehicle Mod Study - J-Turns
6 Runs - Modification 3
Roadwheel Steer Angle (deg)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)
Time (sec)



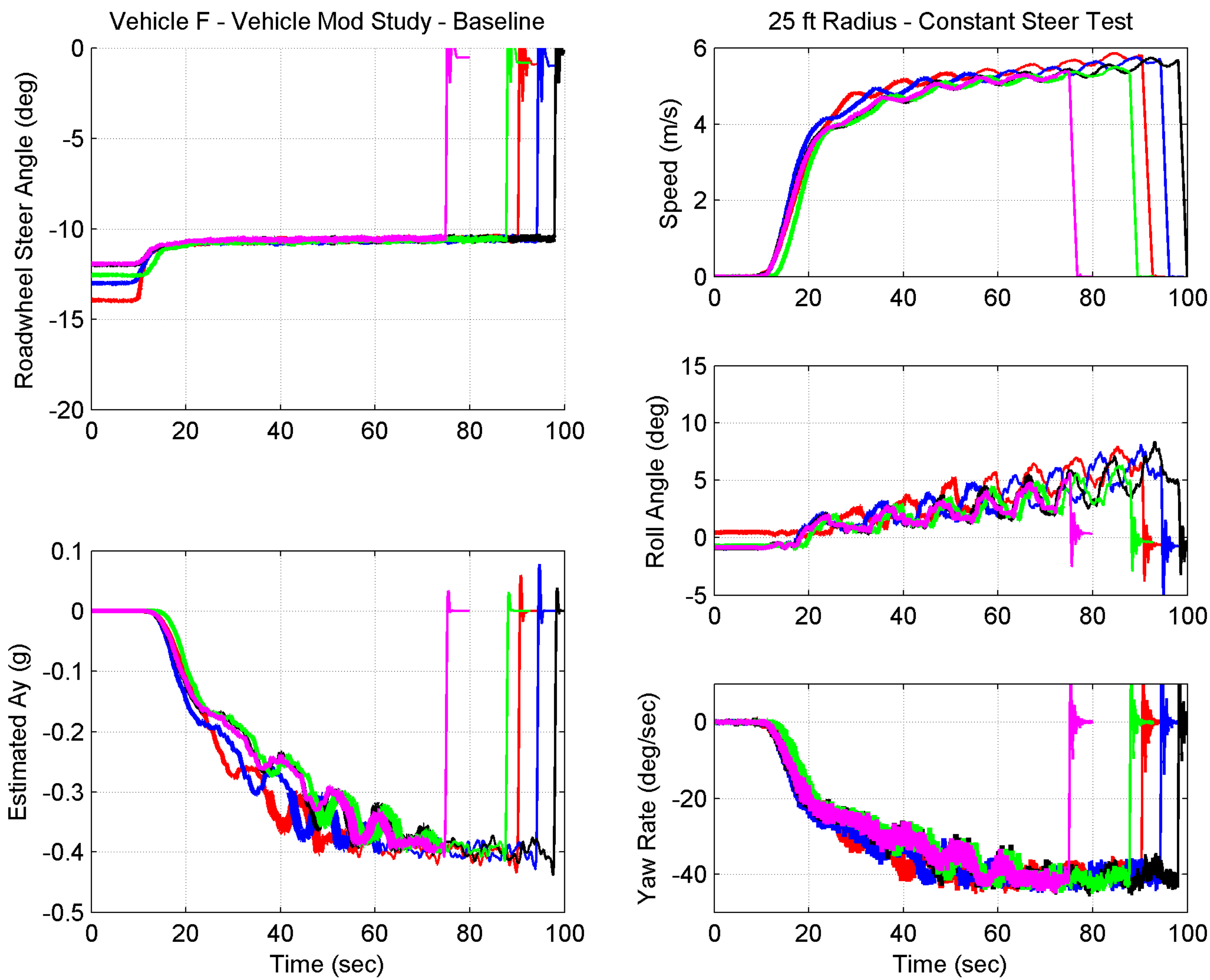
Vehicle F - Vehicle Mod Study - J-Turns - 6 Runs - Modification 3
Lateral Acceleration (g)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (sec)

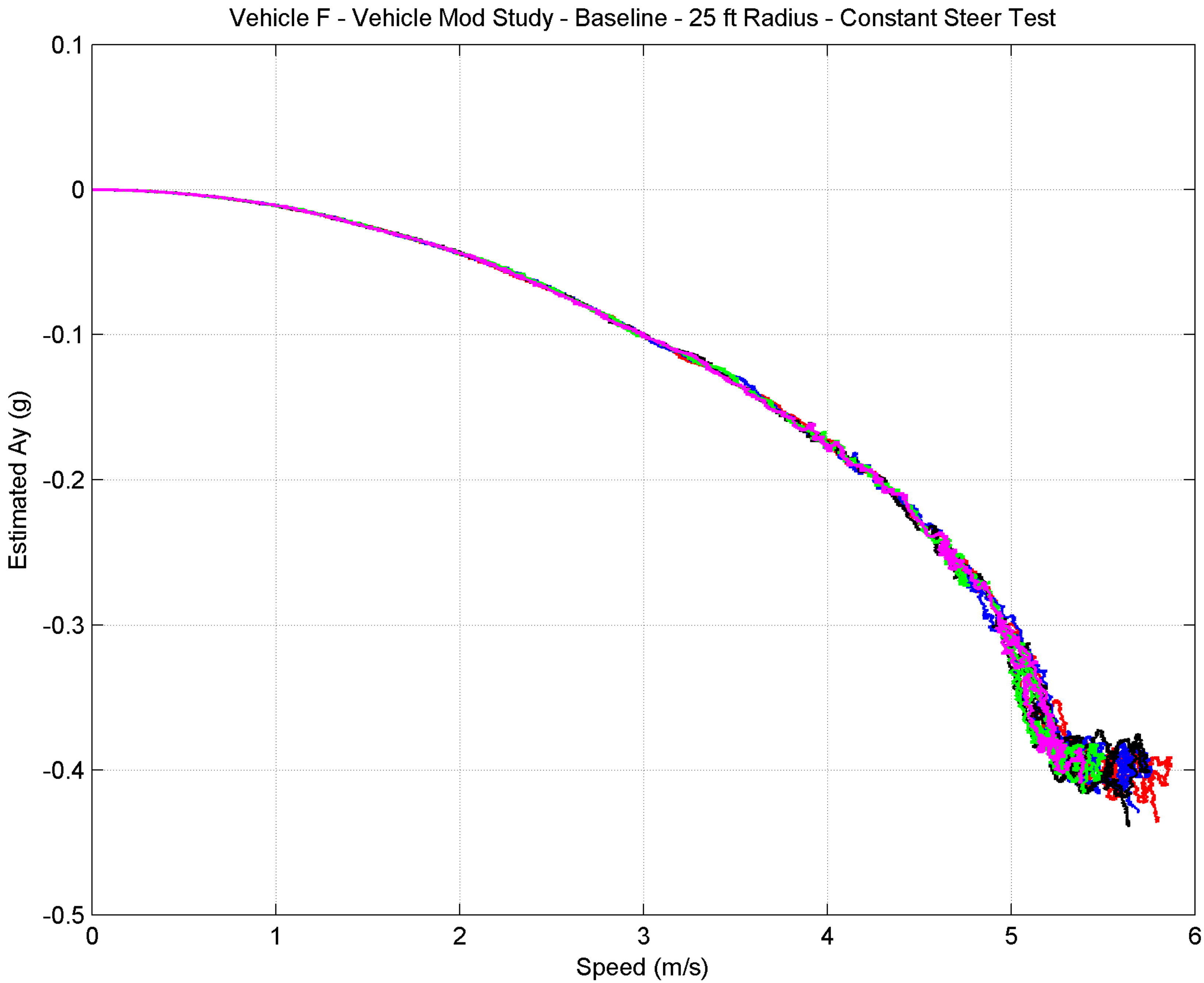
Vehicle F - Vehicle Modification Study

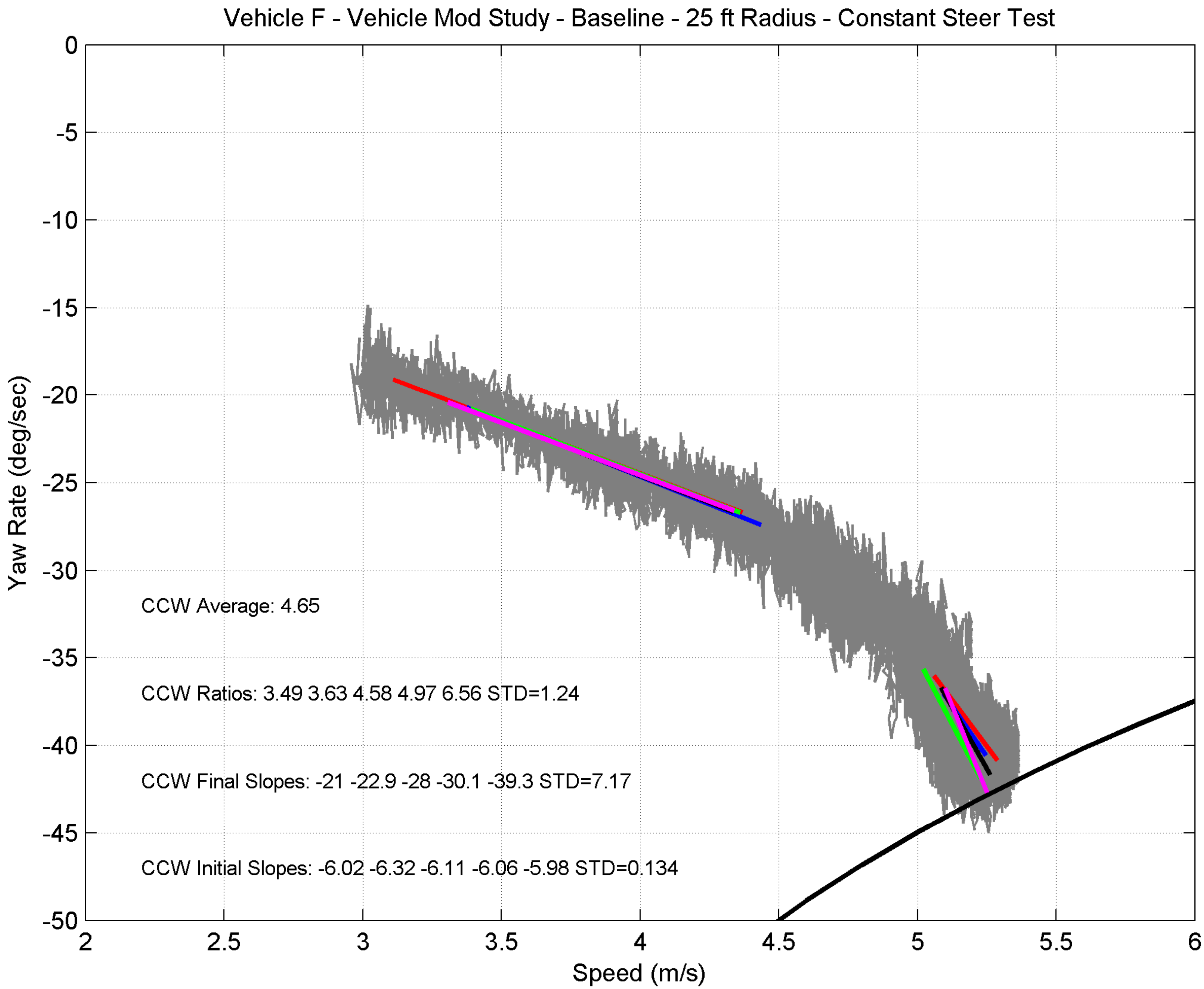
Peak Lateral Accelerations During 2WL J-Turns - All Values in "g's"

	Baseline	Mod 1	Mod 2	Mod 3
Northwest Runs	-0.473	-0.553	-0.476	-0.463
	-0.477	-0.553	-0.476	-0.459
	-0.459	-0.563	-0.498	-0.466
Mean Value of 3 Runs	-0.470	-0.556	-0.483	-0.463
Standard Deviation of 3 Runs	0.010	0.006	0.013	0.003

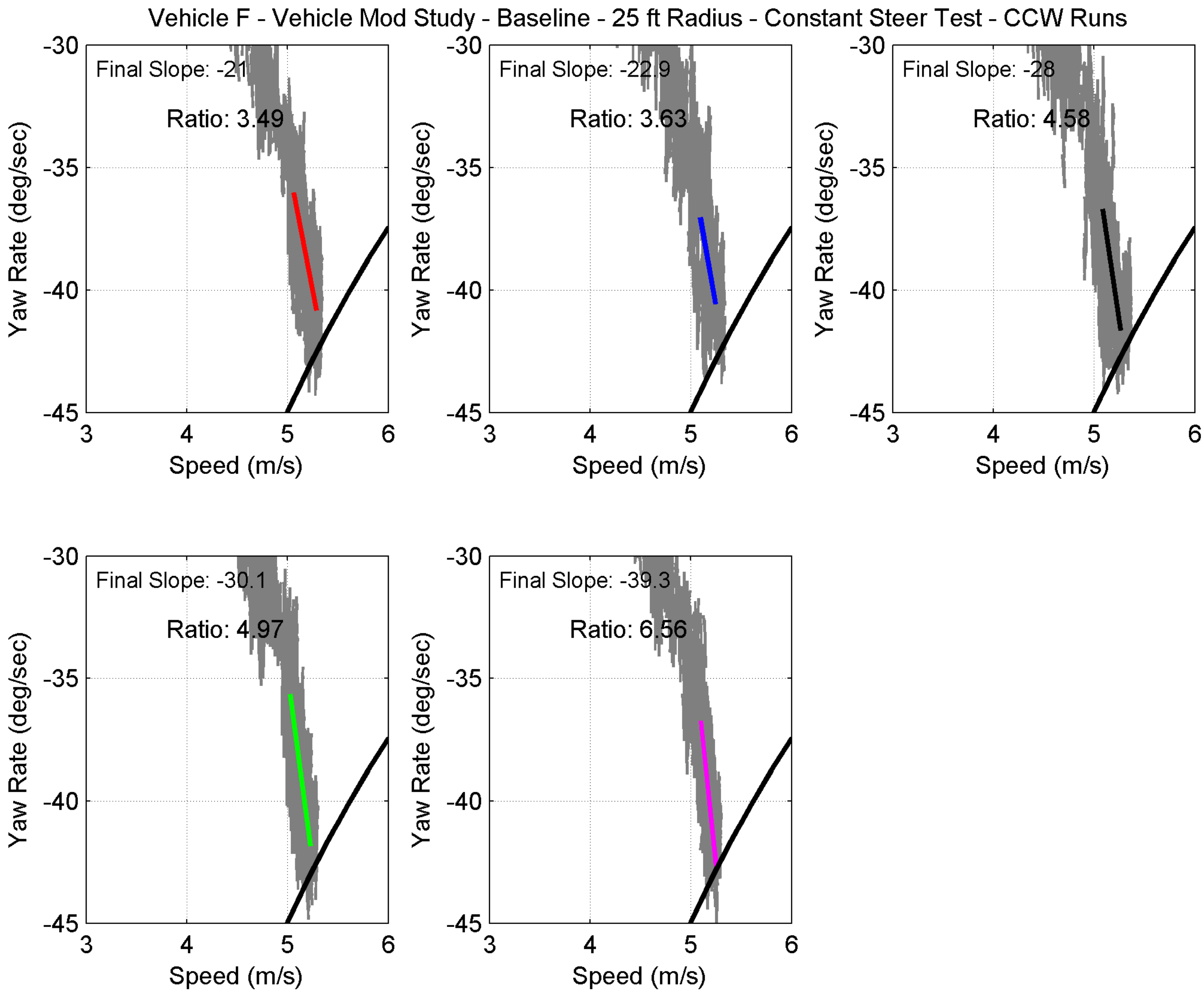
	Baseline	Mod 1	Mod 2	Mod 3
Southeast Runs	-0.460	-0.525	-0.486	-0.446
	-0.460	-0.550	-0.488	-0.430
	-0.459	-0.541	-0.490	-0.445
Mean Value of 3 Runs	-0.460	-0.539	-0.488	-0.440
Standard Deviation of 3 Runs	0.001	0.012	0.002	0.009
Average of All 6 Runs	**0.465**	**0.547**	**0.486**	**0.452**


Vehicle F - Vehicle Mod Study - Baseline
25 ft Radius - Constant Steer Test
Roadwheel Steer Angle (deg)
Speed (m/s)
Roll Angle (deg)
Estimated Ay (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)


Vehicle F - Vehicle Mod Study - Baseline - 25 ft Radius - Constant Steer Test
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
Estimated Ay (g)
0
1
2
3
4
5
6
Speed (m/s)

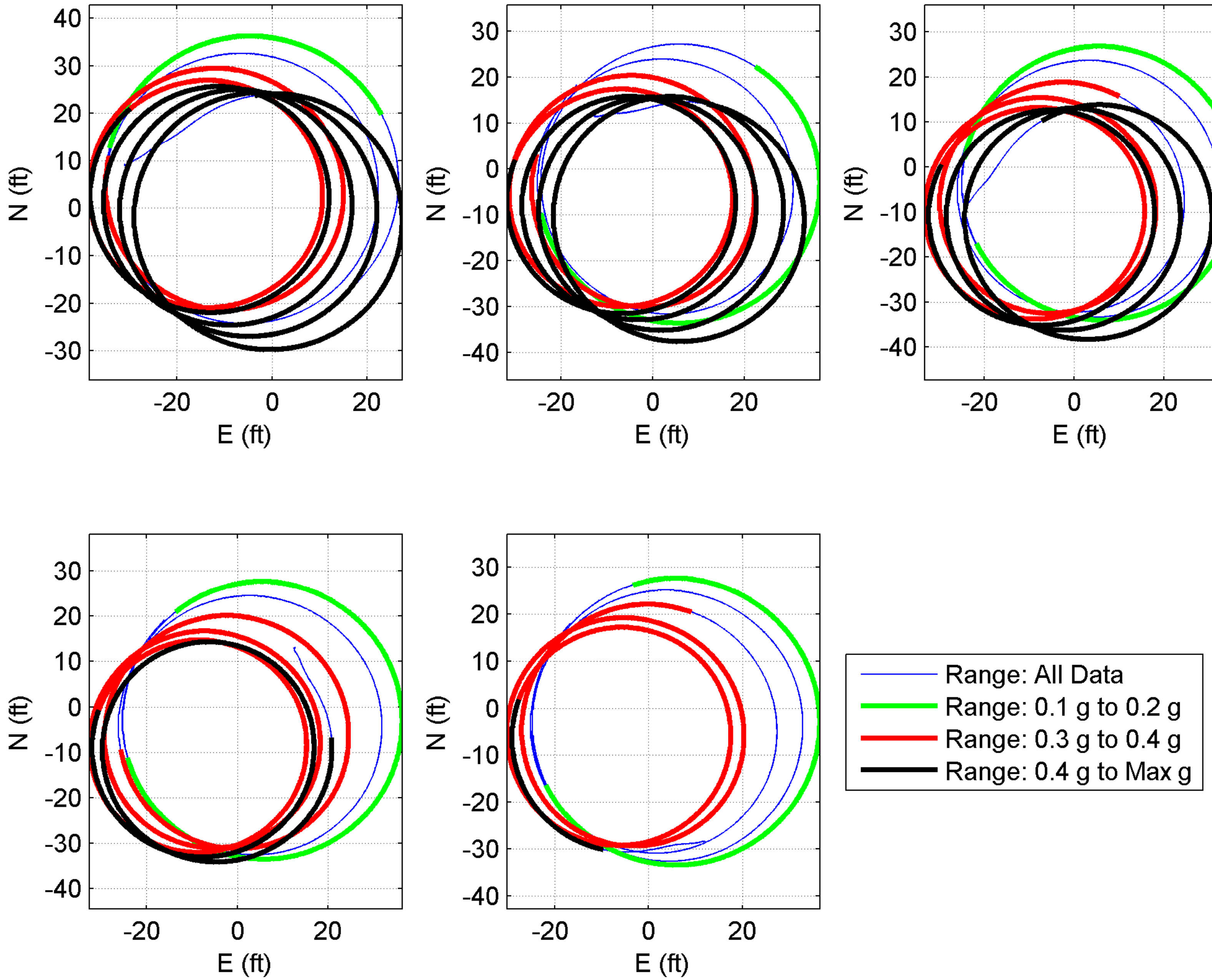


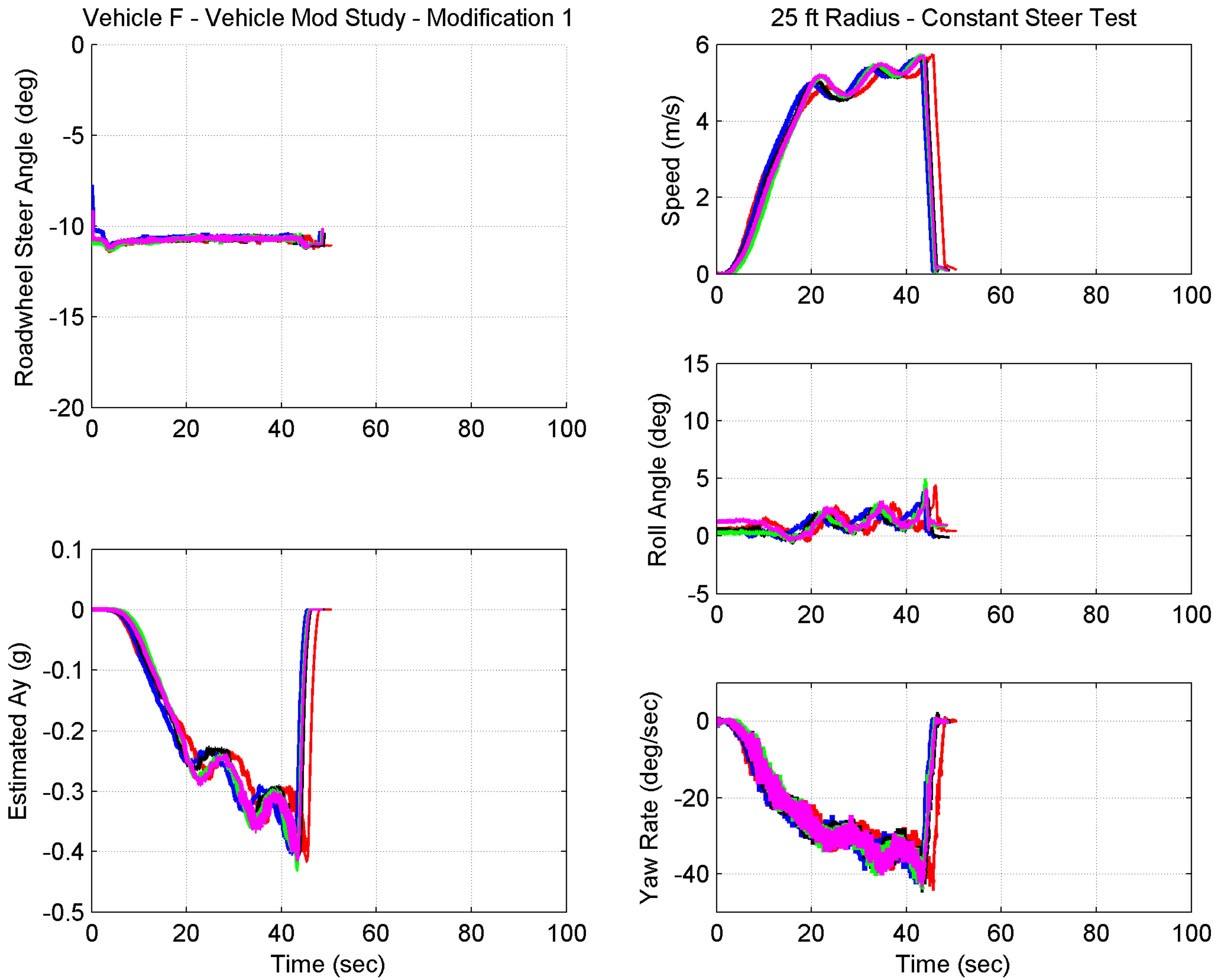
Vehicle F - Vehicle Mod Study - Baseline - 25 ft Radius - Constant Steer Test
Yaw Rate (deg/sec)
Speed (m/s)
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
2
2.5
3
3.5
4
4.5
5
5.5
6
CCW Average: 4.65
CCW Ratios: 3.49 3.63 4.58 4.97 6.56 STD=1.24
CCW Final Slopes: -21 -22.9 -28 -30.1 -39.3 STD=7.17
CCW Initial Slopes: -6.02 -6.32 -6.11 -6.06 -5.98 STD=0.134



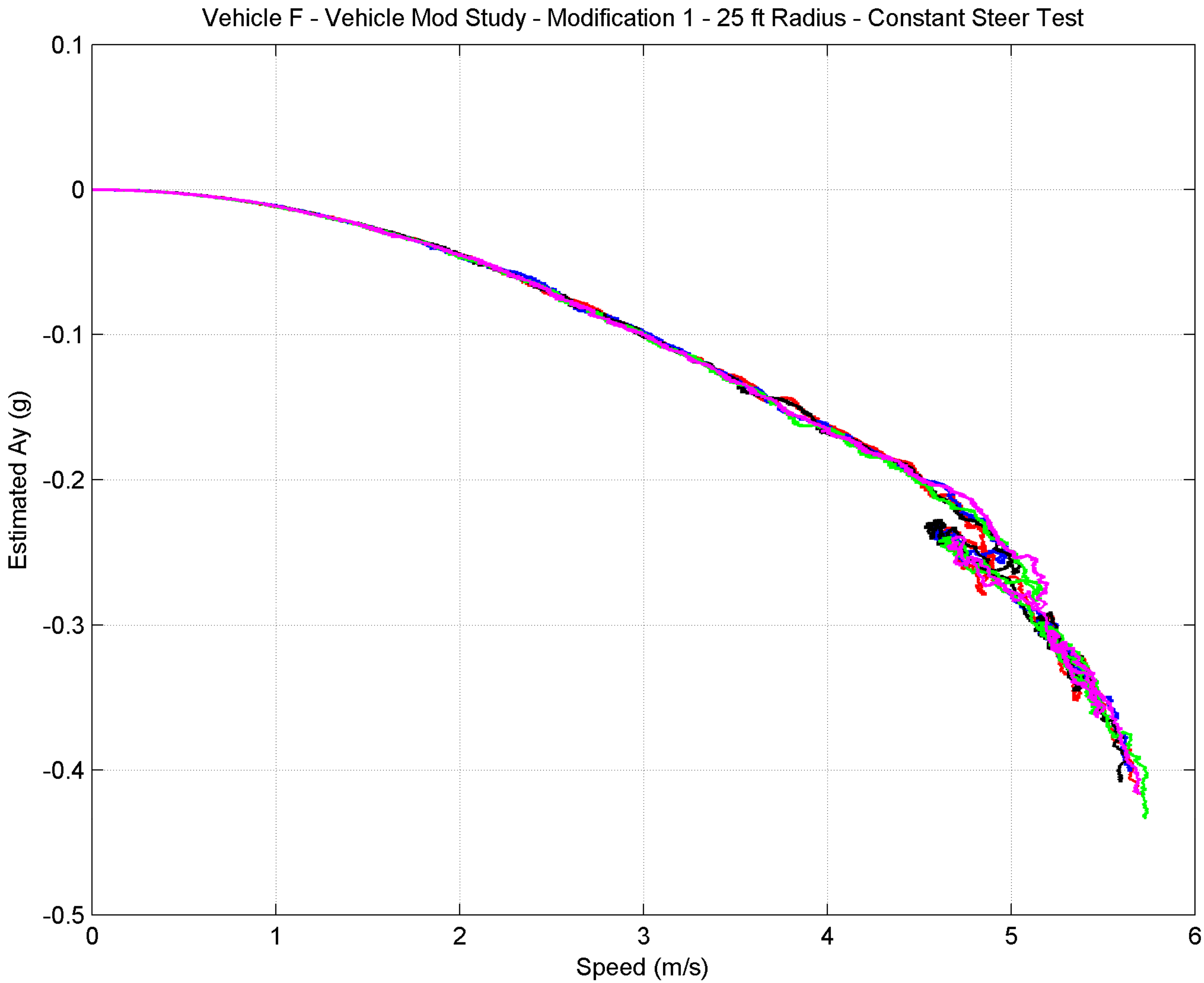
Vehicle F - Vehicle Mod Study - Baseline - 25 ft Radius - Constant Steer Test - CCW Runs
Final Slope: -21
Ratio: 3.49
Final Slope: -22.9
Ratio: 3.63
Final Slope: -28
Ratio: 4.58
Final Slope: -30.1
Ratio: 4.97
Final Slope: -39.3
Ratio: 6.56
Yaw Rate (deg/sec)
Speed (m/s)

Vehicle F - Vehicle Mod Study - Baseline - 25 ft Radius - Constant Steer Test - CCW Runs

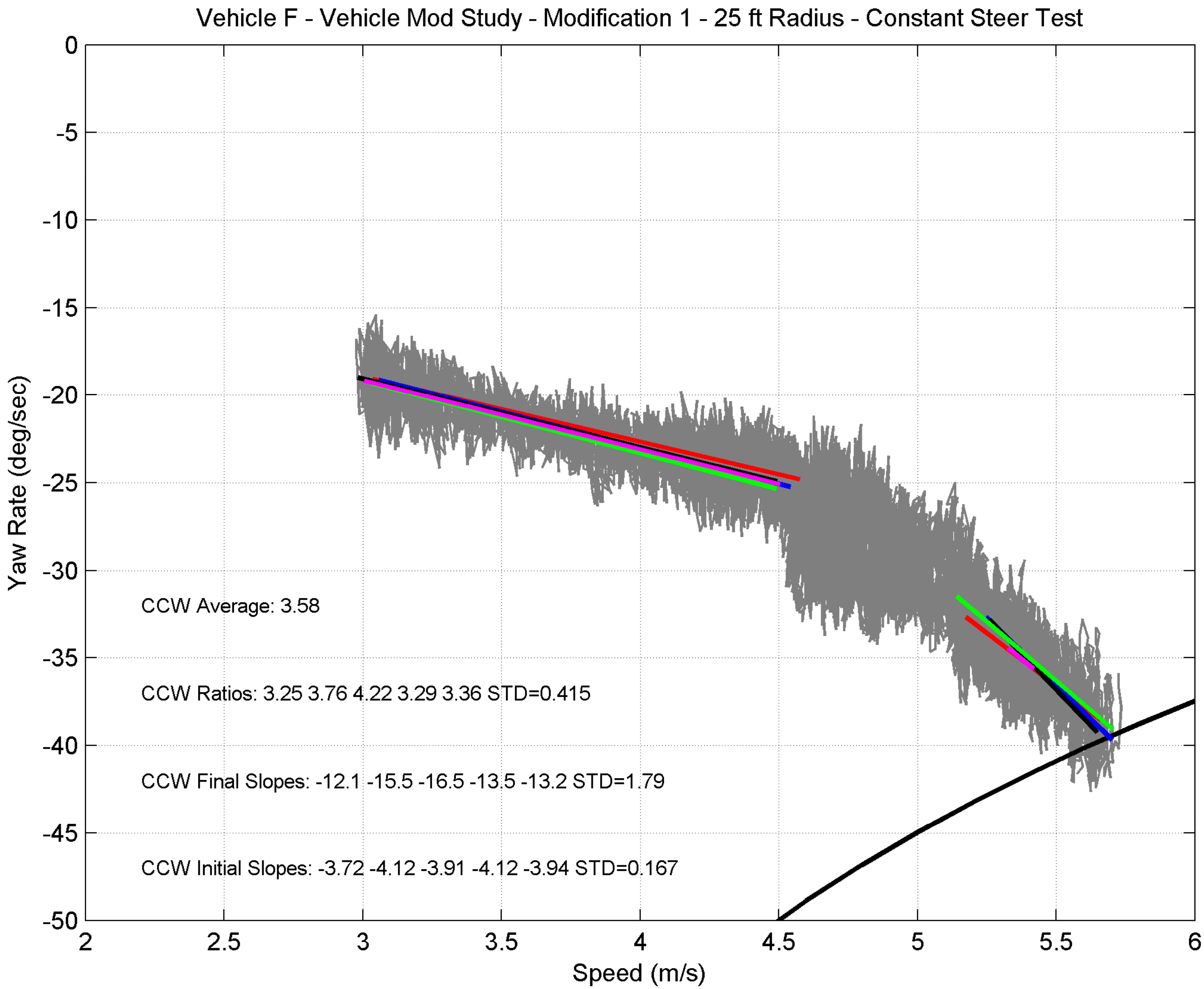


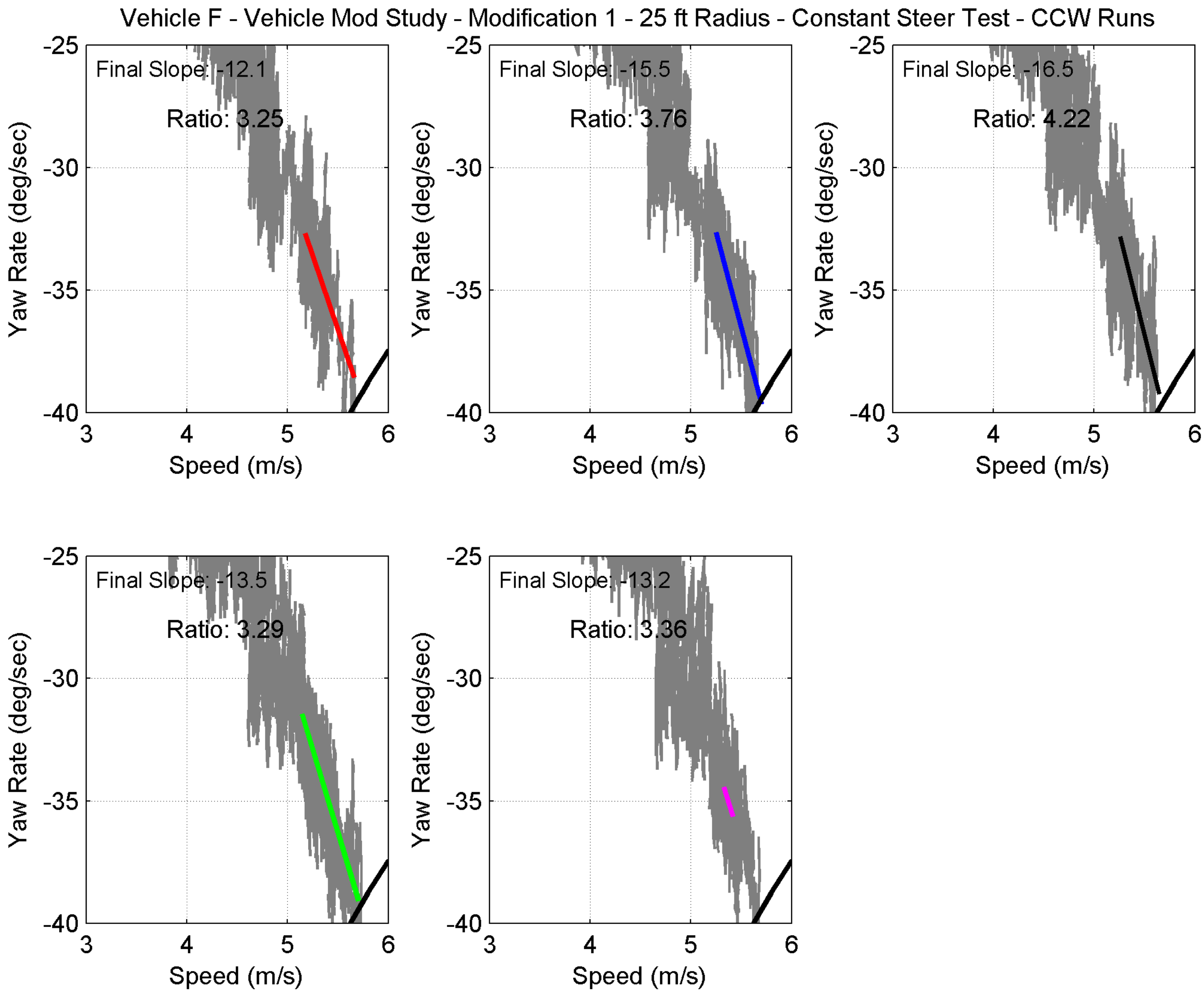


Vehicle F - Vehicle Mod Study - Modification 1
25 ft Radius - Constant Steer Test
Roadwheel Steer Angle (deg)
Speed (m/s)
Roll Angle (deg)
Estimated Ay (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)



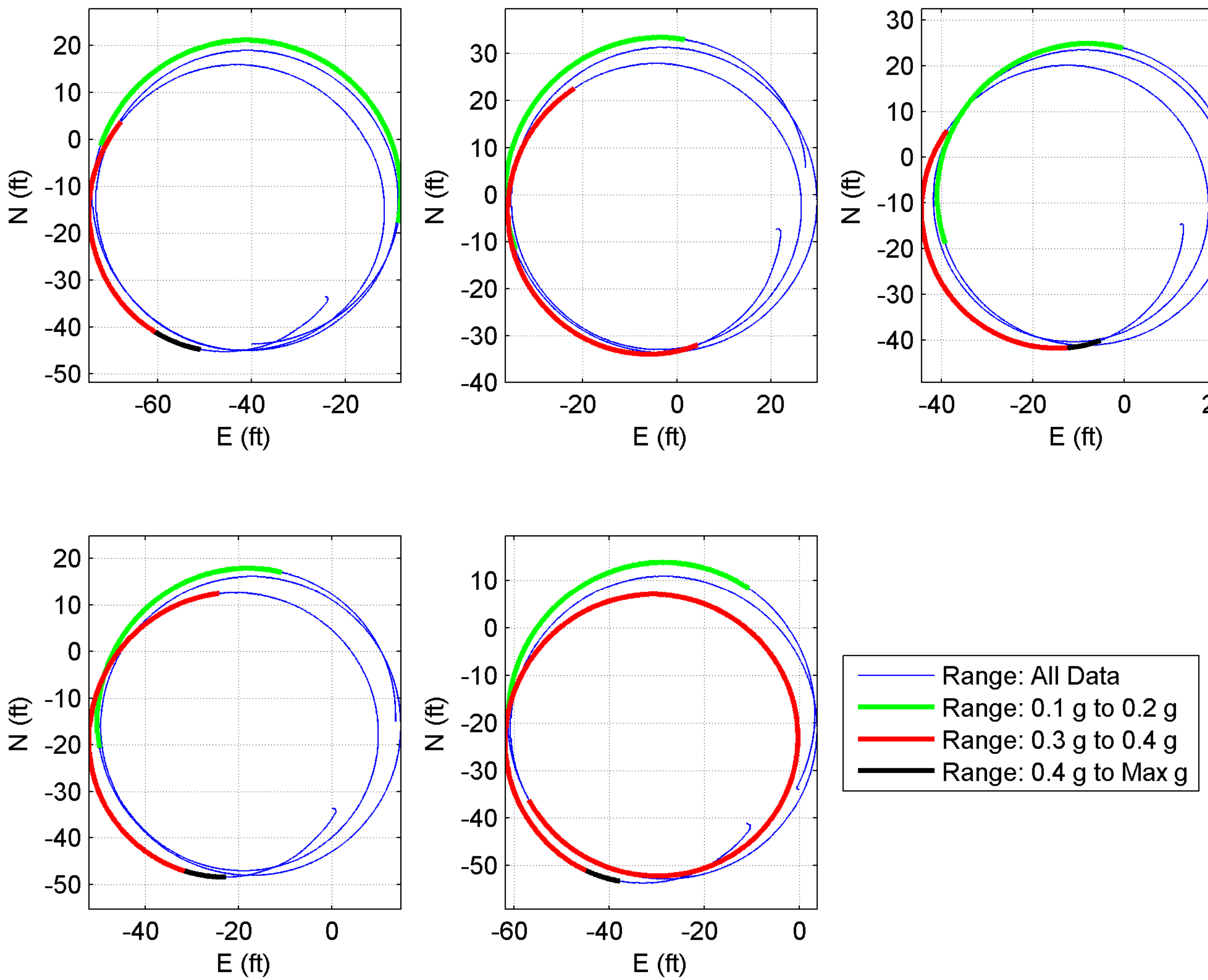
Vehicle F - Vehicle Mod Study - Modification 1 - 25 ft Radius - Constant Steer Test
Estimated Ay (g)
Speed (m/s)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
1
2
3
4
5
6

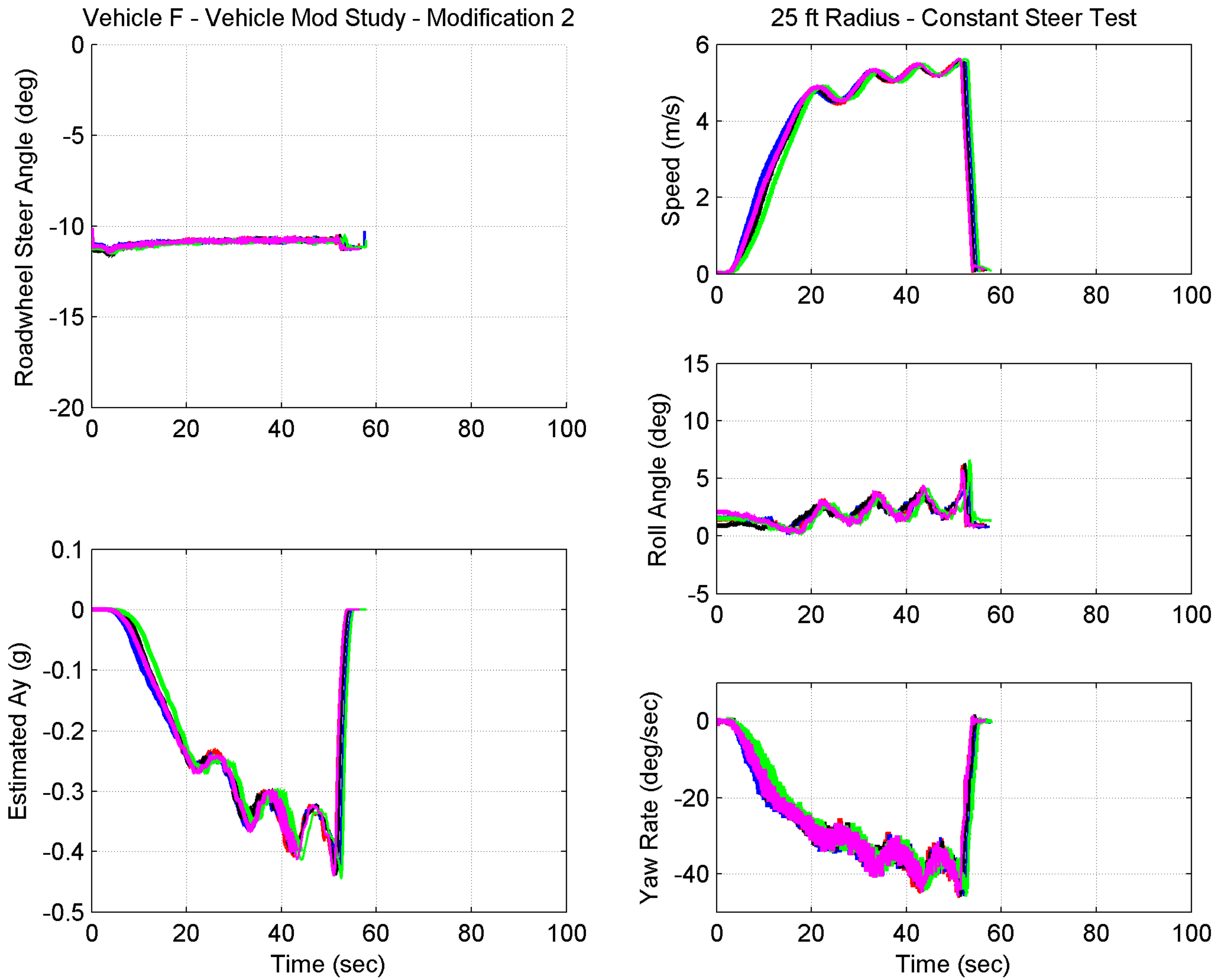

Vehicle F - Vehicle Mod Study - Modification 1 - 25 ft Radius - Constant Steer Test
Yaw Rate (deg/sec)
Speed (m/s)
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
2
2.5
3
3.5
4
4.5
5
5.5
6
CCW Average: 3.58
CCW Ratios: 3.25 3.76 4.22 3.29 3.36 STD=0.415
CCW Final Slopes: -12.1 -15.5 -16.5 -13.5 -13.2 STD=1.79
CCW Initial Slopes: -3.72 -4.12 -3.91 -4.12 -3.94 STD=0.167



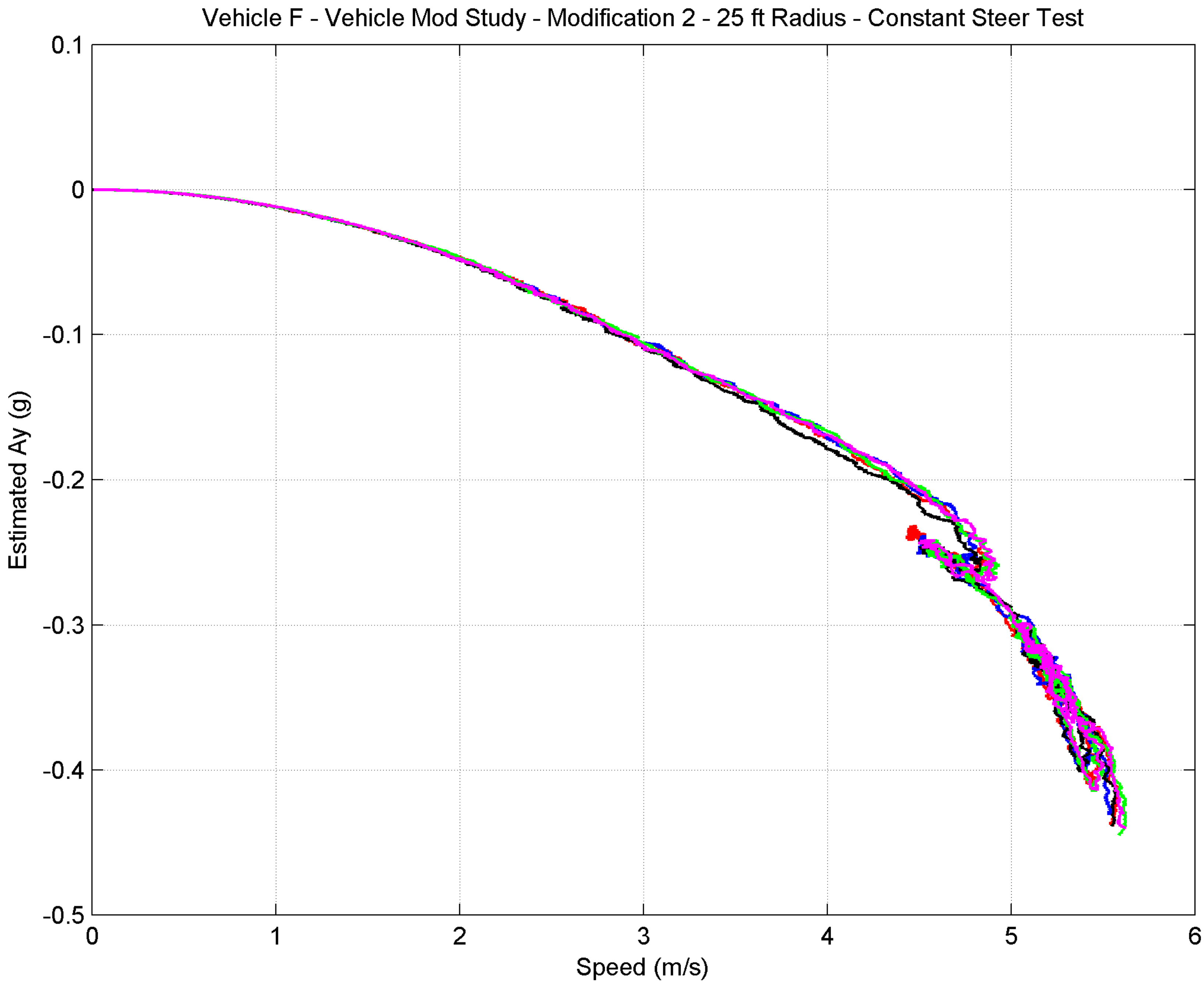
Vehicle F - Vehicle Mod Study - Modification 1 - 25 ft Radius - Constant Steer Test - CCW Runs
Final Slope: -12.1
Ratio: 3.25
Final Slope: -15.5
Ratio: 3.76
Final Slope: -16.5
Ratio: 4.22
Final Slope: -13.5
Ratio: 3.29
Final Slope: -13.2
Ratio: 3.36
Yaw Rate (deg/sec)
Speed (m/s)
-25
-30
-35
-40
3
4
5
6

Vehicle F - Vehicle Mod Study - Modification 1 - 25 ft Radius - Constant Steer Test - CCW Runs

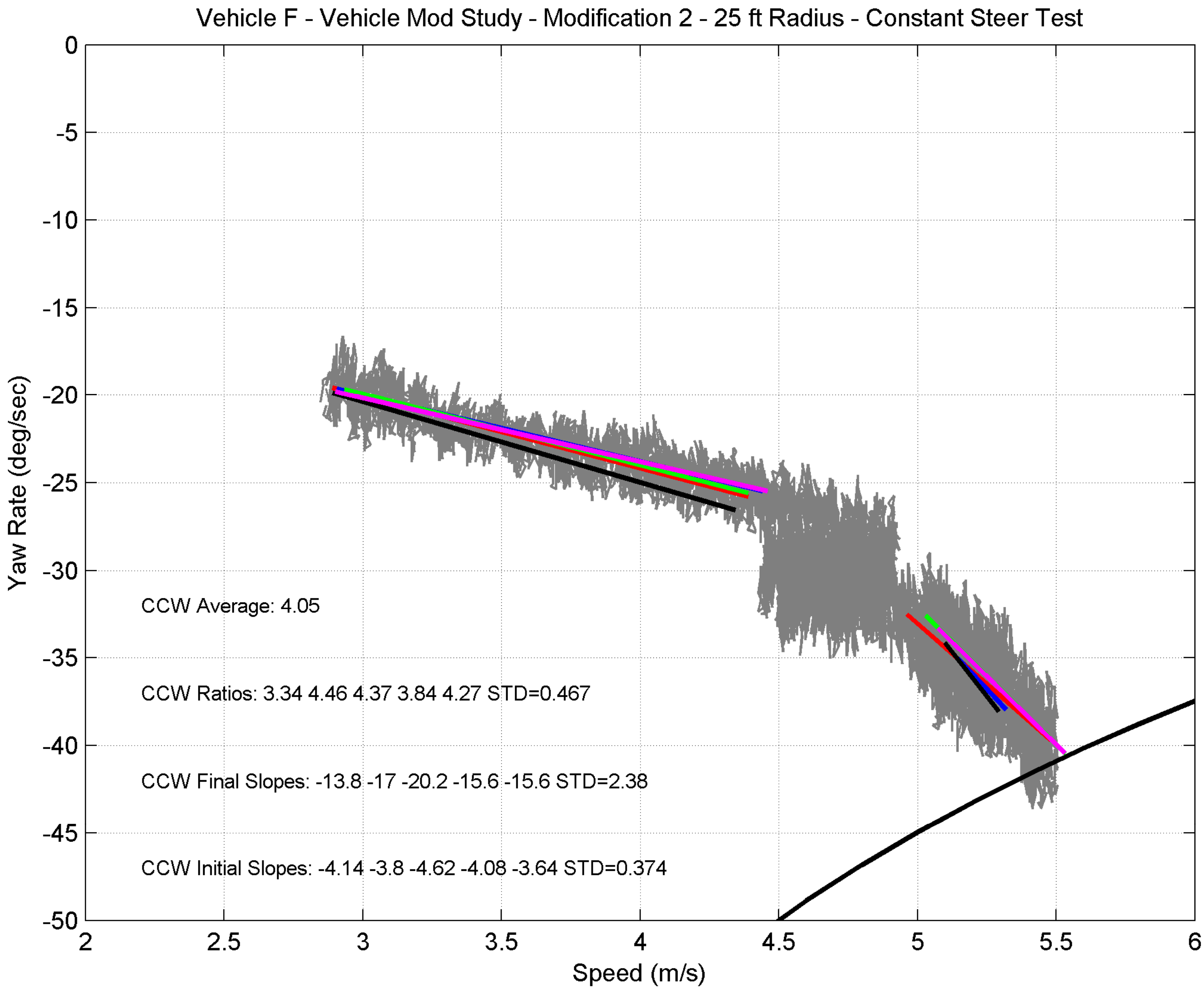




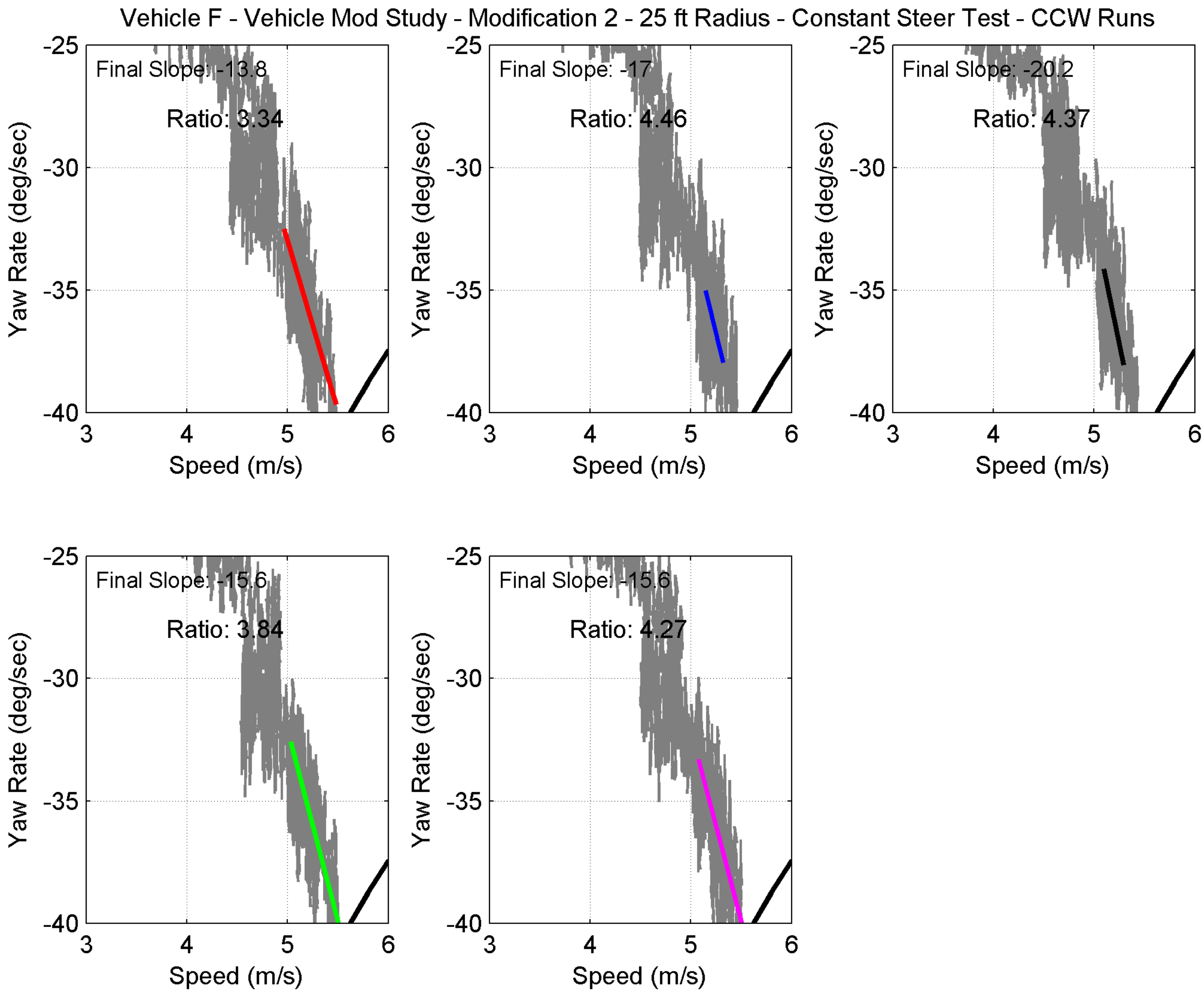
Vehicle F - Vehicle Mod Study - Modification 2
25 ft Radius - Constant Steer Test
Roadwheel Steer Angle (deg)
Speed (m/s)
Roll Angle (deg)
Estimated Ay (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)



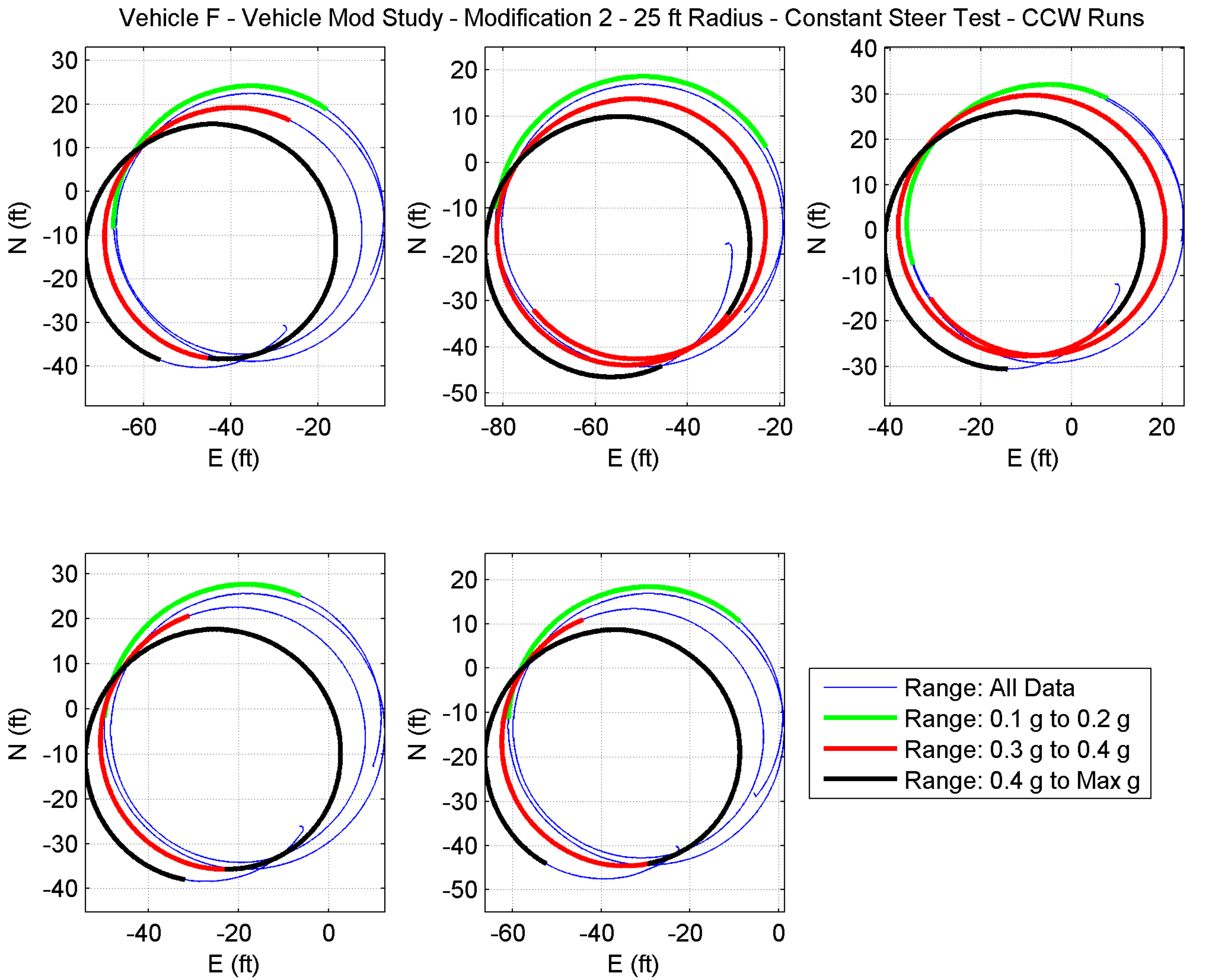
Vehicle F - Vehicle Mod Study - Modification 2 - 25 ft Radius - Constant Steer Test
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
Estimated Ay (g)
0
1
2
3
4
5
6
Speed (m/s)

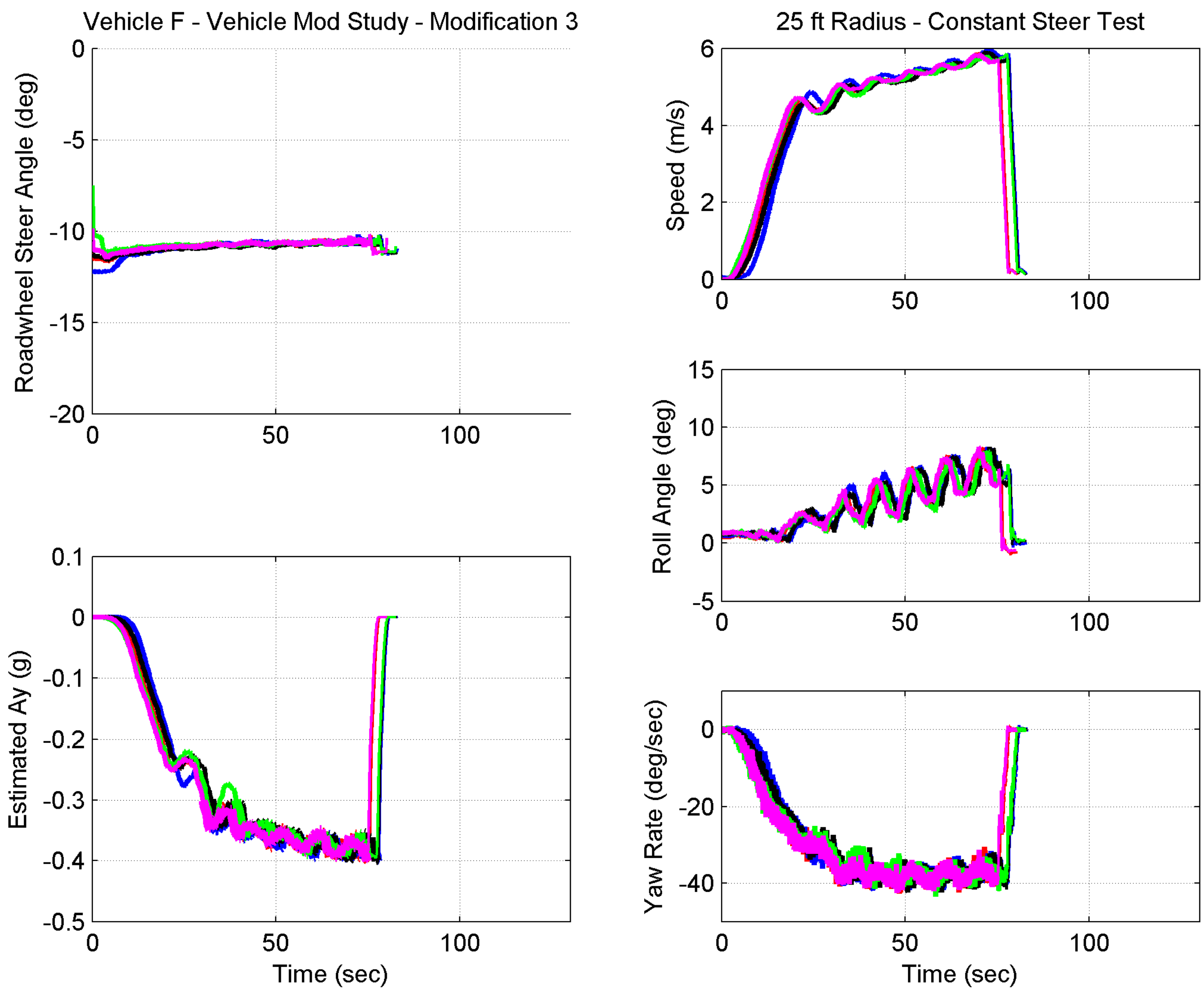


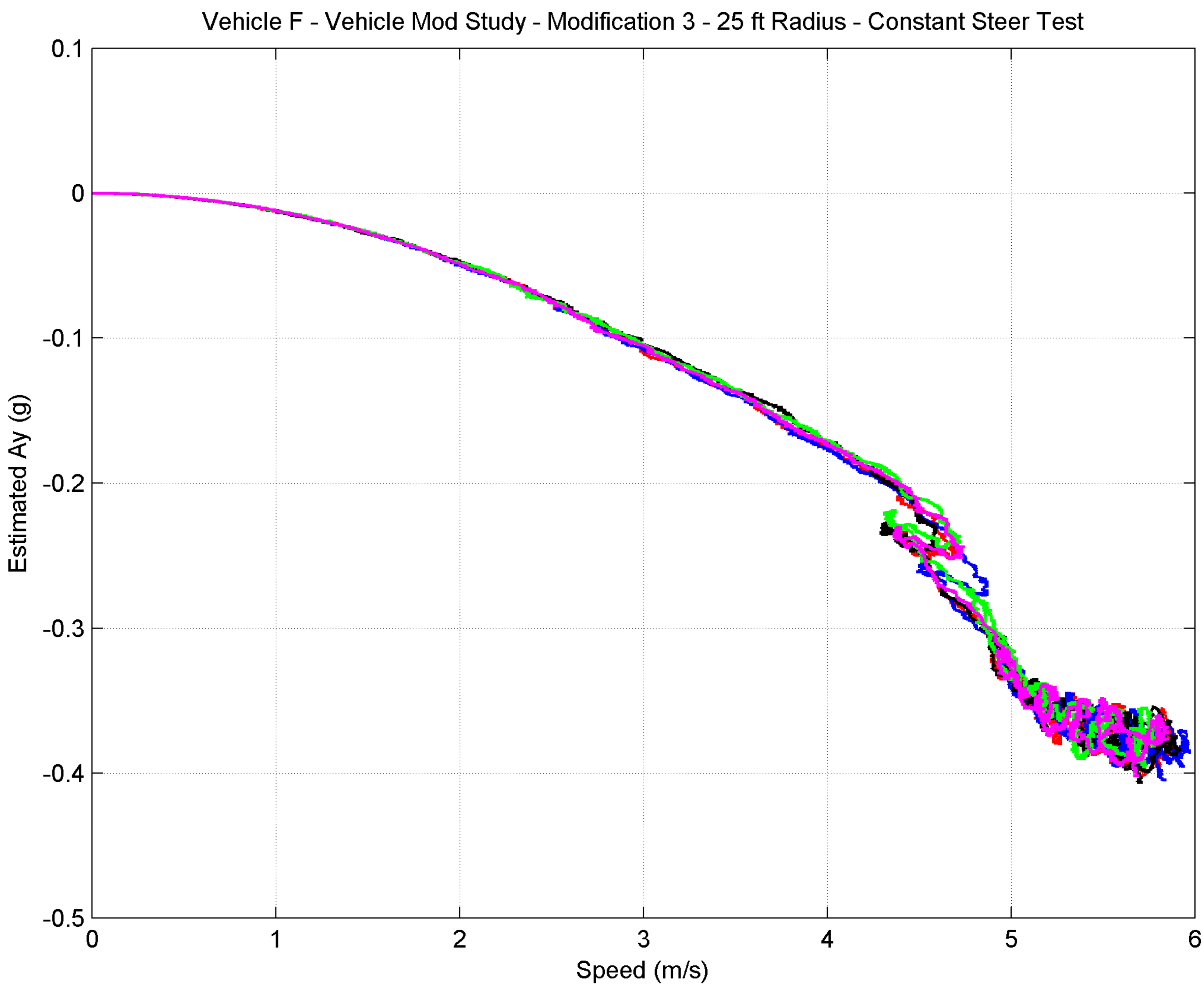
Vehicle F - Vehicle Mod Study - Modification 2 - 25 ft Radius - Constant Steer Test
Yaw Rate (deg/sec)
Speed (m/s)
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
2
2.5
3
3.5
4
4.5
5
5.5
6
CCW Average: 4.05
CCW Ratios: 3.34 4.46 4.37 3.84 4.27 STD=0.467
CCW Final Slopes: -13.8 -17 -20.2 -15.6 -15.6 STD=2.38
CCW Initial Slopes: -4.14 -3.8 -4.62 -4.08 -3.64 STD=0.374



