March 2024

CPSC Staff[1] Statement on SEA, Ltd. (SEA) Report "Development of Enhanced Proof-of-Concept (POC) Electronic Stability Control (ESC) System for All-Terrain Vehicle (ATV) Stability"

The SEA, Ltd. (SEA) report titled "Development of Enhanced Proof-of-Concept (POC) Electronic Stability Control (ESC) System for All-Terrain Vehicles (ATVs)" presents the results of dynamic testing of two all-terrain vehicles equipped with enhanced POC ESC systems that were designed and constructed by SEA. This work was conducted for CPSC under Task Order 61320623F1010 of CPSC contract 61320618D0003.

SEA conducted a series of dynamic tests[2] (on paved surfaces and groomed dirt) on an autonomously controlled model year 2021 ATV equipped with an anti-lock brake system (ABS) and an autonomously controlled model year 2014 ATV without ABS. Both ATVs had enhanced POC ESC systems installed. This exploratory work examined how an enhanced POC ESC system's intervention can monitor real-time vehicle sensor data and then activate braking, drop throttle, or a combination of braking and dropped throttle to limit lateral rollover.

This report will assist CPSC staff as they continue to work to improve standards associated with ATV safety, including working with the Specialty Vehicle Association of America (SVIA) and other interested parties.

[1] This statement was prepared by the CPSC staff, and the attached report was prepared by SEA. The statement and report have not been reviewed or approved by, and may not represent the views of, the Commission.
[2] Test video weblink: https://www.youtube.com/watch?v=ZcXqJJknVAE

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Development of Enhanced Proof-of-Concept (POC) Electronic Stability Control (ESC) System for ATV Stability

for:
Consumer Product Safety Commission

February 2024

Vehicle Dynamics Division
7001 Buffalo Parkway
Columbus, Ohio 43229

Development of Enhanced Proof-of-Concept (POC) Electronic Stability Control (ESC) System for ATV Stability

for:
Consumer Product Safety Commission

"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 the description of work conducted and results from measurements made by SEA, Ltd. (SEA) for the Consumer Product Safety Commission (CPSC) under CPSC contract 61320618D0003, a contract that covers general testing and evaluation of All-Terrain Vehicles (ATVs). An earlier related study under the same contract was conducted during FY2022 and was done under Task Order 61320621F1012. This previous work involved designing and constructing a rudimentary ESC / Instability Mitigation System (IMS) for ATVs equipped with ABS capabilities. It also involved conducting autonomously controlled dynamic tests on ATVs with and without the ESC / IMS on different terrains and using various maneuvers.

The work done for this FY2023 study was conducted during calendar year 2023 and was done under Task Order 61320623F1015. The objectives of this FY2023 study are:

1) The first objective of this task order is to refine the FY2022 ESC system on the ABS-equipped ATV and standard ATV without ABS that will enable real-time controls to mimic a commercially available ESC system. Specifically, the objective is to perform the following:

    - Install the appropriate throttle/braking actuators, test instrumentation, and sensors to measure yaw rate, velocity, acceleration, and steering angle; develop an algorithm to detect pending yaw instability; create a feedback loop system to actuate the appropriate amount of braking and/or drop throttle signal when instability conditions are met.

    - Implement refinements to the rudimentary ESC system that was developed in FY2022 by tuning the levels and timing of the dropped throttle and braking commands. Establish ESC threshold levels that can be dependent on the states of real-time measured or predicted vehicle responses.

    - Conduct autonomously controlled dynamic vehicle turn scenario tests on both ATVs used during the FY2022 study on paved and groomed dirt surfaces.

    - Develop recommended ESC performance metrics and test requirements to mitigate rollovers based on the dynamic testing of the ESC-equipped ATVs.

2) The second objective is to conduct a literature search of available automotive safety technologies that can be applicable to ATVs such as object detection systems to reduce likelihood of collisions. A list of potential technologies to search shall be discussed with the COR prior to initiating the search.

This report covers the work completed regarding the first objective. A standalone report titled *Review of Automotive Safety Technologies Applicable to All-Terrain Vehicles (ATVs)*[1] covers the second objective.

[1] *Review of Automotive Safety Technologies Applicable to All-Terrain Vehicles (ATVs)*, CPSC Contract 61320618D0003, SEA, Ltd. Report to CPSC, January 2024. https://www.cpsc.gov/content/Review-of-Automotive-Safety-Technologies-Applicable-to-All-Terrain-Vehicles-ATVs

The specific tasks under Objective 1) covered in this report include:

1. Install all necessary test instrumentation and robotic hardware for autonomous testing. Modify the FY2022 ESC system on the ABS-equipped ATV and standard ATV without ABS with refinements that will enable additional features such as real-time vehicle responses.

2. Conduct dynamic tests utilizing the autonomous ATV Robotic Test Driver (RTD) installed on both ATVs to evaluate rollover resistance and vehicle handling. Tests shall be conducted on paved and groomed dirt surfaces. The load condition for the testing is operator (95th percentile male) plus instrumentation and outriggers. The list of dynamic test scenarios shall be finalized with the COR.

3. Provide a set of recommended ESC performance metrics to reduce the risk of rollover.

The previous FY2022 work of designing and constructing a rudimentary ESC / Instability Mitigation System (IMS) for ATVs equipped with ABS capabilities laid the foundation for the current study. The report covering the FY2022 work is titled *Development of Proof-of-Concept (POC) Electronic Stability Control (ESC) System for ATV Stability.*[2]

The rudimentary POC ESC system developed in FY2022 demonstrated features for sensing pending rollover instability and then applying braking and dropped throttle conditions to bring the ATV's tested to a stop. The enhanced POC ESC system developed for this work expands the features of the system in two significant ways. First, in addition to using braking and dropped throttle together for ESC intervention, ESC intervention using braking input only and dropped throttle only were developed and demonstrated. Second, features for having the ATV continue its path after ESC intervention was also developed and demonstrated. This second feature included using path following capabilities incorporated into SEA's ATV Robotic Test Driver (RTD) throughout each maneuver, and it included using RTD throttle inputs to have the ATV recover its desired test speed after ESC intervention slowed the vehicle. This second feature was included in the enhanced ESC system as a proof-of-concept for how a human driver could maintain their intended path and recover their desired speed after stability control intervention.

The same two ATVs used in the FY2022 study were used in this study, and they are Vehicle G and Vehicle N. They both have straddle seating, and their intended use is for a single occupant, the driver. Both vehicles have handlebar steering, thumb activated throttles, and hand and foot activated brakes.

Vehicle G is a 2014 Model Year (MY) vehicle that was also tested several times for CPSC studies

[2] *Development of Proof-of-Concept (POC) Electronic Stability Control (ESC) System for ATV Stability,* CPSC Contract 61320618D0003, SEA, Ltd. Report to CPSC, October 2022. **https://www.cpsc.gov/s3fs-public/SEAReportDevelopmentofProofofConceptPOCElectronicStabilityControlSystemforATVs.pdf?VersionId=bHw7fPfLsjO0HugwRDzpyDCsABLa6ZZe**

conducted by SEA between 2016 and 2018.[3,4,5] Vehicle N, is a 2021 MY vehicle that was also tested for CPSC in a FY2021 study conducted to evaluate ABS on ATVs.[6]

Results from previous laboratory tests on Vehicle G and Vehicle N are reproduced in Appendix B of this report. The FY2022 report contained this same appendix (as Appendix A), and it has a section that describes the content of the appendix in detail. Photographs of the test vehicles and test equipment are contained in Appendix C (same appendix is in FY2022 report). Results from previous dynamic tests on Vehicle G and Vehicle N that were used to establish threshold levels for when ESC should be activated to prevent rollover instabilities are contained in Appendix D (same appendix is in FY2022 report). The same threshold values that were used in the FY2022 study were used again in this study, and they are presented in the following section.

Vehicle N has Original Equipment Manufacturer (OEM) installed ABS, and Vehicle G does not have ABS. It is important to have ABS in some situations when ESC activates. ABS prevents braked wheels from locking up, which would limit the effectiveness of ESC intervention. Therefore, for Vehicle G the hand brake actuator of the RTD was programmed to modulate braking inputs to emulate ABS for this vehicle. This emulation of ABS is not as sophisticated as a commercial ABS, but it is useful for helping demonstrate the proof-of-concept ESC system developed.

Table 1 contains a list of assorted vehicle information and tire specifications for the two vehicles tested during this study. Listed are the measured curb weight, measured maximum speed, transmission type, rear suspension type, and OEM driveline setting options. Both vehicles have open rear differentials, and they were tested in two-wheel drive mode. Table 1 also lists the front and rear tire make, tire size, and tire pressure for each vehicle.

This report contains six main sections: Overview, Design of Enhanced POC ESC for ATV Stability, Dynamic Testing, Discussion of Test Results, Potential Test Maneuver to Evaluate ATV Electronic Stability Control, and Summary. There are also four appendices containing test results, photographs of test equipment, and background information.

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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, November 2016. **https://www.cpsc.gov/s3fs-public/SEA_Report_to_CPSC_Vehicle_Characteristics_Measurements_of_All_Terrain_Vehicles.pdf**

4 *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://cpsc-d8-media-prod.s3.amazonaws.com/s3fs-public/SEA-Report-to-CPSC-Rider-Active-ATV-Study-December-2017_0.pdf**

5 *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, February 2018. **https://www.cpsc.gov/s3fs-public/SEA-Report-to-CPSC-Groomed-Dirt-ATV-Study.pdf?eK1E6h7IXBtznyCDatWHofAoHHmwD_nr**

6 *Evaluation of Anti-lock Brake System (ABS) Technology on ATV Stability – Results from Tests on Two 2021 Model Year Vehicles*, CPSC Contract 61320618D0003, SEA, Ltd. Report to CPSC, November 2022. **https://www.cpsc.gov/s3fs-public/SEAReporttoCPSCEvaluationofAntilockBrakeSystemABSonATVStability.pdf?VersionId=7RfLb2qv7hFv20zqVKcAPXiLFcVMXirz**

Table 1: Test Vehicle Information and Tire Specifications		
Vehicle G – No ABS **Curb Weight: 694.0 lb** **Maximum Speed: 69.0 mph** **Test Weight for ESC Study: 912.3 lb**	**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 N – ABS Equipped **Curb Weight: 951.0 lb** **Maximum Speed: 70.0 mph** **Test Weight for ESC Study: 1,164.2 lb**	**Automatic Transmission** **Independent Rear Suspension** **2WD or 4WD**	
	Front Tires	Rear Tires
Tire Make	ITP Terra Cross R/T	ITP Terra Cross R/T
Tire Size	205/75R14 M/C 48M 6 Ply	255/65R14 M/C 55M 6 Ply
Tire Pressure (psi) For Driver plus Cargo < 155 kg (341 lb)	7.0	7.0
Tire Pressure (psi) For Driver plus Cargo > 155 kg (341 lb)	9.0	10.0

2. DESIGN OF ENHANCED POC ESC FOR ATV STABILITY

The enhanced proof-of-concept (POC) ESC system designed for this study uses computer-controlled actuators to control throttle position and braking position during ESC intervention. The same actuators were used on both test vehicles. However, their mounting locations and tuning parameters were specific to the two different vehicles tested. That is, the ESC system designed is not a universal one-size-fits-all system. Tests were conducted using the enhanced POC ESC system on the two vehicles for the purpose of demonstrating the feasibility of using ESC on ATVs.

Figure 1 is a typical diagram used to depict ESC to mitigate vehicle limit oversteer. For on-road passenger vehicles, limit oversteer is generally described as handling or yaw instability that leads to a spin out (as shown on Figure 1). For a typical on-road passenger vehicle with oversteer, as vehicle speed increases the yaw rate gain (amount of yaw rate per degree of steering) increases, promoting conditions that can lead to spin out. For a vehicle with oversteer, as vehicle speed increases the lateral acceleration gain (amount of lateral acceleration per degree of steering) also increases, and it increases more than the yaw rate gain. For on-road passenger vehicles, during steering induced maneuvers the limits of yaw instability (spin out) generally occur before the limits of lateral instability (rollover).

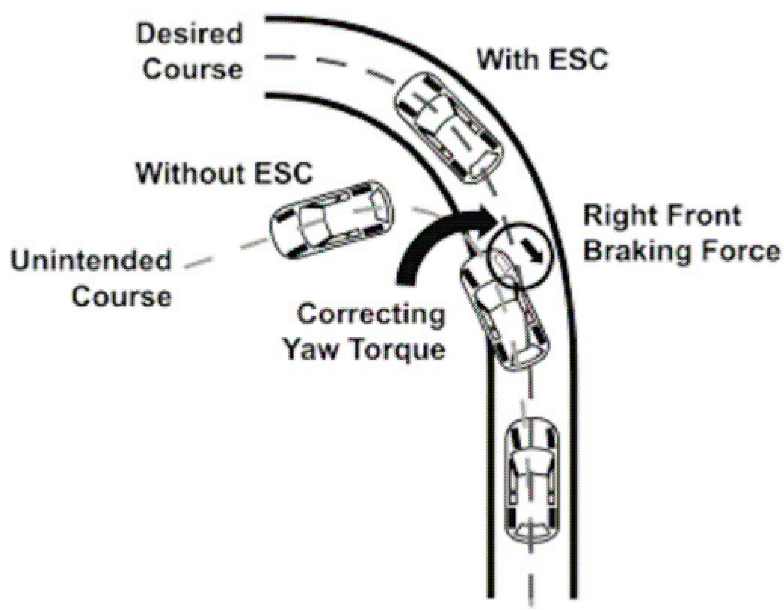

Figure 1: Diagram Depicting ESC to Mitigate Vehicle Oversteer

However, this is not the case for typical ATVs. For a typical ATV with oversteer characteristics, during steering induced maneuvers, as vehicle speed increases the lateral acceleration gain leads to lateral instability (rollover) before the yaw rate gain leads to yaw instability (spin out).

Previous testing conducted by SEA to evaluate ATV stability for CPSC has shown that even ATVs with neutral steer or understeer characteristics typically reach conditions of limit lateral instability before they reach a condition of limit understeer (plow out). Since the ESC system for ATVs developed in this study predominately mitigates lateral instabilities, it could be referred to more generally as a rollover Instability Mitigation System (IMS).

The point of this discussion is that any effort to mitigate yaw instability caused by high yaw rate gain will also limit lateral instability caused by high lateral acceleration gain. The POC ESC designed and implemented in FY2022 did two things to prevent yaw and lateral instabilities, it dropped vehicle speed, and it applied correcting yaw torque using the outside front brake as shown in Figure 1. **The enhanced POC ESC system designed and implemented for this study includes options for using dropped throttle and braking, dropped throttle only, or braking only to limit lateral instability.**

The vehicles were tested unmanned, using SEA's Robotic Test Driver (RTD). As such, there was no human driver in-the-loop to maintain control of the vehicle during and after ESC intervention. For the FY2022 study, the ESC intervention (dropping the throttle and braking the outside front wheel) was left on until the vehicle slowed to rest. In practice, commercial ESC systems cease intervention when pending instability conditions end.

For this FY2023 study, features for having the ATV continue its path after ESC intervention and after instability conditions were mitigated was also developed and demonstrated. This feature included using path following capabilities incorporated into SEA's ATV Robotic Test Driver (RTD) throughout each maneuver, and it included using RTD throttle inputs to have the ATV recover its desired test speed after ESC intervention slowed the vehicle. This feature was included in the enhanced POC ESC system to demonstrate how a loss of stability mitigation system could allow a human driver to maintain their intended path and recover their desired speed after stability control intervention.

2.1 Algorithm Development

A block diagram of the enhanced POC ESC strategy is shown in Figure 2. The enhanced POC ESC developed here is less sophisticated than typical commercial ESC systems. However, as shown in Figure 2, it does have the main features of a typical ESC system including a real time monitor of a suite of vehicle states, an algorithm to evaluate vehicle state conditions to detect pending instability, and a system to actuate ESC when intervention is needed.

Like the FY2022 work, for the enhanced POC ESC three vehicle states are monitored, forward speed, steering input, and ground plane lateral acceleration at the center-of-gravity (CG) of the vehicle. Accelerations are measured using an OxTS RT3002 GPS/IMU mounted in the rear rack areas of the vehicles (for example, see Page 4 of Appendix C). The build-in processing routines in the RT3002 translate the body-fixed accelerations measured at the sensor location to the CG of the vehicle and convert the body-fixed accelerations into ground plane accelerations. The algorithm to detect pending instability compares the current filtered value of the measured ground plane lateral acceleration to a lateral acceleration threshold level based on previous stability measurements made on the vehicles. If the measured lateral acceleration signal exceeds the threshold level, and the vehicle speed and steering are high enough (above their threshold values) to suggest the vehicle is in a state of pending lateral instability, the enhanced POC ESC system will intervene.

For the FY2023 study, three intervention variations were implemented. The first variation, like the FY2022 study, the intervention will drop the throttle and apply braking to the outside front tire. For the second variation, no braking will be applied and only throttle will be dropped. This variation was added as it was deemed that dropping throttle only would provide enough longitudinal deceleration to quickly bring the vehicle to a stable condition without any braking being applied. For the last variation, speed control of the vehicle will be continued while applying braking only. **This last variation was added as it was thought that the transition to the recovery phase would be smoother and more representative of ESC implemented on commercial systems available on passenger vehicles.**

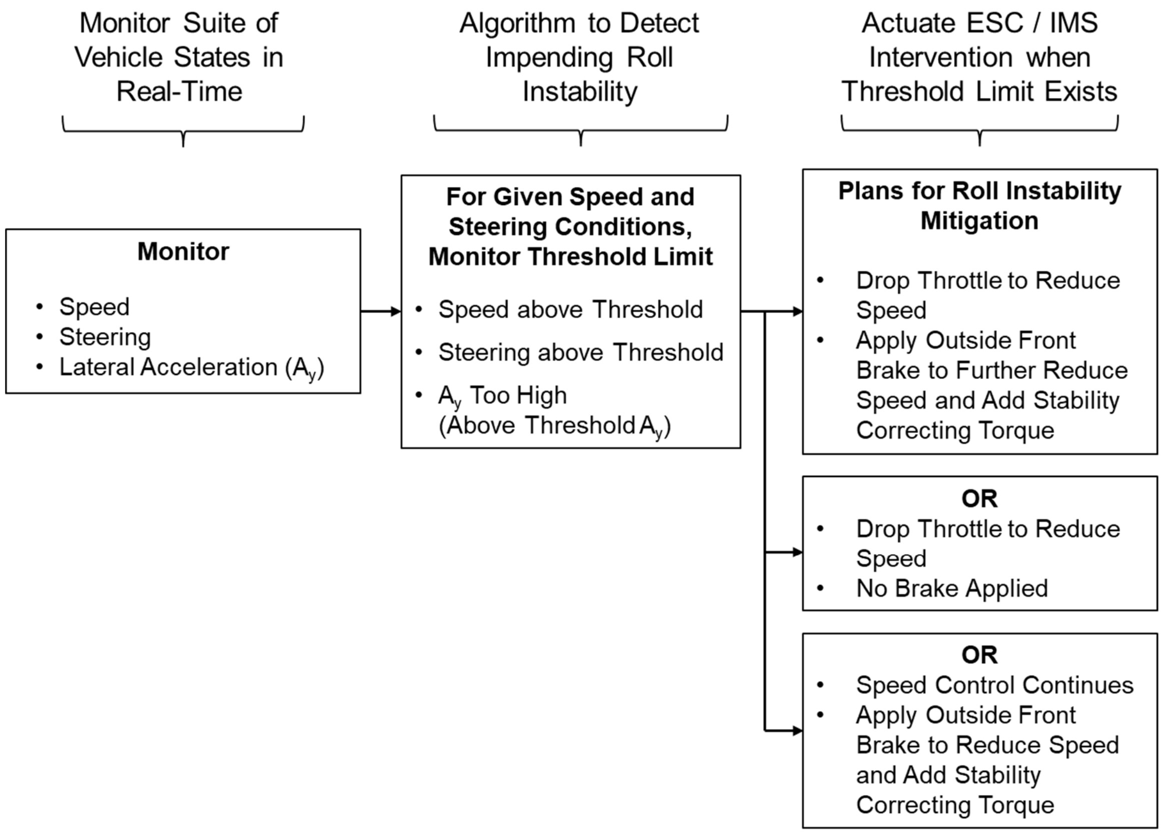

Figure 2: Block Diagram of Enhanced POC ESC Strategy

To determine ESC Threshold lateral acceleration (A_y) levels, previously collected data from dropped throttle J-turn tests, circle tests, and constant steer tests (yaw rate ratio tests) on asphalt and groomed dirt were analyzed (results from these previous dynamic tests conducted on Vehicles G and N are contained in Appendix D) [7]. Factors including the latency caused by real-time filtering the lateral acceleration signal, and the latency between actuating the hand brake and hydraulic brake actuation at the wheel were also considered in selecting the ESC Threshold A_y levels.

Table 2 lists the distinct ESC threshold levels for Vehicles G and N. The ESC Threshold A_y level is 85% of the two-wheel lift (2WL) Threshold A_y, the average minimum peak lateral acceleration that results in 2WL outcomes in 20 mph dropped-throttle J-turn tests conducted on asphalt and

[7] The J-turn tests are rapid steering input maneuvers used to evaluate the tip-up resistance of ATVs. The circle tests and constant steer tests are tests used to evaluate the understeer characteristics of ATVs. Details regarding these tests are contained in several CPSC reports, including, *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, February 2018.
https://www.cpsc.gov/s3fs-public/SEA-Report-to-CPSC-Groomed-Dirt-ATV-Study.pdf?eK1E6h7IXBtznyCDatWHofAoHHmwD_nr

groomed dirt. J-turn maneuvers with 2WL outcomes can lead to rollovers, so 2WL is considered the threshold of imminent rollover. Page 1 of Appendix D contains additional details from the previous 2WL J-turn tests. Pages 2-7 of Appendix D contain plots of lateral acceleration, steer angle, and vehicle speed for previous 2WL J-turn tests, circle tests, and yaw rate ratio tests for both vehicles on asphalt and on groomed dirt.

The lateral acceleration plots in Appendix D show that the lateral acceleration increases faster in the J-turn tests than in the circle or yaw rate ratio tests. The ESC Threshold A_y levels (which are 85% of the 2WL Threshold Ay values) are shown on the lateral acceleration plots. These ESC Threshold A_y levels were selected to allow enough time for the ESC system to intervene and prevent lateral instabilities that would result in rollovers. Time delays resulting from the real-time filter on the measured lateral acceleration, from the delay in vehicle speed reduction on thumb-throttle release, from the delay in response of the brake actuator, and from the delay of the hydraulic brake system all contribute to the overall latency in the ESC system. However, the total latency in the ESC system from the time the true lateral acceleration reaches the ESC Threshold level and the time the vehicle instability is mitigated is less than one second. As the lateral acceleration plots in Appendix D show, using the ESC Threshold A_y levels selected, and having an ESC system that can respond in one second, provides adequate time for the ESC system to intervene and mitigate instabilities even in highly dynamic maneuvers like the rapid steering J-turn tests. The plots also show that the ESC Threshold A_y levels will provide adequate time for intervention in the less dynamic (and quasi-static) maneuvers like circle and yaw rate ratio tests.

The Steering Threshold levels and Speed Threshold levels given in Table 2 are shown on the steering and speed plots in Appendix D. As the plots show, these threshold levels are below the steering and speed values during the more severe portions of the maneuvers. Requiring the vehicle speed and steering input to be above some baseline level indicate that the vehicle is in a maneuver with an instability situation that could be mitigated by ESC intervention. Applying these steering and speed thresholds was done for the sake of including baseline levels of vehicle activity in the proof-of-concept ESC system, like what would likely be done in a commercial ESC system.

Table 2: Vehicle Specific ESC Threshold Levels

ESC Threshold	Vehicle G	Vehicle N
2WL Threshold A_y (g)	0.452	0.548
ESC Threshold A_y (g) (85% of 2WL Threshold A_y)	0.384	0.466
Steering Angle (deg)	9.0	8.0
Vehicle Speed (mph)	10.0	10.0

In this study there was no driver in-the-loop to maintain control of the vehicle during and after ESC intervention, so the RTD had to programmatically maintain steering control while the enhanced POC ESC intervened. Throughout the duration of all tests conducted for this study, including when ESC intervention was on, the RTD continued to do path following steering to maintain the desired path. This enhancement to the POC ESC developed for the previous FY2022 study allowed us to begin evaluating the levels of steering input a human driver might need to maintain path control during and after ESC intervention.

For Vehicle G the RTD hand brake applies only the front service brakes and for Vehicle N the RTD hand brake applies both the front and rear service brakes. For this study, for both vehicles the left front brake was mechanically disconnected (disabled) and only left turning maneuvers were performed to evaluate ESC effectiveness. This provided the ability to apply the outside front brake (and not the inside front brake), which is the best method for imparting a correcting yaw moment (see Figure 1). Page 5 of Appendix C shows the left front brake caliper removed from the brake rotor on Vehicle N, thus disabling left front braking.

For both vehicles in the FY2023 work, an enhancement to the ESC algorithm was to have the ATV recover its desired test speed after ESC intervention slowed the vehicle. Again, this feature was included in the enhanced ESC system as a proof-of-concept for how a loss of stability mitigation system could allow a human driver to maintain their intended path and recover their desired speed after stability control intervention. Two recovery methods were used. The first method (used when Dropped Throttle was part of ESC intervention) used a piecewise linear pre-determined throttle profile. The second method (used when Braking Only was used for ESC intervention) allowed the RTD's speed control algorithm to be applied to the throttle control. That is, the speed controller was commanded to maintain speed before, during, and after ESC intervention states. Enabling the speed controller to be active during the entire maneuver allowed for smoother transition between all three intervention states.

2.2 Algorithm Implementation

The algorithm described above was implemented in the real-time controller of the RTD. For the real-time system, an NI compact-RIO (cRIO) is programmed using LabVIEW. In general, the ESC algorithm is a subroutine that was incorporated such that it "interrupts" the signals which are determined by the main control loop. That is, depending on the state of the vehicle and whether ESC is enabled, and criteria are met, the desired signals for the brake and throttle may be interrupted in favor of the ESC intervention signals.

Further implementation required a state machine[8] to handle some of the nuances that arise from real-time controllers. Three states were required. For the FY2022 work, the third state was State 2, called ESC Abort but was not used for this study. For FY2023, the third state was State 3 and was called ESC Recovery.

- State 0 – ESC Off:
  - Wait for ESC to be Enabled and Criteria to be Met
  - Pass through Current Desired Throttle, Brake, and Steer Commands

- State 1 – ESC ON:
  - Drop Throttle OR Continue Speed Control
  - Apply ESC Brake Level OR No Brake Applied

[8] A state machine is a mathematical abstraction used to design algorithms. A state machine reads a set of inputs and changes to a different state based on those inputs. A state is a description of the status of a system waiting to execute a transition.

- Path Following Steering for All Tests

- State 3 – ESC Recovery
  - Piecewise Linear Throttle Profile OR Continue Speed Control
  - Path Following Steering for All Tests

To go from State 0 to State 1, ESC criteria need to be met. From State 1 to State 3, vehicle speed needs to drop below the 'ESC Recovery Speed'. While in ESC Recovery (State 3) vehicle speed begins building back up. A transition back to ESC intervention (State 1) can occur if ESC criteria are met again and then the transition back to ESC Recovery can re-occur if vehicle speed drops below to 'ESC Recovery Speed'. This process will repeat until the transition back to State 0.

A return to State 0 can occur either by the RTD variable 'User Stop' (Stop or E-stop) going TRUE (meaning the test operator hit the Stop or E-stop button) or by the occurrence of an abort condition. Figure 3 depicts the ESC state machine as implemented.

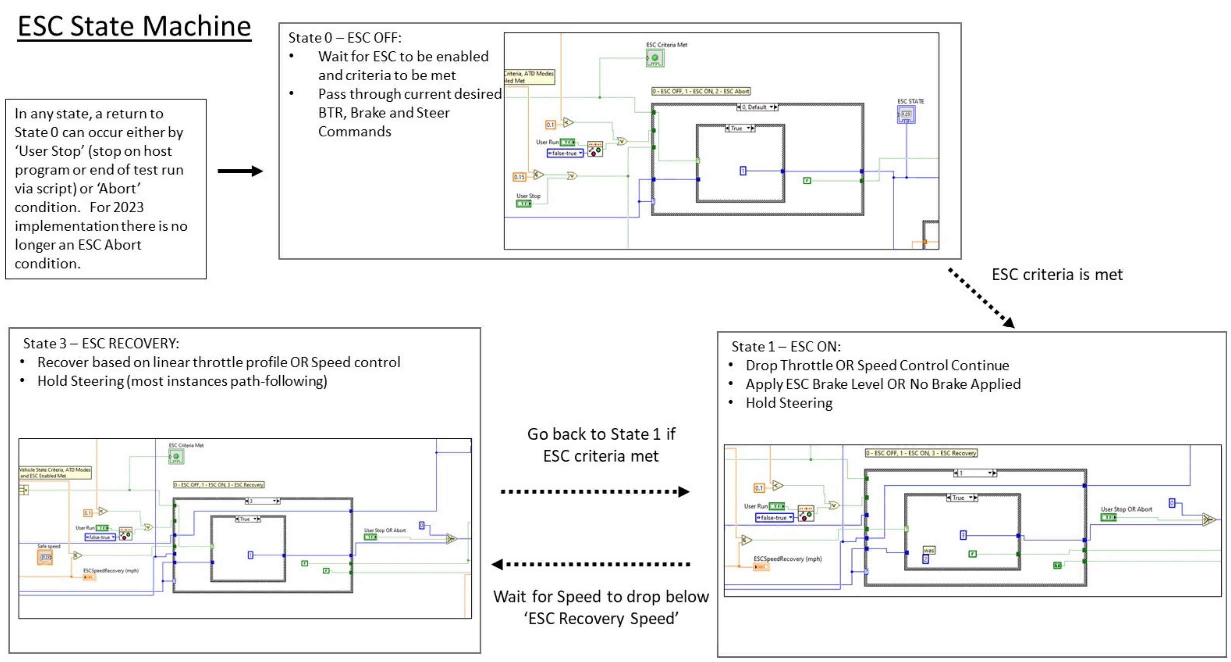

Figure 3: ESC State Machine

2.3 Real-Time Filtering

[This section is taken verbatim from the FY2022 report, and it is reproduced here to provide completeness to this document.]

One of the challenges of this study was to determine a proper real-time filtering technique for filtering vehicle lateral acceleration. Acceleration measurements have inherently high noise levels. Moreover, ATVs have significantly higher vibration levels than typical passenger vehicles, which further confounds this problem. Real-time filters introduce delays that impact the ability of the controller to detect a particular acceleration level. Using MATLAB to analyze previously collected lateral acceleration data, several filtering techniques were explored including moving average filters and single pass low-pass filters. It was determined that an 8th order 6 Hz low-pass

Butterworth filter would work best to filter out noise and minimize delay. Figure 4 shows lateral acceleration data from a J-turn maneuver, with MATLAB's *filter* function (a single pass filter representing a real-time filter) co-plotted with LabVIEW's Butterworth function (the actual real-time filter used in this study) for comparison. The plots from these two filters are on top of each other.

To illustrate the delay associated with single pass filters, data is also shown on Figure 4 from MATLAB's phaseless, two-pass, *filtfilt* routine. The delay in the real-time filters is approximately 150 milliseconds. This delay was accounted for in determining the ESC Threshold A_y levels. All the lateral acceleration plots shown in Appendix D are delayed, they have been filtered using a single pass 8th order 6 Hz low-pass Butterworth filter using MATLAB's *filter* function.

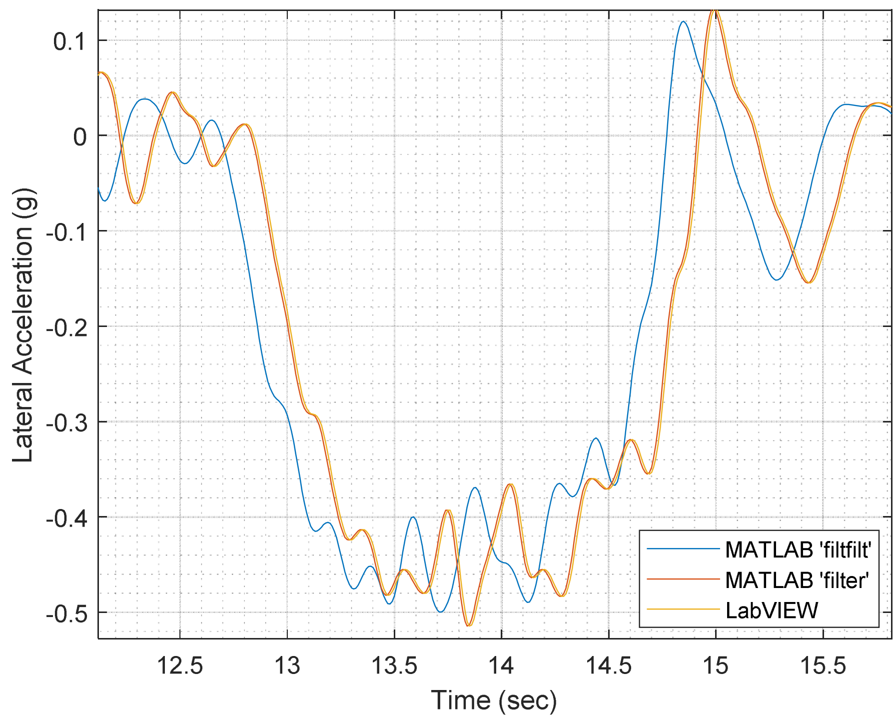

Figure 4: MATLAB and LabVIEW Filter Comparison

2.4 Emulating ABS on Vehicle G

[This section is also taken verbatim from the FY2022 report, and it is reproduced here to provide completeness to this document.]

For Vehicle G, the vehicle without ABS, the hand brake actuator of the RTD was programmed to modulate braking inputs to emulate ABS. Page 8 of Appendix D shows results from a braking and turning maneuver on wet grass that caused ABS activity on the right front wheel of Vehicle N, the vehicle with OEM ABS. The Speed graph on this page shows the timing of the cyclic ABS braking on the right front wheel. There are several cycles of on/off braking per second.

The electric motor used to actuate the hand brake of the ATV RTD is capable of following brake input commands under typical loading conditions at speeds above 40 mm/sec. As configurated on the ATV RTD, the actuator stroke needed for full brake actuation on most ATVs is about 20 mm. Based on this, for Vehicle G the ABS emulation used triangular braking pulses with amplitude up to 10 mm and a frequency of two cycles per second (2 Hz). The graph of Brake Position on Page 9 of Appendix D shows that the actual brake stroke position measured on Vehicle G does a good job of following the desired 10 mm amplitude, triangular brake pulses at 2 Hz. However, there is a delay between the requested (desired) position and actual position of approximately 60 milliseconds. As mentioned, this delay was accounted for when selecting the ESC Threshold A_y level for this vehicle.

