Circle Testing of Two Recreational Off-Highway Vehicles on a Dirt Surface

for:
Consumer Product Safety Commission

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Scientific Expert Analysis™

Vehicle Dynamics Division
7349 Worthington-Galena Rd.
Columbus, Ohio 43085

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

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

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1. OVERVIEW

This report contains results from measurements made by S-E-A, Ltd., for the U.S. Consumer Product Safety Commission (CPSC), under Contract CPSC-D-11-0003, Task Order 0002. The objective of this task is:

- To conduct circle tests consistent with SAE J266 protocol on an off-highway test surface.

Two previous reports, both published in 2011, titled *Vehicle Characteristics Measurements of Recreational Off-Highway Vehicles*[1] and *Vehicle Characteristics Measurements of Recreational Off-Highway Vehicles – Additional Results for Vehicle J*,[2] contain numerous laboratory and dynamic (test track) measurement results for 10 Recreational Off-Highway Vehicles (ROVs). All of the dynamic test results contained in these two reports are for testing conducted on asphalt. As mentioned above, the goal of this effort was to conduct circle tests on an off-highway surface, and in this case, a dirt surface was used for the testing.

Two of the 10 vehicles tested previously, Vehicle F and Vehicle G, were selected by CPSC for testing on the off-highway surface.

The surface used for testing was located at the Transportation Research Center, Inc. (TRC). TRC prepared the surface by cutting and removing any grass and topsoil necessary to produce a circular dirt track. The circular track had an inside radius of nominally 95 ft and an outside radius of nominally 115 ft (200 ft diameter, 20 ft wide circular dirt test track). Overall, the prepared circular track was smooth and flat.

The CPSC ROV outriggers used for previous testing on asphalt surfaces had the potential to dig into the soil surface and disrupt the testing. Therefore, both vehicles were tested without the use of safety outriggers to prevent tip ups or rollover. Also, both vehicles were tested in one loading condition, a representative Operator and Passenger loading configuration.

This report contains three main sections and two appendices that contain test results. The three report sections are Overview, Dynamic Testing, and Discussion of Test Results. Appendix A contains test results for Vehicle F, and Appendix B contains test results for Vehicle G.

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[1] *Vehicle Characteristics Measurements of Recreational Off-Highway Vehicles*, CPSC Contract CPSC-S-10-0014, S-E-A, Ltd. Report to CPSC, April 2011. **http://www.cpsc.gov/library/foia/foia11/os/rov.pdf**.

[2] *Vehicle Characteristics Measurements of Recreational Off-Highway Vehicles – Additional Results for Vehicle J*, CPSC Contract CPSC-S-10-0014, S-E-A, Ltd. Report to CPSC, August 2011. **http://www.cpsc.gov/PageFiles/93928/rovj.pdf**.

2. DYNAMIC TESTING

The dynamic tests, conducted on June 27, 2012, included circle tests on the prepared dirt circle at TRC, as well as on the flat dry asphalt surface of TRC's Vehicle Dynamics Area (VDA).

All of the dynamic tests were performed in one loading configuration, namely a loading configuration that represented the weight of the Operator and Passenger loading configuration as used in previous CPSC testing and described in detail in the previous CPSC reports. The total weigh added to each vehicle above its curb weight was nominally 426 lb, the weight of two 213 lb (95% percentile male) occupants. For this testing, the data acquisition equipment, auxiliary 12 V battery, and on-vehicle sensors and electronics weighed nominally 110 lb, and the test driver weighed 182 lb. To bring the total vehicle weight to the Operator and Passenger weight, a water dummy was placed in the front passengers seat. The water dummy was filled with water and foam to achieve a weight of nominally 134 lb.

Table 1 contains information on the actual Operator and Passenger loading conditions (as reported in the previous CPSC report) and the loading conditions used on July 27, 2012, for conducting the circle tests on the off-highway surface. Both vehicles were loaded to approximate the total vehicle weight of the Operator and Passenger loading configuration, and test equipment was positioned on the test vehicles to approximate the lateral center-of-gravity (CG) position and longitudinal CG position of the Operator and Passenger loading configuration.

Table 1: Loading Conditions of Test Vehicles

	Vehicle F		Vehicle G	
	Operator & Passenger Loading	Off-Highway Loading June 27, 2012	Operator & Passenger Loading	Off-Highway Loading June 27, 2012
Total Vehicle Weight (lb)	1688.0	1691.7	2179.2	2186.6
Left Front Weight (lb)	362.2	367.6	497.8	492.3
Right Front Weight (lb)	367.8	360.5	494.5	490.0
Left Rear Weight (lb)	477.3	474.3	580.8	586.8
Right Rear Weight (lb)	480.7	489.3	606.1	617.5
Front Track Width (in)	50.35	50.35	51.73	51.73
Rear Track Width (in)	48.70	48.70	51.75	51.75
Average Track Width (in)	49.53	49.53	51.74	51.74
Wheelbase (in)	75.05	75.05	79.15	79.15
CG Longitudinal (in)	42.59	42.75	43.11	43.59
CG Lateral (in)	0.13	0.12	0.26	0.34
Steering Ratio (deg/deg)	14.8	14.8	14.7	14.7

Table 2 lists the instrumentation used during the dynamic testing. The RT3002 was mounted in the cargo area of both vehicles, and its longitudinal, lateral, and vertical offsets to the actual vehicle CG location were measured and entered into the RT3002 system software. This information was used to translate the measured quantities to those at the CG of the vehicle. The lateral accelerations measured and reported here are accelerations parallel to the road plane, as opposed to vehicle body fixed accelerations.

No automated steering controller was required for this testing. A Sensor Developments, Inc., sensor was used to measure steering wheel angle for these tests. A photograph of this sensor mounted on one of the test vehicles is shown in Figure 2. A portion of the circular dirt test track can be seen in the background of Figure 2, and a more close-up view of the dirt surface is shown in Figure 3.

Table 2: Instrumentation Used During Dynamic Testing

Transducer	Measurement	Range	Accuracy or Linearity
Oxford Technical Solutions RT3002 Inertial and GPS Navigation System	Longitudinal, Lateral, and Vertical Accelerations	± 10 g	0.1% 1σ
	Roll, Pitch, and Yaw Rates	± 100 deg/s	0.1% 1σ
	Speed	No Limit Specified	0.2% 1σ
	Roll and Pitch Angles	No Limit Specified	0.03° 1σ
	Vehicle Heading and Sideslip Angle	No Limit Specified	0.1° 1σ
Sensor Developments, Inc. Model 01184	Steering Wheel Angle	± 1638 deg	± 0.20 deg

Consistent with SAE Standard J266,[3] constant radius circle tests involve driving a vehicle on a circular path of constant radius (100 ft in this case). The test vehicles were driven in the clockwise (CW) and counterclockwise (CCW) directions. For this testing, the vehicles were driven from a very low speed up to a speed close to the highest speed that the test driver felt comfortable would not tip-up or roll over the test vehicle.

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

Detailed results from all of the circle tests are contained in the appendices. The circle tests were conducted in sets of two tests each, one in the CW direction, and one in the CCW direction. For Vehicle F, six sets of circle tests were conducted on the dirt surface, and two sets were conducted

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

on the asphalt surface. For Vehicle G, three sets of circle tests were conducted on the dirt surface and two sets were conducted on the asphalt surface.

Figure 1: Steering Wheel Angle Sensor Mounted in Test Vehicle

Figure 2: Prepared Dirt Surface after Several Tests were Completed

3. DISCUSSION OF TEST RESULTS

Constant radius (100 ft) circle test results for the representative Operator and Passenger loading configuration for Vehicle F are contained in Appendix A and for Vehicle G in Appendix B.

The first eight pages of Appendix A and the first five pages of Appendix B each contain test results from one set of circle tests, which each consists of one CW test and CCW test. The top half of these pages contain time domain plots of Steer Angle, Lateral Acceleration, Speed, Roll Angle, and Yaw Rate. All of the test data are sampled at 100 Hz. For the circle test results, the data shown were digitally low-pass filtered to 1.0 Hz, using a phaseless, eighth-order, Butterworth filter. The time domain data shown for each vehicle contain all of the data from the time the test driver started the data acquisition (prior to starting to move on the circle) to the time the test driver ended the data acquisition at the end of the test. The thin black lines for the CW and CCW tests show this full range of data. The thicker lines (red for CW and blue for CCW) indicate the range of data from the time the vehicle attained a speed of 4.0 mph, which is a lateral acceleration of 0.01 g on a 100 ft radius circle, until the maximum speed for each test was achieved (generally resulting in a maximum lateral acceleration of between 0.4 and 0.5 g.).

The bottom half of the pages show graphs of Handwheel Steer Angle versus Ay (lateral acceleration). The CW test results are in the upper right quadrants of the graphs, and the CCW test results are in the lower left quadrants of the graphs. The thin red lines show data in the range of vehicle speeds from 4.0 mph to maximum speed achieved during each test. For both the CW and CCW data, there are thicker lines indicating second-order polynomial curve fits to the data. 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:

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

For Vehicle F, Pages 1 through 6 of Appendix A contain results for the six sets of circle tests on dirt, and Pages 7 and 8 contains results for the two sets on asphalt. The data from the tests conducted on dirt are not as smooth or as repeatable as the data from the tests on the asphalt surface. The graphs indicate that the driver's steering inputs were more active (*i.e.*, requiring larger magnitude steering corrections) at all test speeds for the tests conduced on dirt than on asphalt. Lateral acceleration, roll angle, and yaw rate responses were also less smooth for the tests conducted on the dirt surface. As the circle tests on the dirt surface progressed, slight ruts and ridges formed along the wheel paths of travel. These ruts and ridges likely contributed to the less smooth vehicle responses and driver steering inputs.

Page 9 of Appendix A shows summary curve fit results for all six sets of tests on dirt (black lines) and both sets of tests on asphalt (red lines) for Vehicle F. The results for the two tests on asphalt are very repeatable, and they are quite similar to the results obtained for Vehicle F from the previous 2011 testing with outriggers. This current testing indicates (as did the 2011 testing) that on asphalt, this vehicle exhibits a transition from understeer to oversteer at lateral acceleration levels below 0.2 g.

However, the six sets of tests conducted on dirt indicate varying results. Some of the curve fit trends indicate understeer characteristics and some of them indicate transition to oversteer, like the tests on asphalt did. The variations in the relatively large steering corrections for the tests conducted on dirt were the primary cause of the lack of repeatability in the trends of the understeer characteristic curves. Also, the steering magnitude required at low lateral acceleration levels is less on the dirt surface than it is on asphalt. This suggests that front tire tread interaction with the soil provides greater cornering (lateral) forces on the front axle in soil than on asphalt.

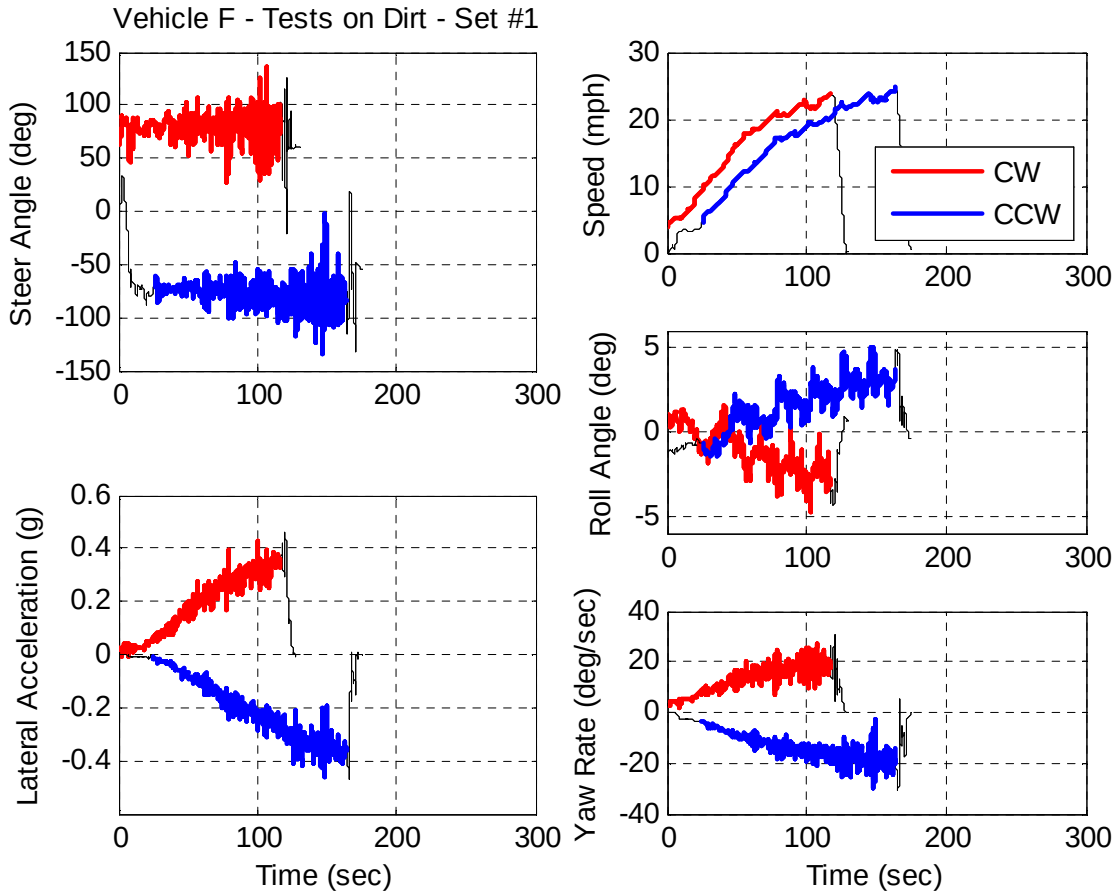
Page 10 of Appendix A shows results from Set #1 tests on dirt and Set #1 tests on asphalt for Vehicle F. The red lines are the underlying data, the black lines are the second-order polynomial curve fits to the data, and the black circles are discrete points from averaging 0.5 second intervals (500 samples) of handwheel angle and lateral acceleration. Basically, this was done to see if using values averaged over some time range (instead of a curve fit) would provide a better (smoother) fit to the underlying data. The discrete points are generally scattered around the curve fit lines; but the scatter is greater for the tests on the dirt surface than for the tests on asphalt.