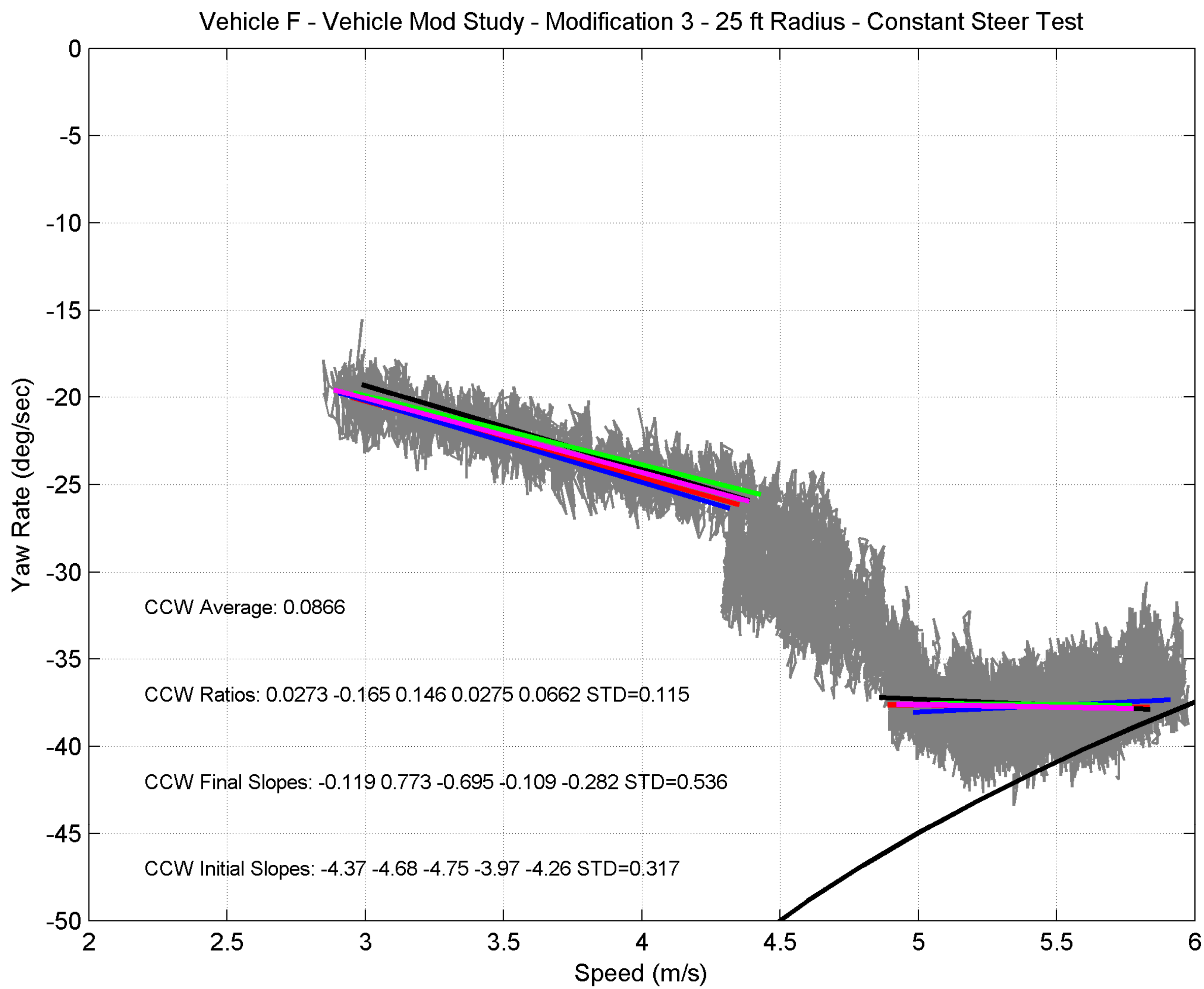
Vehicle F - Vehicle Mod Study - Modification 2 - 25 ft Radius - Constant Steer Test - CCW Runs
Final Slope: -13.8
Ratio: 3.34
Final Slope: -17
Ratio: 4.46
Final Slope: -20.2
Ratio: 4.37
Final Slope: -15.6
Ratio: 3.84
Final Slope: -15.6
Ratio: 4.27
Yaw Rate (deg/sec)
Speed (m/s)


Vehicle F - Vehicle Mod Study - Modification 2 - 25 ft Radius - Constant Steer Test - CCW Runs
N (ft)
E (ft)
Range: All Data
Range: 0.1 g to 0.2 g
Range: 0.3 g to 0.4 g
Range: 0.4 g to Max g

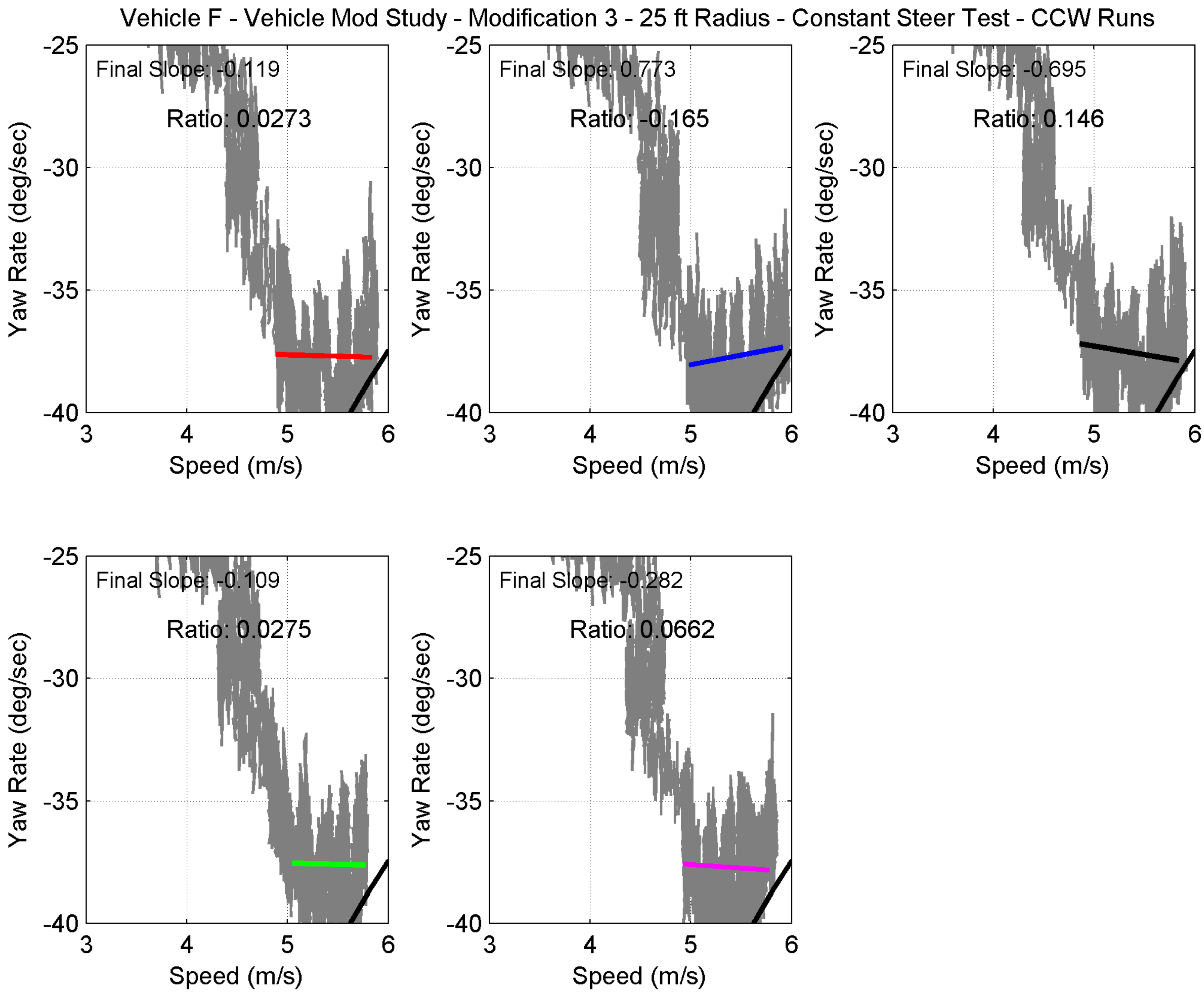

Vehicle F - Vehicle Mod Study - Modification 3
25 ft Radius - Constant Steer Test
Roadwheel Steer Angle (deg)
Speed (m/s)
Roll Angle (deg)
Estimated Ay (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)



Vehicle F - Vehicle Mod Study - Modification 3 - 25 ft Radius - Constant Steer Test
Estimated Ay (g)
Speed (m/s)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
1
2
3
4
5
6

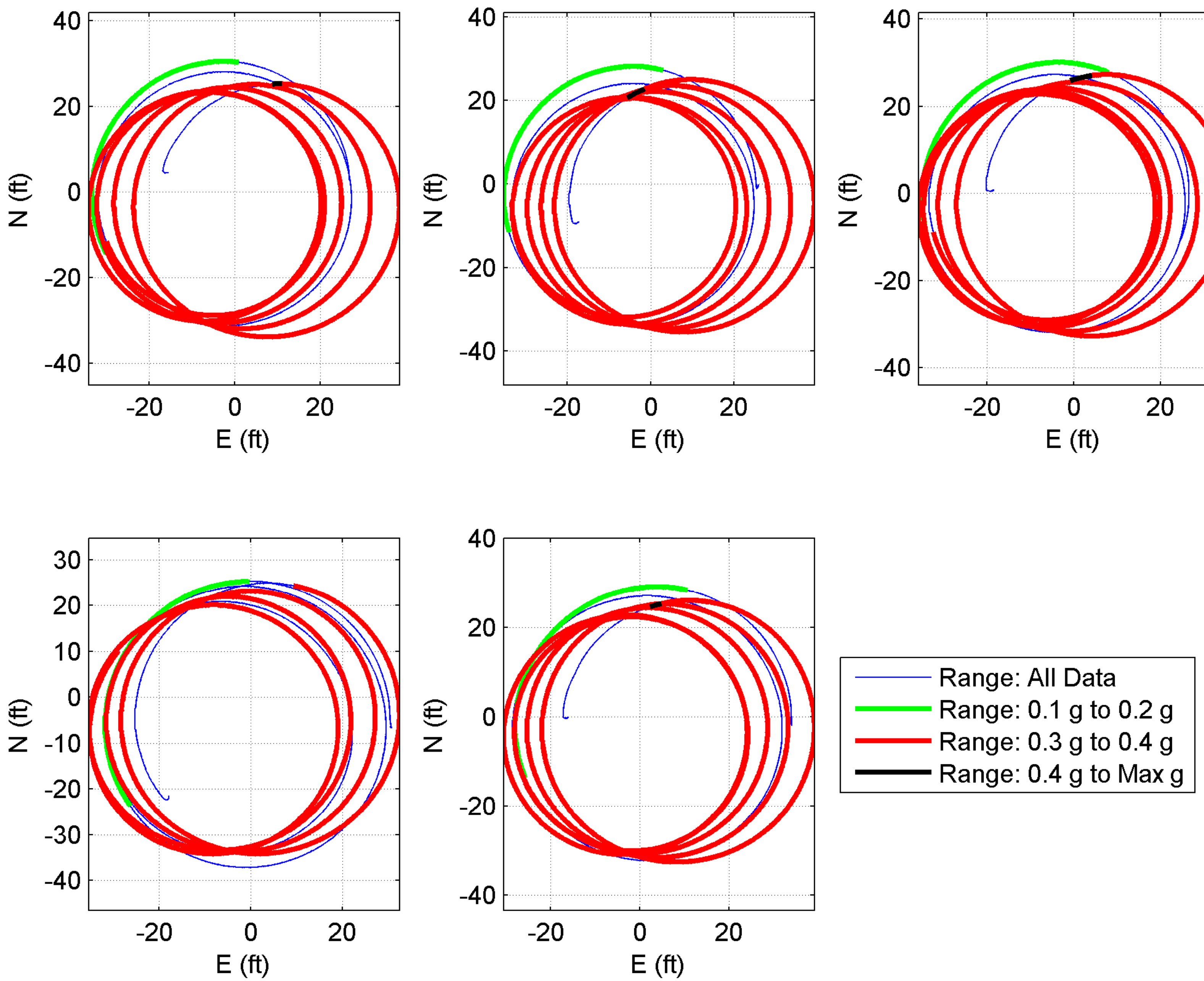


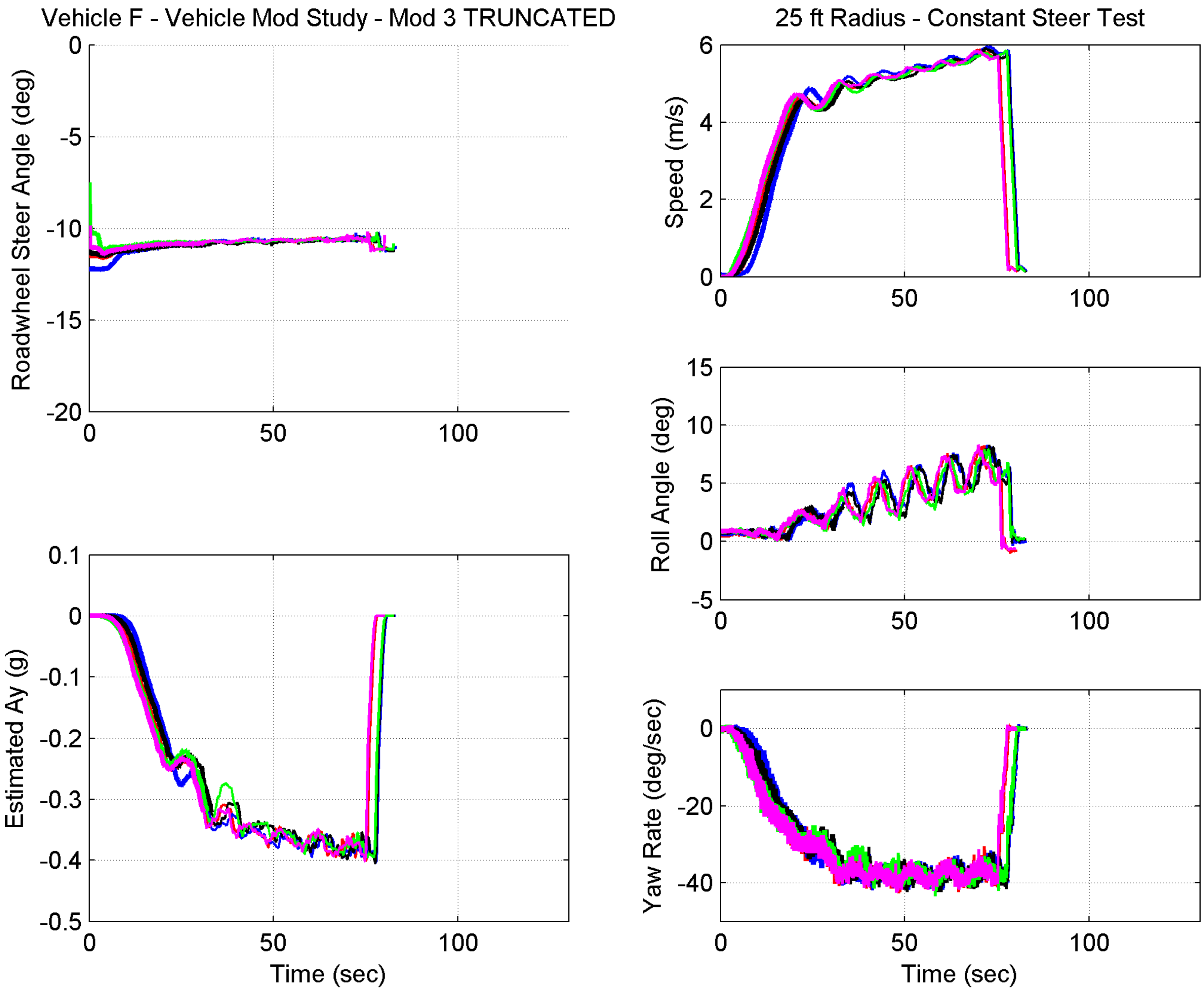
Vehicle F - Vehicle Mod Study - Modification 3 - 25 ft Radius - Constant Steer Test
Yaw Rate (deg/sec)
Speed (m/s)
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
2
2.5
3
3.5
4
4.5
5
5.5
6
CCW Average: 0.0866
CCW Ratios: 0.0273 -0.165 0.146 0.0275 0.0662 STD=0.115
CCW Final Slopes: -0.119 0.773 -0.695 -0.109 -0.282 STD=0.536
CCW Initial Slopes: -4.37 -4.68 -4.75 -3.97 -4.26 STD=0.317



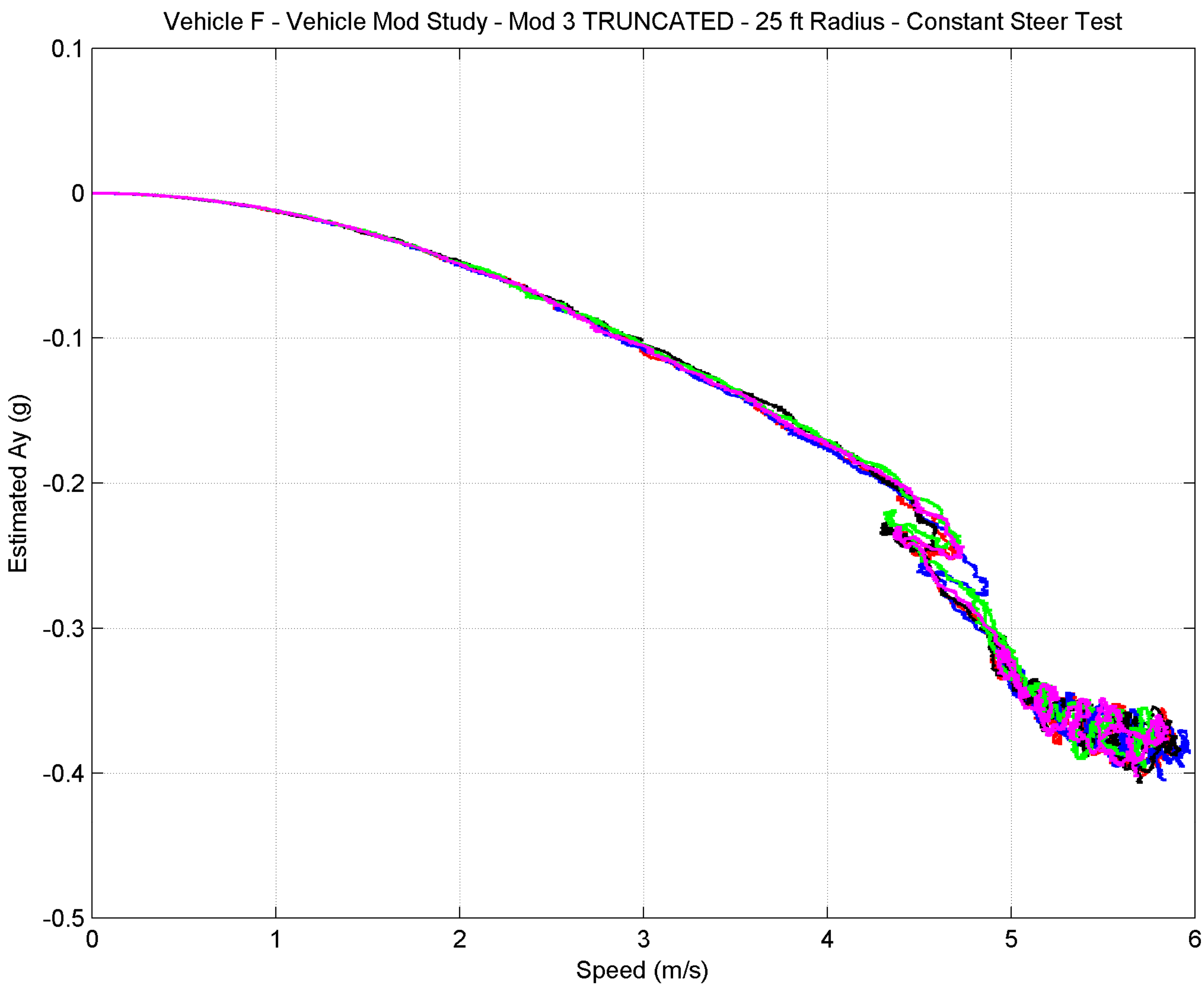
Vehicle F - Vehicle Mod Study - Modification 3 - 25 ft Radius - Constant Steer Test - CCW Runs
Final Slope: -0.119
Ratio: 0.0273
Final Slope: 0.773
Ratio: -0.165
Final Slope: -0.695
Ratio: 0.146
Final Slope: -0.109
Ratio: 0.0275
Final Slope: -0.282
Ratio: 0.0662
Yaw Rate (deg/sec)
Speed (m/s)

Vehicle F - Vehicle Mod Study - Modification 3 - 25 ft Radius - Constant Steer Test - CCW Runs

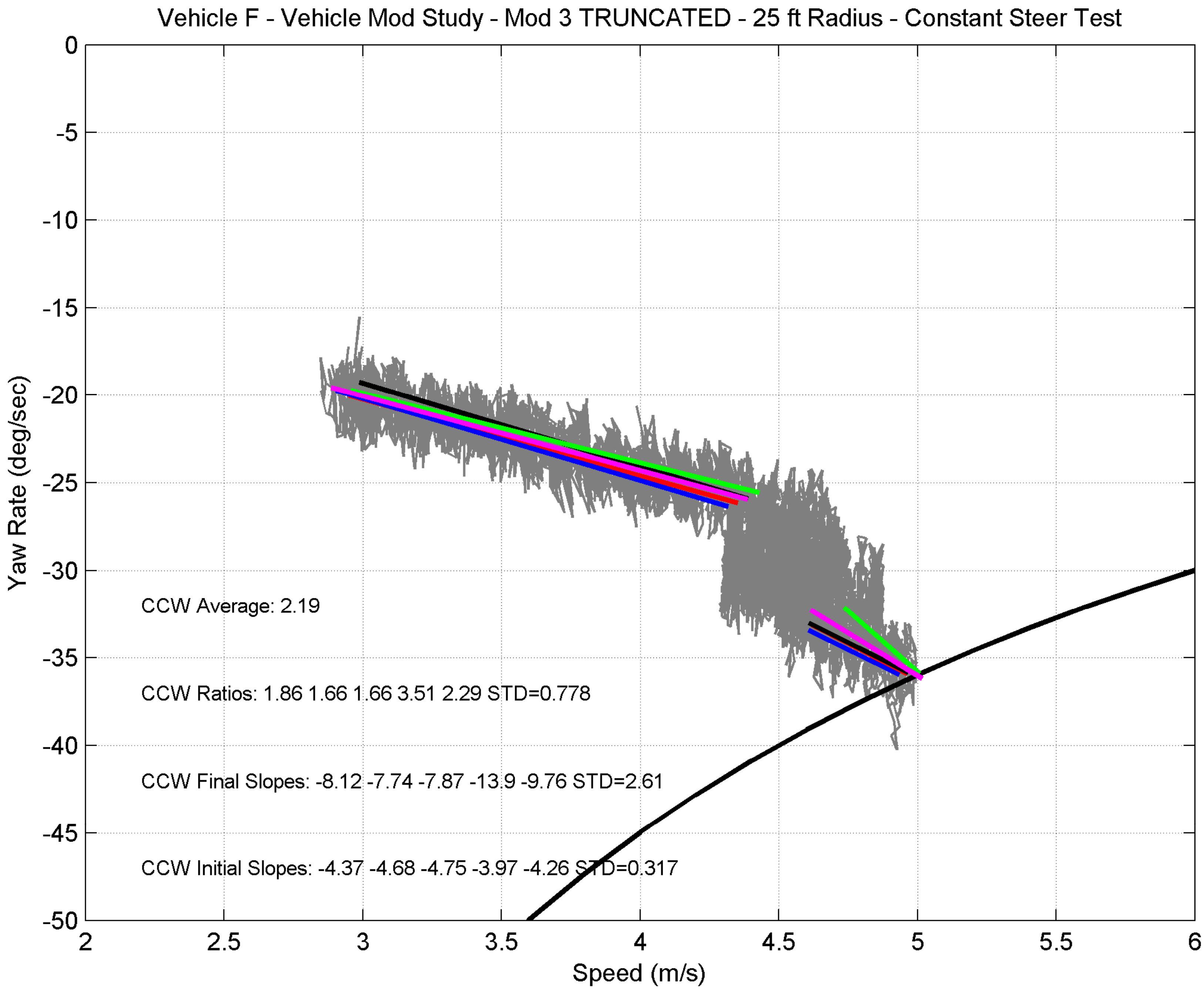




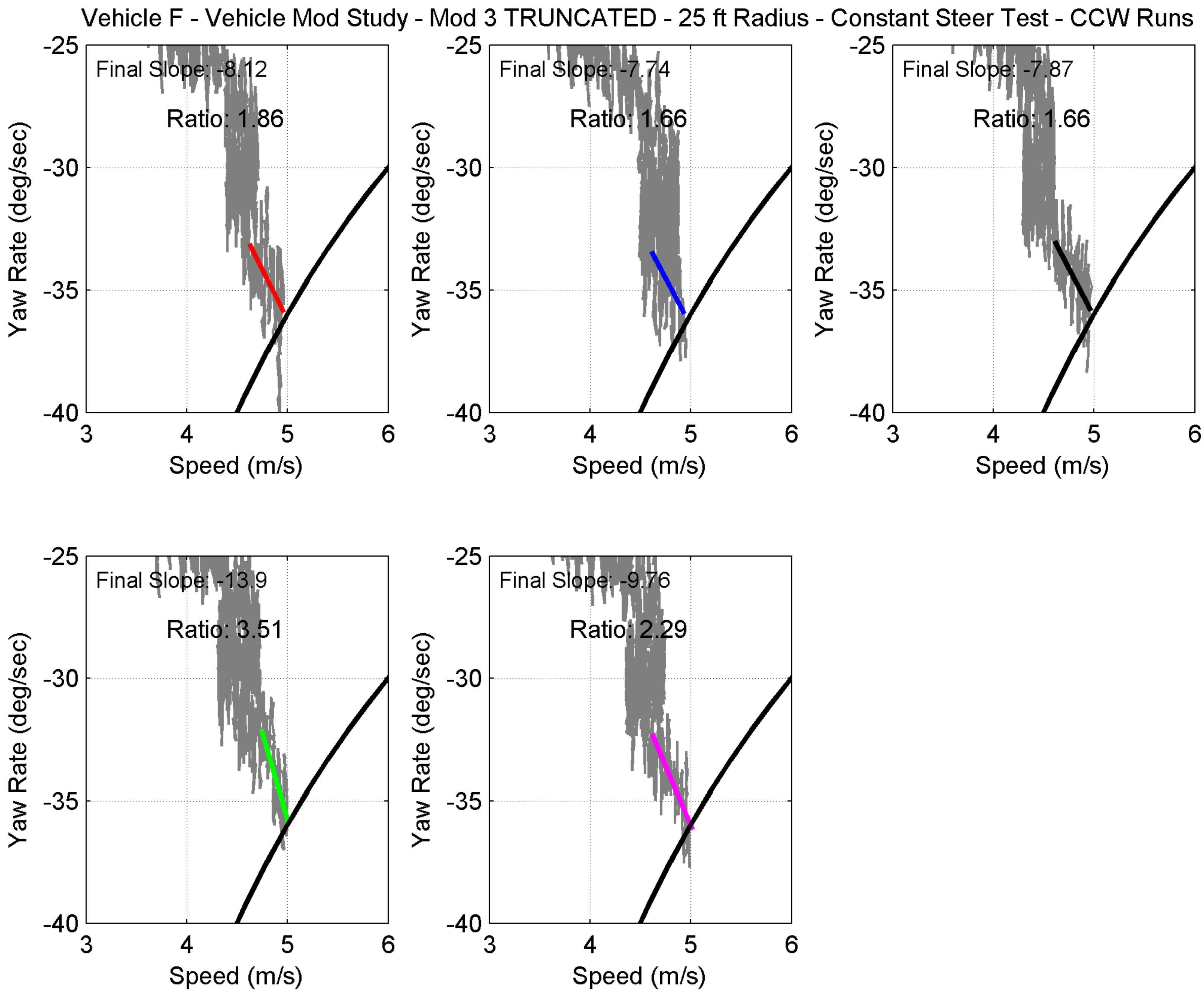
Vehicle F - Vehicle Mod Study - Mod 3 TRUNCATED
Roadwheel Steer Angle (deg)
0
-5
-10
-15
-20
0
50
100
25 ft Radius - Constant Steer Test
Speed (m/s)
6
4
2
0
0
50
100
Roll Angle (deg)
15
10
5
0
-5
0
50
100
Estimated Ay (g)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
50
100
Time (sec)
Yaw Rate (deg/sec)
0
-20
-40
0
50
100
Time (sec)

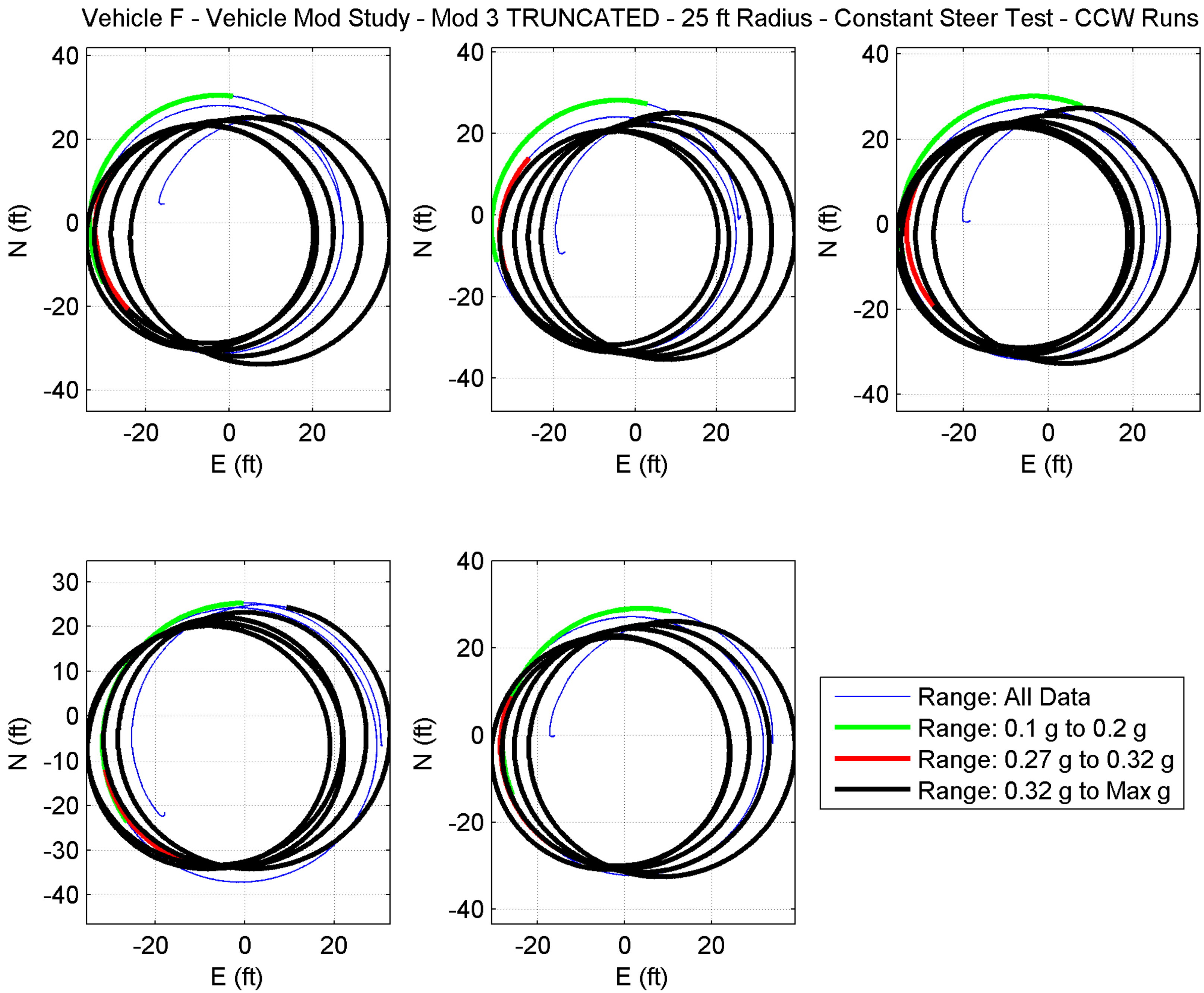


Vehicle F - Vehicle Mod Study - Mod 3 TRUNCATED - 25 ft Radius - Constant Steer Test
Estimated Ay (g)
Speed (m/s)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
1
2
3
4
5
6



Vehicle F - Vehicle Mod Study - Mod 3 TRUNCATED - 25 ft Radius - Constant Steer Test
Yaw Rate (deg/sec)
Speed (m/s)
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
2
2.5
3
3.5
4
4.5
5
5.5
6
CCW Average: 2.19
CCW Ratios: 1.86 1.66 1.66 3.51 2.29 STD=0.778
CCW Final Slopes: -8.12 -7.74 -7.87 -13.9 -9.76 STD=2.61
CCW Initial Slopes: -4.37 -4.68 -4.75 -3.97 -4.26 STD=0.317


Vehicle F - Vehicle Mod Study - Mod 3 TRUNCATED - 25 ft Radius - Constant Steer Test - CCW Runs
Final Slope: -8.12
Ratio: 1.86
Final Slope: -7.74
Ratio: 1.66
Final Slope: -7.87
Ratio: 1.66
Final Slope: -13.9
Ratio: 3.51
Final Slope: -9.76
Ratio: 2.29
Yaw Rate (deg/sec)
Speed (m/s)
-25
-30
-35
-40
3
4
5
6


Vehicle F - Vehicle Mod Study - Mod 3 TRUNCATED - 25 ft Radius - Constant Steer Test - CCW Runs
N (ft)
E (ft)
Range: All Data
Range: 0.1 g to 0.2 g
Range: 0.27 g to 0.32 g
Range: 0.32 g to Max g

Vehicle Modification Study

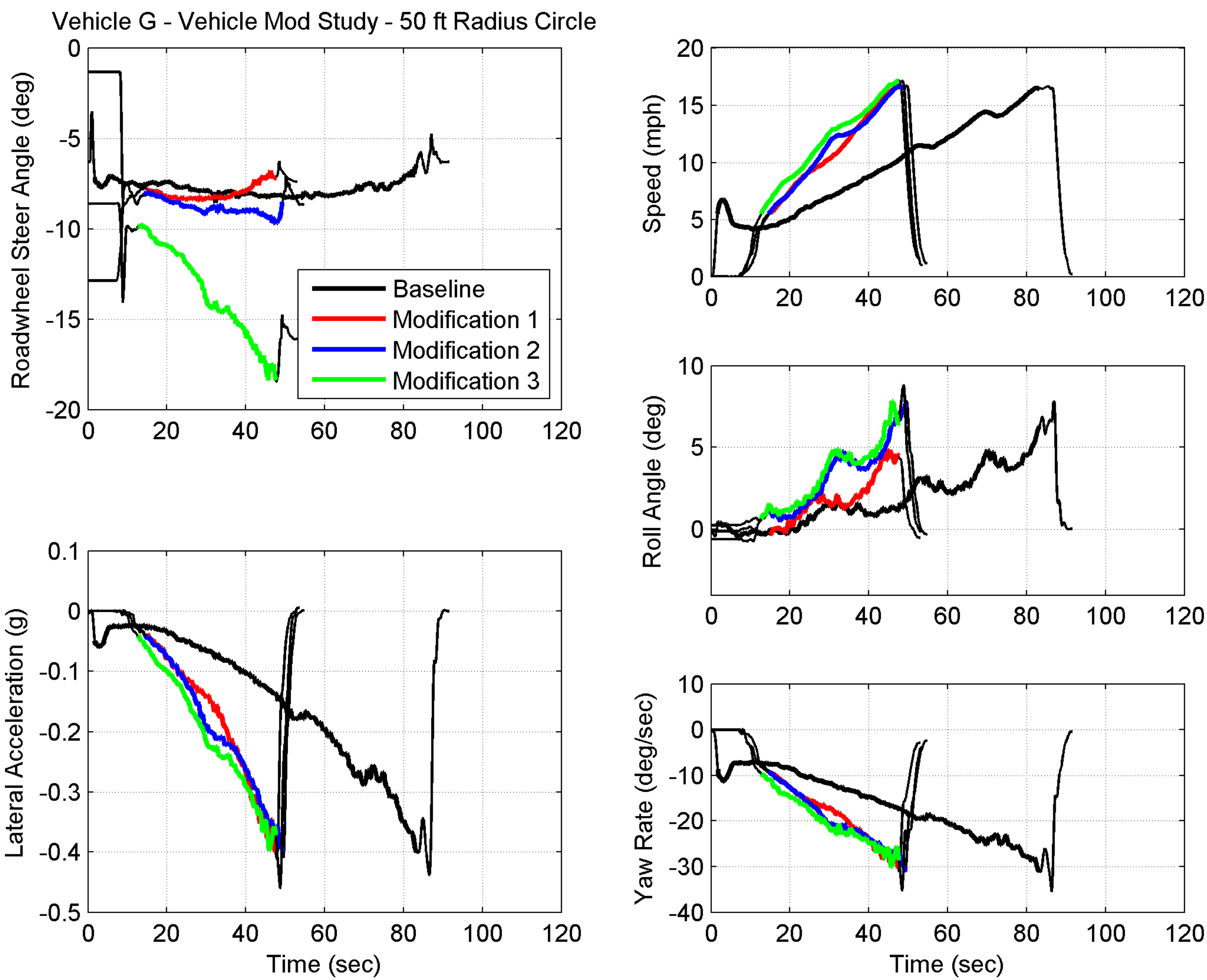
Results for Vehicle G

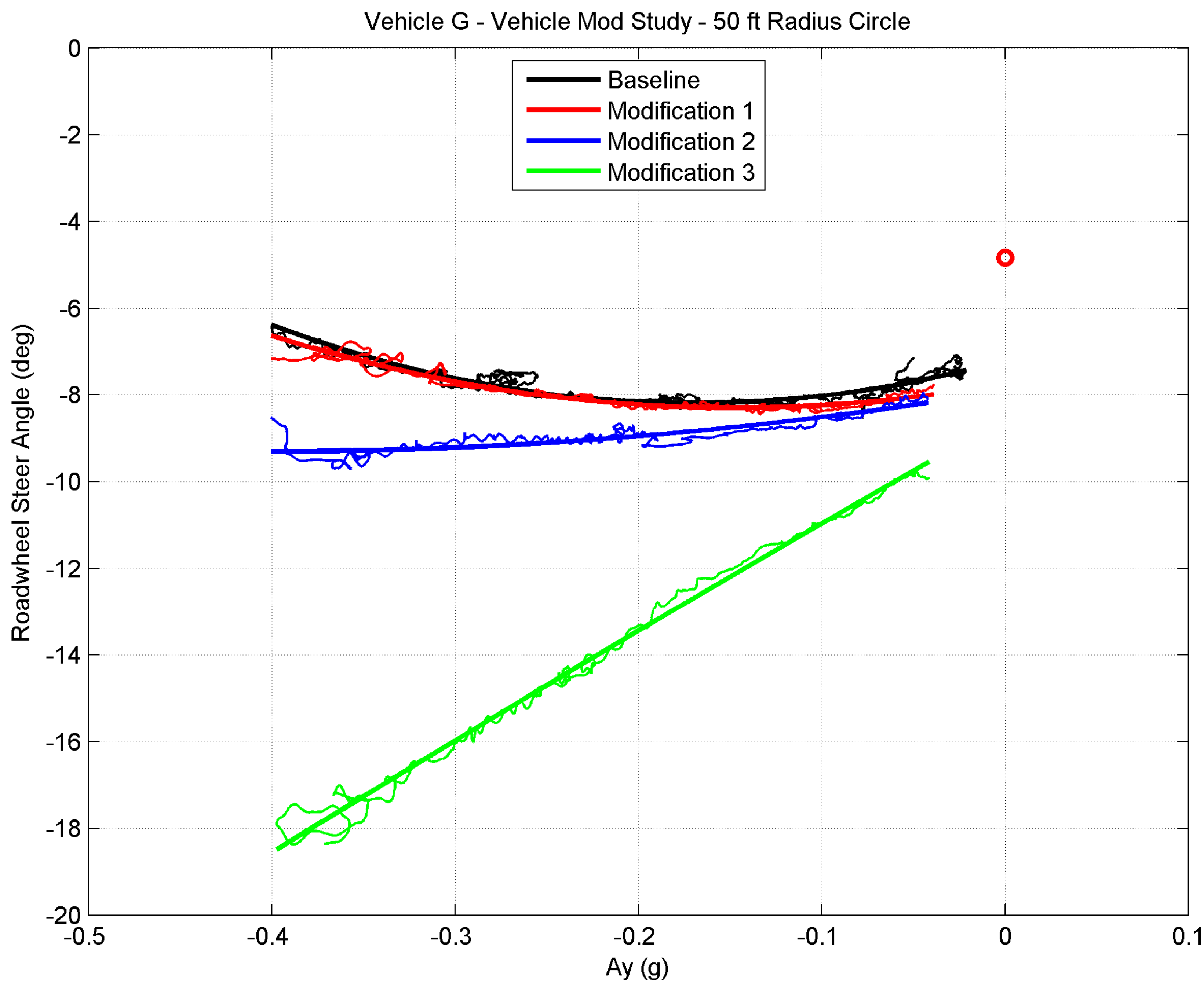
Baseline: Driver Plus Instrumentation (DPI) Loading 0° Rider (Driver) Lean

Mod 1: Driver Plus Instrumentation (DPI) Loading 0° Rider (Driver) Lean
Replaced Front Springs to Increase Front (Roll) Stiffness

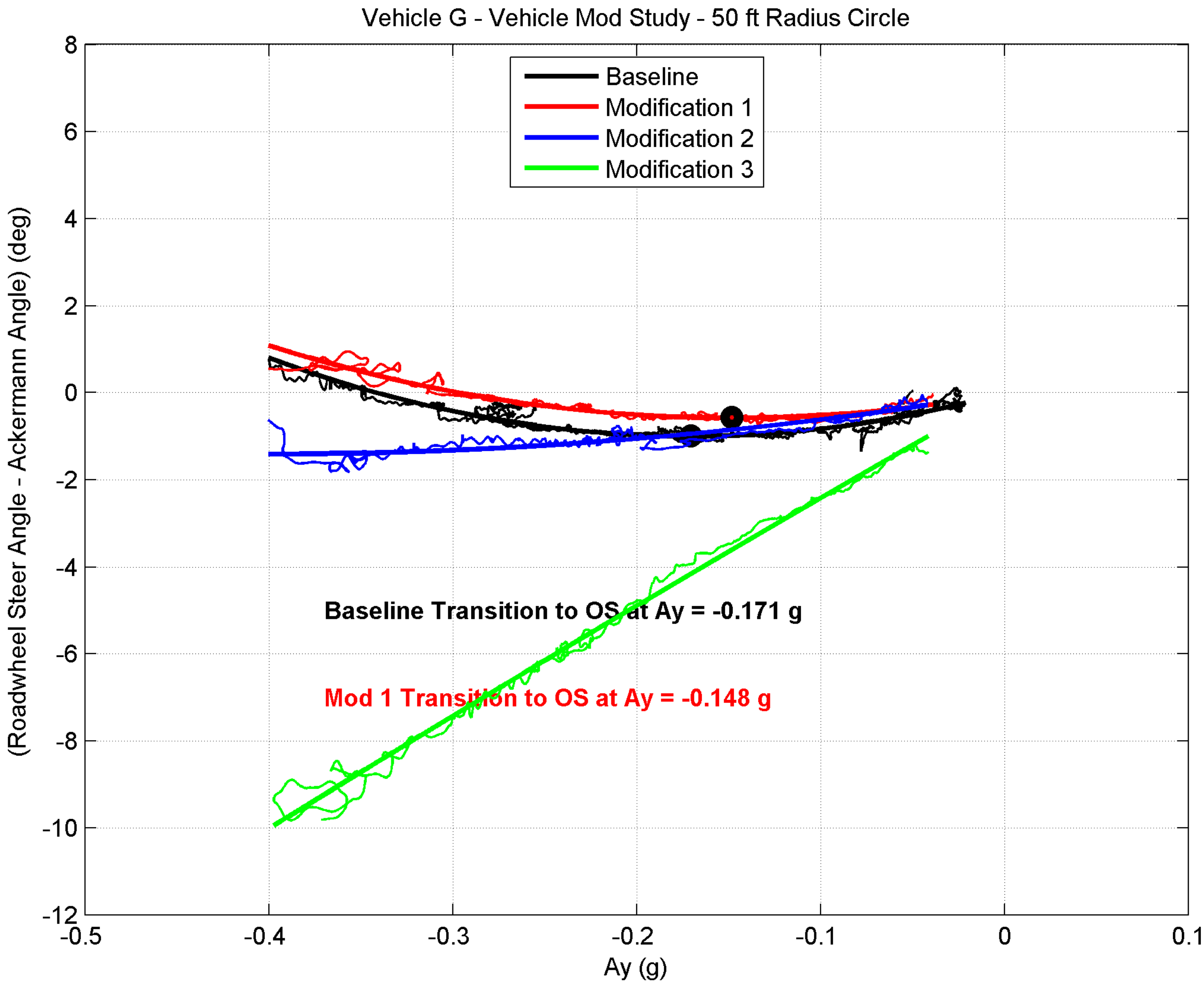
Mod 2: Driver Plus Instrumentation (DPI) Loading 0° Rider (Driver) Lean
Replaced Front Springs to Increase Front (Roll) Stiffness, and
Disconnected Rear Anti-roll Bar to Decrease Rear Roll Stiffness

Mod 3: Driver Plus Instrumentation (DPI) Loading 0° Rider (Driver) Lean
Replaced Front Springs to Increase Front (Roll) Stiffness,
Disconnected Rear Anti-roll Bar to Decrease Rear Roll Stiffness, and
Modified Steering Geometry to Reduce Roll Oversteer

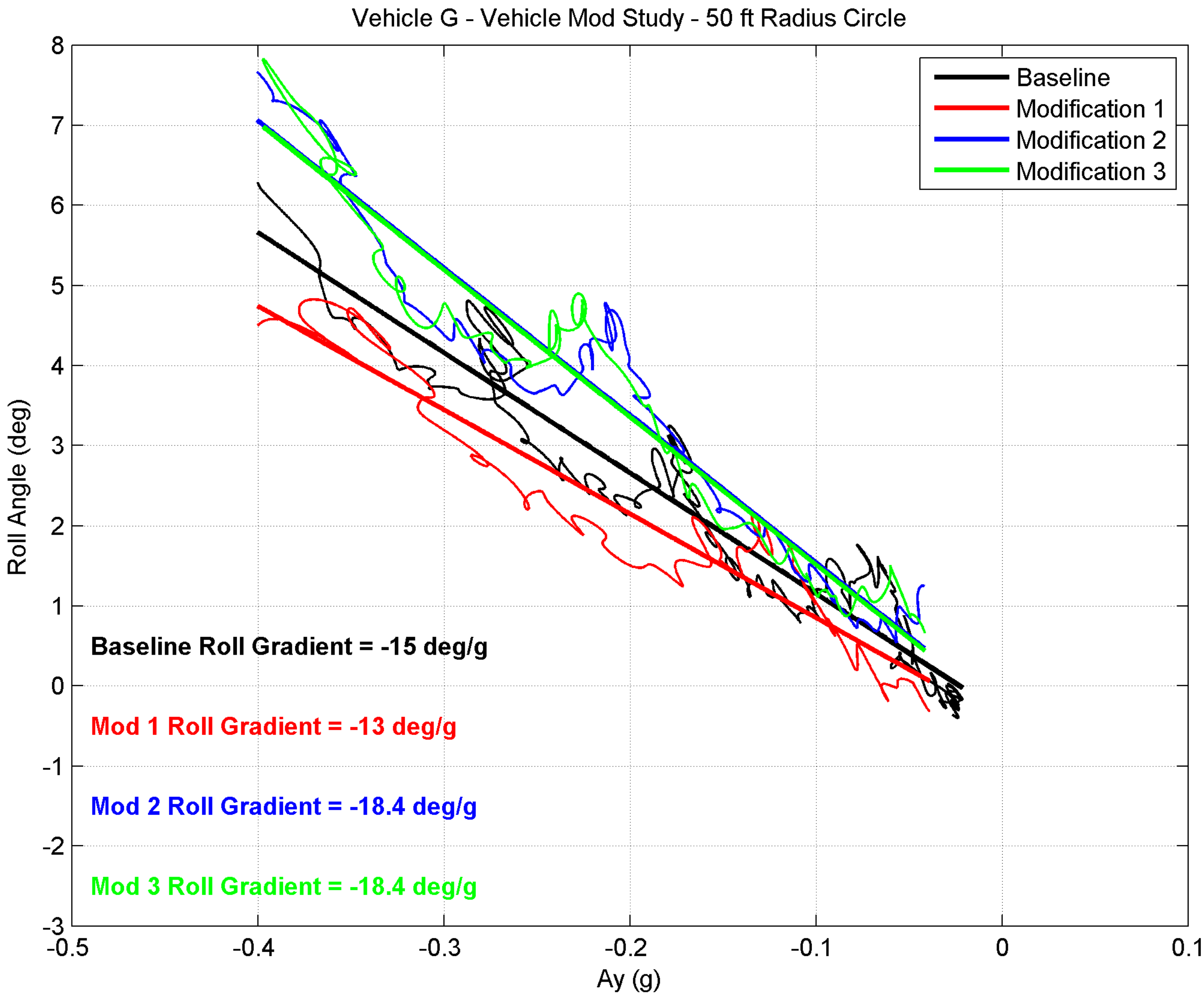

Vehicle G - Vehicle Mod Study - 50 ft Radius Circle
Roadwheel Steer Angle (deg)
Baseline
Modification 1
Modification 2
Modification 3
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)



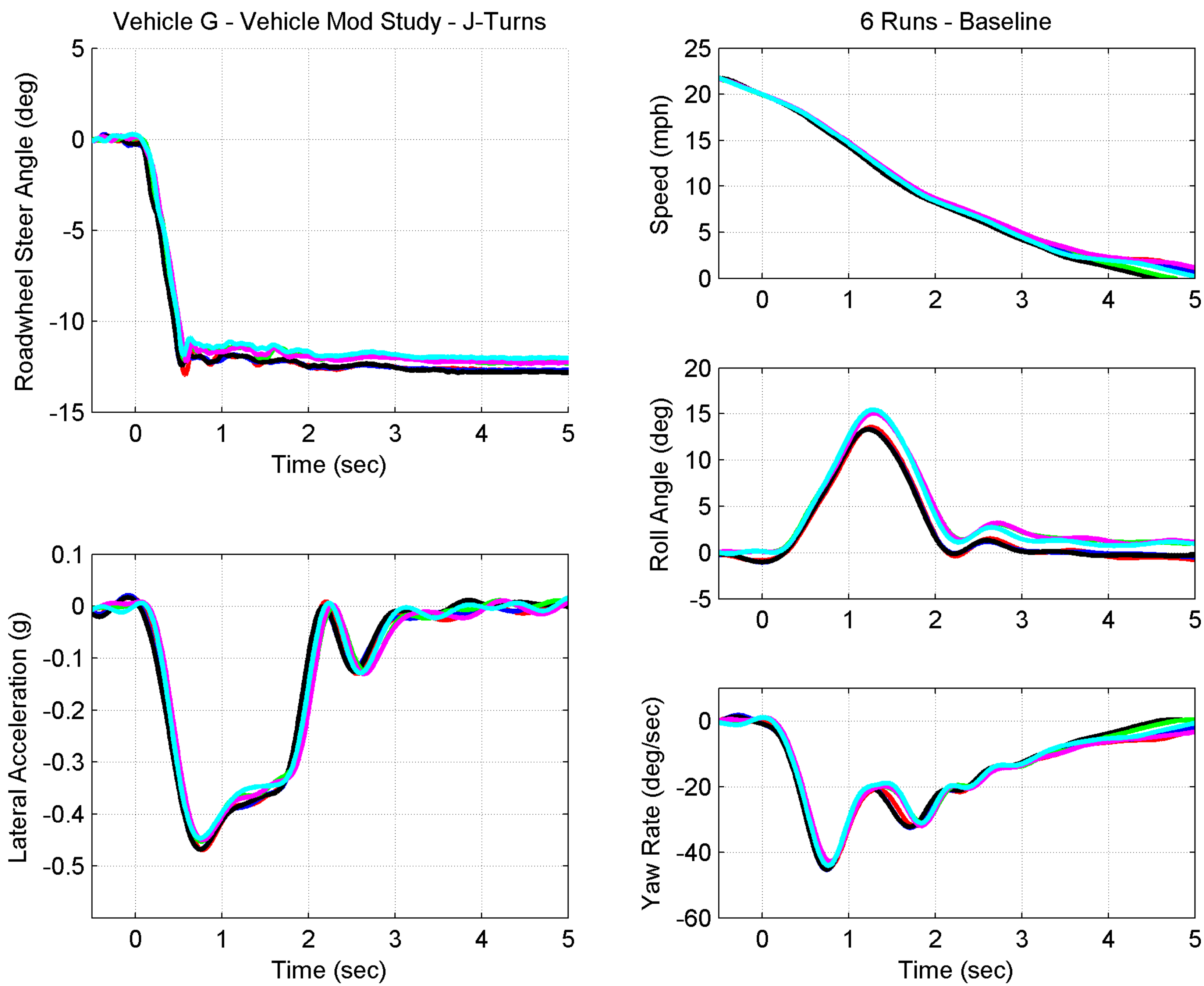
Vehicle G - Vehicle Mod Study - 50 ft Radius Circle
Baseline
Modification 1
Modification 2
Modification 3
Roadwheel Steer Angle (deg)
Ay (g)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1



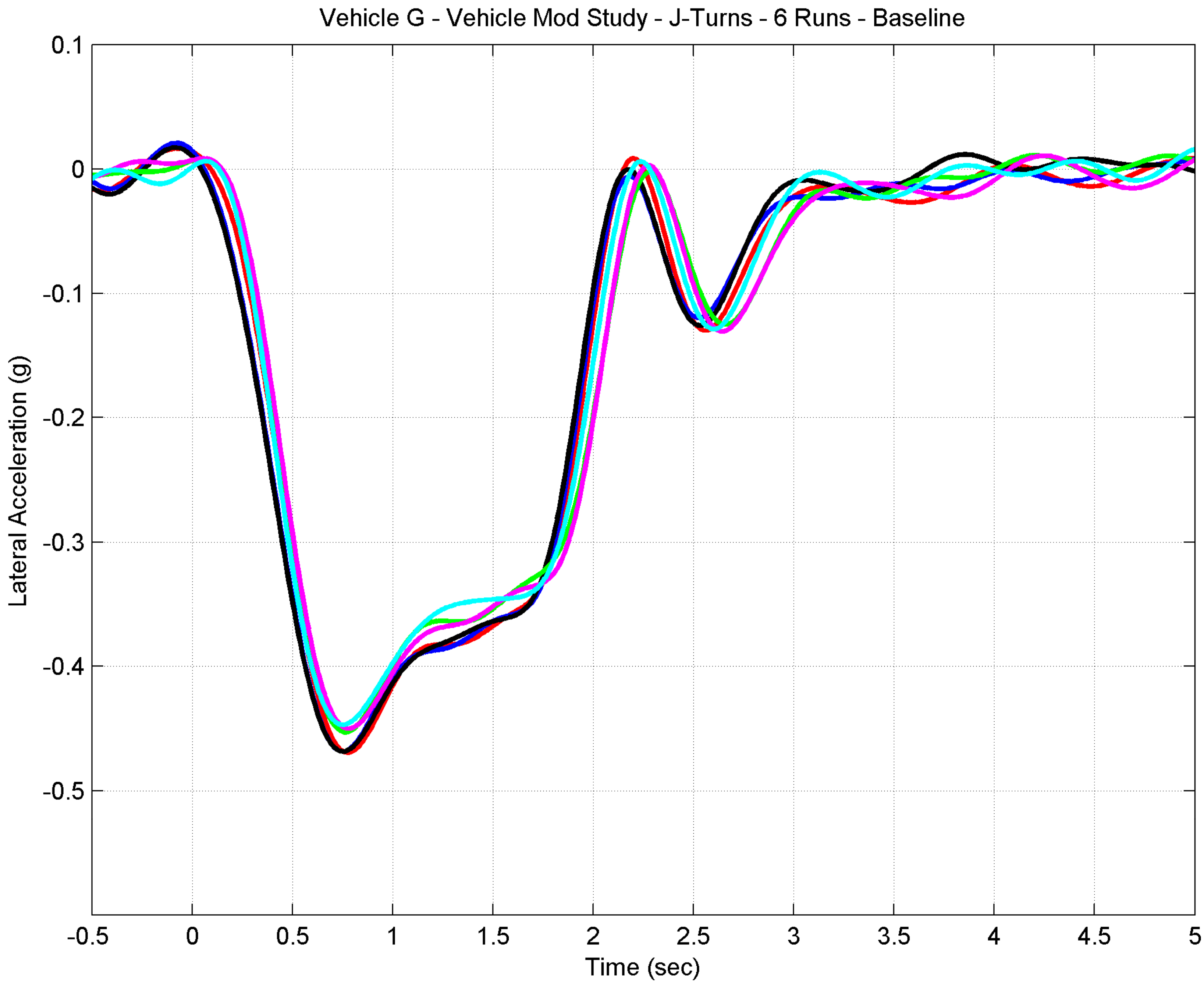
Vehicle G - Vehicle Mod Study - 50 ft Radius Circle
Baseline
Modification 1
Modification 2
Modification 3
Baseline Transition to OS at Ay = -0.171 g
Mod 1 Transition to OS at Ay = -0.148 g
(Roadwheel Steer Angle - Ackermann Angle) (deg)
Ay (g)
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1

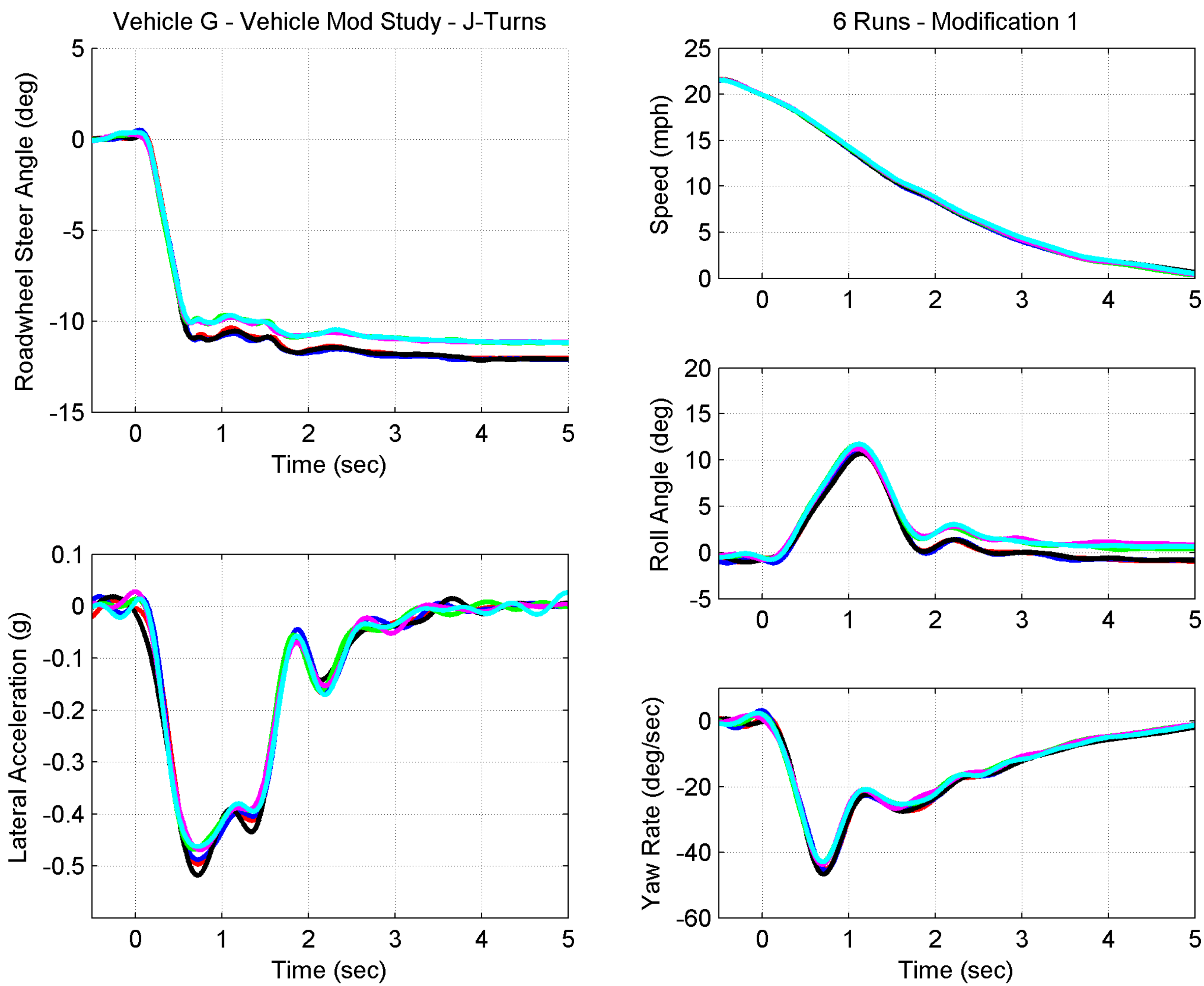


Vehicle G - Vehicle Mod Study - 50 ft Radius Circle
Baseline
Modification 1
Modification 2
Modification 3
Roll Angle (deg)
Ay (g)
8
7
6
5
4
3
2
1
0
-1
-2
-3
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
Baseline Roll Gradient = -15 deg/g
Mod 1 Roll Gradient = -13 deg/g
Mod 2 Roll Gradient = -18.4 deg/g
Mod 3 Roll Gradient = -18.4 deg/g