The amount of braking applied during enhanced POC ESC intervention for both vehicles was test date adjustable. That is, the level of braking could be adjusted based on the vehicles' responses on the day of testing. Also, for Vehicle G, the ABS emulating cyclic braking was set up to have lower and upper bounds. For example, the ABS-like braking levels could be cycled between 40-80% full stroke, or between 60-100% full stroke, etc. Results in Appendix B from the tests conducted using enhanced POC ESC intervention include plots showing applied braking and wheels speeds. The wheel speed graphs show that there was no wheel lockup for either vehicle during any of the ESC runs (all of which used braking). Some of the wheel speed plots show ABS cycling the wheel speeds (on the runs with conditions where ABS prevented wheel lock up).

3. DYNAMIC TESTING

This section describes the dynamic tests conducted on numerous dates in September and October 2023. Both vehicles were tested at SEA in Columbus, Ohio, on their asphalt and groomed dirt vehicle dynamics test pads. Both vehicles tested have automatic transmissions, independent rear suspensions, and were tested in two-wheel drive mode.

This section describes the vehicle loading condition used during the dynamic field tests, the test instrumentation, and the dynamic test maneuvers that were conducted to evaluate the operation of the enhanced POC ESC. The maneuvers were selected to show that the enhanced POC ESC system could use various intervention methods to improve ATV stability and reduce the likelihood of rollovers. The maneuvers involve using the RTD to drive the test vehicles along specified paths at specified speeds. Doing path-following maneuvers demonstrated how a human driver could maintain their intended path and recover their desired speed after stability control intervention. Graphical results from all the dynamic tests are contained in Appendix A.

3.1 Vehicle Loading Condition

The loading condition used for the dynamic testing was the Autonomous Ballast to Driver Loading condition, representing a 213 lb driver only loading condition. This loading condition is the vehicle curb weight plus the weight (nominally 213 lb) of the test instrumentation and equipment that included: measurement transducers, SEA's ATV RTD, SEA's ATV safety outrigger, wheel speed sensors, and a driver ballast weight frame. Pages 1-2 of Appendix C contain photographs of the fully loaded and instrumented test vehicles.

Page 2 of Appendix C identifies the safety outrigger mounted beneath the vehicle, the wheel speed sensors on the left side of the vehicle, and the driver ballast weight frame. The weight frame, constructed of 80/20 T-slot aluminum bars, is used to rigidly hold enough weight to bring the total test weight up to nominally 213 lb above the curb weight for each vehicle. The only weight added to the ballast frame for this study was a 12V battery (used to provide power to the RTD and test equipment) attached to the top of the frame.

The ATV RTD consists of a computer-controlled 24V electric motor (rotary actuator) 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. For throttle control, the ATV RTD includes a computer-controlled 24V electric motor (rotary actuator), with a pulley and wire attachment to the throttle lever, mounted to the aluminum rod. The RTD version used for this study also included a computer-controlled 24V electric motor (linear actuator) to actuate the right-side hand brake for Vehicle G (which operates the front service brakes on Vehicle G) and the left-side hand brake for Vehicle N (which operates the front and rear service brakes on Vehicle N). The brake lever was removed from its handlebar mount and replaced on the front base plate in line with the linear actuator. This configuration provided precise control of the braking inputs needed for the tests that involved braking. Page 3 of Appendix C contains photographs of the RTD actuators used for this study. The ATV RTD also includes a GPS/IMU (OxTS RT3002), an electronics box (with a National Instruments (NI) cRIO, the on-vehicle computer with the motor controllers and data acquisition software), an auxiliary 24V battery, and antennas for wireless communication. These items are shown in the photograph on Page 4 of Appendix C. Page 5 of Appendix C shows the left front brake caliper removed from the brake rotor on Vehicle N, thus disabling left front braking.

Table 3 lists the nominal weights of the components that comprise the Autonomous Ballast to Driver Loading condition.

Table 3: Autonomous Ballast to Driver Loading	
Component	**Nominal Weight (lb)**
Components Mounted at Front of Each Vehicle Base Plate, Steer Actuator, Throttle Actuator, Brake Actuator, and Associated Mounts and Linkages	46.1
Components Mounted at Rear of Each Vehicle Base Plate, Electronics Box, GPS/IMU (RT3002), 24V Battery, and Antennas	62.3
Standard ATV Outrigger	30.8
Wheel Speed Sensors and Associated Electronics	19.8
Weight Frame and Miscellaneous Ballast	54.0
Total Nominal Driver Only Weight	**213.0**

3.2 Test Instrumentation

The on-vehicle instrumentation used during the dynamic testing is listed in Table 4. The GPS/IMU RT3002 was mounted on the rear base frame of each vehicle. For both vehicles tested, the longitudinal, lateral, and vertical offsets from the center of the RT3002 to the actual vehicle CG location were measured and entered into the RT3002 system software. This information was used to translate the measured quantities to those at the CG of the vehicle. The lateral accelerations measured and reported herein are accelerations parallel to the road plane, as opposed to vehicle body-fixed accelerations.

3.3 Dynamic Test Maneuvers

All dynamic tests were path-following maneuvers that included an initial straight path so the test vehicle could achieve a specified speed (entrance speed) prior to reaching the turning portion of the path. The RTD path-following algorithms provided signals to the steering motor to steer the vehicle during the straight and curved portions of the path. The RTD speed-control algorithms provided signals to the throttle actuator to control the forward velocity of the vehicle before ESC intervention, and in the case of Braking Only ESC also during ESC intervention.

The FY2022 study included left turn dropped-throttle, rapid-steering (40 deg/sec handlebar steering input rates) J-turn maneuvers and left turn constant-speed, slowly increasing steer (5 deg/sec handlebar steering input rates) maneuvers. The speeds used during these tests were high enough to generate lateral acceleration levels higher than Threshold A_y levels, so that ESC intervention would be triggered.

Table 4: Instrumentation Used During Dynamic Testing			
Transducer	**Measurement**	**Range**	**Accuracy**
Oxford Technical Solutions (OxTS) RT3002 Inertial and GPS Navigation System	Longitudinal, Lateral, & Vertical Accelerations	± 100 m/s^2 (± 10 g)	0.01 m/s^2 (0.001 g)
	Roll, Pitch, & 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
Wheel Speed Encoders WPT/E512	Wheel Speeds	2,000 rpm Maximum	± 0.25 deg (Angle Position Specification)

The fixed-path maneuvers used in the current study were intended to be more representative of a real-world event that could potentially lead to ATV loss of stability, than the maneuvers used in the FY2022. The paths were generated by recording the GPS positions of paths driven at low speeds (less than 10 mph) by an SEA test driver.

Three types of paths were generated. **The first path type is called the Single Turn Maneuver**. **The single turn paths on asphalt and on groomed dirt are left-turning arched paths with minimum radii of 60 feet or less**. These paths were designed so that entering their curved portions at initial speeds greater than 10 mph would generate lateral acceleration levels higher than Threshold A_y levels, so that ESC intervention would be triggered. After extending through a nearly semicircular portion, these paths continued along a straight-line section. The straight-line section was included to facilitate demonstrating vehicle speed recovery after ESC intervention. (The paths used for all the runs are shown along with the tests results in the Appendix A.)

The second path type is called the Double Turn Maneuver, and it was used for testing Vehicle G on asphalt. **The double turn path included an initial curved section, followed by a straight-line section, followed by a second curved section, and ending with a straight-line section**. At speeds greater than 10 mph, both curved portions would generate lateral acceleration levels higher than Threshold A_y levels, so that ESC intervention would be triggered. The straight-line section between the curves allowed the vehicle time to recover speed after ESC intervention during the first curve, and again the ending straight-line section was included to facilitate demonstrating vehicle speed recovery after ESC intervention during the second curved section.

The third path type is called the Avoidance Maneuver, and it was used for testing Vehicle N on asphalt. **The avoidance maneuver path included an initial curved section to the right followed by a smaller radius curved section to the left, and it ended with a straight-line section**. The path was intended to represent a path that might be taken by a driver swerving to avoid an obstacle. By using a smaller path radius for the second curved section, it was possible to drive the path at a speed which requires ESC intervention during only the second, left-turning curved section of the path. The straight-line section at the end of the path was again added to facilitate demonstrating vehicle speed recovery after ESC intervention during the second curved section.

The SEA-developed RTD software includes path-following algorithms with a collection of parameters used to model driver look-ahead distance, vehicle steering properties, and other steering-related control gains. These parameters were adjusted as needed to maintain path following quality, and the adjustments depended on the vehicle, test surface, path, and speed used for the individual tests.

4. DISCUSSION OF TEST RESULTS

Graphical results from the dynamic tests are contained in Appendix A (Dynamic Test Results). Appendix B (Laboratory Test Results) contains tables with results from the laboratory tests conducted on Vehicles G and N during previous studies. As mentioned, the results contained in this appendix were originally published in reports from previous studies, and additional comments about these results are in the previous reports. While these laboratory results are not particularly germane to the current study, they do show that the enhanced POC ESC system developed can be used to improve ATV stability and reduce the likelihood of rollovers for mid-sized ATVs like Vehicle G and for large ATVs like Vehicle N.

4.1 Discussion of Dynamic Test Results

All test results for each vehicle are presented together, with results for Vehicle G on Pages 1-28 and Vehicle N on Pages 29-60 of Appendix A. For both vehicles, runs conducted on the asphalt test pad are presented before runs conducted on the groomed dirt test pad. Table 5 contains a list of the seven ESC runs for Vehicle G and the eight ESC runs for Vehicle N. For Vehicle G, there were four runs conducted on asphalt and three runs conducted on groomed dirt. For Vehicle N, there were four runs conducted on both test surfaces. On asphalt, for both vehicles there is a second maneuver type in addition to the Single Turn maneuver. The Double Turn maneuver was used for Vehicle G and the Avoidance Maneuver was used for Vehicle N. These maneuvers were included to demonstrate that the enhanced POC ESC could intervene in maneuvers other than just the Single Turn maneuver. On groomed dirt, for both vehicles the Single Turn maneuver was repeated at a higher entrance speed. These maneuvers were included to demonstrate that the enhanced POC ESC could intervene in more severe maneuvers than the baseline maneuvers conducted at lower entrance speed.

The Appendix A page numbers for each run with ESC are included on Table 5. The table lists the maneuver type and the nominal entrance speed of the vehicle when it reached the start of the curved path. Table 5 also lists which of the three ESC intervention variations were used for each run.

For each maneuver type, there was a run conducted without ESC. The runs without ESC were stopped when the measured lateral acceleration exceeded the ESC Threshold A_y level, when the vehicle was approaching the point of two-wheel lift and likely tip up onto the safety outriggers. All runs conducted without ESC resulted in one-wheel lift (inside, left rear wheel lift) when the maneuver was stopped. For runs with ESC, when the ESC Threshold Ay level was achieved the enhanced POC ESC system intervened by using one of the three intervention variations. All runs conducted with enhanced POC ESC resulted in one-wheel lift (inside, left rear wheel lift) when ESC intervened.

Some general comments regarding the graphs presented in Appendix A 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 plots show lateral acceleration filtered using a single pass 8^{th} order 6 Hz low-pass Butterworth filter using MATLAB's *filter* function. This filter is the same as the real-time filter implanted in the enhanced POC ESC algorithm, so the plots show lateral acceleration with the same amount of filtering and latency as was used in the real-time monitoring of lateral acceleration.

- The steering angles shown on the graphs are roadwheel steer angles, which are the RTD steer actuator input angles (handlebar angles) divided by the measured steering ratio.

Table 5: Runs Conducted using Both Vehicles: Surface Type, Maneuver Type, Entrance Speed, Run Name, ESC Intervention Variation, and Page Numbers for Each Run

Vehicle & Surface	Maneuver and Entrance Speed	Run Name	ESC Intervention Variation	Pages
G on Asphalt	Single Left Turn Maneuver – 16 mph	G1	Brake and Throttle	1-4
		G2	Throttle Only	5-8
		G3	Brake Only	9-12
	Double Left Turn Maneuver – 16 mph	G4	Brake Only	13-16
G on Groomed Dirt	Single Left Turn Maneuver – 15 mph	G5	Brake and Throttle	17-20
		G6	Throttle Only	21-24
	Single Left Turn Maneuver – 17 mph	G7	Brake and Throttle	25-28
N on Asphalt	Single Left Turn Maneuver – 16 mph	N1	Brake and Throttle	29-32
		N2	Throttle Only	33-36
		N3	Brake Only	37-40
	Avoidance (2-turn) Maneuver – 14 mph	N4	Brake and Throttle	41-44
N on Groomed Dirt	Single Left Turn Maneuver – 15 mph	N5	Brake and Throttle	45-48
		N6	Throttle Only	49-52
		N7	Brake Only	53-56
	Single Left Turn Maneuver – 17 mph	N8	Brake and Throttle	57-60

4.1.1 General Description of Results Presented in Appendix A for each Run

For every run, regardless of the maneuver type, test surface type, or ESC intervention variation, there are four pages of graphical results:

1. The first page of each run in Appendix A contains time domain plots of Roadwheel Steer Angle, Speed, Lateral Acceleration, Pitch Angle, Roll Angle, and Yaw Rate, with results from the run with enhanced POC ESC plotted in blue and results from the run without ESC plotted in red. These time domain plots, as well as all time domain plots in Appendix A, go from a little before 5 seconds (when the test vehicle is achieving its specified entrance speed) to the end time of the run, when the test vehicle speed goes to zero.
2. The second page of each run in Appendix A has two columns. The left column contains

graphs from the run without ESC and the right column contains graphs from the run with enhanced POC ESC. Each column contains three graphs: a North versus East Path Plot, and time domain plots of Lateral Acceleration and Longitudinal Acceleration. The Lateral Acceleration graph in the right column, for tests with ESC, contains region(s) that are shaded when the ESC algorithm senses "active", when the criteria of ESC Threshold A_y, Threshold Steering, and Threshold Speed are all exceeded.

3. The third page of each run in Appendix A also has two columns, one with graphs from the run without ESC and one with graphs from the run with enhanced POC ESC. Each column contains three graphs: time domain plots of Throttle Stroke, Brake Stroke, and Speed. The speed graphs contain plots of the left front (LF), right front (RF), left rear (LR), and right rear (RR) wheel speeds (with translational speed units of mph).
4. The fourth page of each run in Appendix A also has two columns with graphs from the ESC run only. The graph in the left column is an enlarged version of the North versus East Path Plot. This graph shows the position of the vehicle at 0.25 second intervals, starting at time equals five seconds through the time when the vehicle comes to rest at the end of the maneuver. The numbers on this path plot graph are times (in seconds) from the start of the run. The red band on the path indicates the time and position when ESC intervention is on. Plots of vehicle speed and lateral acceleration are shown in the right column. The shaded region in the Lateral Acceleration plot indicating ESC ON corresponds to the time of the red band show on the Path Plot.

4.1.2 Detailed Description of Results for Runs without ESC and for Runs with each ESC Intervention Variation

The following paragraphs describe results in Appendix A for runs conducting without ESC (No ESC) and runs with the three ESC intervention variations (Brake and Throttle, Throttle Only, and Brake Only):

1. Runs without ESC

   As mentioned, for each maneuver type there was a run conducted without ESC. These runs were conducted to demonstrate that the severity of the maneuvers conducted would likely result in tip-up of the test vehicles. The runs without ESC were stopped when the measured lateral acceleration reached the Abort A_y level, the point when the vehicle was approaching two-wheel lift and likely tip up onto the safety outriggers. For both vehicles, the Abort A_y level was set slightly above the ESC Threshold A_y level. As was done in the FY2022 study, when the Abort A_y level was reached, these runs were stopped by simultaneously dropping the throttle and applying end-of-run braking to bring the vehicle to a stop. For example, the left column of Page 3 of Appendix A shows the Throttle Stroke and Brake Stroke applied during a Vehicle G run without ESC. The first page graphs for each run in Appendix A show that vehicle speed drops earlier in the maneuver for the run with ESC than the run without ESC. This occurs because ESC intervention starts when the vehicle lateral acceleration reaches the ESC Threshold Ay level, compared to a non-ESC run in which the Threshold Ay level is exceeded before the throttle and brake are applied to end the run.

   During all runs without ESC, the RTD maintained path-following steering control, and the roadwheel steer angles needed to maintain path control are shown in top left plot on the first page for each run.

2. ESC Intervention using Brake and Throttle

   Results from Run G1 of Vehicle G with Brake and Throttle ESC invention are contained on Pages 1-4 of Appendix A. For Vehicle G, the ESC Threshold Ay level is 0.384 g. The lateral acceleration plots on Pages 2 and 4 of Appendix A show that ESC intervenes when the lateral acceleration reaches this level, and that ESC intervention ends when the lateral acceleration falls below this level. The throttle stroke drops to zero and the brake stroke applies braking (cycling braking for Vehicle G to emulate ABS) when the ESC is on. After the ESC-on condition ends, the throttle is commanded to go to specified stroke and then increase gradually so the vehicle speed can increase towards its initial entrance speed. The speed plot on Page 1 shows that the vehicle sped up to about 14 mph before it reached the position on the path where the RTD was instructed to stop the run by applying end-of-run level braking to stop the vehicle.

   During all runs with ESC, the RTD maintained path-following steering control, and the roadwheel steer angles needed to maintain path control are shown in top left plot on the first page for each run.

3. ESC Intervention using Throttle Only

   Results from Run G2 of Vehicle G with Throttle Only ESC invention are contained on Pages 5-8 of Appendix A. For this ESC variation, the throttle stroke drops to zero when the ESC is on. After the ESC-on condition ends, the throttle is commanded to go to a specified stroke and then increase gradually so the vehicle speed can increase towards its initial entrance speed. The speed plot on Page 5 shows that the vehicle sped up to close to 15 mph before it reached the position on the path where the RTD was instructed to stop the run by applying end-of-run level braking to stop the vehicle.

4. ESC Intervention using Brake Only

   Results from Run G3 of Vehicle G with Brake Only ESC invention are contained on Pages 9-12 of Appendix A. For this ESC variation, the brake stroke applies braking (cycling braking for Vehicle G to emulate ABS) when the ESC is on. After the ESC-on condition ends, the Brake Stroke returns to zero. During this ESC intervention variation, the throttle is not dropped, and the RTD maintains speed control throughout the entire run. The throttle stroke plot on Page 11 shows that the throttle increased when the vehicle entered the curved portion of the maneuver to compensate for speed scrubbing off during the turn (this happens in all the ESC intervention runs prior to ESC intervention). For the Brake Only runs, the RTD maximum throttle level was set to prevent the vehicle from speeding up too much during and after ESC intervention. The throttle stroke maximum for the ESC run shown on Page 11 was set to 12.5 mm. The throttle stroke allowed the vehicle speed to increase gradually towards its initial entrance speed. The speed plot on Page 9 shows that the vehicle sped up to its entrance speed of 16 mph prior to reaching the position on the path where the RTD was instructed to apply braking to stop the vehicle.

Results from all ESC runs show that all three variations of ESC intervention can intervene to mitigate the potential for vehicle tip-up. The results also show that speed recovery throttle inputs and path-following steering inputs were maintained after ESC intervention to demonstrate how a human driver could maintain their intended path and recover their desired speed after stability control intervention.

The runs using Throttle Only and Brake Only had less aggressive ESC intervention than the Brake and Throttle runs. Comparing graphs for maneuvers that used all three intervention variations show that the magnitudes of longitudinal decelerations and pitch angles at the onset of ESC intervention for the Throttle Only and Brake Only runs were less than the Brake and Throttle runs.

For all three intervention types, the steering inputs generated by the RTD path-following algorithms are relatively smooth, even during periods of ESC intervention, suggesting a human driver could maintain steering control of an ATV equipped with the enhanced POC ESC system.

4.1.3 Detailed Description of Results for Various Maneuver Types

The previous section provided descriptions of results (without ESC and with all three ESC intervention variations) from Single Turn maneuvers. The descriptions regarding ESC intervention during the various ESC variations are the same for all maneuvers. The following paragraphs describe the results from the other maneuvers.

Results from the Double Turn maneuver used for Vehicle G (Run G4) are shown on Pages 13-16 of Appendix A. The path for this maneuver (path plots shown on Pages 14 and 16) included two left turning sections, with each turn designed to activate ESC intervention using the specified initial curve entrance speed. For this maneuver on asphalt, Brake Only ESC intervention was used. The lateral acceleration plots on Pages 14 and 16, and the path plot on Page 16, show that ESC intervened during both curved sections of the path. After ESC intervention during the first curve, the vehicle speed increased to the initial entrance speed of 16 mph before the vehicle reached the second curve. After ESC intervention during the second curve, the vehicle speed recovered, and the vehicle followed the straight section at the end of the path until it reached the end position when the RTD stopped the vehicle. This run demonstrated that the enhanced POC ESC could intervene in maneuvers other than just the Single Turn maneuver.

Results from the Avoidance Maneuver used for Vehicle N (Run N4) are shown on Pages 41-44 of Appendix A. For this maneuver on asphalt, Brake and Throttle ESC intervention was used. The path for this maneuver (path plots shown on Pages 42 and 44) included an initial curved section to the right followed by a smaller radius curved section to the left, and it ended with a straight-line section. The lateral acceleration plots on Pages 42 and 44 show that ESC intervened only during the second (left) curved section of the path. The lateral acceleration during the first curved section did not reach the ESC Threshold Ay level of 0.466 for Vehicle N. After ESC intervention during the second curve, the vehicle speed began to recover as the vehicle followed the straight section at the end of the path until it reached the end position when the RTD stopped the vehicle. This run also demonstrated that the enhanced POC ESC could intervene in maneuvers other than just the Single Turn maneuver.

Results from Single Turn maneuver runs using a higher entrance speed (17 mph) than the baseline runs (15 mph) were also conducted. These runs used Brake and Throttle ESC intervention and they were conducted on the groomed dirt surface using both Vehicle G (Pages 25-28) and Vehicle N (Pages 57-60). For both vehicles, ESC intervened earlier in the curve when the higher entrance speed was used because the ESC Threshold Ay levels were reached earlier in the curve. These two runs demonstrated that the enhanced POC ESC could intervene during maneuvers using multiple entrance speeds.

Results from these runs using different maneuver conditions again showed that the enhanced POC ESC can intervene to mitigate the potential for vehicle tip-up. The results also show that speed recovery throttle inputs and path-following steering inputs were maintained after ESC intervention to demonstrate how a human driver could maintain their intended path and recover their desired speed after stability control intervention.

5. POTENTIAL TEST MANEUVER TO EVALUATE ATV ELECTRONIC STABILITY CONTROL

The last task of Objective 1 is to provide a set of recommended ESC performance metrics and test requirements to mitigate rollovers based on dynamic testing of ESC-equipped ATVs. For passenger vehicles Federal Motor Vehicle Safety Standard (FMVSS) 126[9] incorporates a dynamic compliance test called the sine-with-dwell maneuver to evaluate ESC effectiveness. This maneuver is designed to induce yaw instability to the test vehicle. The yaw instability that can occur during sine-with-dwell maneuvers on vehicles without ESC is a spin out, often referred to as limit oversteer. There are two performance requirements of FMVSS 126. The first requirement is the Vehicle Lateral Stability requirement, which requires that the yaw rate of the test vehicle diminish after the sine-with-dwell steering input ends. This requirement indicates that the vehicle did not spin out during the maneuver. The second requirement is the Vehicle Responsiveness requirement, which requires that the lateral displacement of the test vehicle exceeds a specified value after the start of the sine-with-dwell steering input. This requirement indicates that the ESC system on the test vehicle is not so aggressive that it overly reduces responsiveness to driver steering inputs.

During all severe dynamic tests conducted during numerous studies for CPSC to evaluate the limit performance of ATVs, the ATVs experienced limit rollover instability and not limit yaw instability conditions. That is, the tests resulted in tip-ups and not spin-outs (limit oversteer) or plow outs (limit understeer). The lateral rollover resistances (Ay thresholds) of ATVs are lower than for passenger vehicles. Because of this, ATVs experience tip-up outcomes during severe tests on asphalt and groomed dirt before the lateral tire forces exceed the tire-to-surface friction capacity which would lead to yaw instabilities. **Therefore, the sine-with-dwell maneuver is not a good candidate for an ATV stability maneuver, as roll instabilities precede (and generally preclude) yaw instabilities**[10]. Moreover, the sine-with-dwell maneuver test procedure is quite complicated because it requires a slowly increasing steering maneuver as a pre-test and significant pre and post test data processing to evaluate whether the vehicle passes the FMVSS 126 test requirements.

To evaluate ATV ESC (or probably better referred to as Instability Mitigation System (IMS)), a potential test maneuver is to use a constant radius, quadrant path like the one shown in Figure 5. For this maneuver, the ATV must enter the curved path at an entrance speed high enough to induce two-wheel lift. The instability mitigation system (IMS or ESC) would intervene to prevent two-wheel lift and allow the vehicle to navigate the entire path.

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[9] *Laboratory Test Procedure for FMVSS 126, Electronic Stability Control Systems*, TP-126-03, September 9, 2011, https://www.nhtsa.gov/sites/nhtsa.gov/files/documents/tp-126-03_tag.pdf

[10] Comments herein regarding ATV stability limit conditions are based on tests conducted on asphalt and groomed dirt surfaces. These surfaces have greater tire-to-surface friction capacity than low friction surfaces like snow and ice. On low friction surfaces, ATVs are likely more prone to experiencing yaw instabilities.

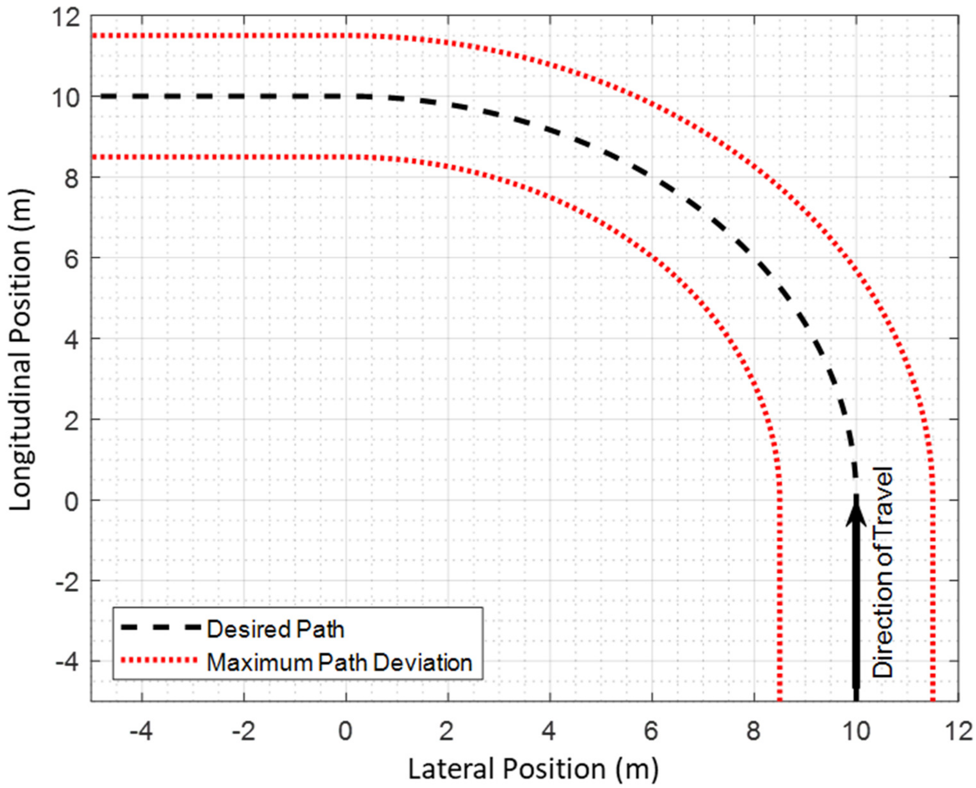

Figure 5: Potential Maneuver Path used to Evaluate ATV ESC

Table 6 lists Tilt Table Ratio (TTR), Static Stability Factor (SSF), and threshold lateral acceleration (Threshold A_y) levels of 14 vehicles that have been measured by SEA for CPSC[11,12]. The Threshold Ay levels were determined from dropped-throttle J-turn maneuvers where two-wheel lift occurred. The Threshold A_y results presented in Table 6 are for tests conducted using the Automated Test Driver with driver ballast loading to represent an upright operator position. ATVs are rider active vehicles, and operators can lean into turns to increase Threshold A_y levels. A previous study conducted using 12 of the 14 vehicles listed in Table 6 showed that the Threshold A_y levels increase by an average of about 0.05 g when the operator is leaning moderately into the turn.[13] Nevertheless, the Table 6 Threshold A_y values determined from tests representing an upright operator position were used to establish the severity of the potential test maneuver.

Of these vehicles, the maximum Threshold A_y was found to be 0.600 g (Vehicle H). This lateral acceleration level was used to determine the entrance speed for the potential test maneuver. A vehicle travelling at 7.8 m/sec (17.5 mph) on a path with a 10 m (32.8 ft) radius would generate

[11] *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, November 2016. https://www.cpsc.gov/s3fs-public/SEA_Report_to_CPSC_Vehicle_Characteristics_Measurements_of_All_Terrain_Vehicles.pdf

[12] *Evaluation of Anti-lock Brake System (ABS) Technology on ATV Stability – Results from Tests on Two 2021 Model Year Vehicles*, CPSC Contract 61320618D0003, SEA, Ltd. Report to CPSC, November 2022. https://www.cpsc.gov/s3fs-public/SEAReporttoCPSCEvaluationofAntilockBrakeSystemABSonATVStability.pdf?VersionId=7RfLb2qv7hFv20zqVKcAPXiLFcVMXirz

[13] *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://cpsc-d8-media-prod.s3.amazonaws.com/s3fs-public/SEA-Report-to-CPSC-Rider-Active-ATV-Study-December-2017_0.pdf**

0.620 g of lateral acceleration. Under constant throttle input, vehicle speed scrubs off when a vehicle is turning. However, based on ATV tests conducted previously for CPSC, using an entrance speed of 7.8 m/s will generate enough lateral acceleration in the curve to exceed all the Threshold Ay levels of the vehicles previously tested. This means that all ATVs previously tested would require rollover instability mitigation to pass the potential test requirements.

The 14 vehicles contained in Table 6 are models of popular ATVs that have Threshold A_y values ranging from 0.427 to 0.600 g's, and these provide a good cross-section of the ATV industry. This body of Threshold A_y data support the recommended procedure, where a driving path that will induce 0.620 g of lateral acceleration is an appropriate test procedure.

A variation of this maneuver would be to make the entry speed be vehicle dependent, where the threshold lateral acceleration established during a pre-test J-turn maneuver would be used. In the absence of this, data collected in the laboratory could be leveraged to extrapolate the threshold lateral acceleration limit. That is, as was demonstrated in previous studies, a strong relationship was established between SSF and Threshold A_y and between TTR and Threshold A_y.[14] For instance, Vehicle A, which had a Threshold A_y of 0.385 g, the entry speed could be 6.1 m/sec (13.7 mph). Setting up the test procedures for vehicle-specific entrances speeds would become onerous (like pre-test requirements imposed in FMVSS 126). **Requiring all vehicles in this class to navigate a simple 10 m (32.8 ft) circular path using a fixed entrance speed of 7.8 m/s (17.5 mph) is less burdensome than using vehicle-specific entrance speeds, and it technically evaluates all ATVs in the same way regardless of their Threshold Ay level.**

Using a fixed path and fixed entrance speeds means that vehicles with low Threshold A_y levels will have their ESC intervene earlier in the curve than vehicles with high Threshold A_y levels. Nonetheless, with appropriate ESC intervention all ATVs should be able to navigate the entire path without experiencing two-wheel lift. This was demonstrated in this study using the enhanced POC ESC. The same path and same entrance speed (16 mph) were used for Vehicle G (Threshold Ay of 0.452) and Vehicle N (Threshold Ay of 0.548) on asphalt. The path plots on Page 4 of Appendix A for Vehicle G (Run G1) and Page 32 of Appendix A for Vehicle N (Run N1) show that the enhanced ESC (using the Brake and Throttle variation of ESC in this example) activated earlier in the curve for Vehicle G than for Vehicle N. Both vehicles recovered speed and navigated through the entire path.

Like FMVSS 126, the maneuver must be performed in both turning directions. The left turning direction path is Figure 5, and the right turn direction path would be the same quadrant path to the right. Also, like FMVSS 126, the test would have two performance requirements. For ATVs, the requirements would be a Vehicle Roll Stability requirement and a Vehicle Responsiveness requirement:

1. **Vehicle Roll Stability Requirement**: The test vehicle must navigate through the entire maneuver path without the vehicle exhibiting two-wheel lift. One-wheel lift is acceptable because the severity of a maneuver that has only one-wheel lift outcome will not lead to a tip up or rollover (assuming no increase in severity during the maneuver). Also, many of these vehicle's lateral acceleration threshold for two-wheel lift can be significantly higher

[14] *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, November 2016. https://www.cpsc.gov/s3fs-public/SEA_Report_to_CPSC_Vehicle_Characteristics_Measurements_of_All_Terrain_Vehicles.pdf

than their lateral acceleration threshold at the onset of one-wheel lift. The test driver or robotic test driver shall not drop the mechanical throttle position that was required to achieve the vehicle entrance speed prior to the onset of ESC activation. Also, the test driver or robotic test driver shall not apply any mechanical braking through the entire maneuver path.

2. **Vehicle Responsiveness Requirement**: The vehicle must navigate along the entire desired path with a maximum path deviation of ±1.5 m (±4.92 ft). This requires that the stability intervention system must not be too aggressive to induce significant understeer or oversteer behavior, causing the ATV to veer far off the desired path.

Additional requirements to perform the test procedure include:

- A data acquisition system with a GPS/IMU to record vehicle states including linear accelerations, angular rates, angular orientations, vehicle speed, latitude, and longitude.
- Tests shall be conducted using vehicle safety outriggers to prevent potential vehicle rollovers.

There are numerous additional aspects that need to be developed and specified to have this potential test be a complete test procedure. Some of these include:

- Tests could be conducted with a human operator or using a driving robot with path-following capabilities. Considerations are needed for specifying whether either of these are required or allowing both as an option.
- Considerations for operator lean allowances need to be specified, regardless of whether the tests are conducted with a human operator or using a driving robot with path-following capabilities.
- The length of the straight lead into the curved path needs to be established, and it needs to be long enough for the ATVs tested to achieve a steady entrance speed.
- The length of the straight lead exit at the end of the curved path needs to be established, and it needs to be long enough to verify that the ATV maintained path control capability after ESC intervention.
- Specifications/allowances regarding the weight of test driver or driving robot system, test instrumentation, and safety outriggers need to be established.
- Specifications regarding the tire pressures and tire conditions, as well as other vehicle conditions need to be established.
- Specification regarding allowances for test surface type, test surface grade, environmental conditions, and vehicle conditions (e.g., fuel level, operating temperature, driveline settings, equipment accessories, etc.) need to be established.
- Specifications regarding data collection and data post processing need to be established.
- Specifications regarding stability control system features such as telltale lights for system status need to be established.