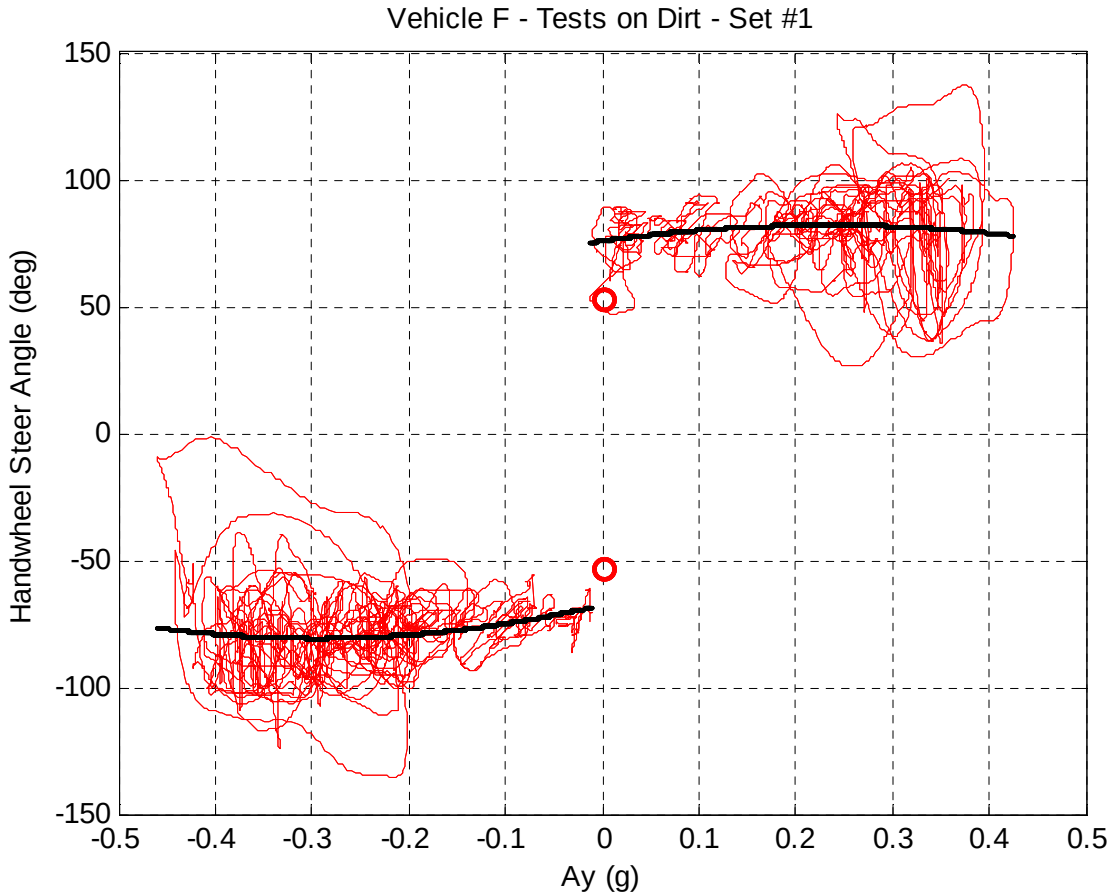
For Vehicle G, pages 1 through 3 of Appendix B contain results for the three sets of circle tests on dirt and pages 4 and 5 contain results for the two sets on asphalt. As was the case for Vehicle F, the data from the tests conducted on dirt are not as smooth or as repeatable as the data from the tests on the asphalt surface. Again, the graphs indicate that the driver's steering inputs were more active (*i.e.*, requiring larger magnitude steering corrections) at all test speeds for the tests conducted on dirt than on asphalt. Lateral acceleration, roll angle, and yaw rate responses were also less smooth for the tests conducted on the dirt surface. As the circle tests on the dirt surface progressed, slight ruts and ridges formed along the wheel paths of travel. These ruts and ridges likely contributed to the less smooth vehicle responses and driver steering inputs.

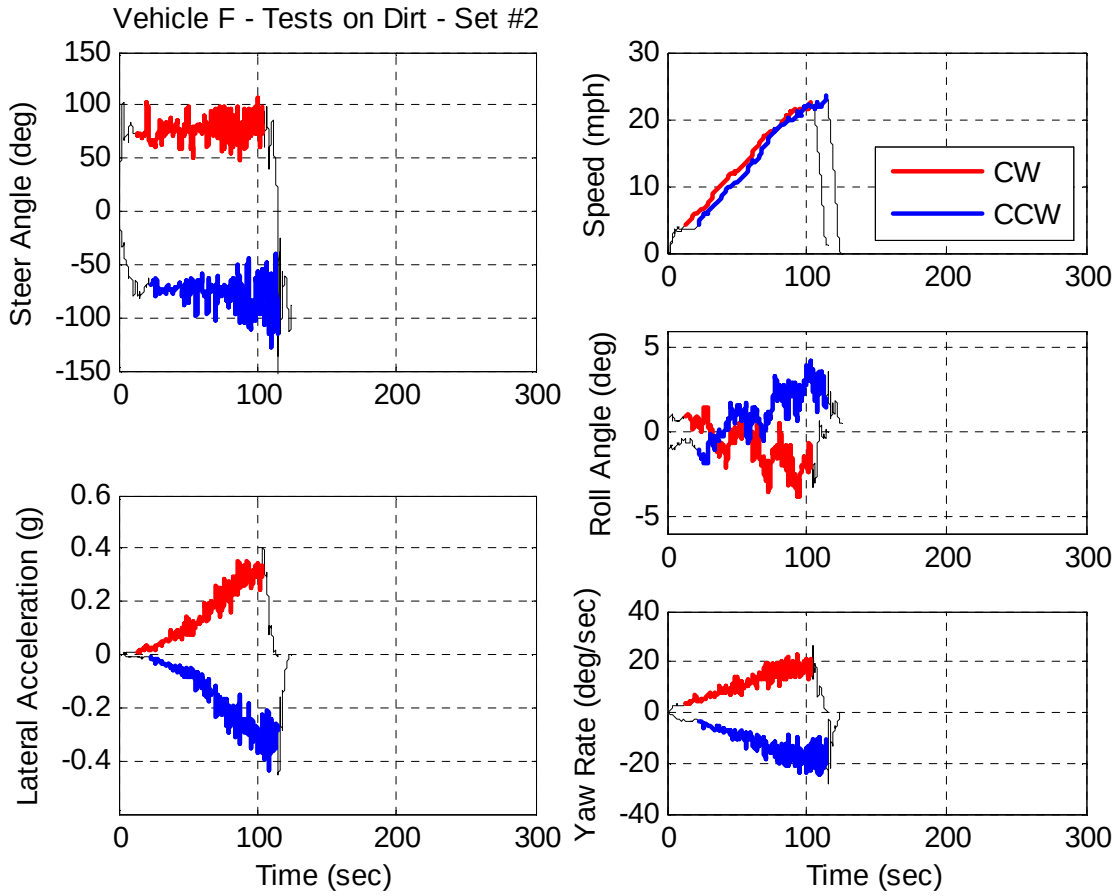
Page 6 of Appendix B shows summary curve fit results for all three sets of tests on dirt (black lines) and both sets of tests on asphalt (red lines) for Vehicle G. The results for the two tests on asphalt are very repeatable, and they are quite similar to the results obtained for Vehicle G from the previous 2011 testing with outriggers. This current testing indicates (as did the 2011 testing) that on asphalt, this vehicle exhibits understeer at all lateral acceleration levels.

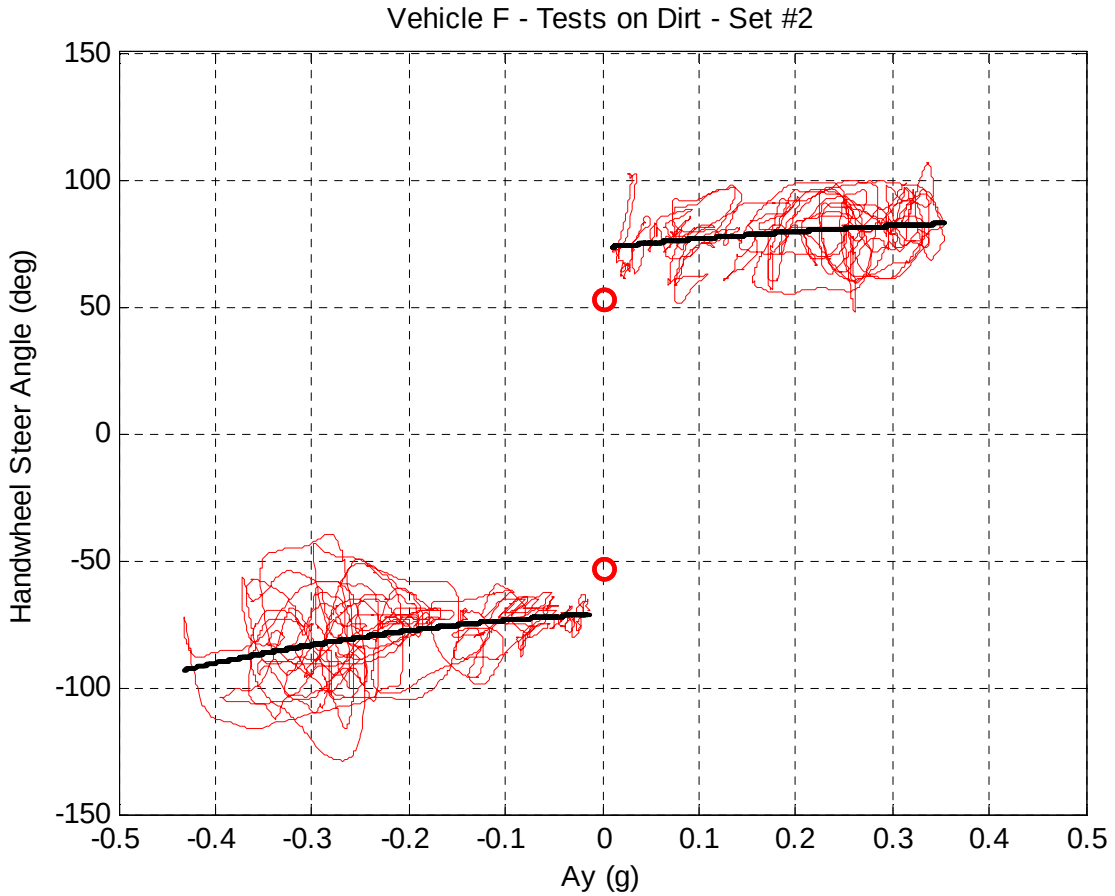
However, the three sets of tests conducted on dirt indicate varying results. Some of the curve fit trends indicate transition to oversteer and some of them indicate understeer at all lateral levels, like the tests on asphalt did. For the tests conducted on dirt, the variations in the relatively large steering corrections were the primary cause for the lack of repeatability in the trends of the understeer characteristic curves.

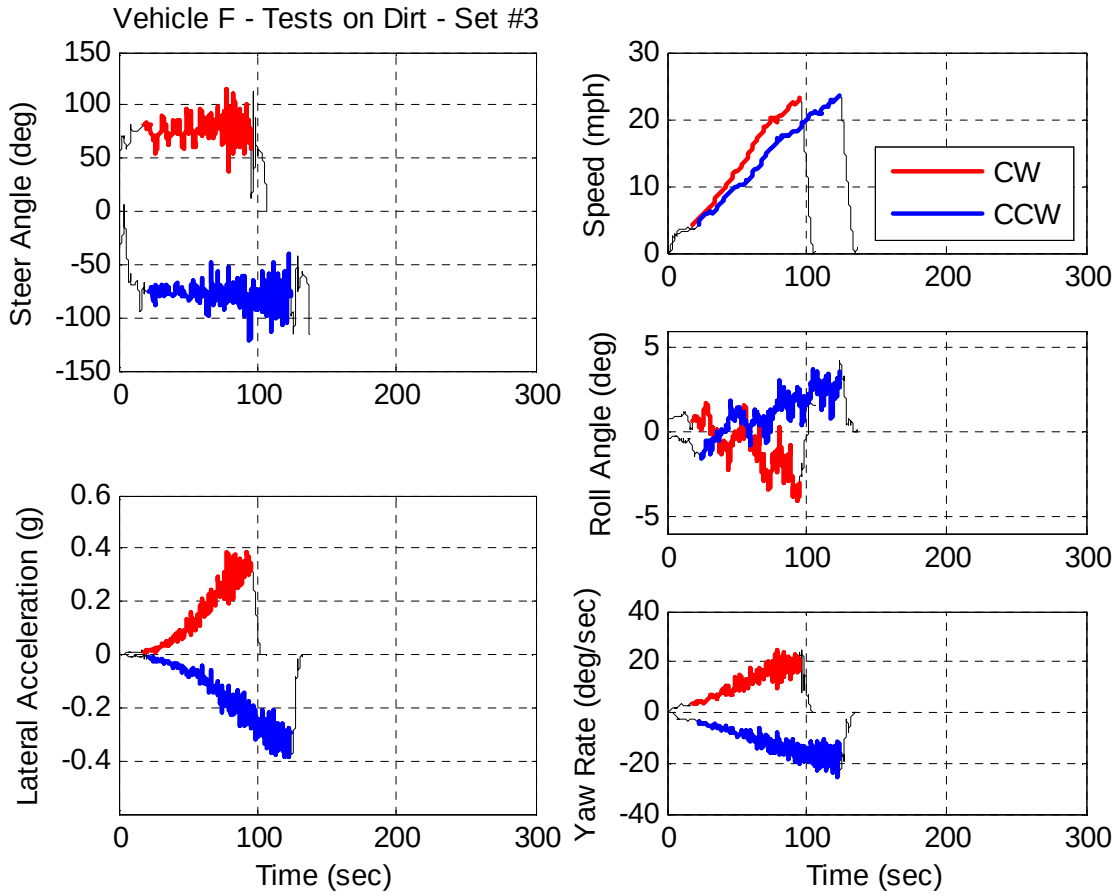
Page 7 of Appendix B shows results from Set #1 tests on dirt and Set #1 tests on asphalt for Vehicle G. The red lines are the underlying data, the black lines are the second-order polynomial curve fits to the data, and the black circles are discrete points from averaging 0.5 second intervals (500 samples) of handwheel angle and lateral acceleration. The discrete points are generally scattered around the curve fit lines; but again, the scatter is greater for the tests on the dirt surface than for the tests on asphalt.