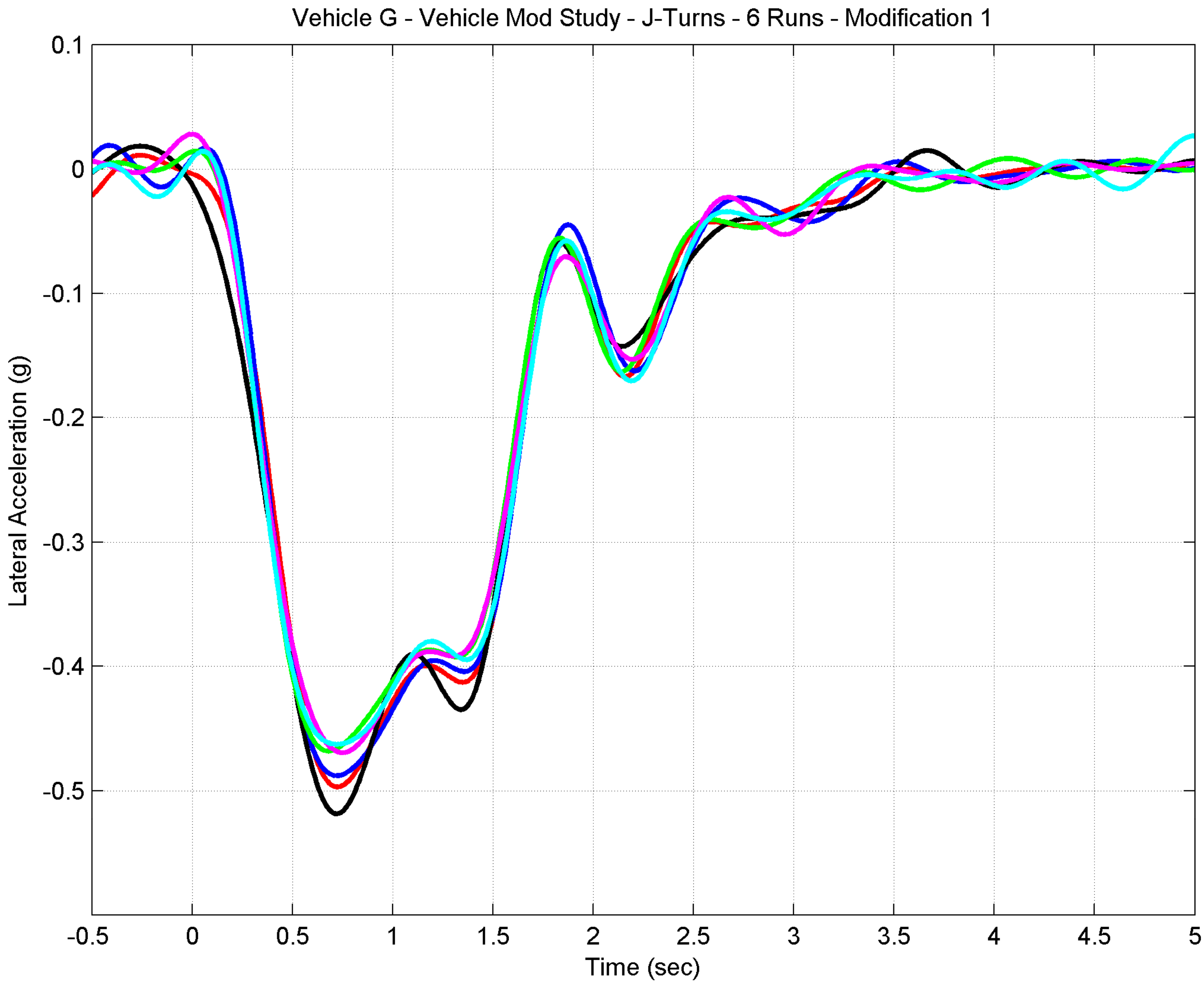


Vehicle G - Vehicle Mod Study - J-Turns
6 Runs - Baseline
Roadwheel Steer Angle (deg)
Lateral Acceleration (g)
Speed (mph)
Roll Angle (deg)
Yaw Rate (deg/sec)
Time (sec)

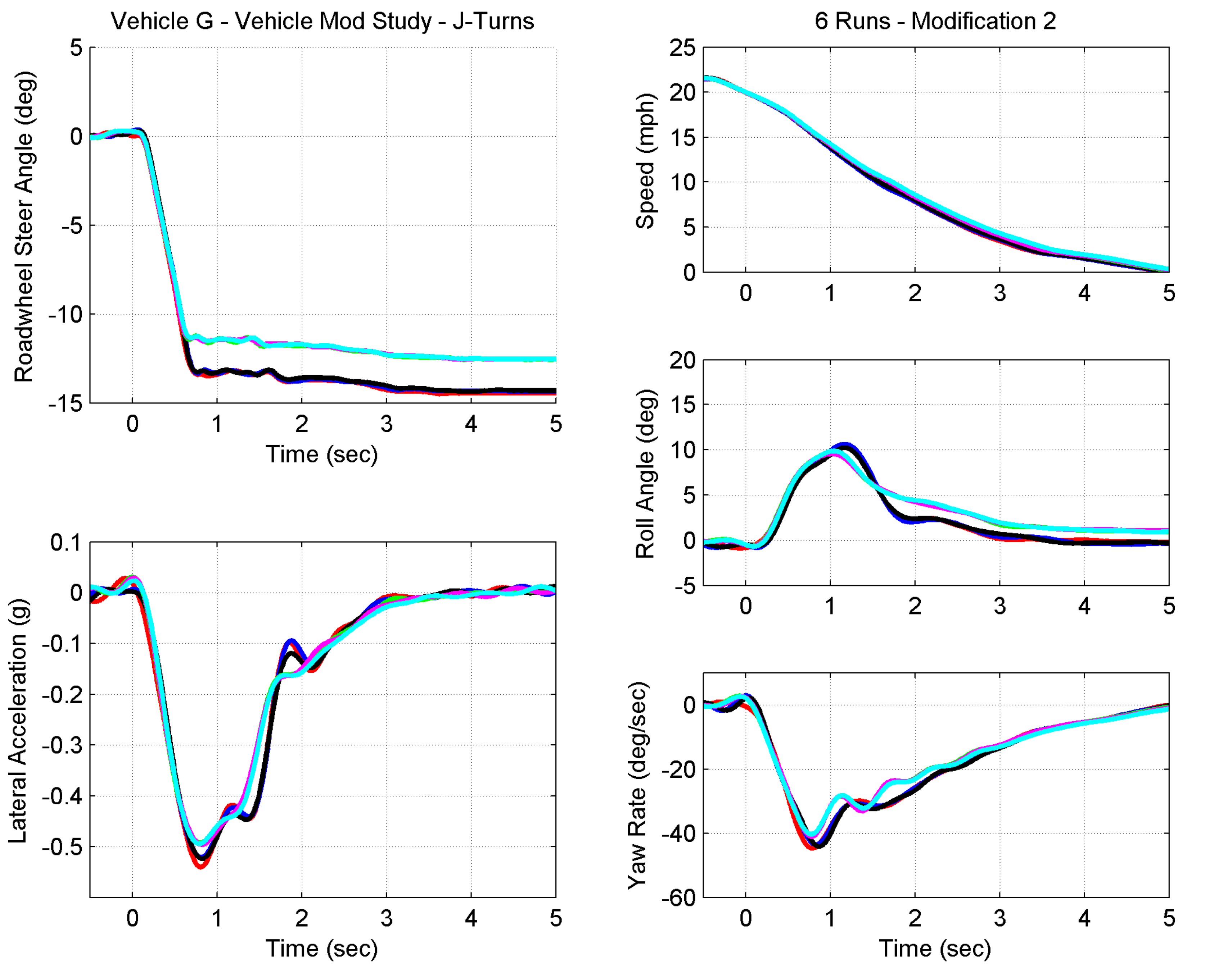

Vehicle G - Vehicle Mod Study - J-Turns - 6 Runs - Baseline
Lateral Acceleration (g)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (sec)

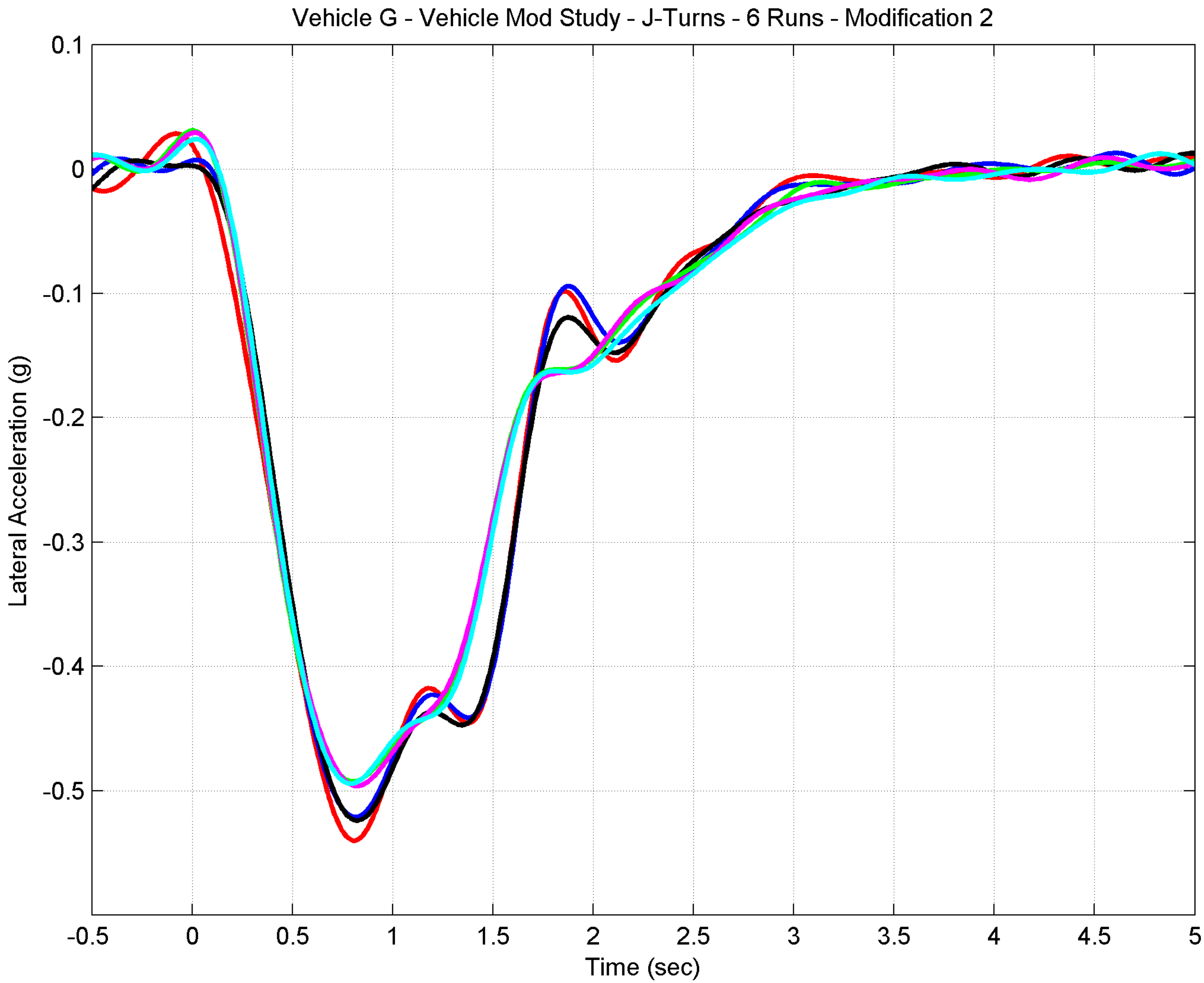


Vehicle G - Vehicle Mod Study - J-Turns
6 Runs - Modification 1
Roadwheel Steer Angle (deg)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)

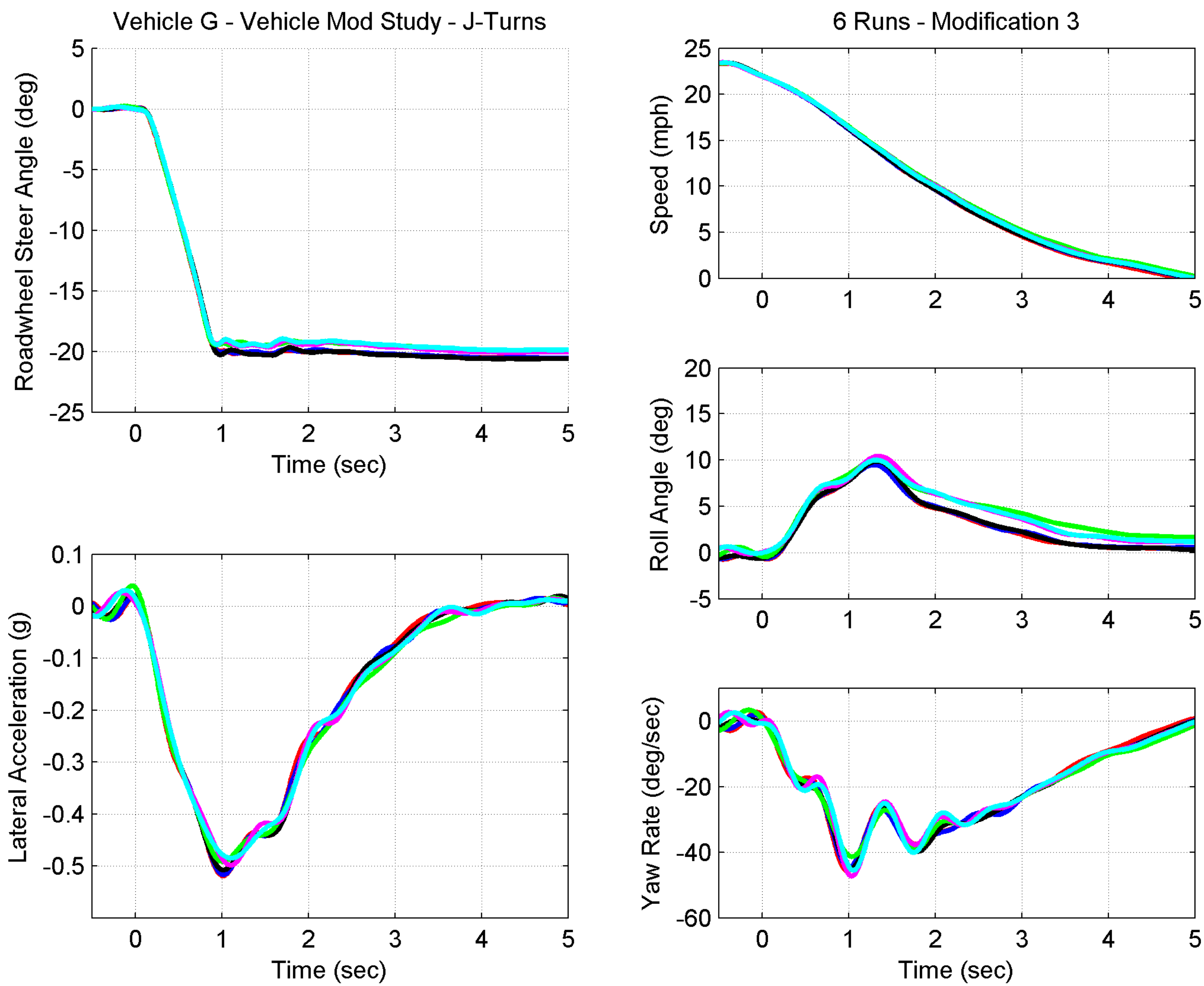


Vehicle G - Vehicle Mod Study - J-Turns - 6 Runs - Modification 1
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
Lateral Acceleration (g)
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (sec)

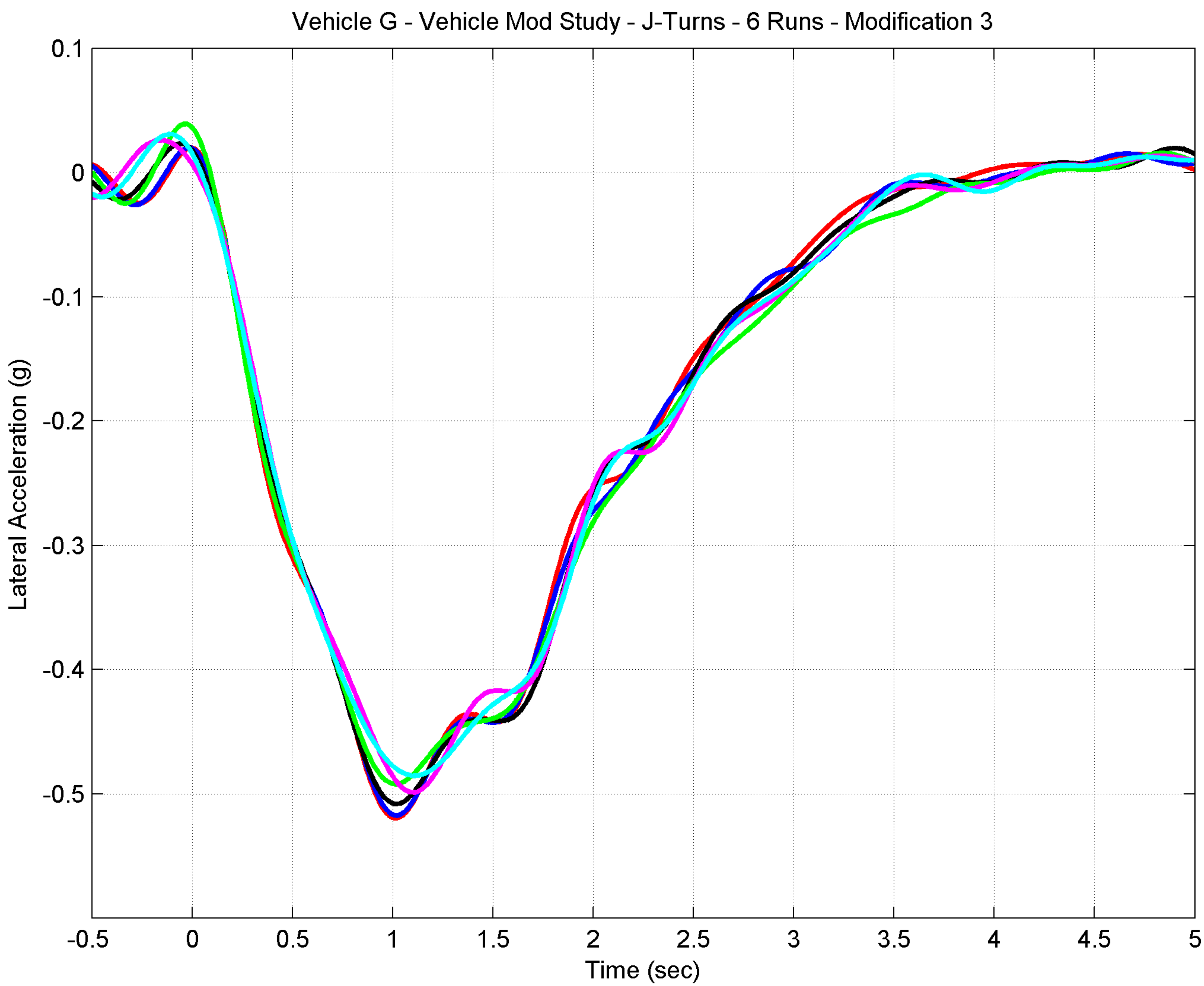

Vehicle G - Vehicle Mod Study - J-Turns
6 Runs - Modification 2
Roadwheel Steer Angle (deg)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)
Time (sec)



Vehicle G - Vehicle Mod Study - J-Turns - 6 Runs - Modification 2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
Lateral Acceleration (g)
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (sec)



Vehicle G - Vehicle Mod Study - J-Turns
6 Runs - Modification 3
Roadwheel Steer Angle (deg)
Time (sec)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Time (sec)
Yaw Rate (deg/sec)
Time (sec)

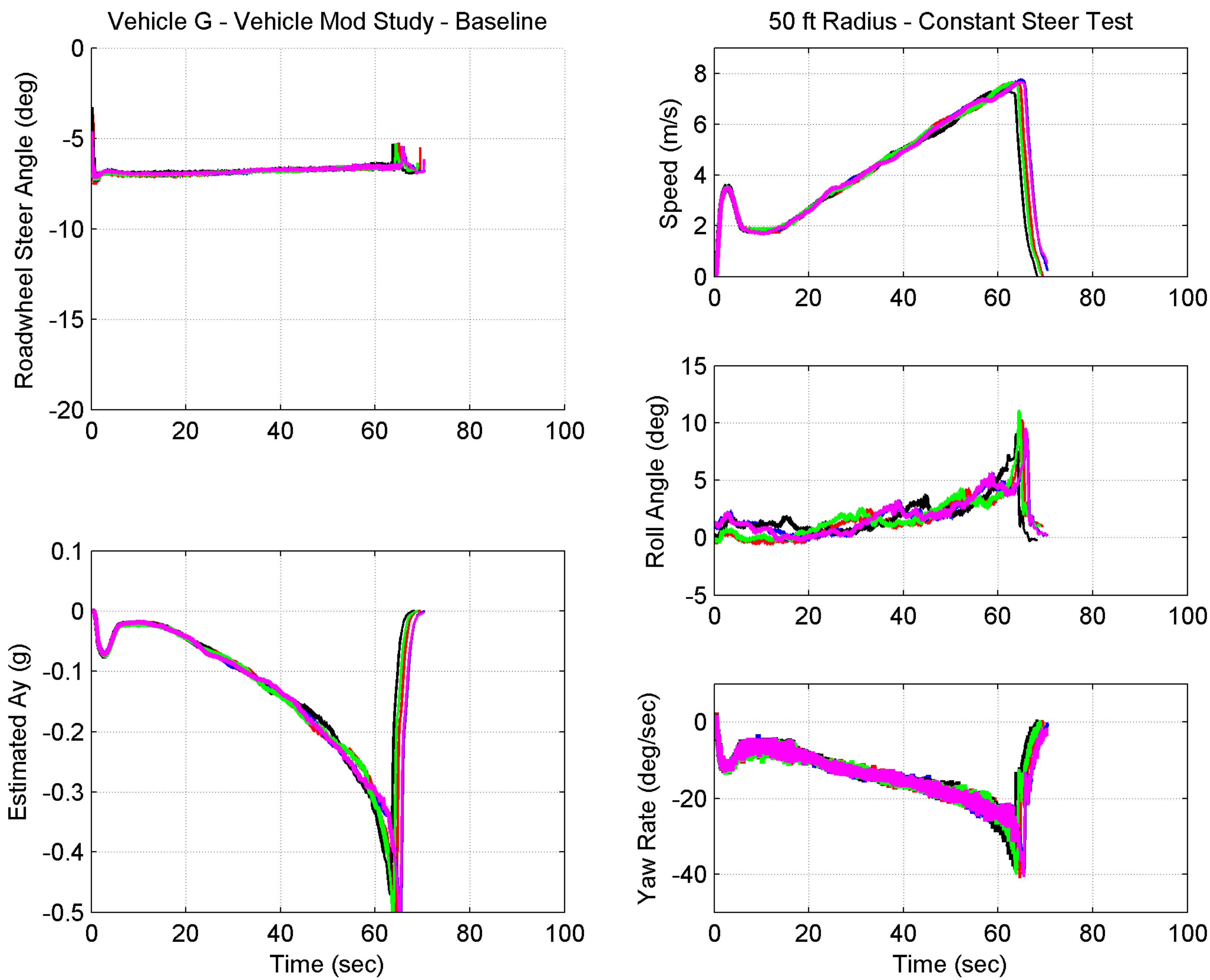

Vehicle G - Vehicle Mod Study - J-Turns - 6 Runs - Modification 3
Lateral Acceleration (g)
Time (sec)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

Vehicle G - Vehicle Modification Study

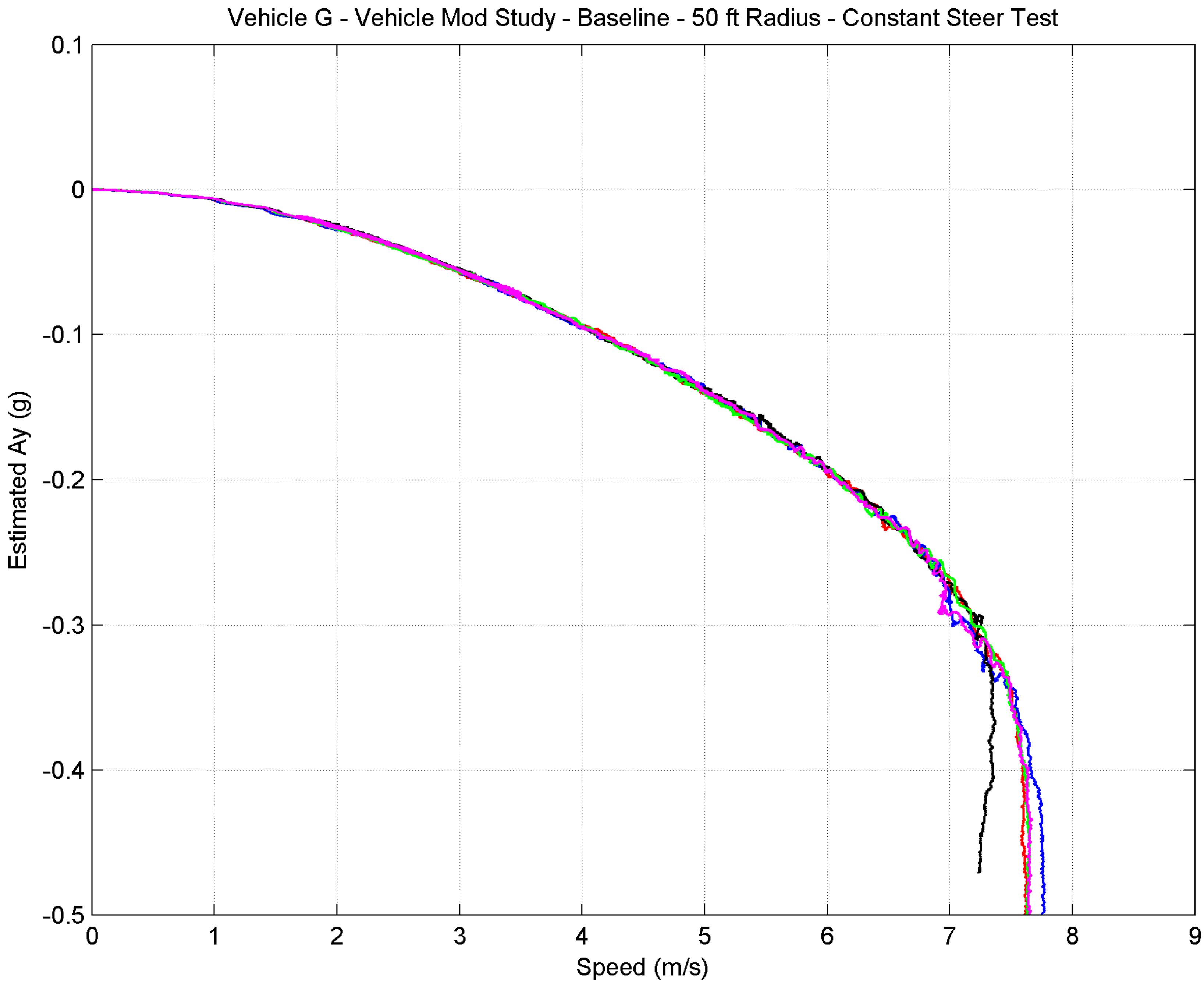
Peak Lateral Accelerations During 2WL J-Turns - All Values in "g's"

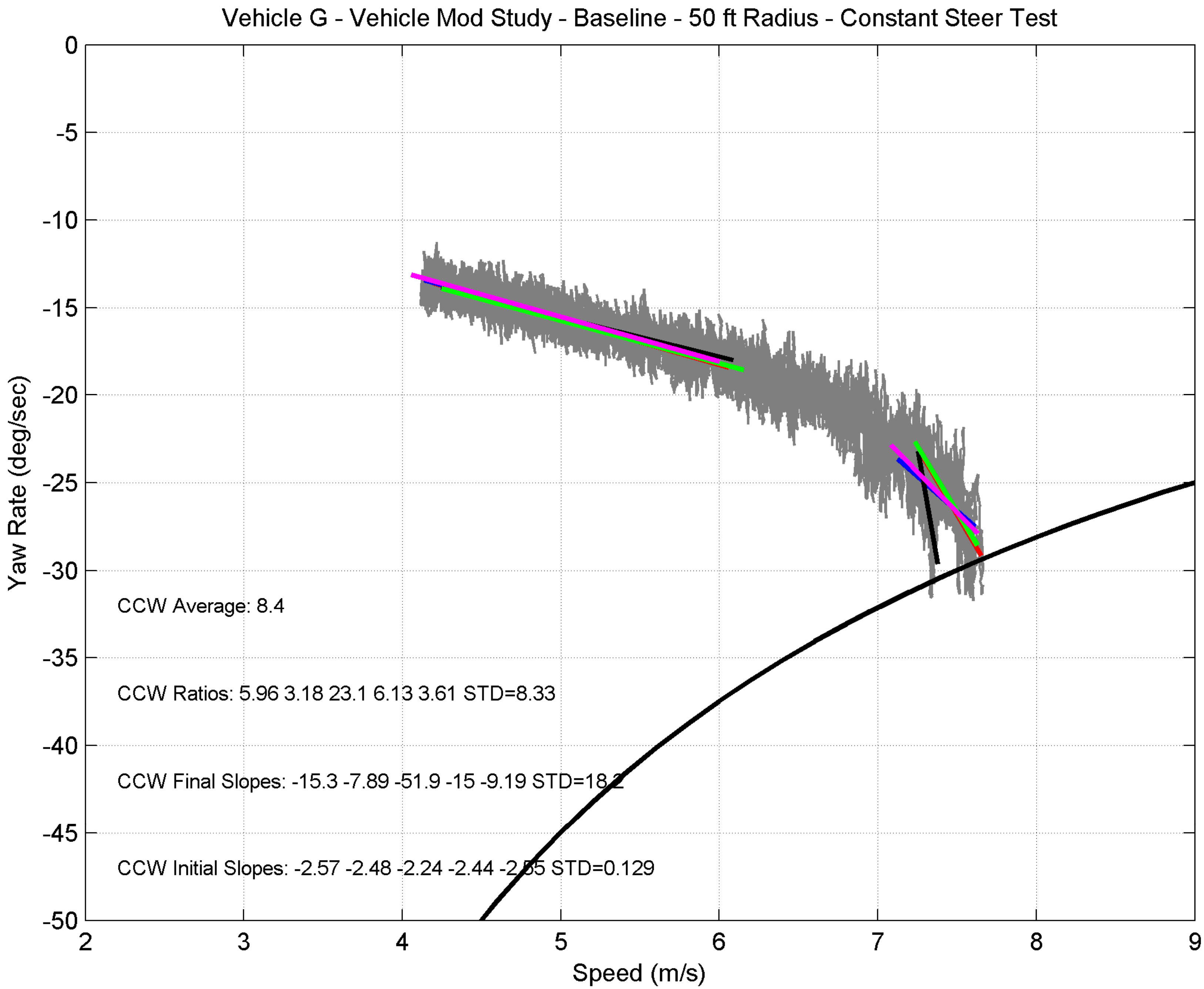
	Baseline	Mod 1	Mod 2	Mod 3
Northwest Runs	-0.469	-0.497	-0.540	-0.519
	-0.468	-0.488	-0.521	-0.517
	-0.468	-0.518	-0.524	-0.508
Mean Value of 3 Runs	-0.469	-0.501	-0.529	-0.515
Standard Deviation of 3 Runs	0.000	0.016	0.010	0.006

	Baseline	Mod 1	Mod 2	Mod 3
Southeast Runs	-0.453	-0.468	-0.493	-0.492
	-0.450	-0.469	-0.496	-0.499
	-0.447	-0.463	-0.494	-0.485
Mean Value of 3 Runs	-0.450	-0.467	-0.494	-0.492
Standard Deviation of 3 Runs	0.003	0.004	0.002	0.007
Average of All 6 Runs	**0.459**	**0.484**	**0.511**	**0.504**

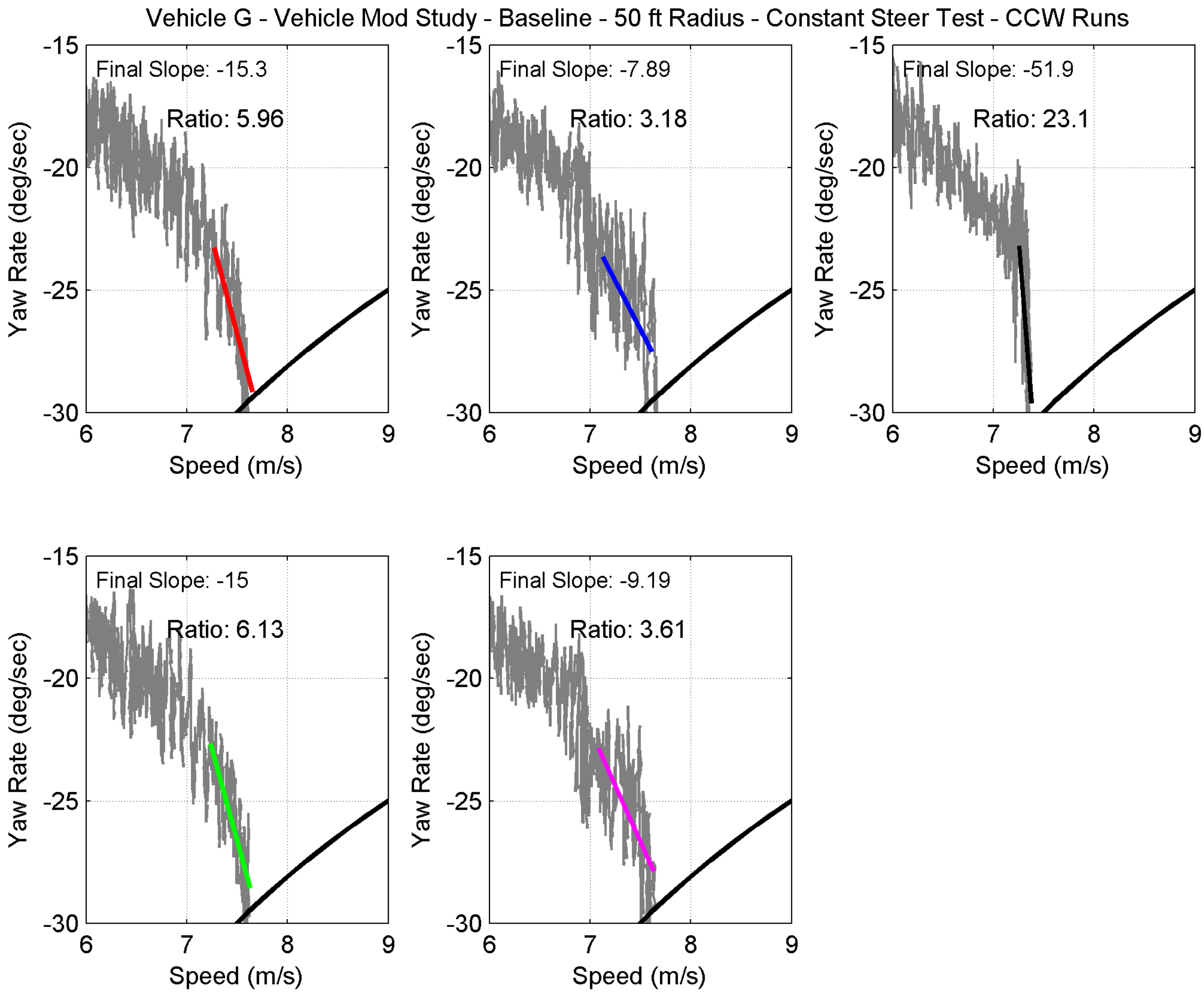


Vehicle G - Vehicle Mod Study - Baseline
50 ft Radius - Constant Steer Test
Roadwheel Steer Angle (deg)
0
-5
-10
-15
-20
0
20
40
60
80
100
Speed (m/s)
8
6
4
2
0
Roll Angle (deg)
15
10
5
0
-5
Estimated Ay (g)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
Time (sec)
Yaw Rate (deg/sec)
-20
-40
Time (sec)

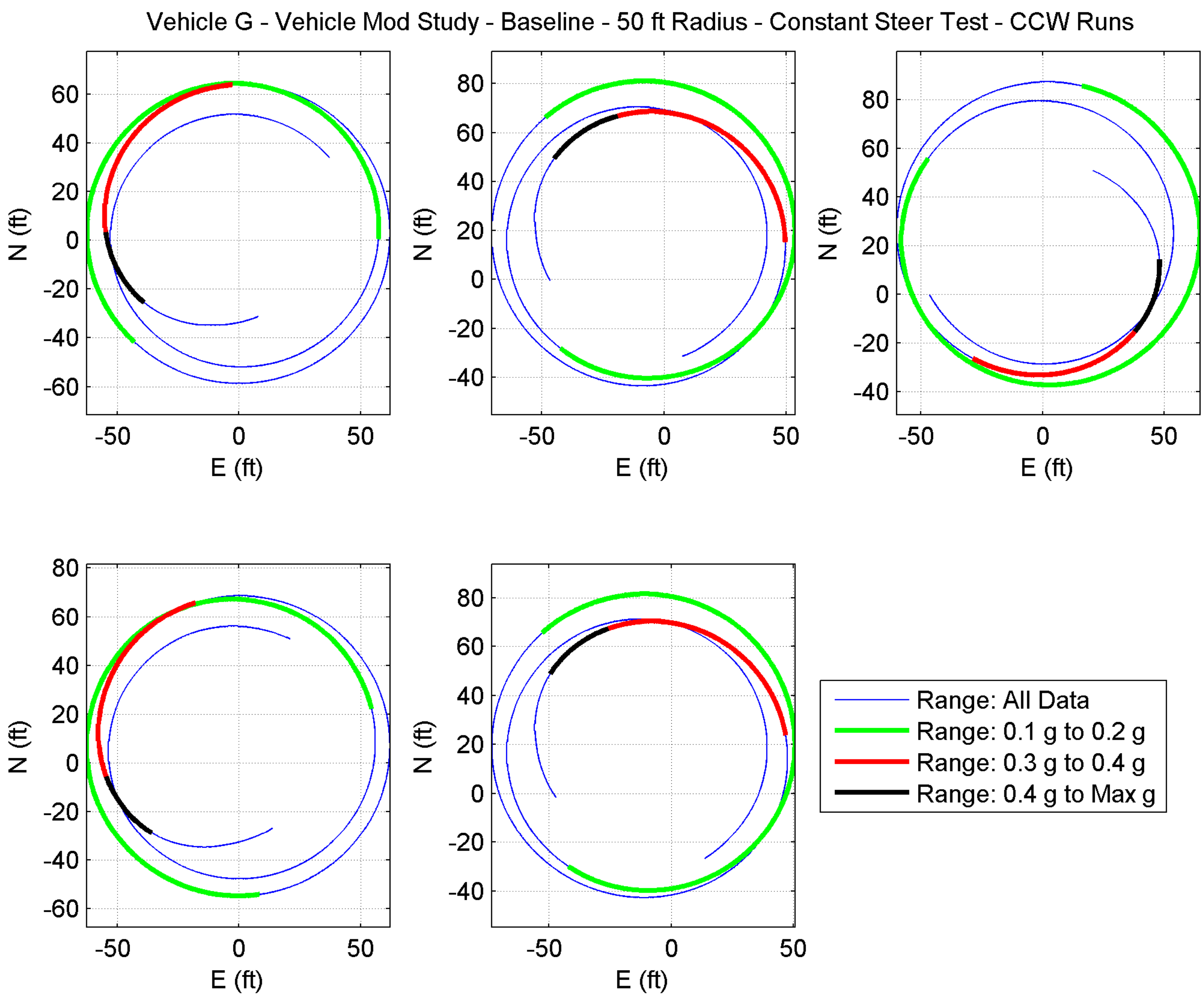

Vehicle G - Vehicle Mod Study - Baseline - 50 ft Radius - Constant Steer Test
Estimated Ay (g)
Speed (m/s)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
1
2
3
4
5
6
7
8
9

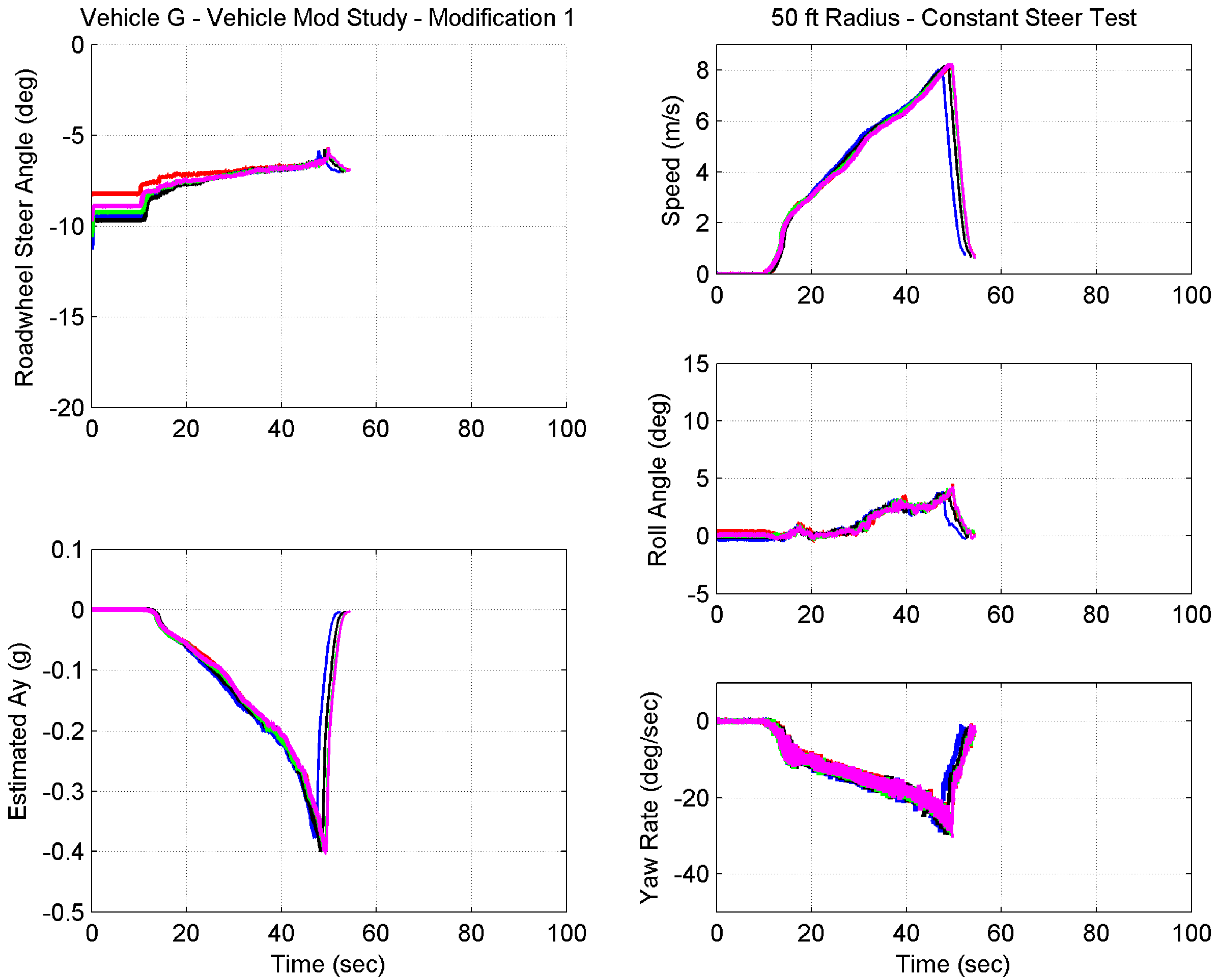


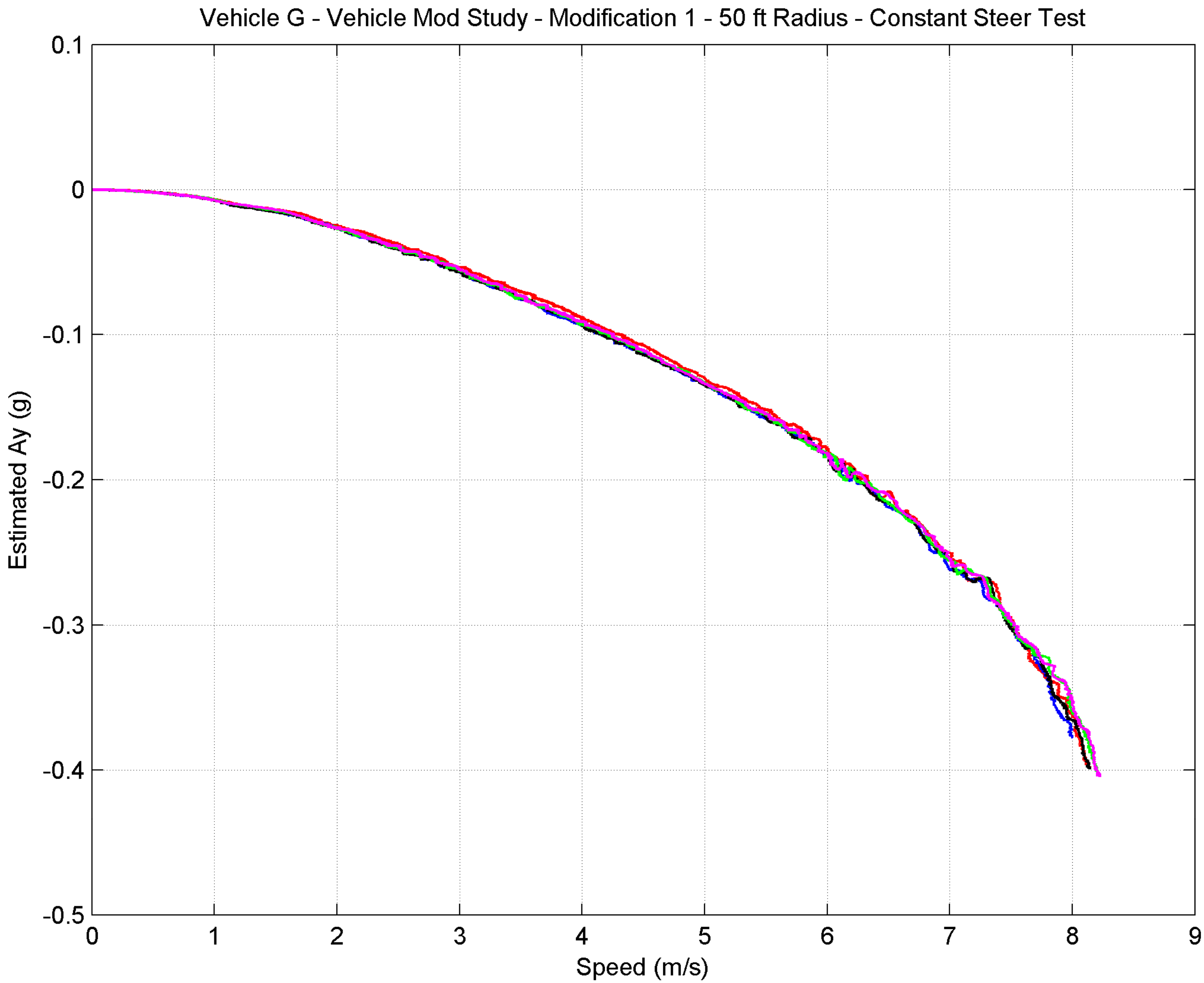
Vehicle G - Vehicle Mod Study - Baseline - 50 ft Radius - Constant Steer Test
Yaw Rate (deg/sec)
Speed (m/s)
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
2
3
4
5
6
7
8
9
CCW Average: 8.4
CCW Ratios: 5.96 3.18 23.1 6.13 3.61 STD=8.33
CCW Final Slopes: -15.3 -7.89 -51.9 -15 -9.19 STD=18.2
CCW Initial Slopes: -2.57 -2.48 -2.24 -2.44 -2.55 STD=0.129



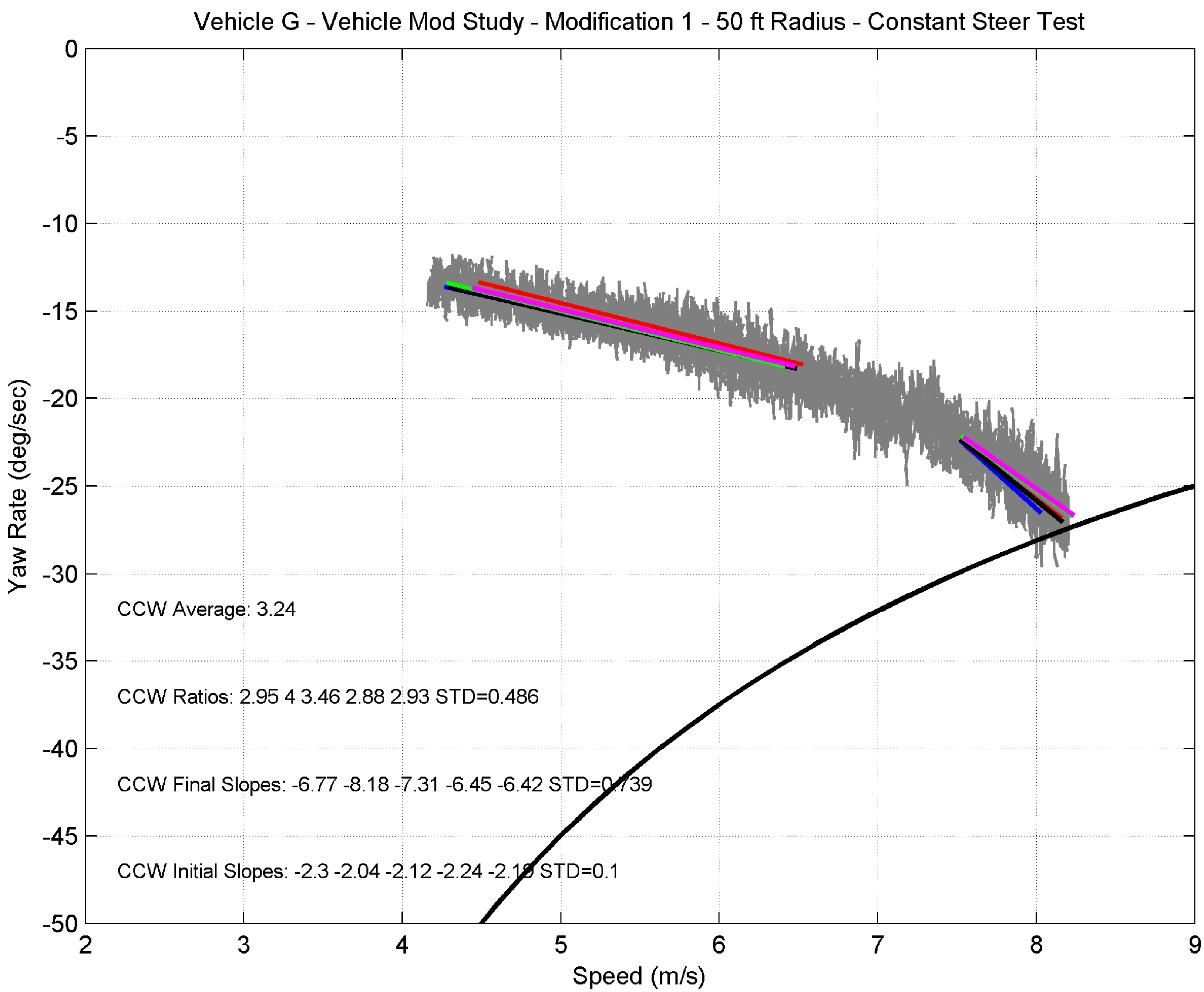
Vehicle G - Vehicle Mod Study - Baseline - 50 ft Radius - Constant Steer Test - CCW Runs
Final Slope: -15.3
Ratio: 5.96
Final Slope: -7.89
Ratio: 3.18
Final Slope: -51.9
Ratio: 23.1
Final Slope: -15
Ratio: 6.13
Final Slope: -9.19
Ratio: 3.61
Yaw Rate (deg/sec)
Speed (m/s)
-15
-20
-25
-30
6
7
8
9


Vehicle G - Vehicle Mod Study - Baseline - 50 ft Radius - Constant Steer Test - CCW Runs
N (ft)
E (ft)
Range: All Data
Range: 0.1 g to 0.2 g
Range: 0.3 g to 0.4 g
Range: 0.4 g to Max g

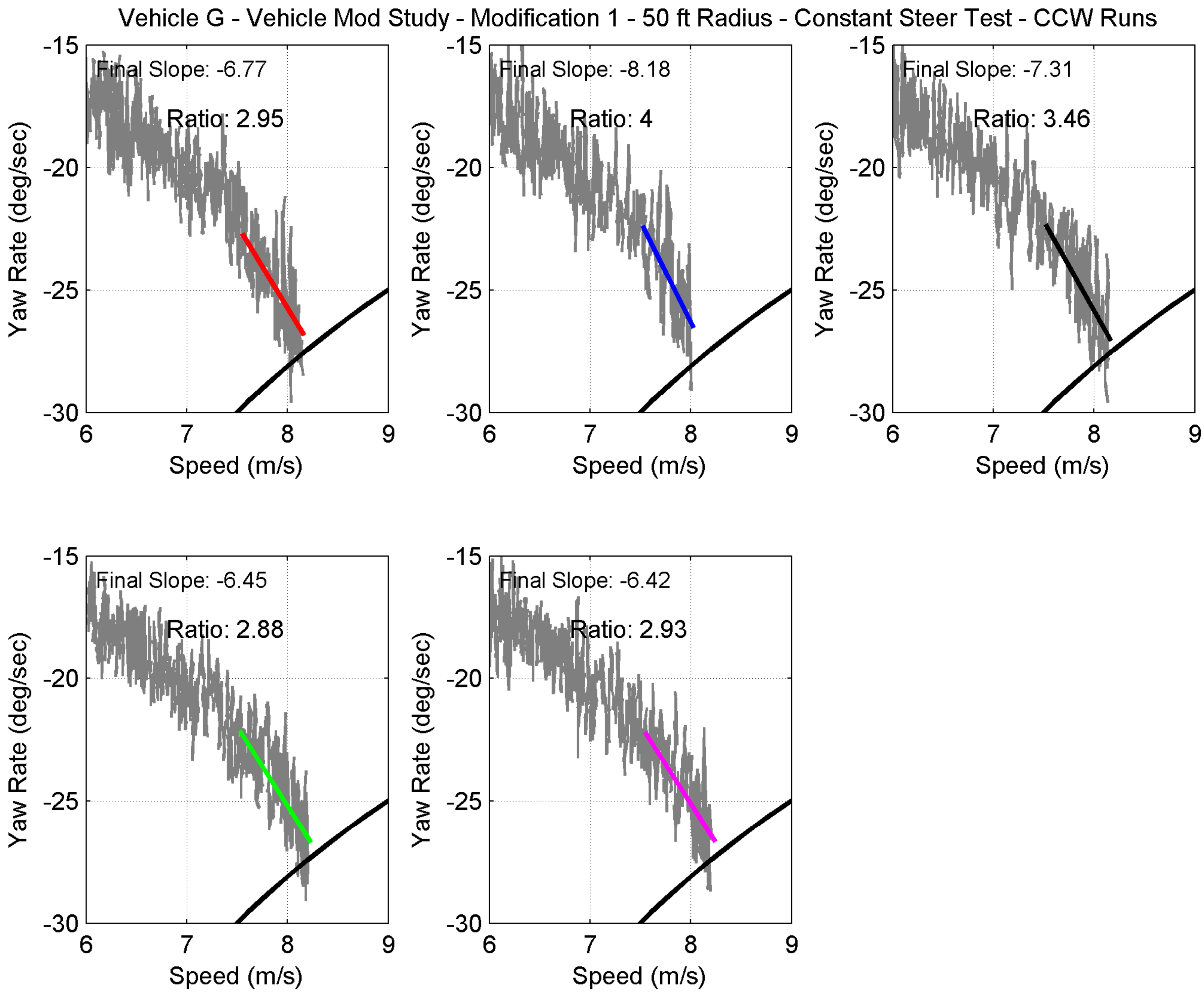

Vehicle G - Vehicle Mod Study - Modification 1
50 ft Radius - Constant Steer Test
Roadwheel Steer Angle (deg)
Speed (m/s)
Roll Angle (deg)
Estimated Ay (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)



Vehicle G - Vehicle Mod Study - Modification 1 - 50 ft Radius - Constant Steer Test
Estimated Ay (g)
Speed (m/s)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
1
2
3
4
5
6
7
8
9

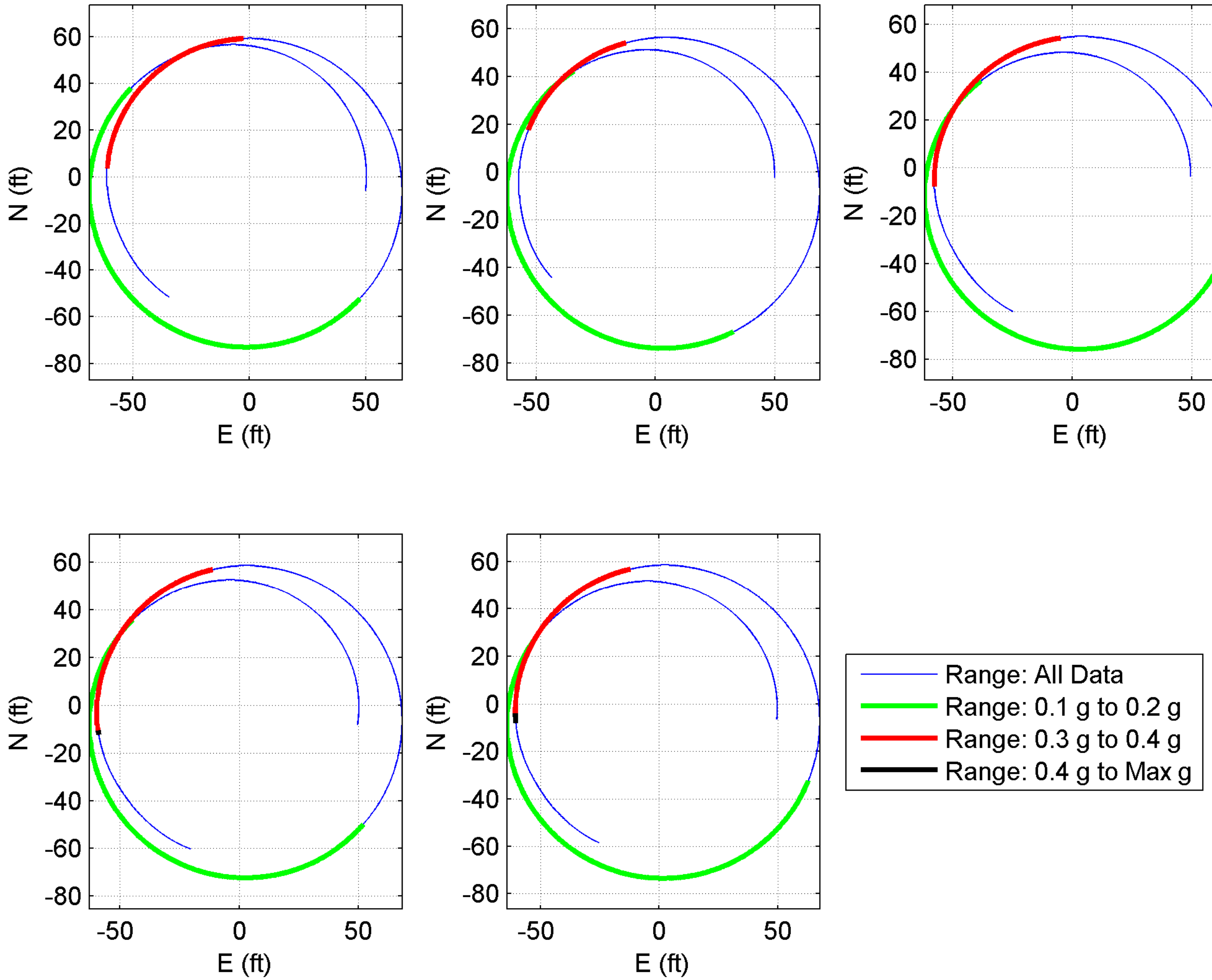


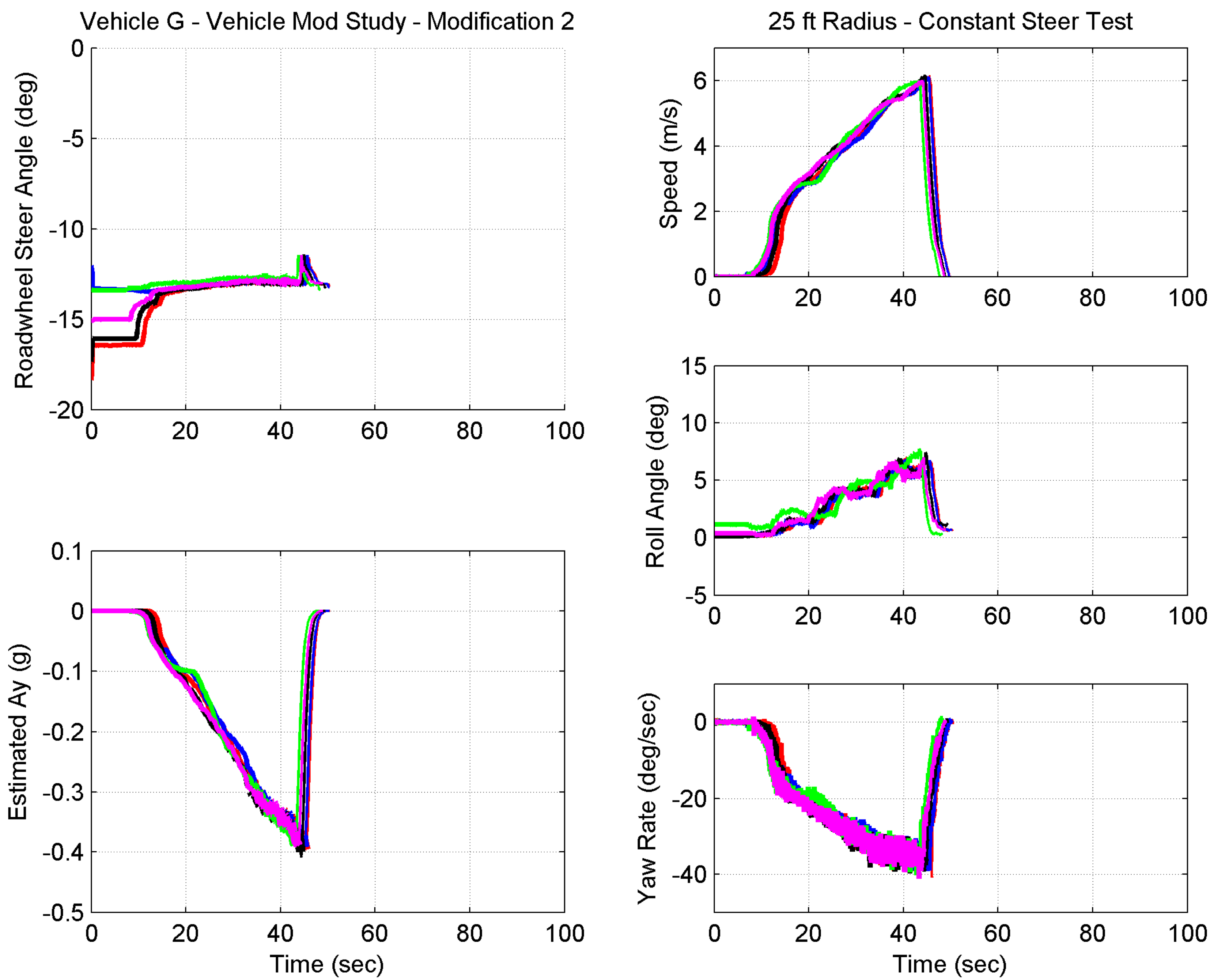
Vehicle G - Vehicle Mod Study - Modification 1 - 50 ft Radius - Constant Steer Test
Yaw Rate (deg/sec)
Speed (m/s)
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
2
3
4
5
6
7
8
9
CCW Average: 3.24
CCW Ratios: 2.95 4 3.46 2.88 2.93 STD=0.486
CCW Final Slopes: -6.77 -8.18 -7.31 -6.45 -6.42 STD=0.739
CCW Initial Slopes: -2.3 -2.04 -2.12 -2.24 -2.19 STD=0.1