The potential test and its requirements make no mention of how an ESC system must be deployed on an ATV. That is, the ESC system is regarded as a black box, and only its function and effectiveness would be evaluated via the potential test. Producers of production ESC systems (presumably ATV OEMs and/or Tier 1 suppliers) could deploy any type of electronics and algorithms needed to sense pending rollover conditions.

A production stability control system could use Threshold A_y, a surrogate of Threshold A_y, or other conditions based on measured, modeled, or predicted variables to determine when to engage and disengage ESC activity. Also, production systems would likely be designed to only activate ESC if the vehicle is traveling above a specified speed, possibly only if the steering input is above some specified level, and possibly only under other operating conditions.

Unlike the methods used in this study to mechanically actuate the driver steering and brake controls, a production stability control system would likely require an ATV to have electronic throttle control and electronic braking control. With electronic throttle control and brake control, a stability control system can interject intervention speed and braking control signals without interrupting the driver's throttle position or brake position (if any) while driving during stability control intervention.

Production ESC intervention methods to mitigate pending tip-up, such as reducing vehicle speed and applying selected brakes, would be black box and presumably vehicle specific. The levels, timing, and duration of dropped throttle and braking would need to be determined by the developers of the production ESC system.

Lastly, any production stability control system will need to operate when the vehicle is in cross-slope conditions. When operating on cross slopes, the sensed lateral acceleration will be affected by the severity the cross slope. Methods for compensating ESC intervention to account for operating on nonlevel, cross-sloping surfaces need to be considered and addressed.

Table 6: Summary of Tilt Table Ratio, Static Stability Factor and Lateral Acceleration Threshold			
	Tilt Table Ratio (TTR)	**Static Stability Factor (SSF)**	**Threshold A_y* (g)**
Vehicle A	0.480	0.728	0.427
Vehicle B	0.624	0.826	0.566
Vehicle C	0.598	0.853	0.512
Vehicle D	0.650	0.837	0.554
Vehicle E	0.648	0.857	0.566
Vehicle F	0.484	0.708	0.445
Vehicle G	0.545	0.777	0.452
Vehicle H	0.666	0.870	0.600
Vehicle I	0.585	0.794	0.539
Vehicle J	0.591	0.810	0.505
Vehicle K	0.662	0.873	0.547
Vehicle L	0.657	0.858	0.560
Vehicle M	0.704	0.851	0.559
Vehicle N	0.687	0.867	0.548

*Dynamic tests were conducted in the Autonomous Robotic Test Driver Loading Condition. Threshold Ay values are the average of values from tests on asphalt and groomed dirt.

5. SUMMARY

The objectives of this study were fulfilled. Part of the first objective was to develop and deploy an enhanced proof-of-concept (POC) Electronic Stability Control (ESC) system and test its effectiveness on two different ATVs. Results from tests with the enhanced POC ESC system showed that it could mitigate ATV roll instabilities, and that it could reduce the likelihood of rollover events. Another part of the first objective was to develop recommended ESC performance metrics and test requirements to mitigate rollovers based on the dynamic testing of the ESC-equipped ATVs. This report covers the work done to complete this objective.

The second objective was to conduct a literature search of available automotive safety technologies that can be applicable to ATVs such as object detection systems to reduce likelihood of collisions. A standalone report titled *Review of Automotive Safety Technologies Applicable to All-Terrain Vehicles (ATVs)* [15] covers the second objective.

The enhanced POC ESC developed included two main features beyond those of the rudimentary POC ESC system designed in the previous FY2022 study[16]. First, in addition to using braking and dropped throttle for ESC intervention, ESC intervention variations using braking input only and dropped throttle only were developed and demonstrated. Second, features for having the ATV continue its path after ESC intervention were also developed and demonstrated. This second feature included using path following capabilities incorporated into SEA's ATV Robotic Test Driver (RTD) throughout each maneuver, and it included using RTD throttle inputs to have the ATV recover its desired test speed after ESC intervention slowed the vehicle. This second feature was included in the enhanced ESC system as a proof-of-concept for how a human driver could maintain their intended path and recover their desired speed after stability control intervention.

Tests of both vehicles on asphalt and groomed dirt surfaces using a Single Turn maneuver demonstrated that all three variations of ESC intervention were effective in preventing ATV two-wheel lifts and tip-ups onto the safety outriggers. Further, the enhanced ESC system demonstrated that vehicle speed could be recovered after ESC intervention and that the test vehicles could navigate through the entire maneuver path without exhibiting two-wheel lift.

The effectiveness of the enhanced POC ESC system was also evaluated using additional maneuver types and maneuver severities. A Double Turn maneuver on asphalt was used for Vehicle G and an Avoidance Maneuver on asphalt was used for Vehicle N. Higher speed, more severe Single Turn maneuvers on groomed dirt were used for both Vehicle G and Vehicle N. In all four of these maneuvers, the enhanced ESC system was shown to be effective in preventing two-wheel lift as the vehicles navigated the entire maneuver paths.

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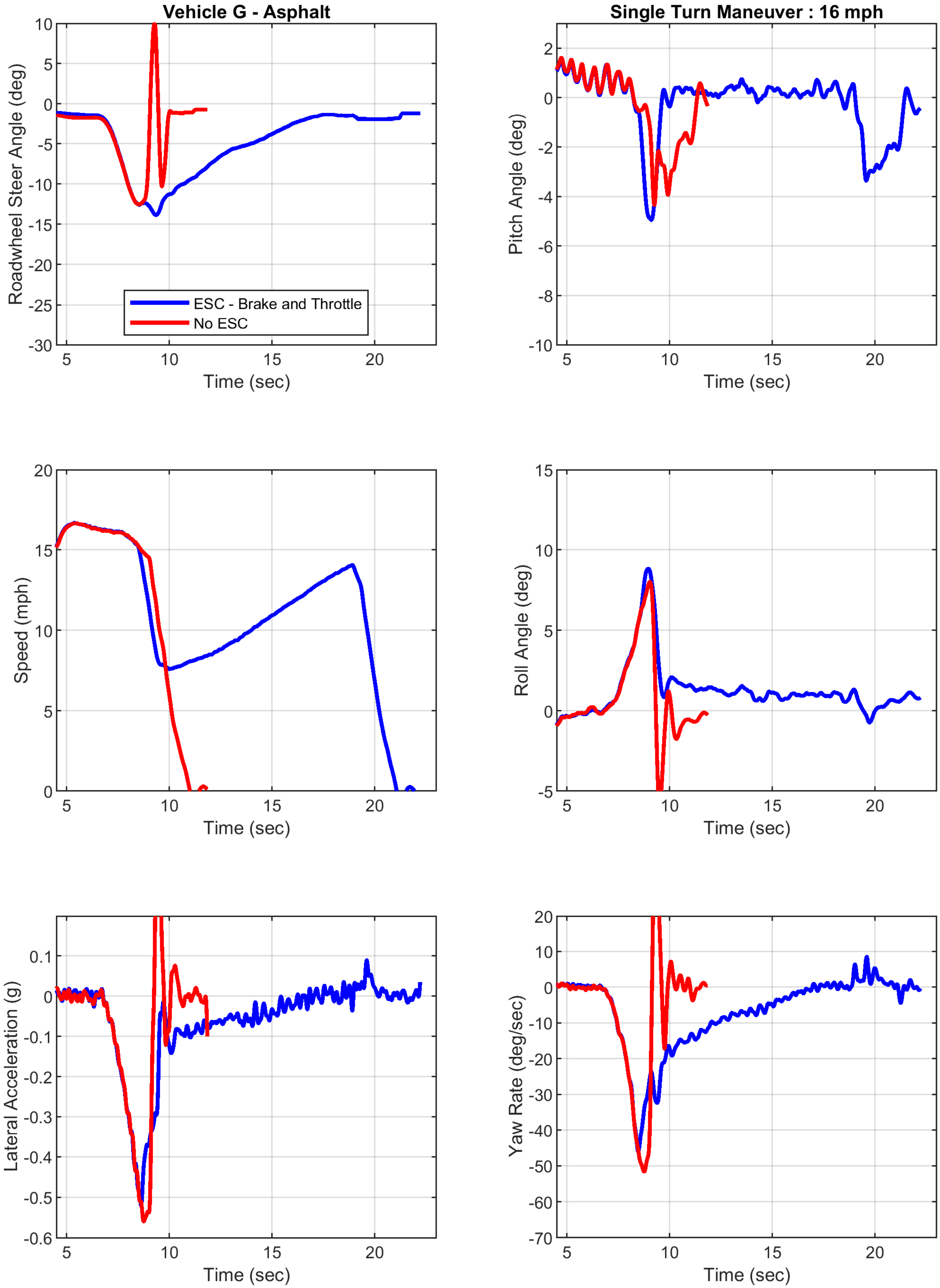
[15] *Review of Automotive Safety Technologies Applicable to All-Terrain Vehicles (ATVs)*, CPSC Contract 61320618D0003, SEA, Ltd. Report to CPSC, January 2024. **https://www.cpsc.gov/content/Review-of-Automotive-Safety-Technologies-Applicable-to-All-Terrain-Vehicles-ATVs**

[16] *Development of Proof-of-Concept (POC) Electronic Stability Control (ESC) System for ATV Stability,* CPSC Contract 61320618D0003, SEA, Ltd. Report to CPSC, October 2022. **https://www.cpsc.gov/s3fs-public/SEAReportDevelopmentofProofofConceptPOCElectronicStabilityControlSystemforATVs.pdf?VersionId=bHw7fPfLsjO0HugwRDzpyDCsABLa6ZZe**

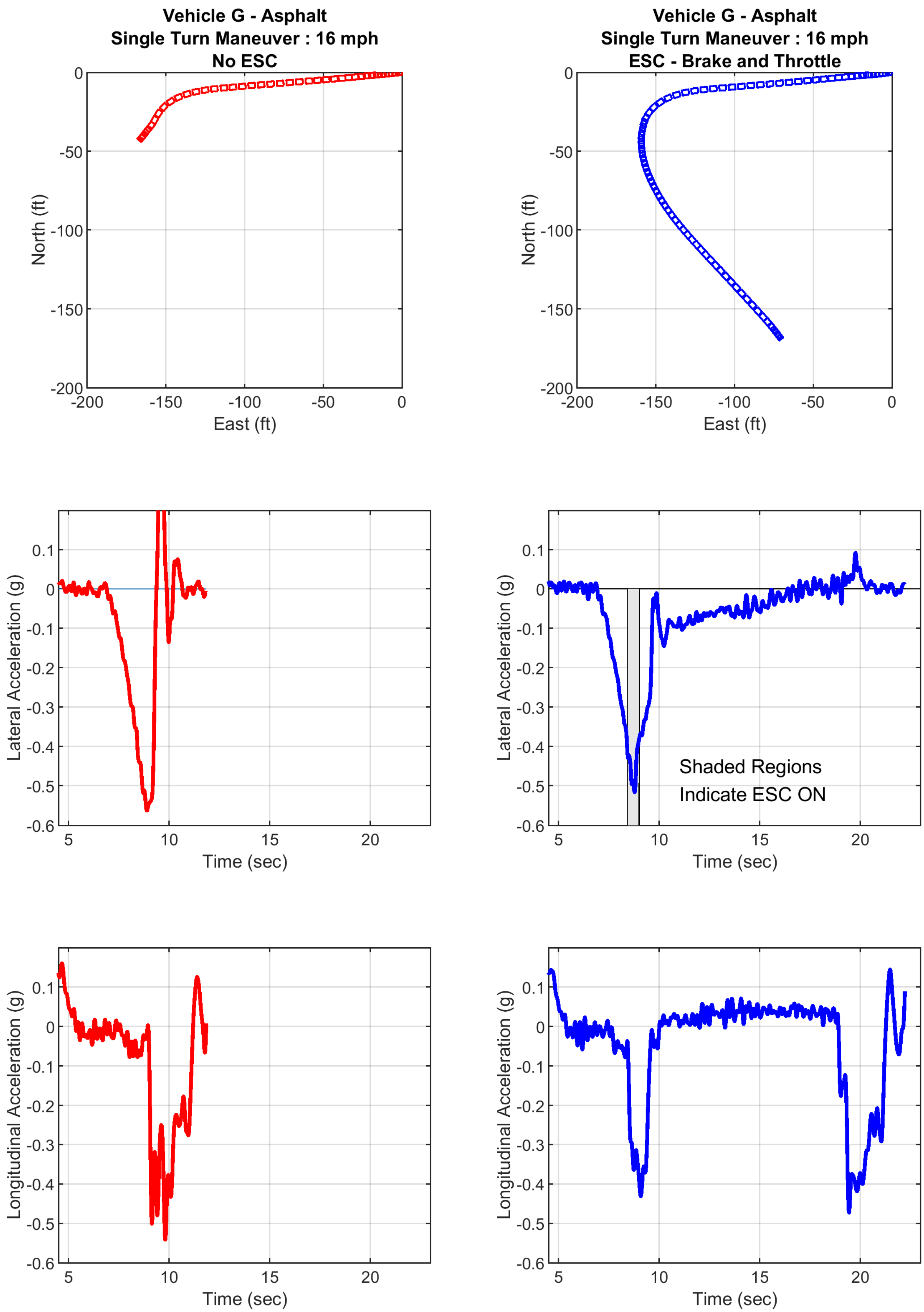
Since there was no human driver in-the-loop to maintain directional control of the vehicles before, during and after ESC intervention, steering inputs were generated by the RTD path-following algorithms. These steering inputs were successful in maintaining control of the ATVs, and preventing desired path deviations of more than 1.5 m. The steering inputs generated by the RTD path-following algorithms were relatively smooth, even during periods of ESC intervention, suggesting a human driver could maintain steering control of an ATV equipped with the enhanced POC ESC system. However, further studies could be conducted to confirm that the steering torques required to maintain a smooth path using the RTD (which has a high steering torque capacity) are not so large to affect a human operator's ability to maintain a smooth path.

A potential test maneuver with proposed test requirements was developed based off the work conducted in this study. The maneuver involves driving a test ATV through a portion of the circular path using an entrance speed designed to cause tip-up of current model ATVs without ESC. A roll stability ESC system, like the enhanced POC ESC system developed for this study, could intervene during the potential test maneuver, and allow the ATV to navigate the test maneuver path without experiencing two-wheel lift. Also, comments regarding additional aspects of a formal test to evaluate effectiveness of ATV ESC are provided in this report.

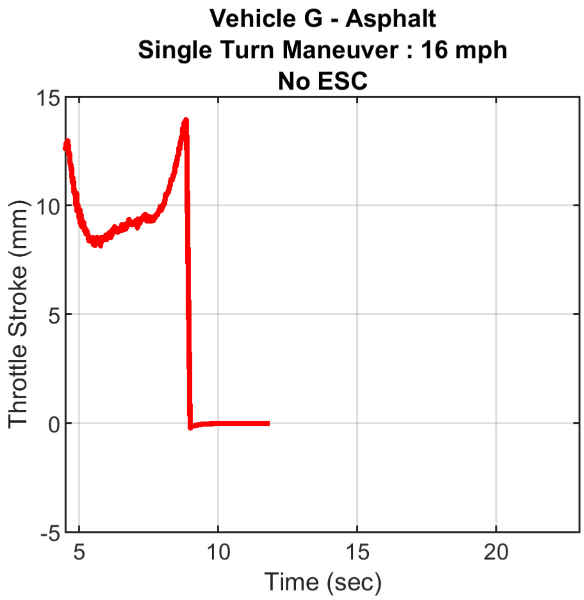
Run G1 – Vehicle G, Asphalt, Single Turn Maneuver, 16 mph – ESC: Brake and Throttle

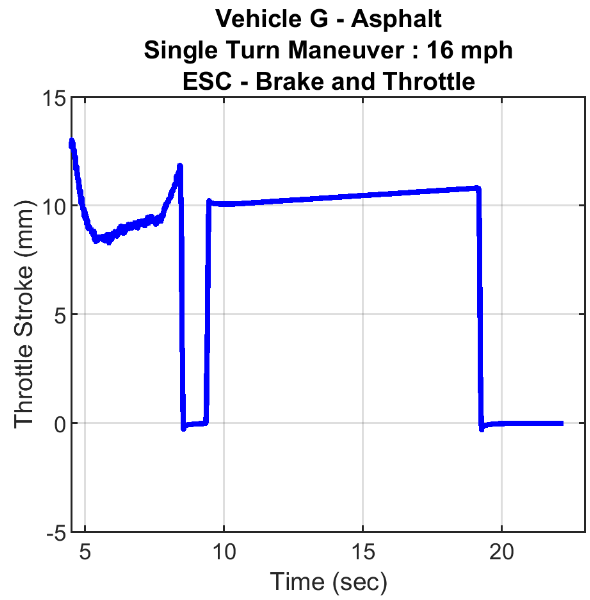


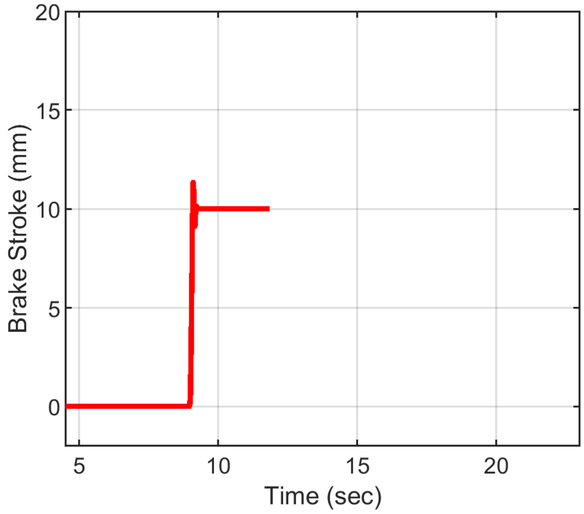
Run G1 – Vehicle G, Asphalt, Single Turn Maneuver, 16 mph – ESC: Brake and Throttle

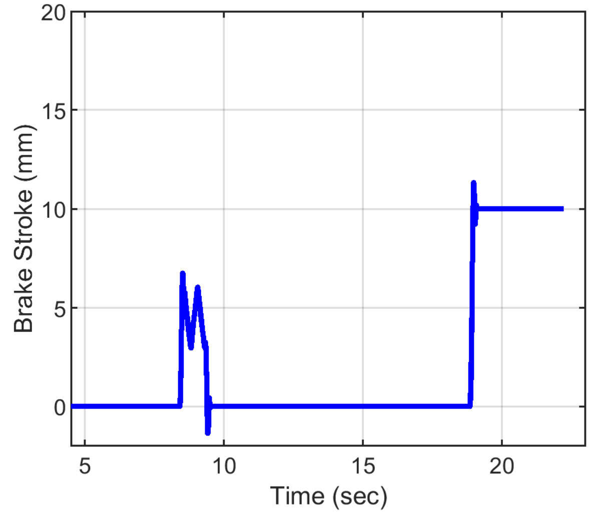


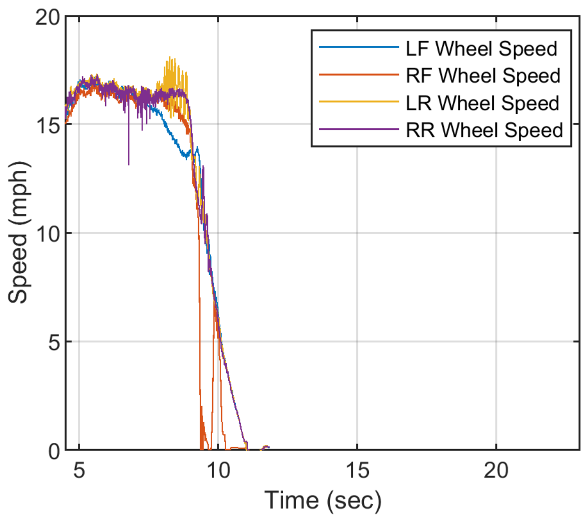
Run G1 – Vehicle G, Asphalt, Single Turn Maneuver, 16 mph – ESC: Brake and Throttle

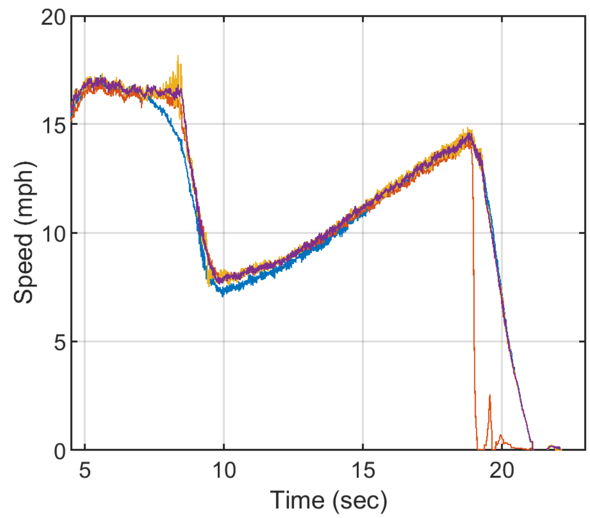




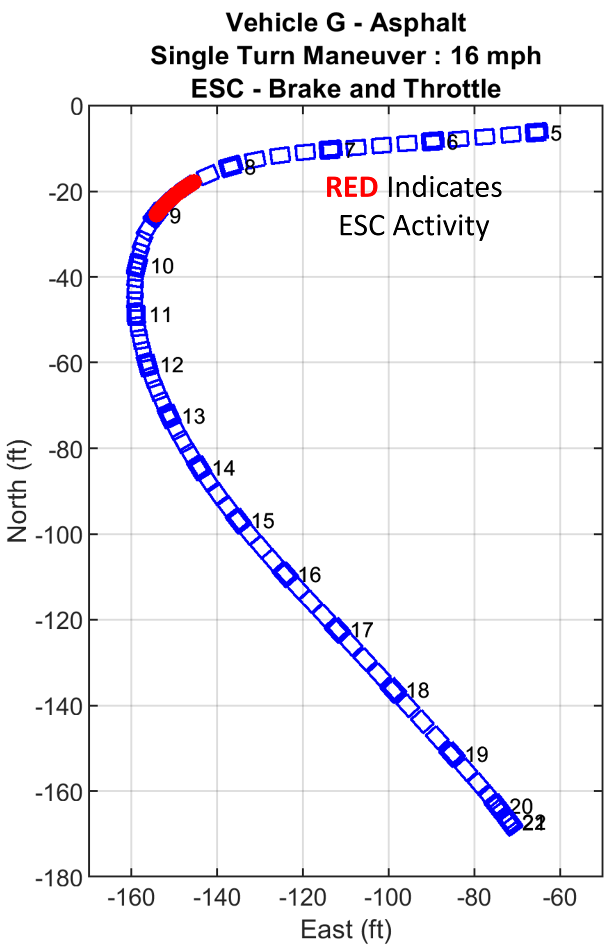


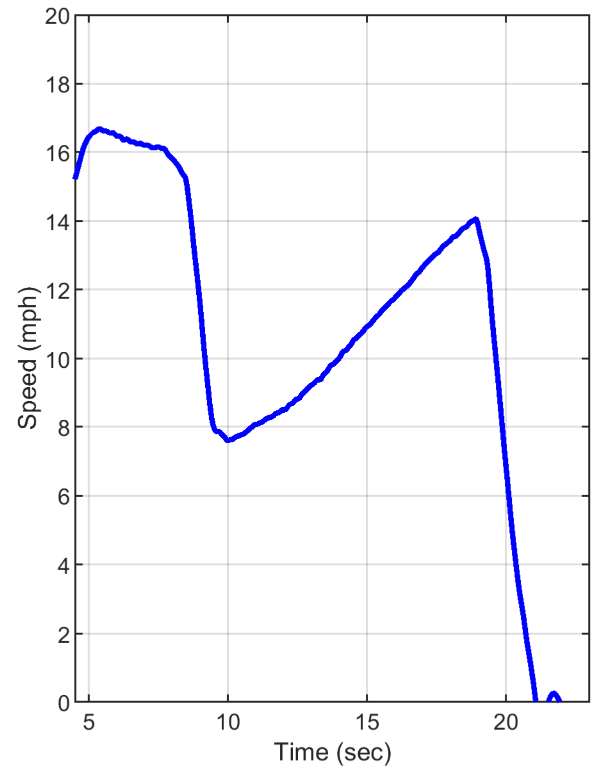


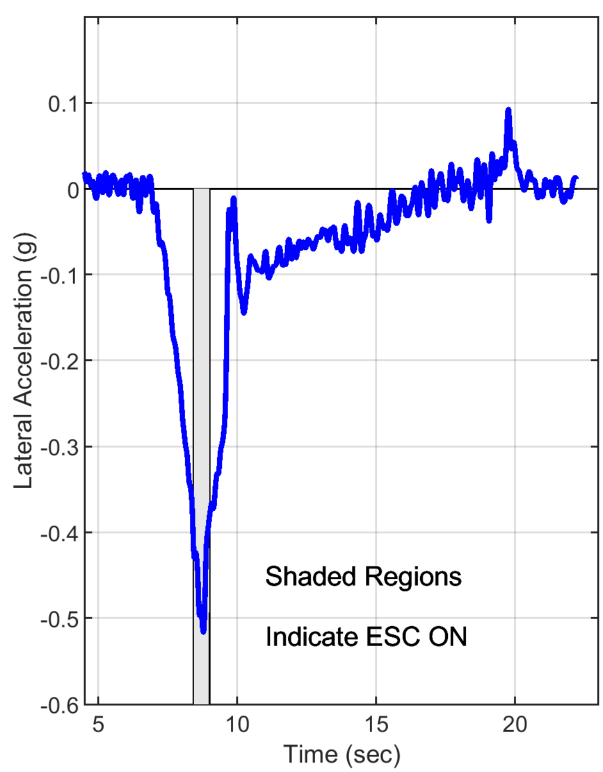




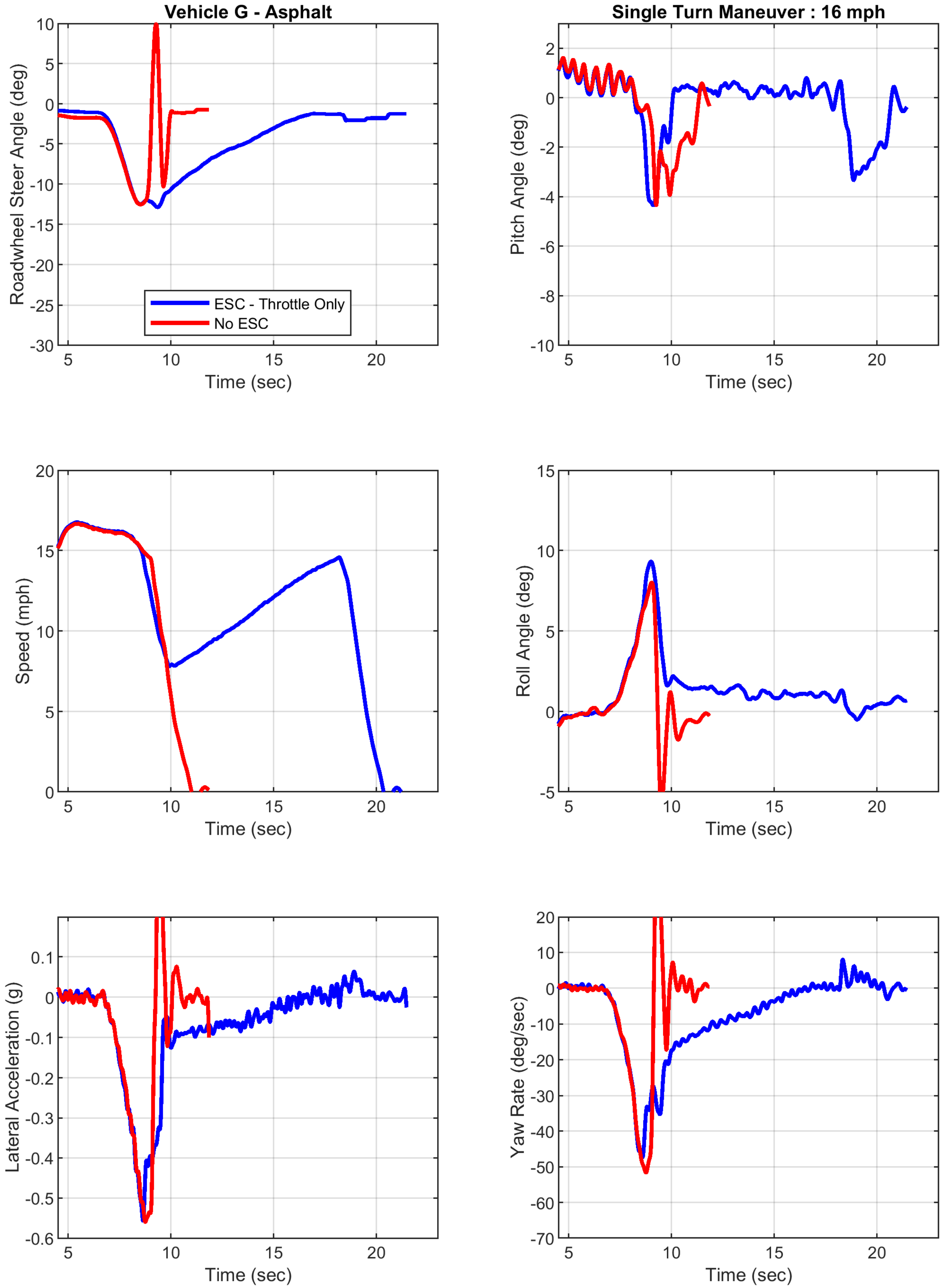
Run G1 – Vehicle G, Asphalt, Single Turn Maneuver, 16 mph – ESC: Brake and Throttle







Run G2 – Vehicle G, Asphalt, Single Turn Maneuver, 16 mph – ESC: Throttle Only



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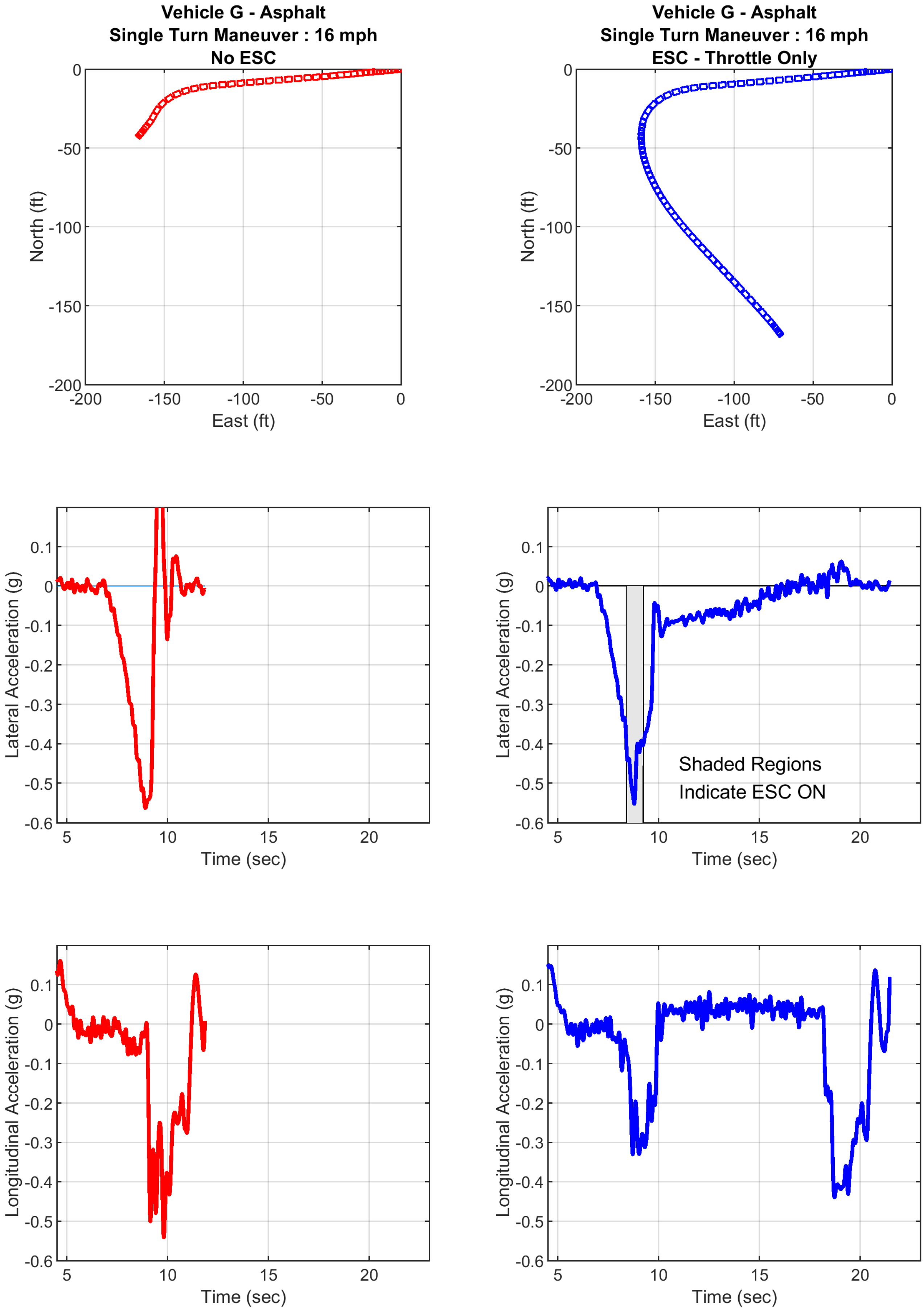
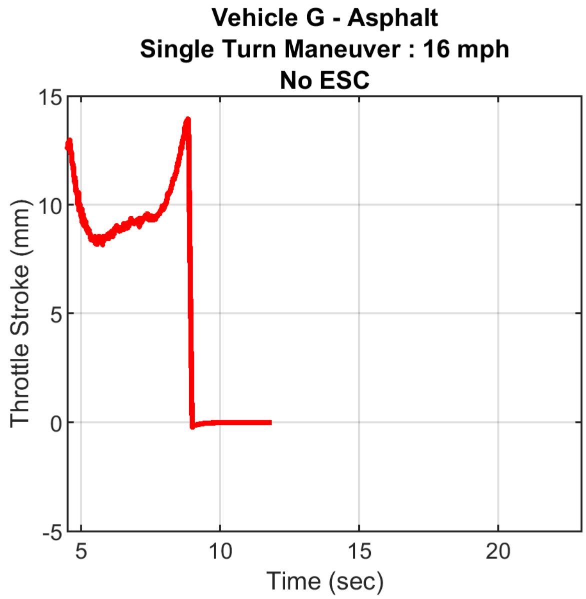
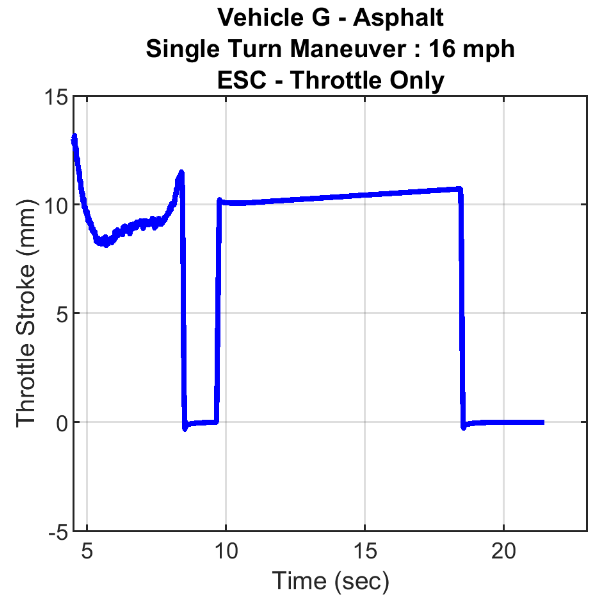
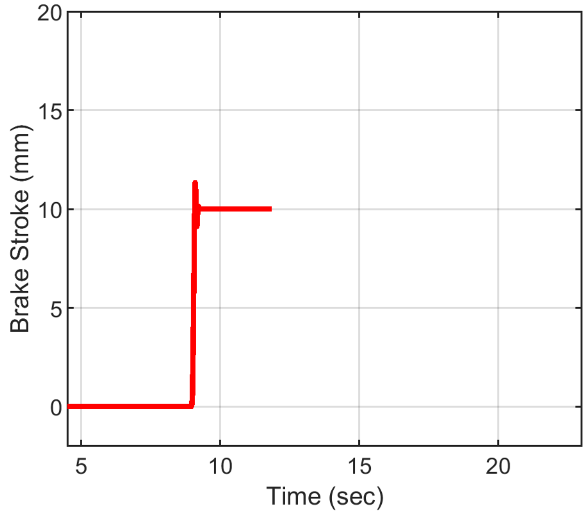
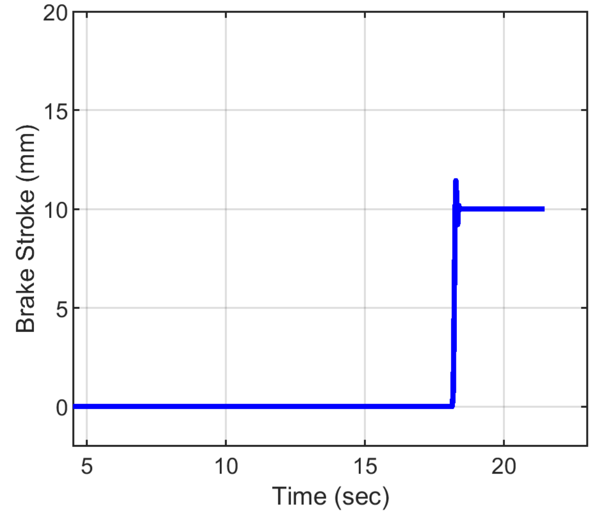