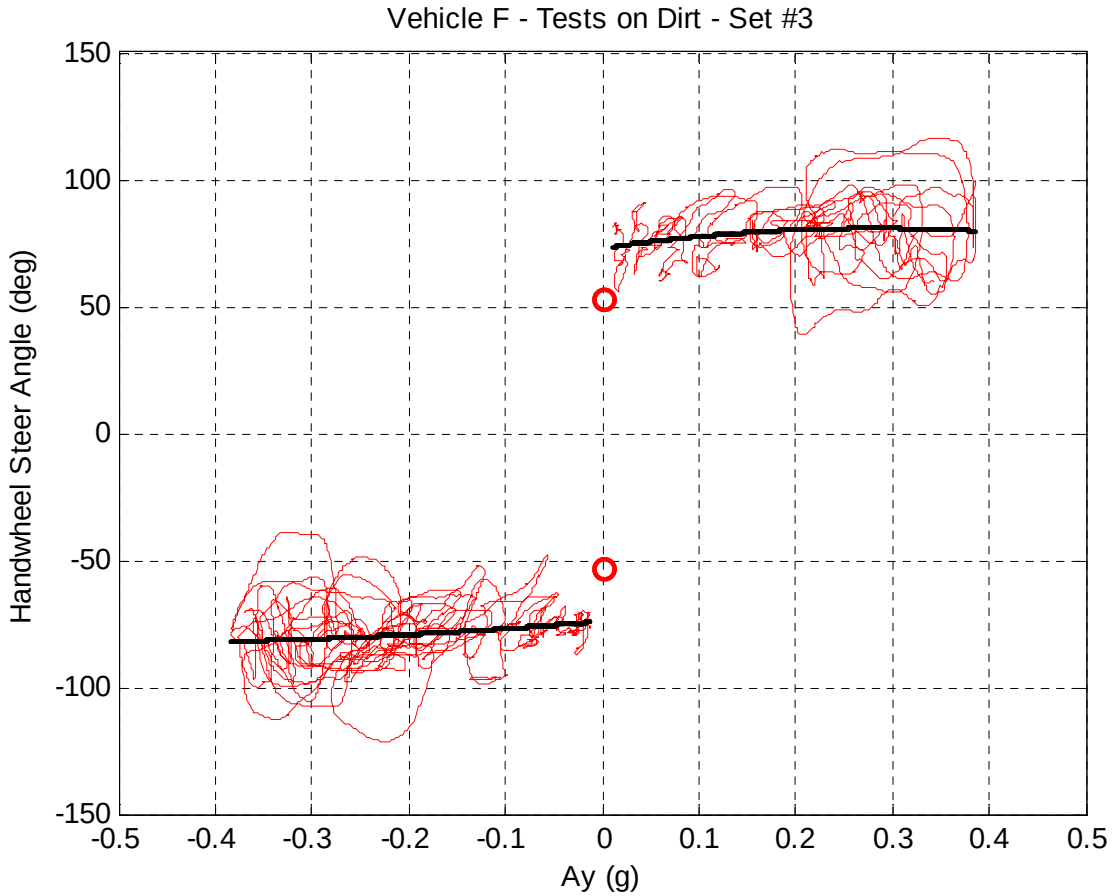

Vehicle F - Tests on Dirt - Set #1
Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

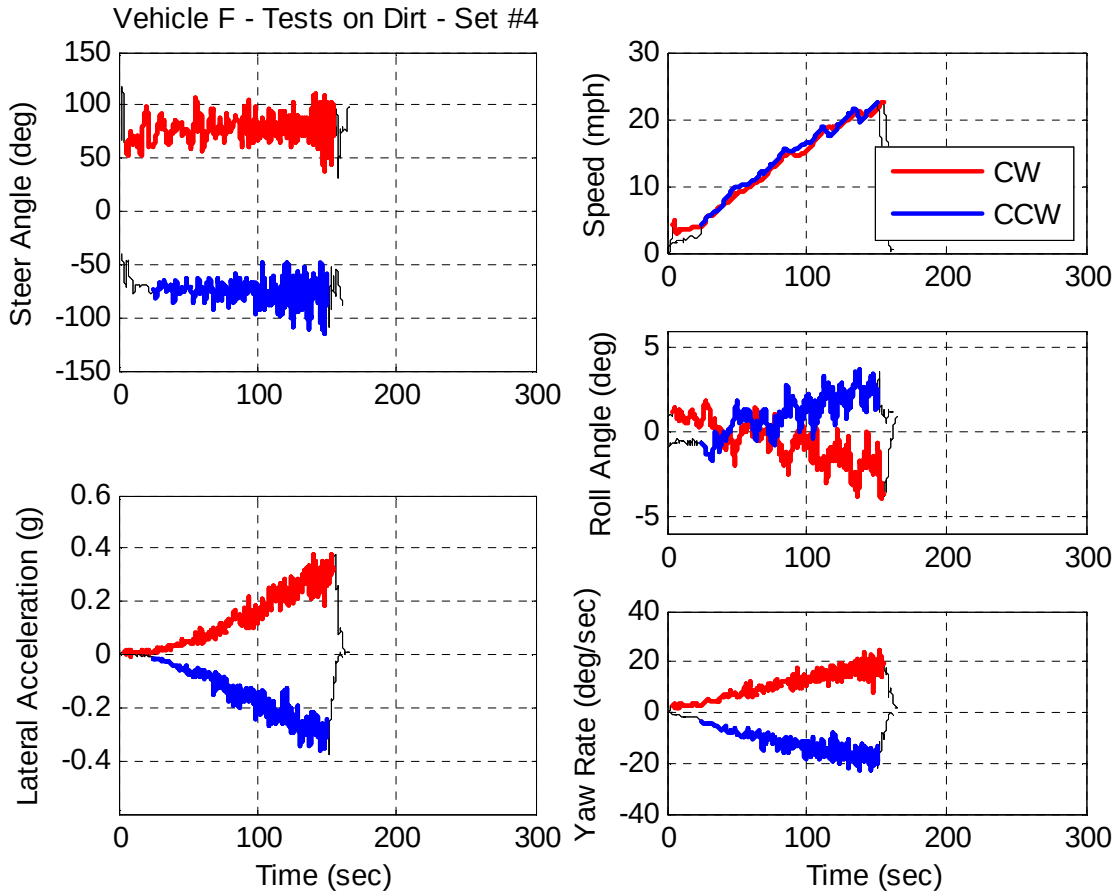

Vehicle F - Tests on Dirt - Set #1
Handwheel Steer Angle (deg)
Ay (g)

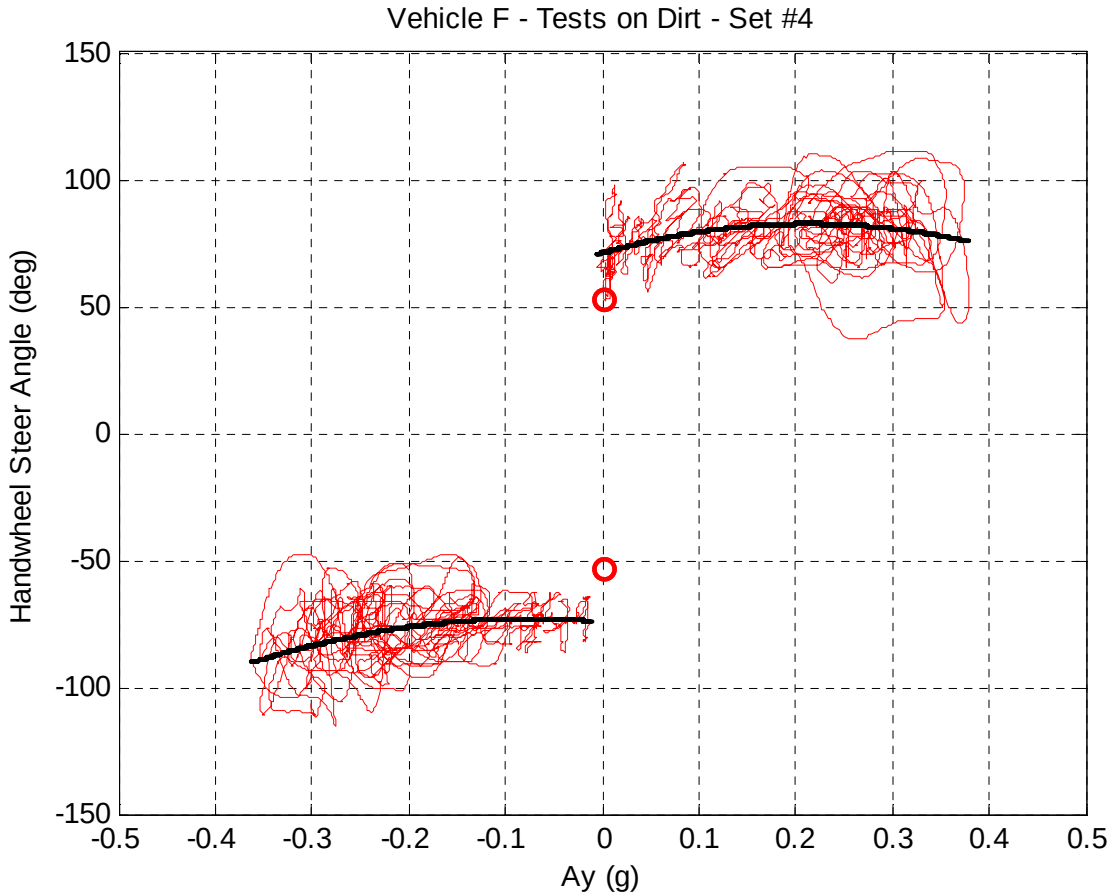

Vehicle F - Tests on Dirt - Set #2
Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

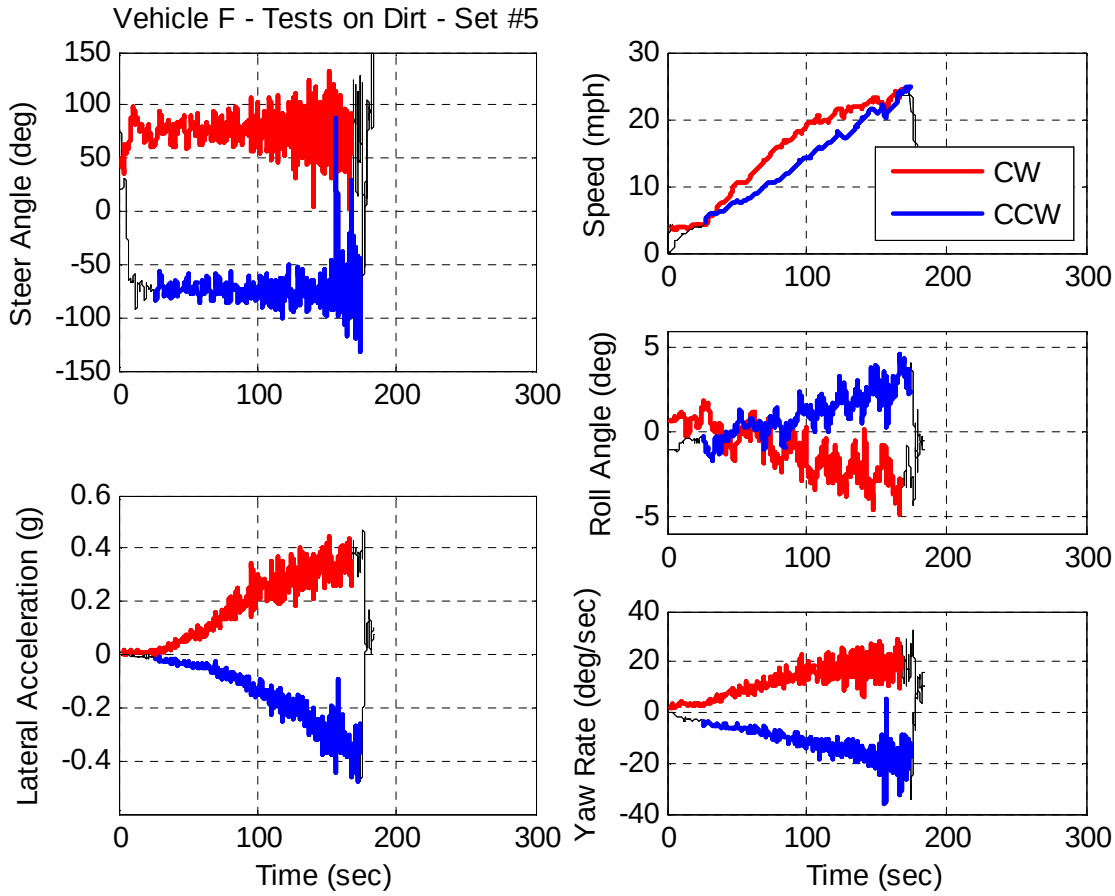

Vehicle F - Tests on Dirt - Set #2
Handwheel Steer Angle (deg)
Ay (g)