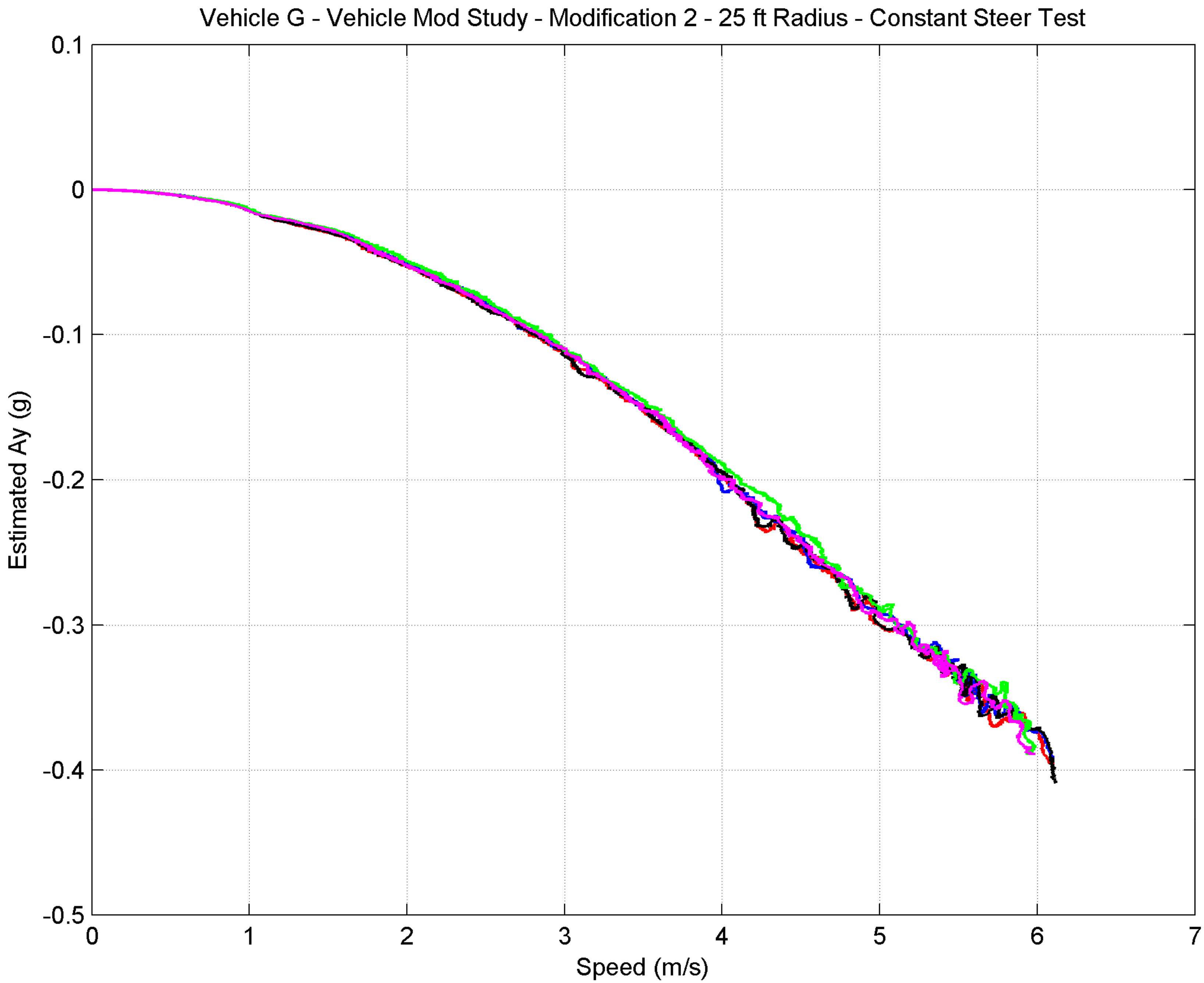
Vehicle G - Vehicle Mod Study - Modification 1 - 50 ft Radius - Constant Steer Test - CCW Runs
Final Slope: -6.77
Ratio: 2.95
Final Slope: -8.18
Ratio: 4
Final Slope: -7.31
Ratio: 3.46
Final Slope: -6.45
Ratio: 2.88
Final Slope: -6.42
Ratio: 2.93
Yaw Rate (deg/sec)
Speed (m/s)
-15
-20
-25
-30
6
7
8
9

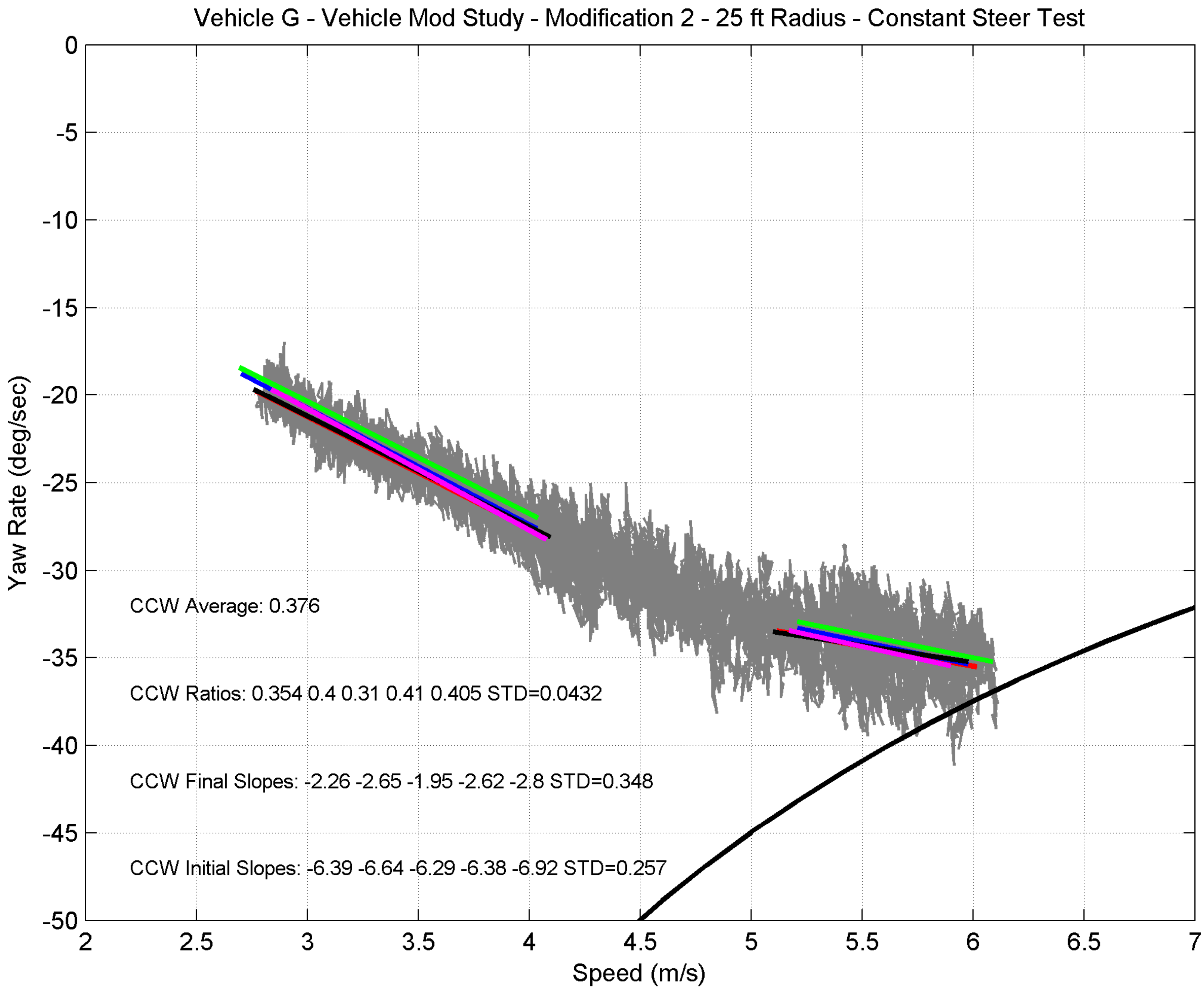
Vehicle G - Vehicle Mod Study - Modification 1 - 50 ft Radius - Constant Steer Test - CCW Runs





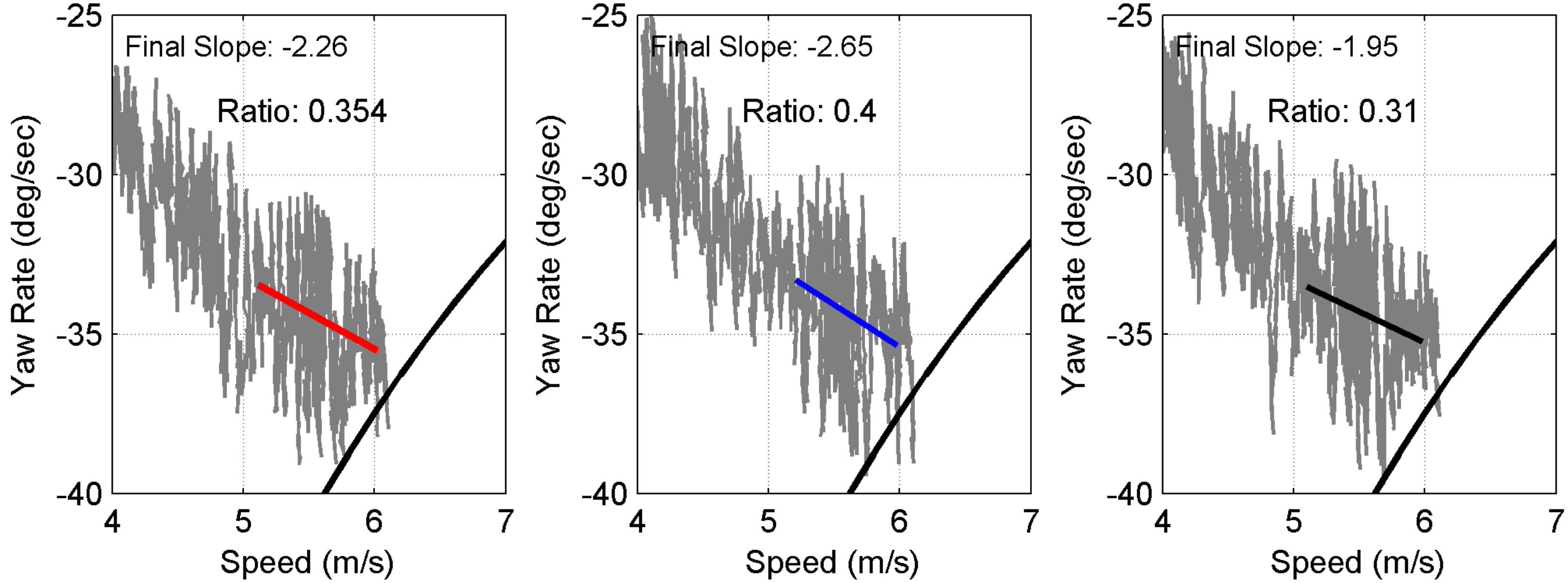
Vehicle G - Vehicle Mod Study - Modification 2
25 ft Radius - Constant Steer Test
Roadwheel Steer Angle (deg)
0
-5
-10
-15
-20
0
20
40
60
80
100
Speed (m/s)
6
4
2
0
Roll Angle (deg)
15
10
5
0
-5
Estimated Ay (g)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
Yaw Rate (deg/sec)
0
-20
-40
Time (sec)
Time (sec)

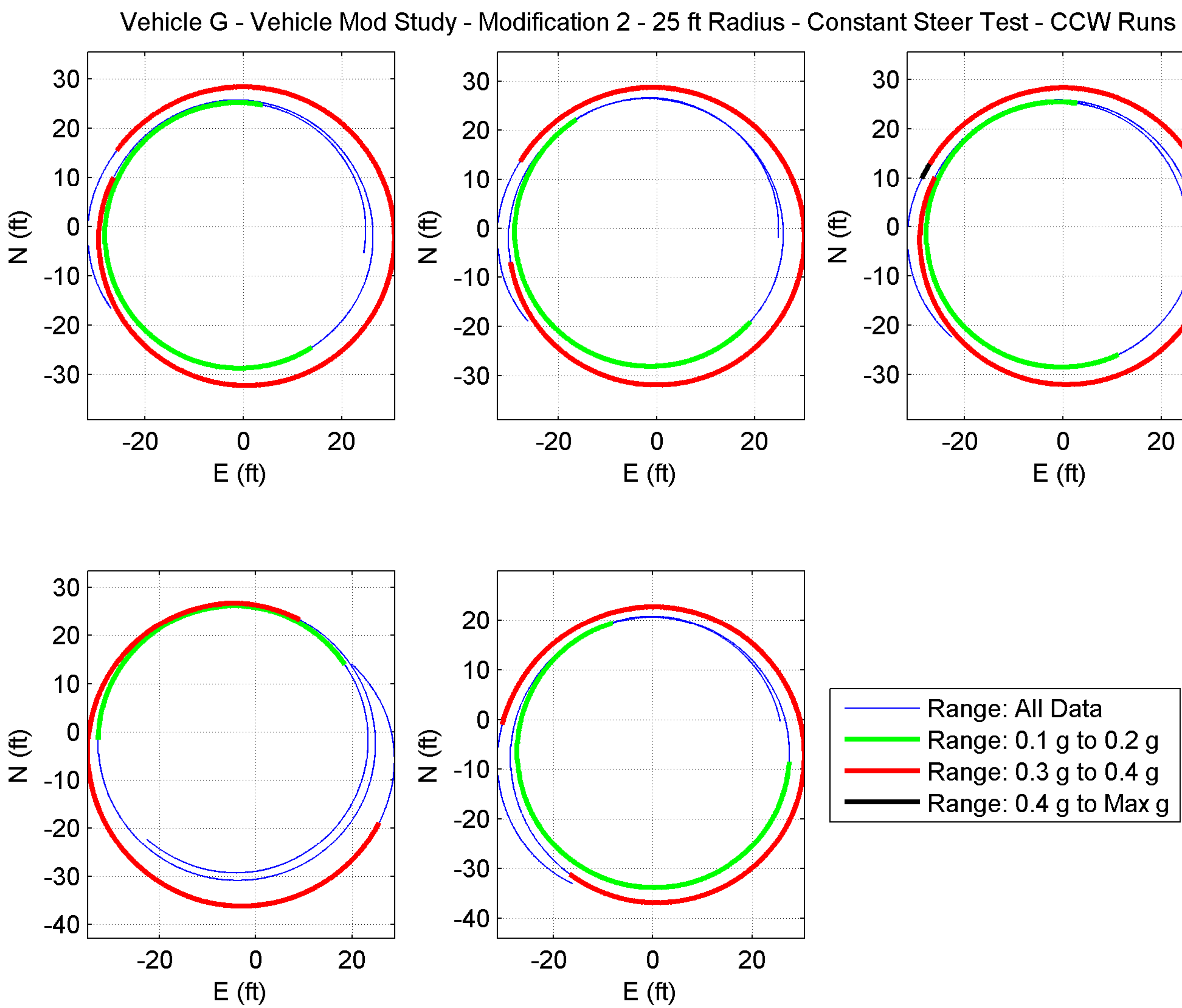

Vehicle G - Vehicle Mod Study - Modification 2 - 25 ft Radius - Constant Steer Test
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
Estimated Ay (g)
0
1
2
3
4
5
6
7
Speed (m/s)



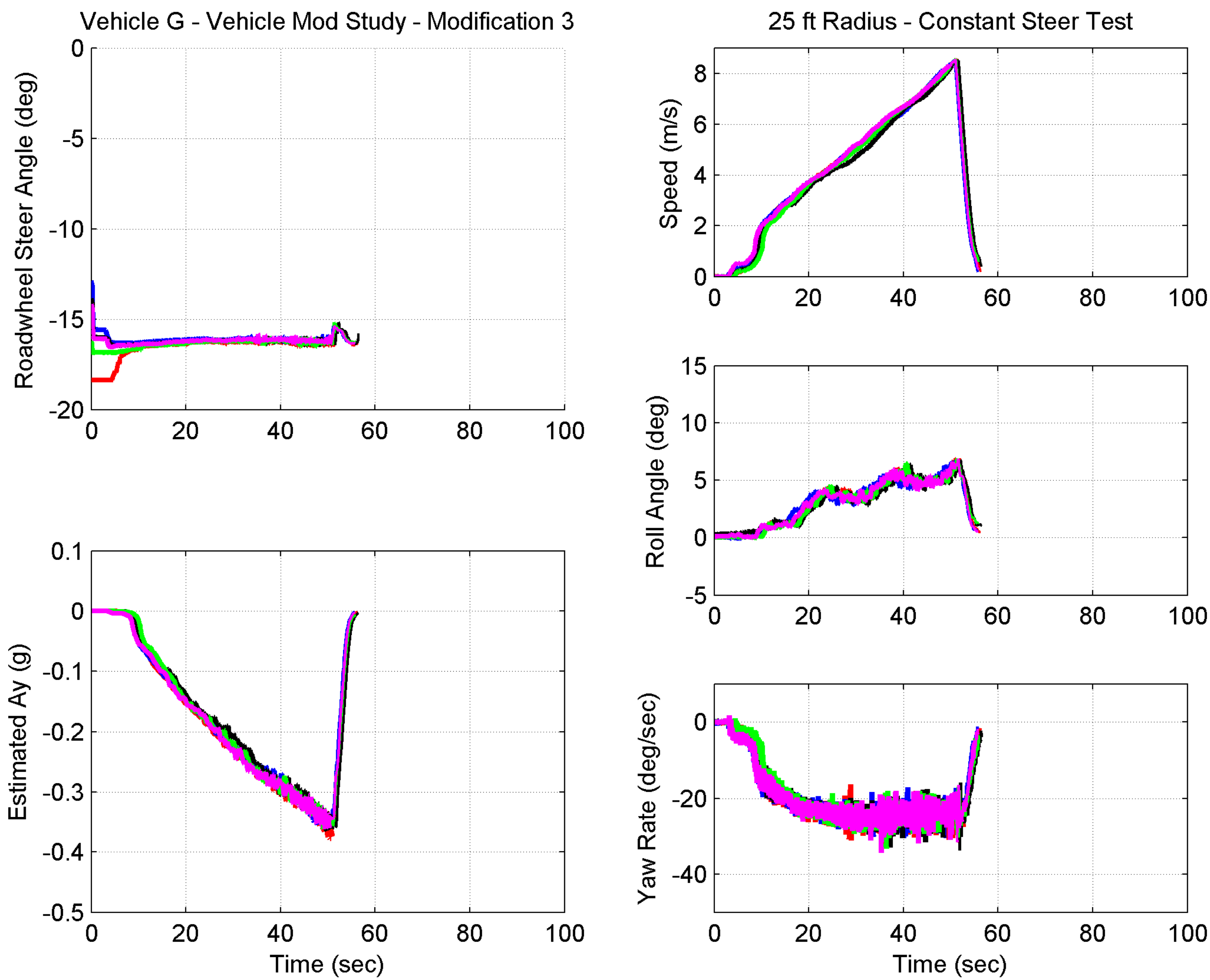
Vehicle G - Vehicle Mod Study - Modification 2 - 25 ft Radius - Constant Steer Test
Yaw Rate (deg/sec)
Speed (m/s)
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
CCW Average: 0.376
CCW Ratios: 0.354 0.4 0.31 0.41 0.405 STD=0.0432
CCW Final Slopes: -2.26 -2.65 -1.95 -2.62 -2.8 STD=0.348
CCW Initial Slopes: -6.39 -6.64 -6.29 -6.38 -6.92 STD=0.257

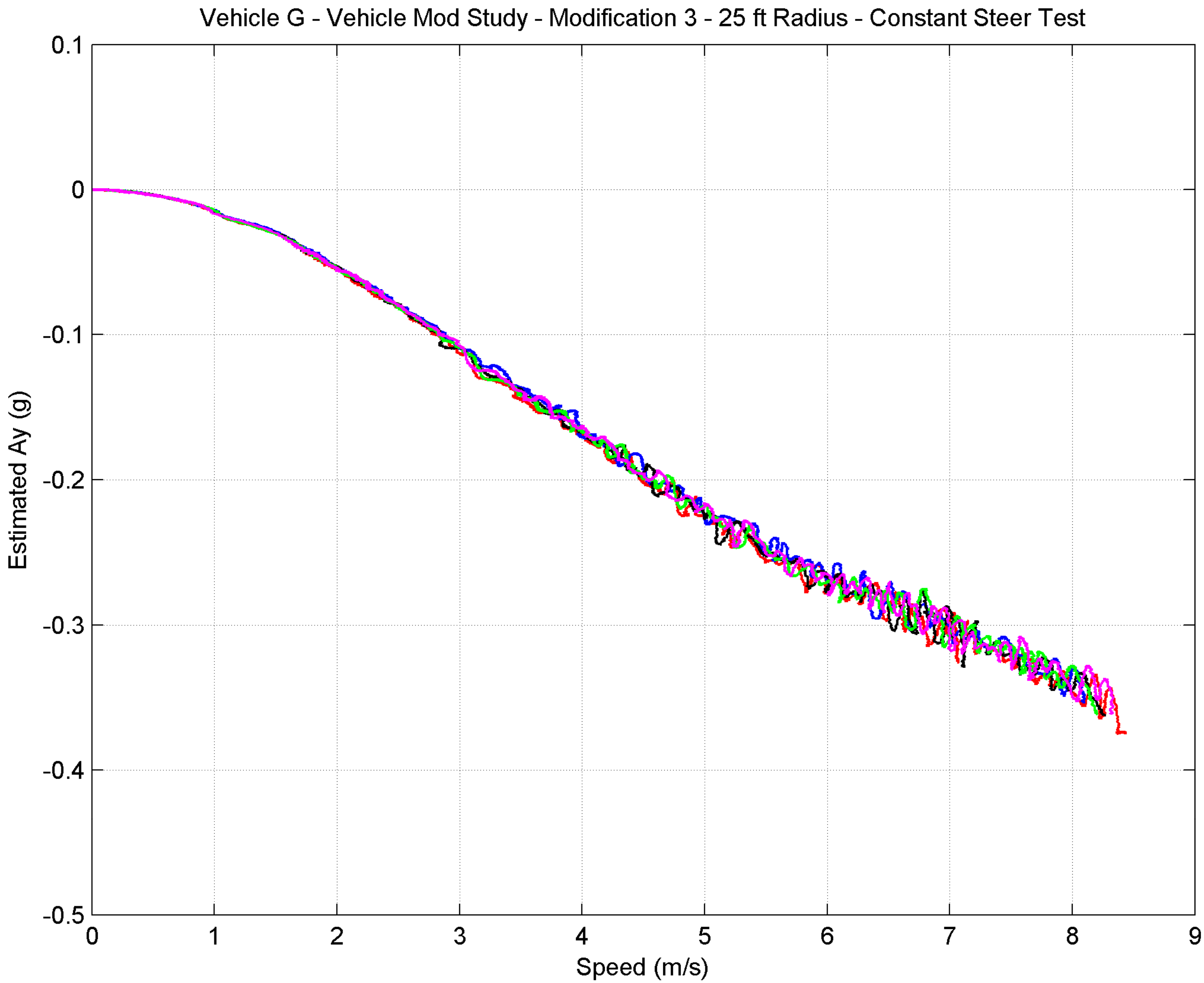
Vehicle G - Vehicle Mod Study - Modification 2 - 25 ft Radius - Constant Steer Test - CCW Runs

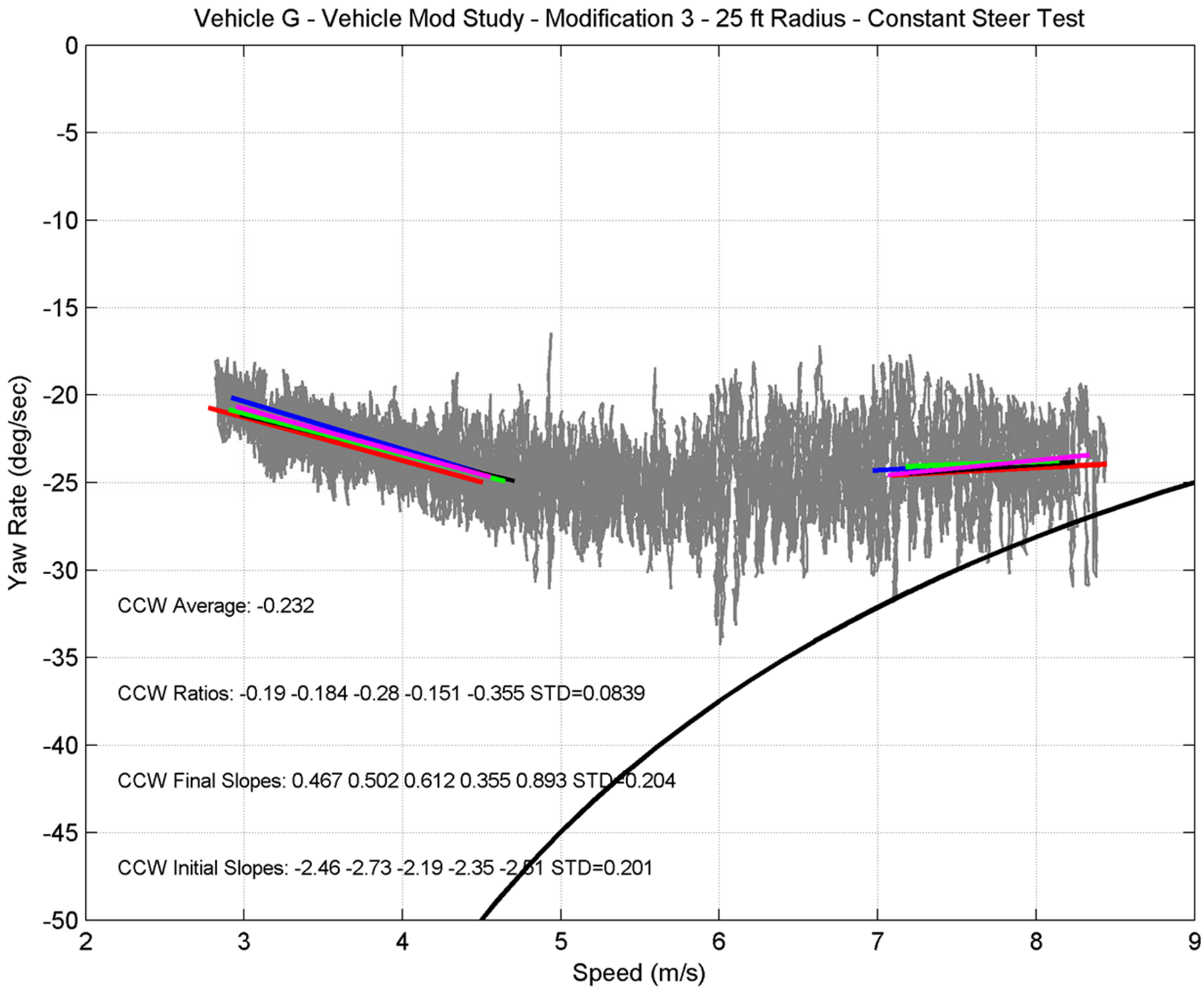


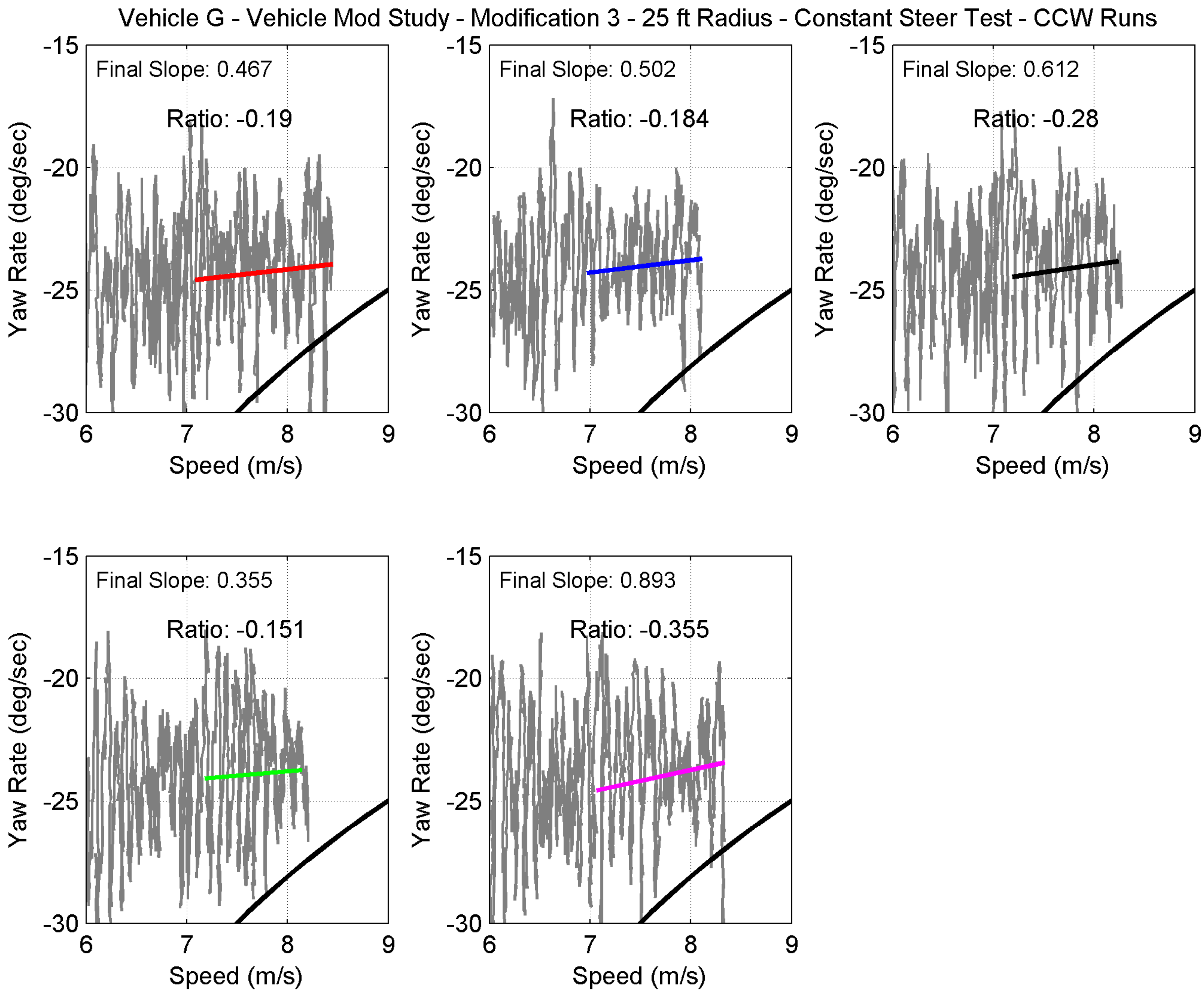


Vehicle G - Vehicle Mod Study - Modification 2 - 25 ft Radius - Constant Steer Test - CCW Runs
N (ft)
E (ft)
Range: All Data
Range: 0.1 g to 0.2 g
Range: 0.3 g to 0.4 g
Range: 0.4 g to Max g

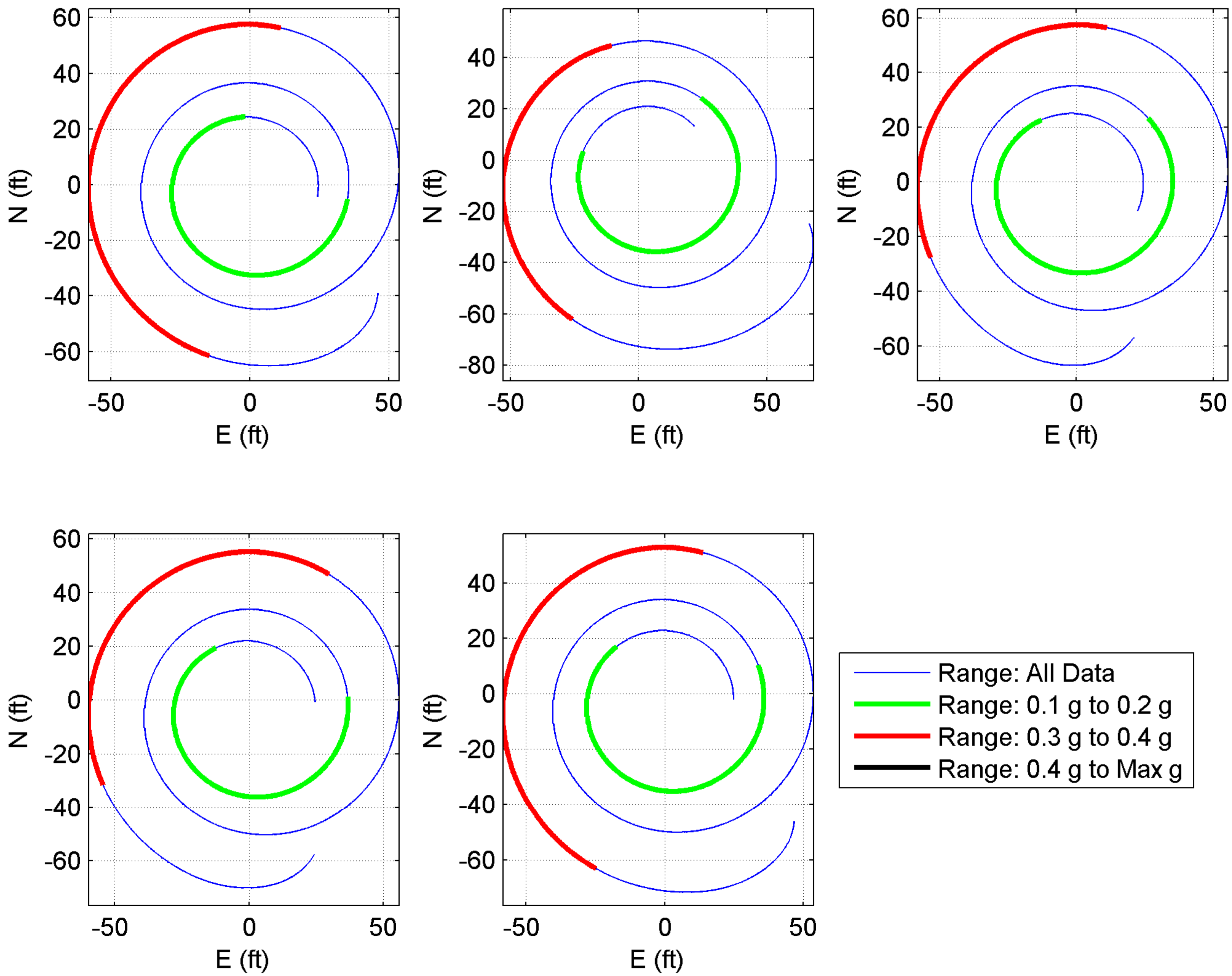

Vehicle G - Vehicle Mod Study - Modification 3
25 ft Radius - Constant Steer Test
Roadwheel Steer Angle (deg)
Speed (m/s)
Roll Angle (deg)
Estimated Ay (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)


Vehicle G - Vehicle Mod Study - Modification 3 - 25 ft Radius - Constant Steer Test
Estimated Ay (g)
Speed (m/s)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
1
2
3
4
5
6
7
8
9


Vehicle G - Vehicle Mod Study - Modification 3 - 25 ft Radius - Constant Steer Test
Yaw Rate (deg/sec)
Speed (m/s)
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
2
3
4
5
6
7
8
9
CCW Average: -0.232
CCW Ratios: -0.19 -0.184 -0.28 -0.151 -0.355 STD=0.0839
CCW Final Slopes: 0.467 0.502 0.612 0.355 0.893 STD=0.204
CCW Initial Slopes: -2.46 -2.73 -2.19 -2.35 -2.51 STD=0.201


Vehicle G - Vehicle Mod Study - Modification 3 - 25 ft Radius - Constant Steer Test - CCW Runs
Final Slope: 0.467
Ratio: -0.19
Final Slope: 0.502
Ratio: -0.184
Final Slope: 0.612
Ratio: -0.28
Final Slope: 0.355
Ratio: -0.151
Final Slope: 0.893
Ratio: -0.355
Yaw Rate (deg/sec)
Speed (m/s)
-15
-20
-25
-30
6
7
8
9

Vehicle G - Vehicle Mod Study - Modification 3 - 25 ft Radius - Constant Steer Test - CCW Runs



Vehicle Modification Study

Results for Vehicle K

Baseline: Driver Plus Instrumentation (DPI) Loading 0° Rider (Driver) Lean

All Modification Testing Conducted With:

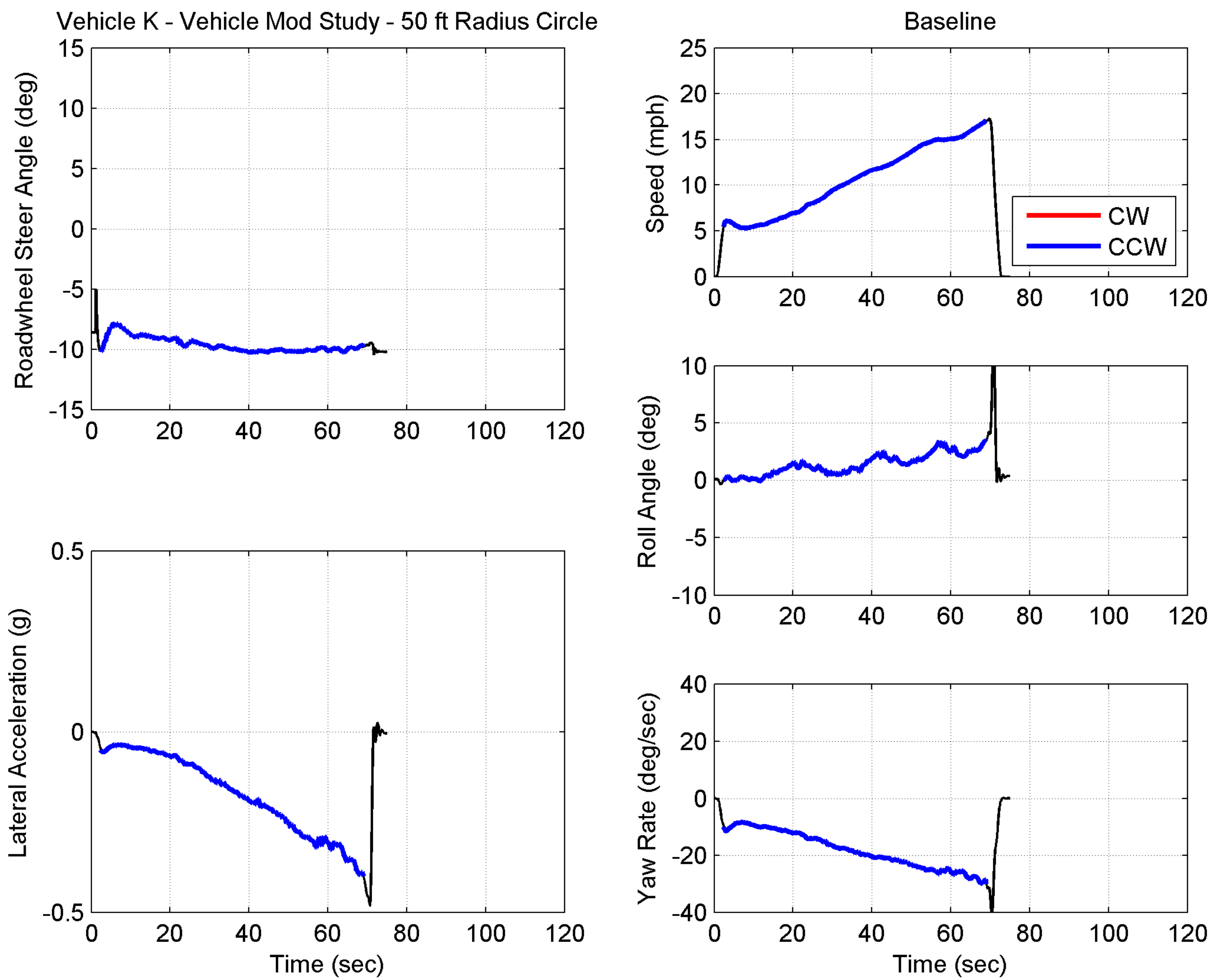
- Driver Plus Instrumentation (DPI) Loading 0° Rider (Driver) Lean
- Vehicle Equipped with Selectable "Locked" or "Open" Rear Differential
- Left Turn/CCW and Right Turn/CW Directions

Mod 1: Tested on **Asphalt** with **Locked** Rear Differential

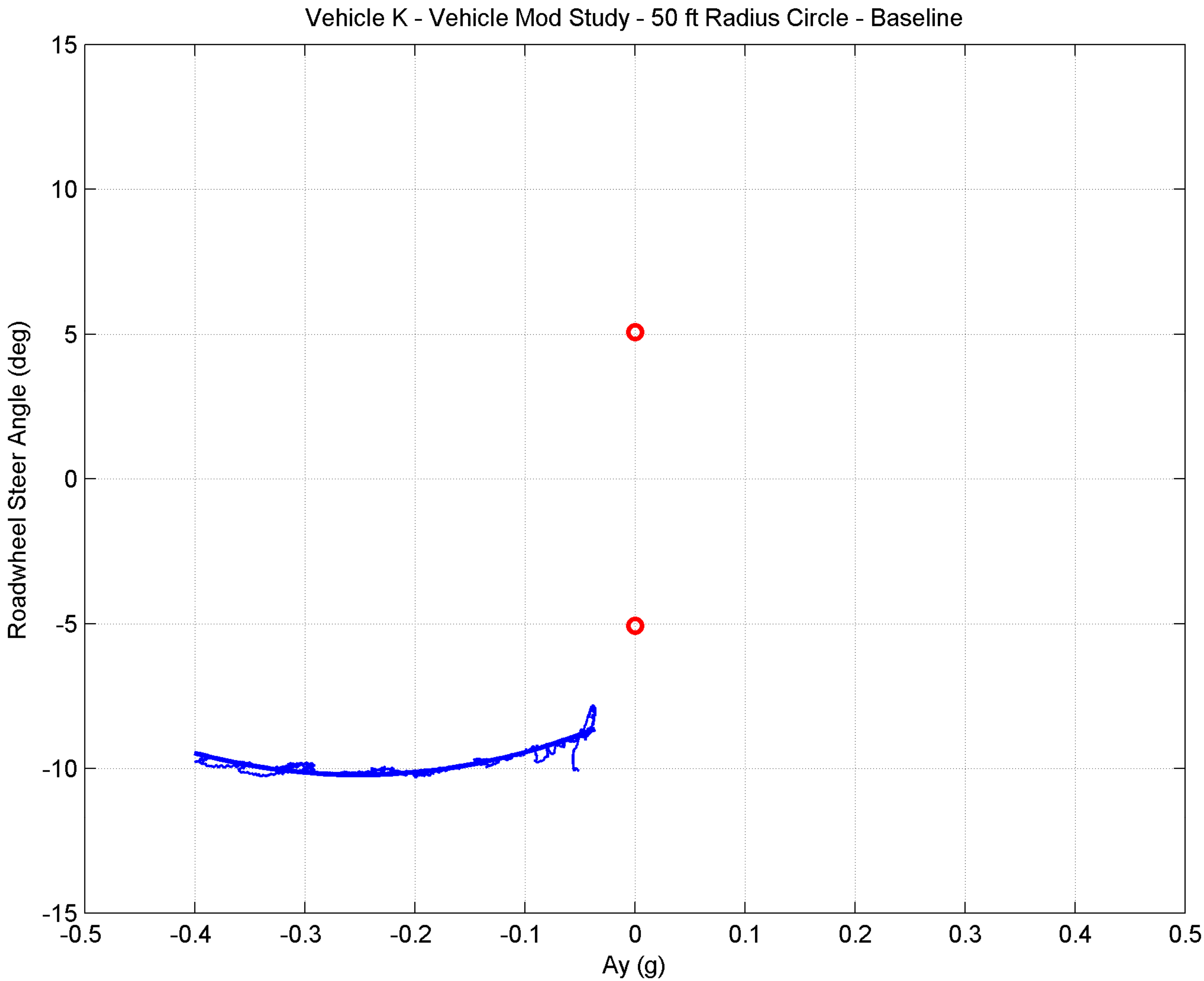
Mod 2: Tested on **Asphalt** with **Open** Rear Differential

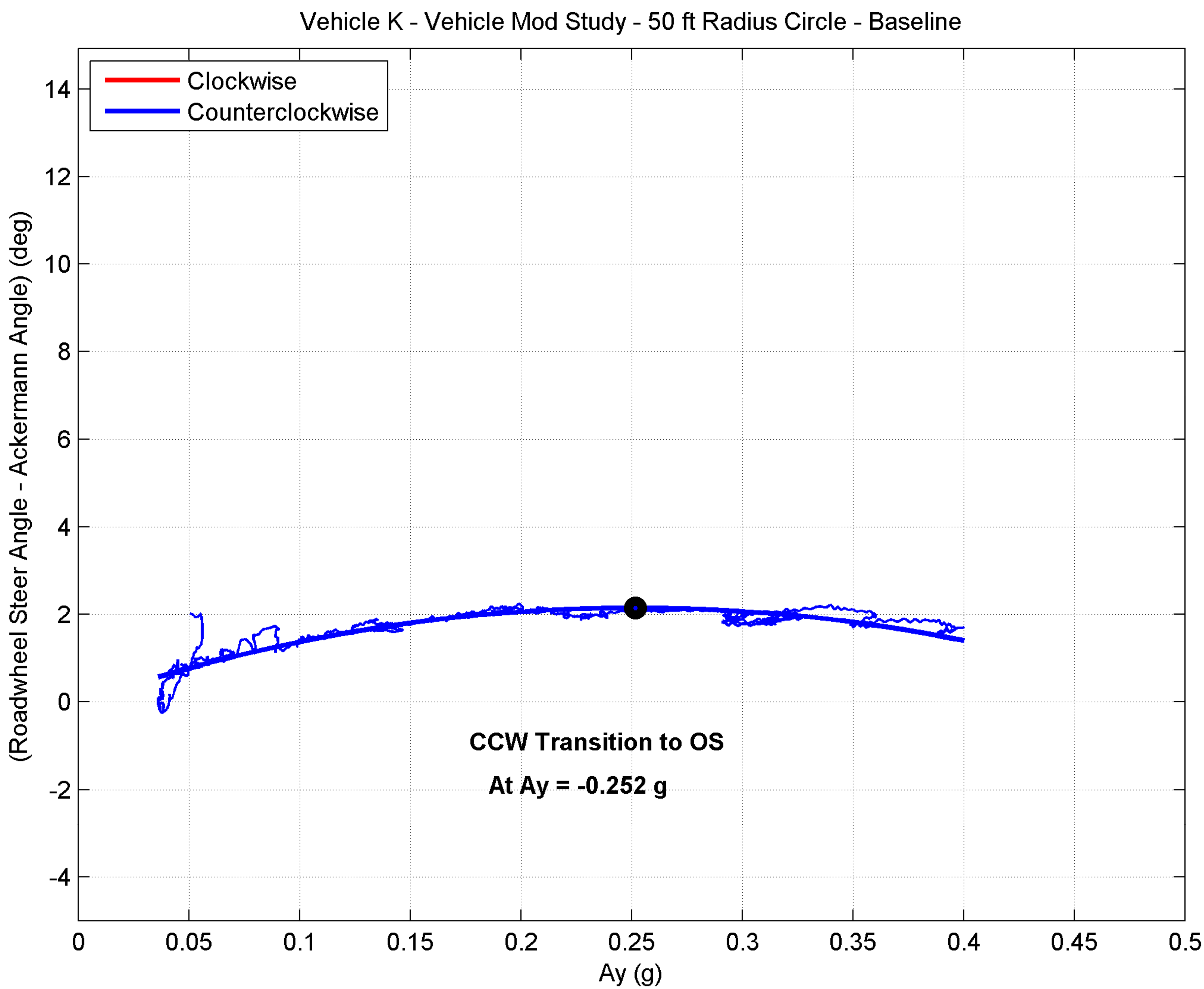
Mod 3: Tested on **Groomed Dirt** with **Locked** Rear Differential

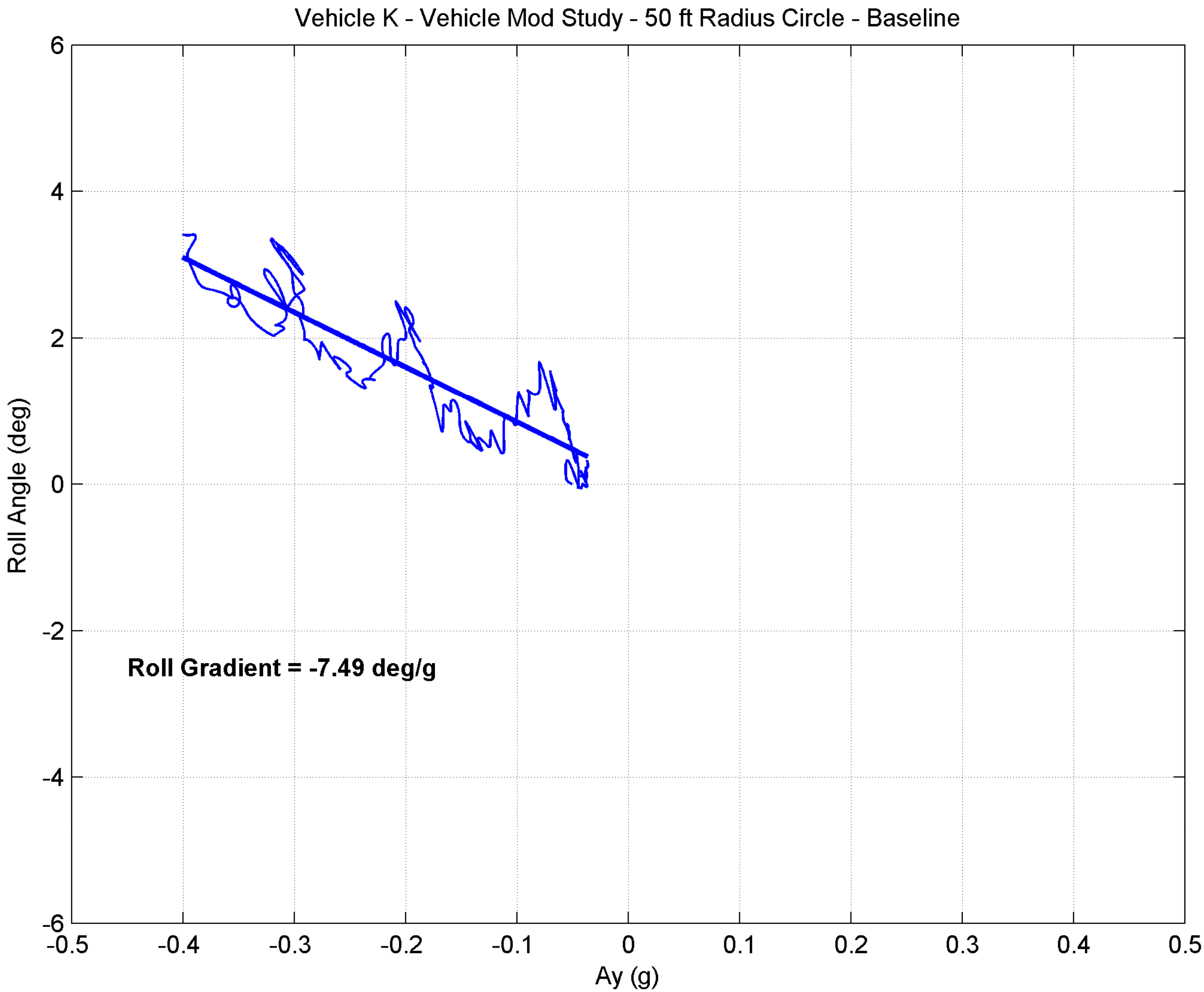
Mod 4: Tested on **Groomed Dirt** with **Open** Rear Differential

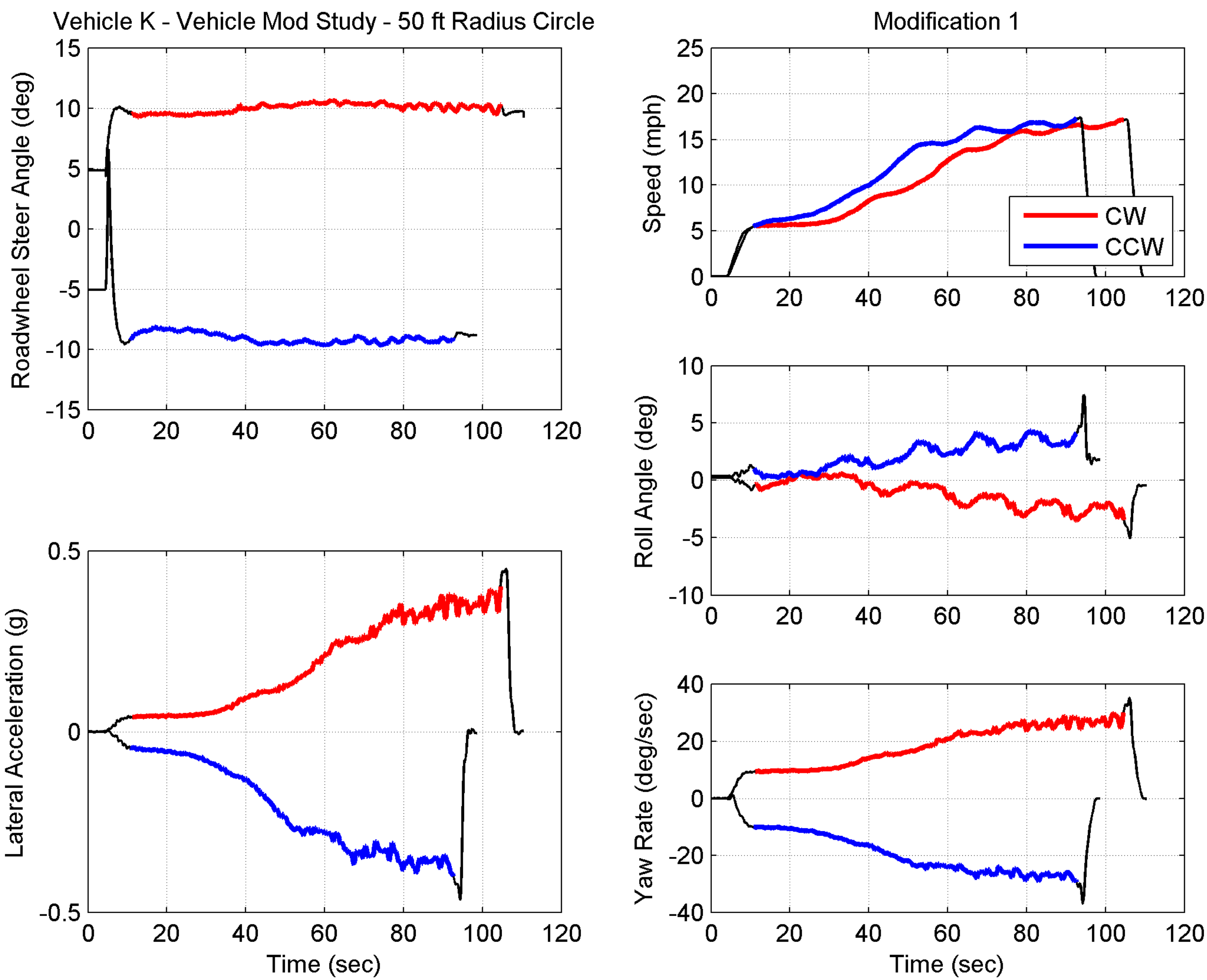


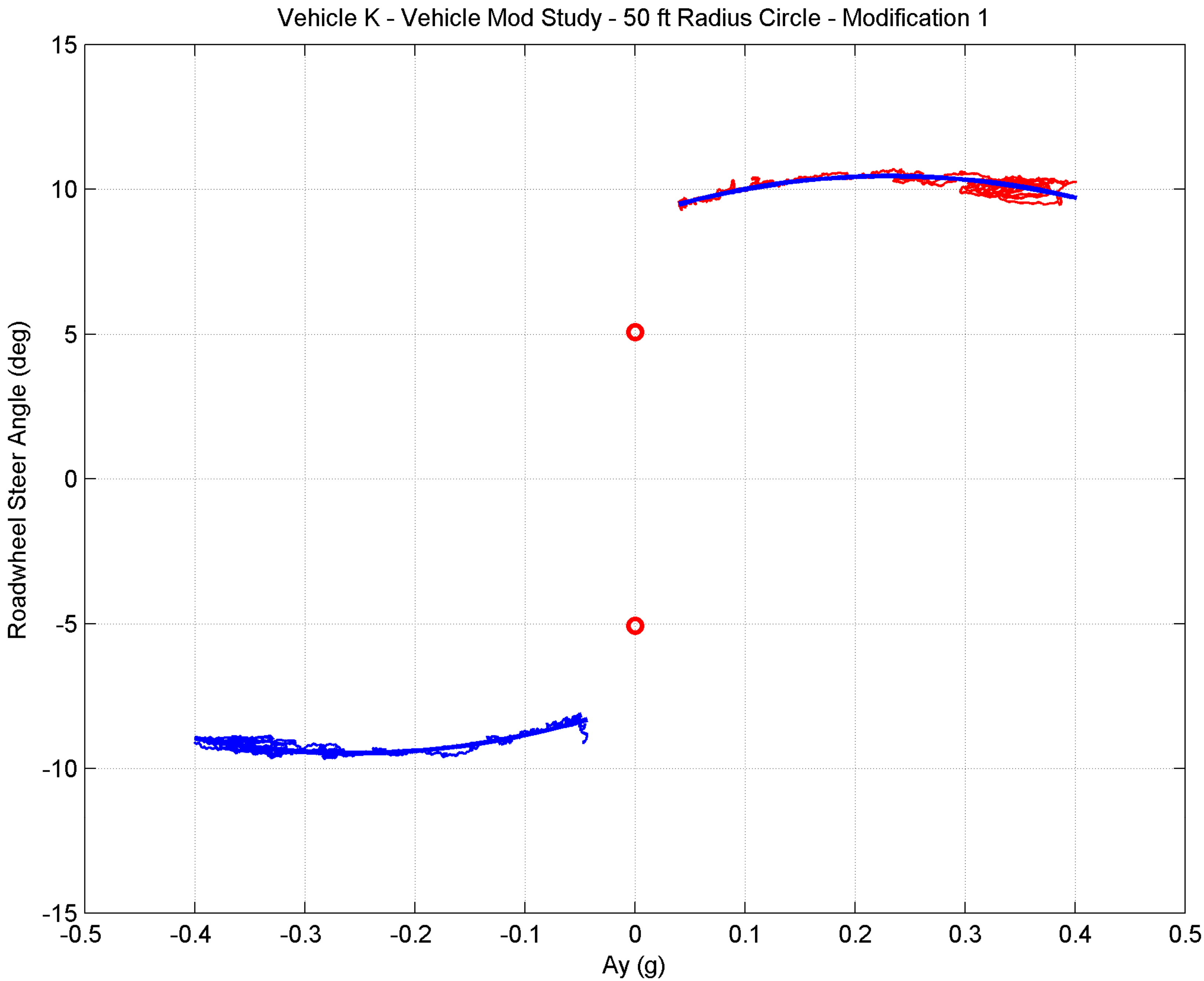
Vehicle K - Vehicle Mod Study - 50 ft Radius Circle
Baseline
Roadwheel Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

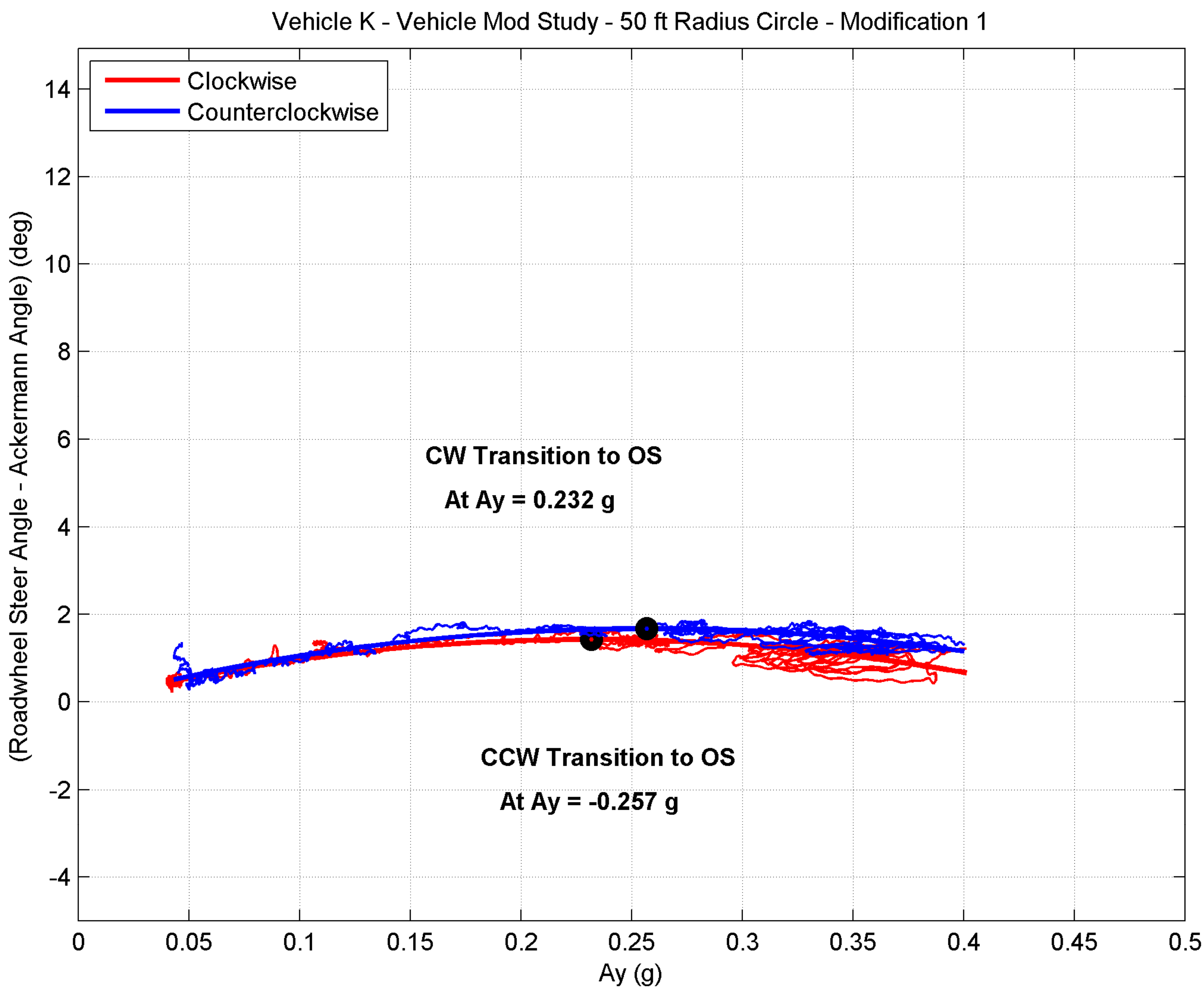

Vehicle K - Vehicle Mod Study - 50 ft Radius Circle - Baseline
Roadwheel Steer Angle (deg)
Ay (g)
15
10
5
0
-5
-10
-15
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5