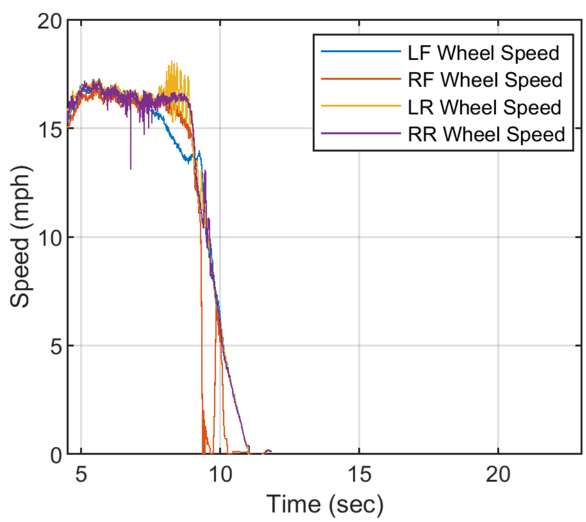
Run G2 – Vehicle G, Asphalt, Single Turn Maneuver, 16 mph – ESC: Throttle Only

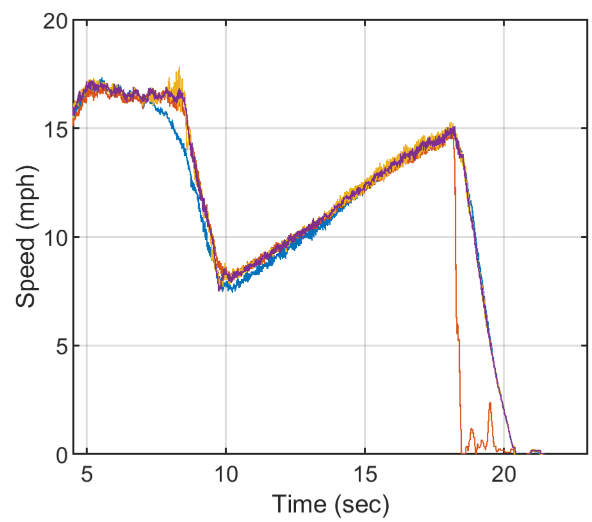




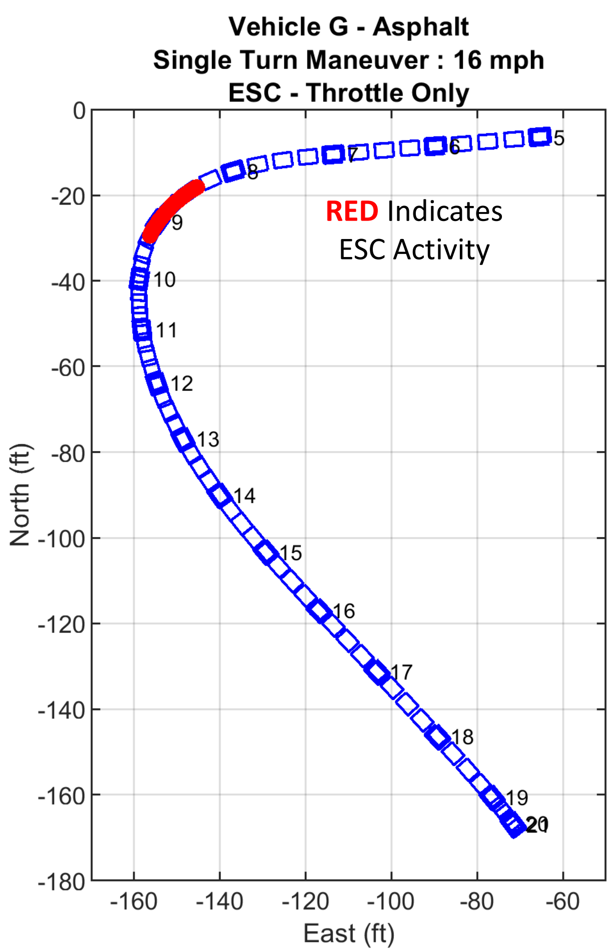


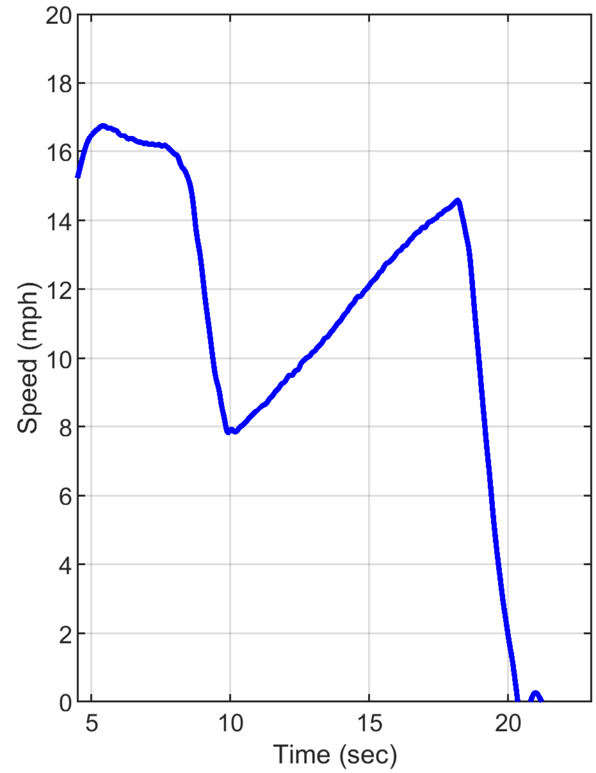


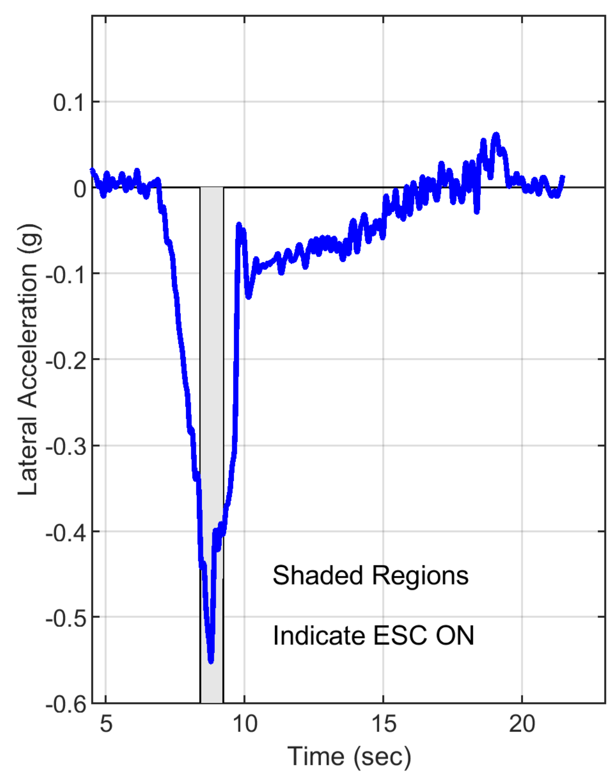




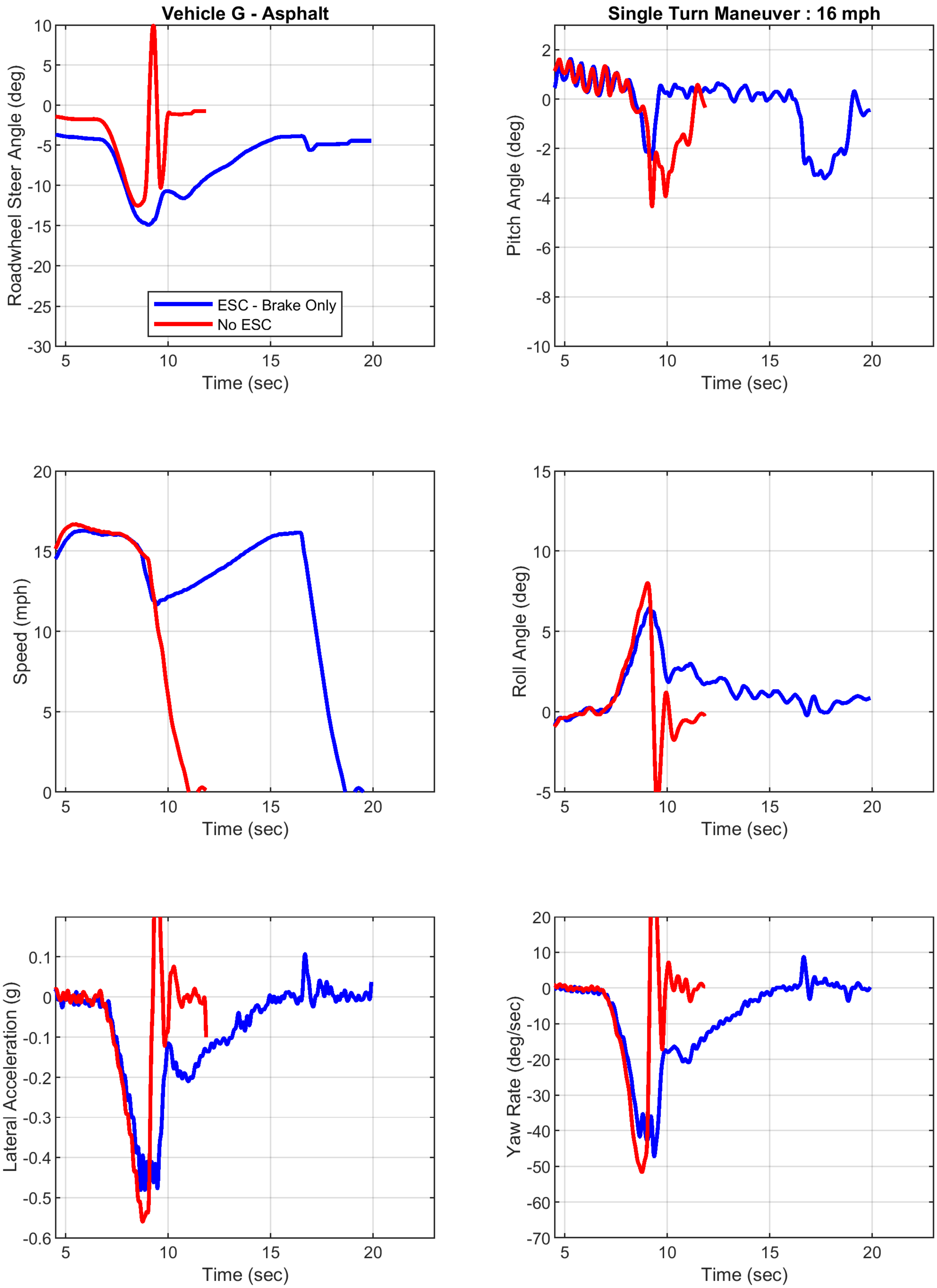
Run G2 – Vehicle G, Asphalt, Single Turn Maneuver, 16 mph – ESC: Throttle Only



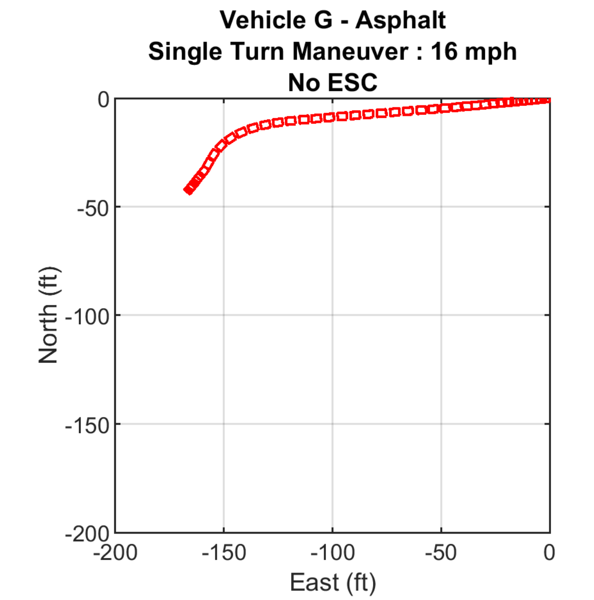


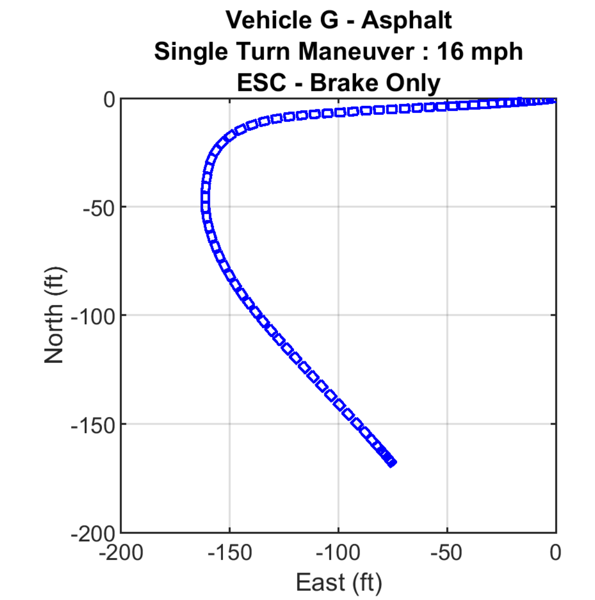


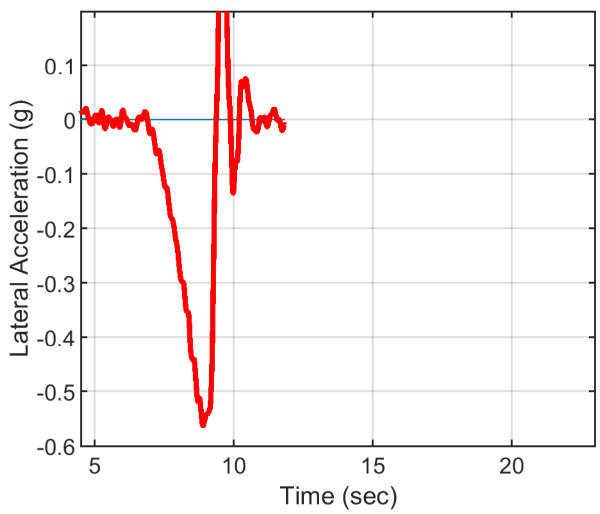
Run G3 – Vehicle G, Asphalt, Single Turn Maneuver, 16 mph – ESC: Brake Only

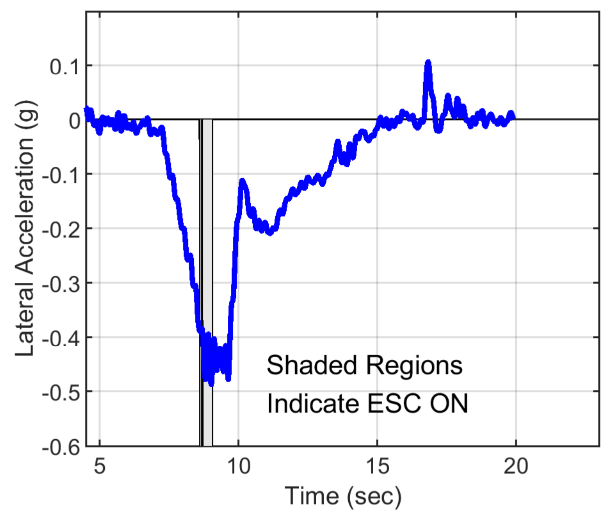


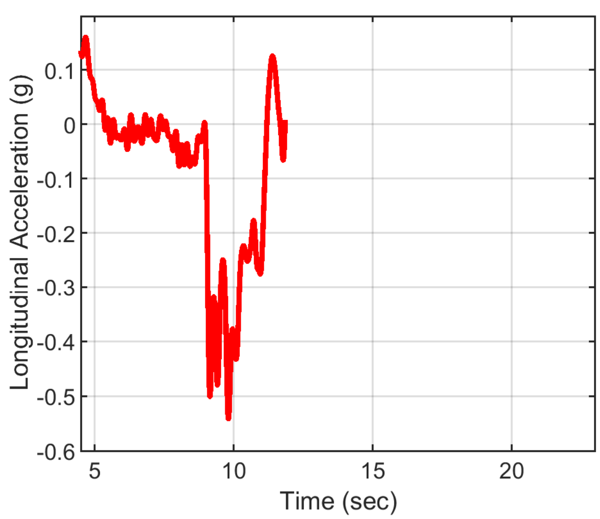
Run G3 – Vehicle G, Asphalt, Single Turn Maneuver, 16 mph – ESC: Brake Only

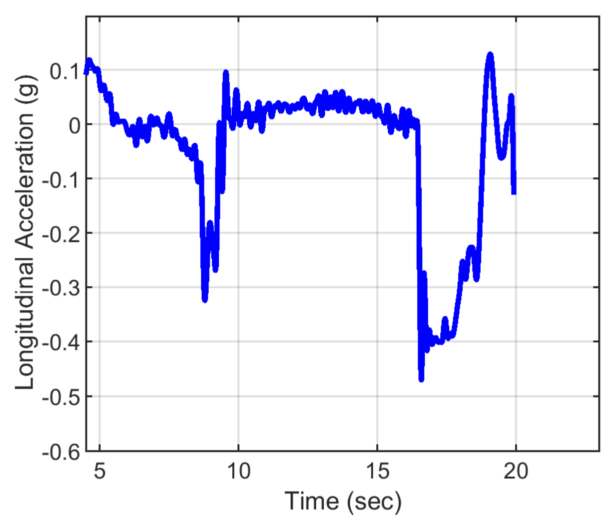




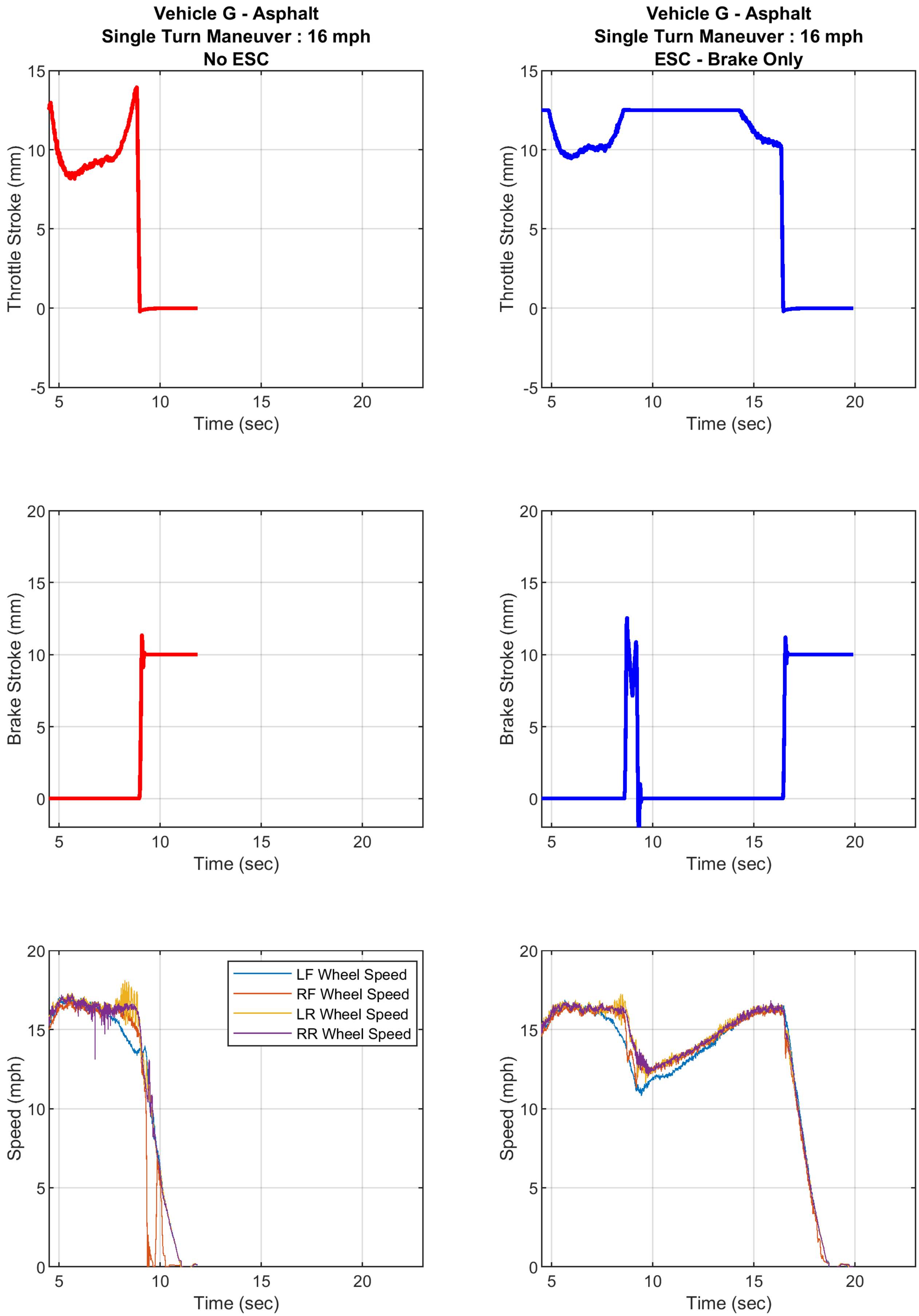




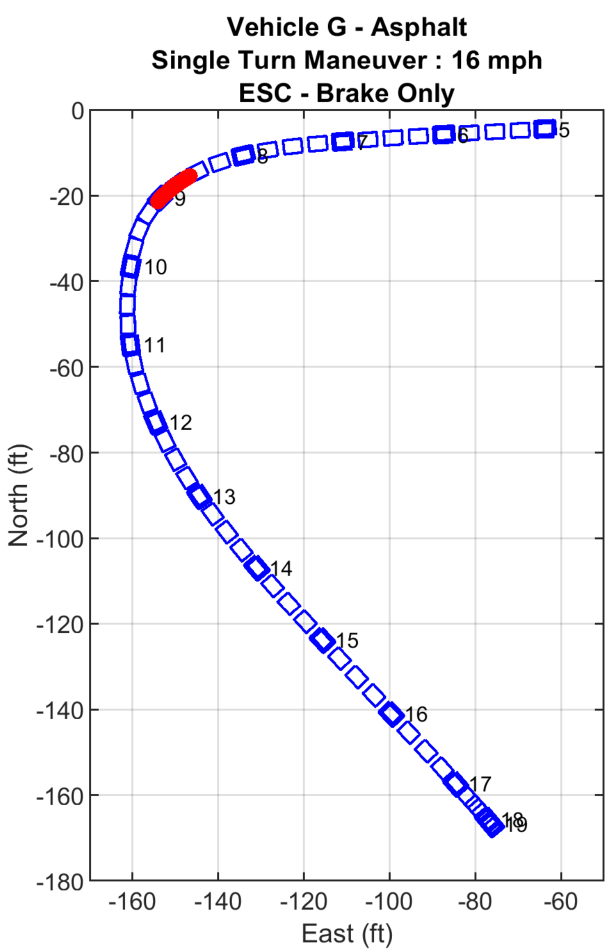


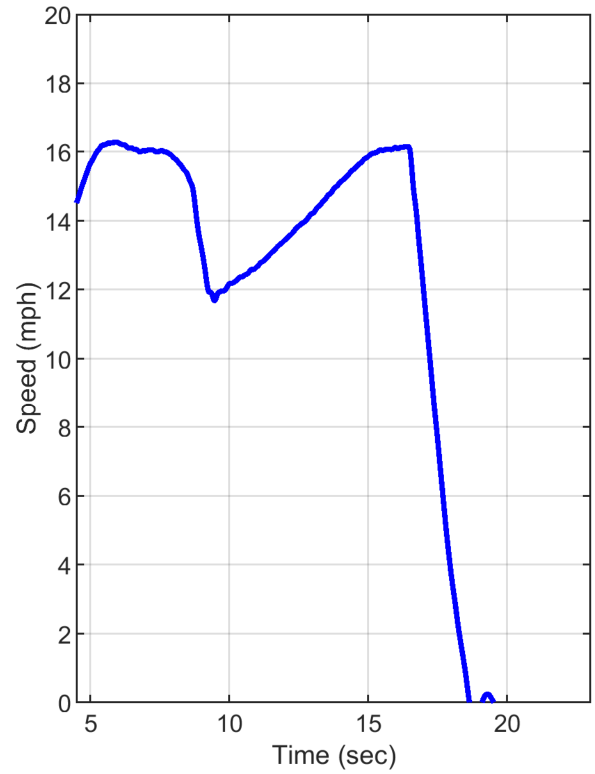


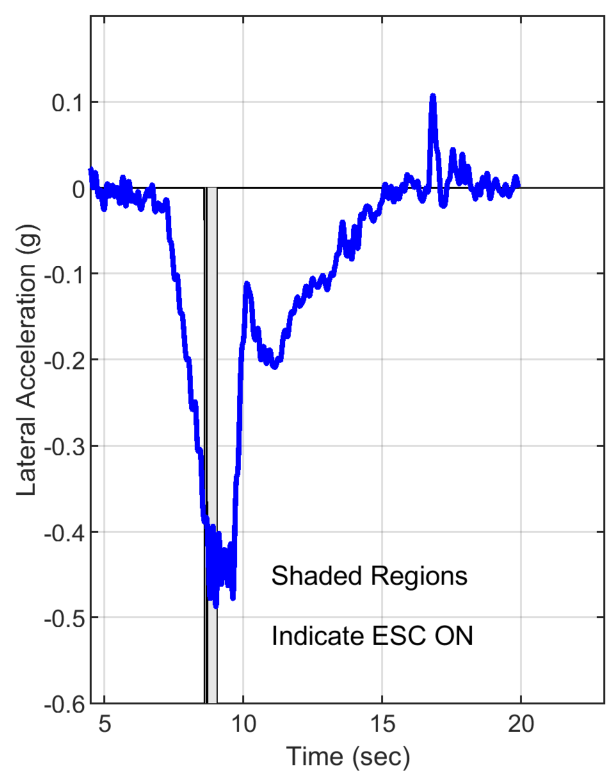
Run G3 – Vehicle G, Asphalt, Single Turn Maneuver, 16 mph – ESC: Brake Only



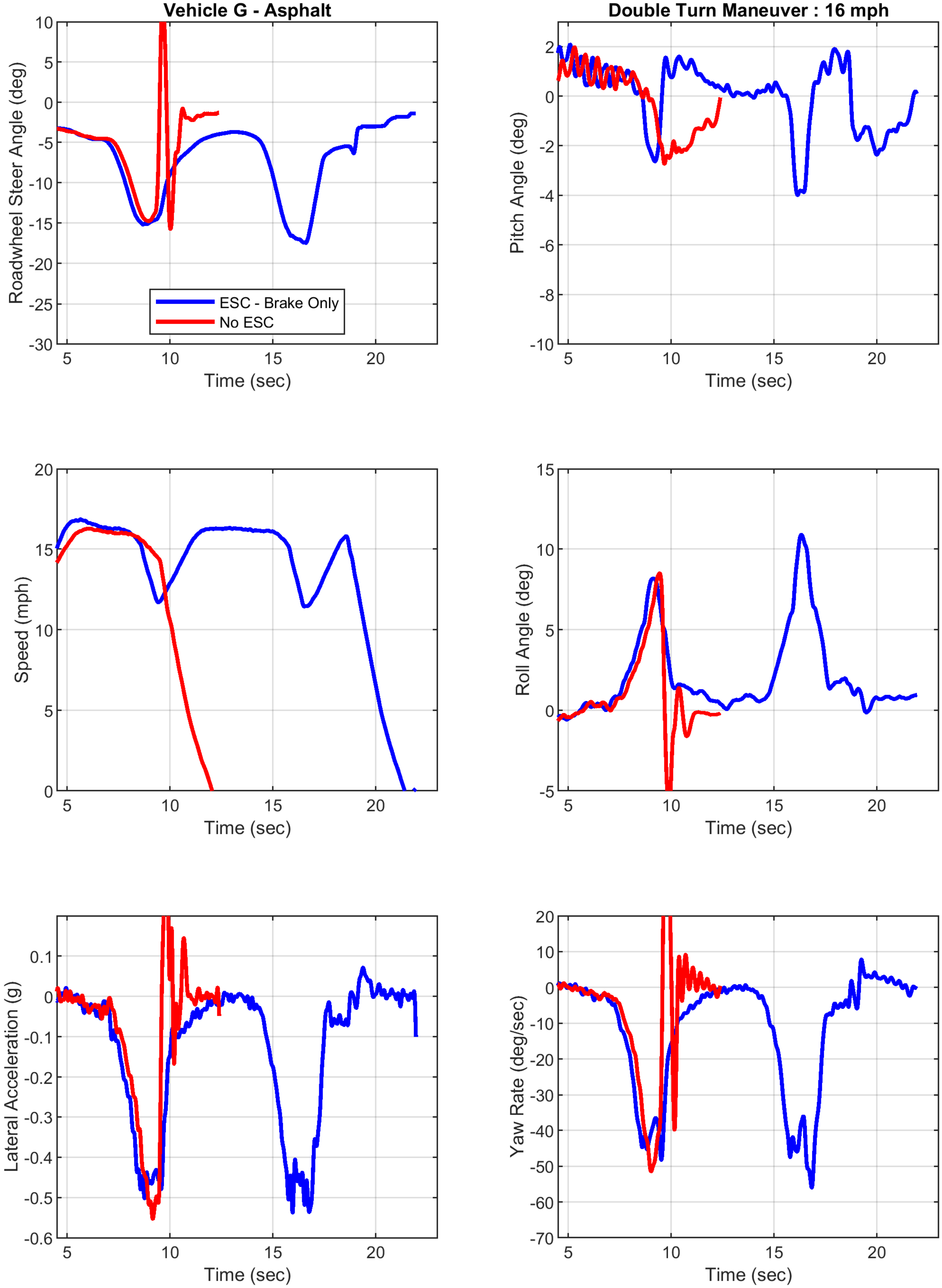
Run G3 – Vehicle G, Asphalt, Single Turn Maneuver, 16 mph – ESC: Brake Only



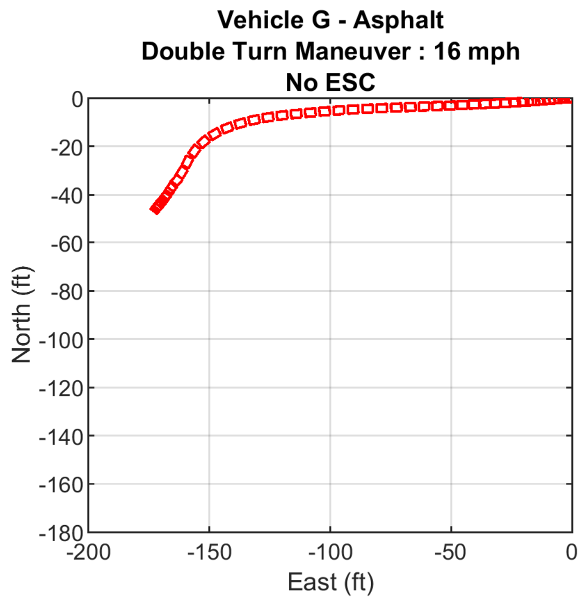


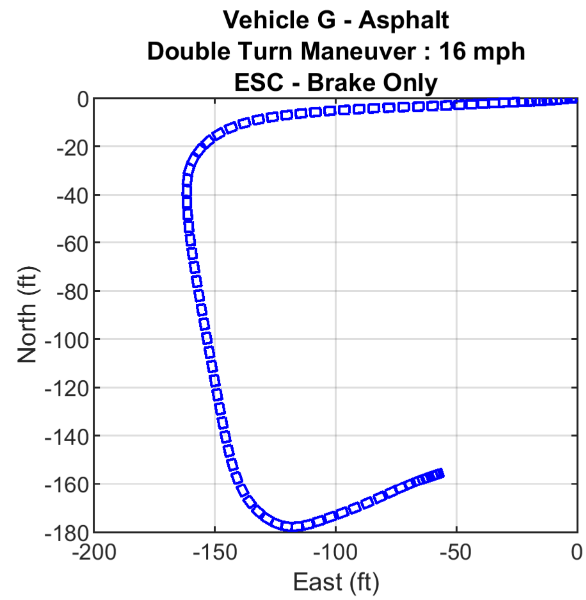


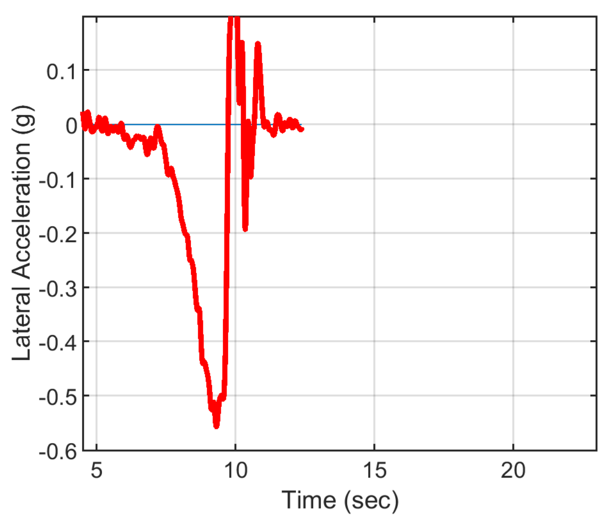
Run G4 – Vehicle G, Asphalt, Double Turn Maneuver, 16 mph – ESC: Brake Only