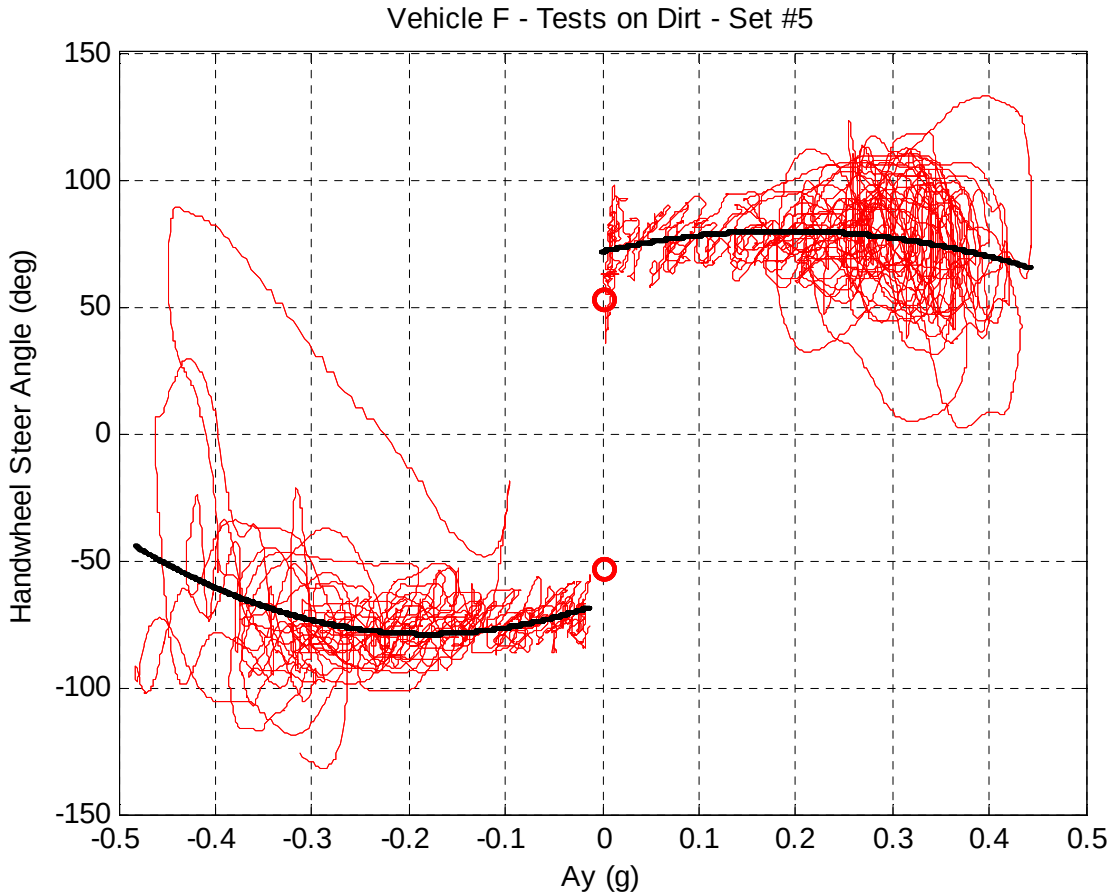

Vehicle F - Tests on Dirt - Set #3
Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

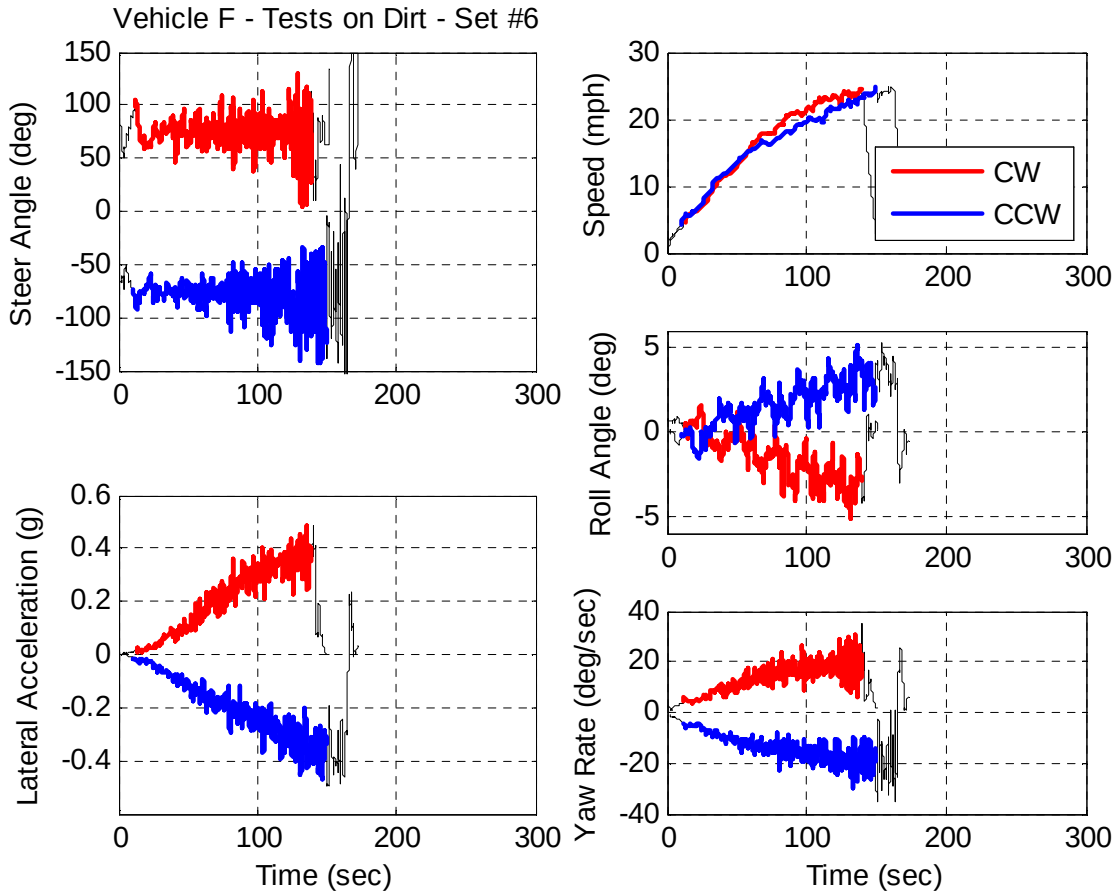

Vehicle F - Tests on Dirt - Set #3
Handwheel Steer Angle (deg)
Ay (g)

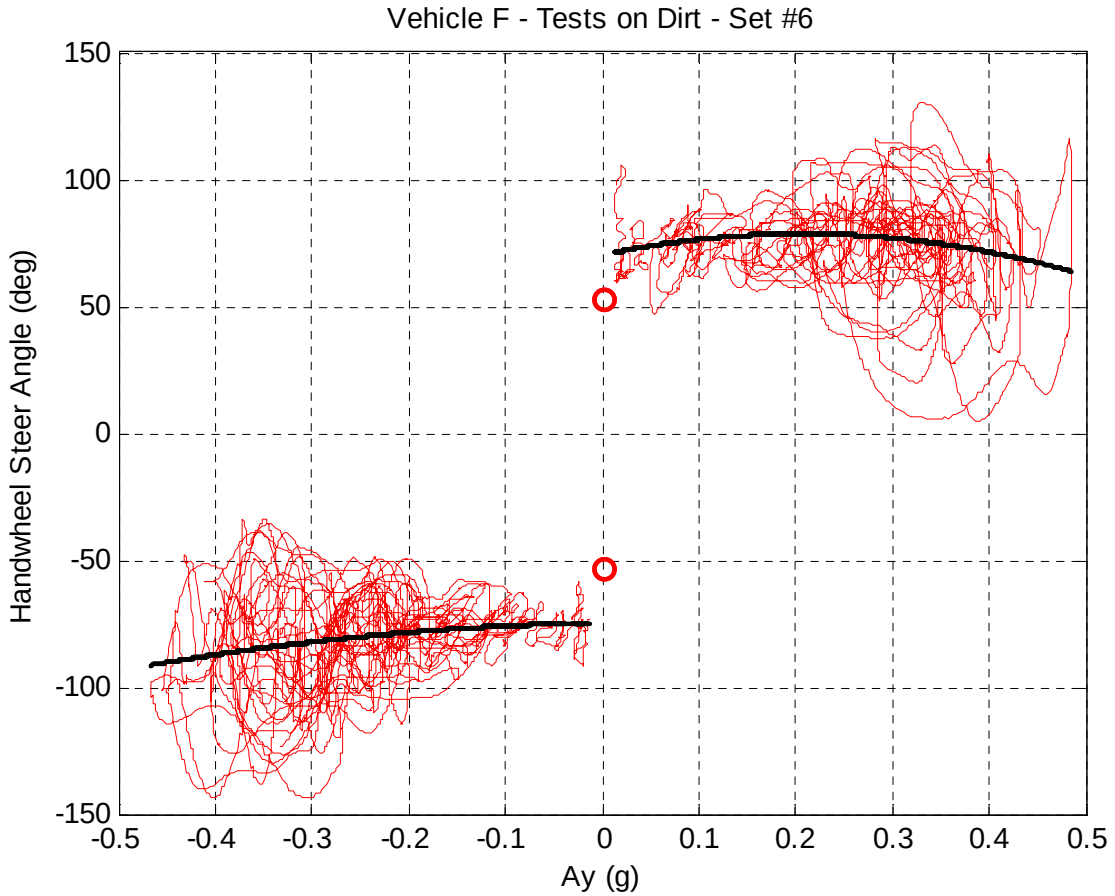

Vehicle F - Tests on Dirt - Set #4
Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

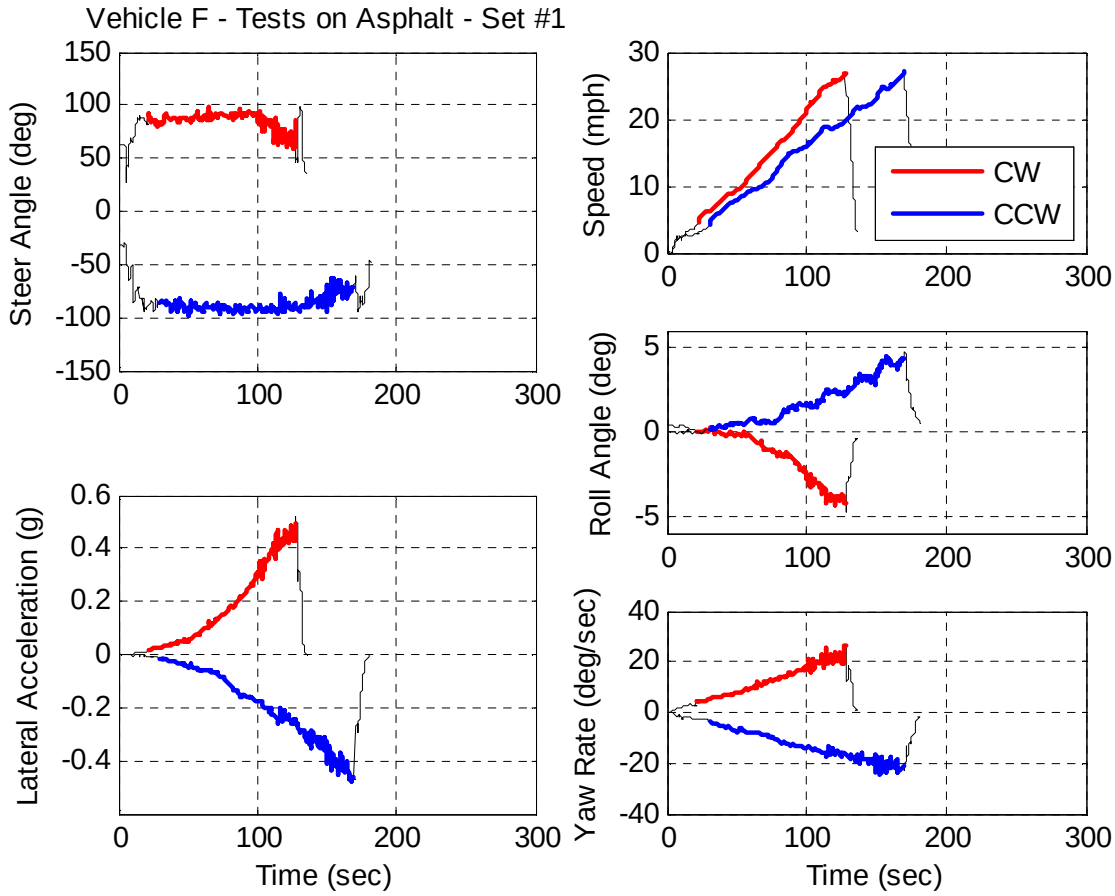

Vehicle F - Tests on Dirt - Set #4
Handwheel Steer Angle (deg)
Ay (g)

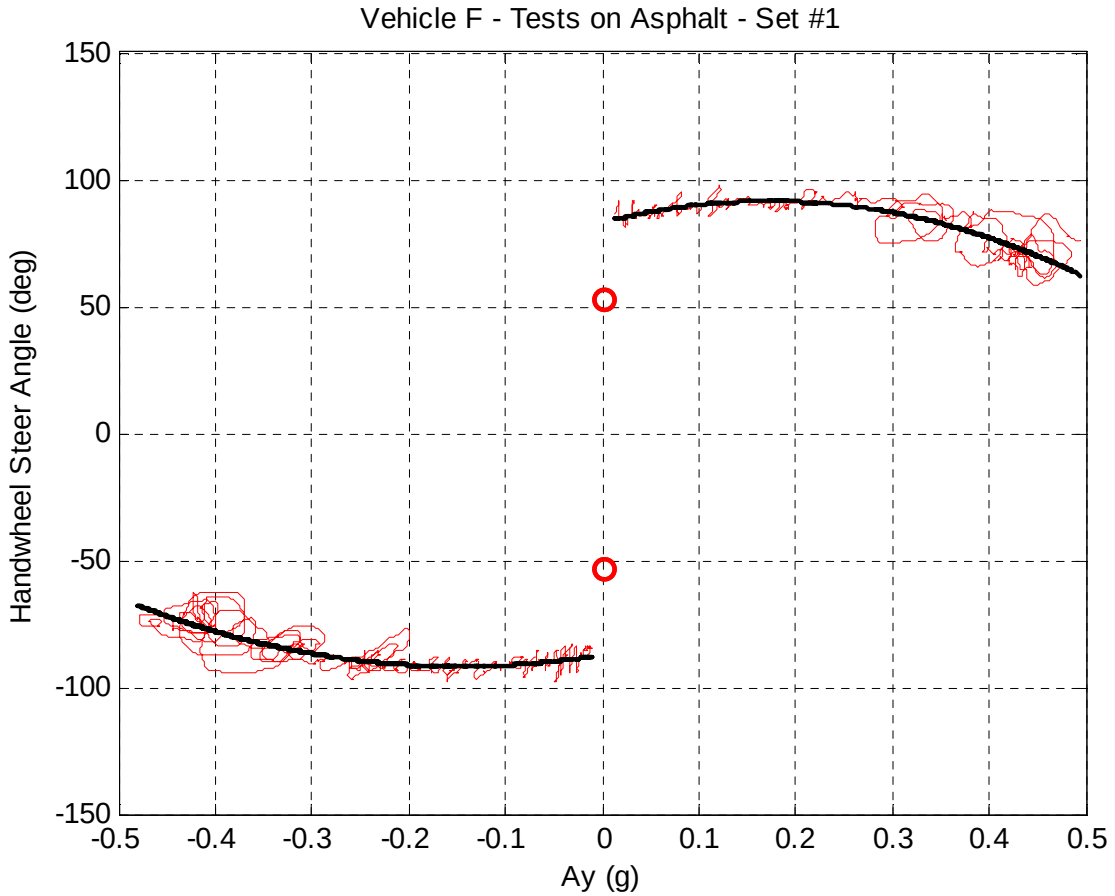

Vehicle F - Tests on Dirt - Set #5
Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