Vehicle K - Vehicle Mod Study - 50 ft Radius Circle - Baseline
Clockwise
Counterclockwise
14
12
10
8
6
4
2
0
-2
-4
(Roadwheel Steer Angle - Ackermann Angle) (deg)
CCW Transition to OS
At Ay = -0.252 g
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Ay (g)

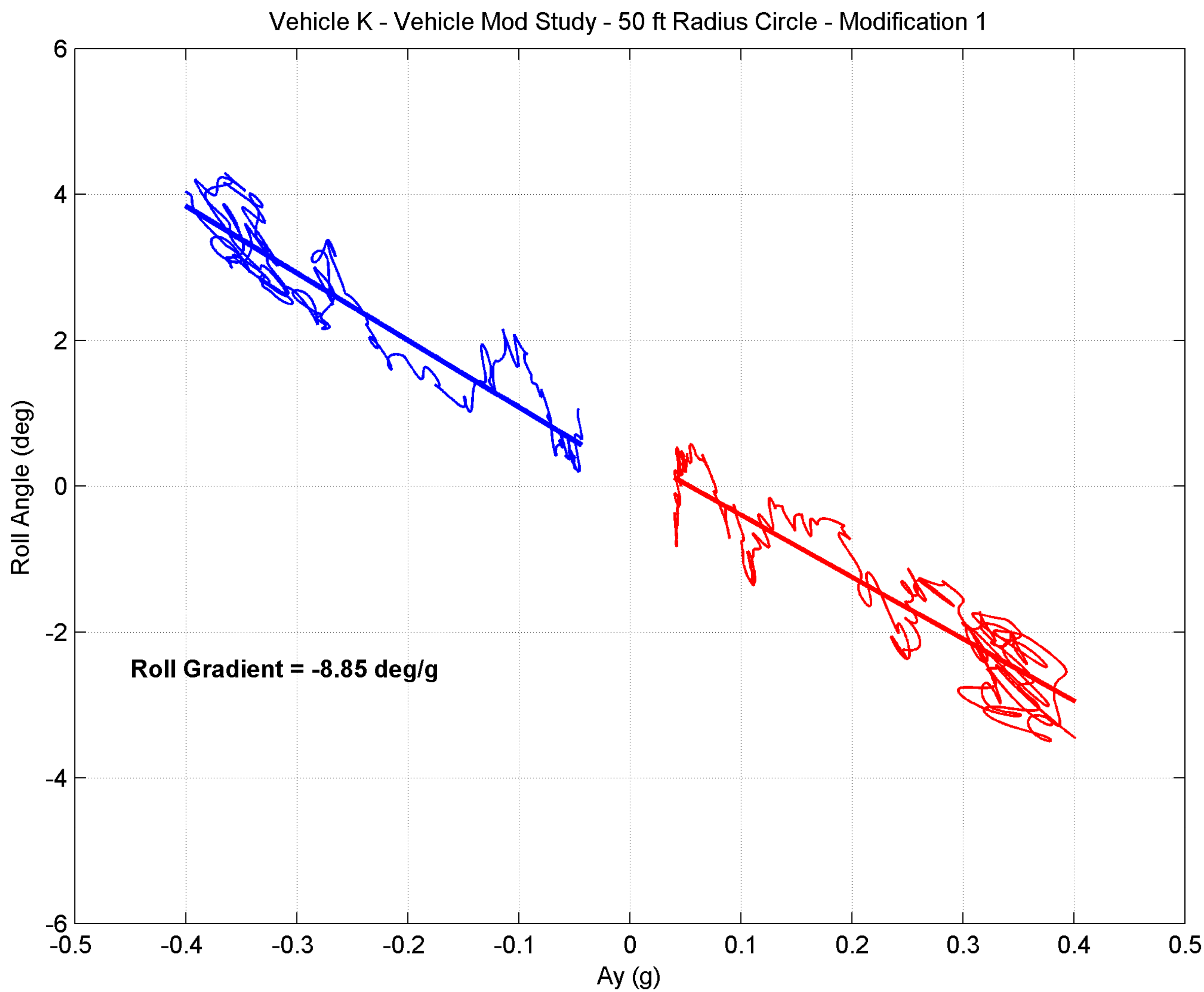

Vehicle K - Vehicle Mod Study - 50 ft Radius Circle - Baseline
6
4
2
0
-2
-4
-6
Roll Angle (deg)
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
Ay (g)
Roll Gradient = -7.49 deg/g

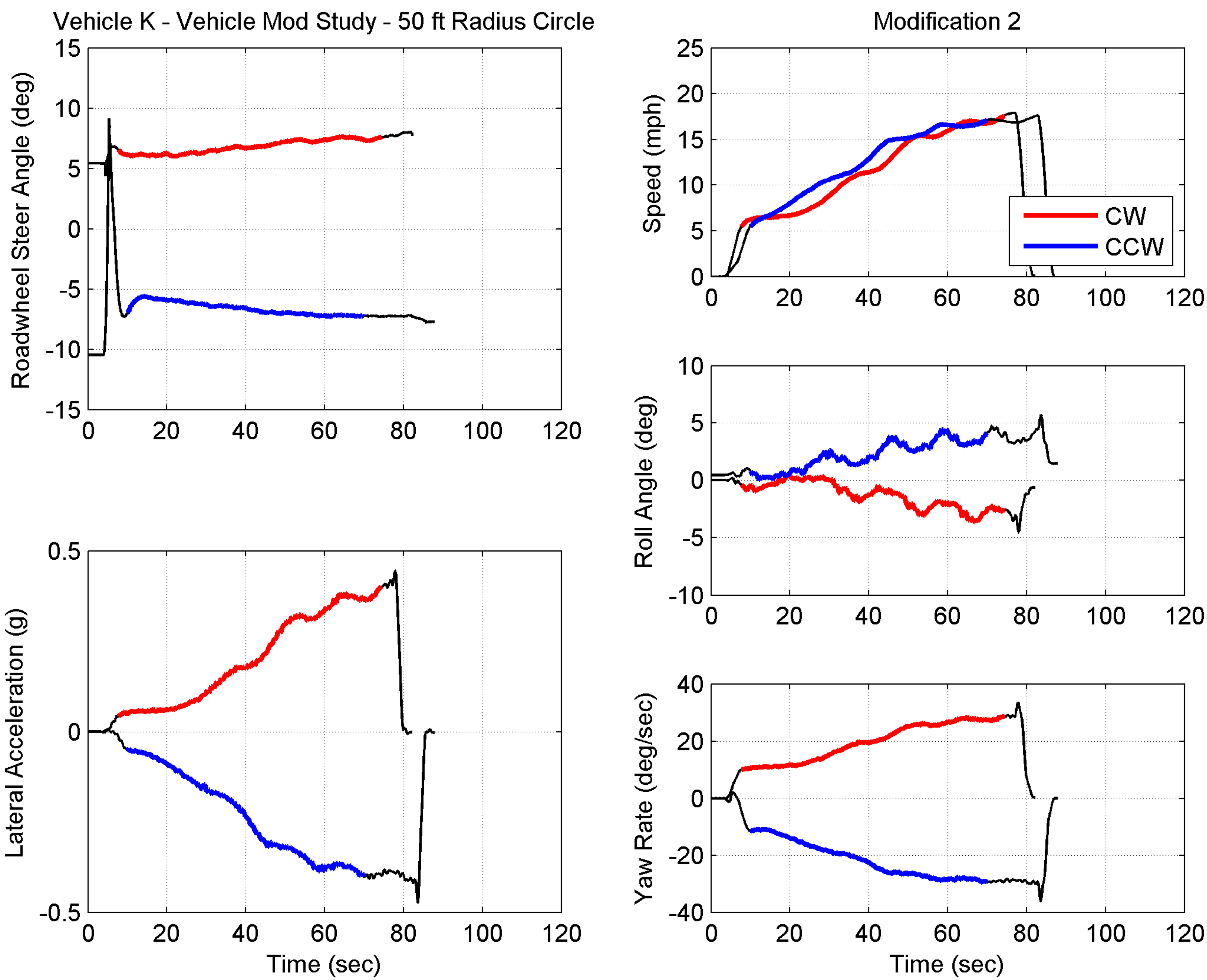

Vehicle K - Vehicle Mod Study - 50 ft Radius Circle
Modification 1
Roadwheel Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

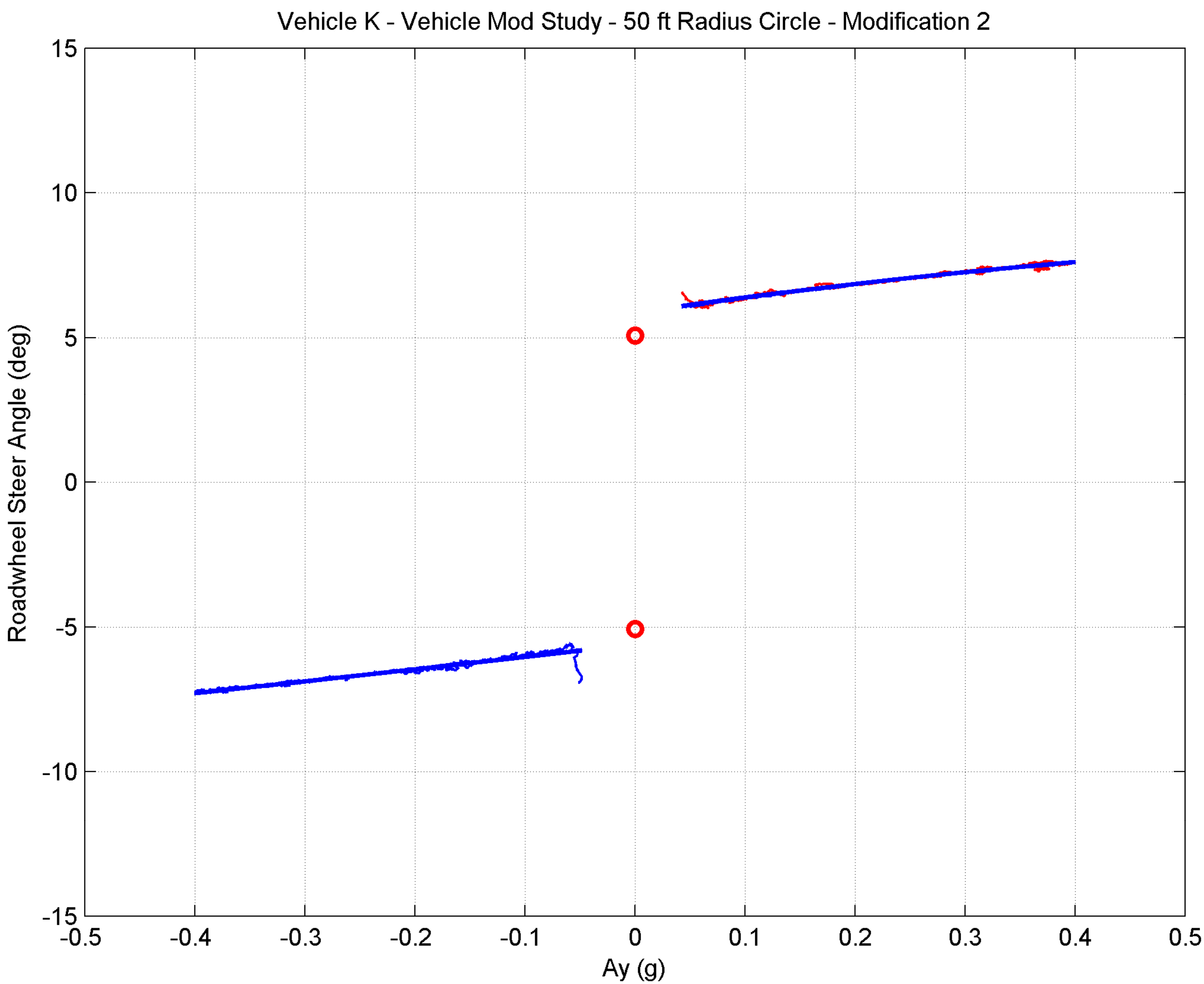

Vehicle K - Vehicle Mod Study - 50 ft Radius Circle - Modification 1
15
10
5
0
-5
-10
-15
Roadwheel Steer Angle (deg)
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
Ay (g)



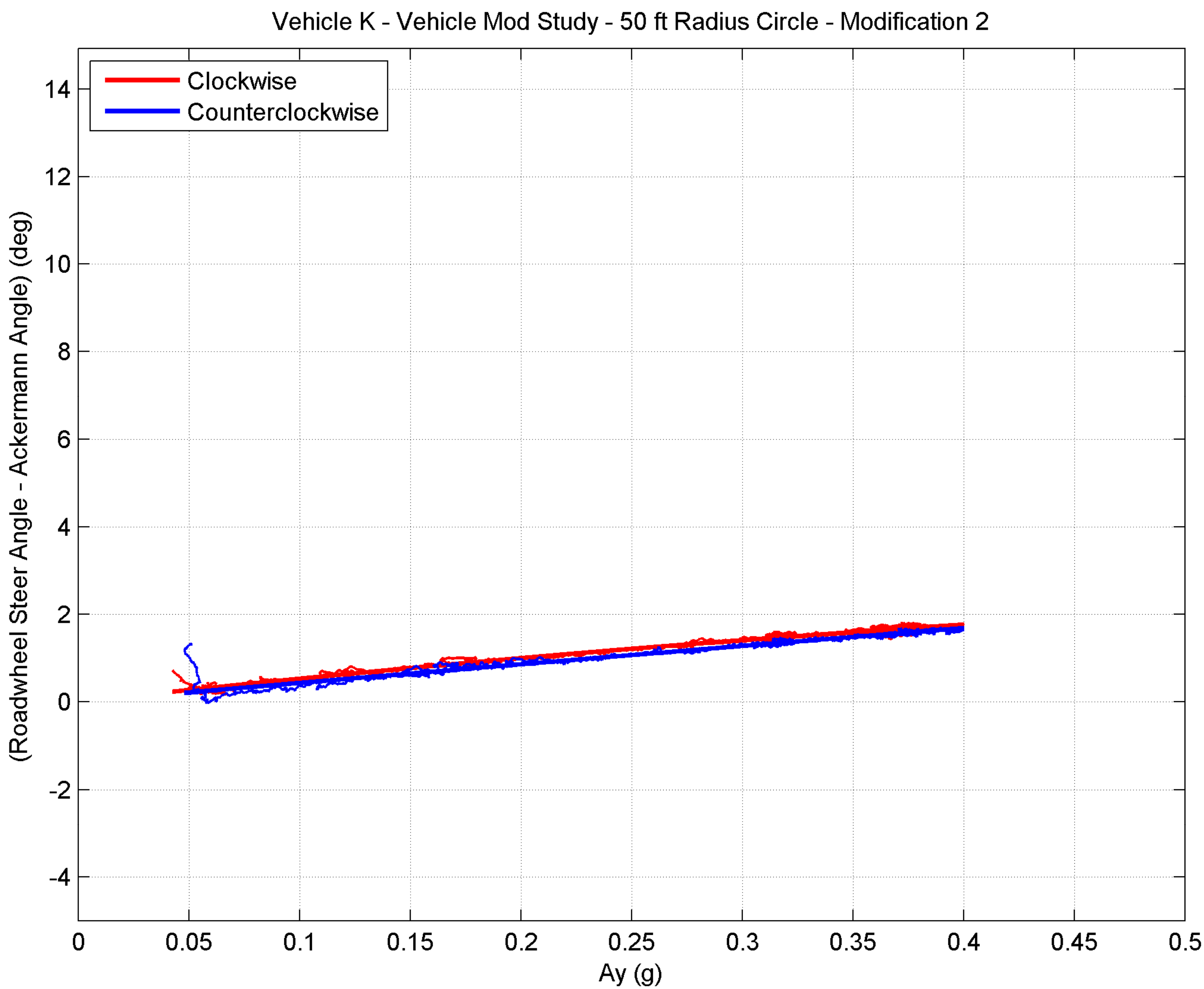
Vehicle K - Vehicle Mod Study - 50 ft Radius Circle - Modification 1
Clockwise
Counterclockwise
CW Transition to OS
At Ay = 0.232 g
CCW Transition to OS
At Ay = -0.257 g
(Roadwheel Steer Angle - Ackermann Angle) (deg)
Ay (g)
14
12
10
8
6
4
2
0
-2
-4
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5


Vehicle K - Vehicle Mod Study - 50 ft Radius Circle - Modification 1
Roll Angle (deg)
Ay (g)
Roll Gradient = -8.85 deg/g
6
4
2
0
-2
-4
-6
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5

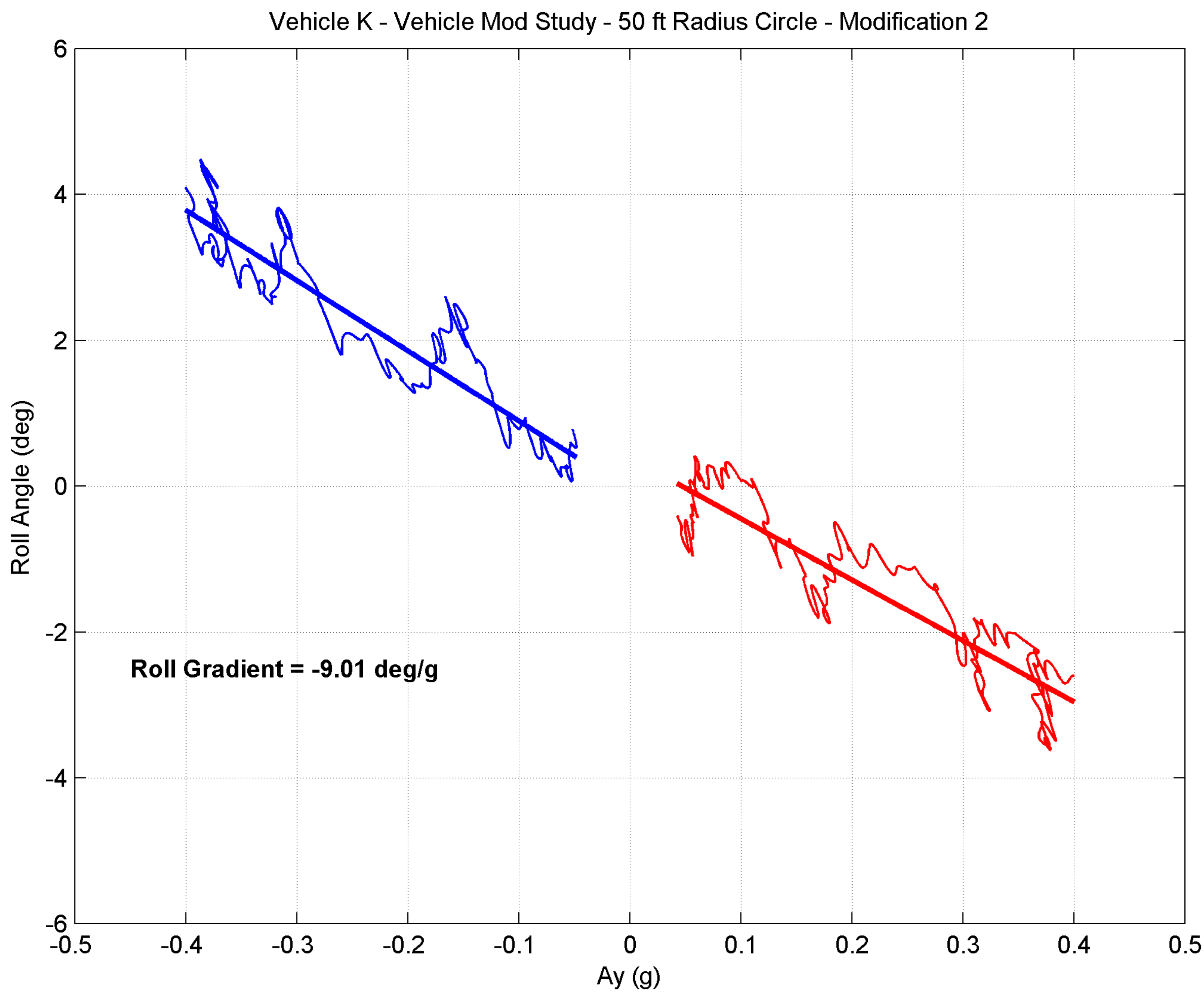

Vehicle K - Vehicle Mod Study - 50 ft Radius Circle
Modification 2
Roadwheel Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

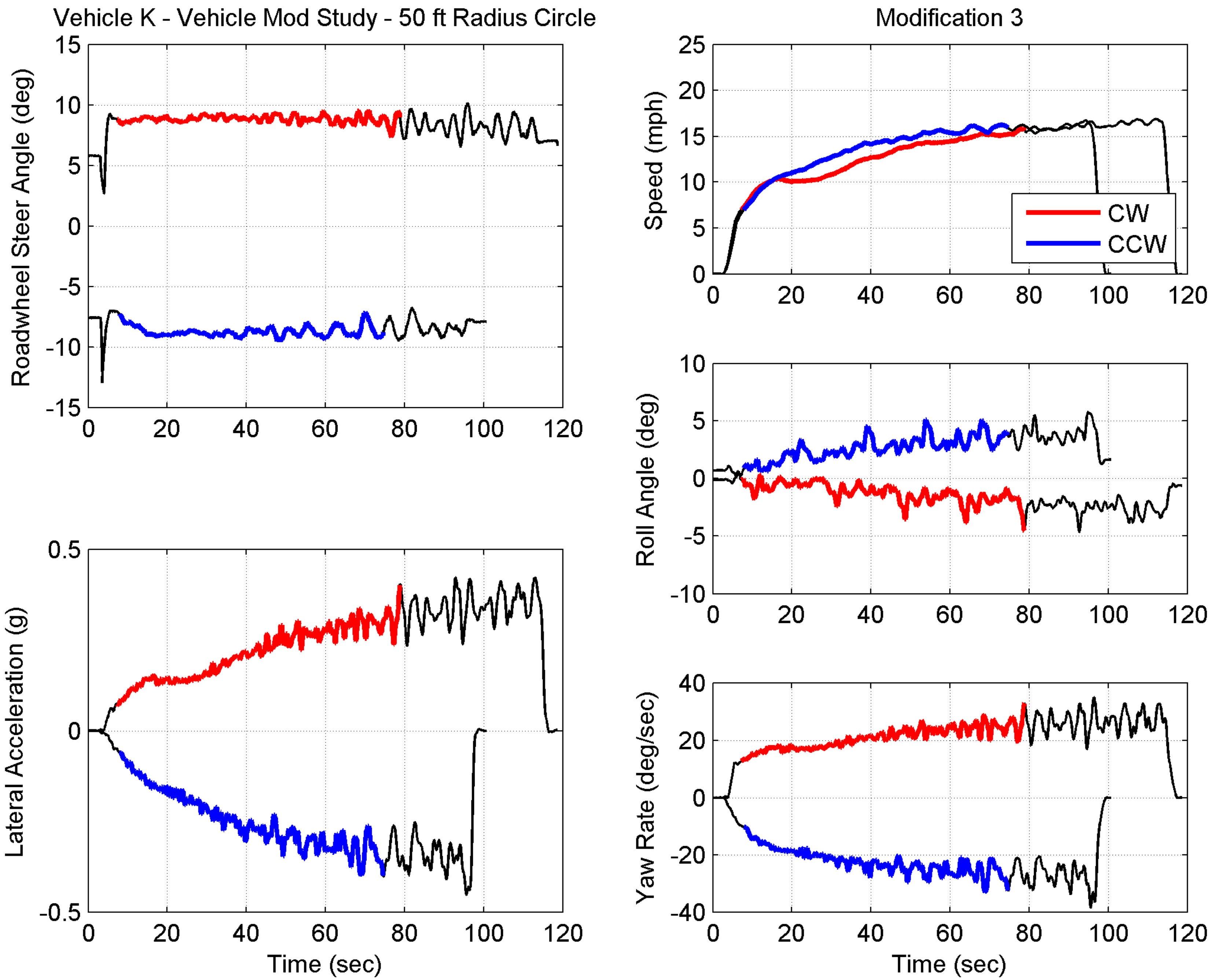


Vehicle K - Vehicle Mod Study - 50 ft Radius Circle - Modification 2
Roadwheel Steer Angle (deg)
Ay (g)
15
10
5
0
-5
-10
-15
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5

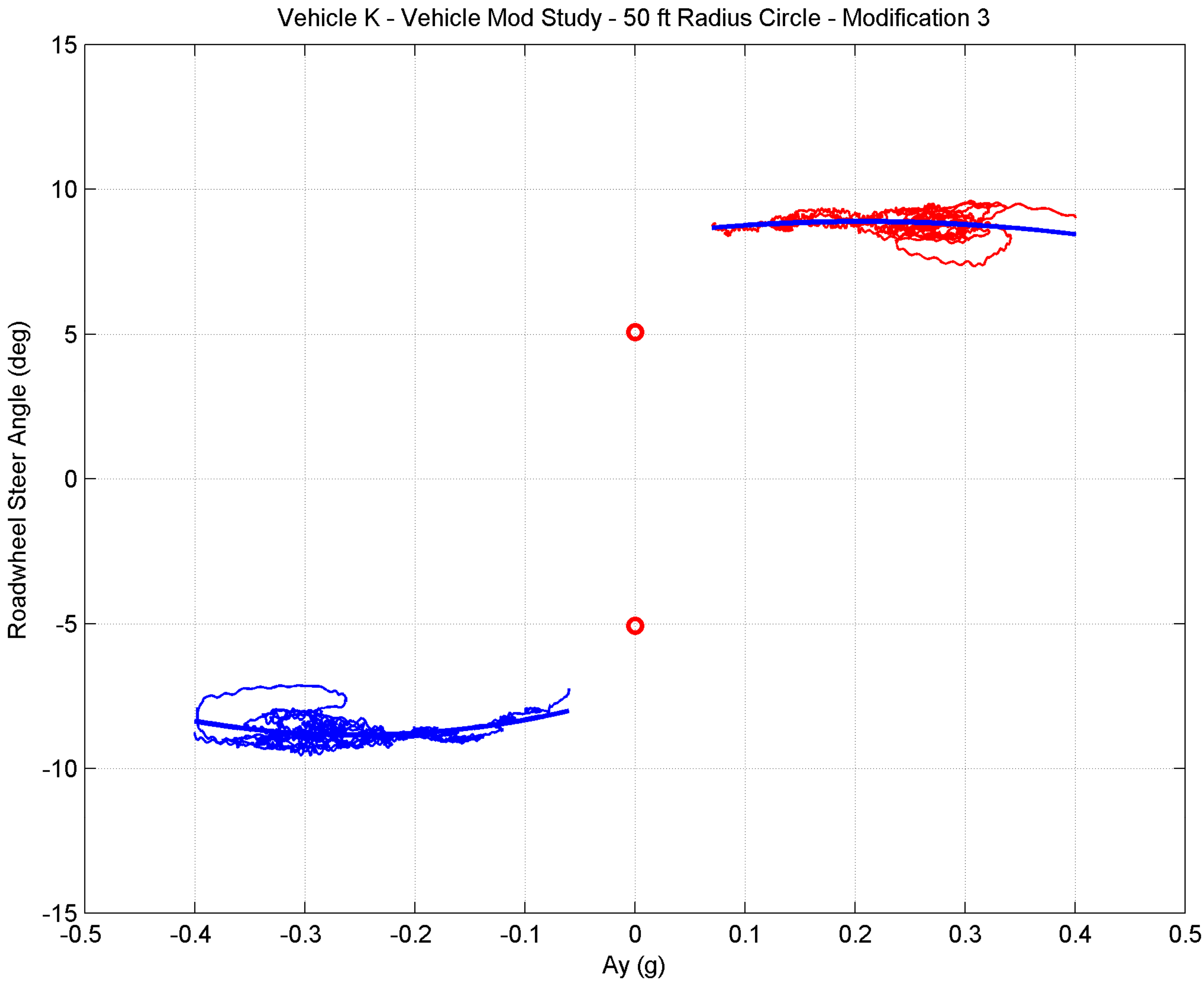


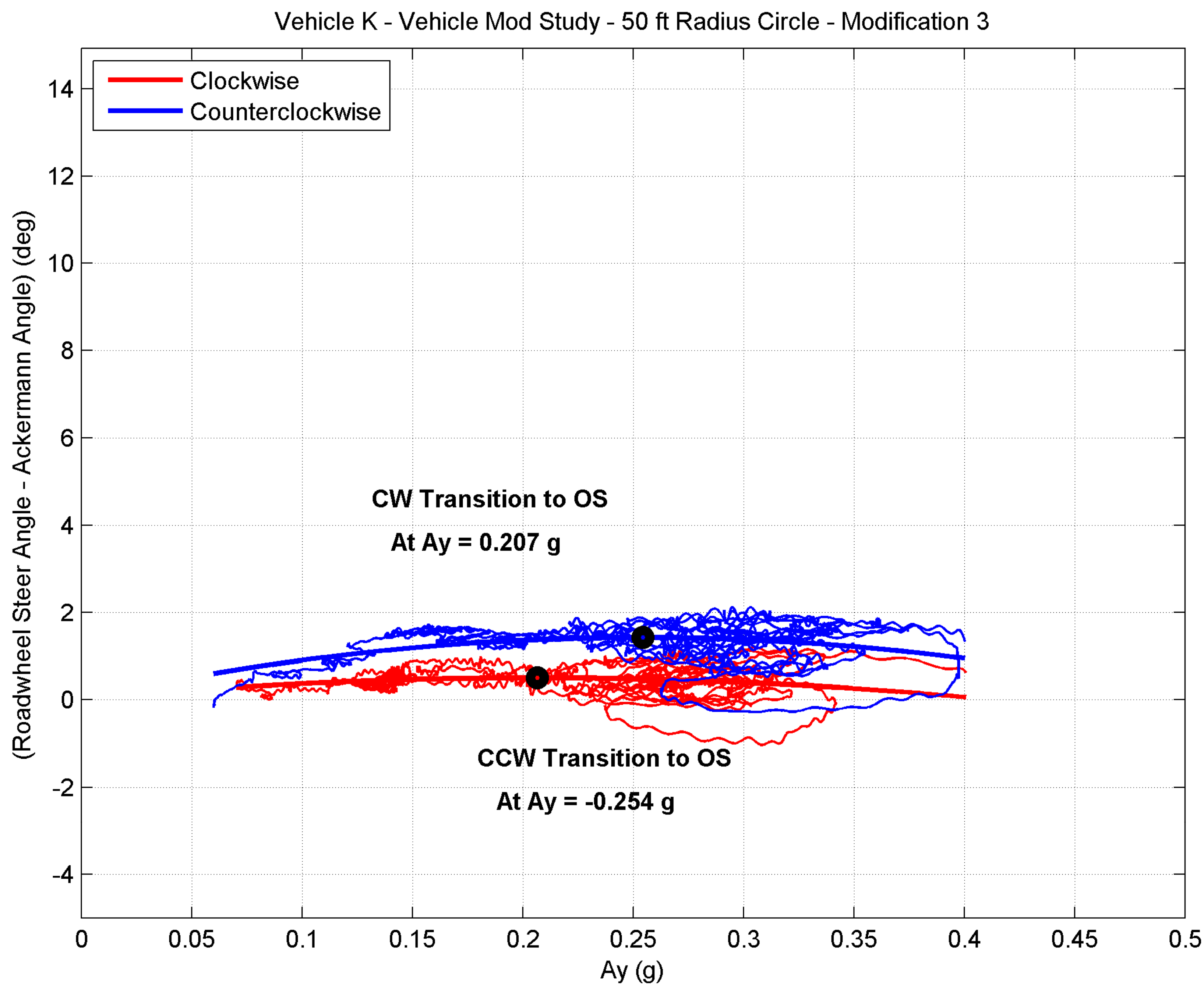
Vehicle K - Vehicle Mod Study - 50 ft Radius Circle - Modification 2
Clockwise
Counterclockwise
(Roadwheel Steer Angle - Ackermann Angle) (deg)
14
12
10
8
6
4
2
0
-2
-4
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Ay (g)

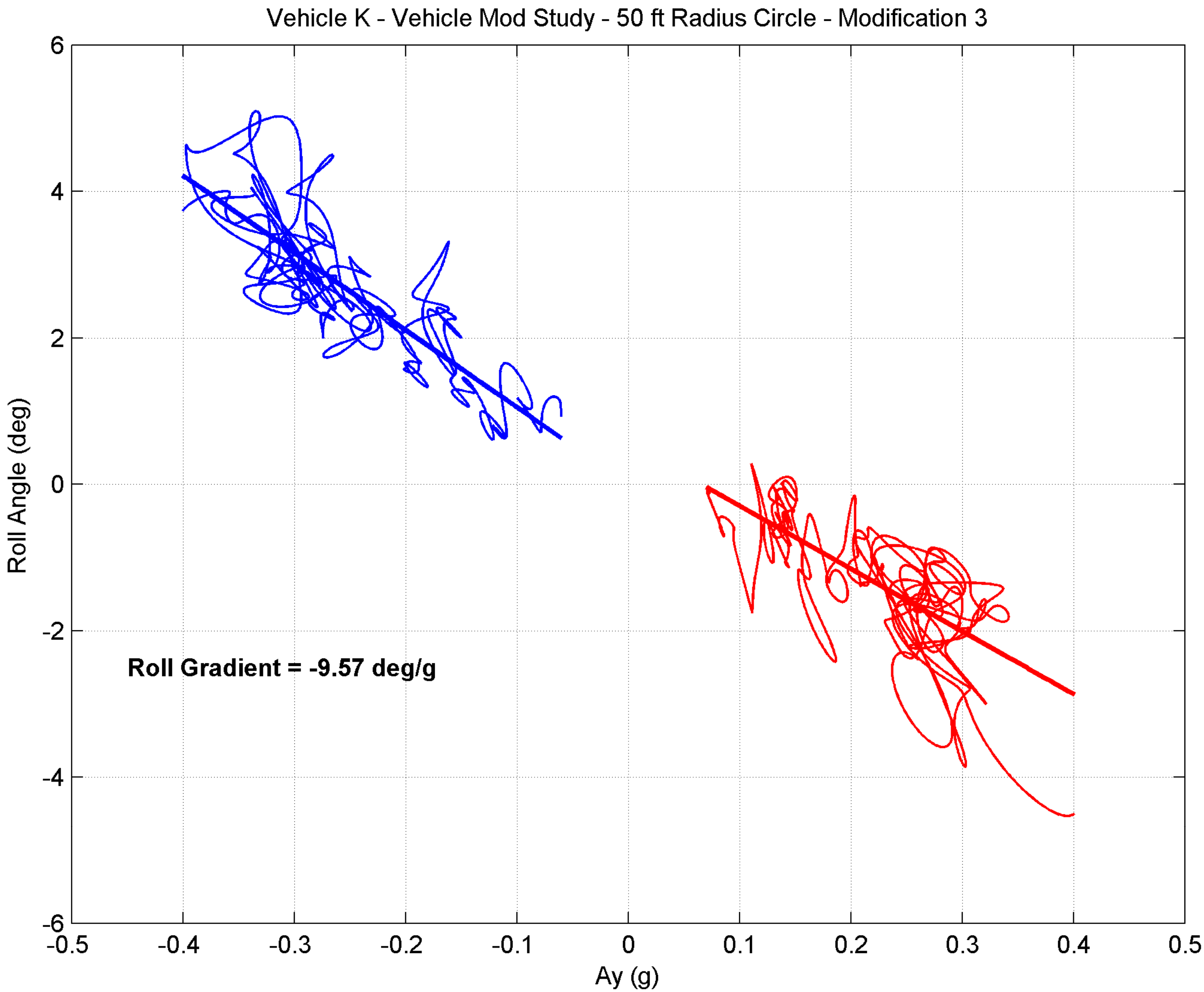

Vehicle K - Vehicle Mod Study - 50 ft Radius Circle - Modification 2
Roll Angle (deg)
Ay (g)
Roll Gradient = -9.01 deg/g
6
4
2
0
-2
-4
-6
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5

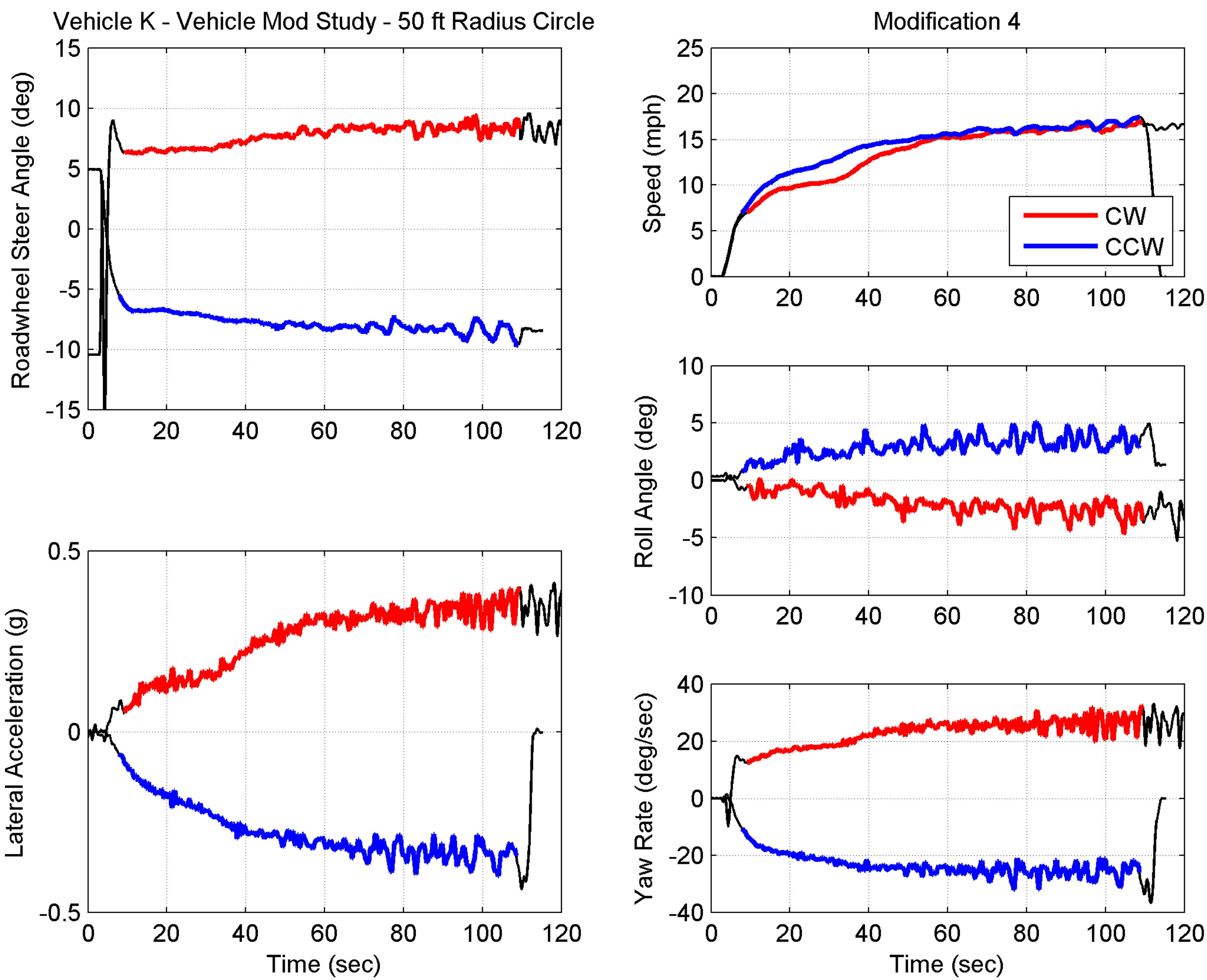


Vehicle K - Vehicle Mod Study - 50 ft Radius Circle
Modification 3
Roadwheel Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

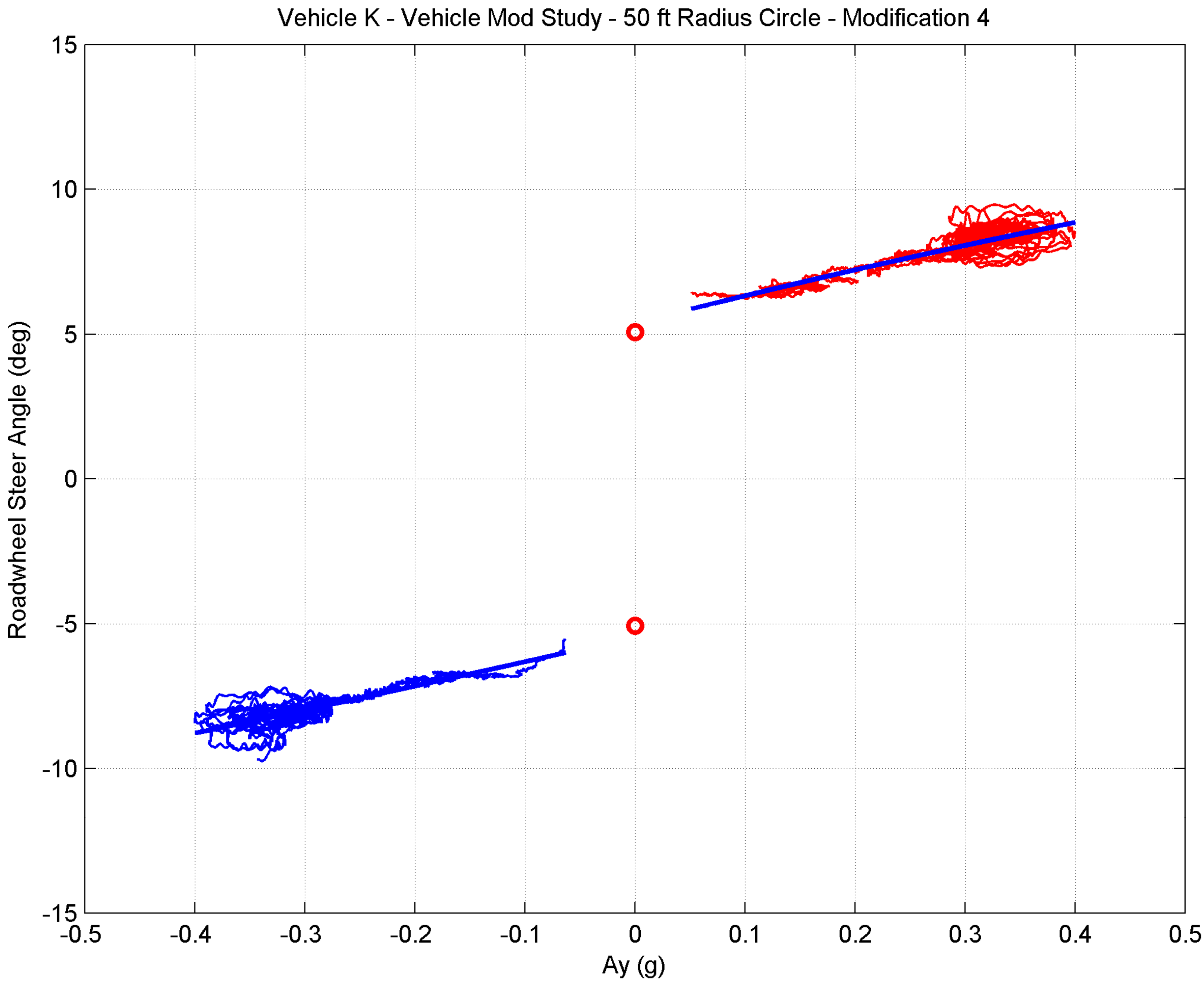

Vehicle K - Vehicle Mod Study - 50 ft Radius Circle - Modification 3
Roadwheel Steer Angle (deg)
15
10
5
0
-5
-10
-15
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
Ay (g)


Vehicle K - Vehicle Mod Study - 50 ft Radius Circle - Modification 3
Clockwise
Counterclockwise
CW Transition to OS
At Ay = 0.207 g
CCW Transition to OS
At Ay = -0.254 g
(Roadwheel Steer Angle - Ackermann Angle) (deg)
Ay (g)
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

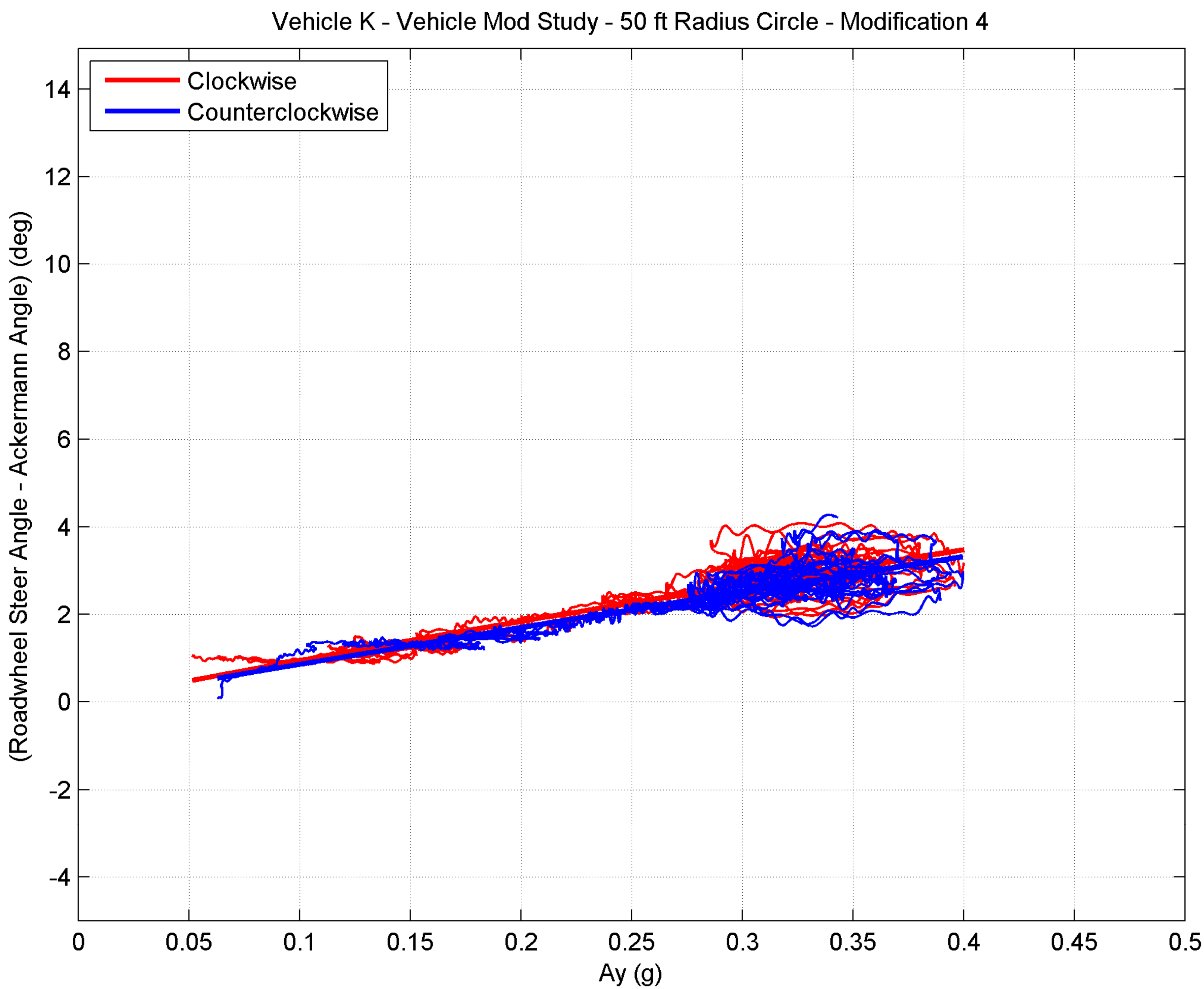

Vehicle K - Vehicle Mod Study - 50 ft Radius Circle - Modification 3
Roll Angle (deg)
Ay (g)
Roll Gradient = -9.57 deg/g
6
4
2
0
-2
-4
-6
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5

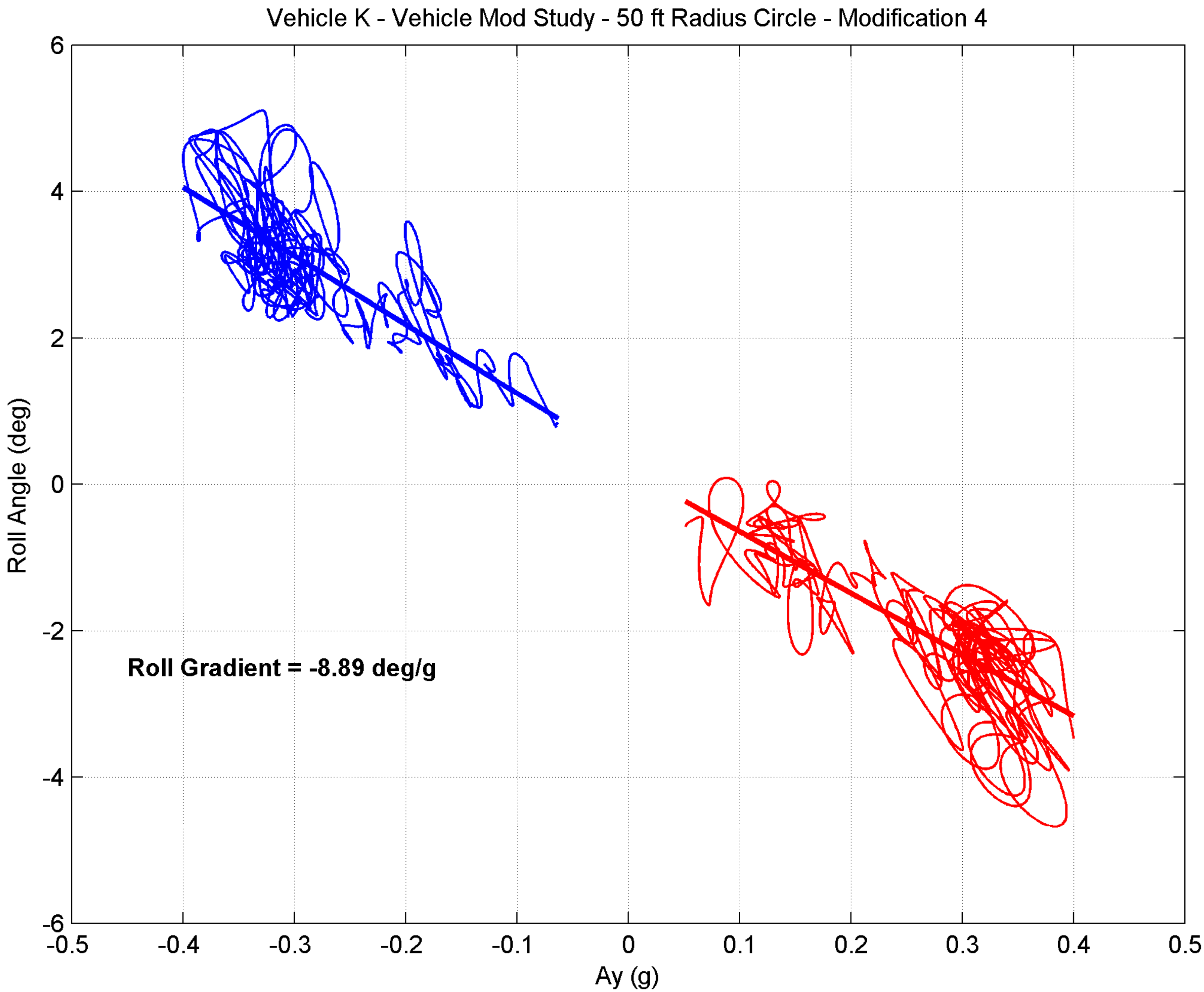


Vehicle K - Vehicle Mod Study - 50 ft Radius Circle
Modification 4
Roadwheel Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

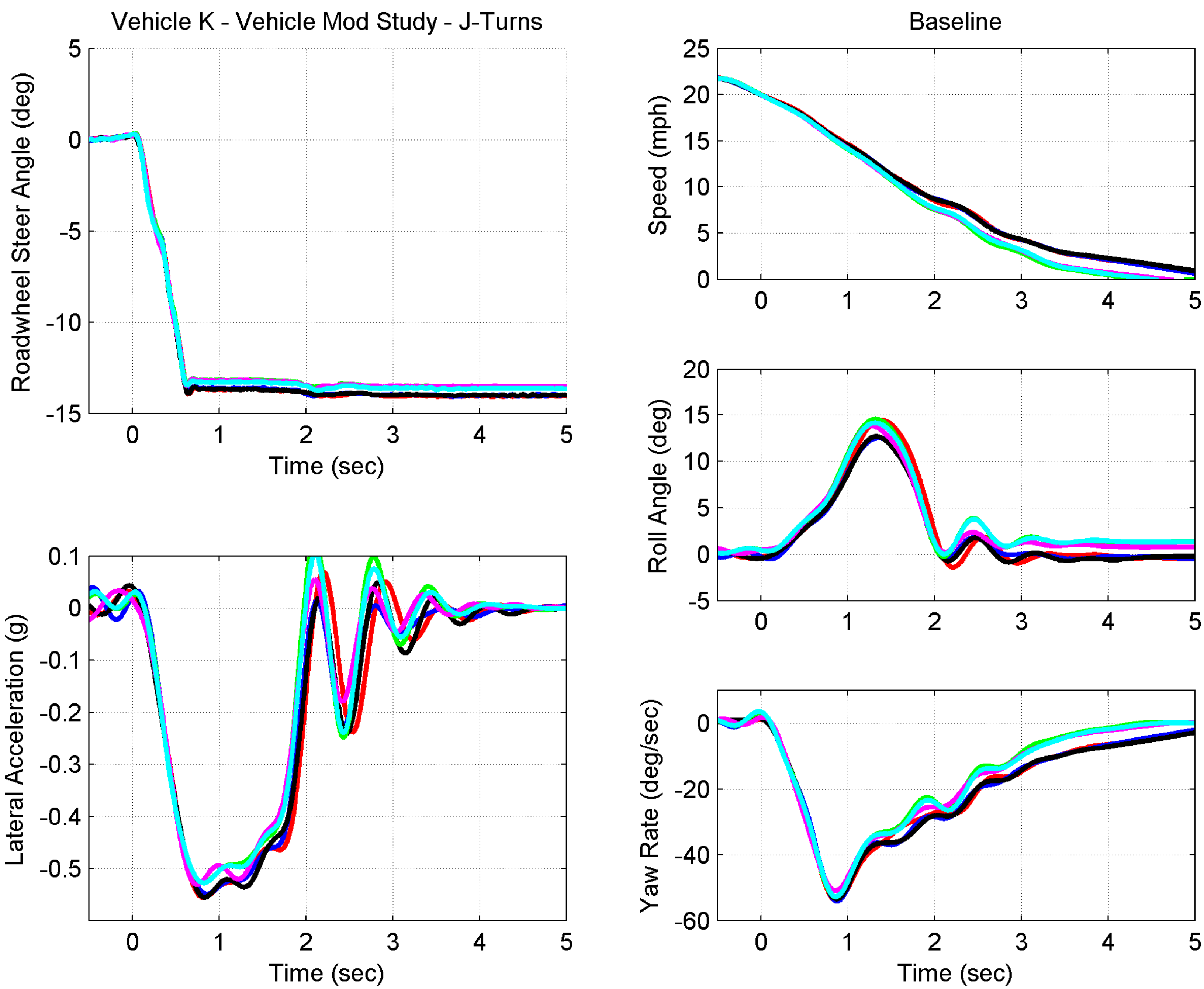


Vehicle K - Vehicle Mod Study - 50 ft Radius Circle - Modification 4
Roadwheel Steer Angle (deg)
15
10
5
0
-5
-10
-15
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
Ay (g)

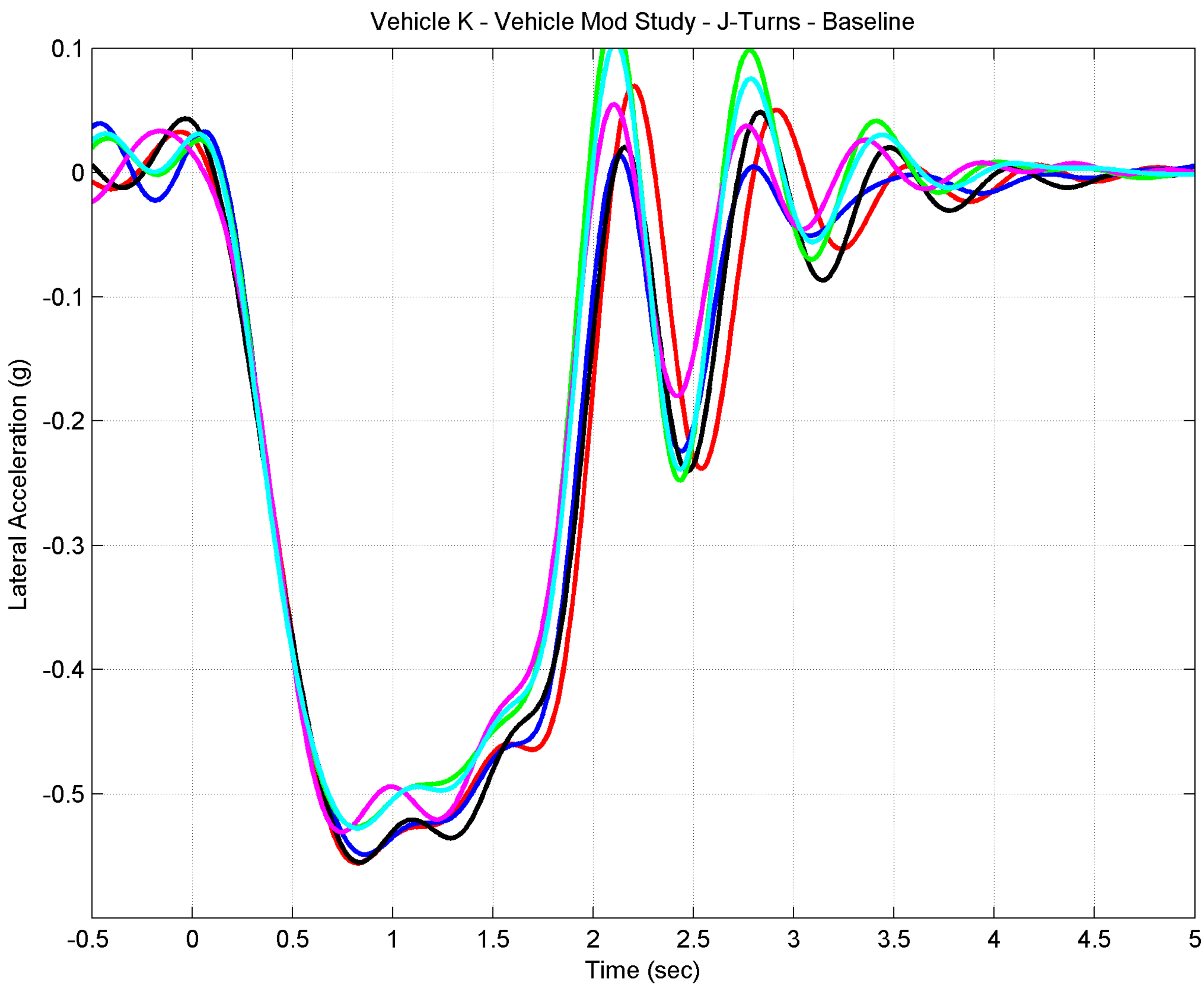

Vehicle K - Vehicle Mod Study - 50 ft Radius Circle - Modification 4
Clockwise
Counterclockwise
(Roadwheel Steer Angle - Ackermann Angle) (deg)
14
12
10
8
6
4
2
0
-2
-4
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
Ay (g)

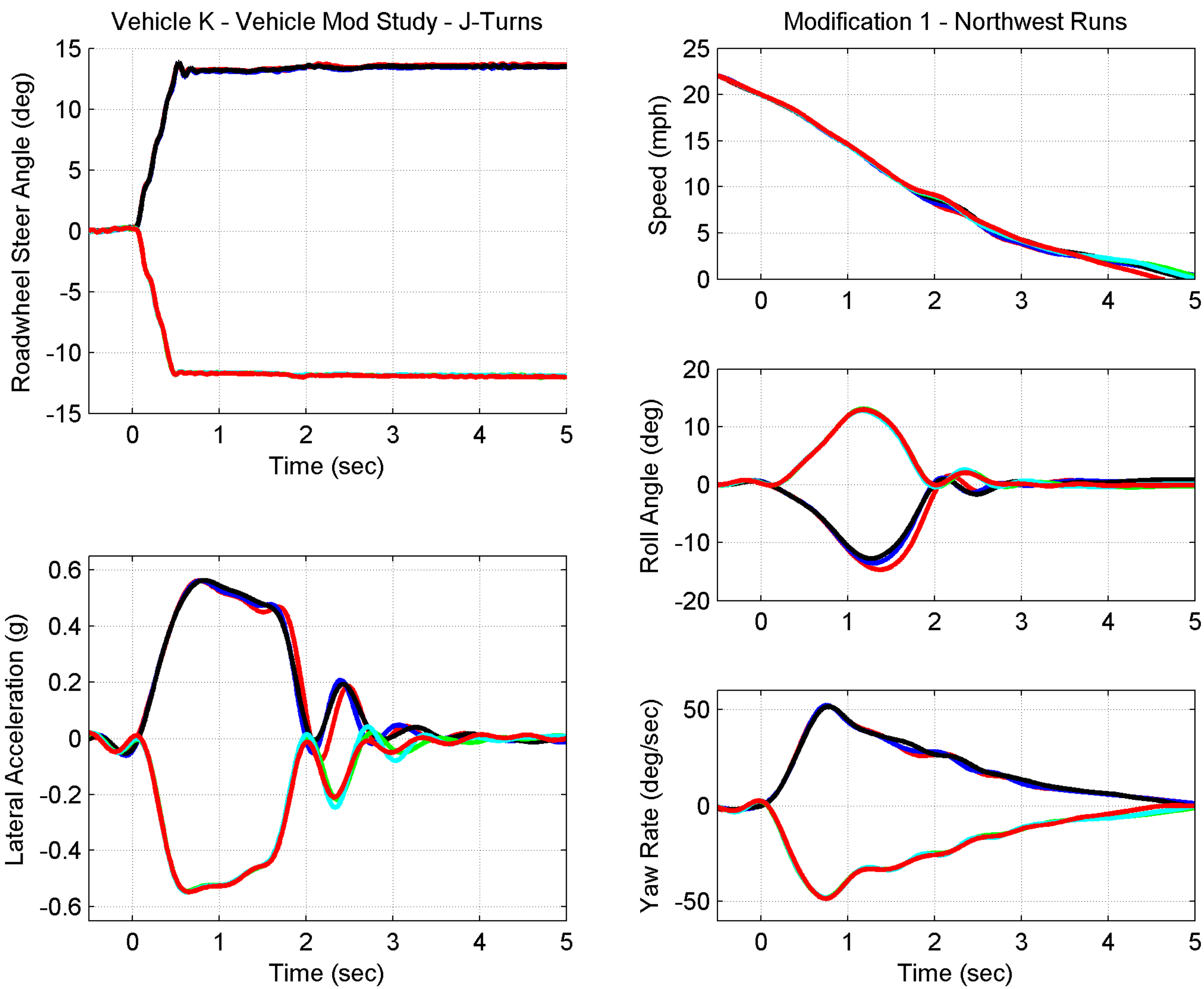


Vehicle K - Vehicle Mod Study - 50 ft Radius Circle - Modification 4
Roll Angle (deg)
Ay (g)
Roll Gradient = -8.89 deg/g
6
4
2
0
-2
-4
-6
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5