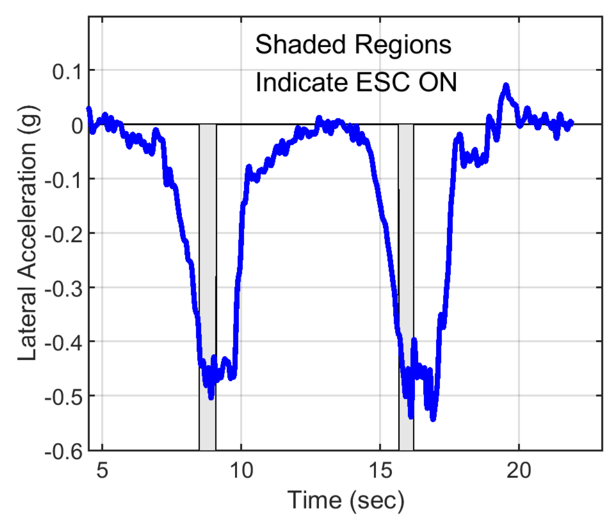


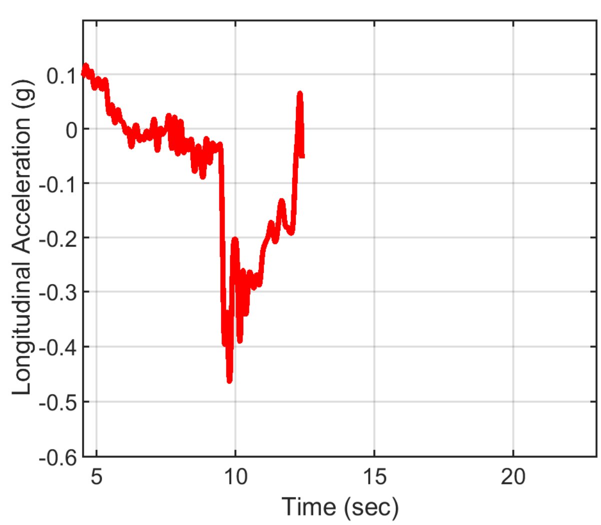
Run G4 – Vehicle G, Asphalt, Double Turn Maneuver, 16 mph – ESC: Brake Only

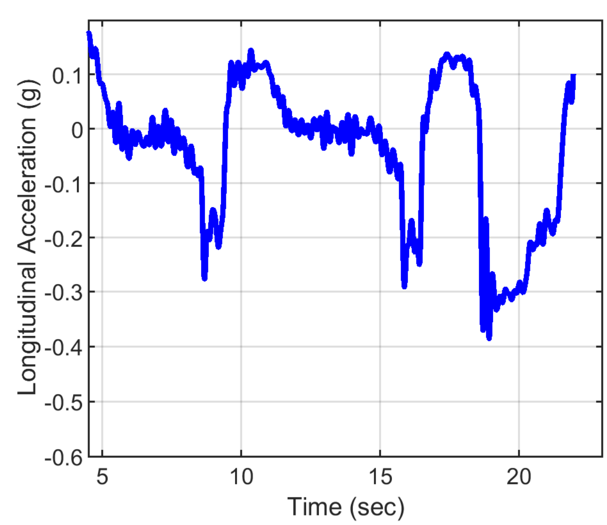




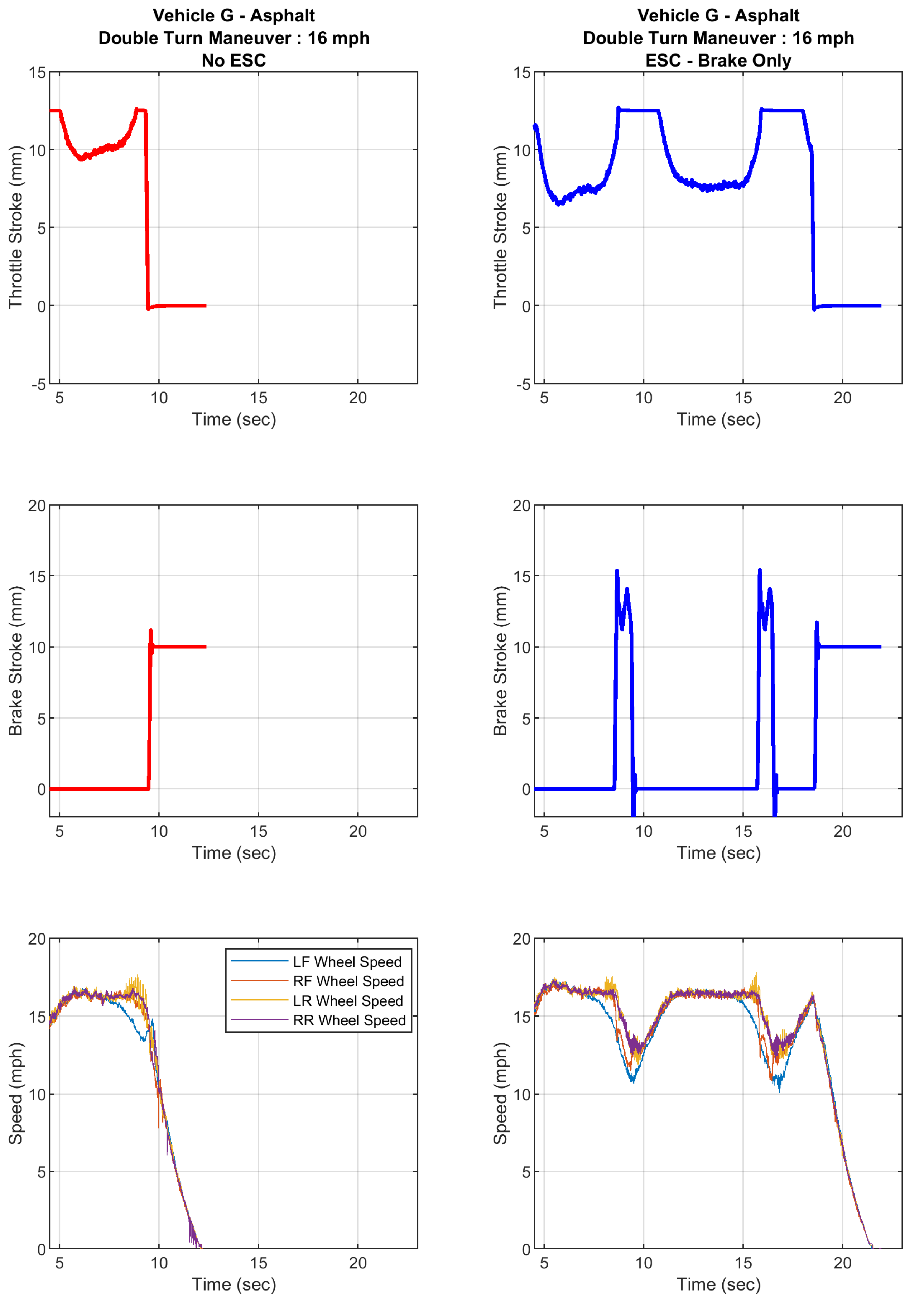




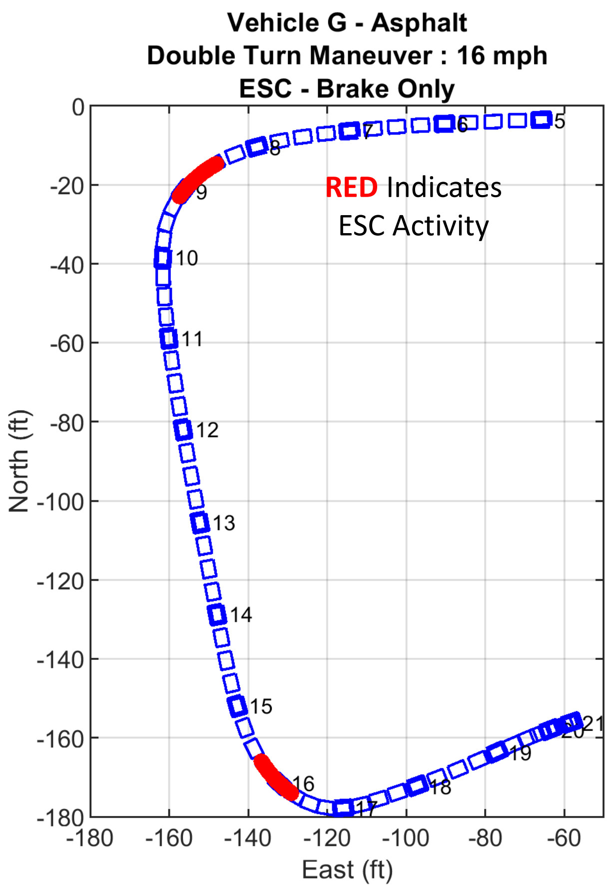


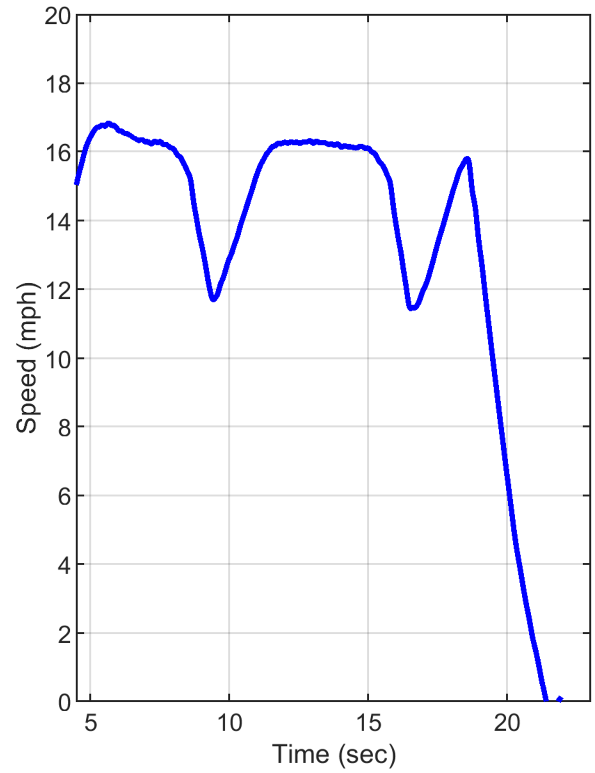


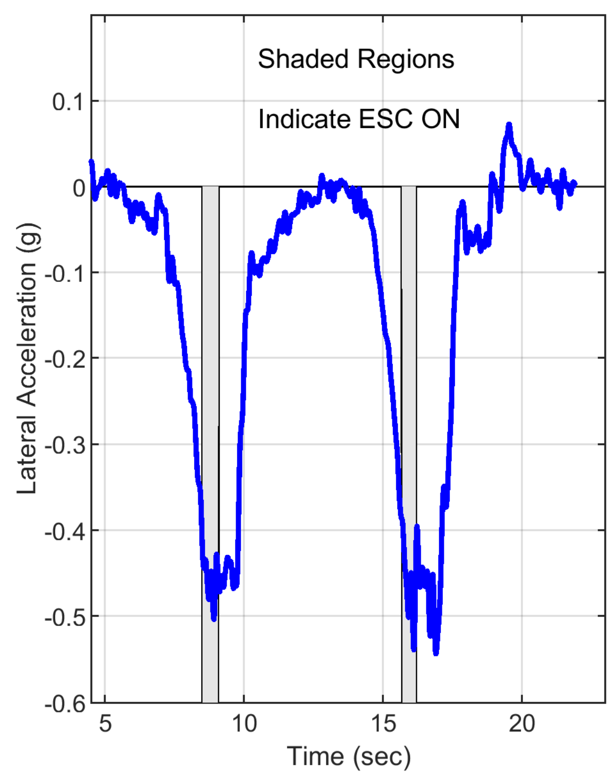
Run G4 – Vehicle G, Asphalt, Double Turn Maneuver, 16 mph – ESC: Brake Only



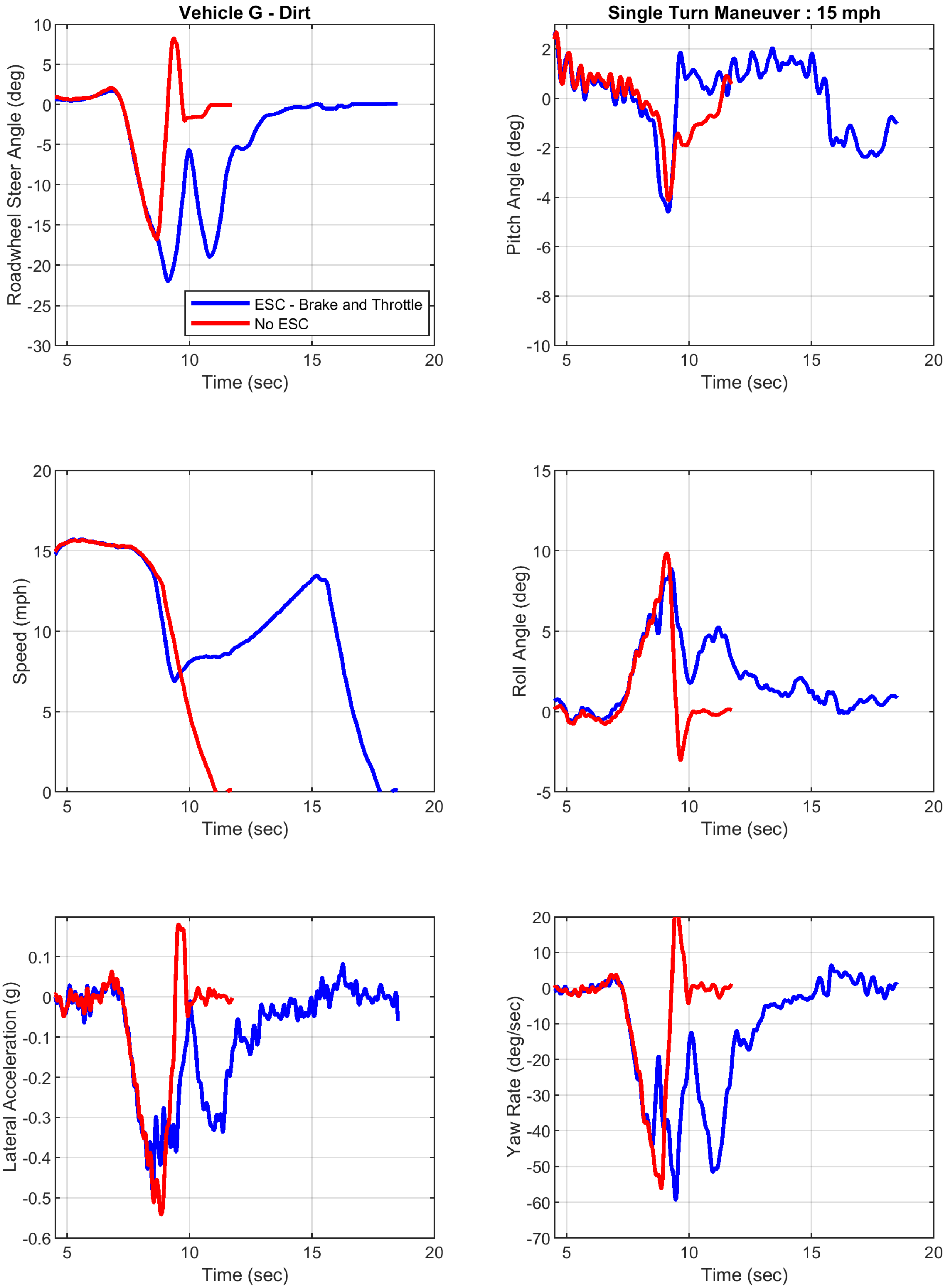
Run G4 – Vehicle G, Asphalt, Double Turn Maneuver, 16 mph – ESC: Brake Only



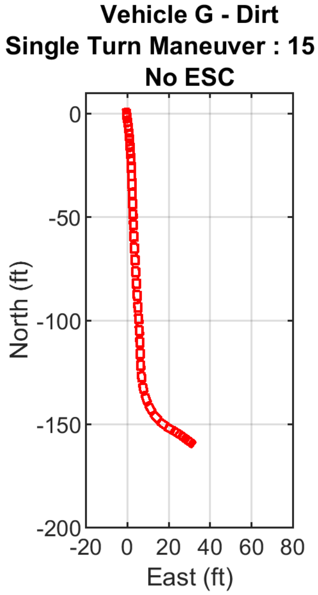


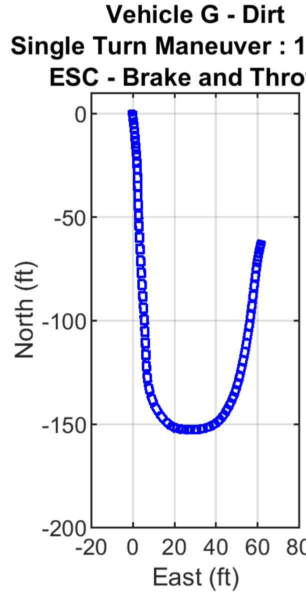


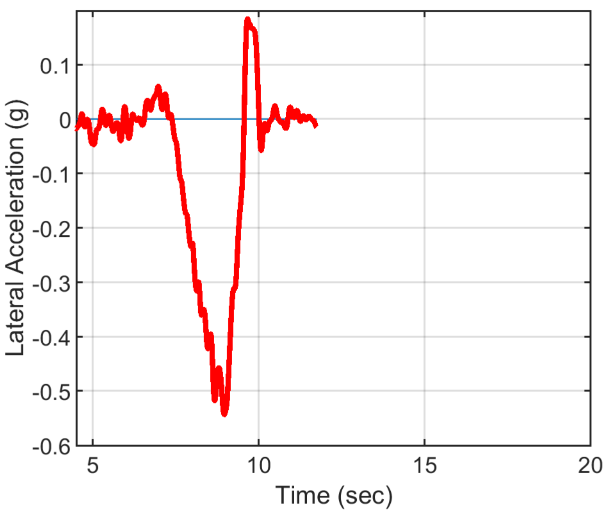
Run G5 – Vehicle G, Dirt, Single Turn Maneuver, 15 mph – ESC: Brake and Throttle

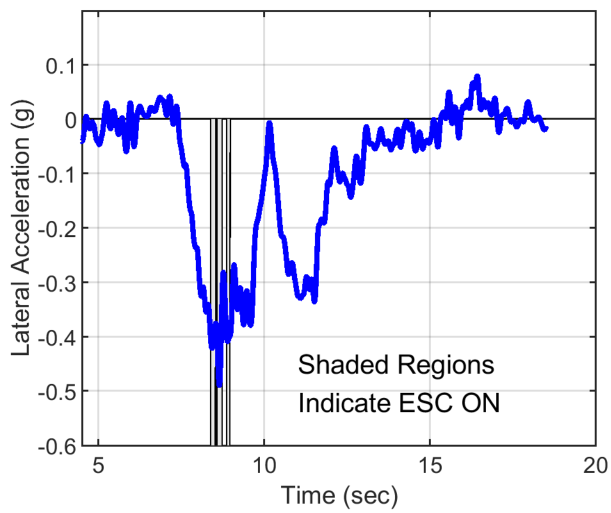


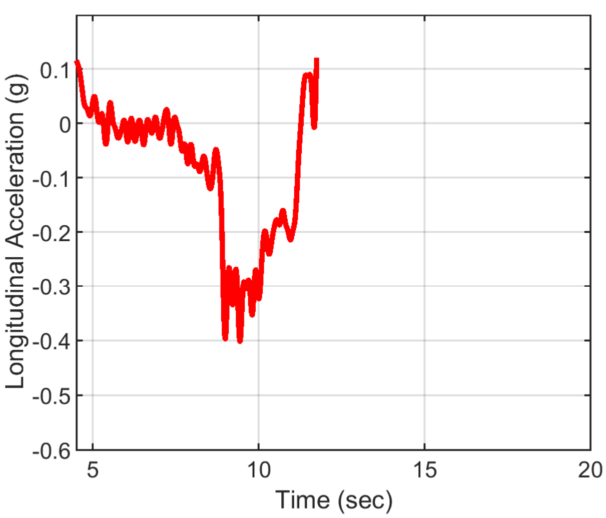
Run G5 – Vehicle G, Dirt, Single Turn Maneuver, 15 mph – ESC: Brake and Throttle

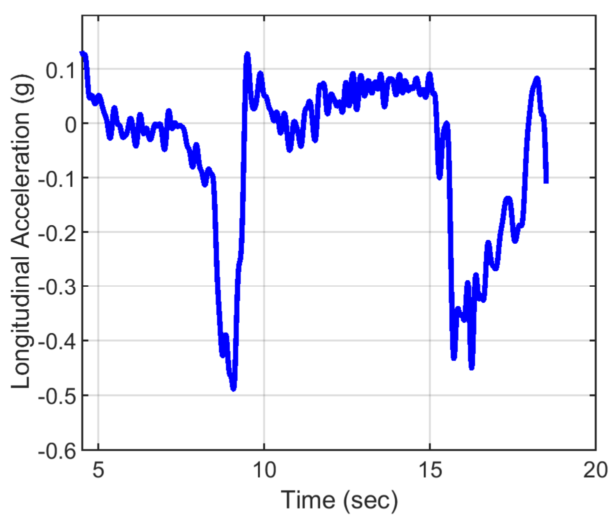




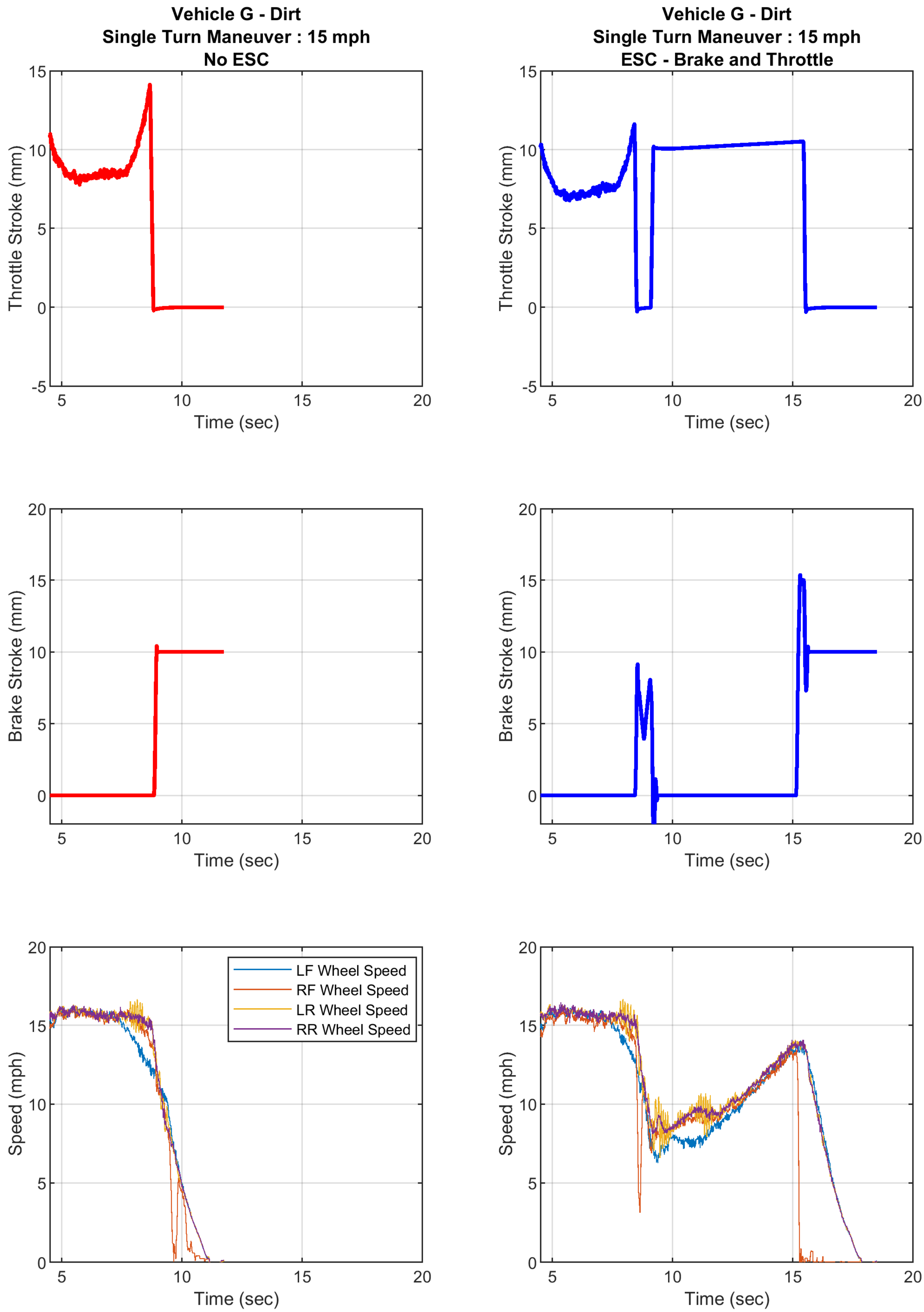




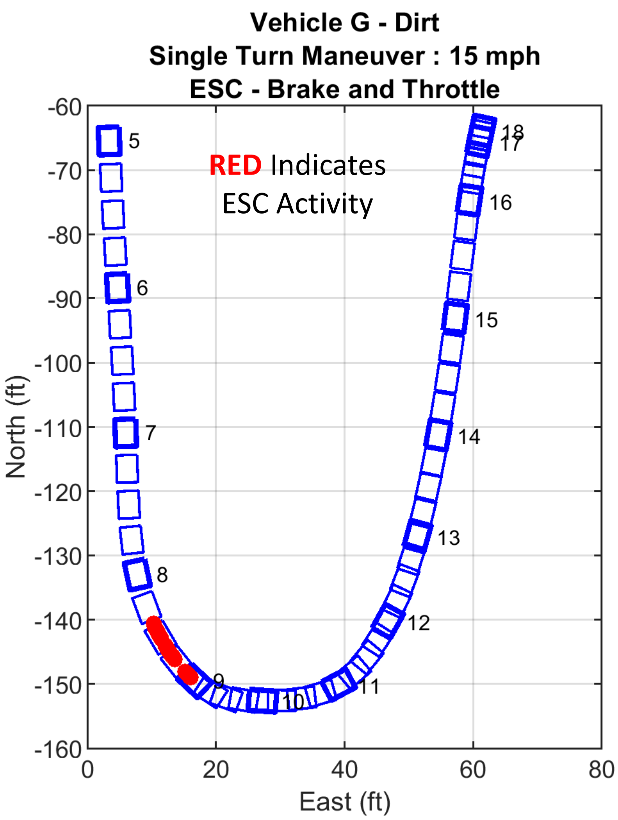


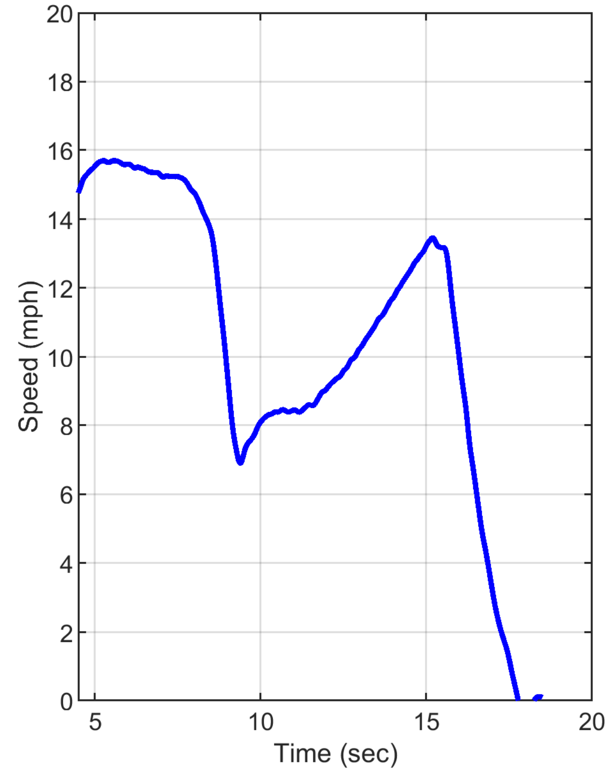


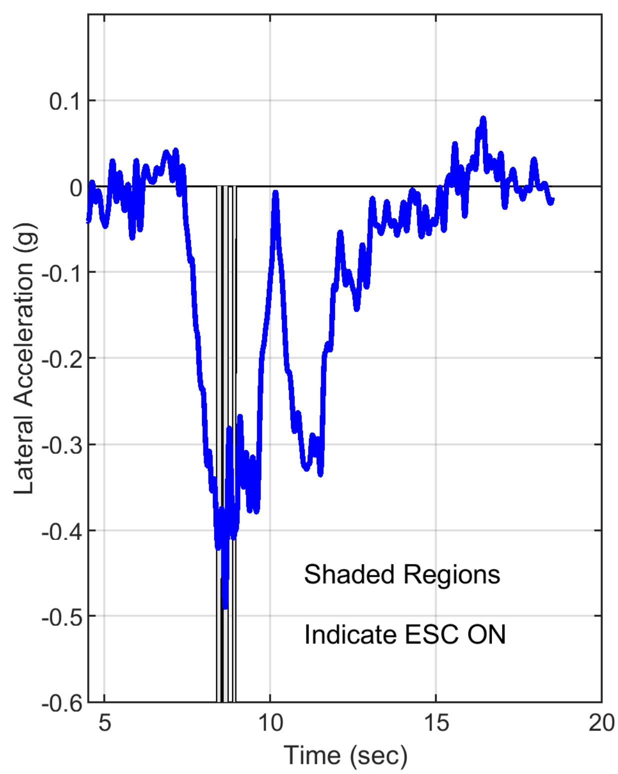
Run G5 – Vehicle G, Dirt, Single Turn Maneuver, 15 mph – ESC: Brake and Throttle



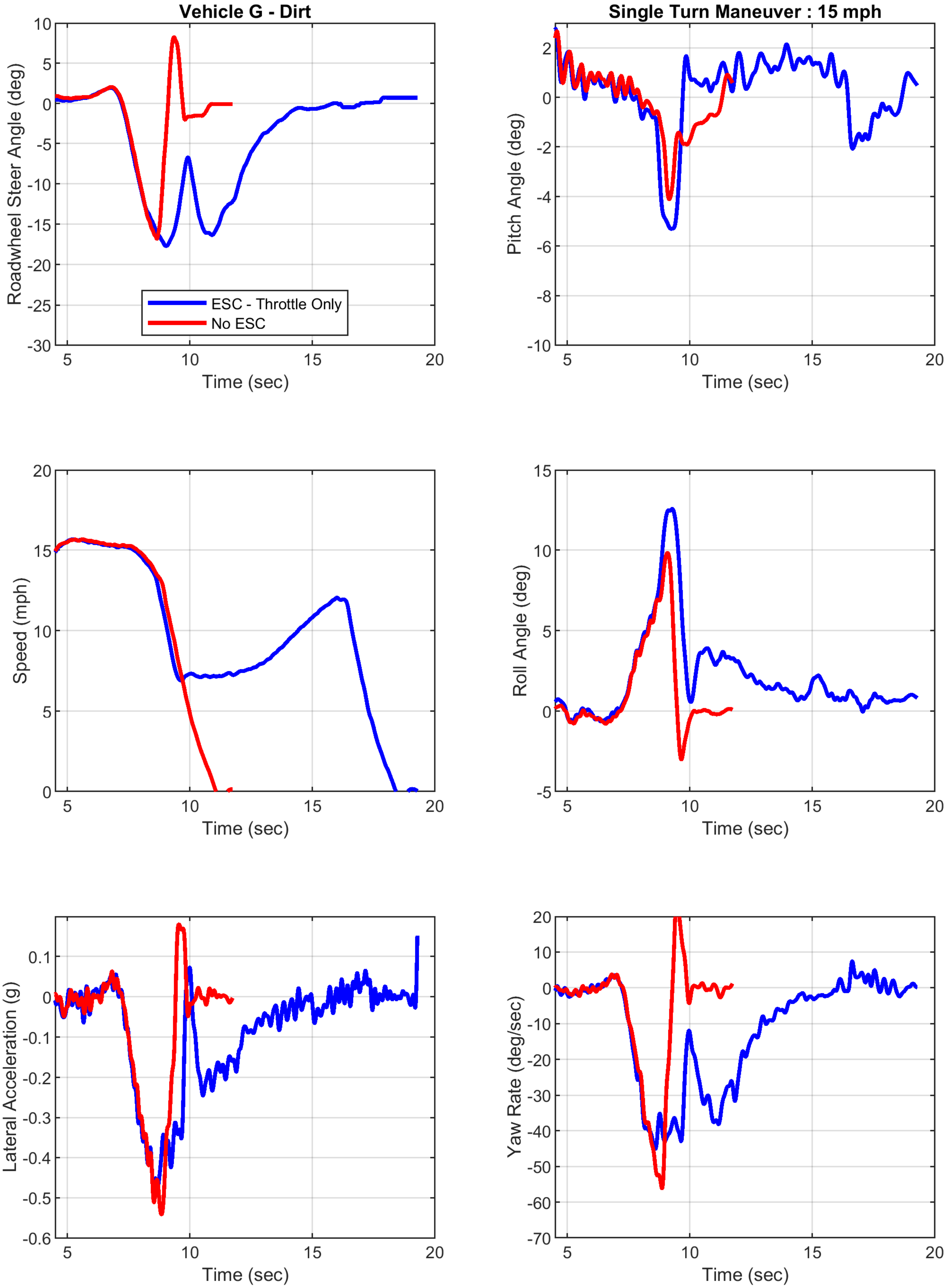
Run G5 – Vehicle G, Dirt, Single Turn Maneuver, 15 mph – ESC: Brake and Throttle