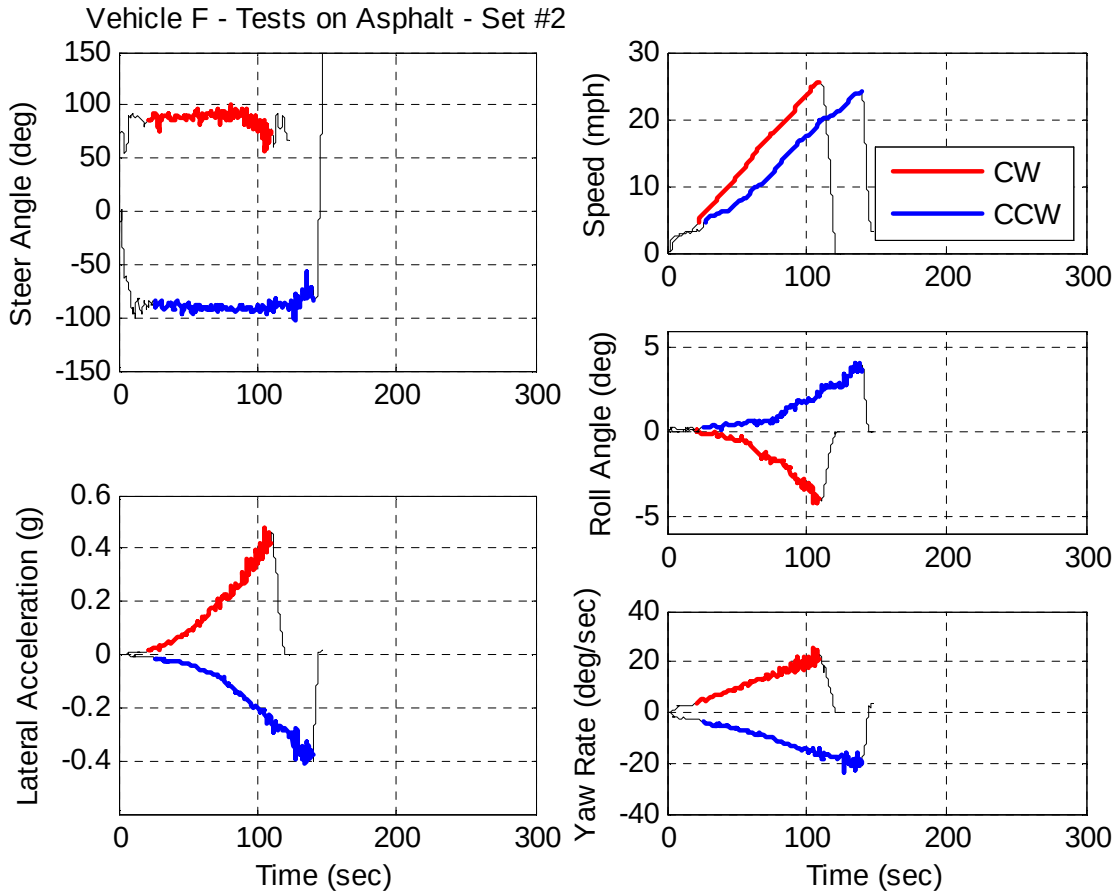

Vehicle F - Tests on Dirt - Set #5
Handwheel Steer Angle (deg)
Ay (g)

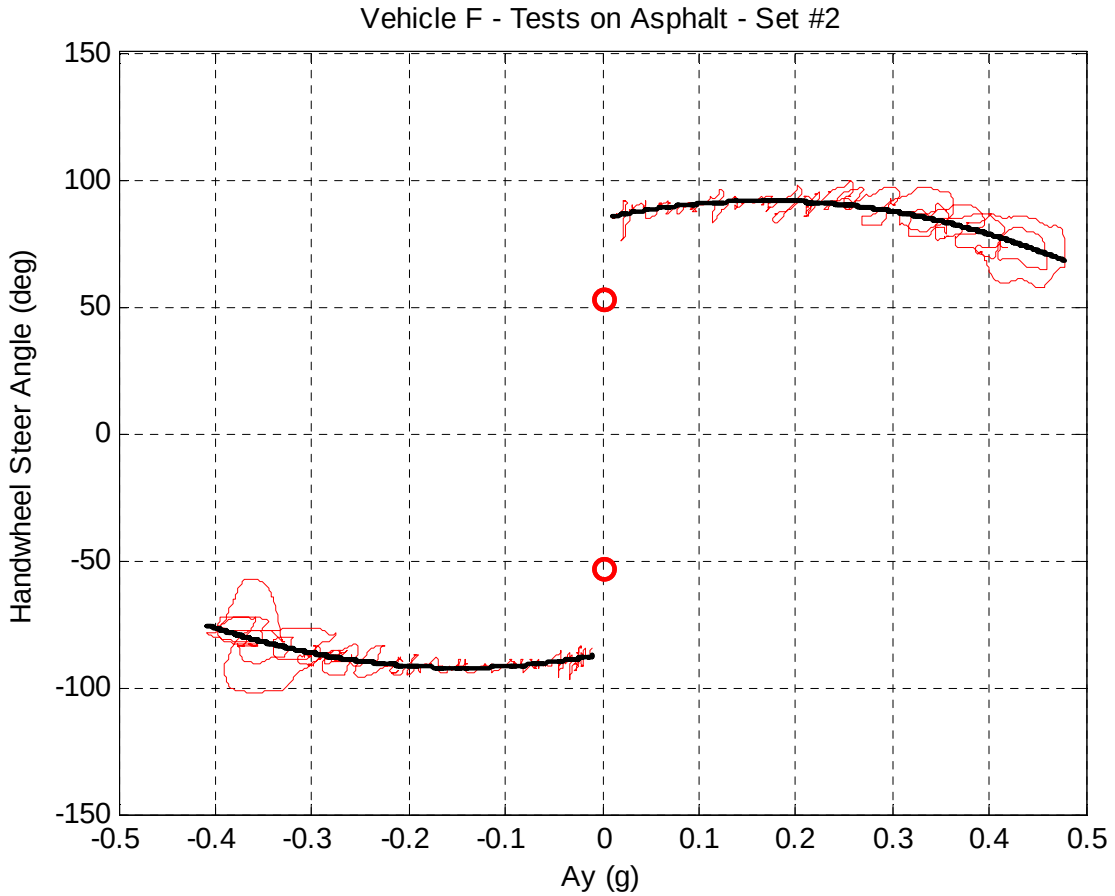

Vehicle F - Tests on Dirt - Set #6
Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

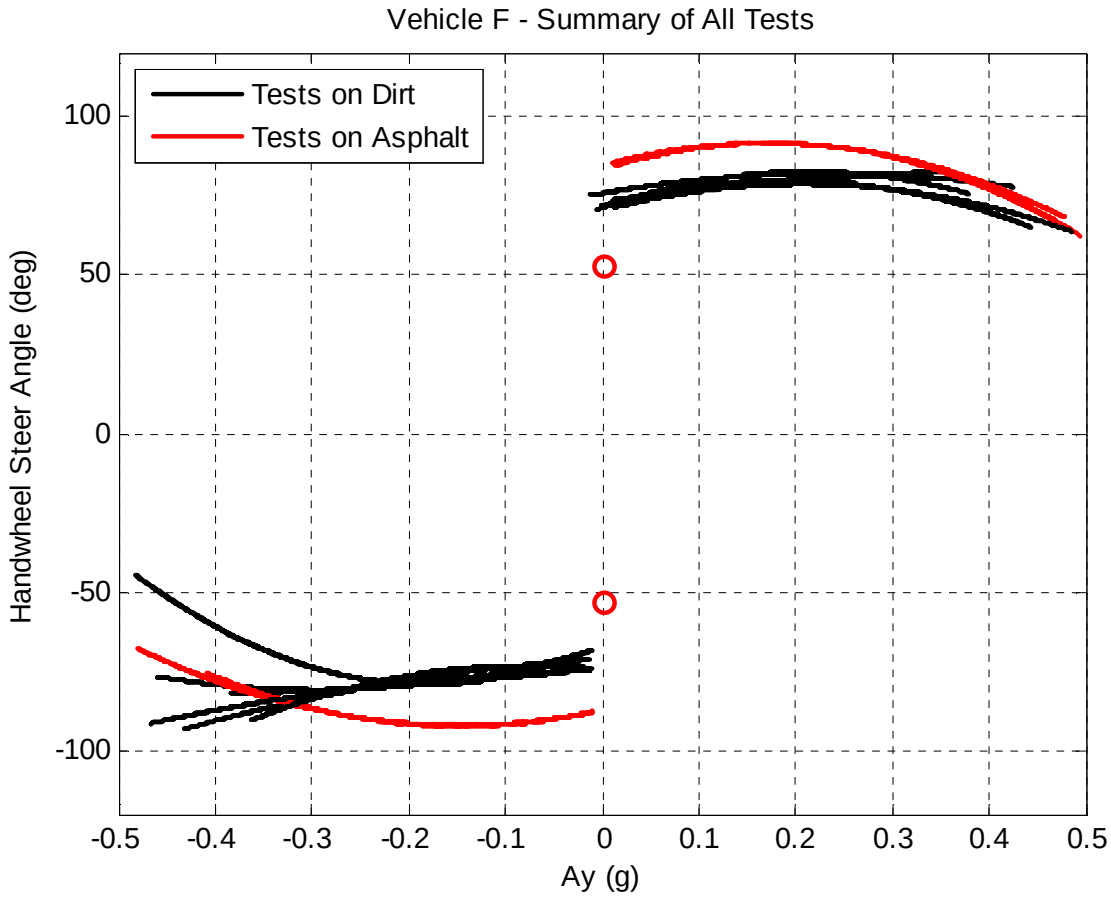

Vehicle F - Tests on Dirt - Set #6
Handwheel Steer Angle (deg)
Ay (g)

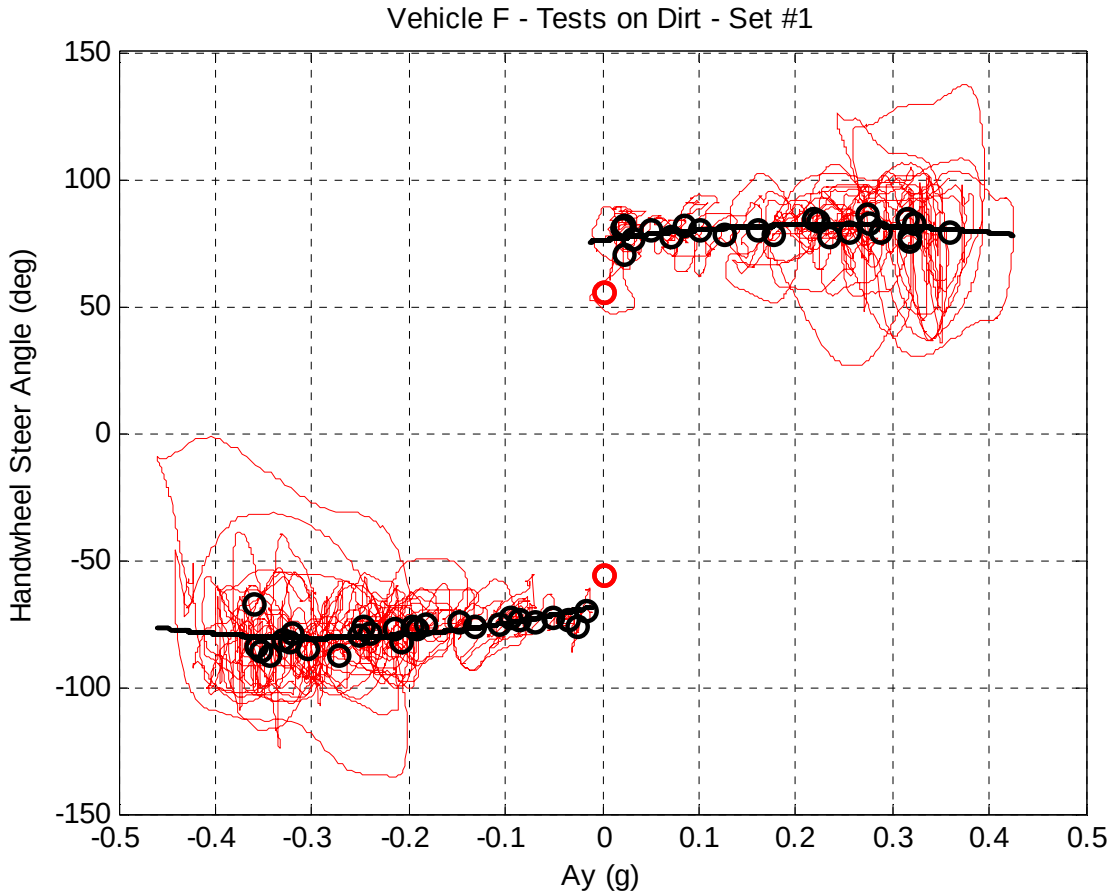

Vehicle F - Tests on Asphalt - Set #1
Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