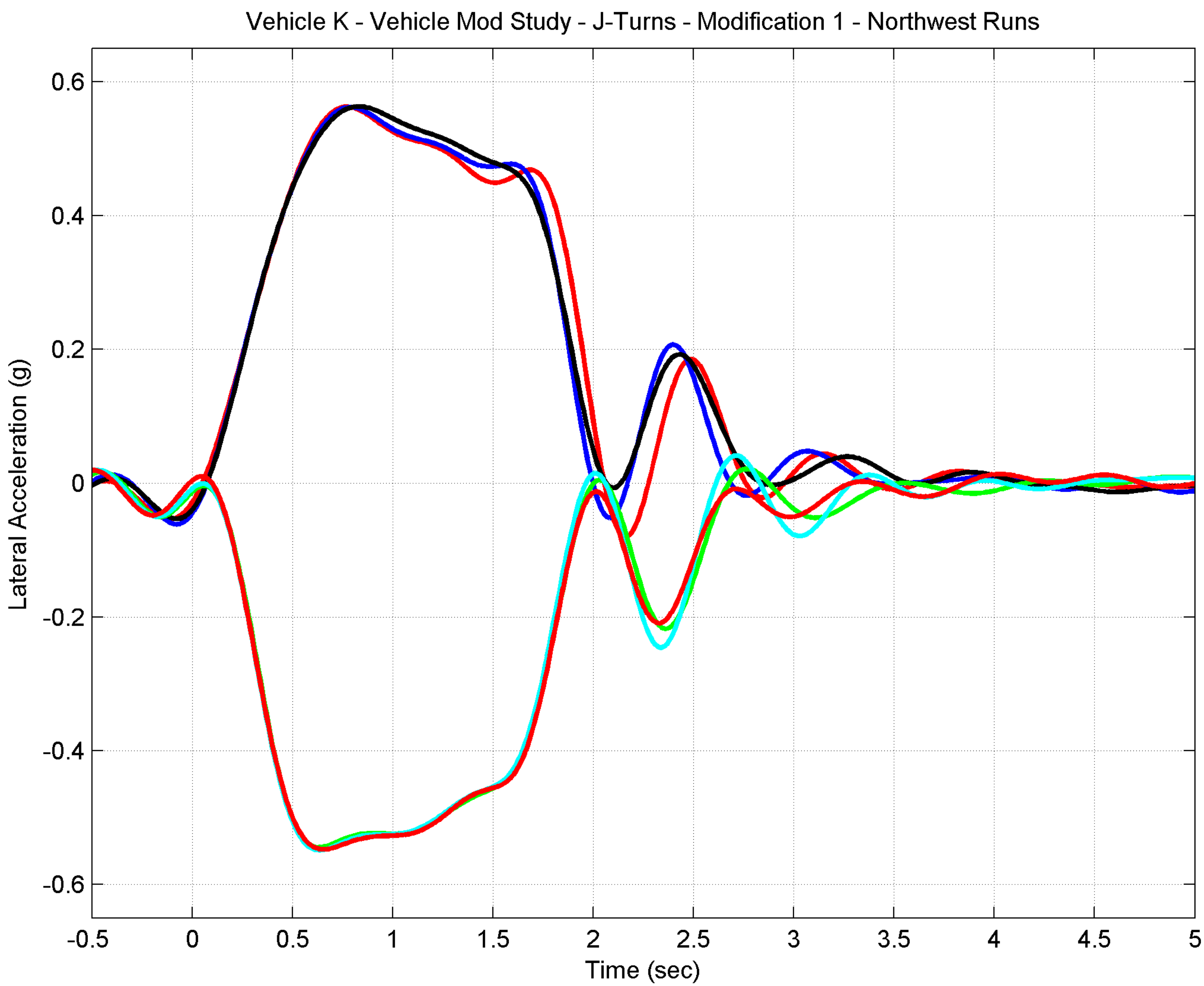


Vehicle K - Vehicle Mod Study - J-Turns
Baseline
Roadwheel Steer Angle (deg)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)
Time (sec)

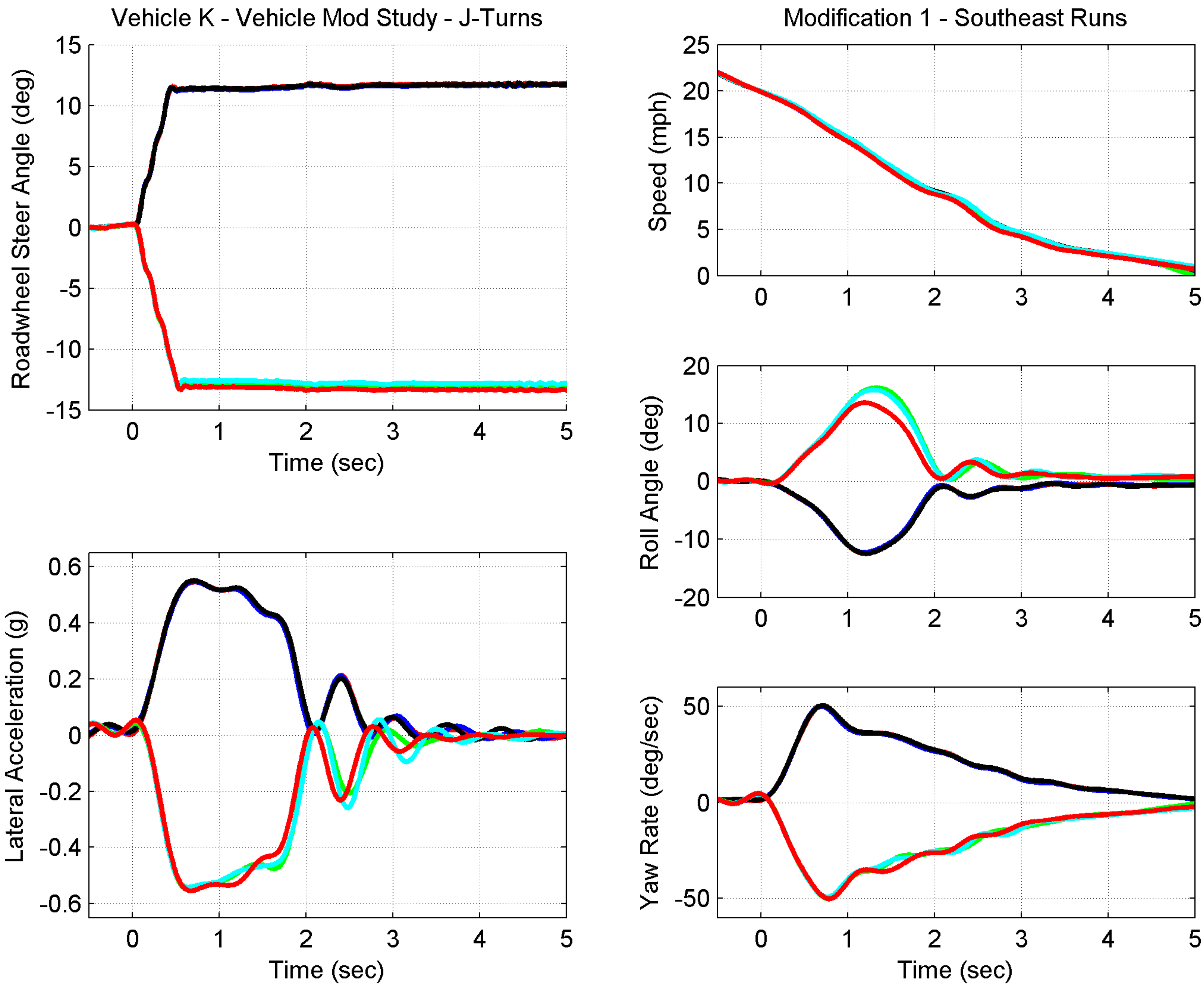

Vehicle K - Vehicle Mod Study - J-Turns - Baseline
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
Lateral Acceleration (g)
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (sec)

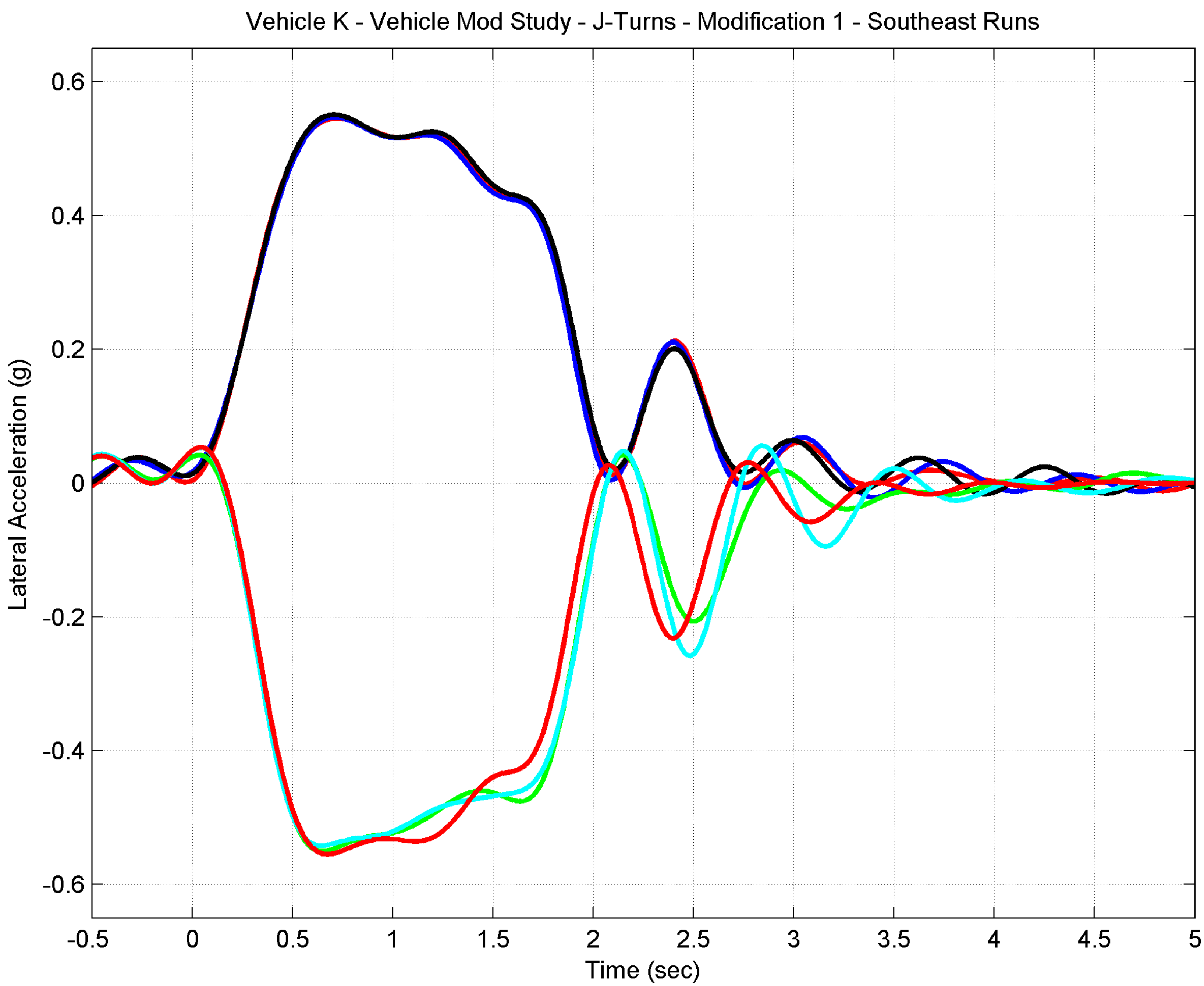


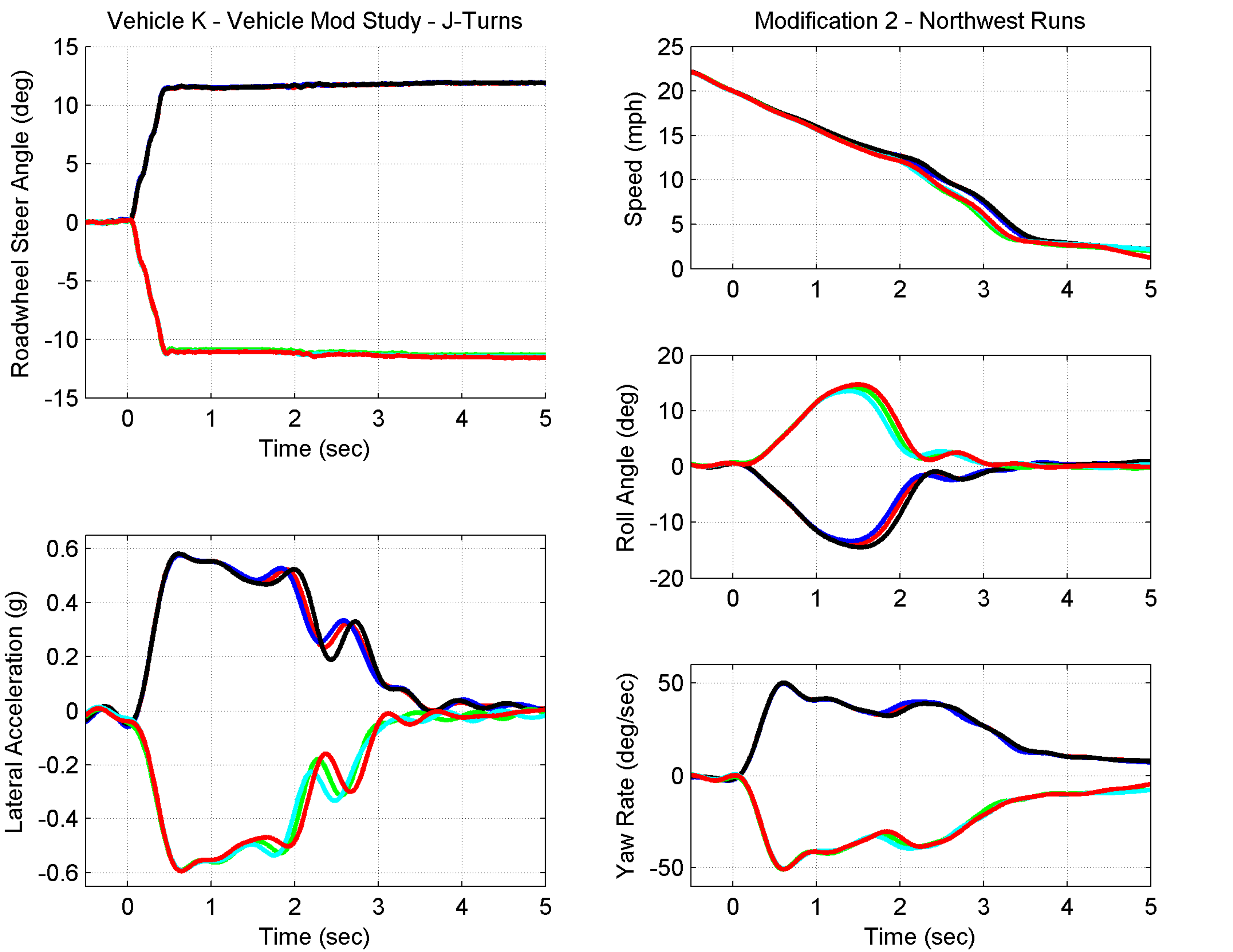
Vehicle K - Vehicle Mod Study - J-Turns
Modification 1 - Northwest Runs
Roadwheel Steer Angle (deg)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)
Time (sec)

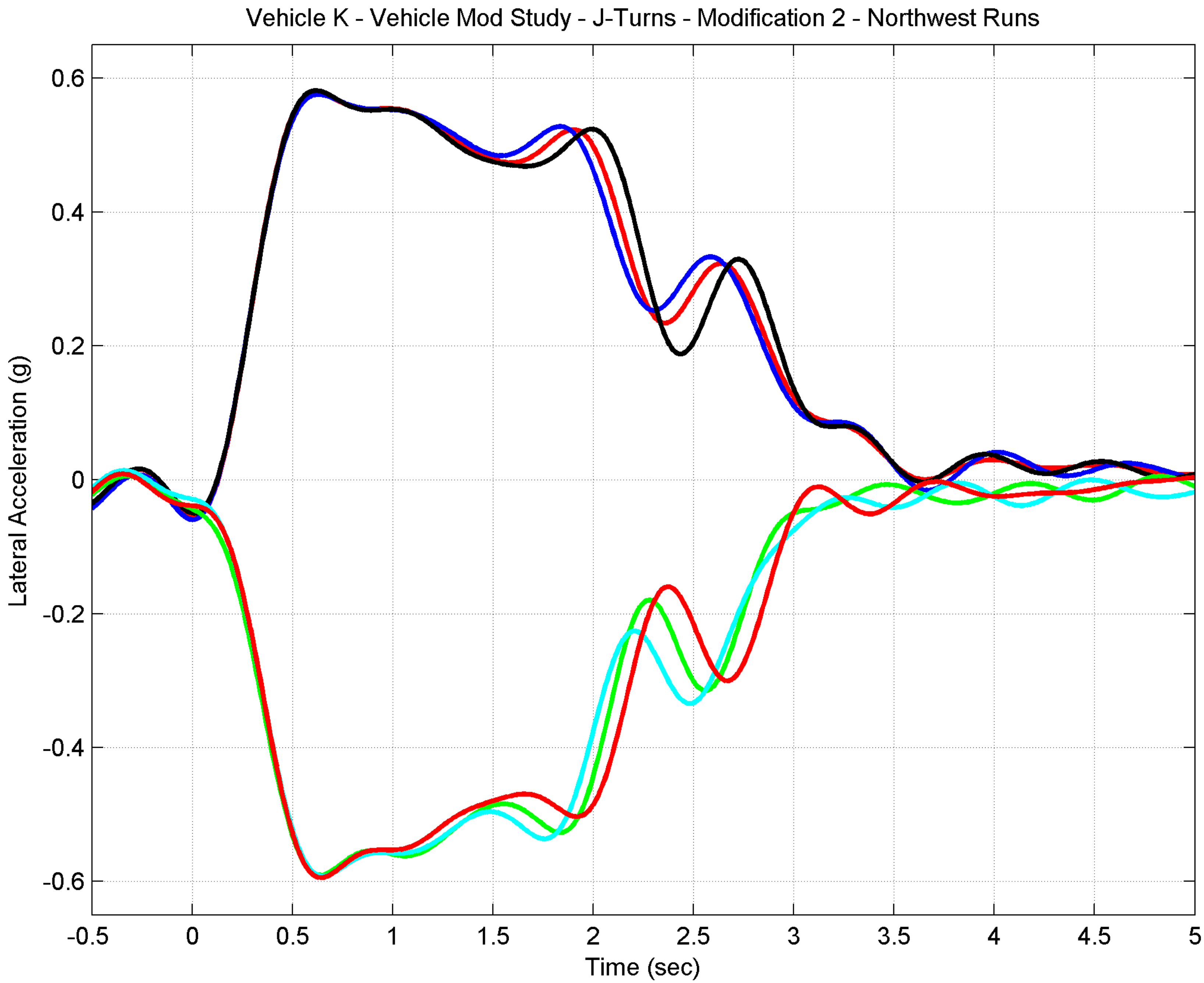


Vehicle K - Vehicle Mod Study - J-Turns - Modification 1 - Northwest Runs
Lateral Acceleration (g)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (sec)

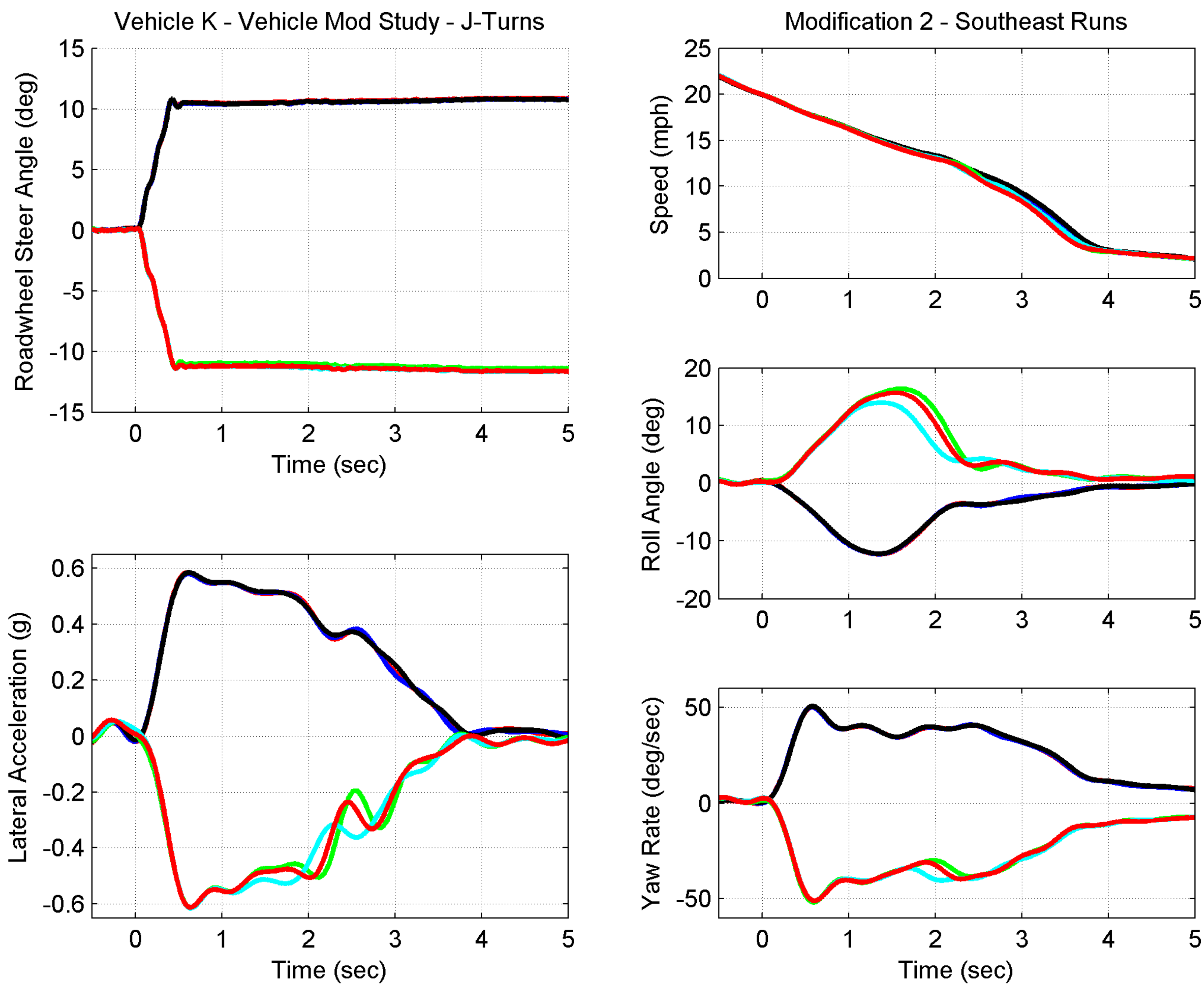

Vehicle K - Vehicle Mod Study - J-Turns
Modification 1 - Southeast Runs
Roadwheel Steer Angle (deg)
15
10
5
0
-5
-10
-15
Time (sec)
Speed (mph)
25
20
15
10
5
0
Roll Angle (deg)
20
10
0
-10
-20
Lateral Acceleration (g)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Time (sec)
Yaw Rate (deg/sec)
50
0
-50
Time (sec)
0
1
2
3
4
5


Vehicle K - Vehicle Mod Study - J-Turns - Modification 1 - Southeast 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)

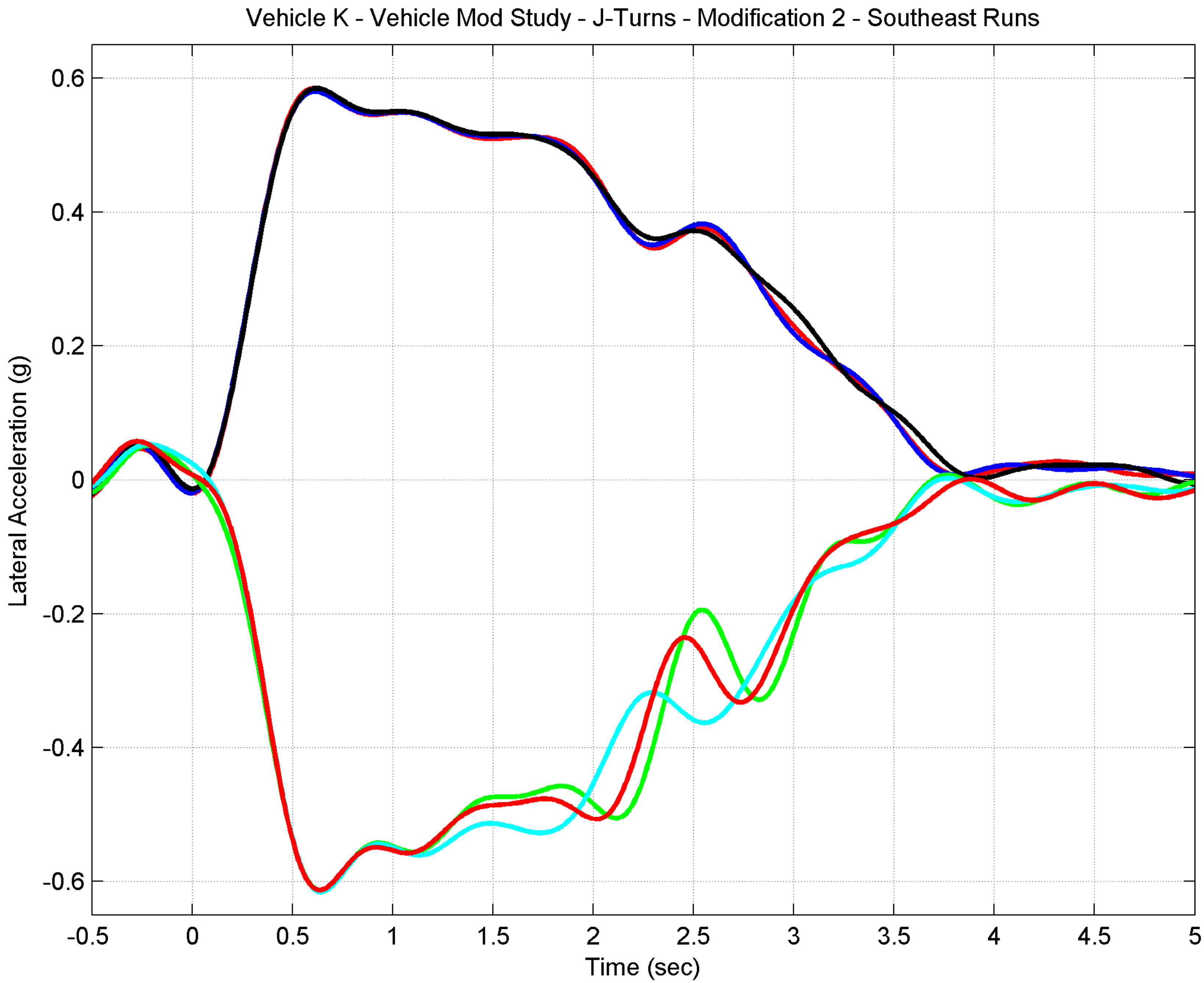

Vehicle K - Vehicle Mod Study - J-Turns
Modification 2 - Northwest Runs
Roadwheel Steer Angle (deg)
Time (sec)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Time (sec)
Yaw Rate (deg/sec)
Time (sec)

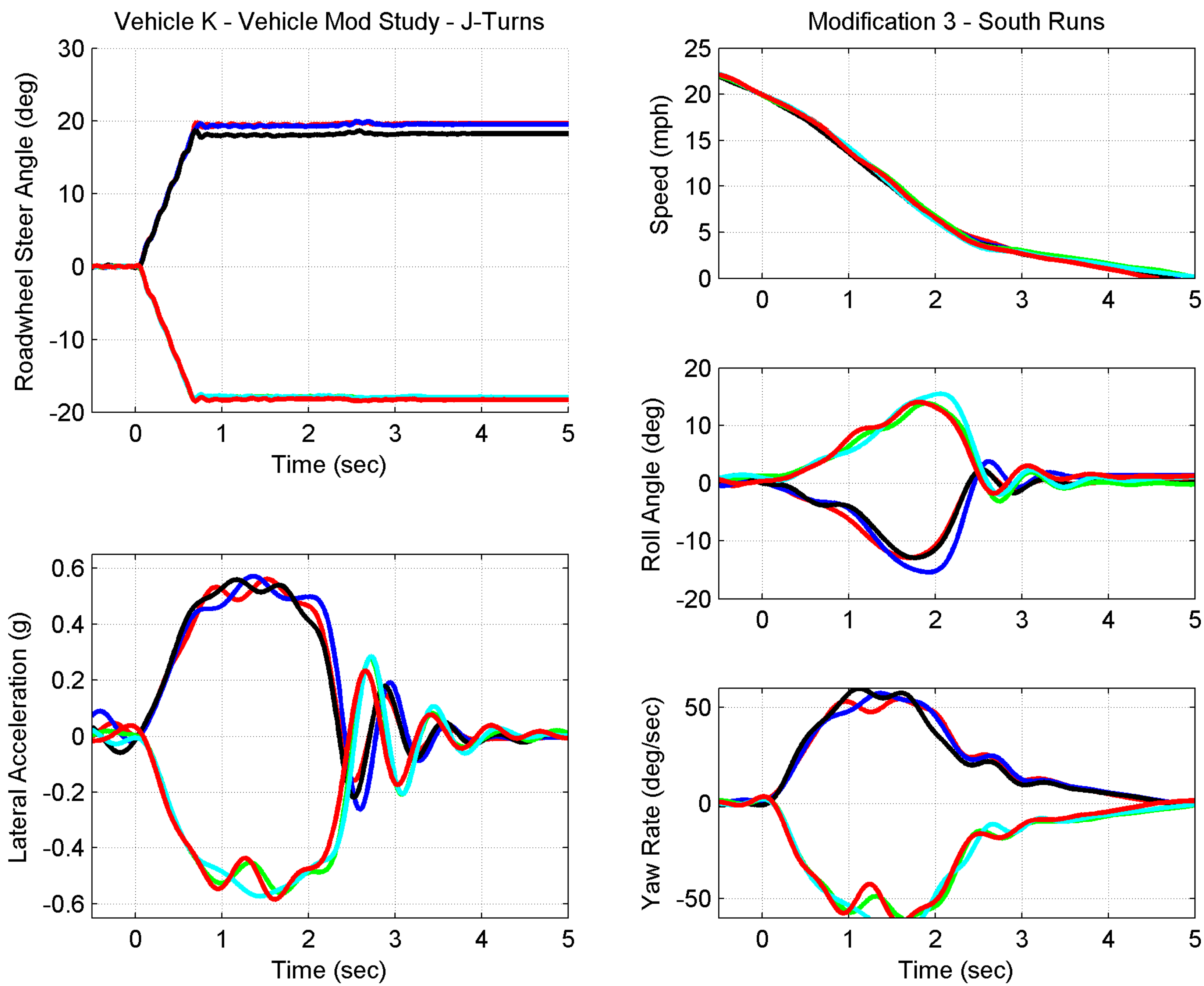


Vehicle K - Vehicle Mod Study - J-Turns - Modification 2 - Northwest Runs
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Lateral Acceleration (g)
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (sec)

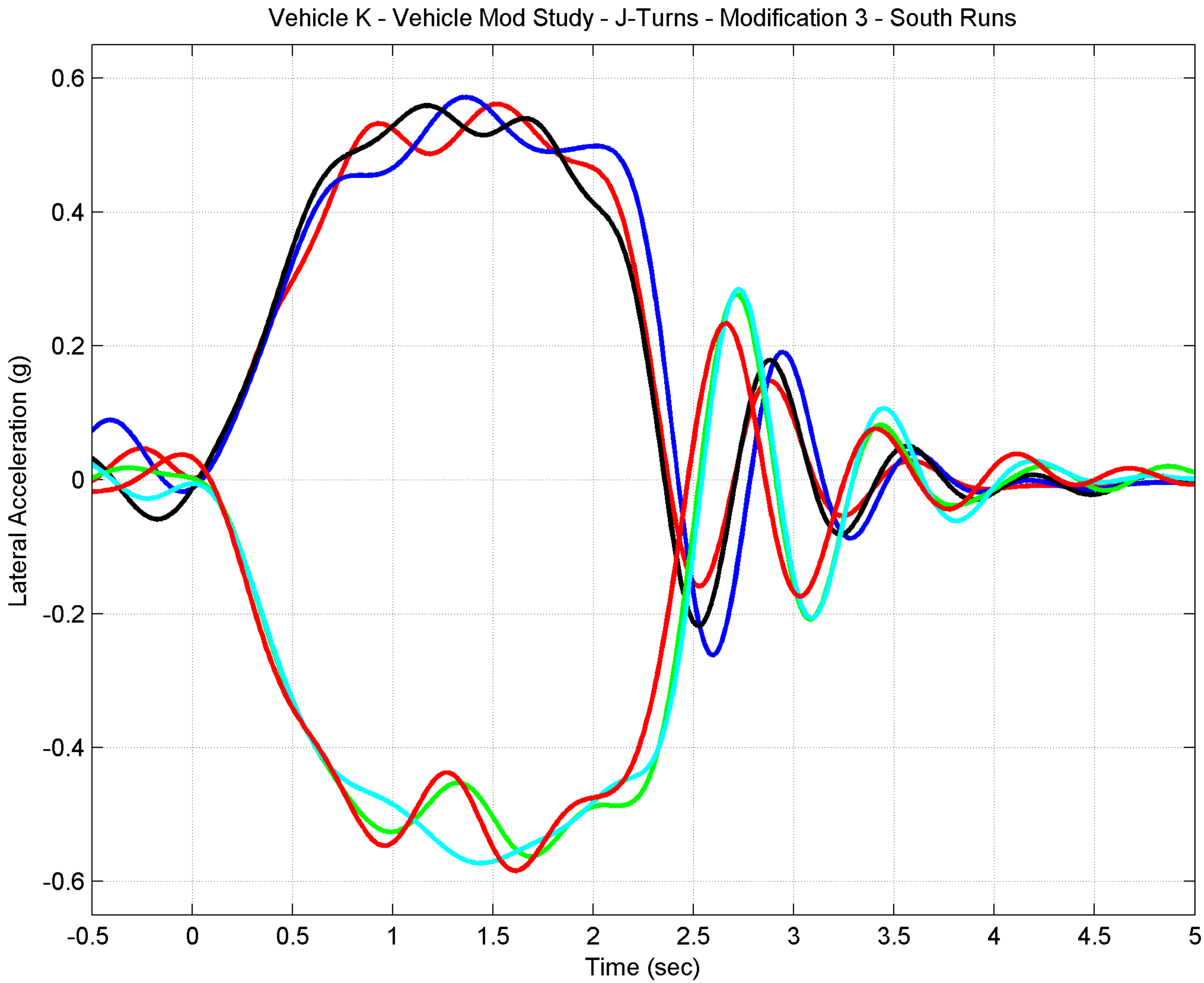


Vehicle K - Vehicle Mod Study - J-Turns
Modification 2 - Southeast Runs
Roadwheel Steer Angle (deg)
15
10
5
0
-5
-10
-15
0
1
2
3
4
5
Time (sec)
Speed (mph)
25
20
15
10
5
0
Roll Angle (deg)
20
10
0
-10
-20
Lateral Acceleration (g)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Yaw Rate (deg/sec)
50
0
-50

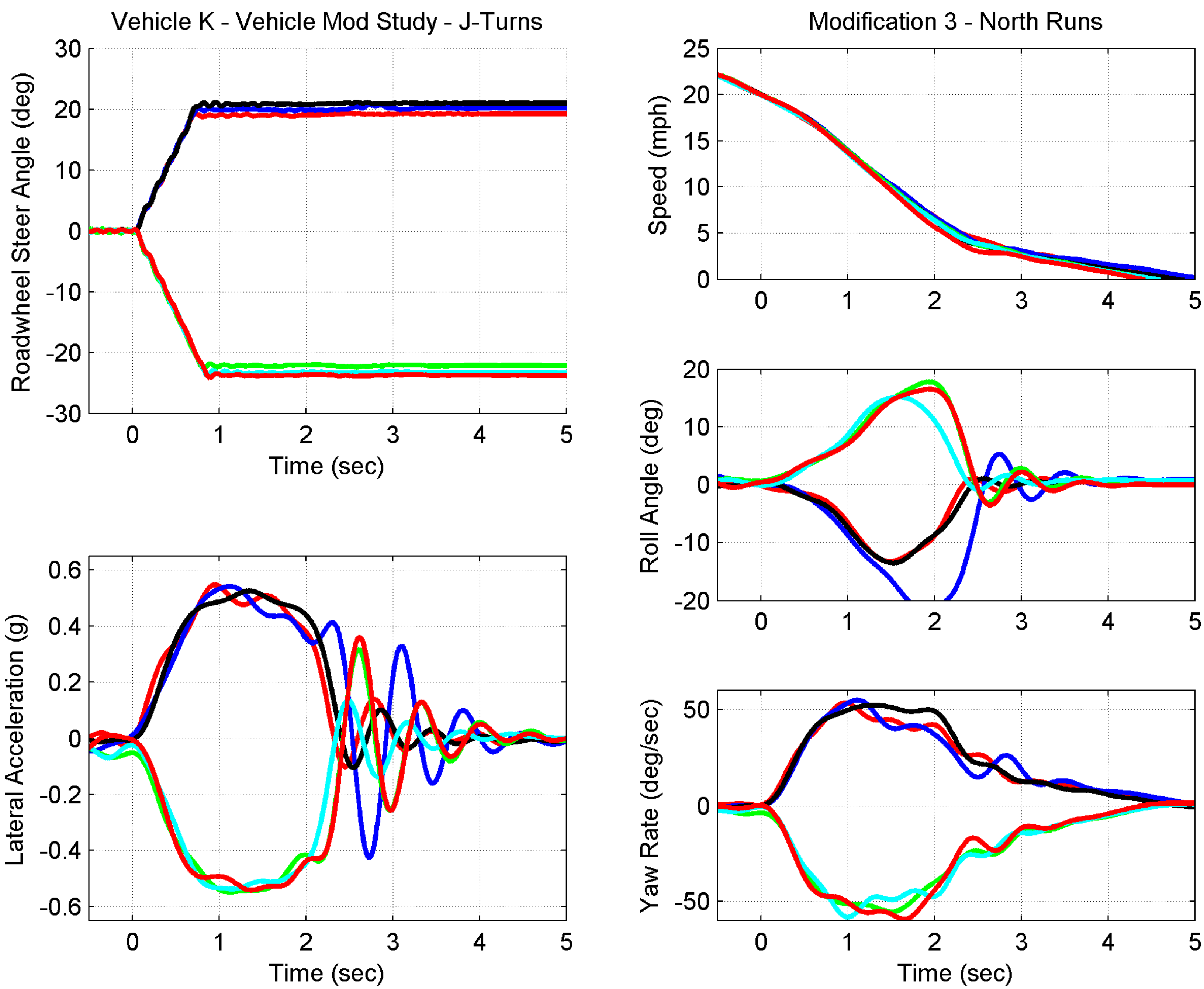

Vehicle K - Vehicle Mod Study - J-Turns - Modification 2 - Southeast Runs
Lateral Acceleration (g)
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (sec)



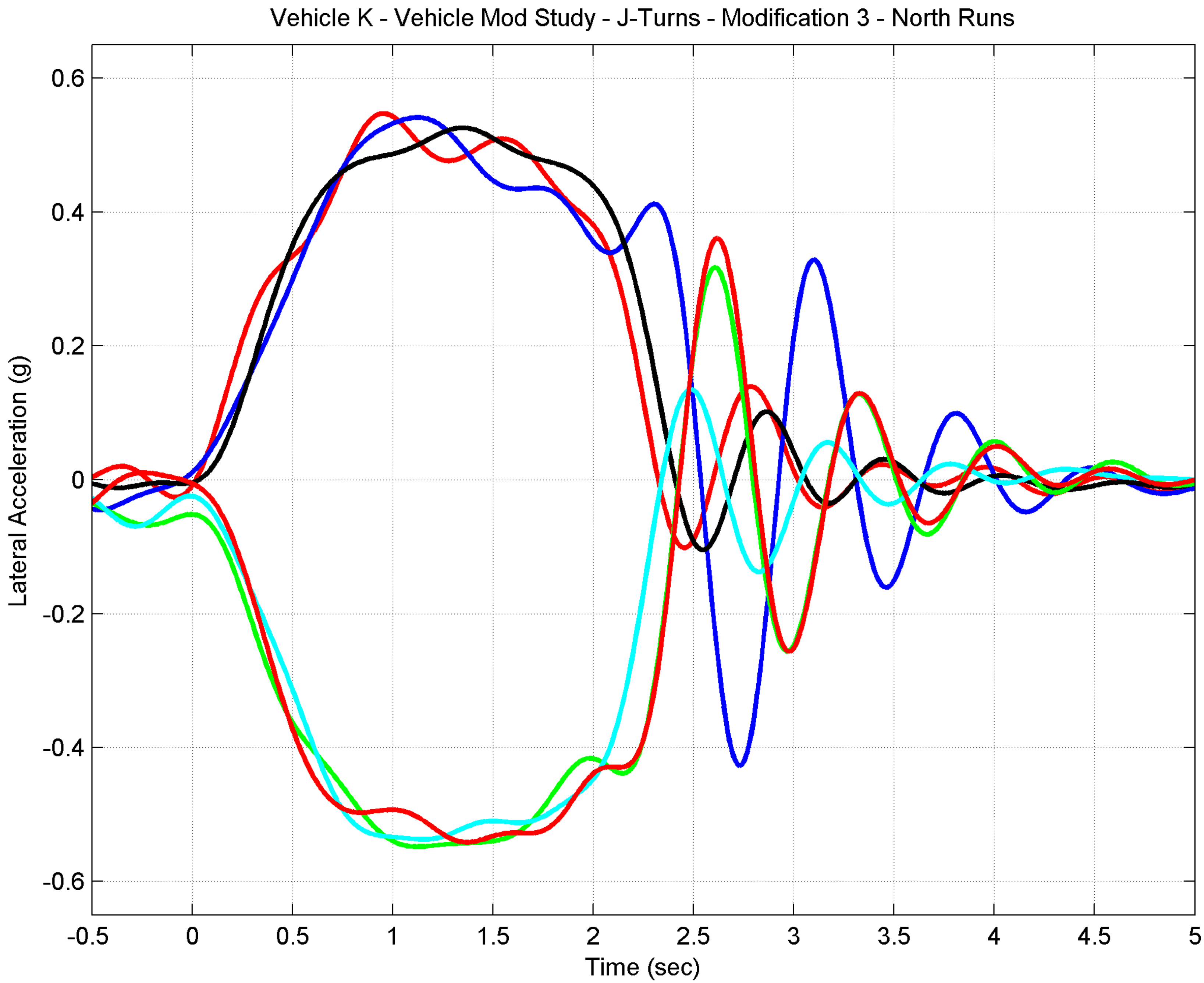
Vehicle K - Vehicle Mod Study - J-Turns
Modification 3 - South Runs
Roadwheel Steer Angle (deg)
Time (sec)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)



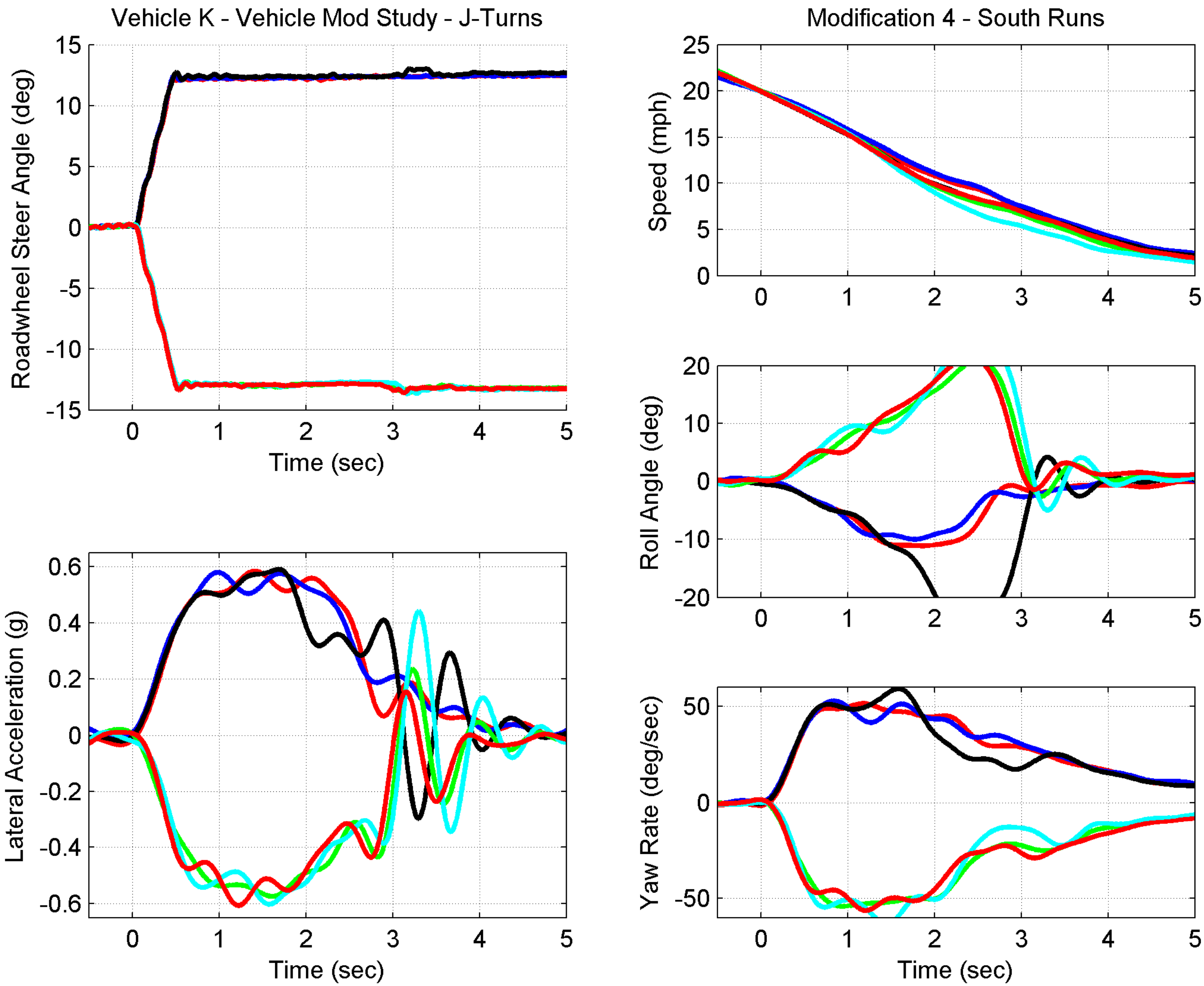
Vehicle K - Vehicle Mod Study - J-Turns - Modification 3 - South Runs
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Lateral Acceleration (g)
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (sec)

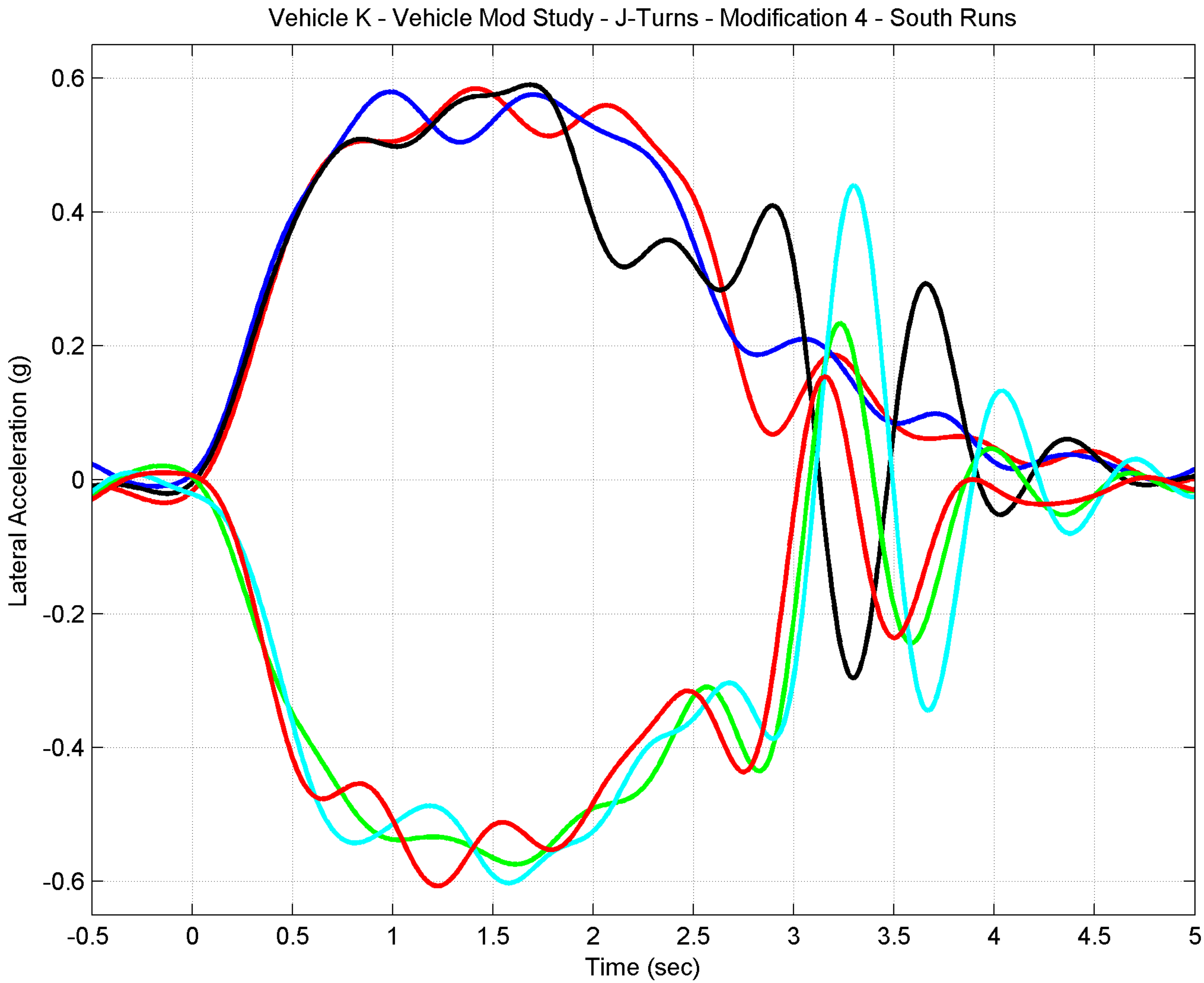


Vehicle K - Vehicle Mod Study - J-Turns
Modification 3 - North Runs
Roadwheel Steer Angle (deg)
Time (sec)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)

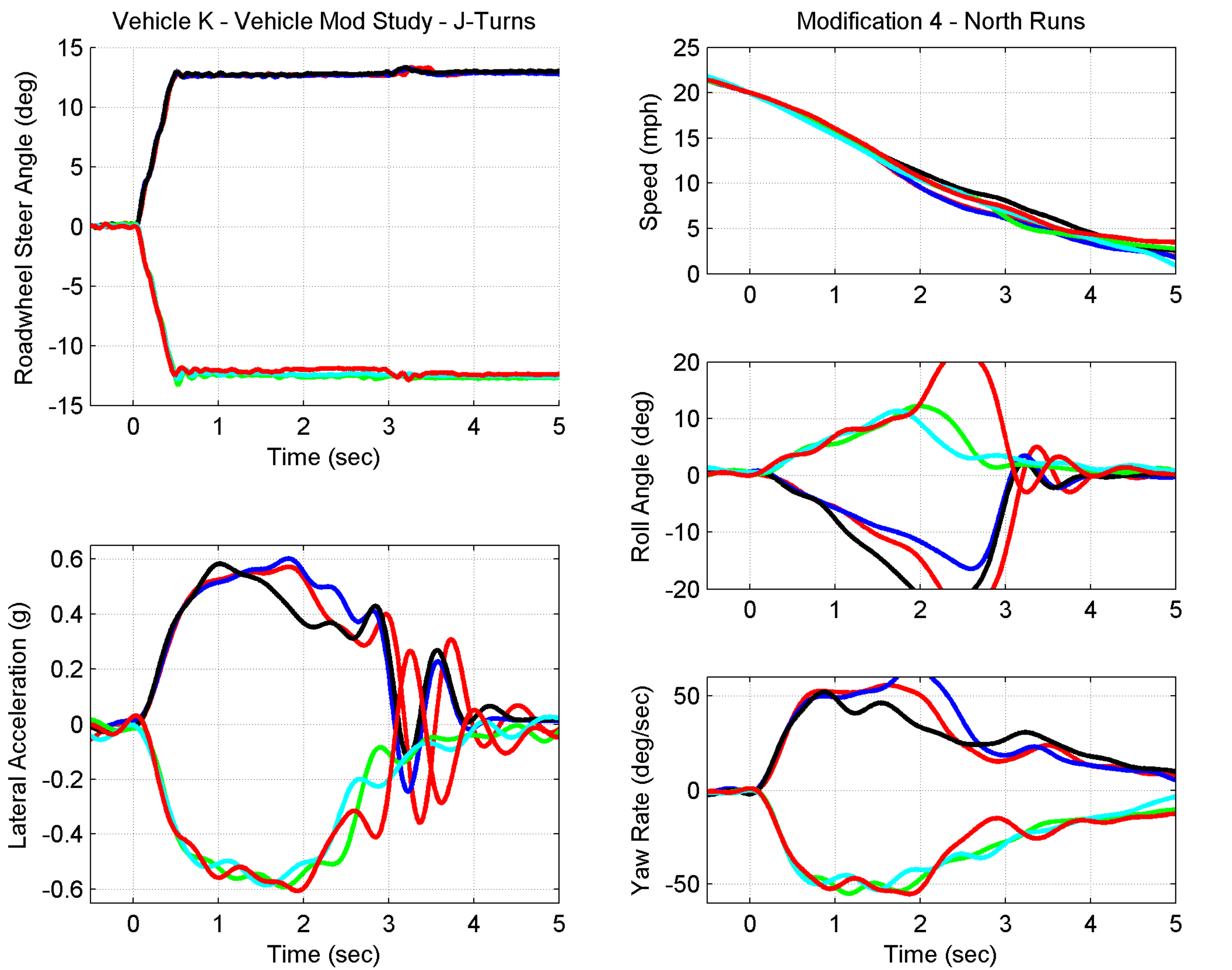


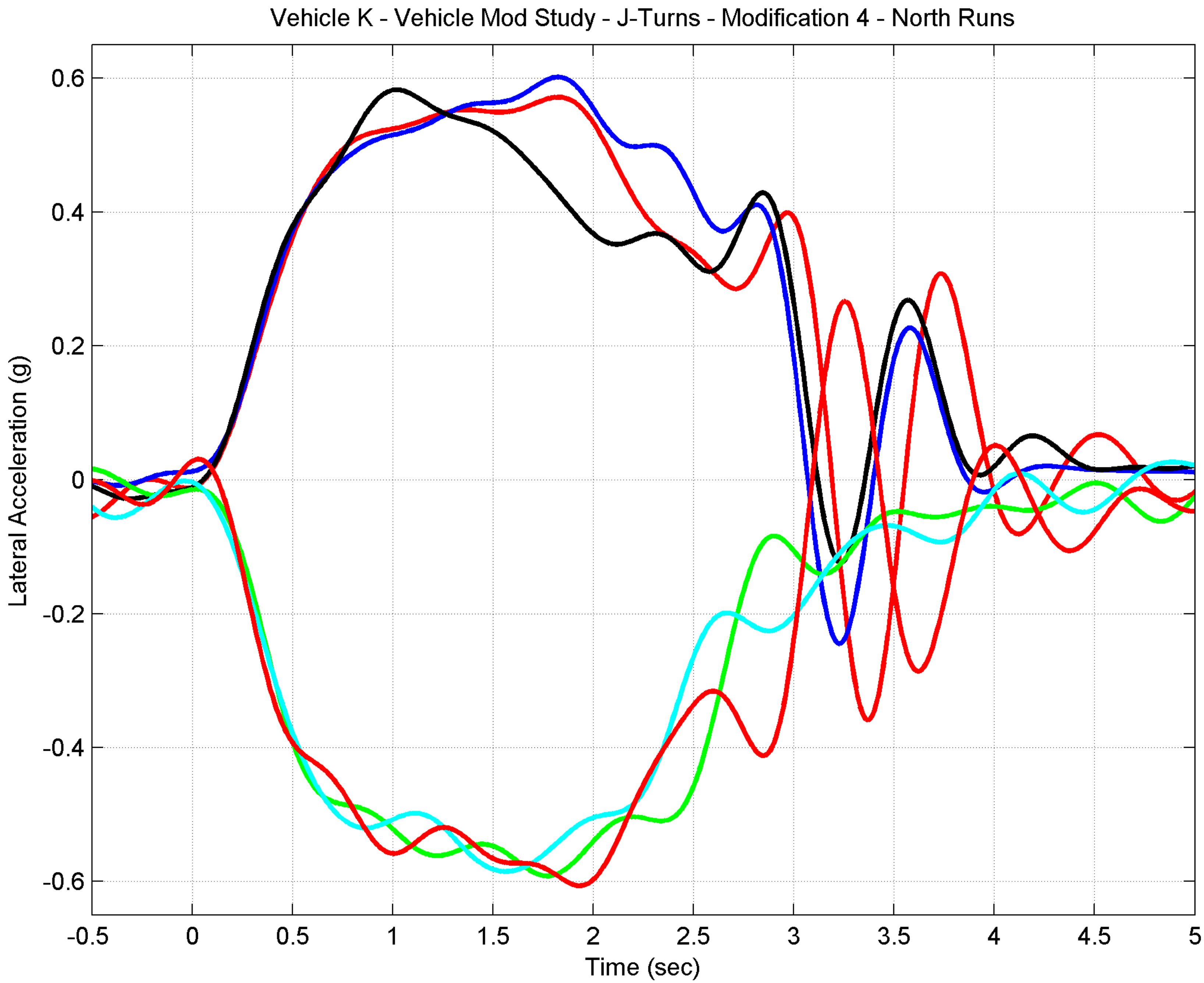
Vehicle K - Vehicle Mod Study - J-Turns - Modification 3 - North Runs
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Lateral Acceleration (g)
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (sec)


Vehicle K - Vehicle Mod Study - J-Turns
Modification 4 - South Runs
Roadwheel Steer Angle (deg)
Time (sec)
Lateral Acceleration (g)
Time (sec)
Speed (mph)
Roll Angle (deg)
Yaw Rate (deg/sec)
Time (sec)



Vehicle K - Vehicle Mod Study - J-Turns - Modification 4 - South 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 K - Vehicle Mod Study - J-Turns
Modification 4 - North Runs
Roadwheel Steer Angle (deg)
Time (sec)
Speed (mph)
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)



Vehicle K - Vehicle Mod Study - J-Turns - Modification 4 - North 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)

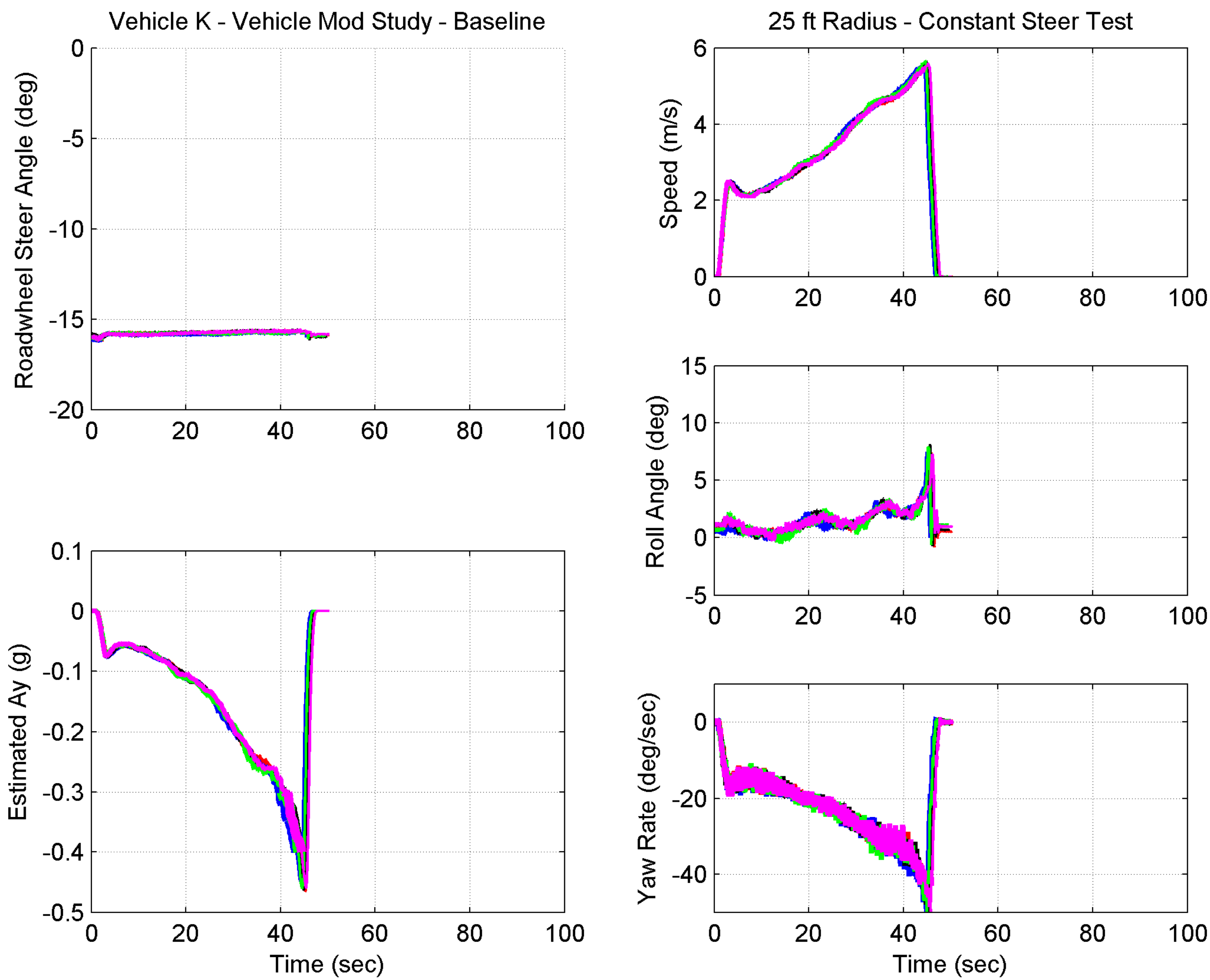
Vehicle K - Vehicle Modification Study

Peak Lateral Accelerations During 2WL J-Turns - All Values in "g's"

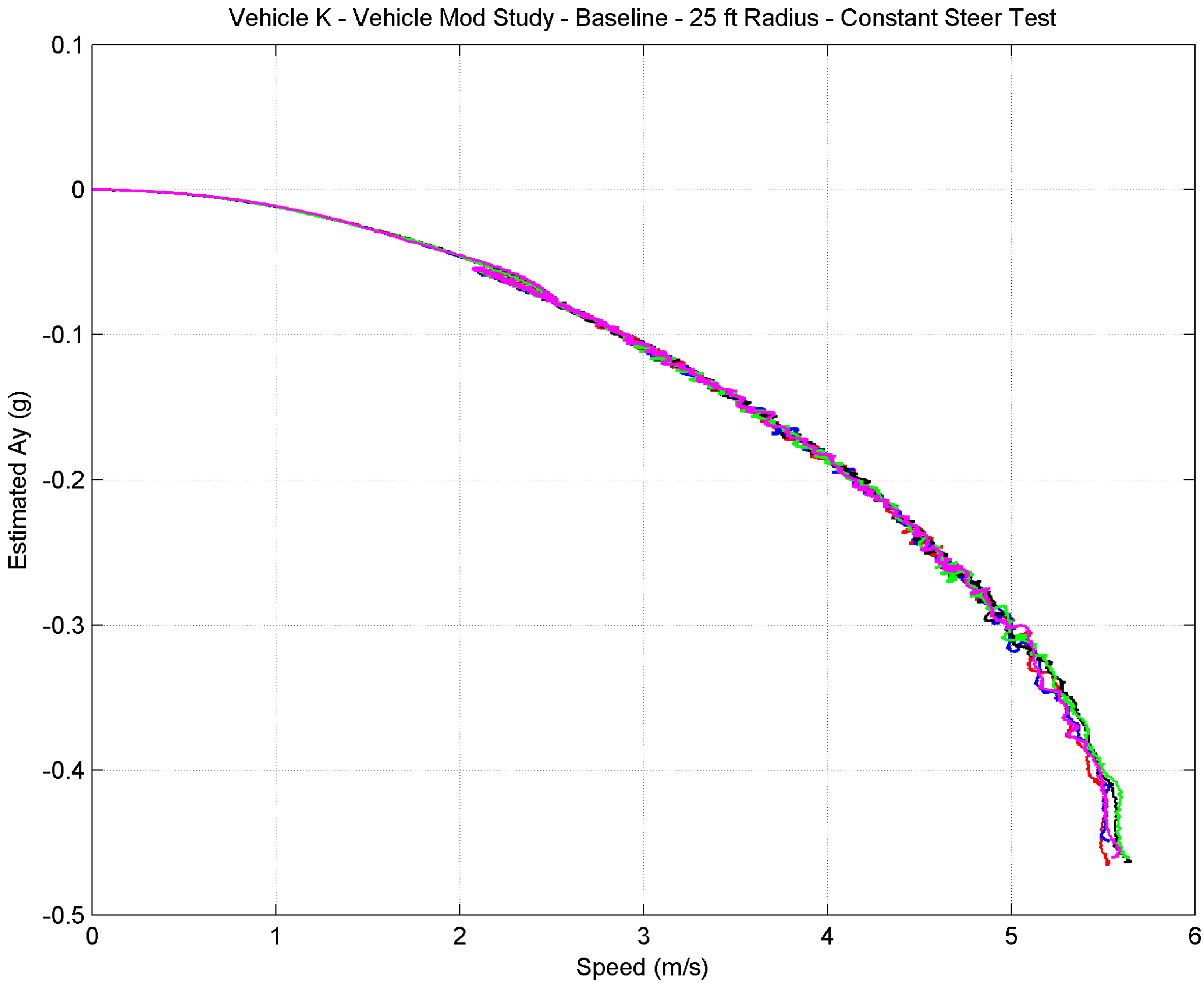
	Baseline	Mod 1	Mod 2	Mod 3	Mod 4
Northwest (on Asphalt) South (on Dirt) Runs RIGHT Turns	NA	0.563	0.580	0.561	0.584
	NA	0.562	0.576	0.572	0.580
	NA	0.563	0.581	0.559	0.590
Northwest (on Asphalt) South (on Dirt) Runs LEFT Turns	-0.556	-0.544	-0.591	-0.563	-0.575
	-0.549	-0.549	-0.592	-0.573	-0.603
	-0.555	-0.548	-0.595	-0.584	-0.607
Mean Absolute Value of NW (or South) Runs	0.554	0.555	0.586	0.569	0.590