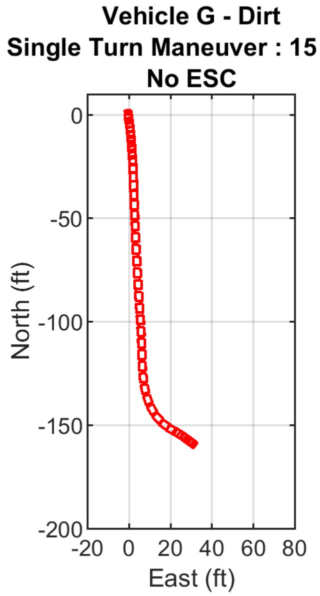


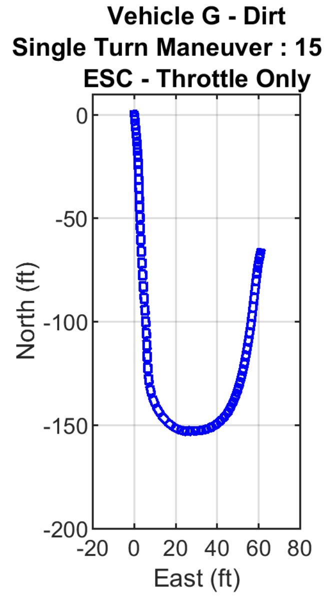


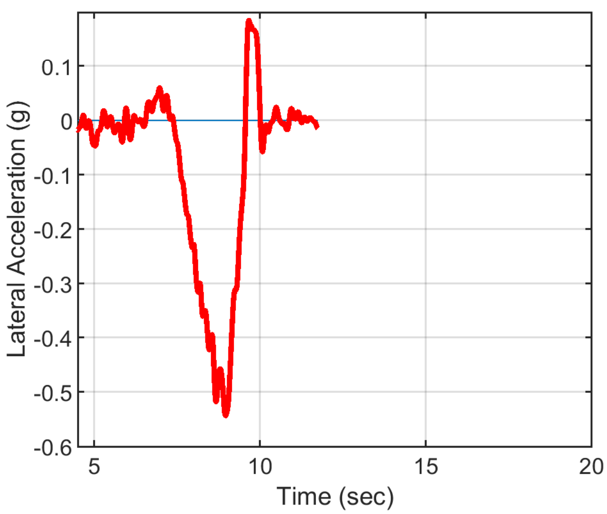
Run G6 – Vehicle G, Dirt, Single Turn Maneuver, 15 mph – ESC: Throttle Only

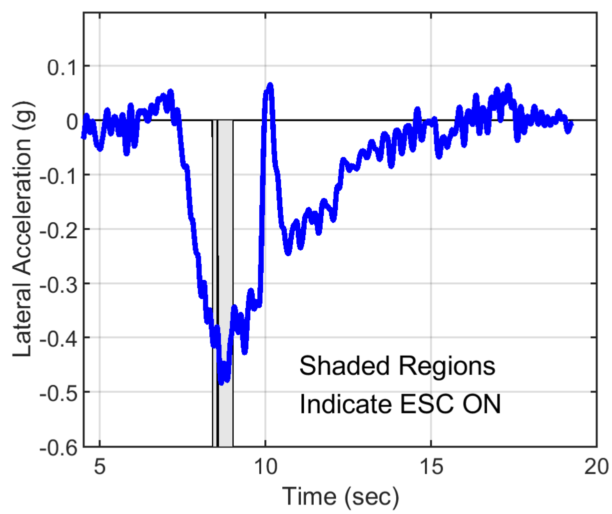


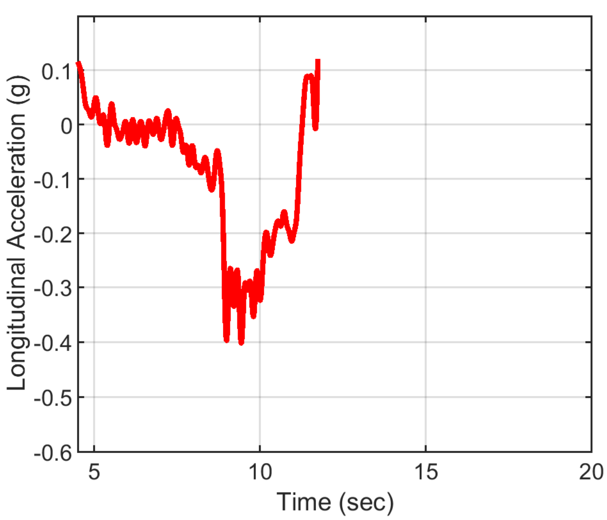
Run G6 – Vehicle G, Dirt, Single Turn Maneuver, 15 mph – ESC: Throttle Only

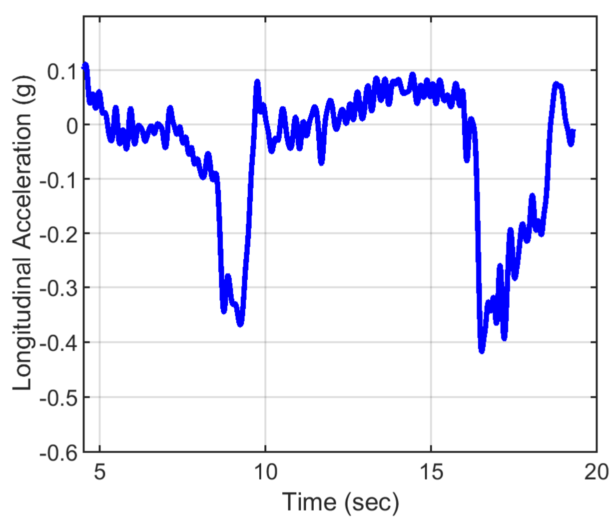




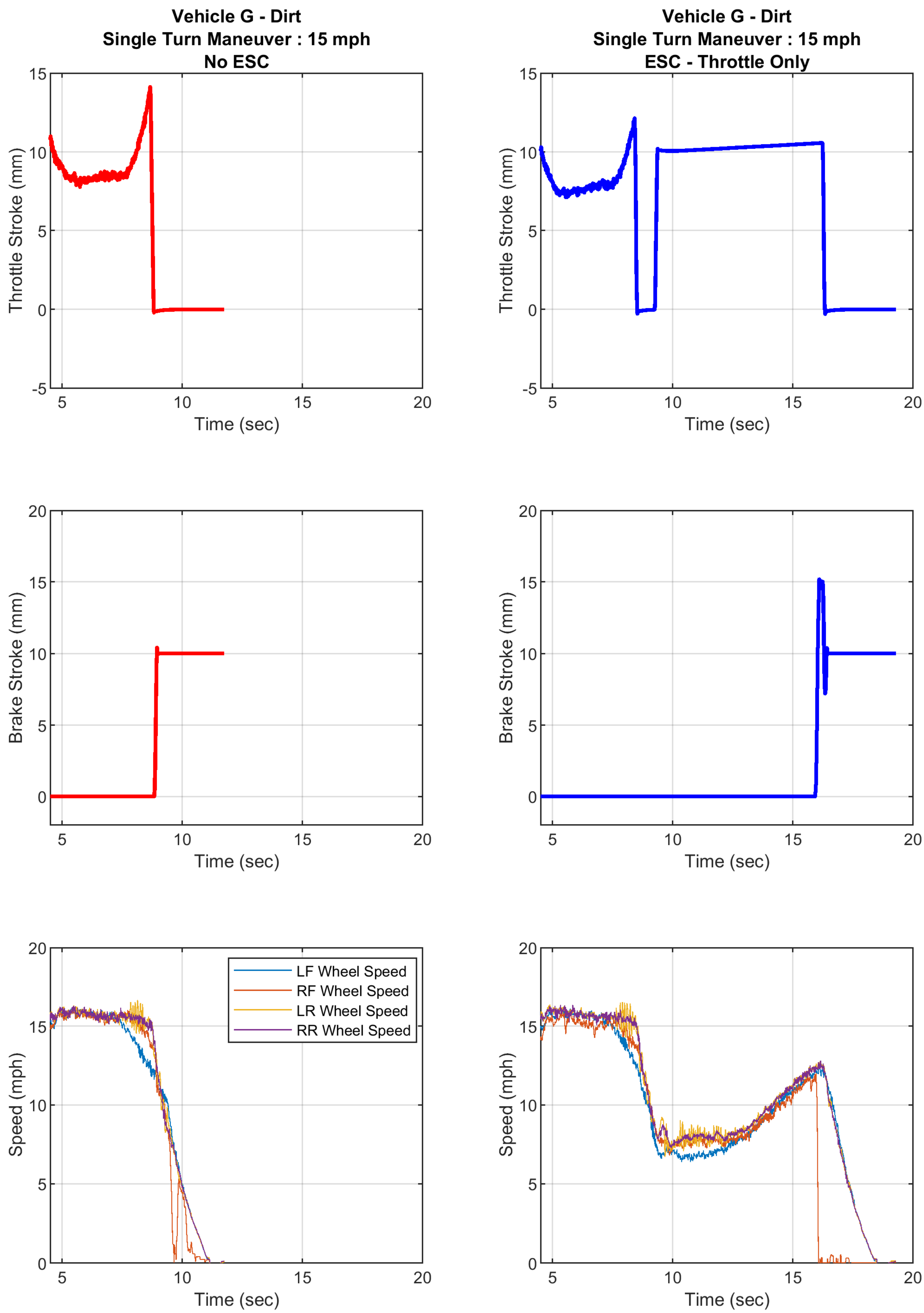




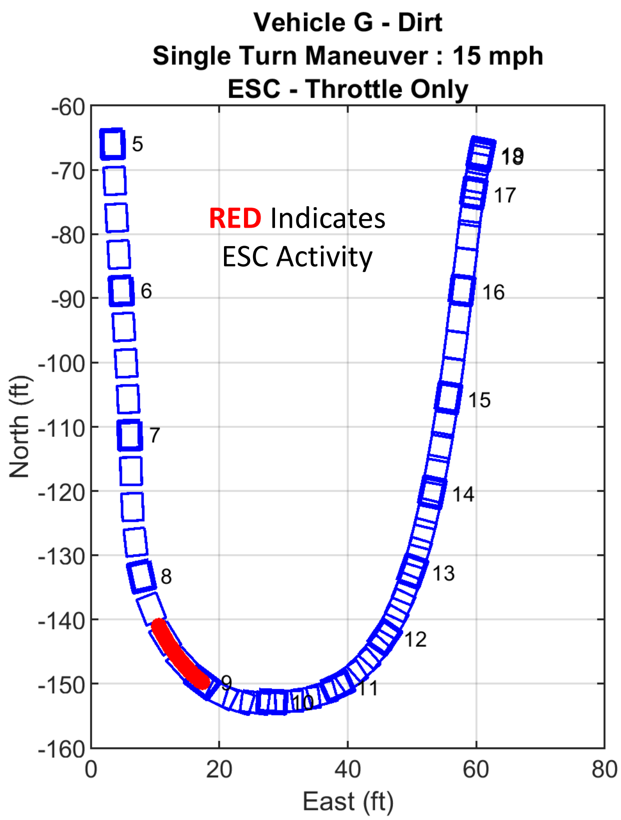


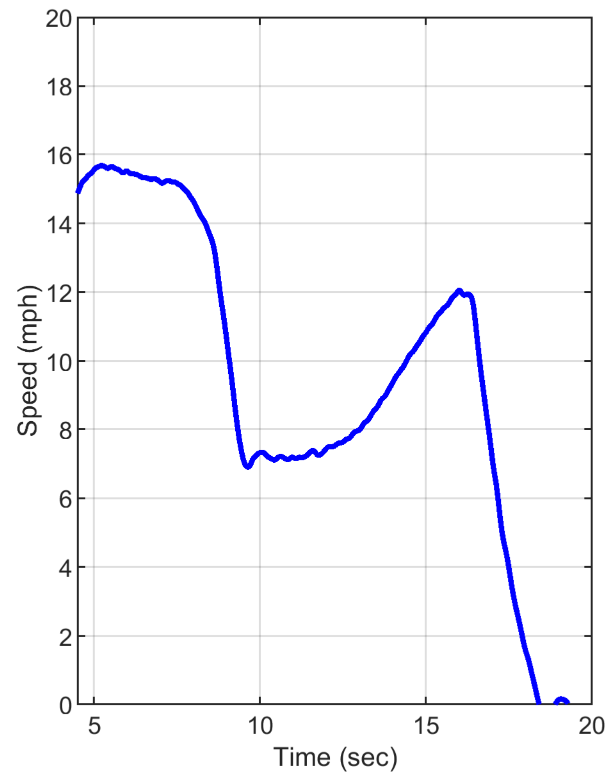


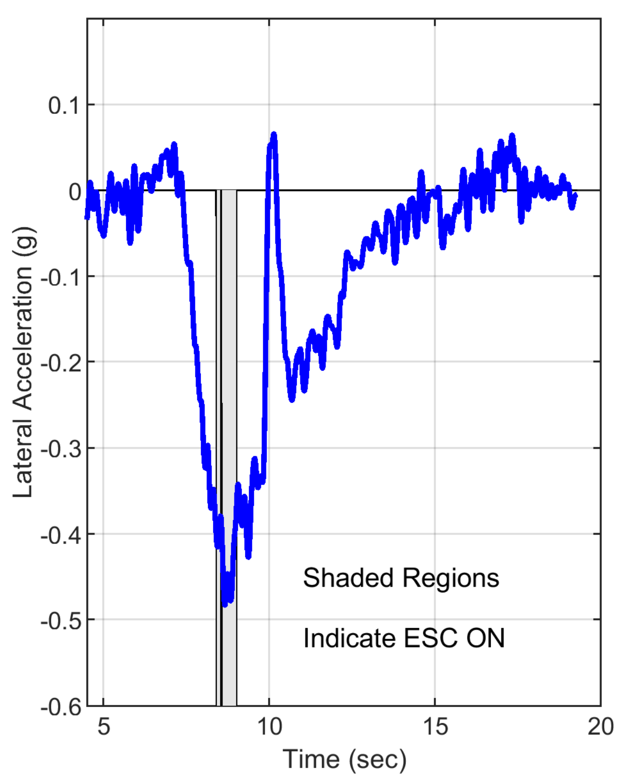
Run G6 – Vehicle G, Dirt, Single Turn Maneuver, 15 mph – ESC: Throttle Only



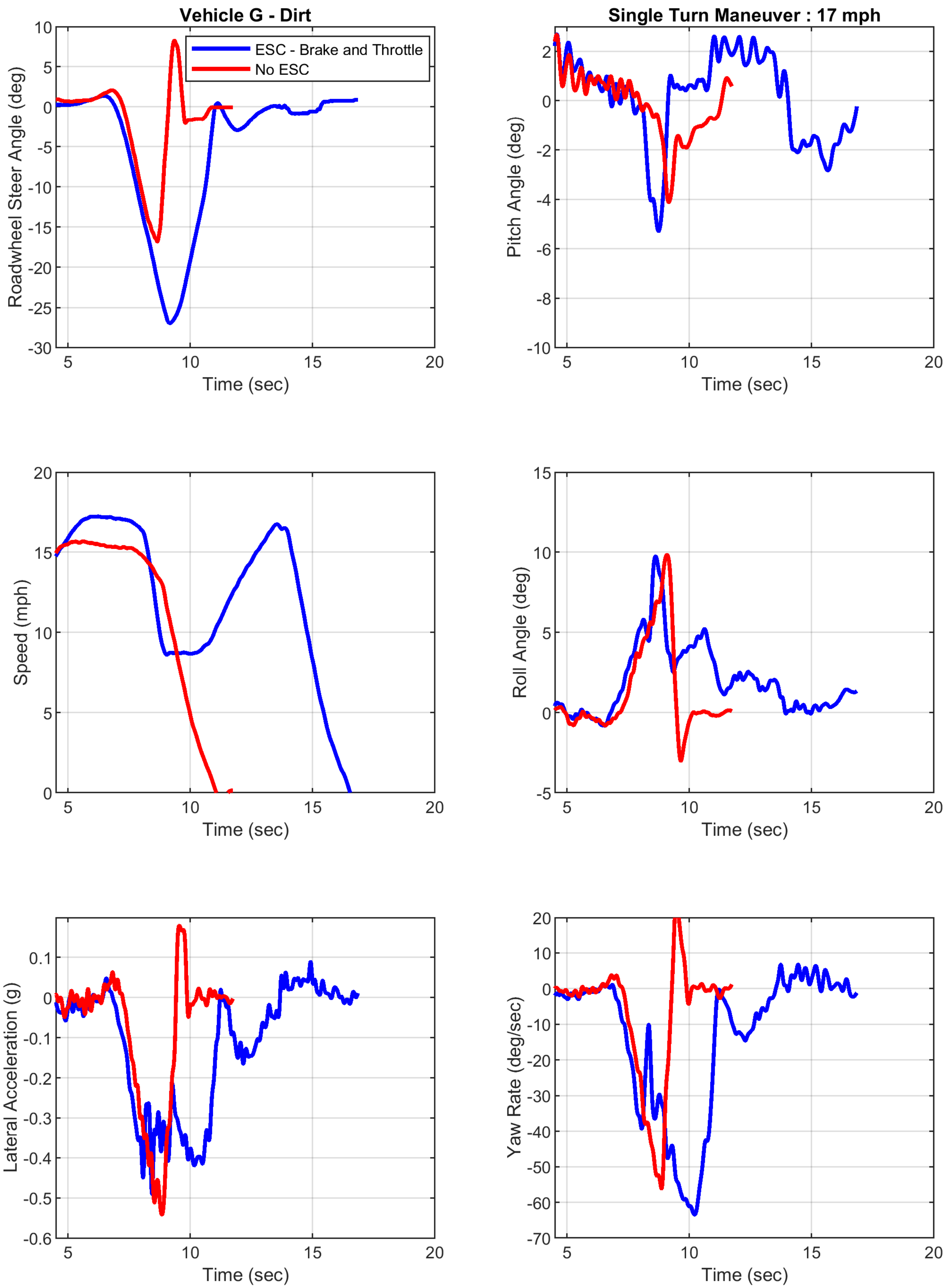
Run G6 – Vehicle G, Dirt, Single Turn Maneuver, 15 mph – ESC: Throttle Only



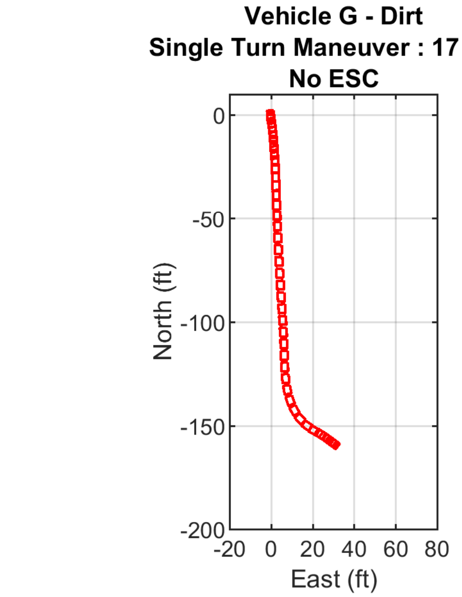


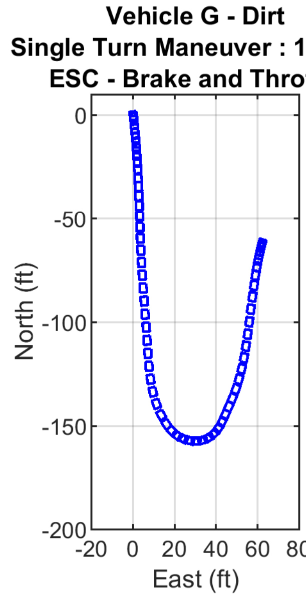


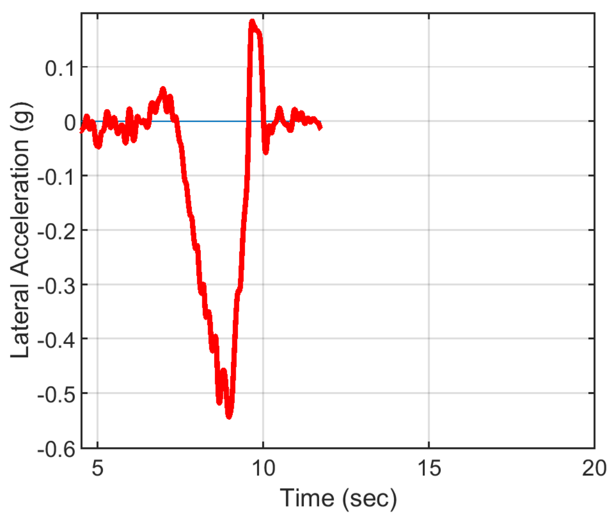
Run G7 – Vehicle G, Dirt, Single Turn Maneuver, 17 mph – ESC: Brake and Throttle

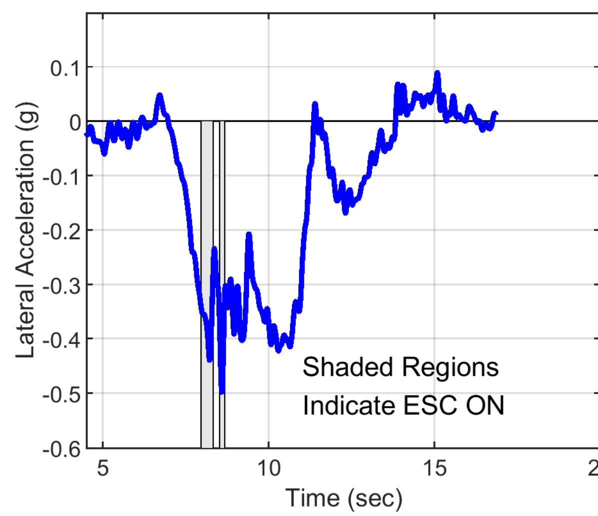


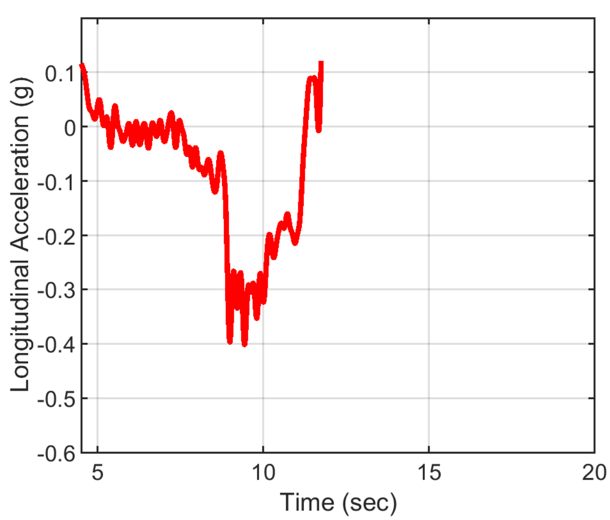
Run G7 – Vehicle G, Dirt, Single Turn Maneuver, 17 mph – ESC: Brake and Throttle

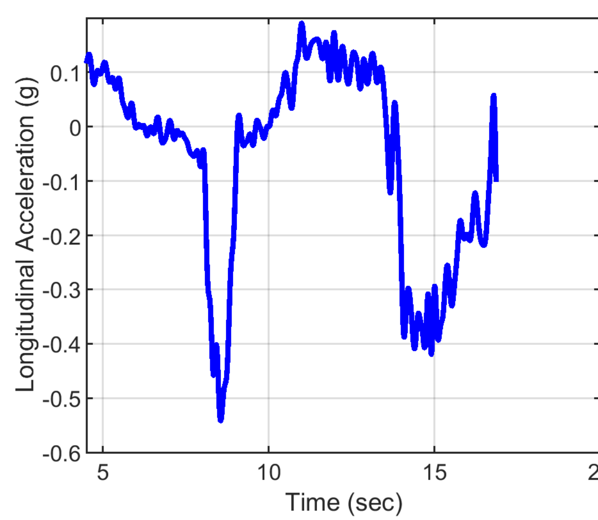




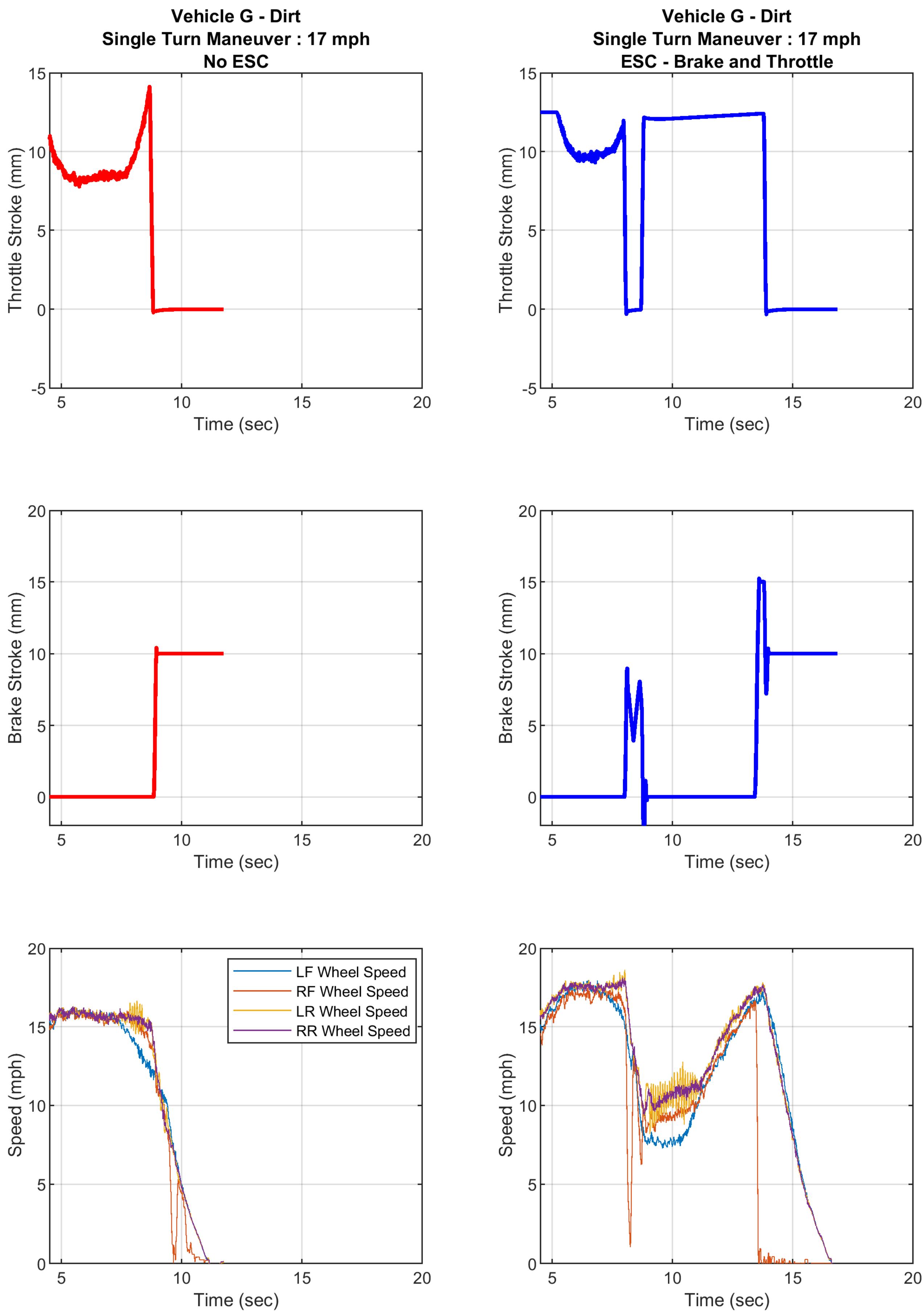




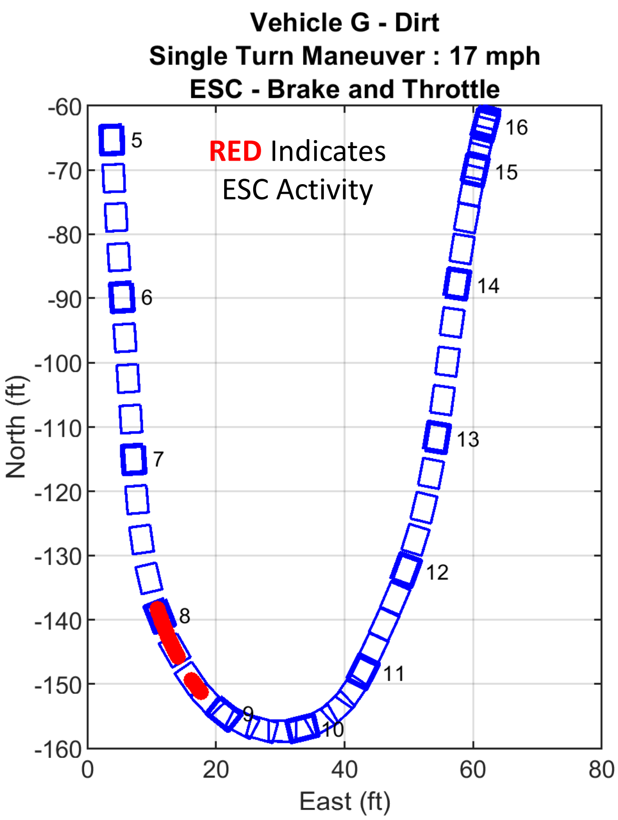


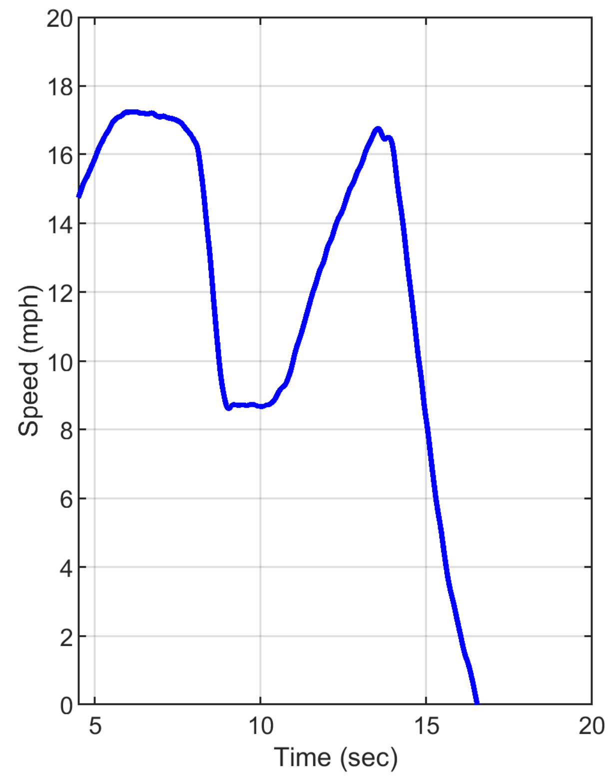


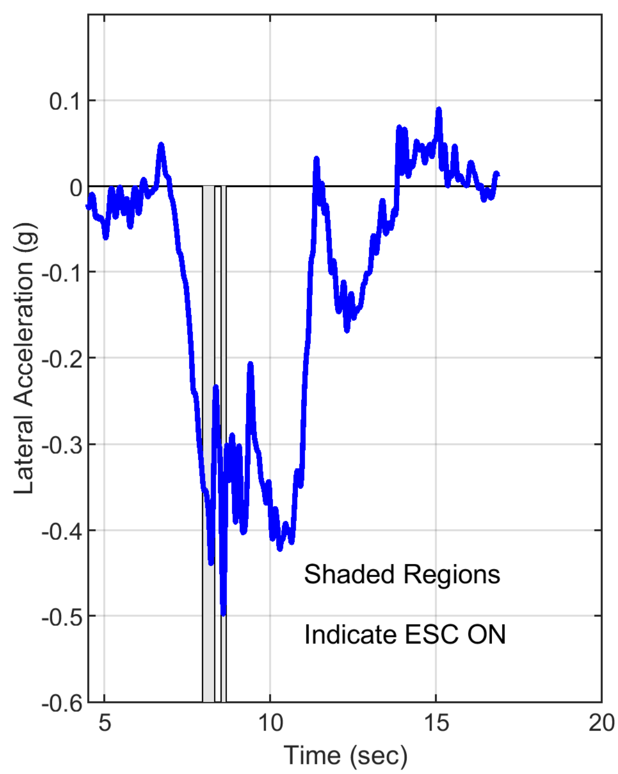
Run G7 – Vehicle G, Dirt, Single Turn Maneuver, 17 mph – ESC: Brake and Throttle



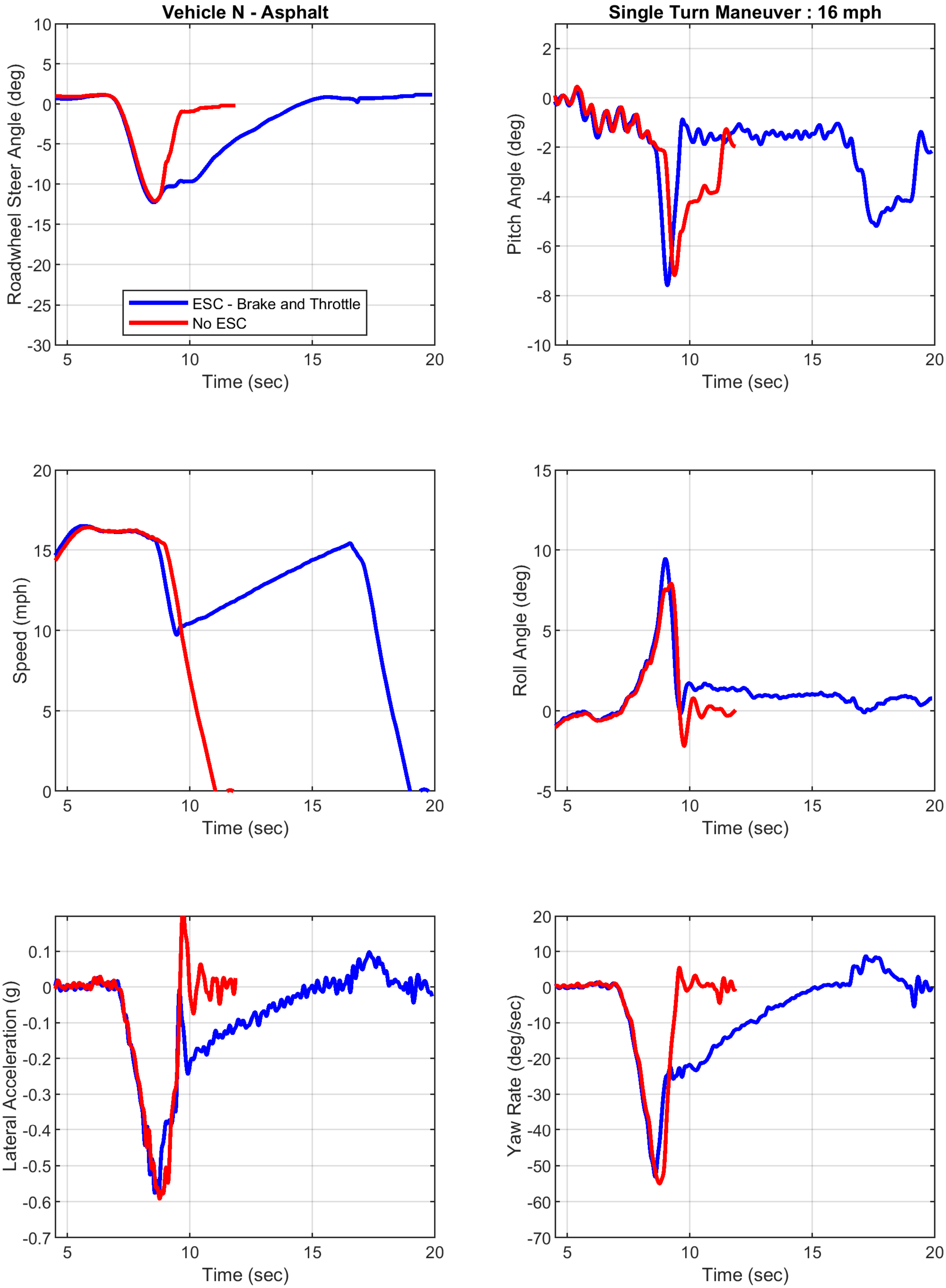
Run G7 – Vehicle G, Dirt, Single Turn Maneuver, 17 mph – ESC: Brake and Throttle