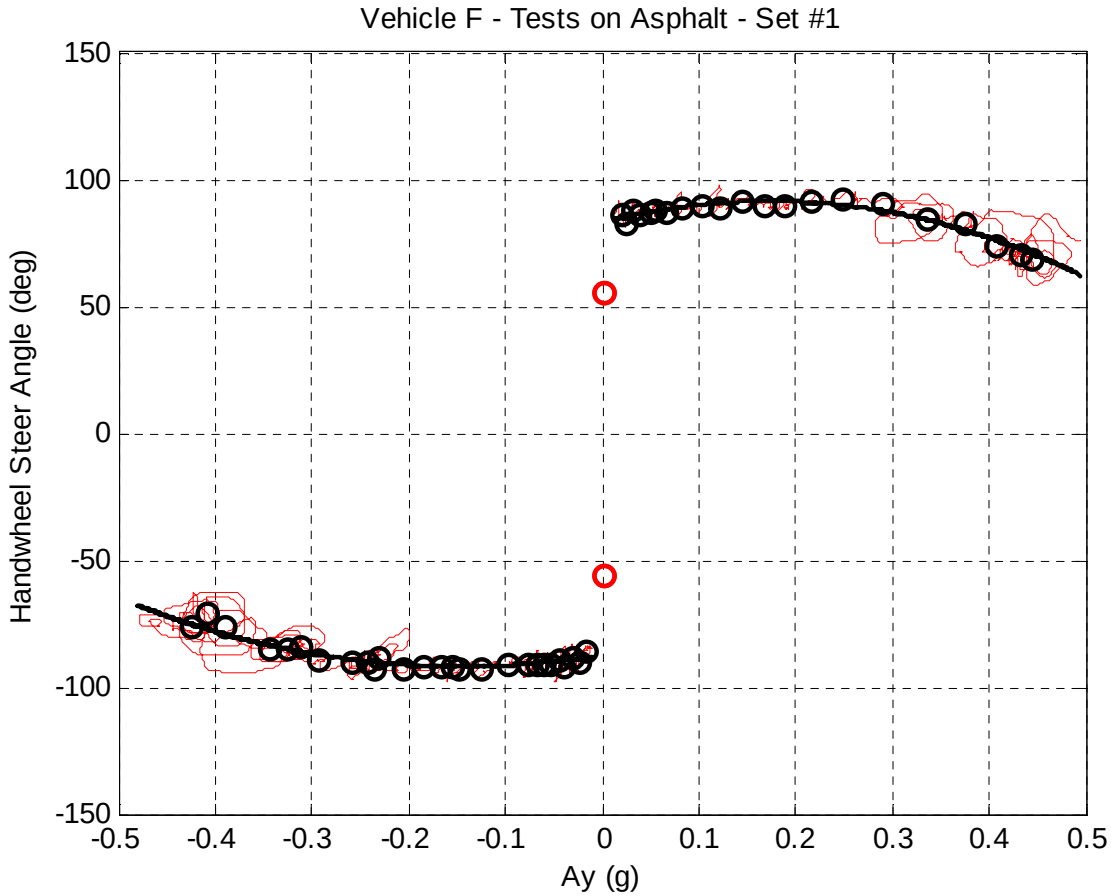

Vehicle F - Tests on Asphalt - Set #1
Handwheel Steer Angle (deg)
Ay (g)

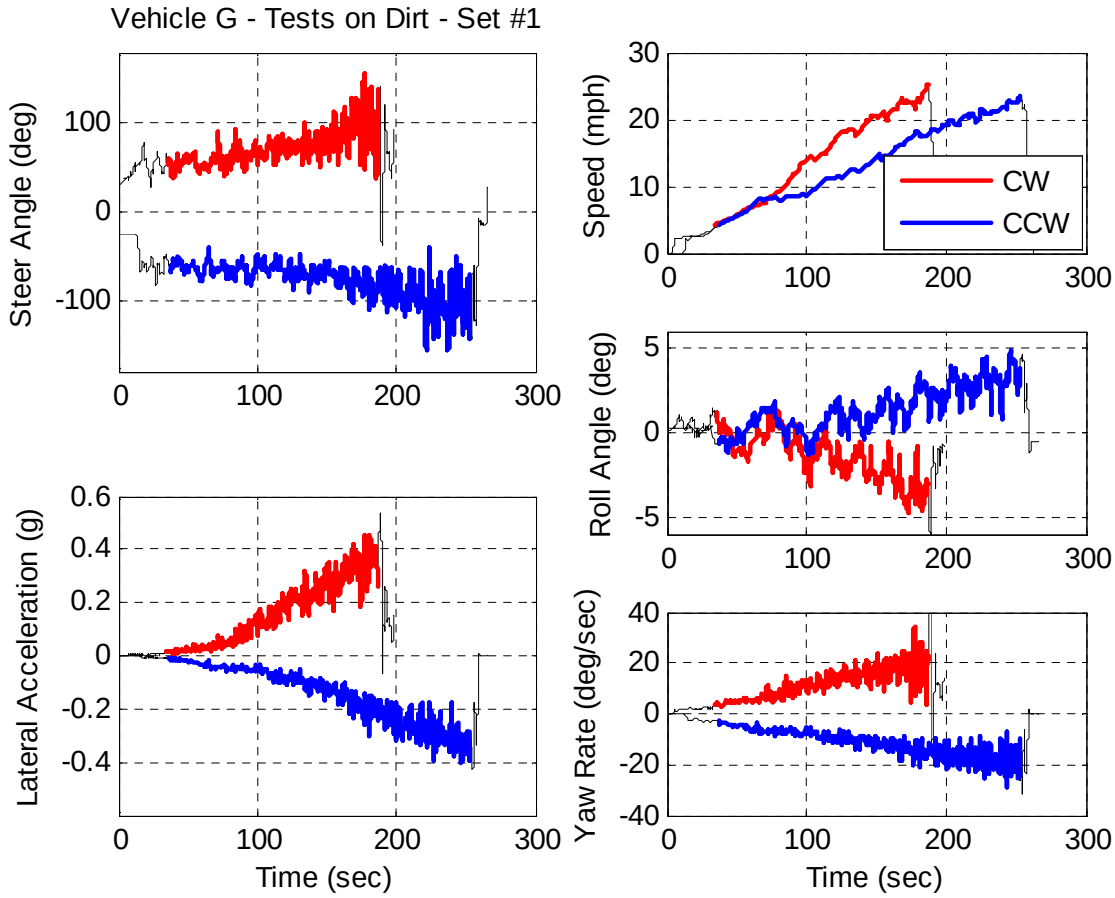

Vehicle F - Tests on Asphalt - Set #2
Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

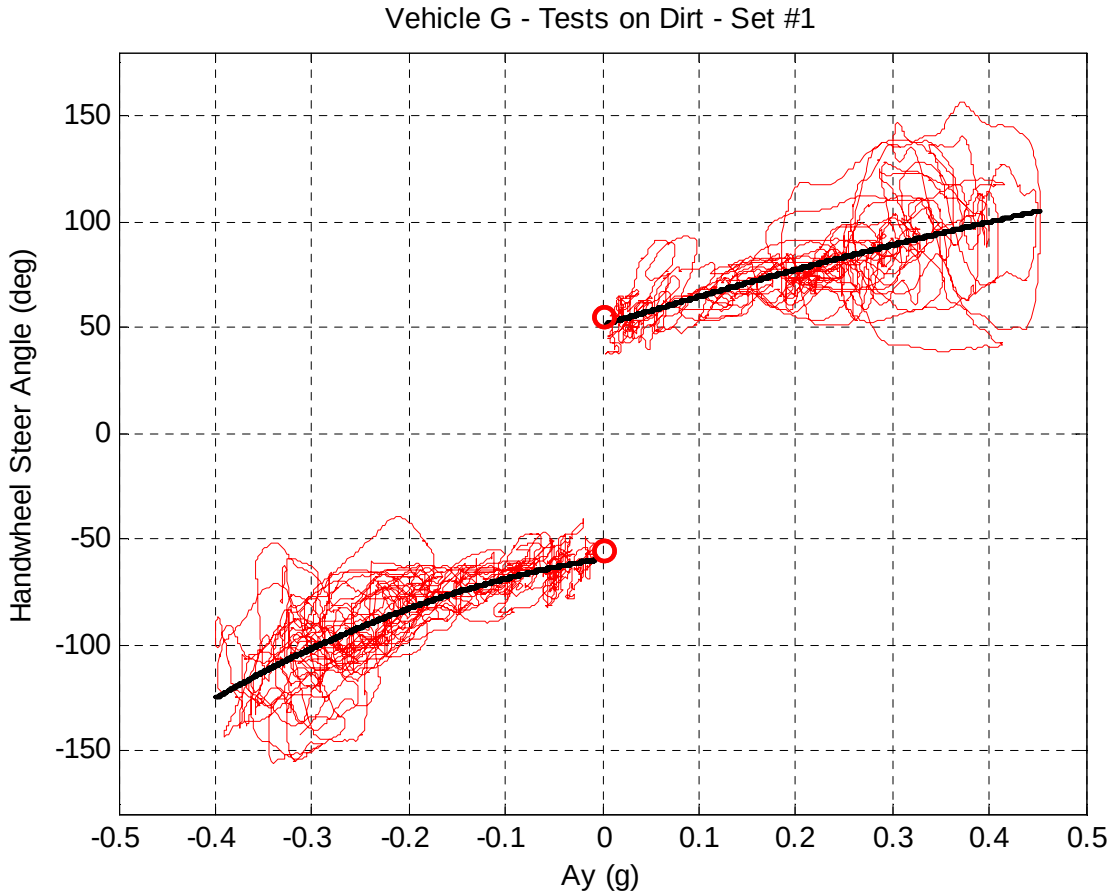

Vehicle F - Tests on Asphalt - Set #2
Handwheel Steer Angle (deg)
Ay (g)

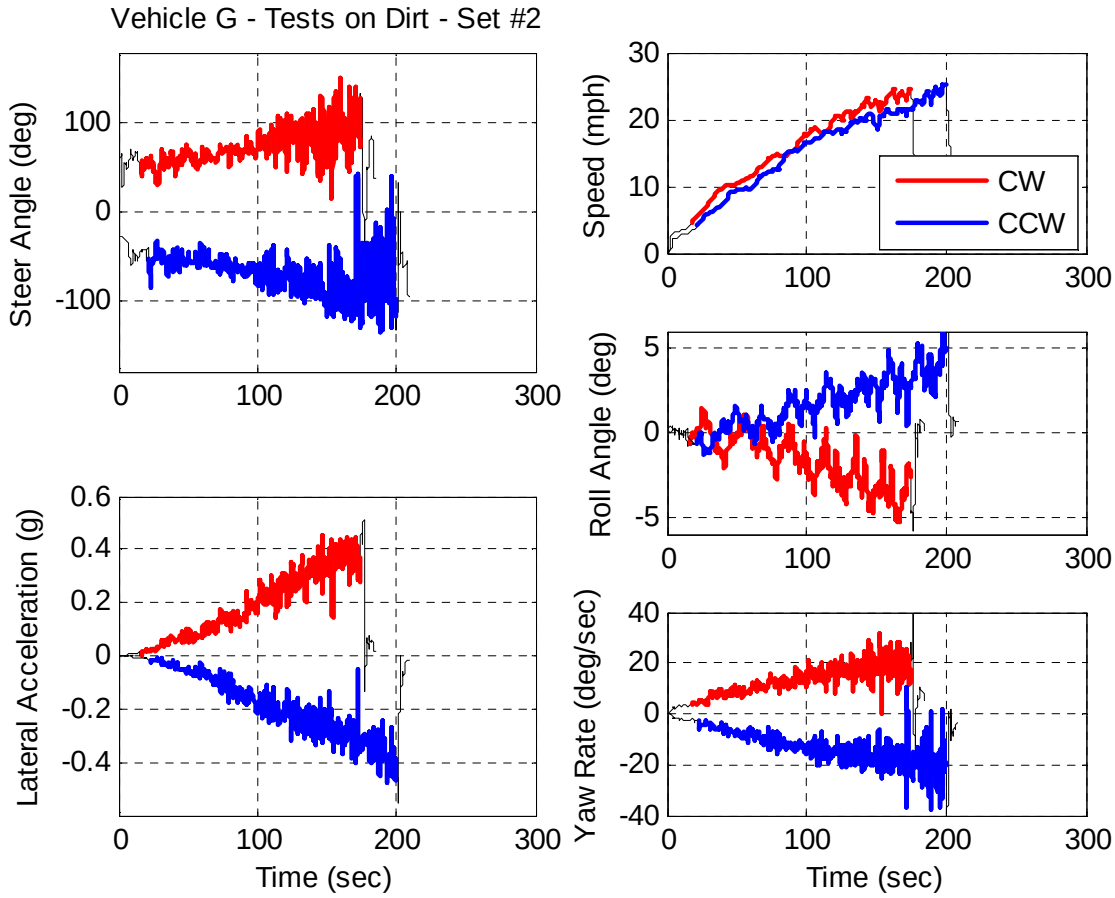

Vehicle F - Summary of All Tests
Tests on Dirt
Tests on Asphalt
Handwheel Steer Angle (deg)
100
50
0
-50
-100
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
Ay (g)

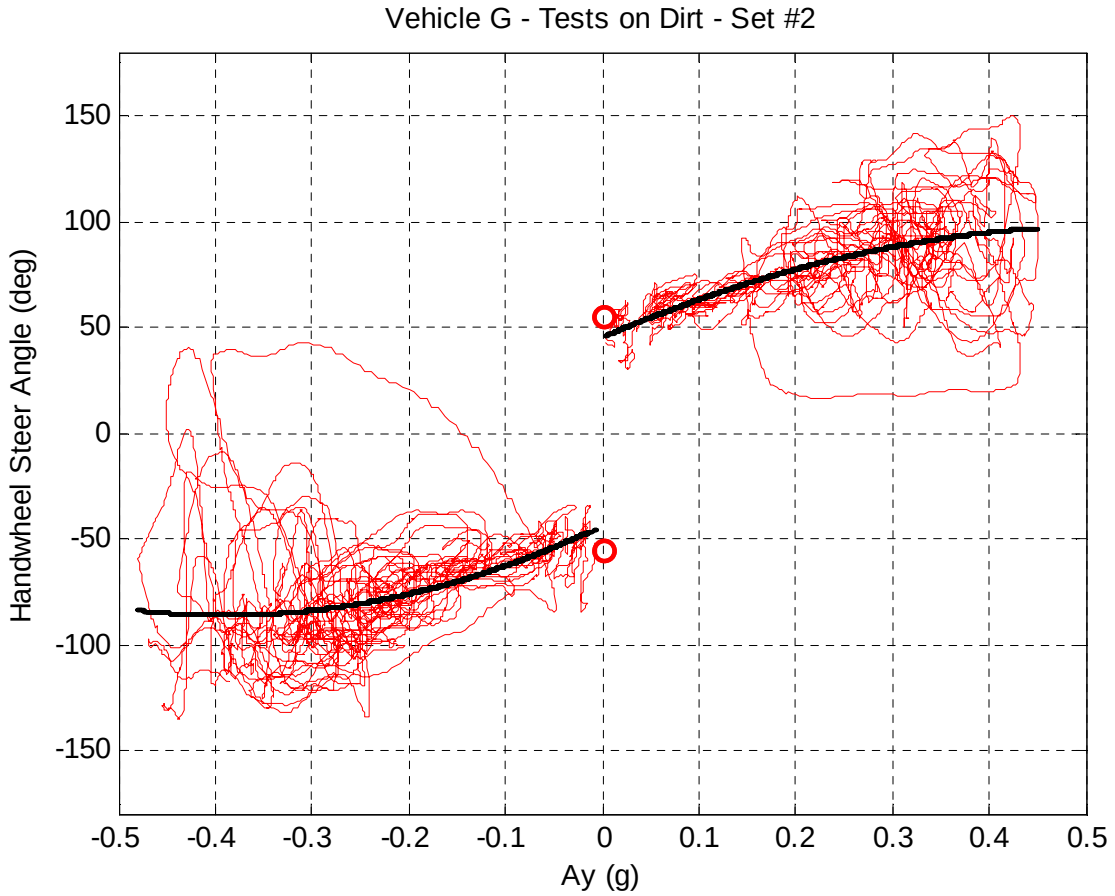

Vehicle F - Tests on Dirt - Set #1
Handwheel Steer Angle (deg)
Ay (g)
150
100
50
0
-50
-100
-150
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5