	Baseline	Mod 1	Mod 2	Mod 3	Mod 4
Southeast (on Asphalt) North (on Dirt) Runs RIGHT Turns	NA	0.545	0.585	0.547	0.572
	NA	0.547	0.580	0.541	0.602
	NA	0.551	0.585	0.526	0.583
Southeast (on Asphalt) North (on Dirt) Runs LEFT Turns	-0.527	-0.551	-0.614	-0.548	-0.592
	-0.531	-0.542	-0.616	-0.537	-0.585
	-0.528	-0.555	-0.613	-0.542	-0.607
Mean Absolute Value of SE (or North) Runs	0.529	0.549	0.599	0.540	0.590

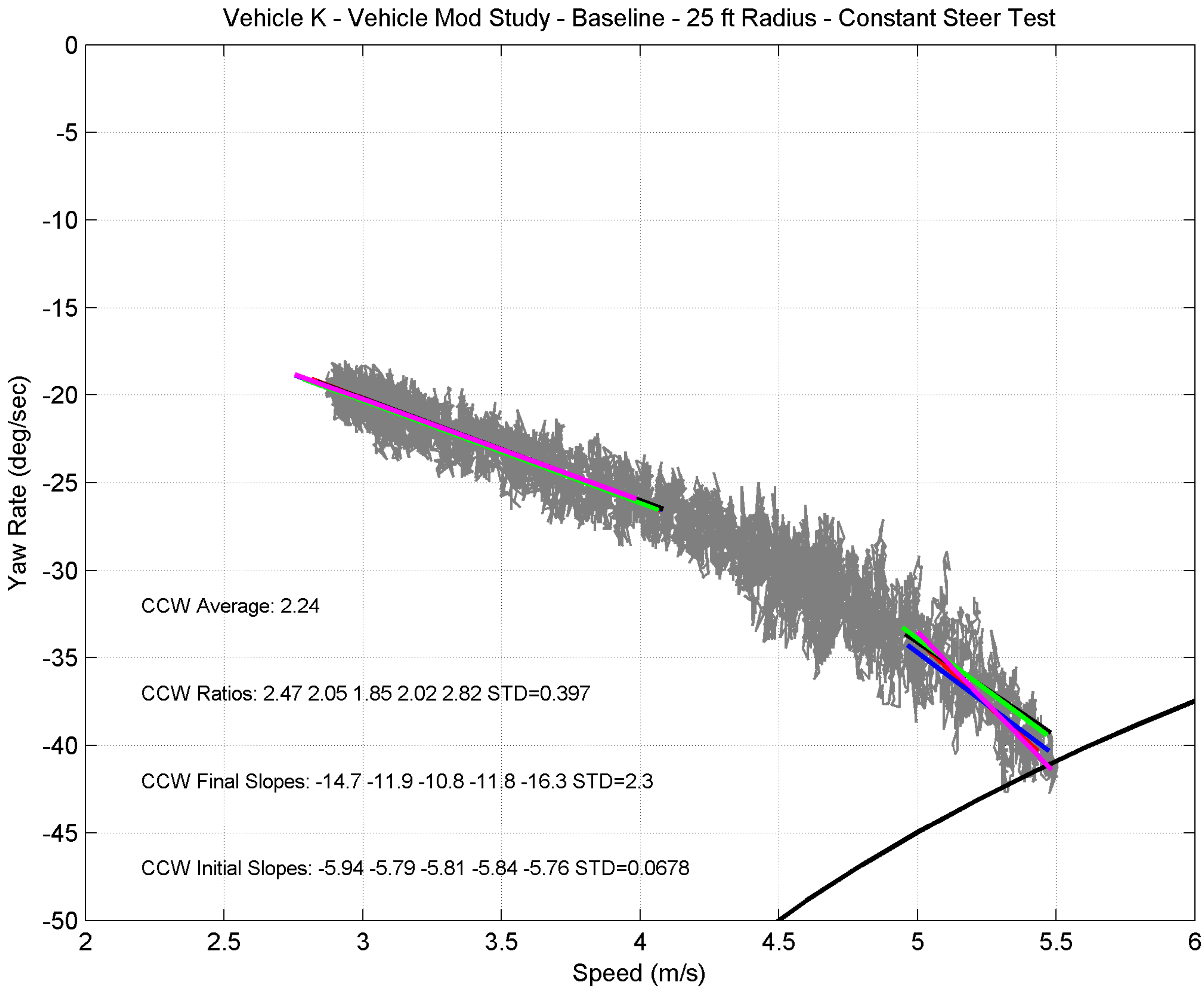
Average of All Runs	**0.541**	**0.552**	**0.592**	**0.554**	**0.590**

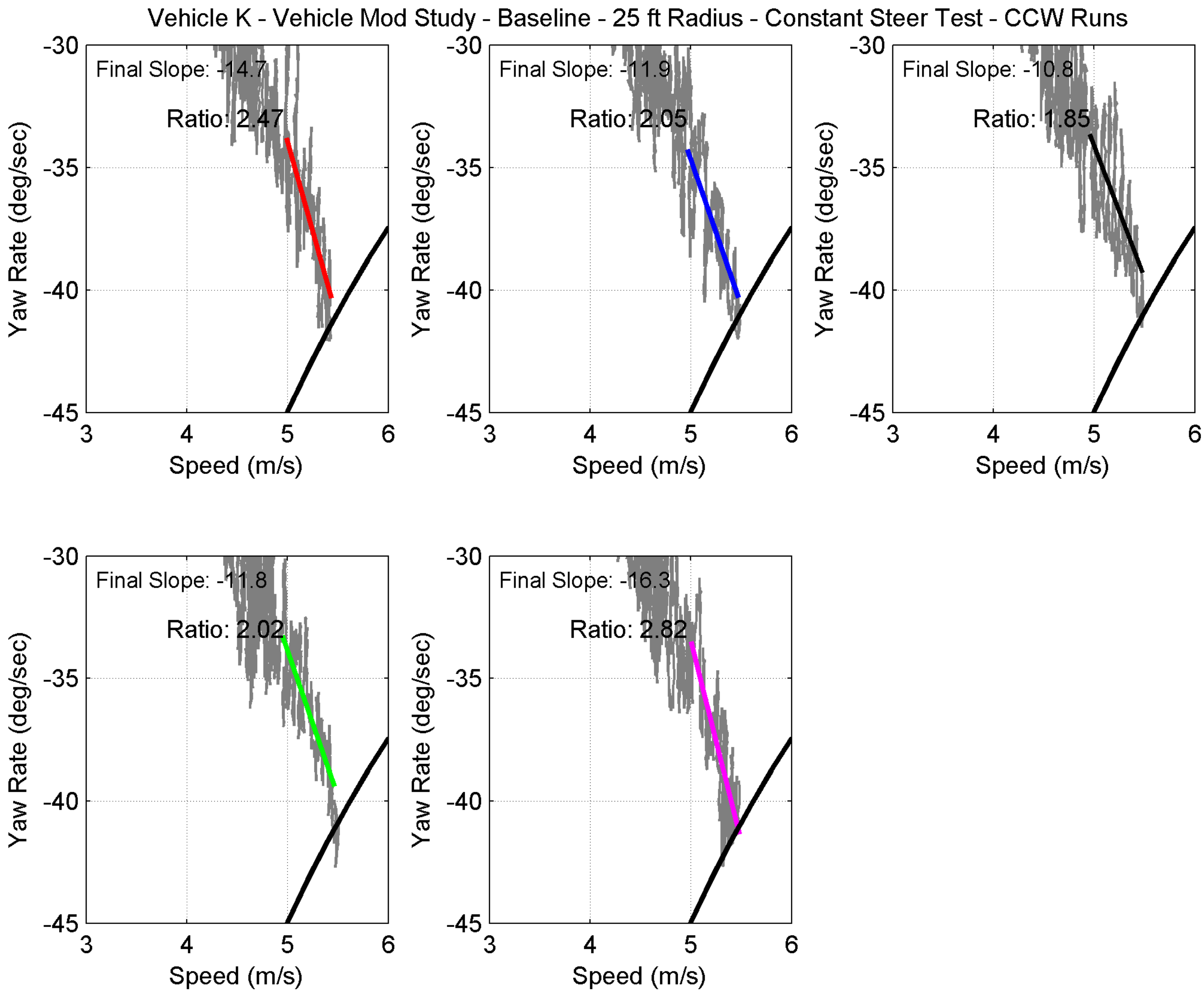


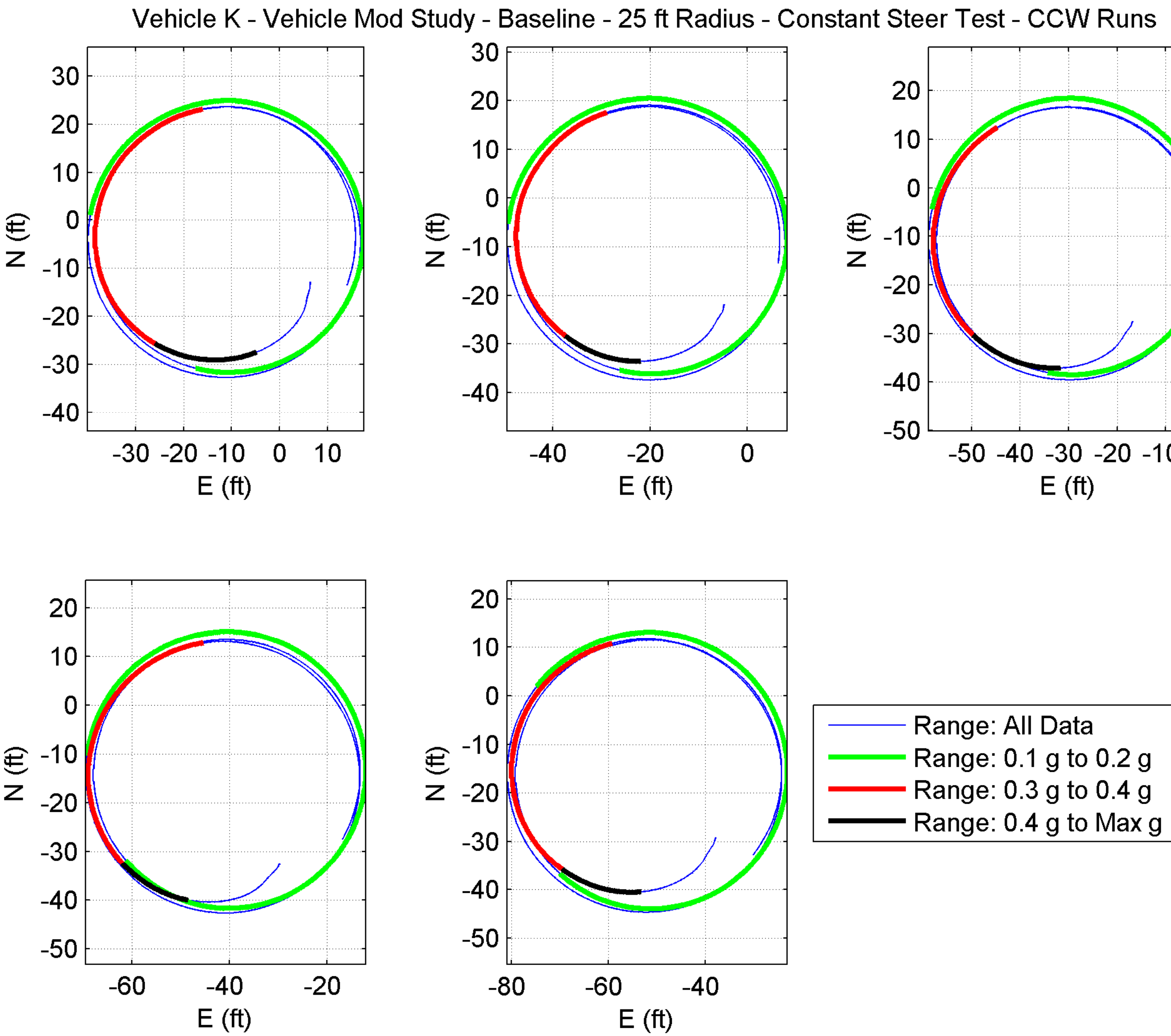
Vehicle K - Vehicle Mod Study - Baseline
25 ft Radius - Constant Steer Test
Roadwheel Steer Angle (deg)
Speed (m/s)
Roll Angle (deg)
Estimated Ay (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

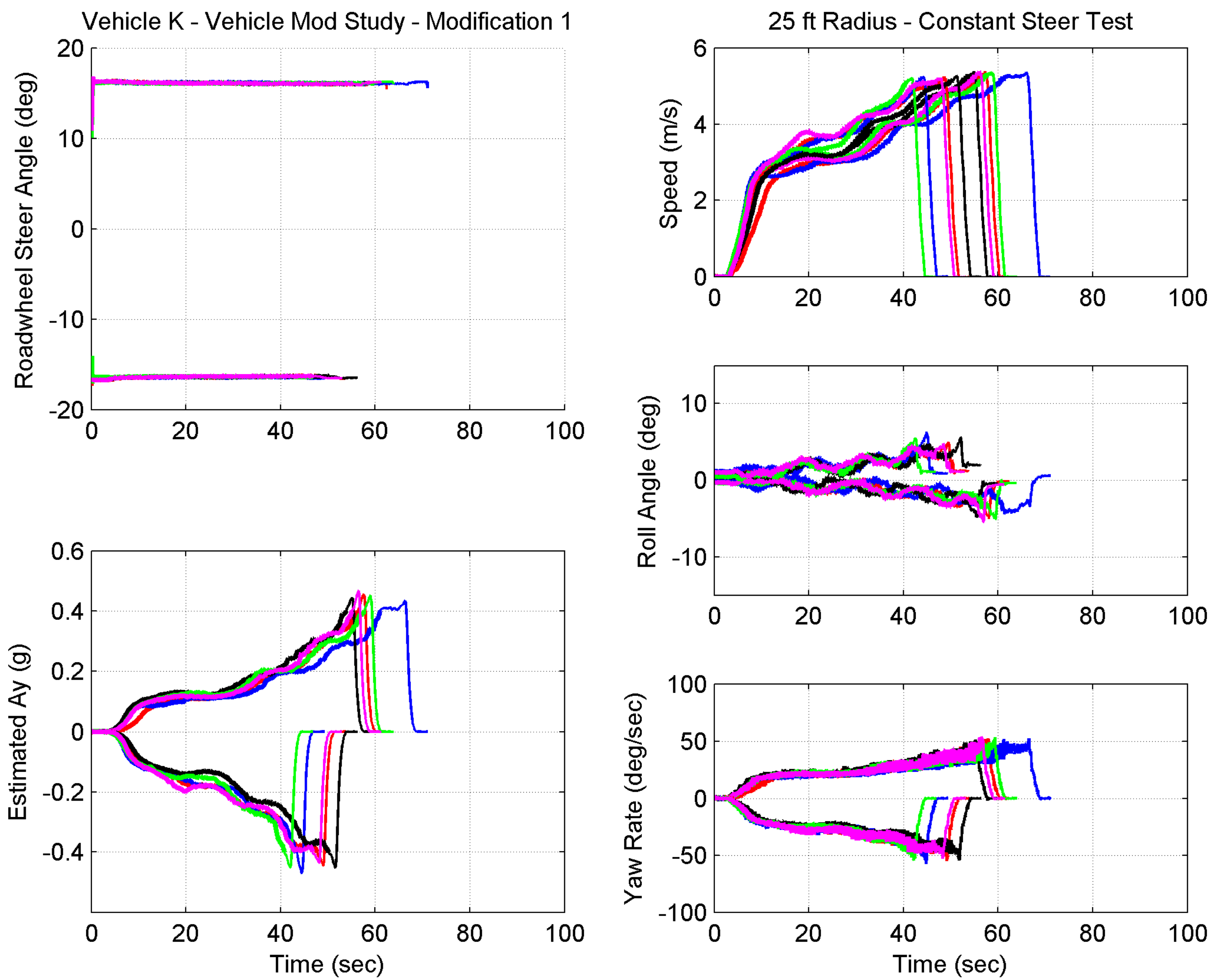


Vehicle K - Vehicle Mod Study - Baseline - 25 ft Radius - Constant Steer Test
Estimated Ay (g)
Speed (m/s)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
1
2
3
4
5
6

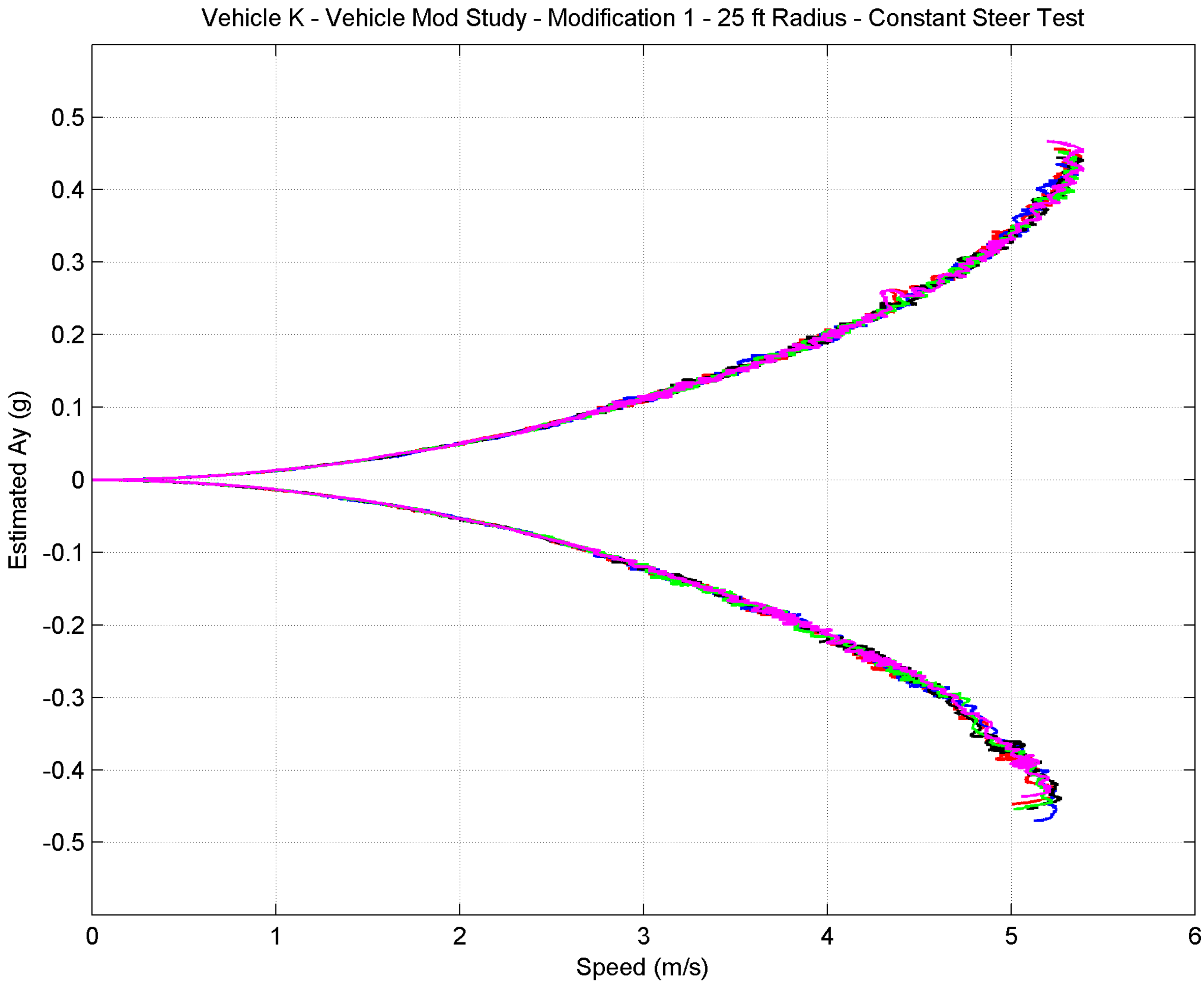

Vehicle K - Vehicle Mod Study - Baseline - 25 ft Radius - Constant Steer Test
Yaw Rate (deg/sec)
Speed (m/s)
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
2
2.5
3
3.5
4
4.5
5
5.5
6
CCW Average: 2.24
CCW Ratios: 2.47 2.05 1.85 2.02 2.82 STD=0.397
CCW Final Slopes: -14.7 -11.9 -10.8 -11.8 -16.3 STD=2.3
CCW Initial Slopes: -5.94 -5.79 -5.81 -5.84 -5.76 STD=0.0678

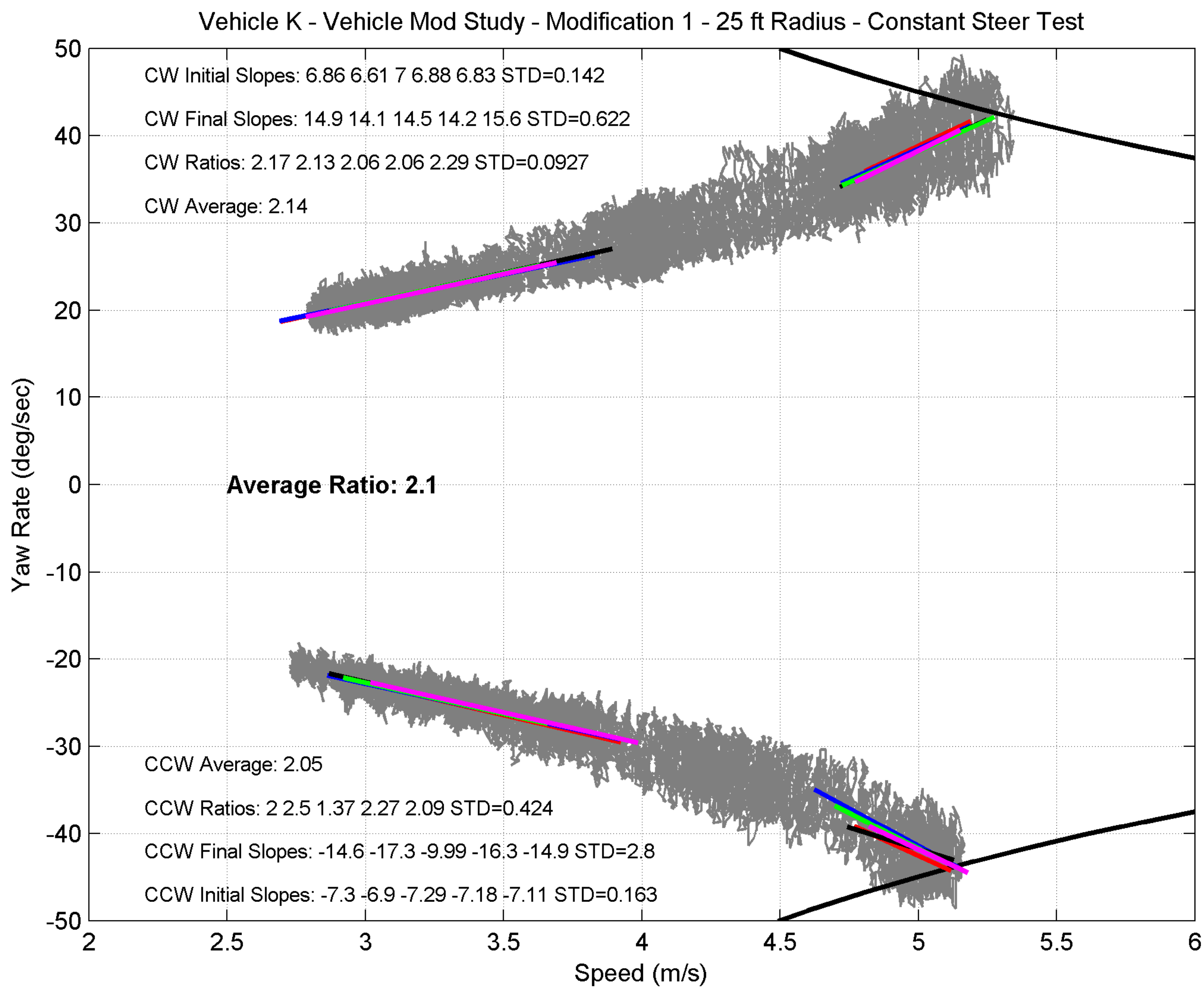

Vehicle K - Vehicle Mod Study - Baseline - 25 ft Radius - Constant Steer Test - CCW Runs
Final Slope: -14.7
Ratio: 2.47
Final Slope: -11.9
Ratio: 2.05
Final Slope: -10.8
Ratio: 1.85
Final Slope: -11.8
Ratio: 2.02
Final Slope: -16.3
Ratio: 2.82
Yaw Rate (deg/sec)
Speed (m/s)

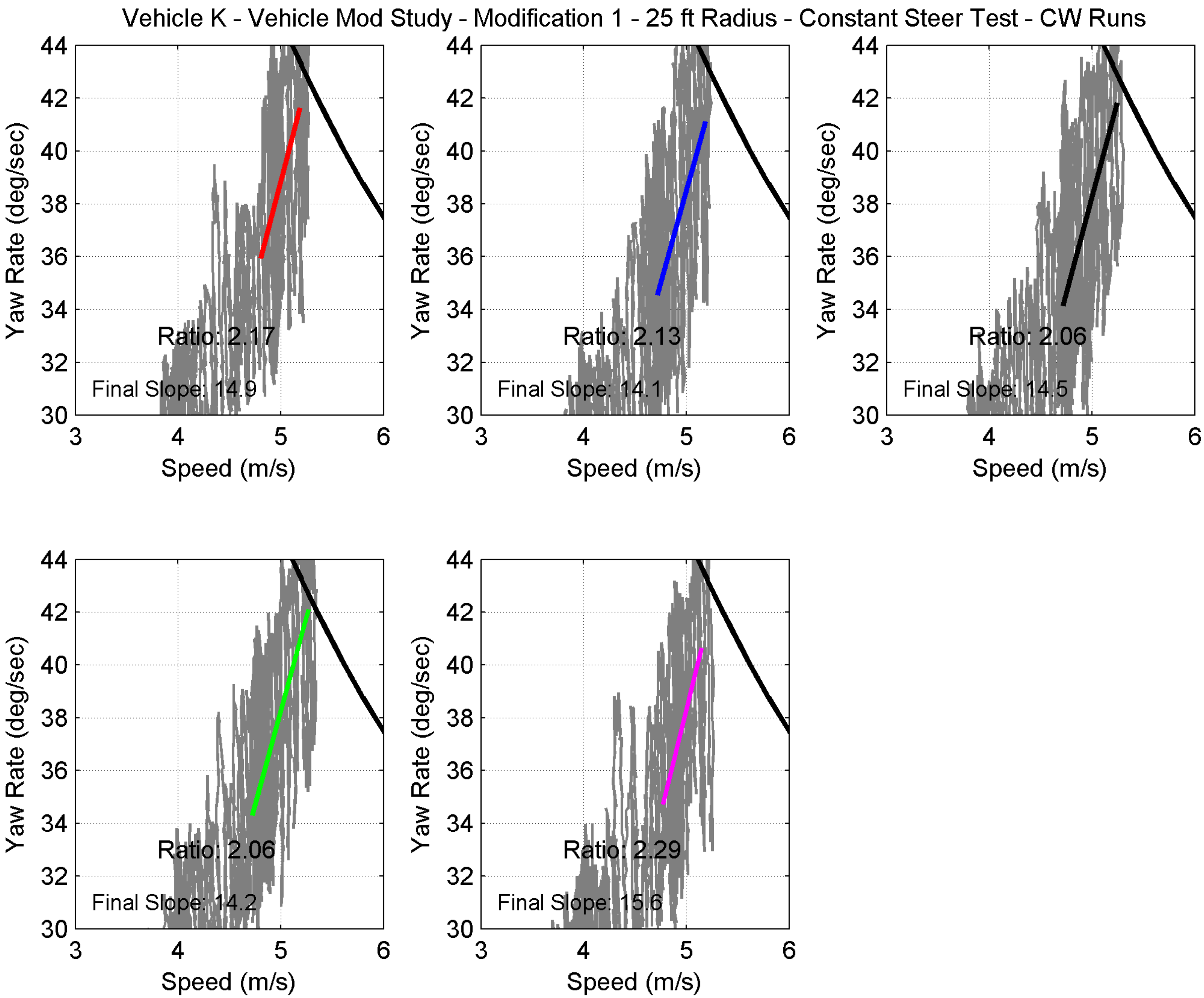

Vehicle K - Vehicle Mod Study - Baseline - 25 ft Radius - Constant Steer Test - CCW Runs
N (ft)
E (ft)
Range: All Data
Range: 0.1 g to 0.2 g
Range: 0.3 g to 0.4 g
Range: 0.4 g to Max g

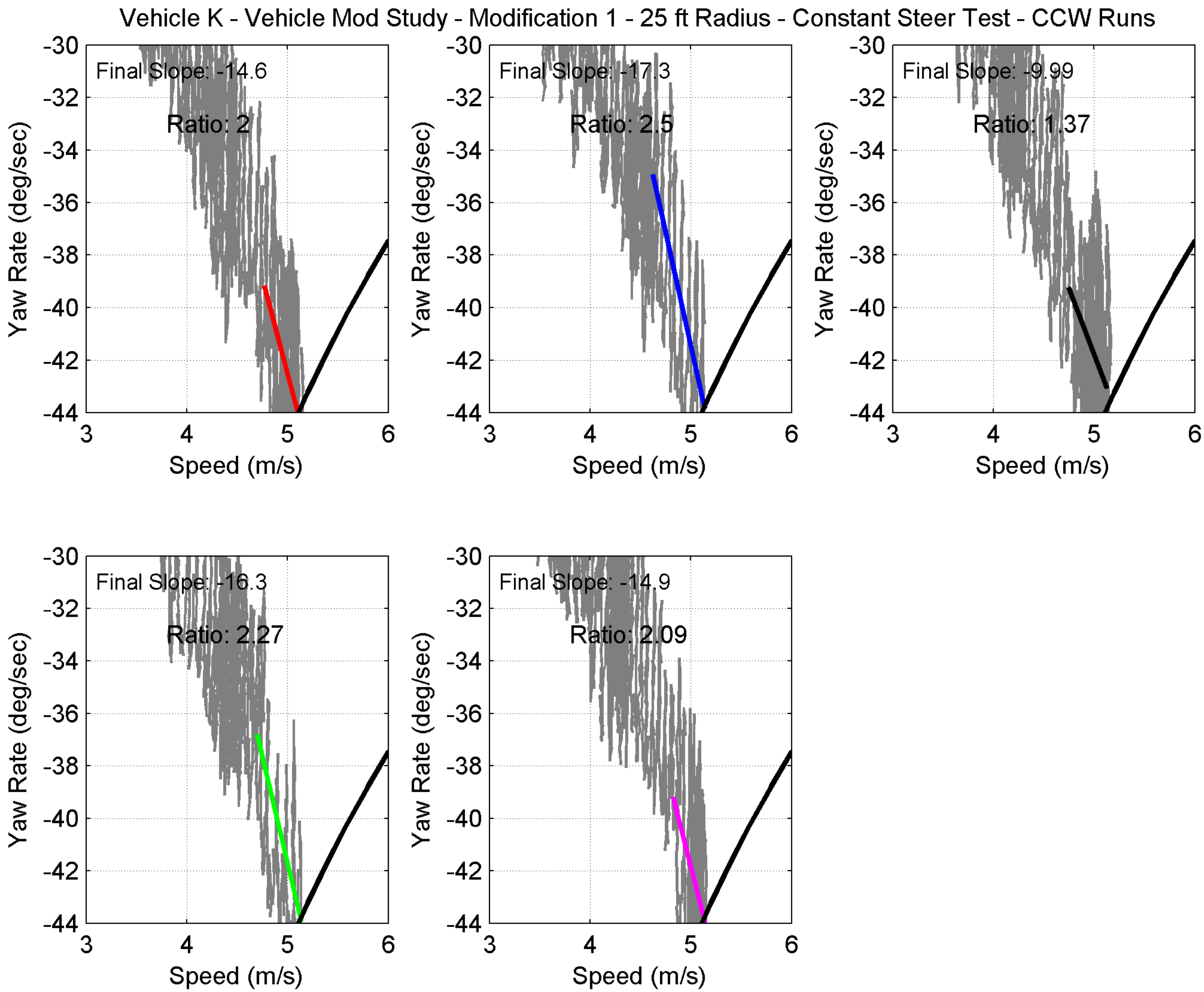


Vehicle K - Vehicle Mod Study - Modification 1
25 ft Radius - Constant Steer Test
Roadwheel Steer Angle (deg)
Speed (m/s)
Roll Angle (deg)
Estimated Ay (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)


Vehicle K - Vehicle Mod Study - Modification 1 - 25 ft Radius - Constant Steer Test
Estimated Ay (g)
Speed (m/s)
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
1
2
3
4
5
6

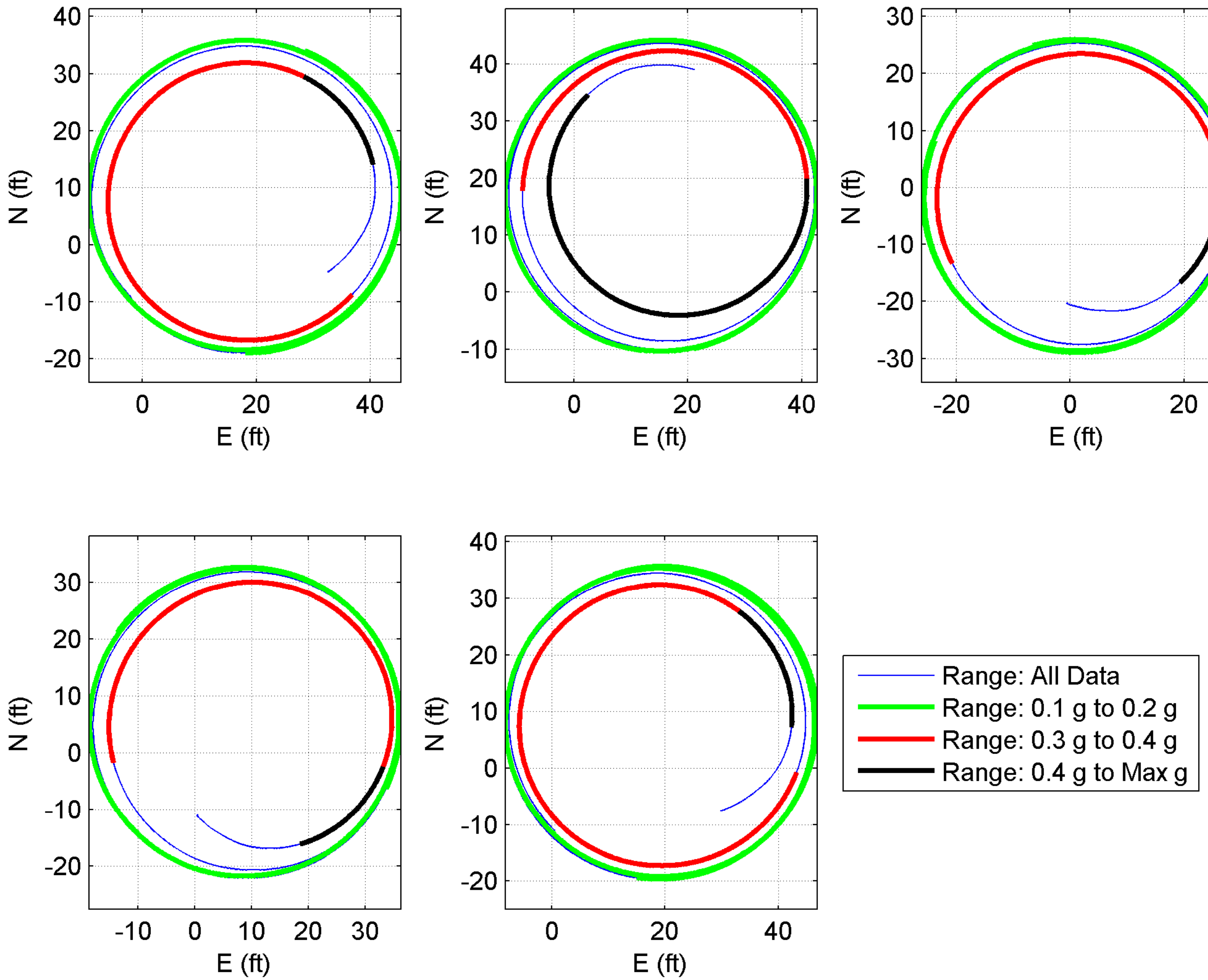

Vehicle K - Vehicle Mod Study - Modification 1 - 25 ft Radius - Constant Steer Test
CW Initial Slopes: 6.86 6.61 7 6.88 6.83 STD=0.142
CW Final Slopes: 14.9 14.1 14.5 14.2 15.6 STD=0.622
CW Ratios: 2.17 2.13 2.06 2.06 2.29 STD=0.0927
CW Average: 2.14
Average Ratio: 2.1
CCW Average: 2.05
CCW Ratios: 2 2.5 1.37 2.27 2.09 STD=0.424
CCW Final Slopes: -14.6 -17.3 -9.99 -16.3 -14.9 STD=2.8
CCW Initial Slopes: -7.3 -6.9 -7.29 -7.18 -7.11 STD=0.163
Yaw Rate (deg/sec)
Speed (m/s)
50
40
30
20
10
0
-10
-20
-30
-40
-50
2
2.5
3
3.5
4
4.5
5
5.5
6


Vehicle K - Vehicle Mod Study - Modification 1 - 25 ft Radius - Constant Steer Test - CW Runs
Yaw Rate (deg/sec)
Speed (m/s)
Ratio: 2.17
Final Slope: 14.9
Ratio: 2.13
Final Slope: 14.1
Ratio: 2.06
Final Slope: 14.5
Ratio: 2.06
Final Slope: 14.2
Ratio: 2.29
Final Slope: 15.6

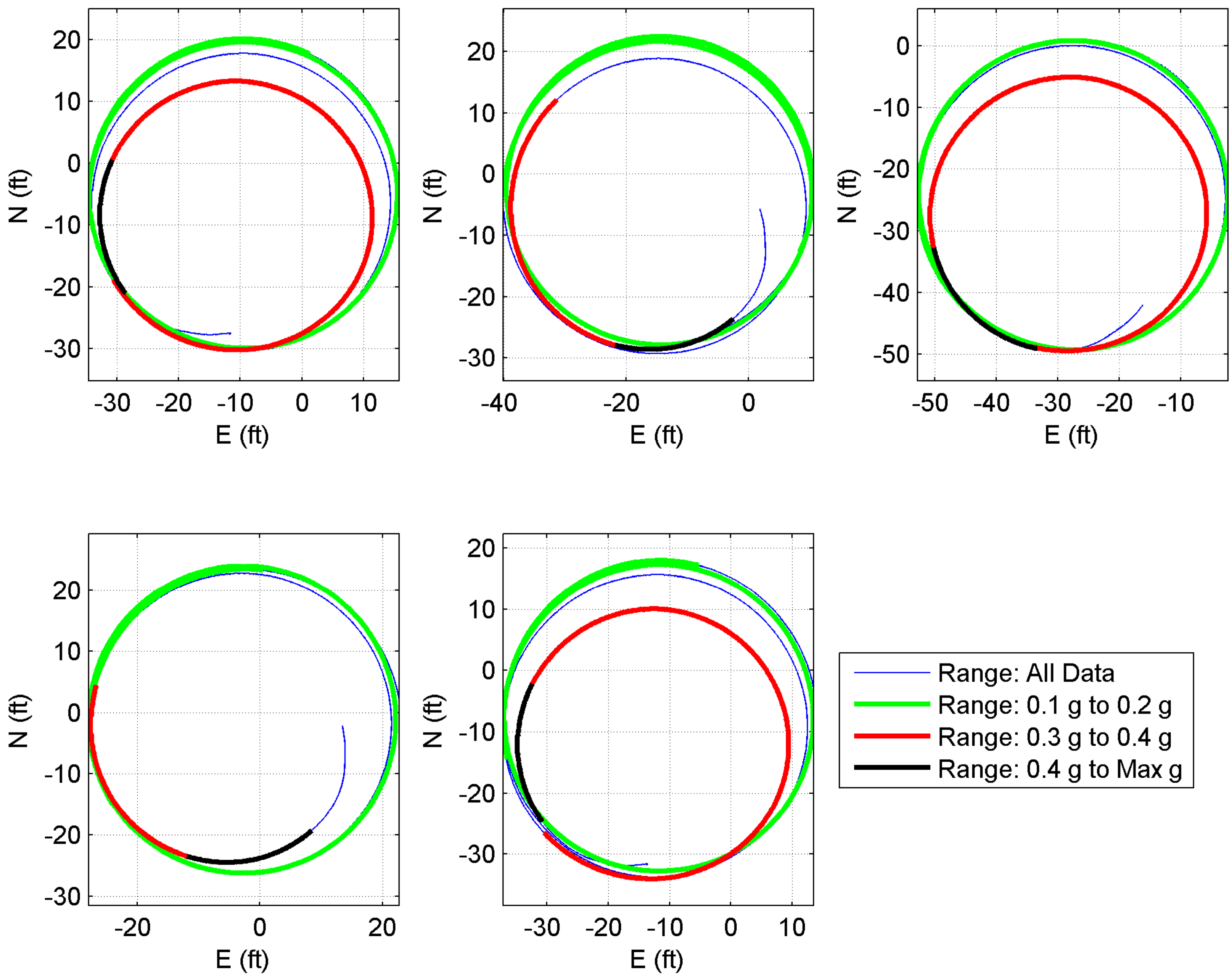


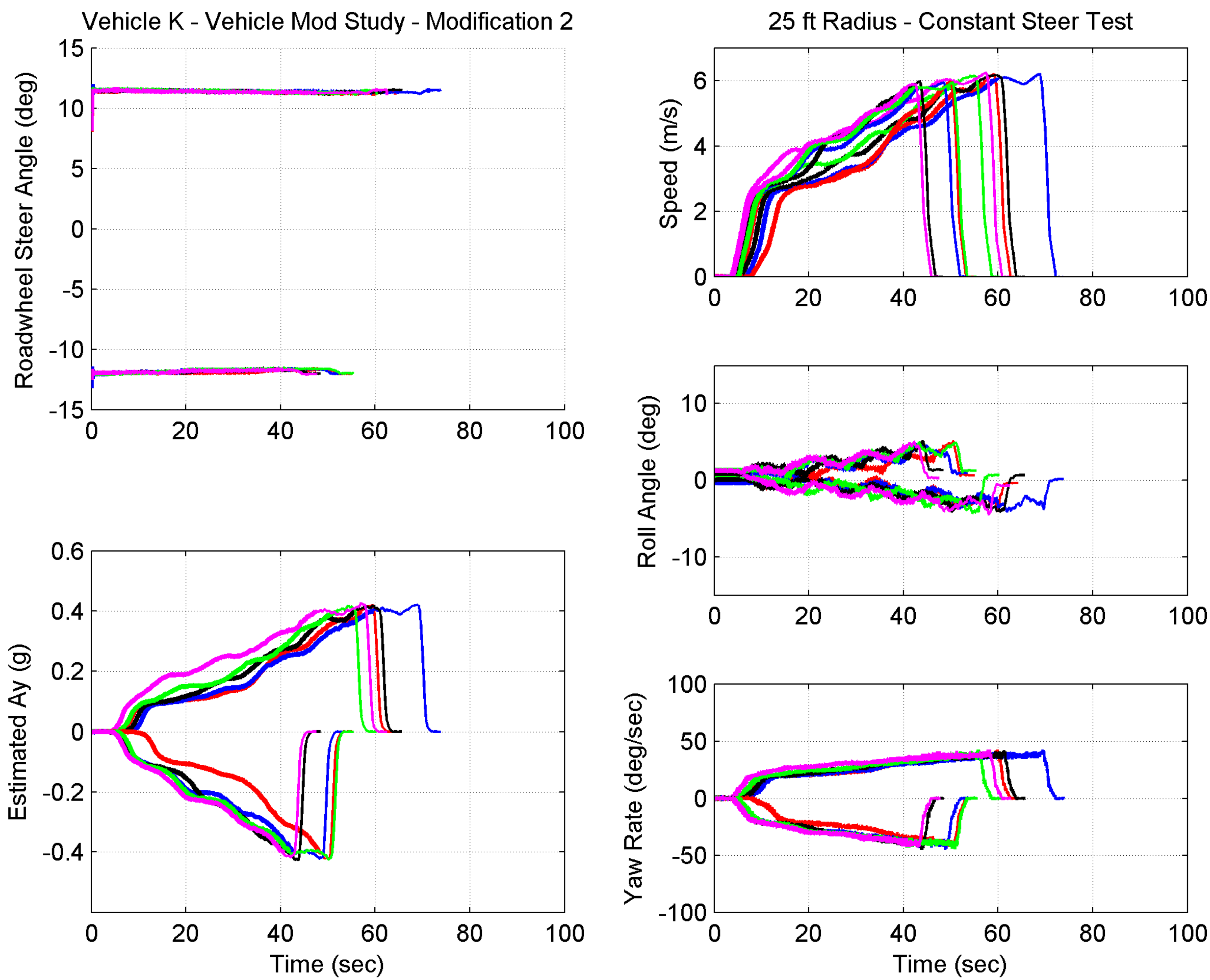
Vehicle K - Vehicle Mod Study - Modification 1 - 25 ft Radius - Constant Steer Test - CCW Runs
Final Slope: -14.6
Ratio: 2
Final Slope: -17.3
Ratio: 2.5
Final Slope: -9.99
Ratio: 1.37
Final Slope: -16.3
Ratio: 2.27
Final Slope: -14.9
Ratio: 2.09
Yaw Rate (deg/sec)
Speed (m/s)

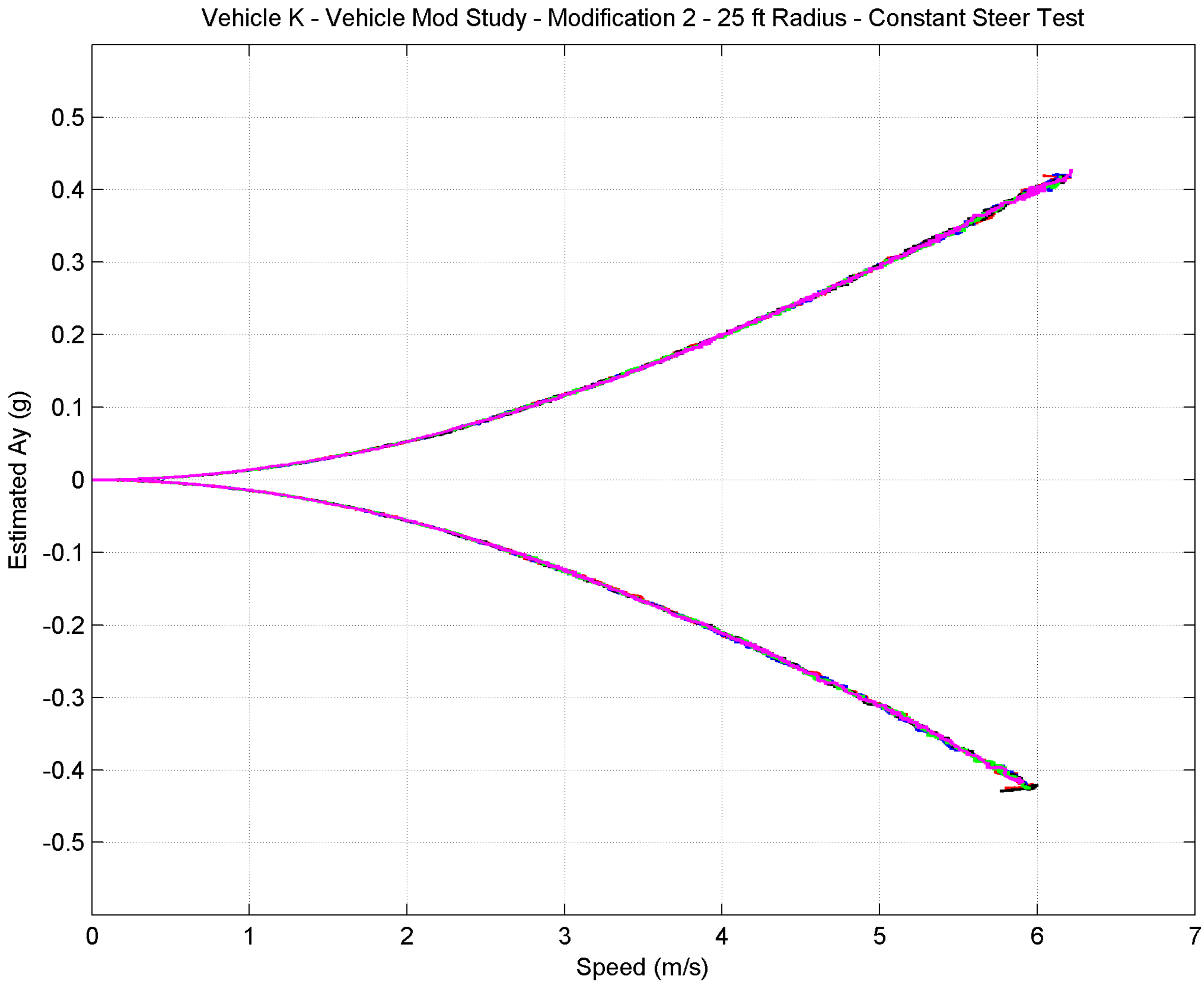
Vehicle K - Vehicle Mod Study - Modification 1 - 25 ft Radius - Constant Steer Test - CW Runs

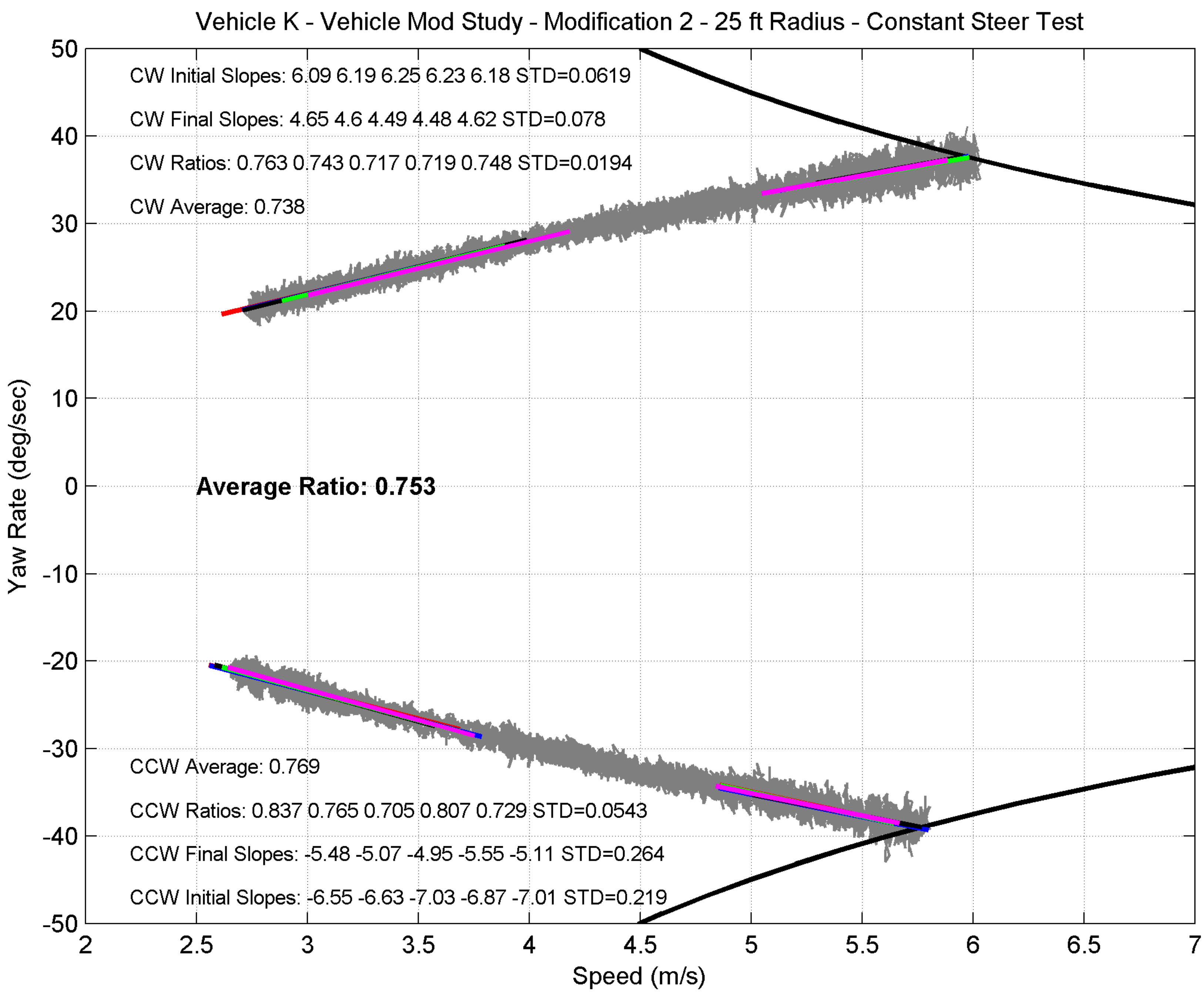


Vehicle K - Vehicle Mod Study - Modification 1 - 25 ft Radius - Constant Steer Test - CCW Runs

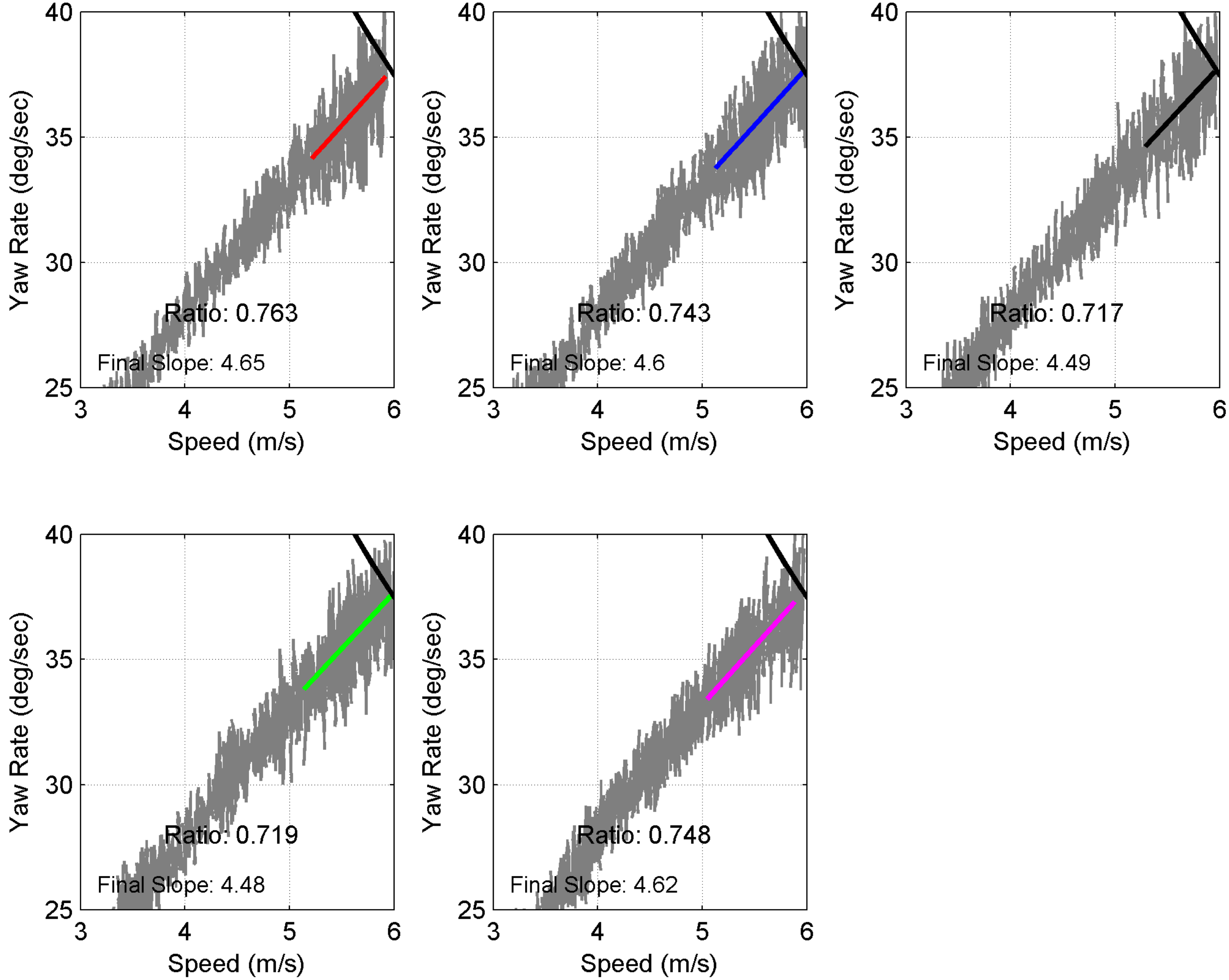


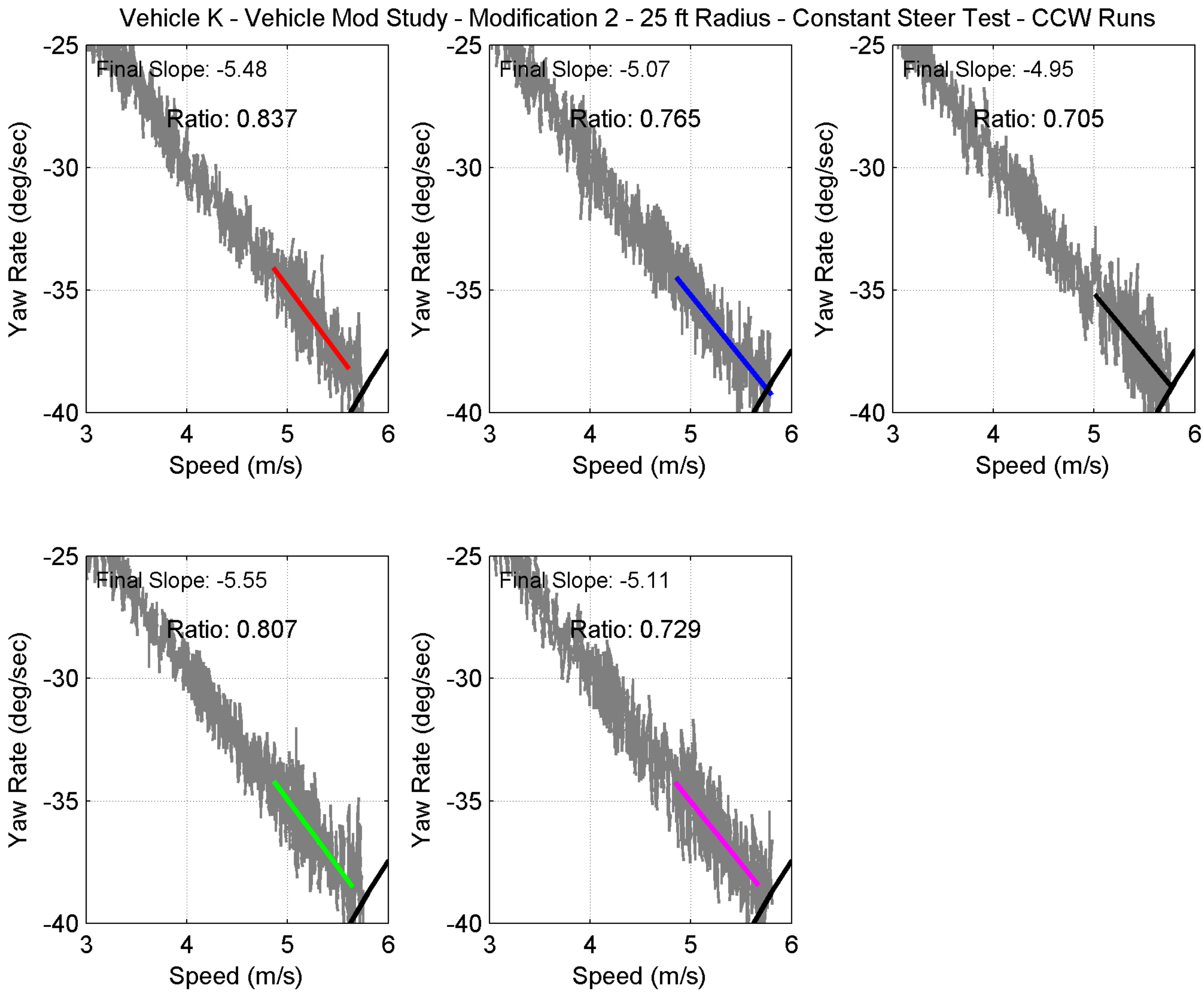

Vehicle K - Vehicle Mod Study - Modification 2
25 ft Radius - Constant Steer Test
Roadwheel Steer Angle (deg)
Speed (m/s)
Roll Angle (deg)
Estimated Ay (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

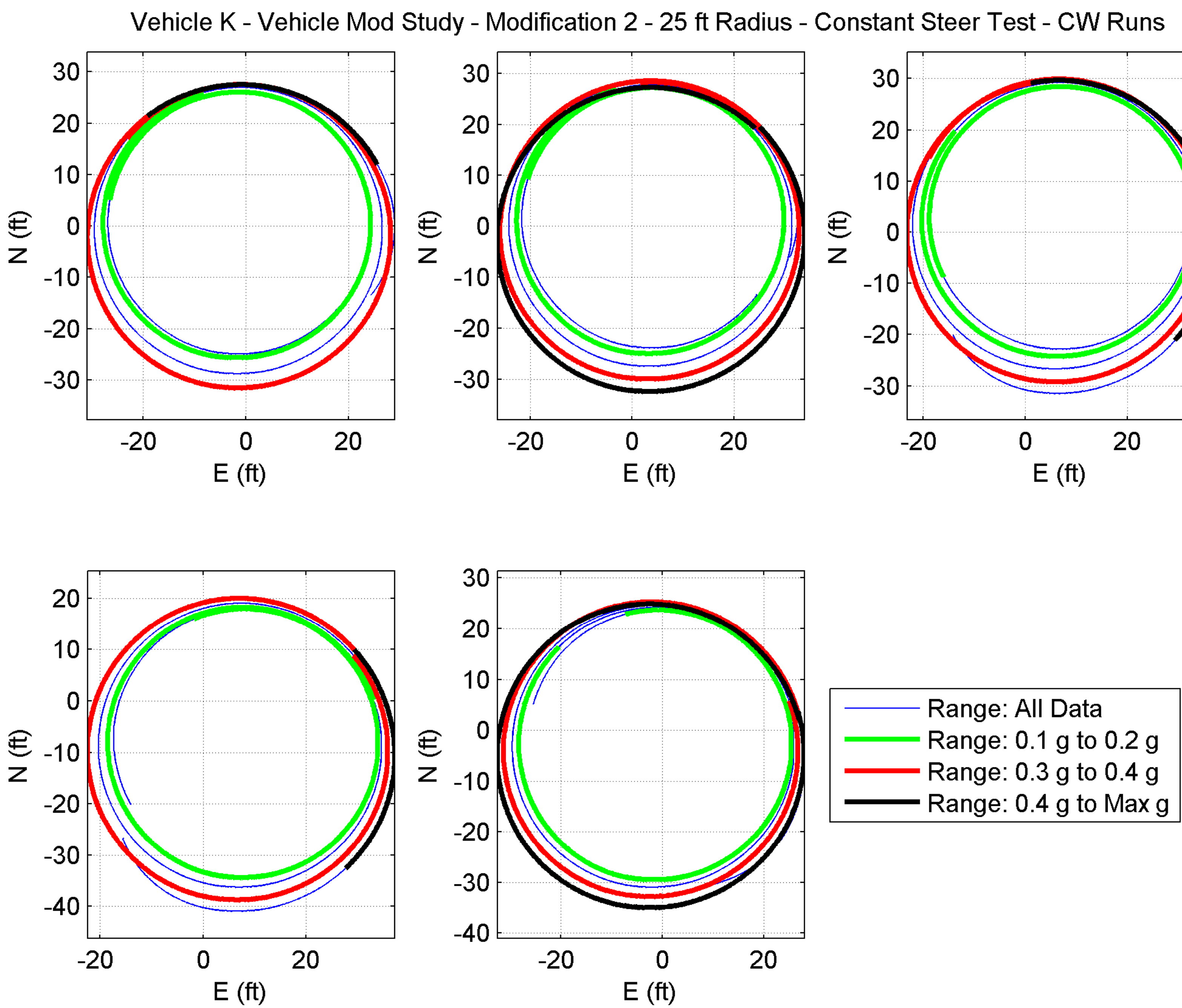

Vehicle K - Vehicle Mod Study - Modification 2 - 25 ft Radius - Constant Steer Test
Estimated Ay (g)
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
1
2
3
4
5
6
7
Speed (m/s)