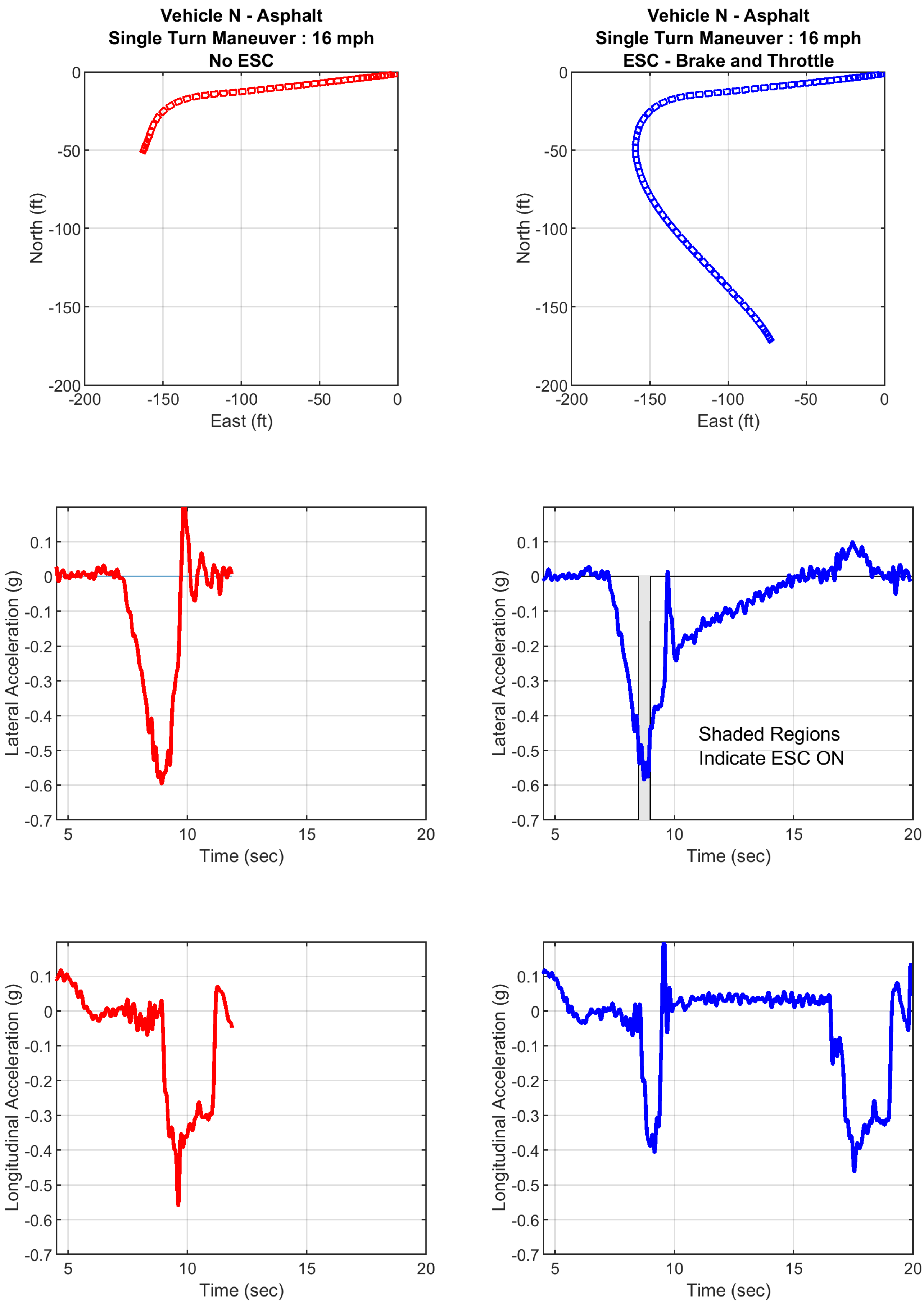




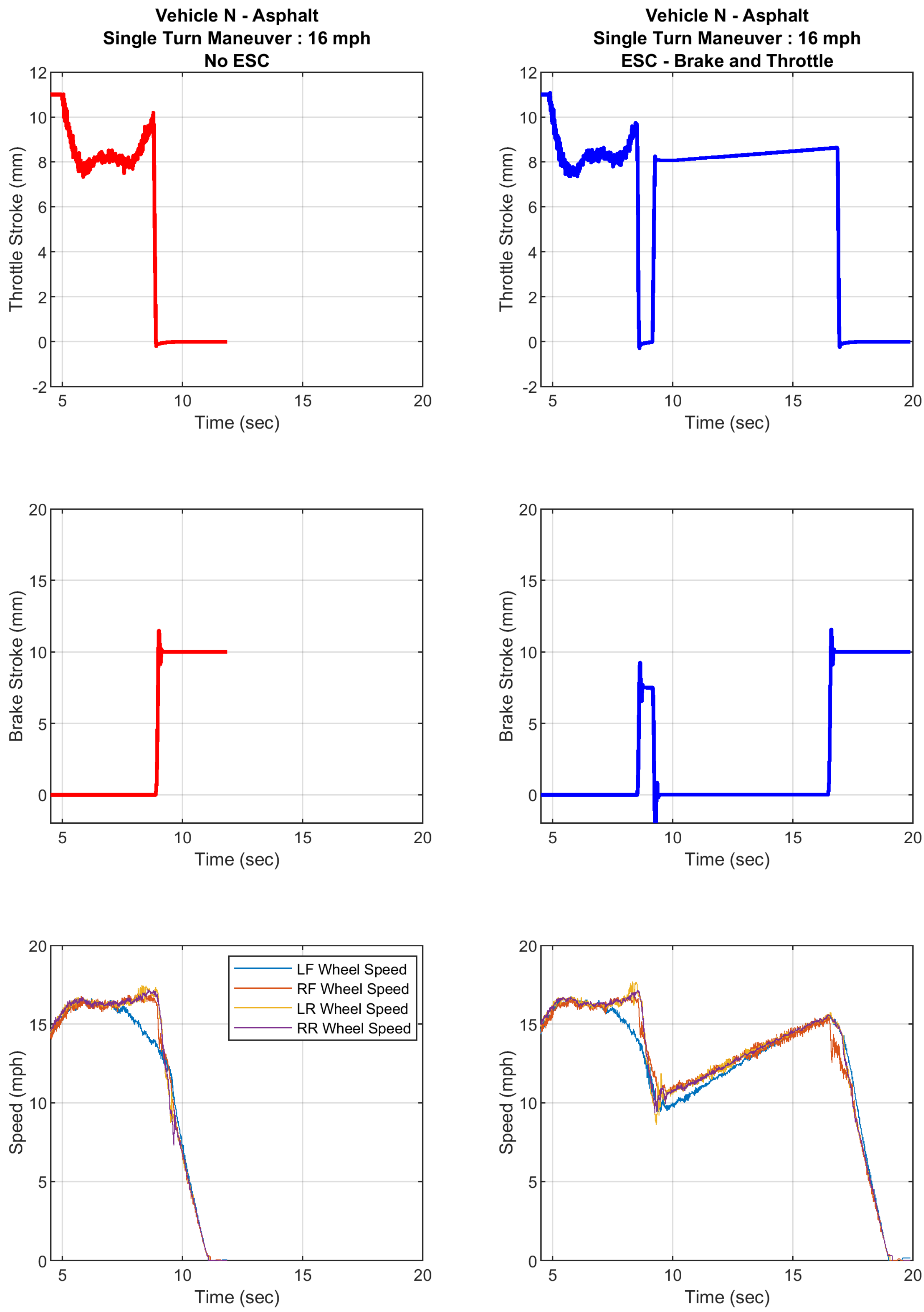
Run N1 – Vehicle N, Asphalt, Single Turn Maneuver, 16 mph – ESC: Brake and Throttle



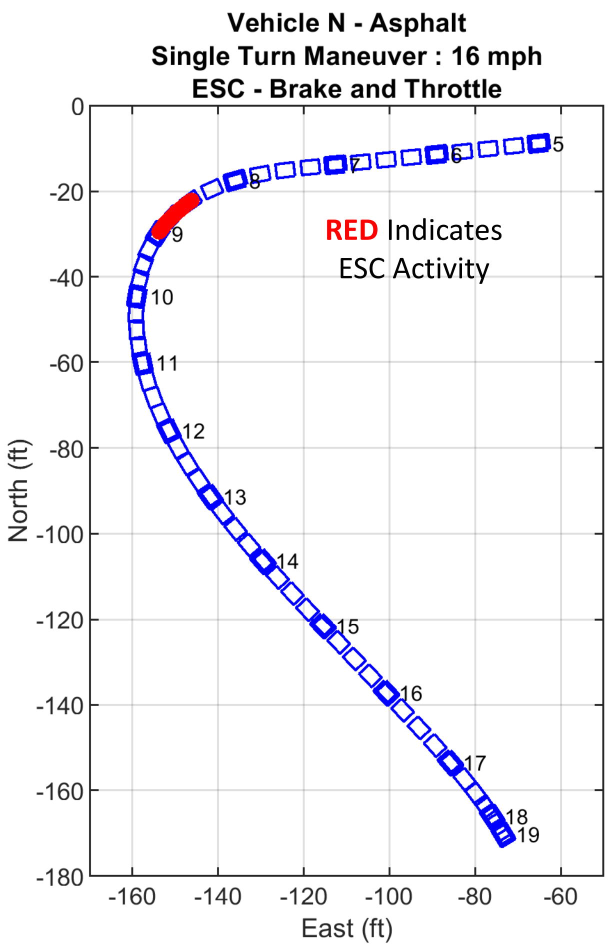
Run N1 – Vehicle N, Asphalt, Single Turn Maneuver, 16 mph – ESC: Brake and Throttle

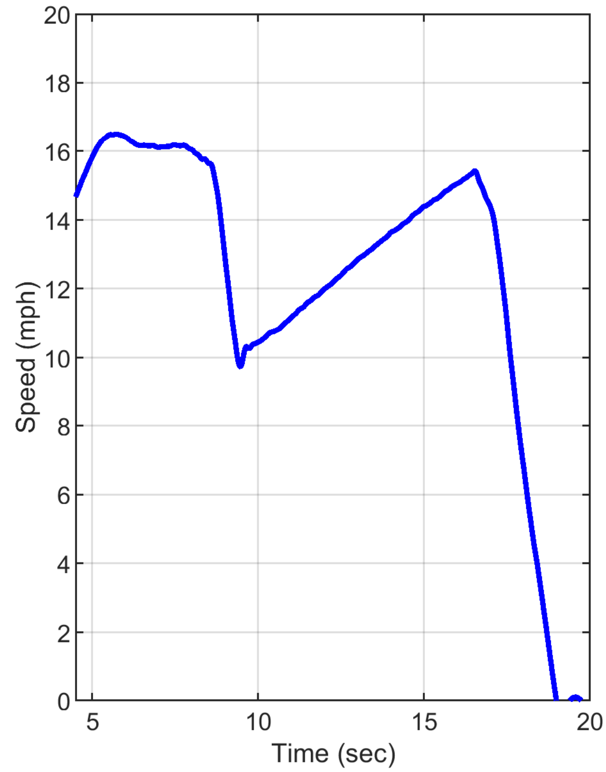


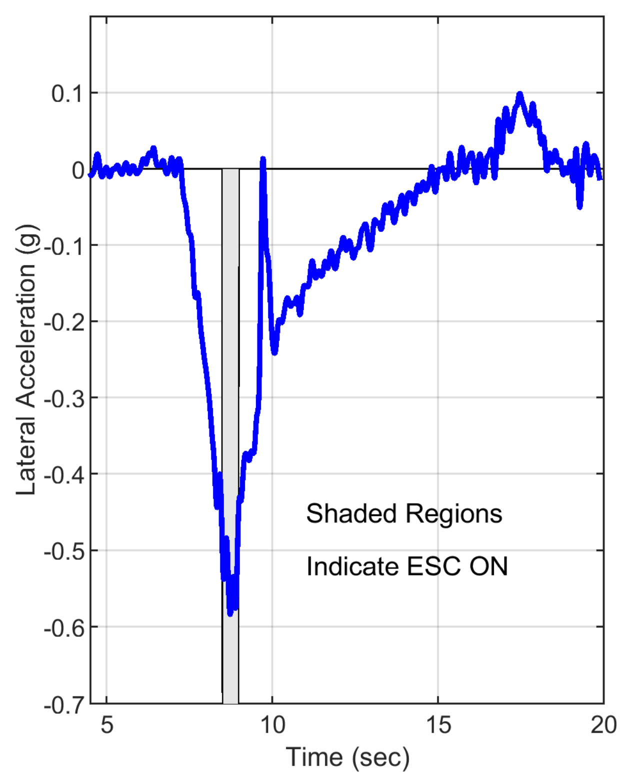
Run N1 – Vehicle N, Asphalt, Single Turn Maneuver, 16 mph – ESC: Brake and Throttle



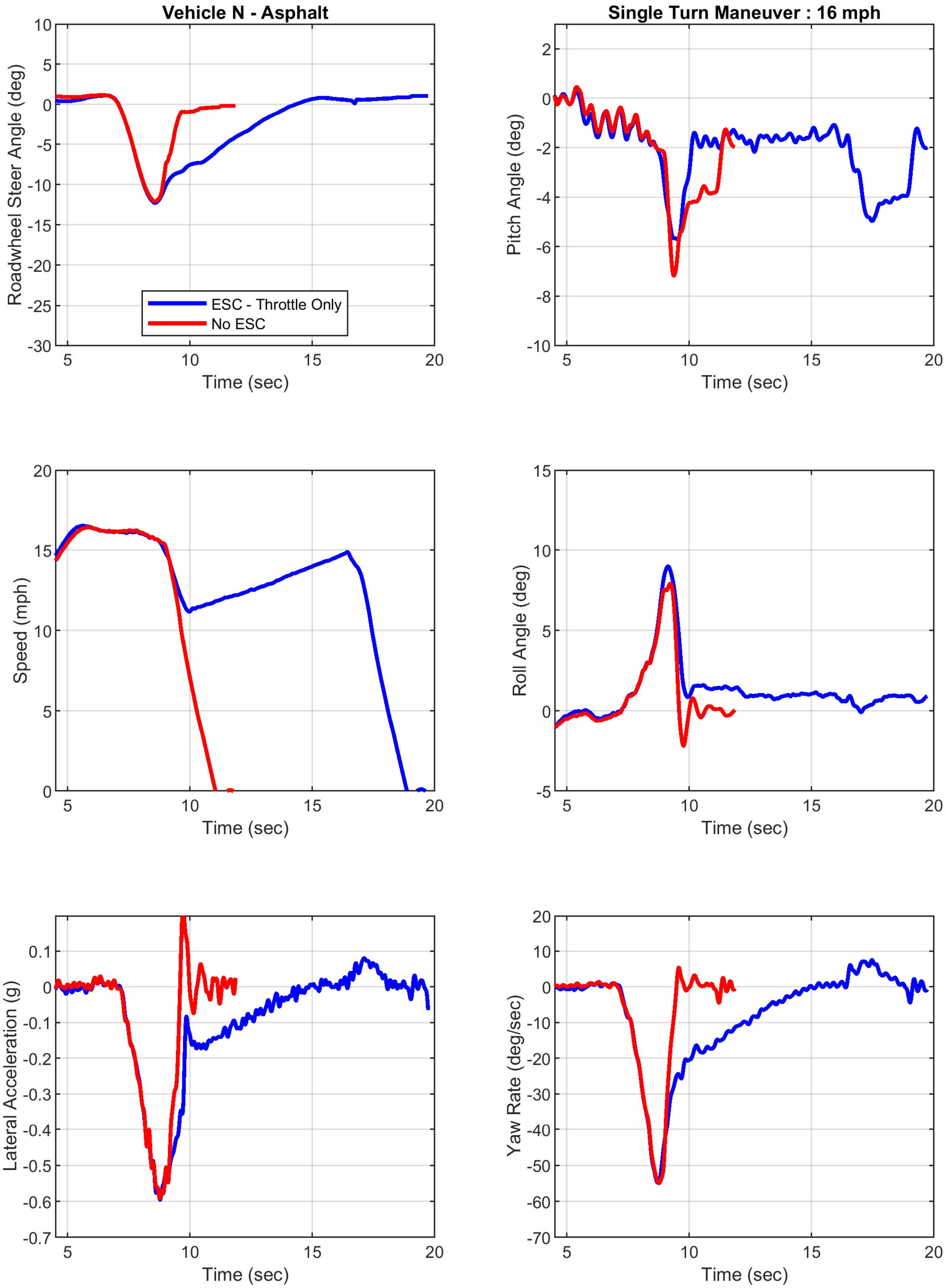
Run N1 – Vehicle N, Asphalt, Single Turn Maneuver, 16 mph – ESC: Brake and Throttle



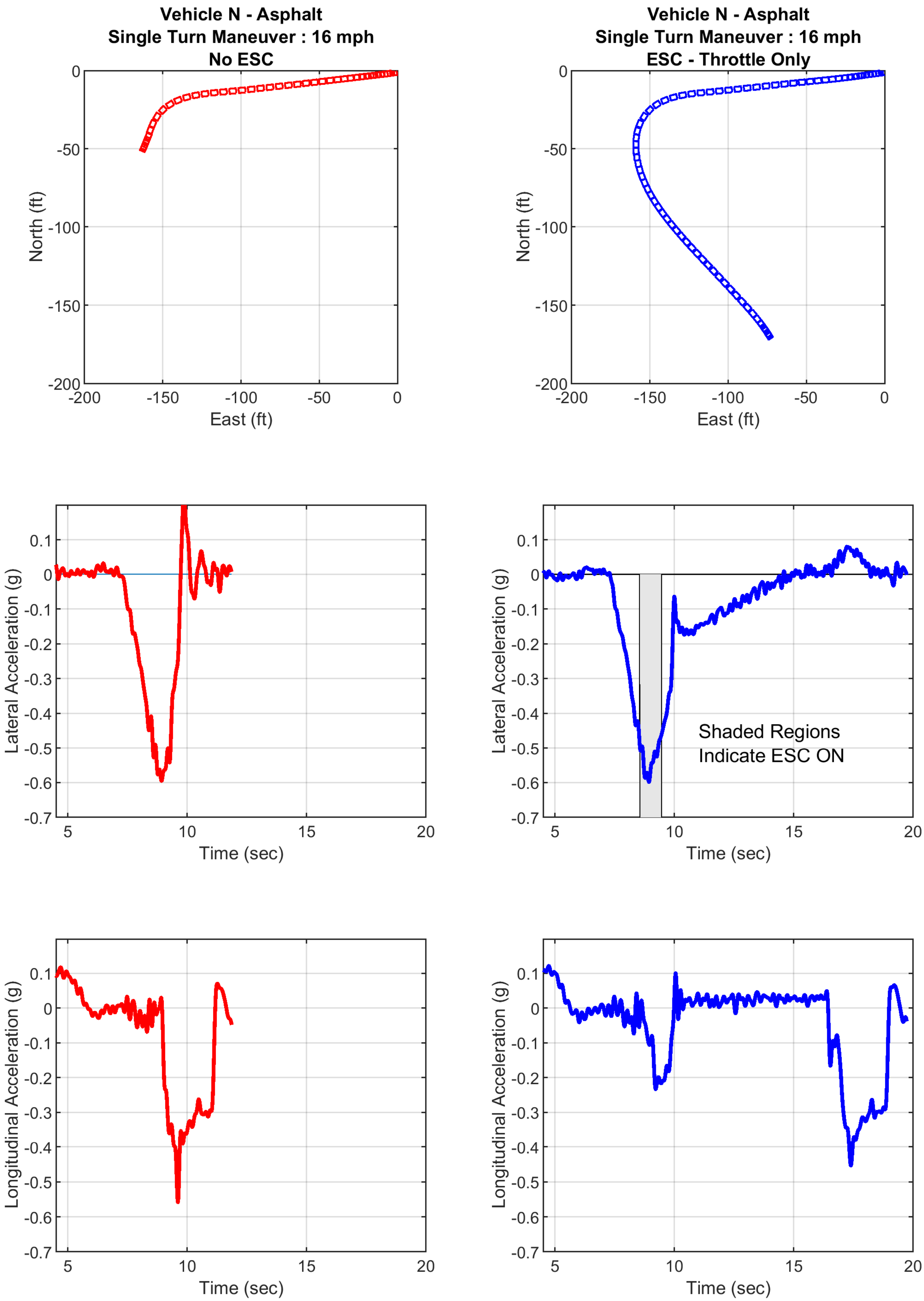




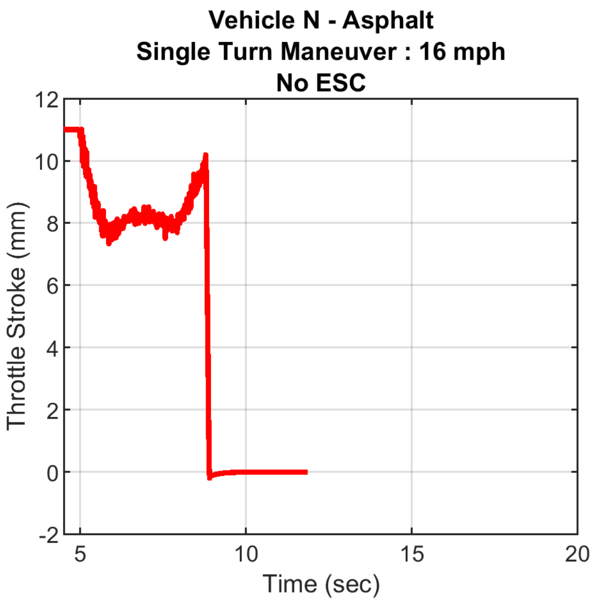
Run N2 – Vehicle N, Asphalt, Single Turn Maneuver, 16 mph – ESC: Throttle Only

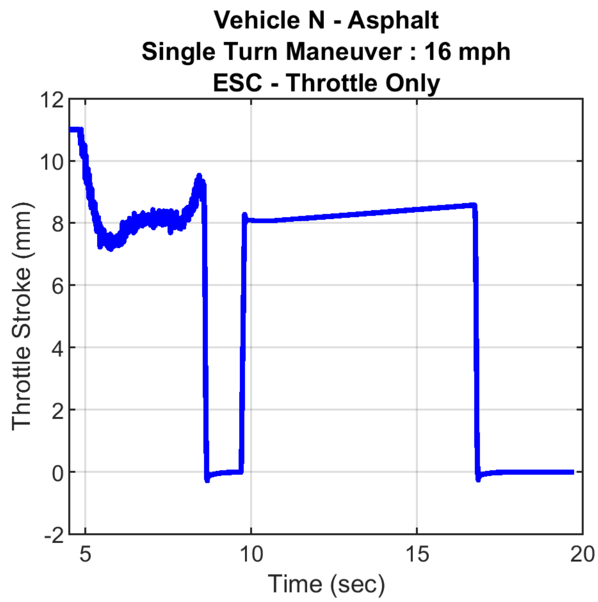


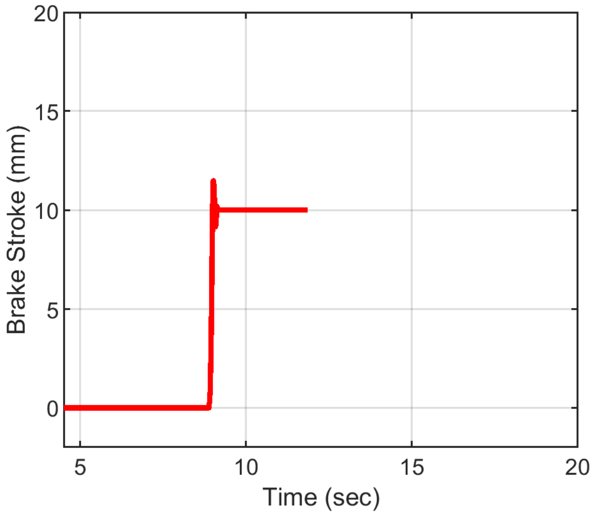
Run N2 – Vehicle N, Asphalt, Single Turn Maneuver, 16 mph – ESC: Throttle Only

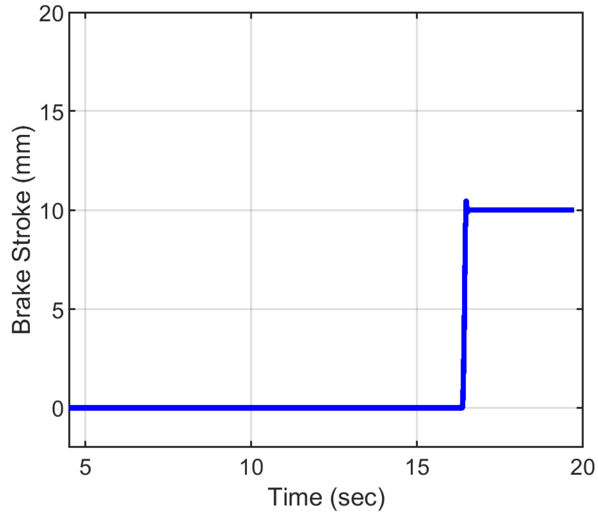


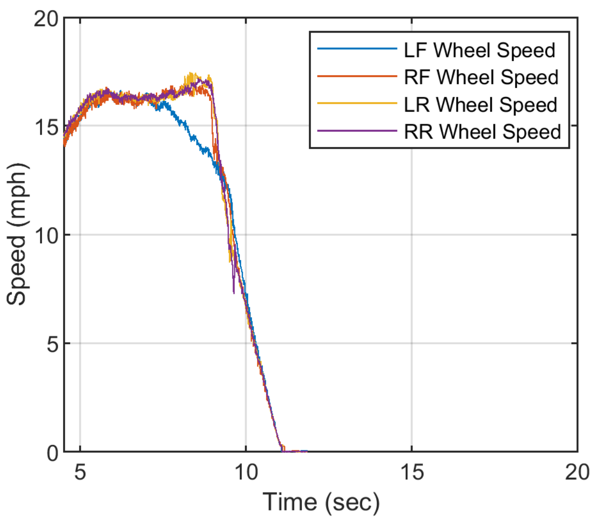
Run N2 – Vehicle N, Asphalt, Single Turn Maneuver, 16 mph – ESC: Throttle Only

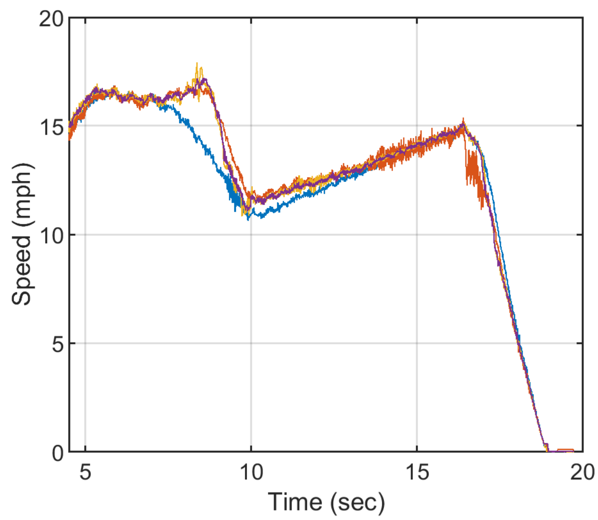




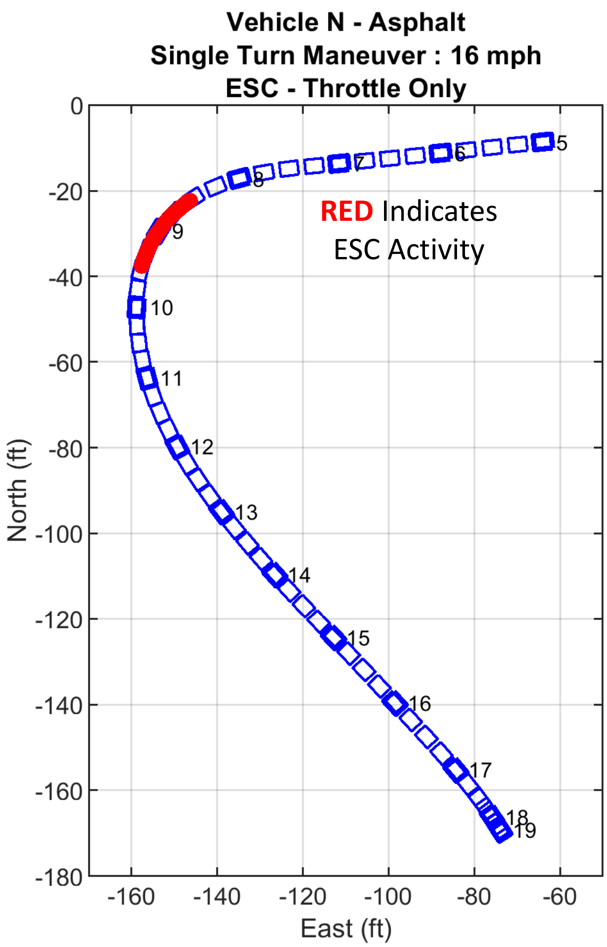


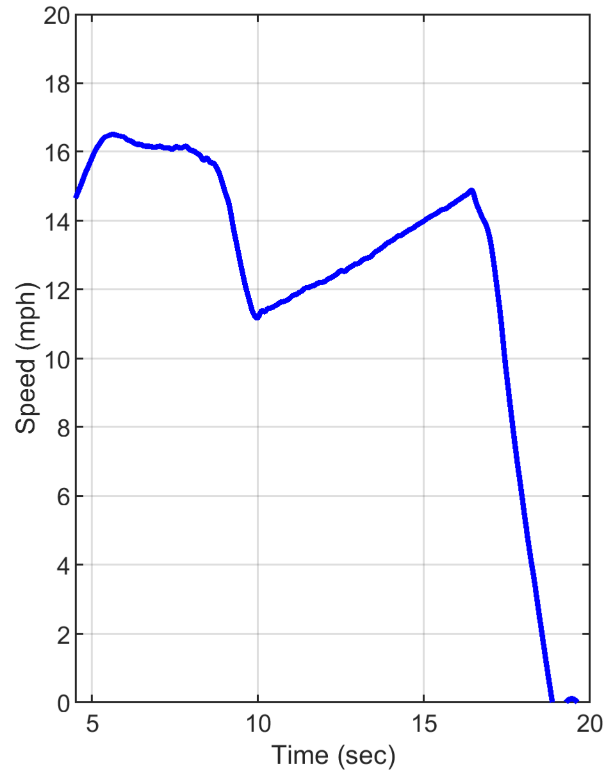


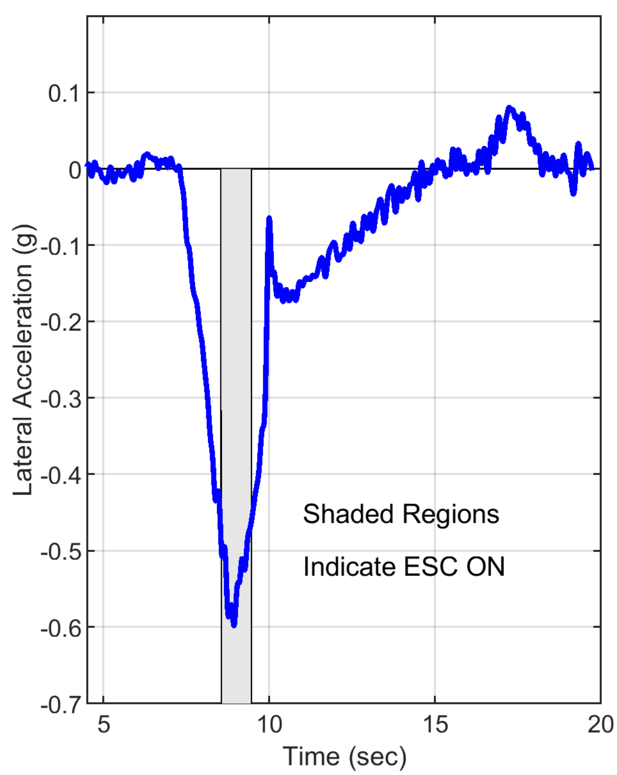




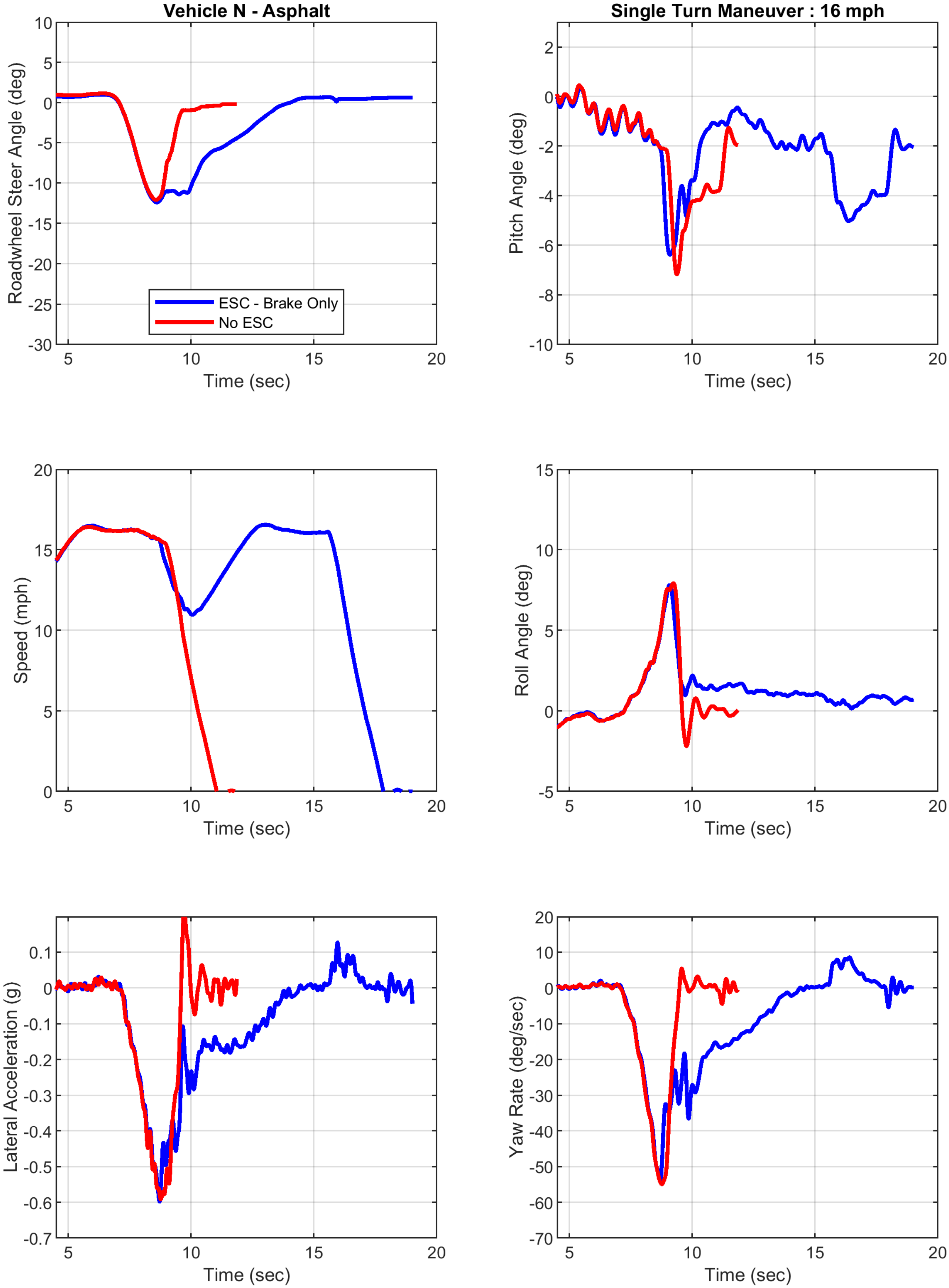
Run N2 – Vehicle N, Asphalt, Single Turn Maneuver, 16 mph – ESC: Throttle Only