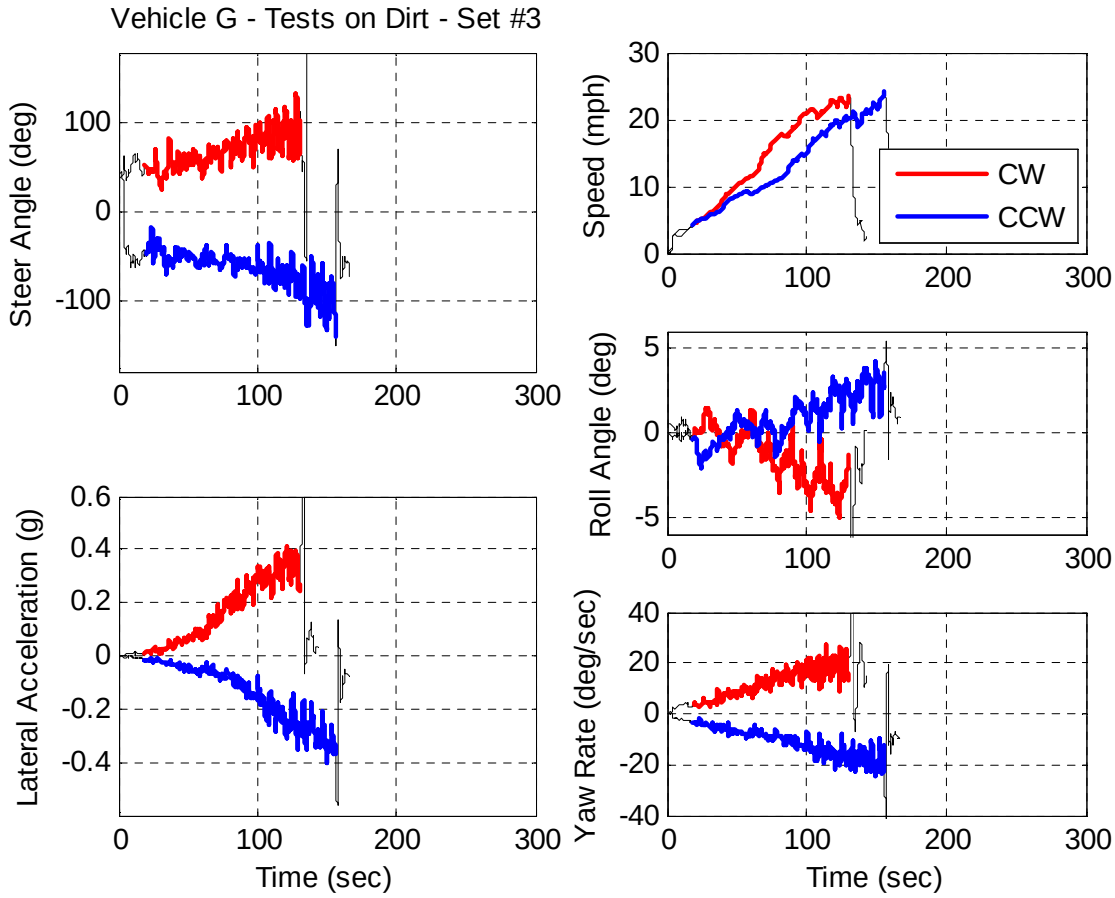

Vehicle F - Tests on Asphalt - Set #1
Handwheel Steer Angle (deg)
Ay (g)
150
100
50
0
-50
-100
-150
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5


Vehicle G - Tests on Dirt - Set #1
Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

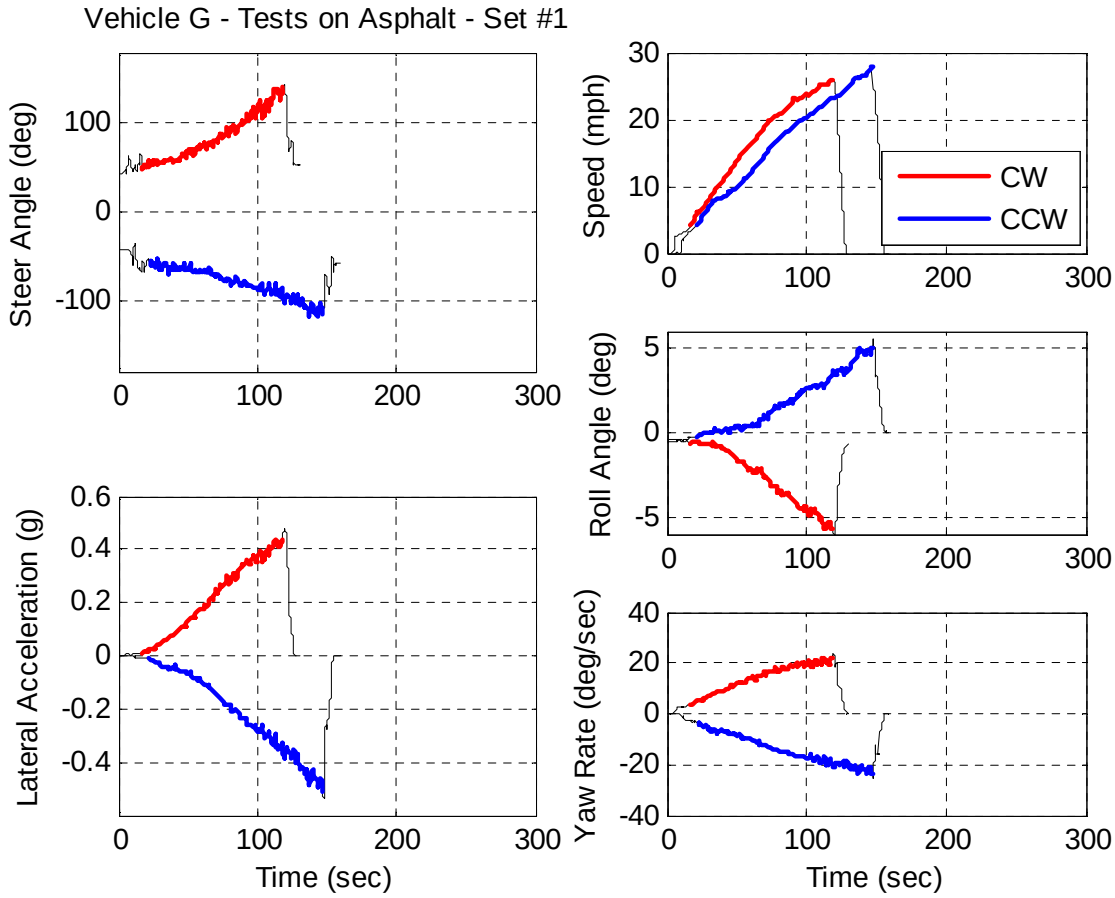

Vehicle G - Tests on Dirt - Set #1
Handwheel Steer Angle (deg)
Ay (g)

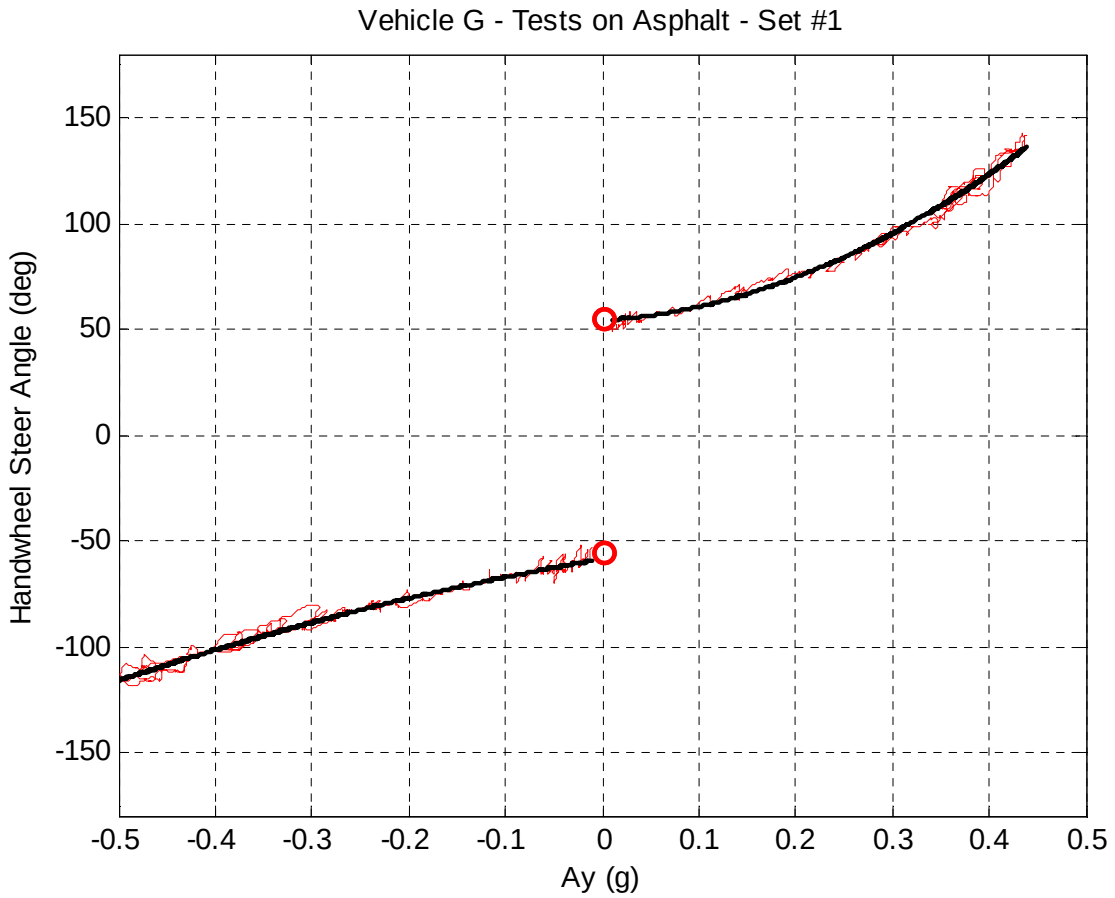

Vehicle G - Tests on Dirt - Set #2
Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

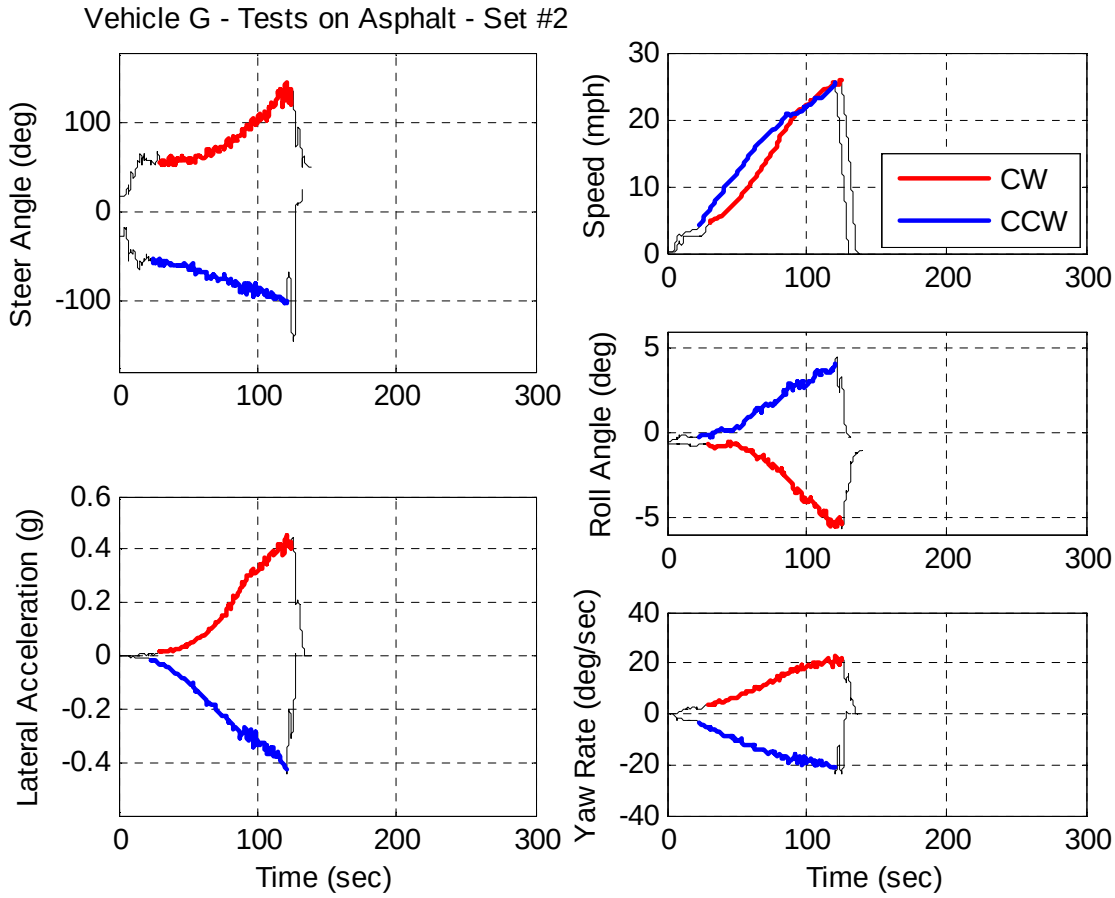

Vehicle G - Tests on Dirt - Set #2
Handwheel Steer Angle (deg)
Ay (g)