Vehicle K - Vehicle Mod Study - Modification 2 - 25 ft Radius - Constant Steer Test
CW Initial Slopes: 6.09 6.19 6.25 6.23 6.18 STD=0.0619
CW Final Slopes: 4.65 4.6 4.49 4.48 4.62 STD=0.078
CW Ratios: 0.763 0.743 0.717 0.719 0.748 STD=0.0194
CW Average: 0.738
Average Ratio: 0.753
CCW Average: 0.769
CCW Ratios: 0.837 0.765 0.705 0.807 0.729 STD=0.0543
CCW Final Slopes: -5.48 -5.07 -4.95 -5.55 -5.11 STD=0.264
CCW Initial Slopes: -6.55 -6.63 -7.03 -6.87 -7.01 STD=0.219
Yaw Rate (deg/sec)
Speed (m/s)
50
40
30
20
10
0
-10
-20
-30
-40
-50
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7

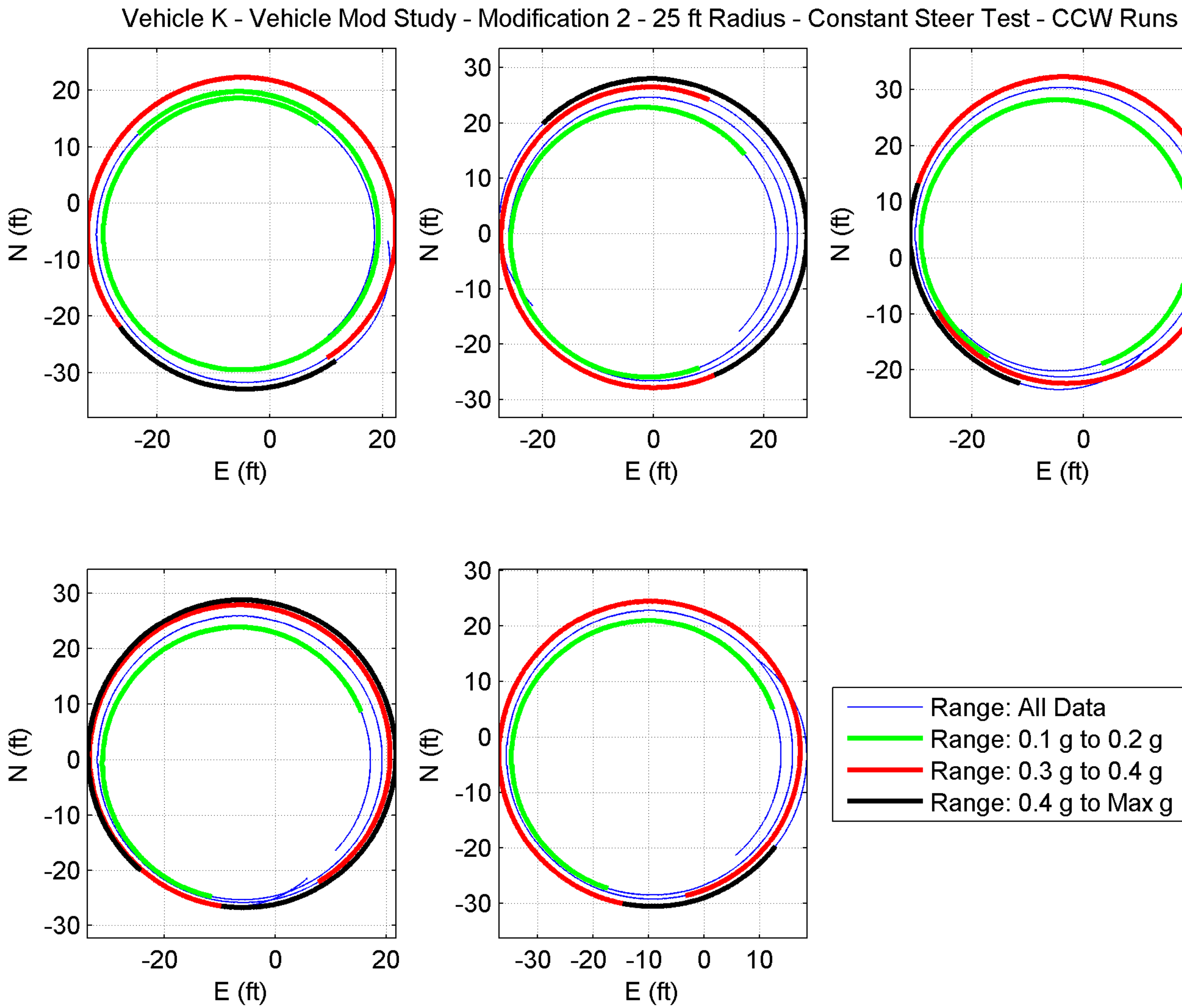
Vehicle K - Vehicle Mod Study - Modification 2 - 25 ft Radius - Constant Steer Test - CW Runs

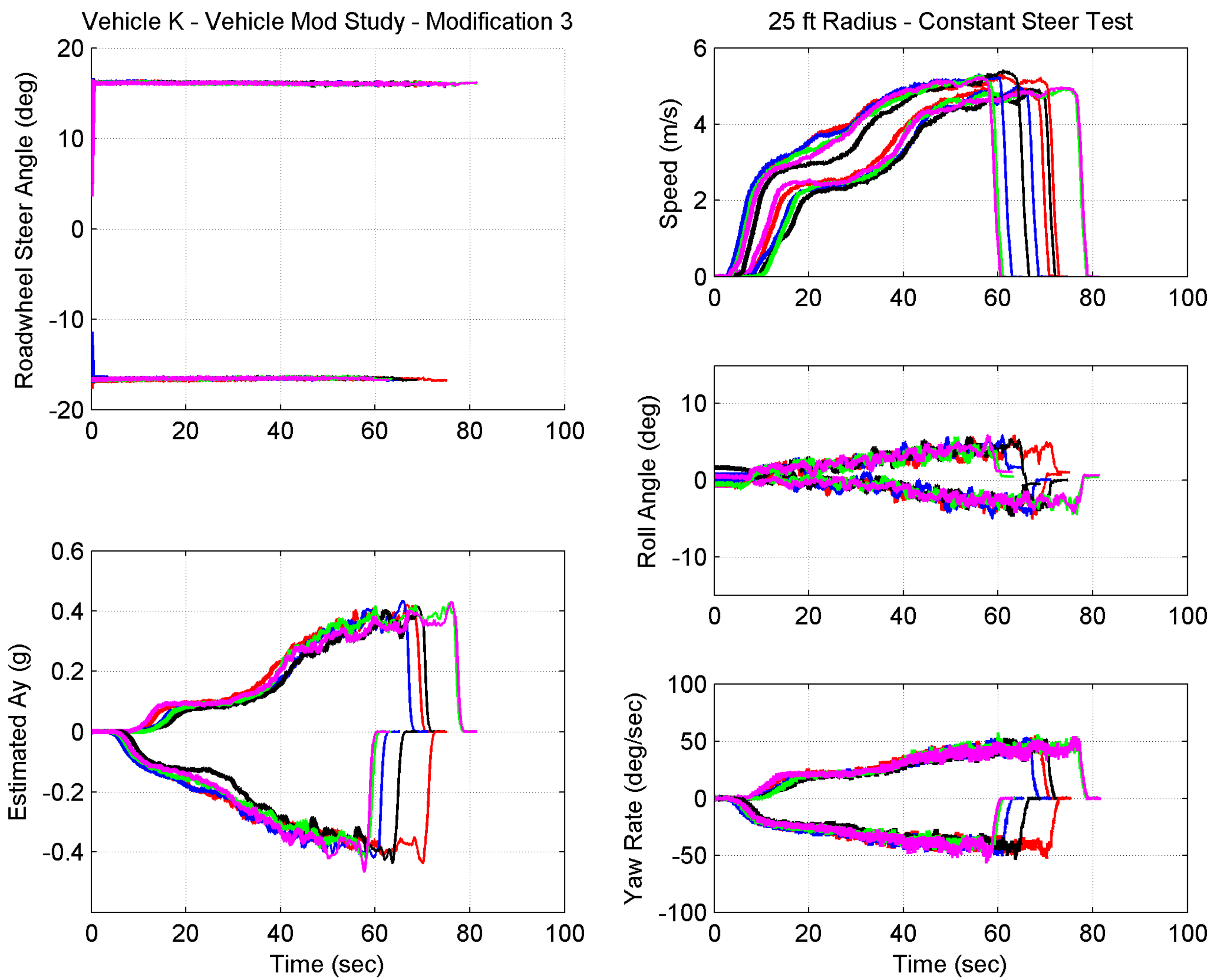


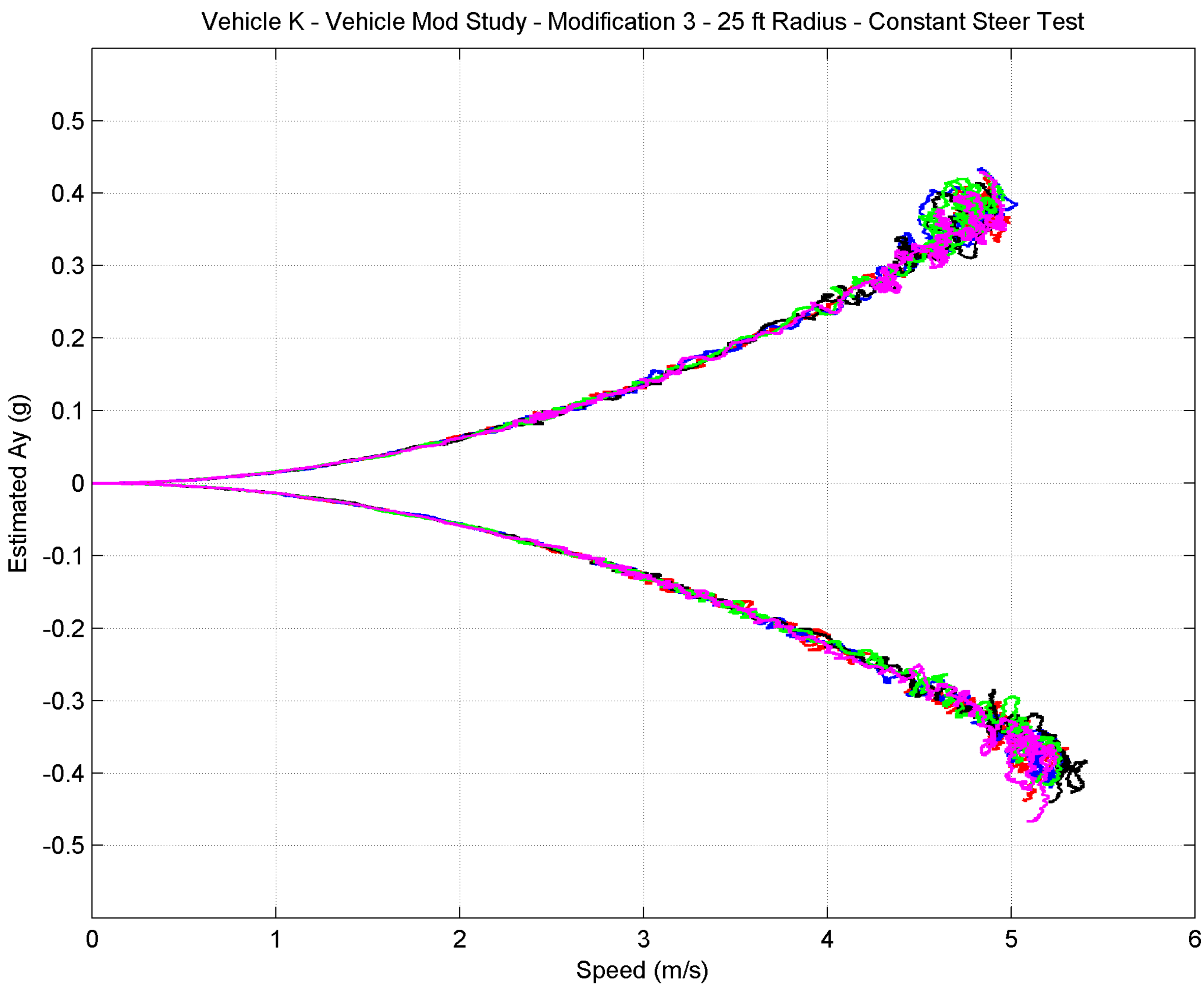

Vehicle K - Vehicle Mod Study - Modification 2 - 25 ft Radius - Constant Steer Test - CCW Runs
Final Slope: -5.48
Ratio: 0.837
Final Slope: -5.07
Ratio: 0.765
Final Slope: -4.95
Ratio: 0.705
Final Slope: -5.55
Ratio: 0.807
Final Slope: -5.11
Ratio: 0.729
Yaw Rate (deg/sec)
Speed (m/s)
-25
-30
-35
-40
3
4
5
6

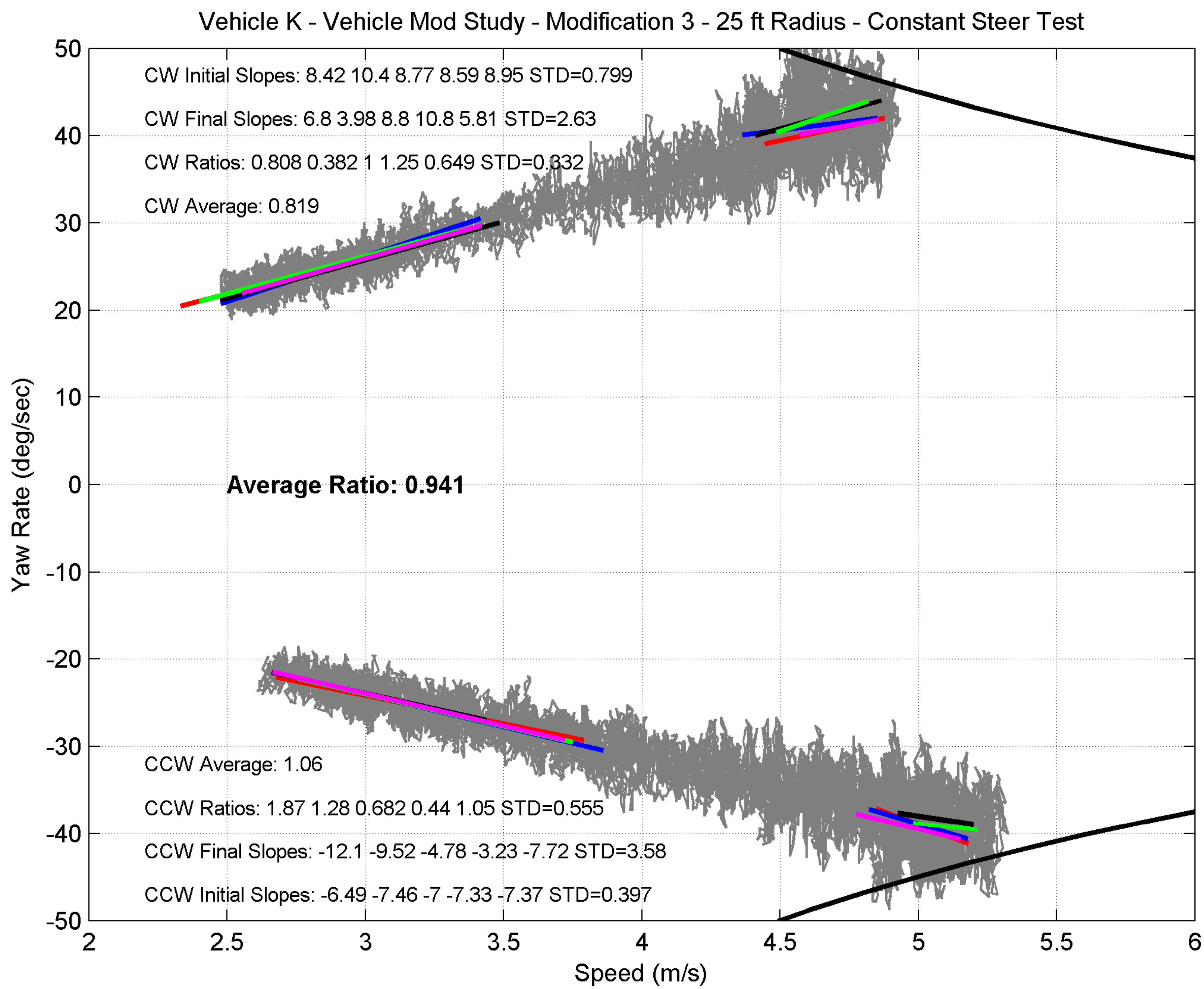


Vehicle K - Vehicle Mod Study - Modification 2 - 25 ft Radius - Constant Steer Test - CW Runs
N (ft)
E (ft)
Range: All Data
Range: 0.1 g to 0.2 g
Range: 0.3 g to 0.4 g
Range: 0.4 g to Max g

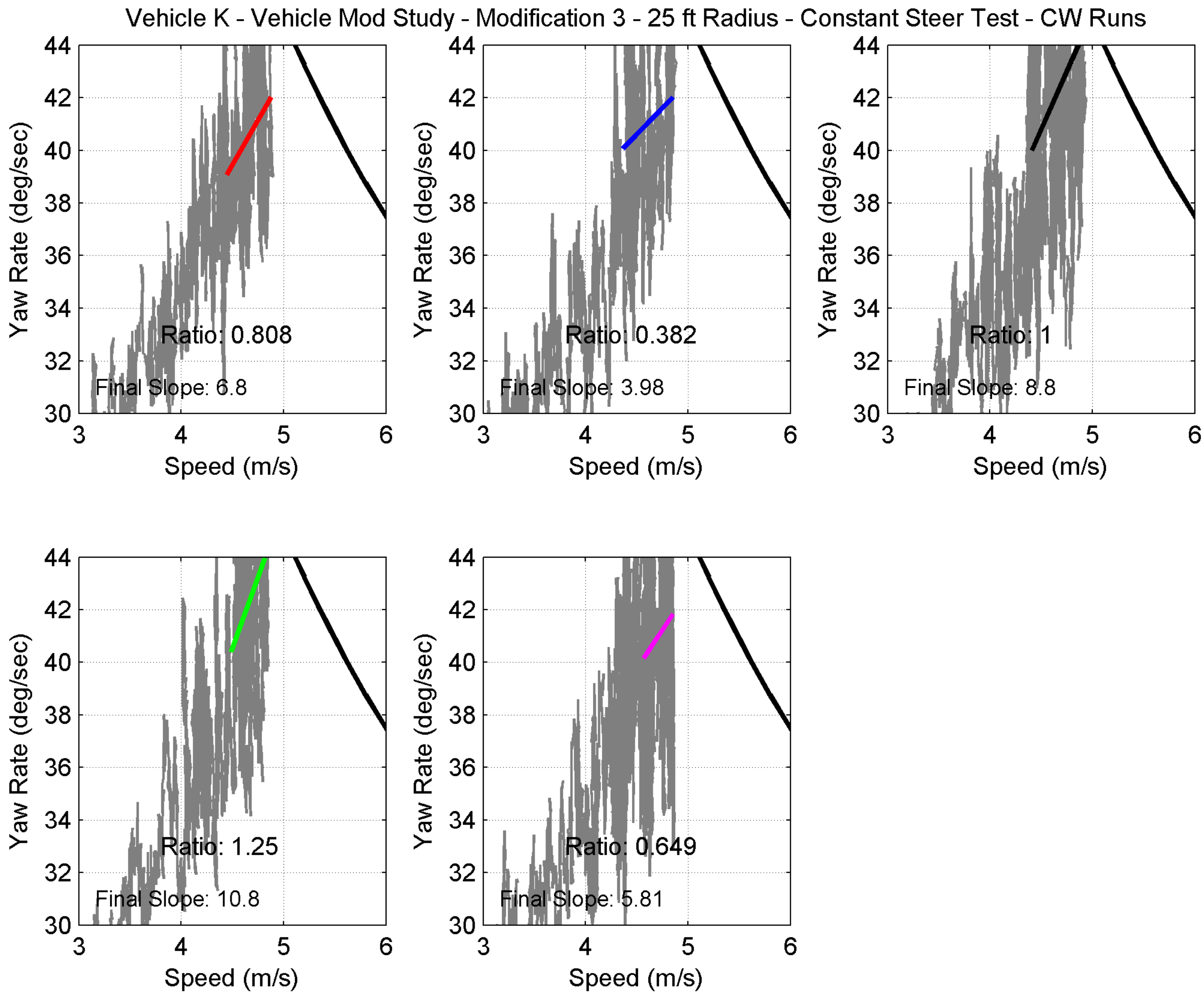

Vehicle K - Vehicle Mod Study - Modification 2 - 25 ft Radius - Constant Steer Test - CCW Runs
N (ft)
E (ft)
Range: All Data
Range: 0.1 g to 0.2 g
Range: 0.3 g to 0.4 g
Range: 0.4 g to Max g

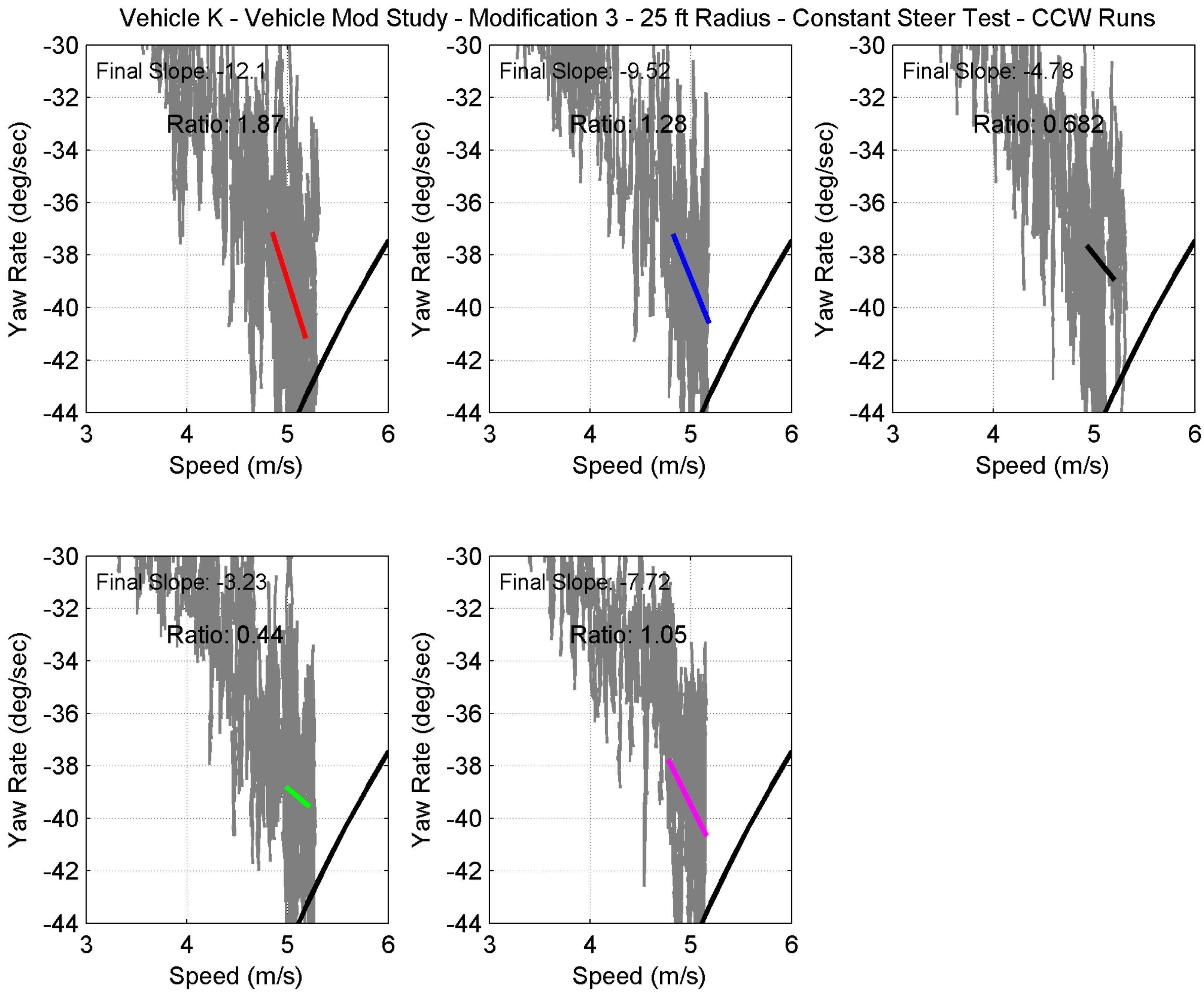

Vehicle K - Vehicle Mod Study - Modification 3
25 ft Radius - Constant Steer Test
Roadwheel Steer Angle (deg)
Speed (m/s)
Roll Angle (deg)
Estimated Ay (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

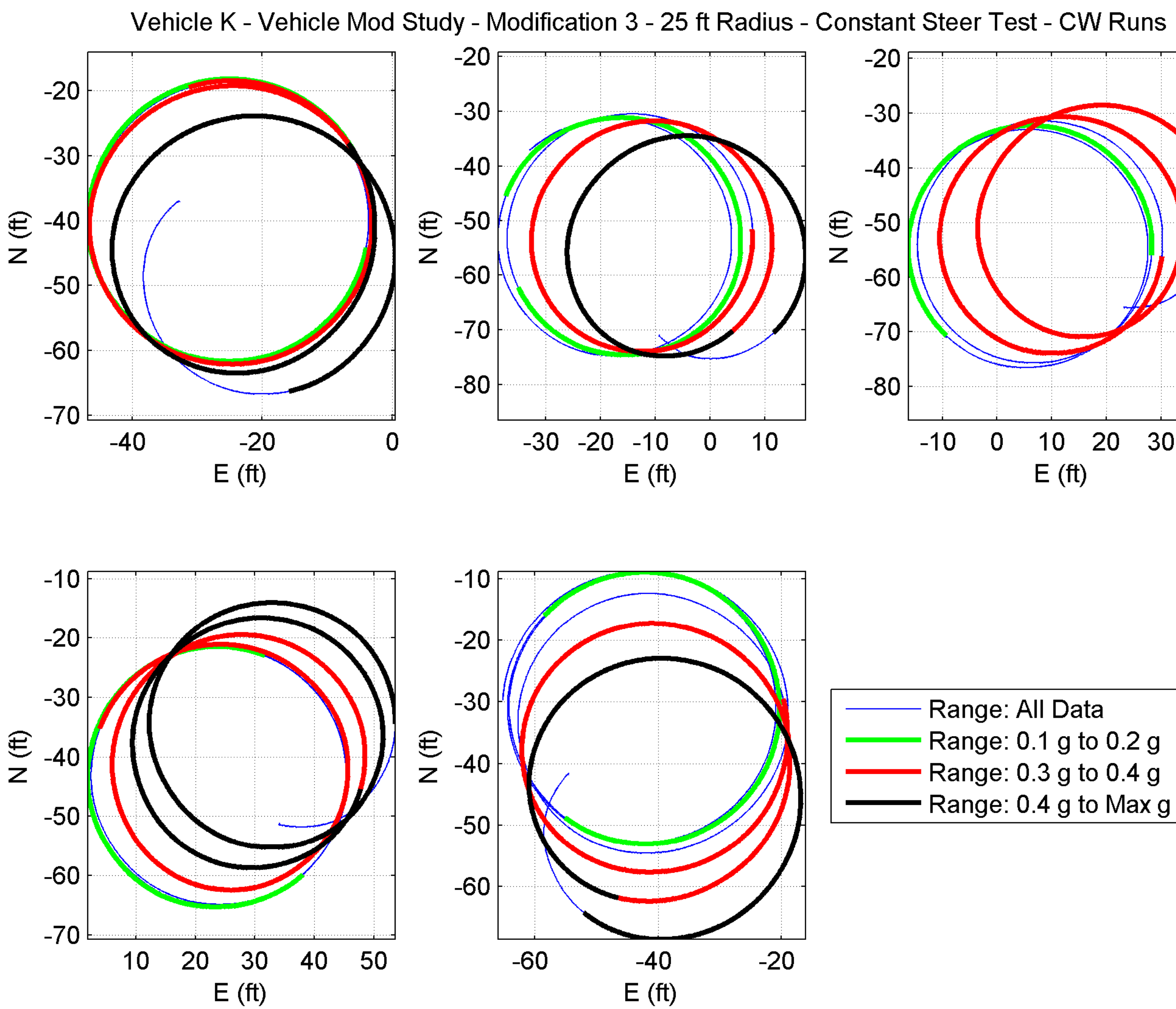

Vehicle K - Vehicle Mod Study - Modification 3 - 25 ft Radius - Constant Steer Test
Estimated Ay (g)
Speed (m/s)
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
1
2
3
4
5
6

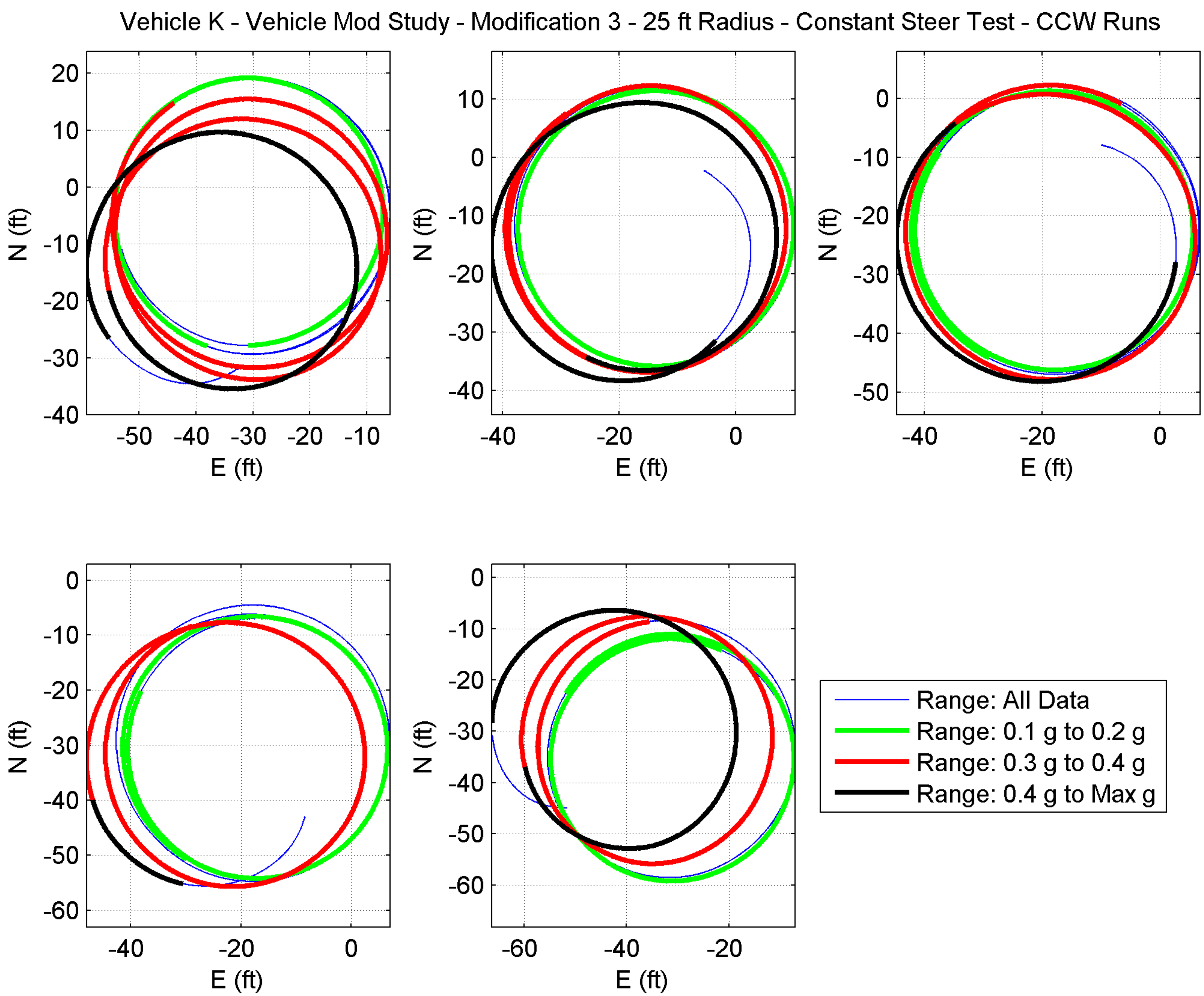


Vehicle K - Vehicle Mod Study - Modification 3 - 25 ft Radius - Constant Steer Test
CW Initial Slopes: 8.42 10.4 8.77 8.59 8.95 STD=0.799
CW Final Slopes: 6.8 3.98 8.8 10.8 5.81 STD=2.63
CW Ratios: 0.808 0.382 1 1.25 0.649 STD=0.332
CW Average: 0.819
Average Ratio: 0.941
CCW Average: 1.06
CCW Ratios: 1.87 1.28 0.682 0.44 1.05 STD=0.555
CCW Final Slopes: -12.1 -9.52 -4.78 -3.23 -7.72 STD=3.58
CCW Initial Slopes: -6.49 -7.46 -7 -7.33 -7.37 STD=0.397
Yaw Rate (deg/sec)
Speed (m/s)
50
40
30
20
10
0
-10
-20
-30
-40
-50
2
2.5
3
3.5
4
4.5
5
5.5
6

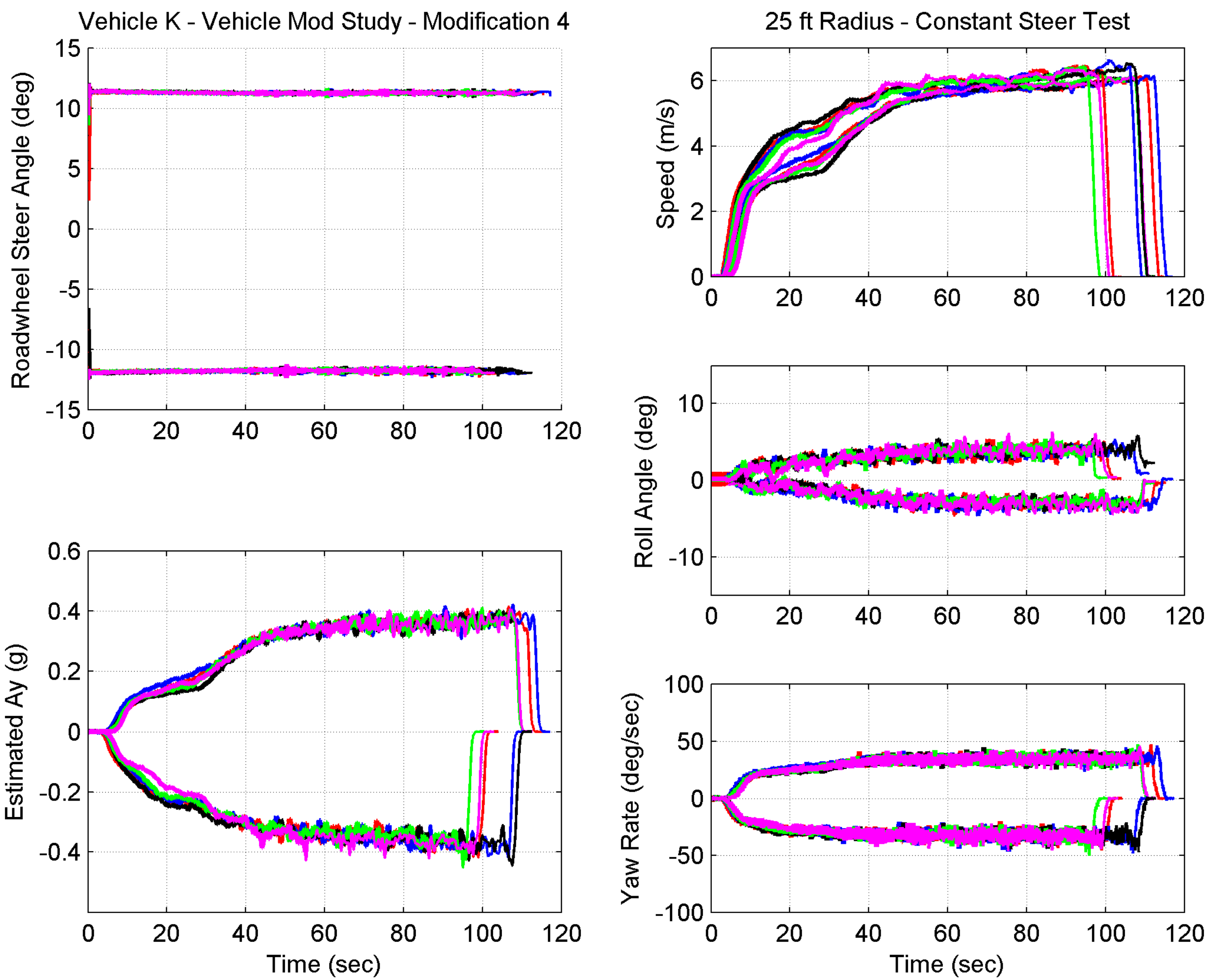

Vehicle K - Vehicle Mod Study - Modification 3 - 25 ft Radius - Constant Steer Test - CW Runs
Yaw Rate (deg/sec)
Speed (m/s)
Ratio: 0.808
Final Slope: 6.8
Ratio: 0.382
Final Slope: 3.98
Ratio: 1
Final Slope: 8.8
Ratio: 1.25
Final Slope: 10.8
Ratio: 0.649
Final Slope: 5.81

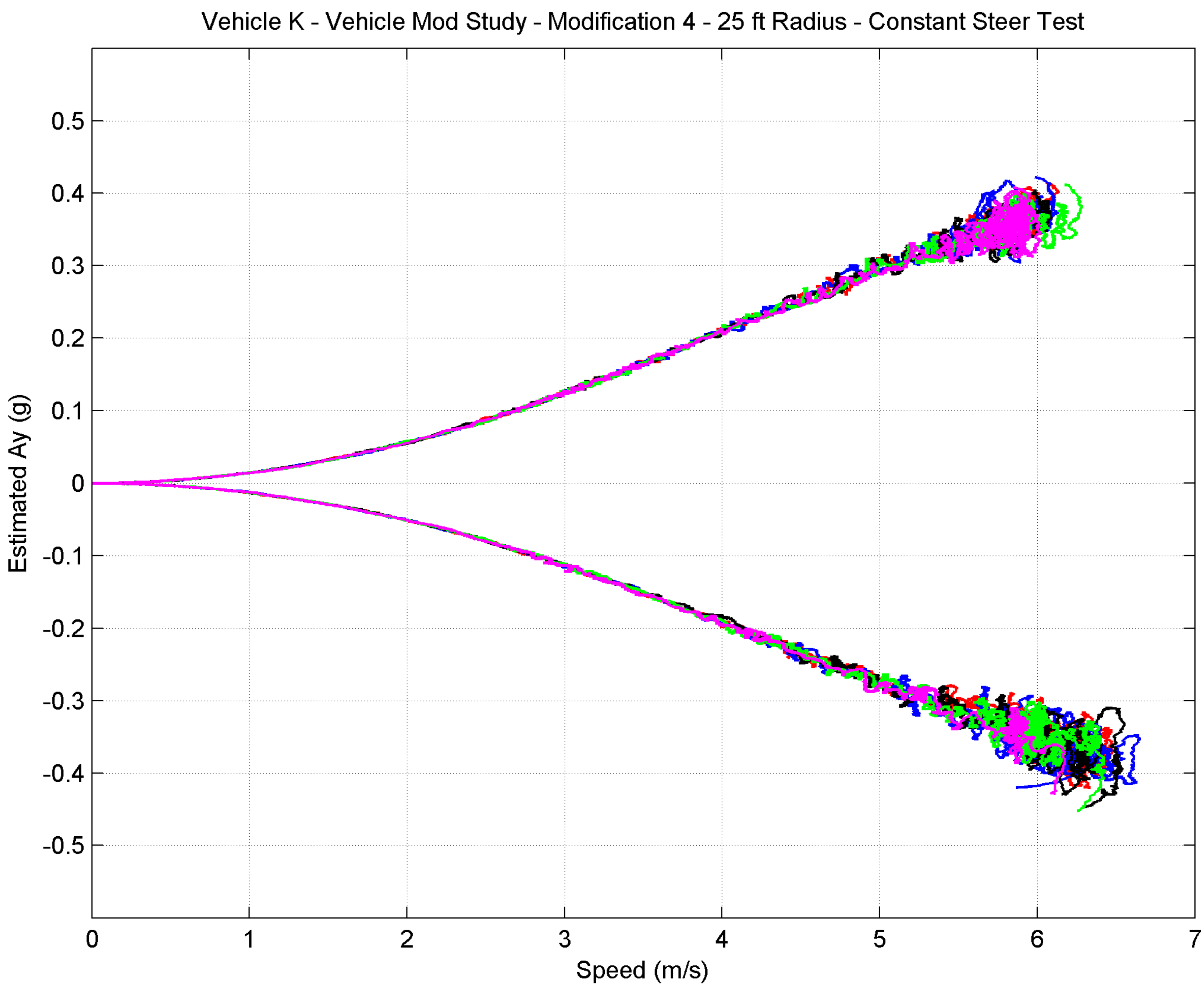

Vehicle K - Vehicle Mod Study - Modification 3 - 25 ft Radius - Constant Steer Test - CCW Runs
Final Slope: -12.1
Ratio: 1.87
Final Slope: -9.52
Ratio: 1.28
Final Slope: -4.78
Ratio: 0.682
Final Slope: -3.23
Ratio: 0.44
Final Slope: -7.72
Ratio: 1.05
Yaw Rate (deg/sec)
Speed (m/s)
-30
-32
-34
-36
-38
-40
-42
-44
3
4
5
6


Vehicle K - Vehicle Mod Study - Modification 3 - 25 ft Radius - Constant Steer Test - CW Runs
N (ft)
E (ft)
Range: All Data
Range: 0.1 g to 0.2 g
Range: 0.3 g to 0.4 g
Range: 0.4 g to Max g

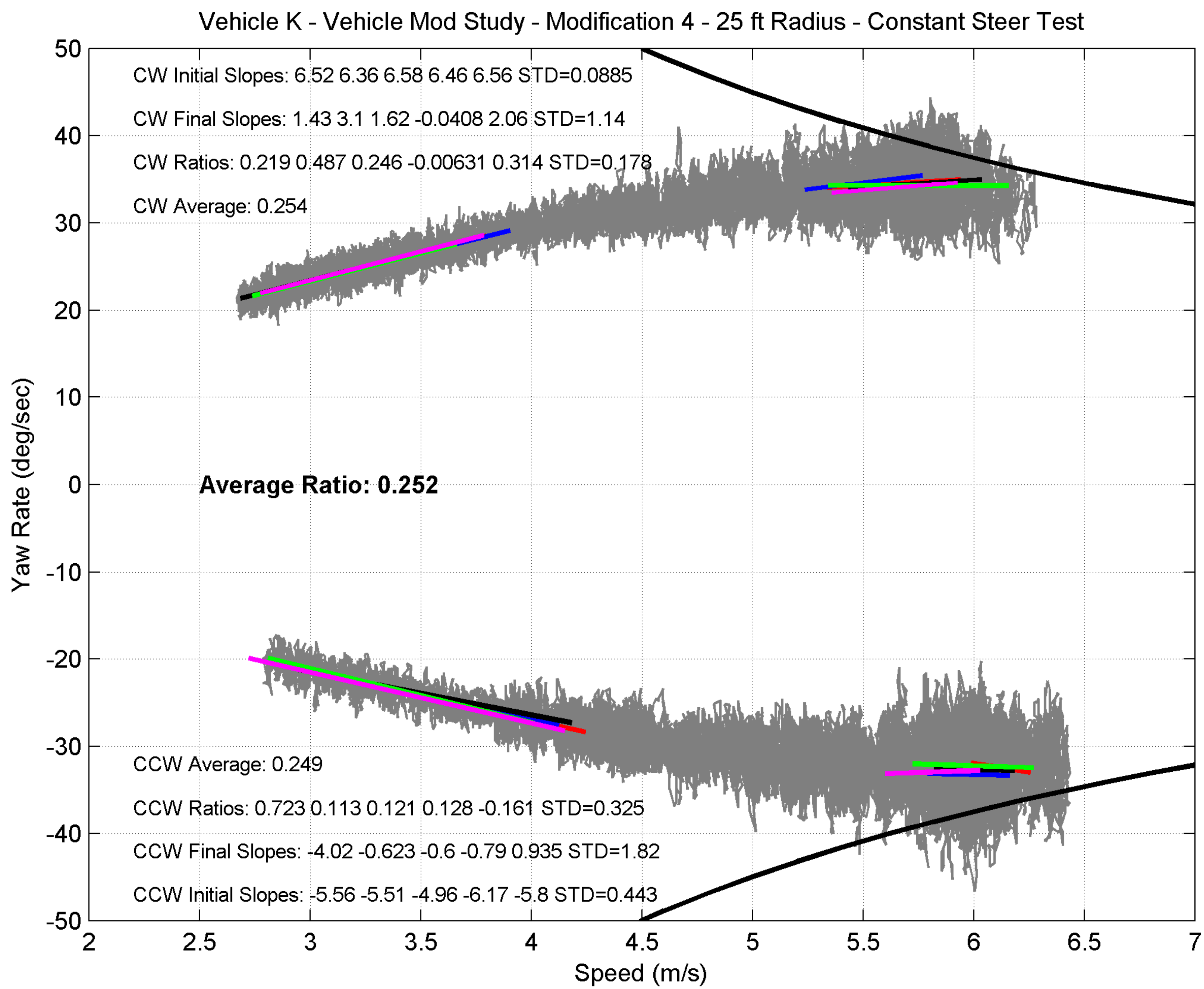


Vehicle K - Vehicle Mod Study - Modification 3 - 25 ft Radius - Constant Steer Test - CCW Runs
N (ft)
E (ft)
Range: All Data
Range: 0.1 g to 0.2 g
Range: 0.3 g to 0.4 g
Range: 0.4 g to Max g

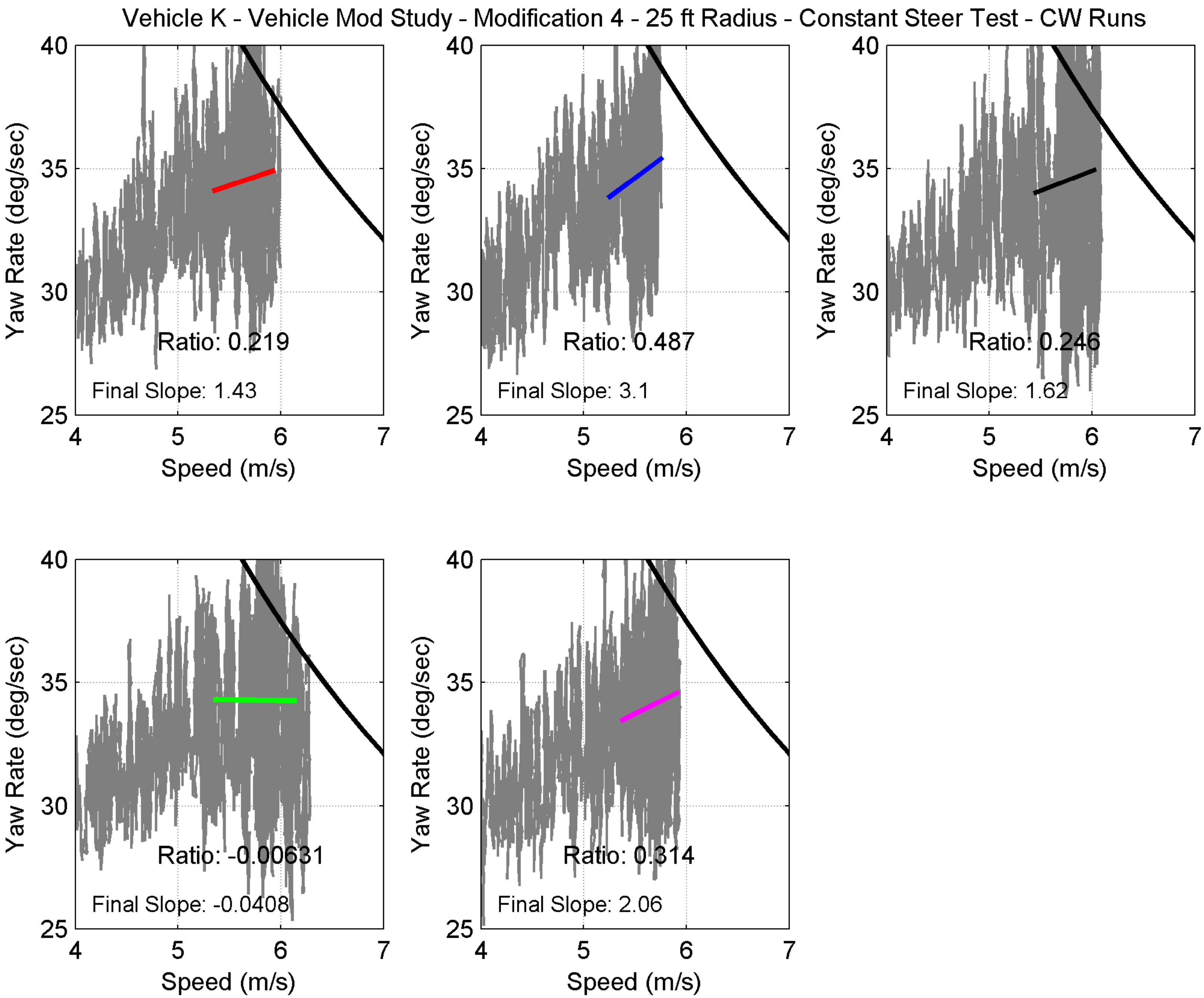

Vehicle K - Vehicle Mod Study - Modification 4
25 ft Radius - Constant Steer Test
Roadwheel Steer Angle (deg)
Speed (m/s)
Roll Angle (deg)
Estimated Ay (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

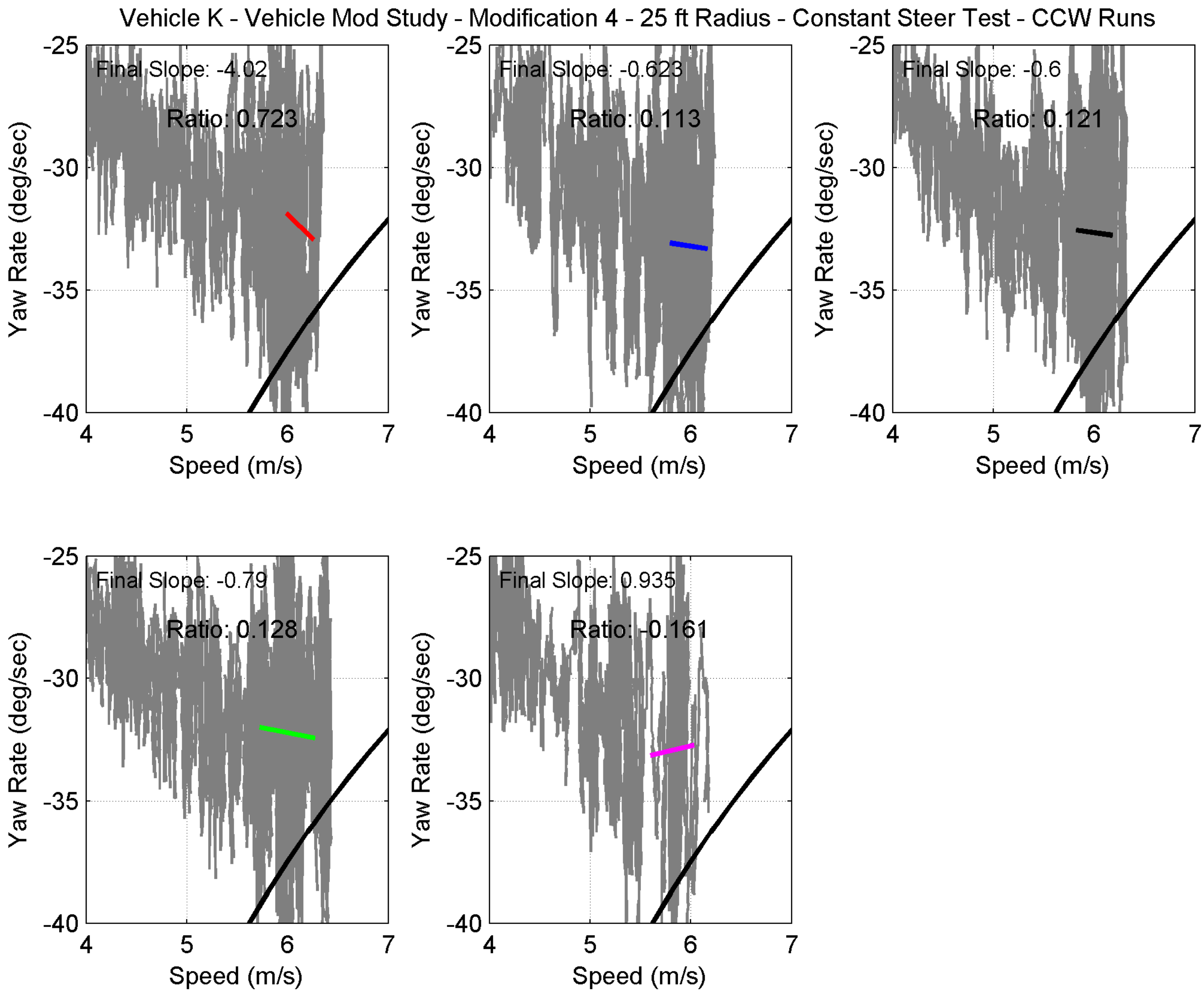


Vehicle K - Vehicle Mod Study - Modification 4 - 25 ft Radius - Constant Steer Test
Estimated Ay (g)
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
1
2
3
4
5
6
7
Speed (m/s)



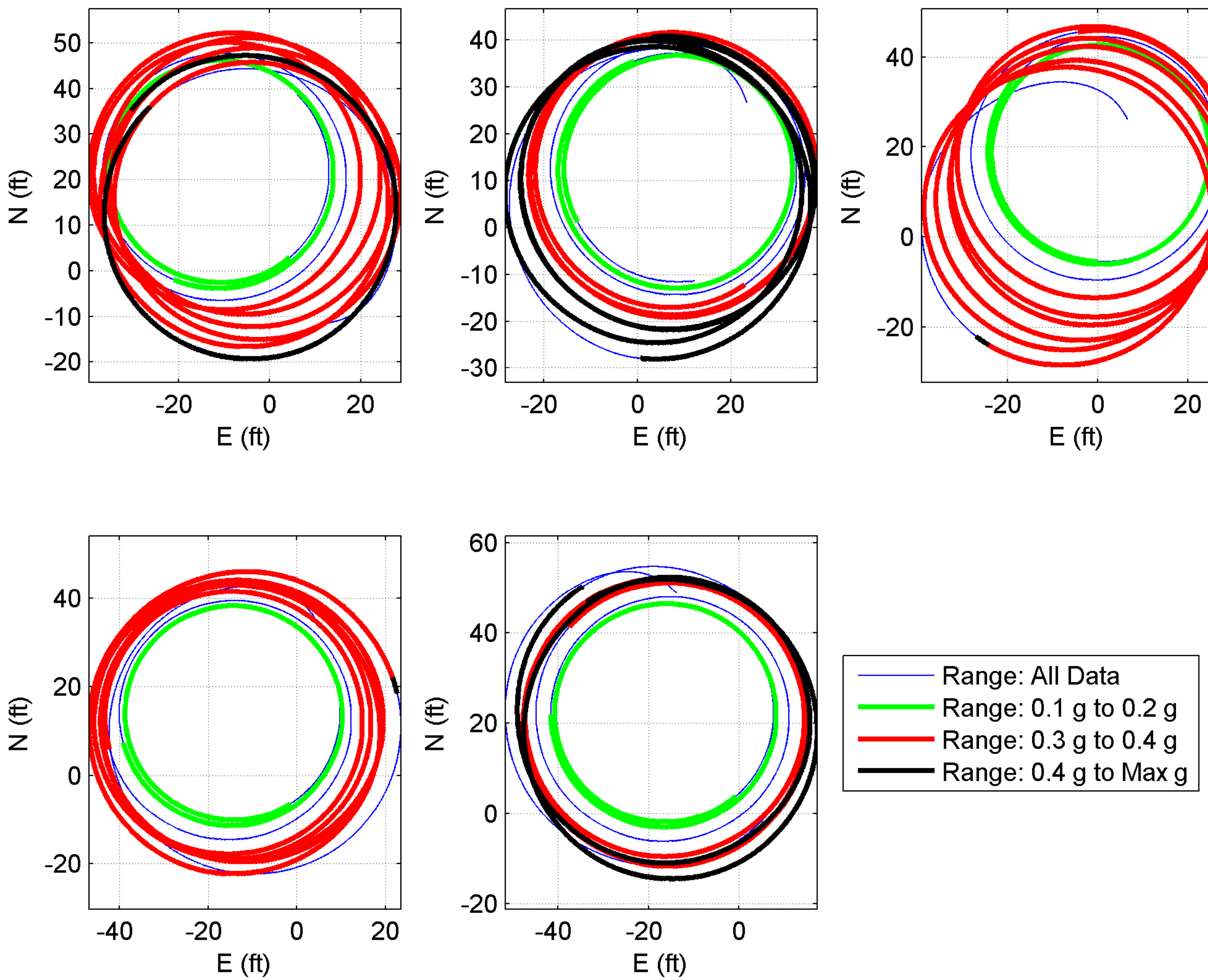
Vehicle K - Vehicle Mod Study - Modification 4 - 25 ft Radius - Constant Steer Test
CW Initial Slopes: 6.52 6.36 6.58 6.46 6.56 STD=0.0885
CW Final Slopes: 1.43 3.1 1.62 -0.0408 2.06 STD=1.14
CW Ratios: 0.219 0.487 0.246 -0.00631 0.314 STD=0.178
CW Average: 0.254
Average Ratio: 0.252
CCW Average: 0.249
CCW Ratios: 0.723 0.113 0.121 0.128 -0.161 STD=0.325
CCW Final Slopes: -4.02 -0.623 -0.6 -0.79 0.935 STD=1.82
CCW Initial Slopes: -5.56 -5.51 -4.96 -6.17 -5.8 STD=0.443
Yaw Rate (deg/sec)
Speed (m/s)
50
40
30
20
10
0
-10
-20
-30
-40
-50
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7

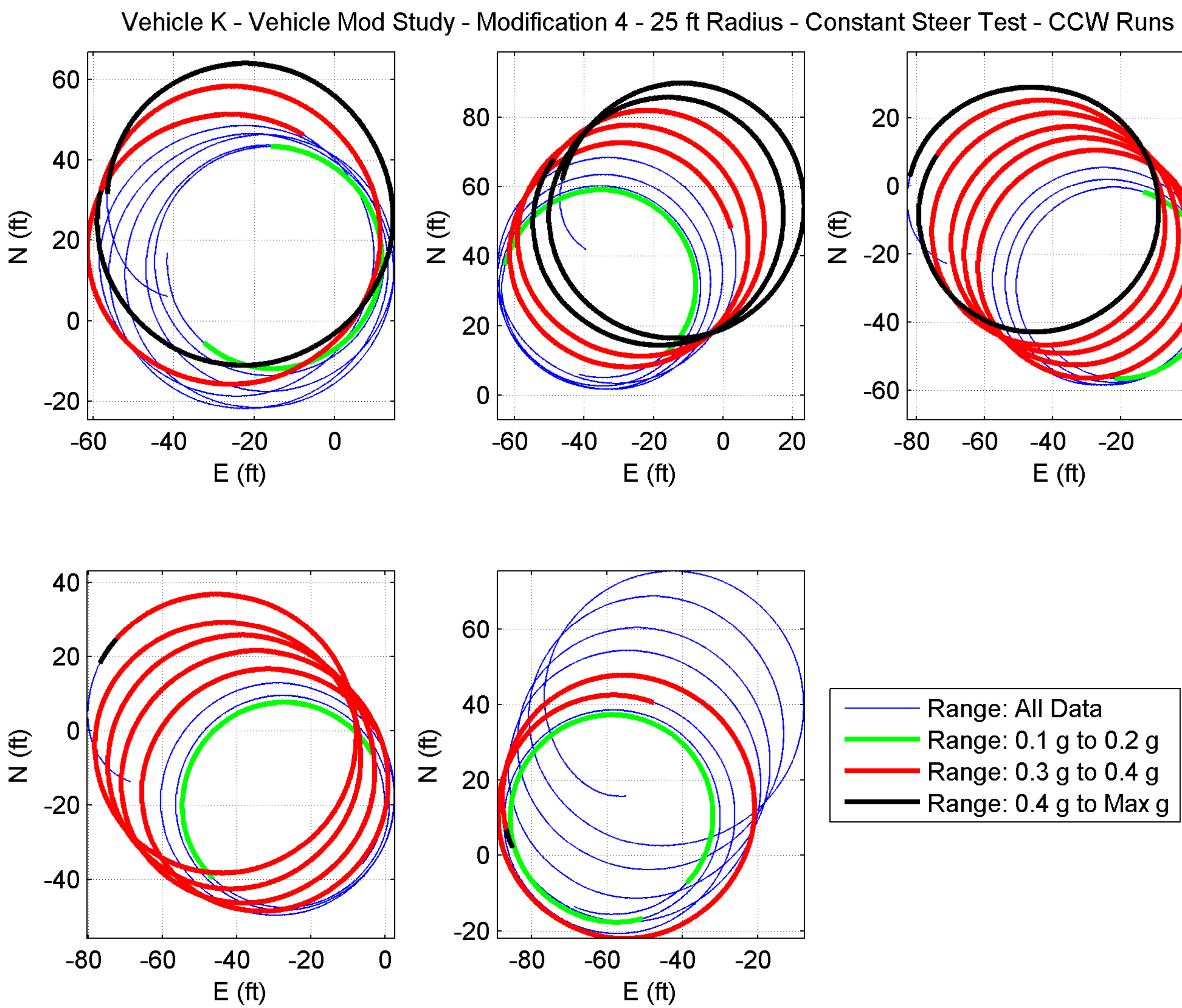

Vehicle K - Vehicle Mod Study - Modification 4 - 25 ft Radius - Constant Steer Test - CW Runs
Yaw Rate (deg/sec)
Speed (m/s)
Ratio: 0.219
Final Slope: 1.43
Ratio: 0.487
Final Slope: 3.1
Ratio: 0.246
Final Slope: 1.62
Ratio: -0.00631
Final Slope: -0.0408
Ratio: 0.314
Final Slope: 2.06



Vehicle K - Vehicle Mod Study - Modification 4 - 25 ft Radius - Constant Steer Test - CCW Runs
Final Slope: -4.02
Ratio: 0.723
Final Slope: -0.623
Ratio: 0.113
Final Slope: -0.6
Ratio: 0.121
Final Slope: -0.79
Ratio: 0.128
Final Slope: 0.935
Ratio: -0.161
Yaw Rate (deg/sec)
Speed (m/s)
-25
-30
-35
-40
4
5
6
7

Vehicle K - Vehicle Mod Study - Modification 4 - 25 ft Radius - Constant Steer Test - CW Runs





Vehicle K - Vehicle Mod Study - Modification 4 - 25 ft Radius - Constant Steer Test - CCW Runs
N (ft)
E (ft)
Range: All Data
Range: 0.1 g to 0.2 g
Range: 0.3 g to 0.4 g
Range: 0.4 g to Max g