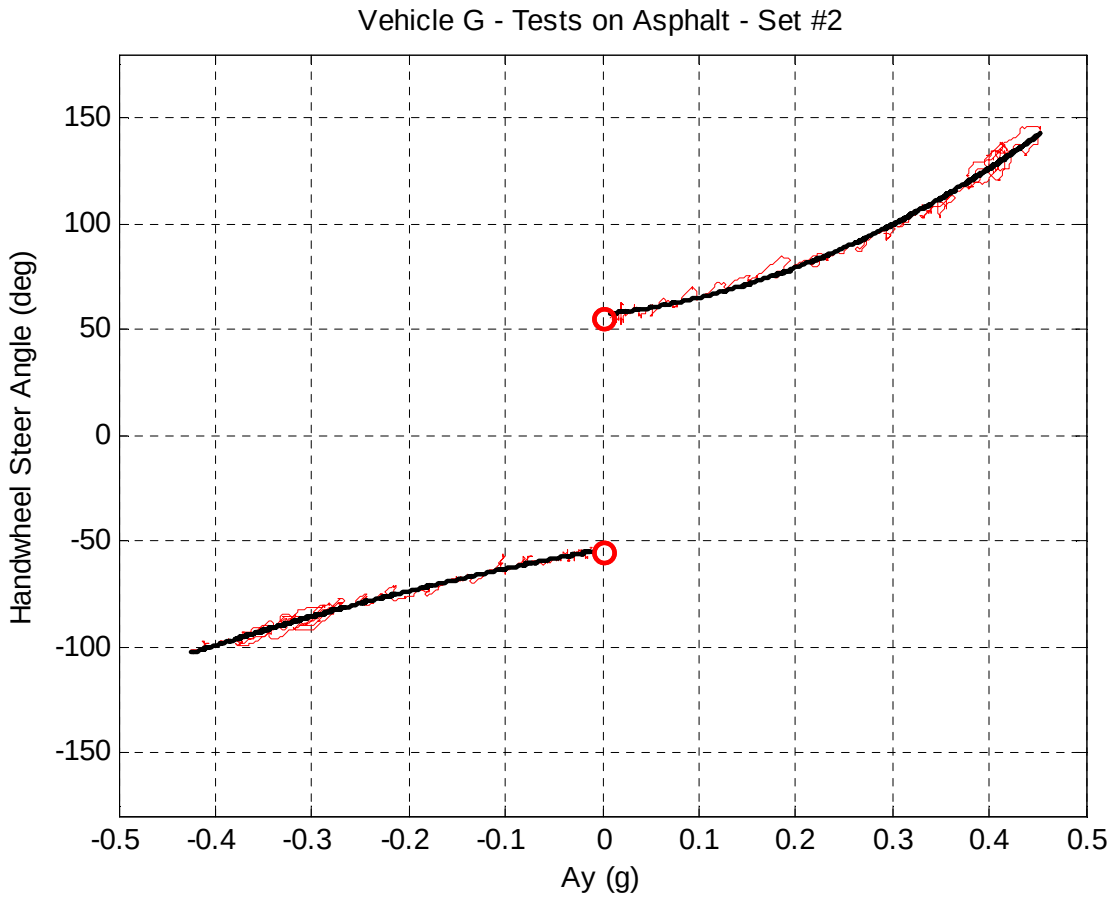

Vehicle G - Tests on Dirt - Set #3
Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

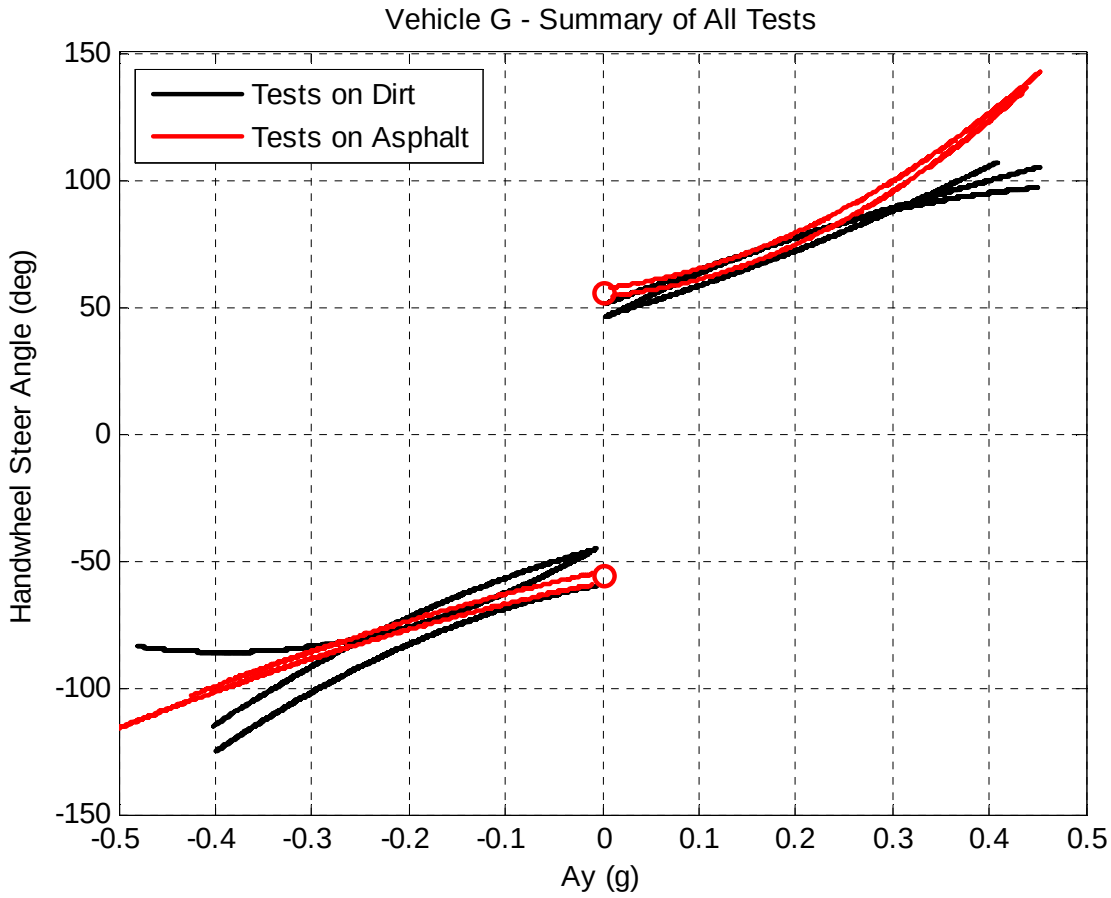

Vehicle G - Tests on Dirt - Set #3
Handwheel Steer Angle (deg)
Ay (g)

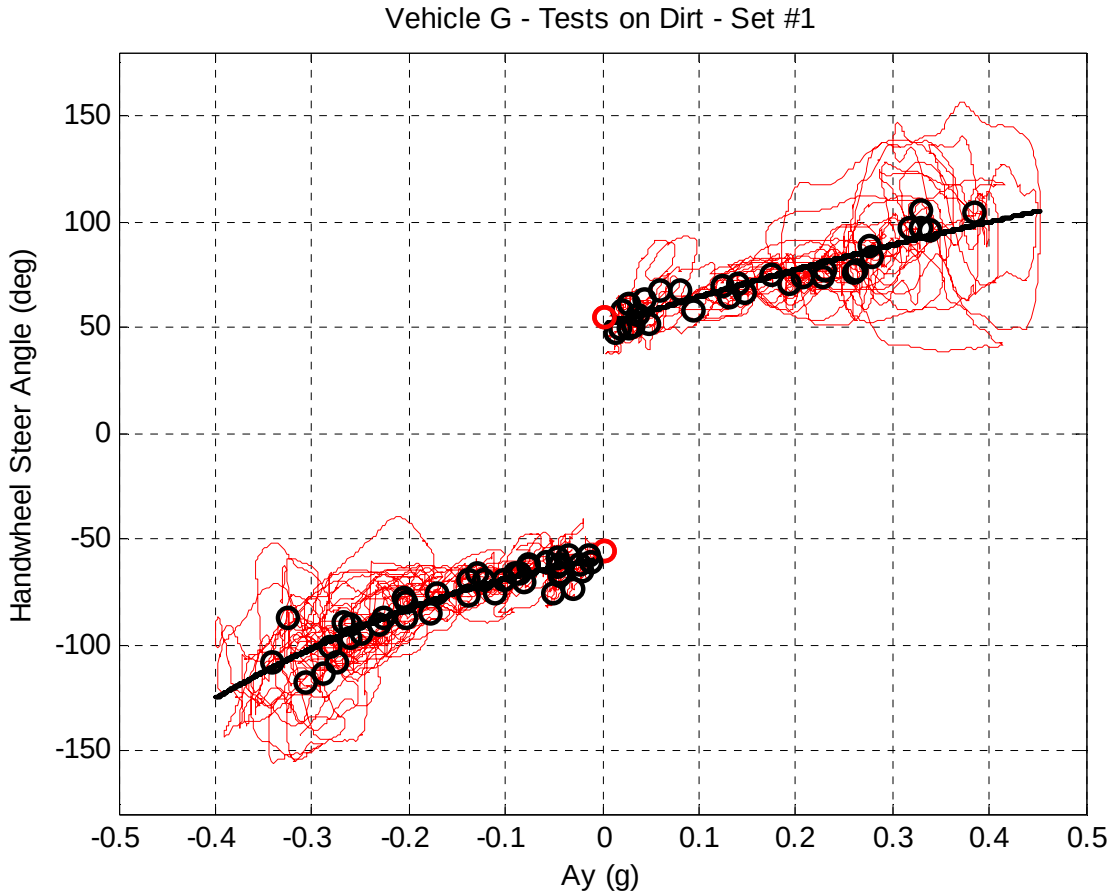

Vehicle G - Tests on Asphalt - Set #1
Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)

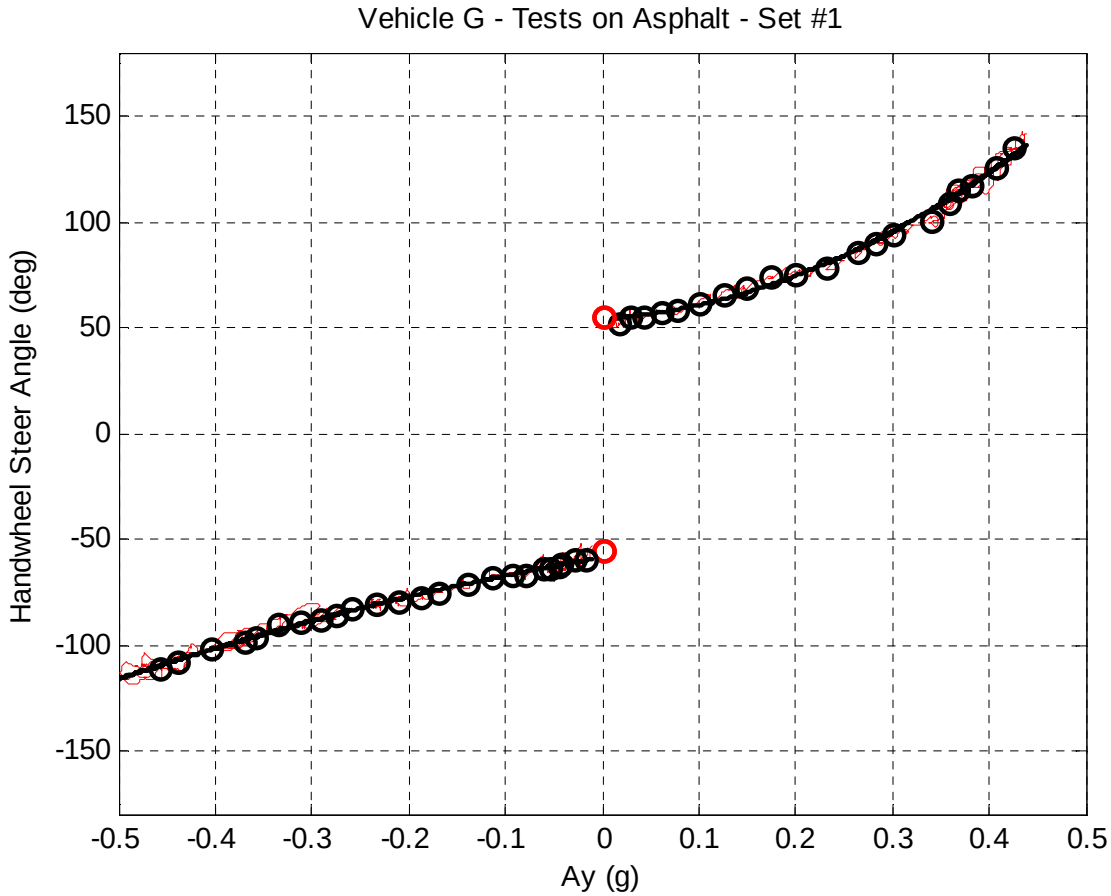

Vehicle G - Tests on Asphalt - Set #1
Handwheel Steer Angle (deg)
Ay (g)


Vehicle G - Tests on Asphalt - Set #2
Steer Angle (deg)
Speed (mph)
CW
CCW
Roll Angle (deg)
Lateral Acceleration (g)
Yaw Rate (deg/sec)
Time (sec)
Time (sec)


Vehicle G - Tests on Asphalt - Set #2
Handwheel Steer Angle (deg)
Ay (g)


Vehicle G - Summary of All Tests
Tests on Dirt
Tests on Asphalt
Handwheel Steer Angle (deg)
150
100
50
0
-50
-100
-150
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
Ay (g)


Vehicle G - Tests on Dirt - Set #1
Handwheel Steer Angle (deg)
150
100
50
0
-50
-100
-150
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
Ay (g)


Vehicle G - Tests on Asphalt - Set #1
Handwheel Steer Angle (deg)
150
100
50
0
-50
-100
-150
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
Ay (g)