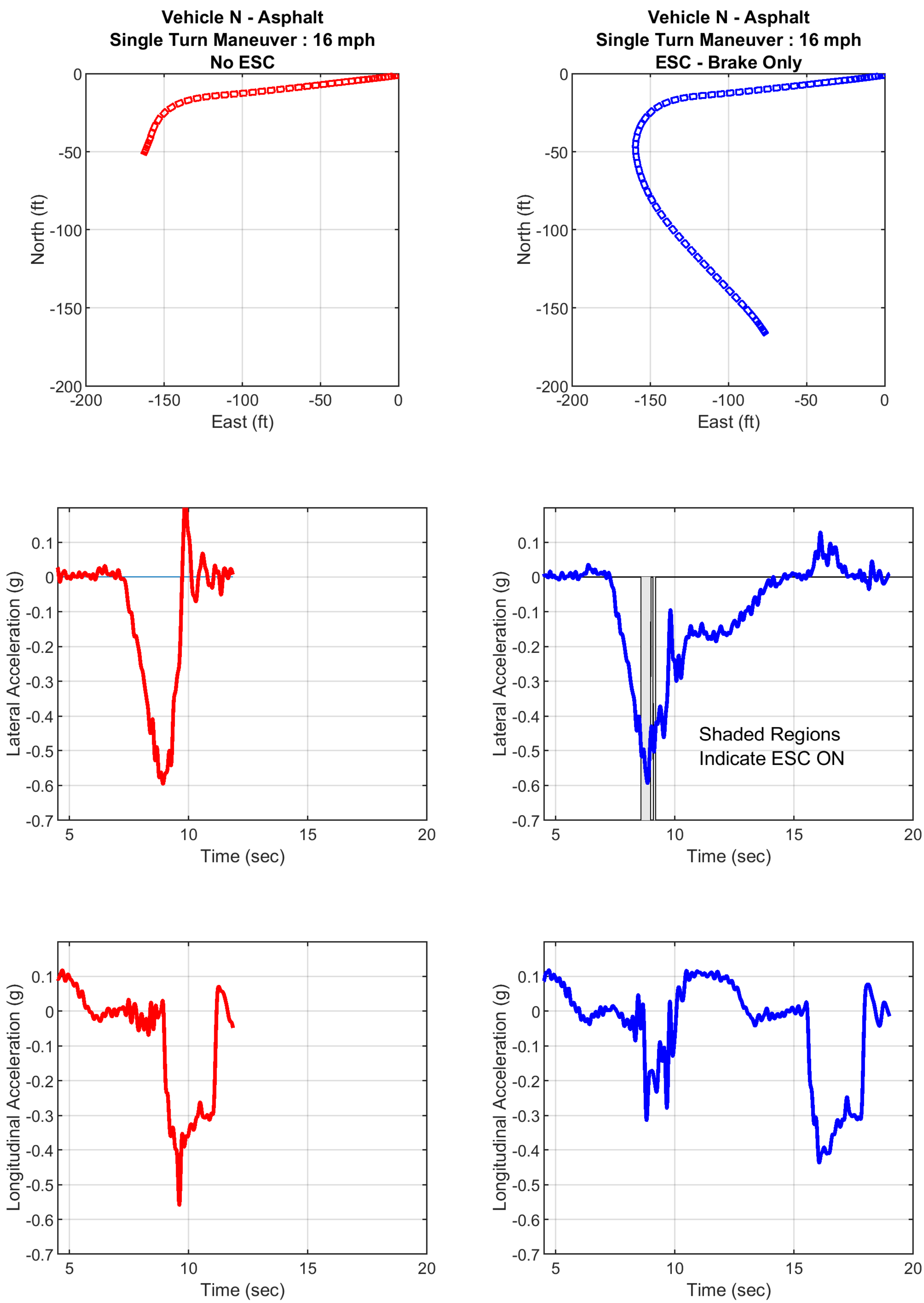




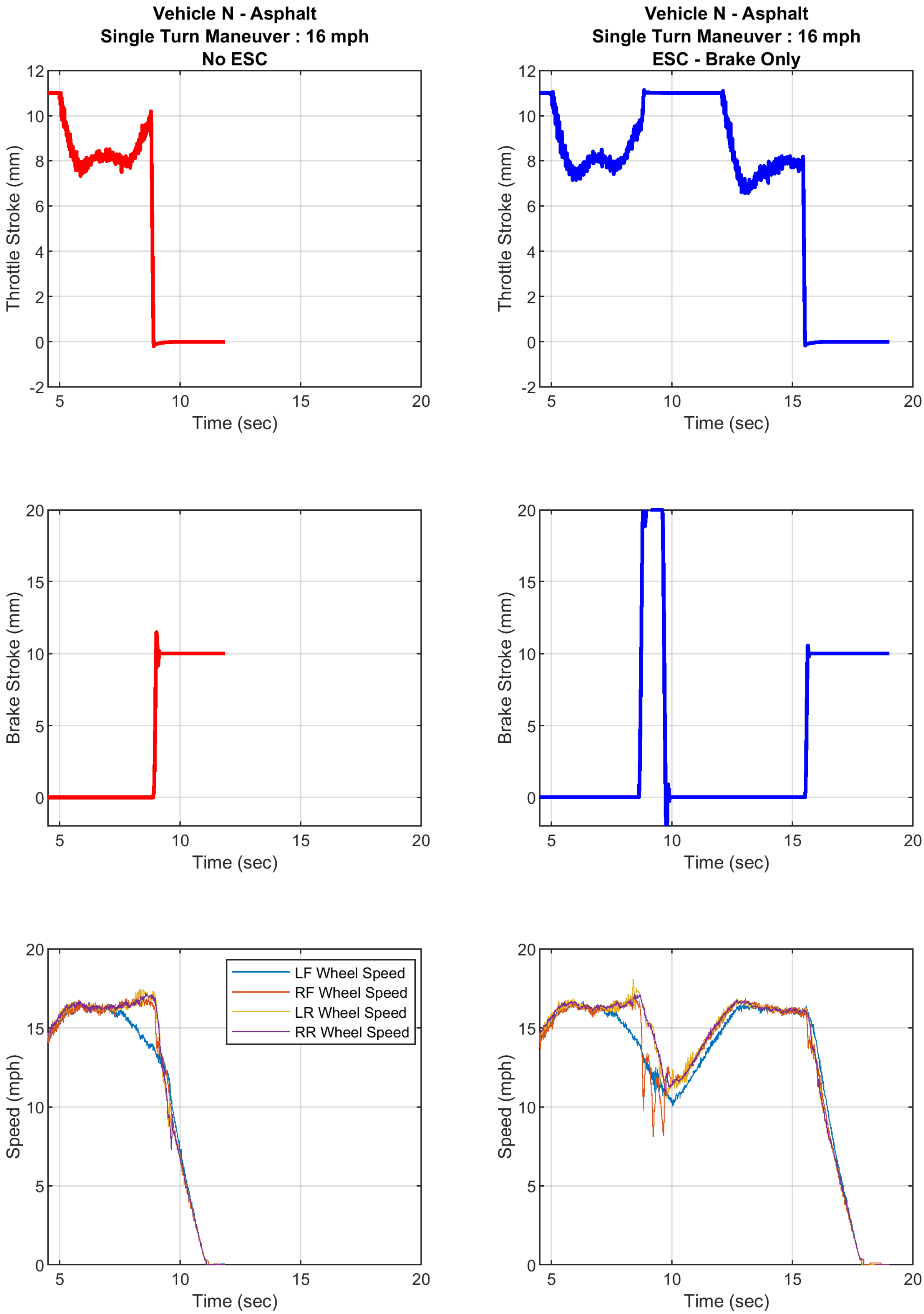
Run N3 – Vehicle N, Asphalt, Single Turn Maneuver, 16 mph – ESC: Brake Only



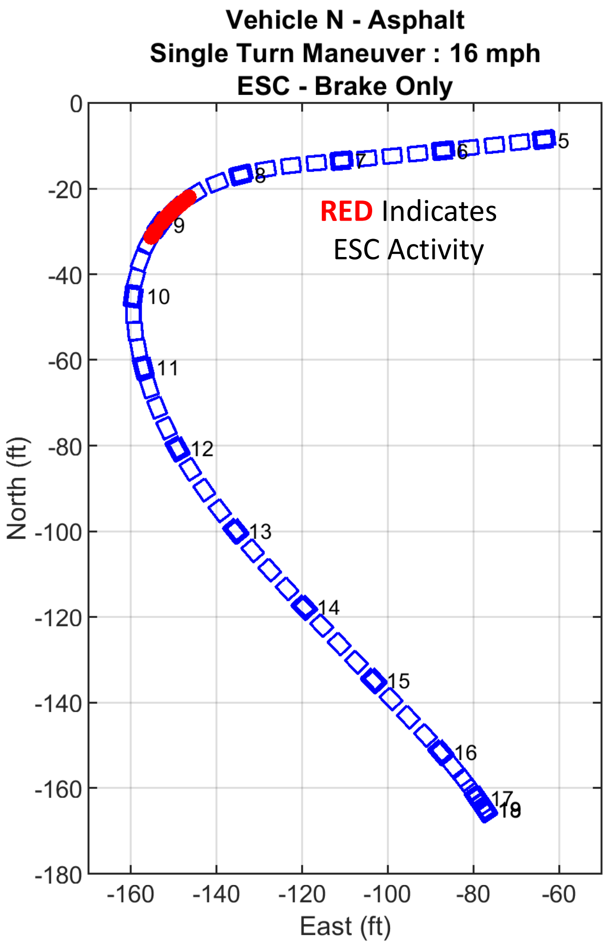
Run N3 – Vehicle N, Asphalt, Single Turn Maneuver, 16 mph – ESC: Brake Only

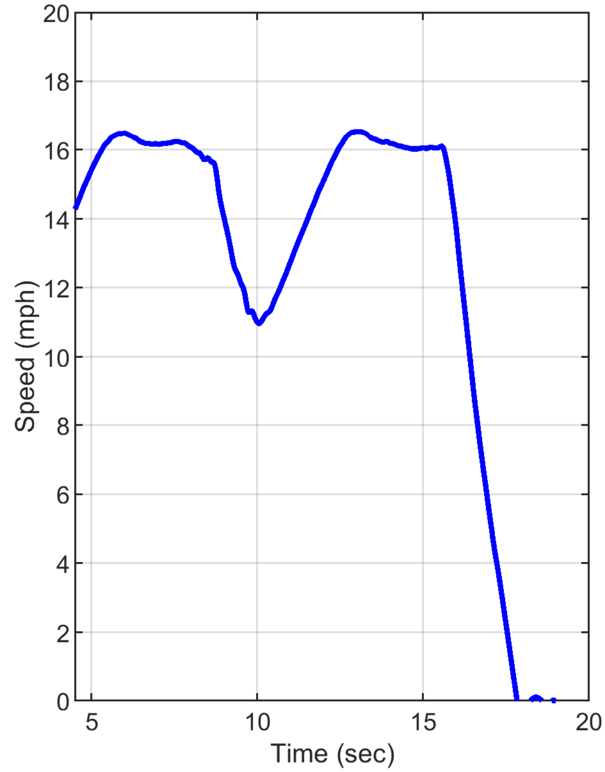


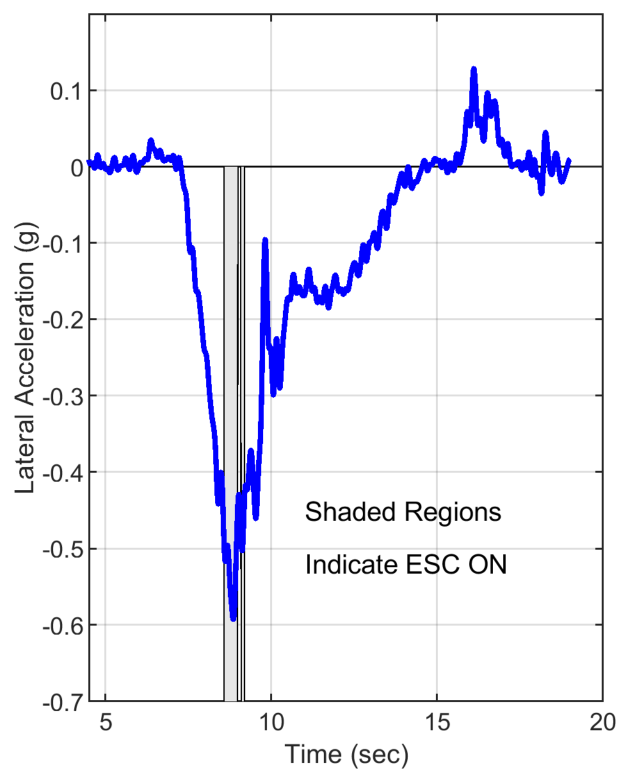
Run N3 – Vehicle N, Asphalt, Single Turn Maneuver, 16 mph – ESC: Brake Only



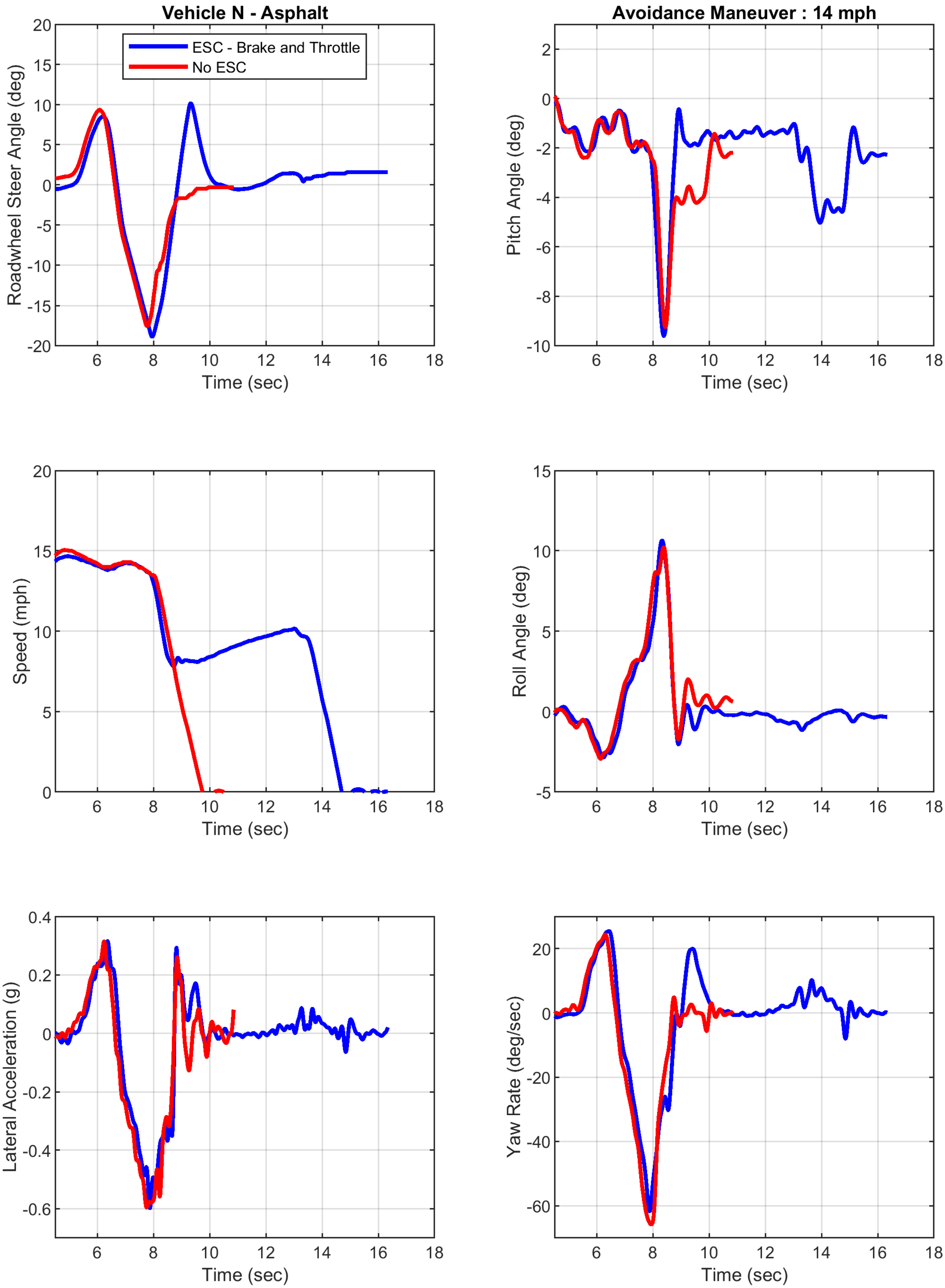
Run N3 – Vehicle N, Asphalt, Single Turn Maneuver, 16 mph – ESC: Brake Only



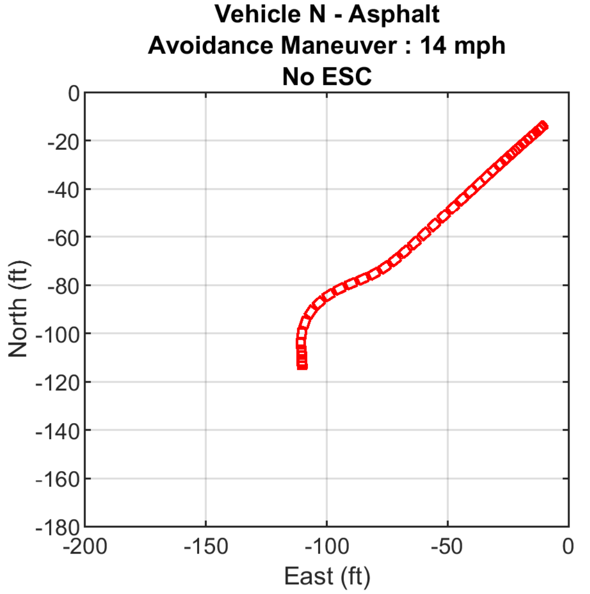


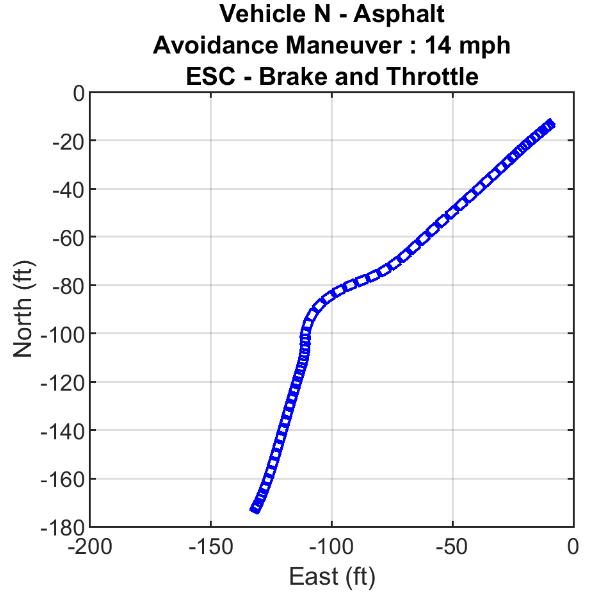


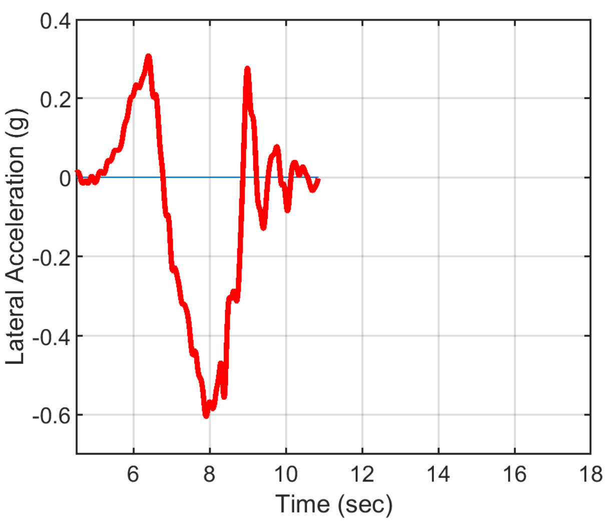
Run N4 – Vehicle N, Asphalt, Avoidance Maneuver, 14 mph – ESC: Brake and Throttle

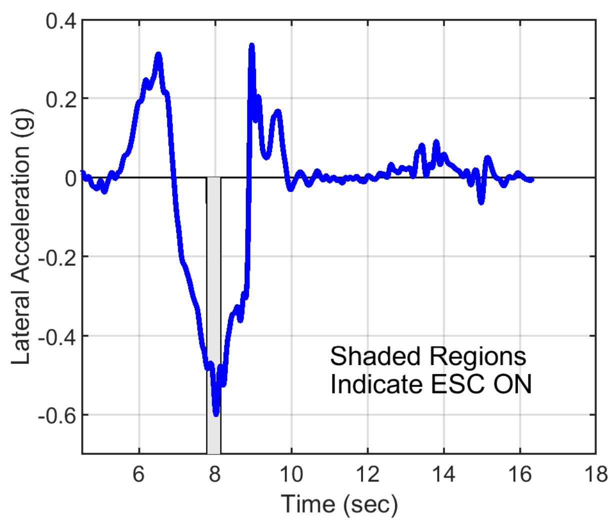


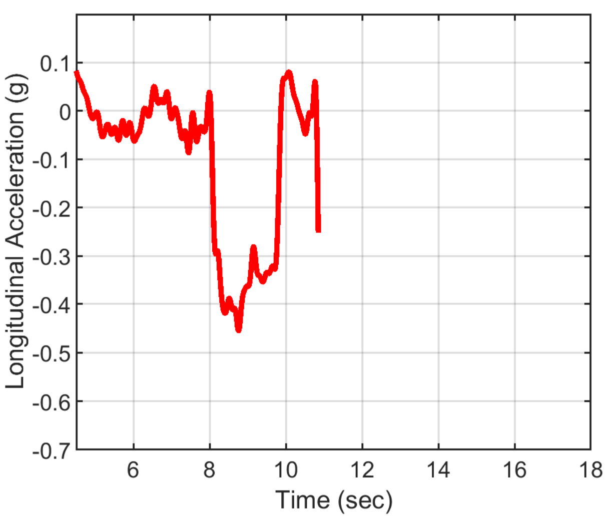
Run N4 – Vehicle N, Asphalt, Avoidance Maneuver, 14 mph – ESC: Brake and Throttle

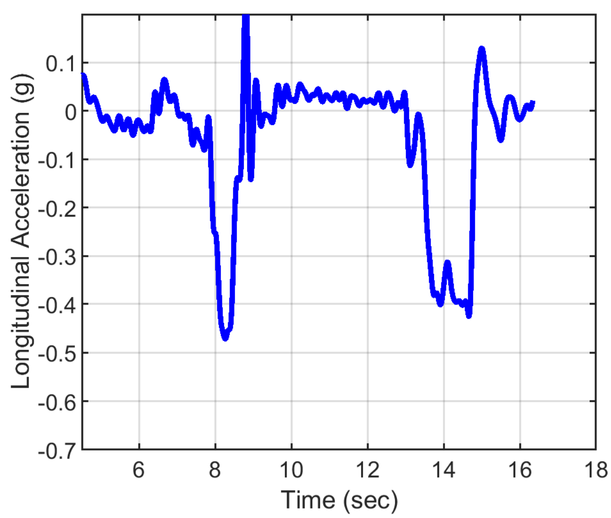




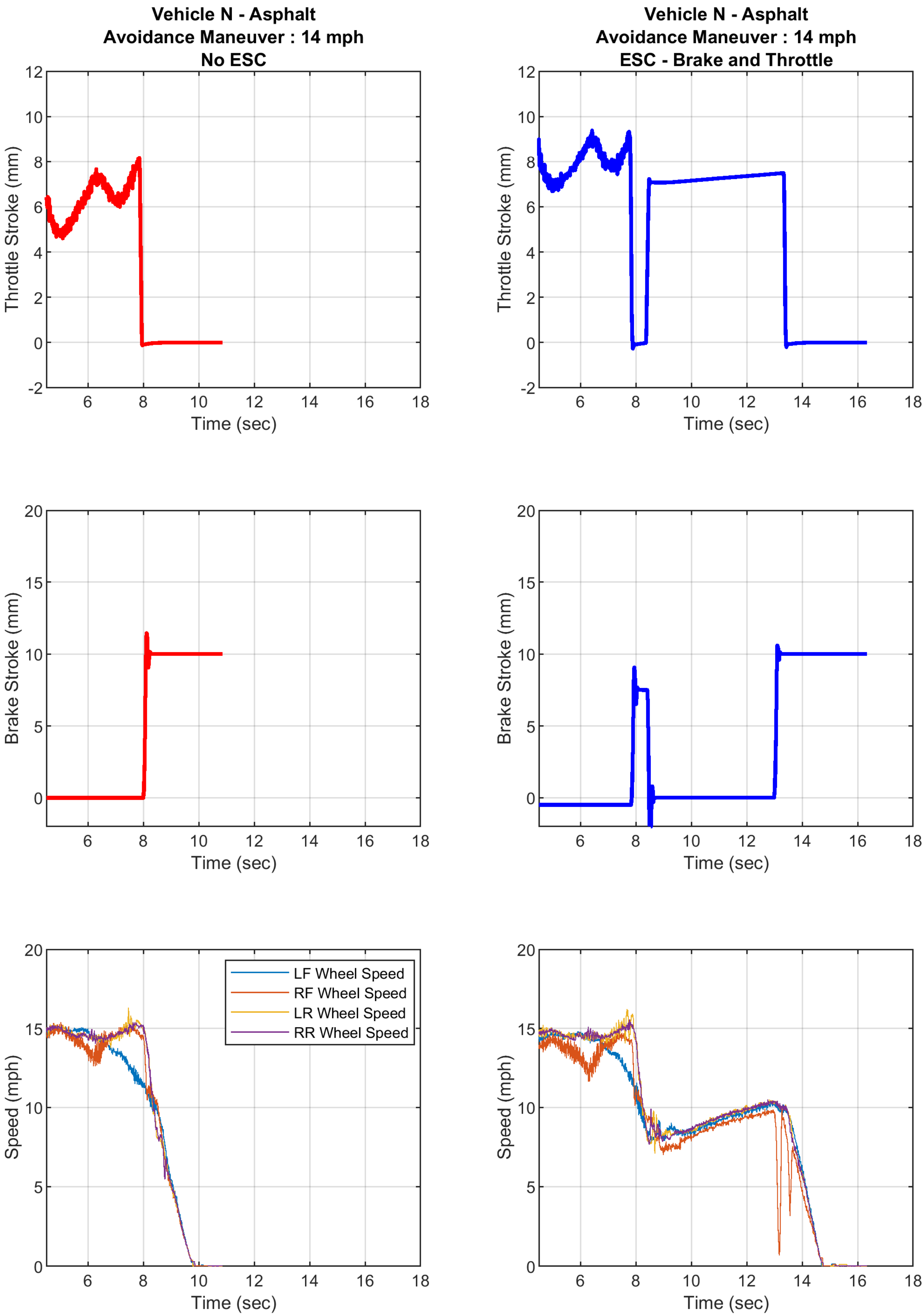




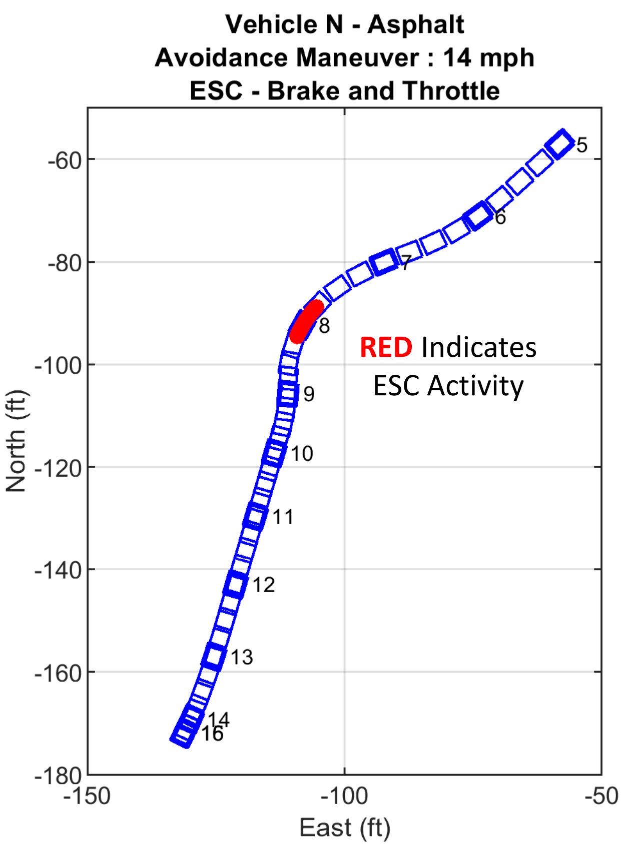


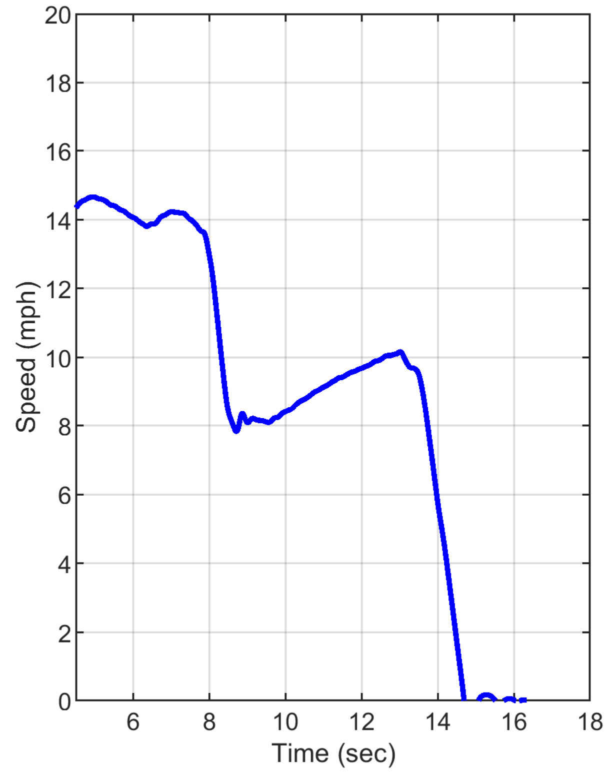


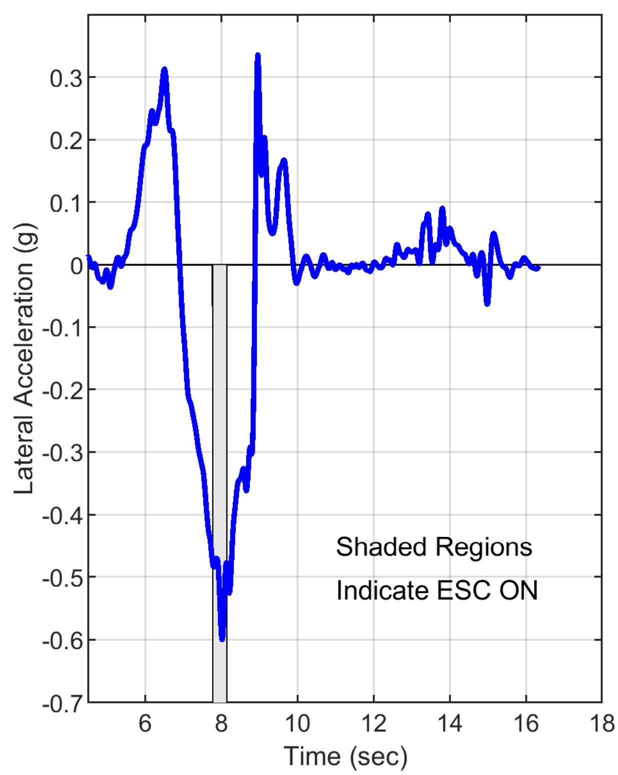
Run N4 – Vehicle N, Asphalt, Avoidance Maneuver, 14 mph – ESC: Brake and Throttle



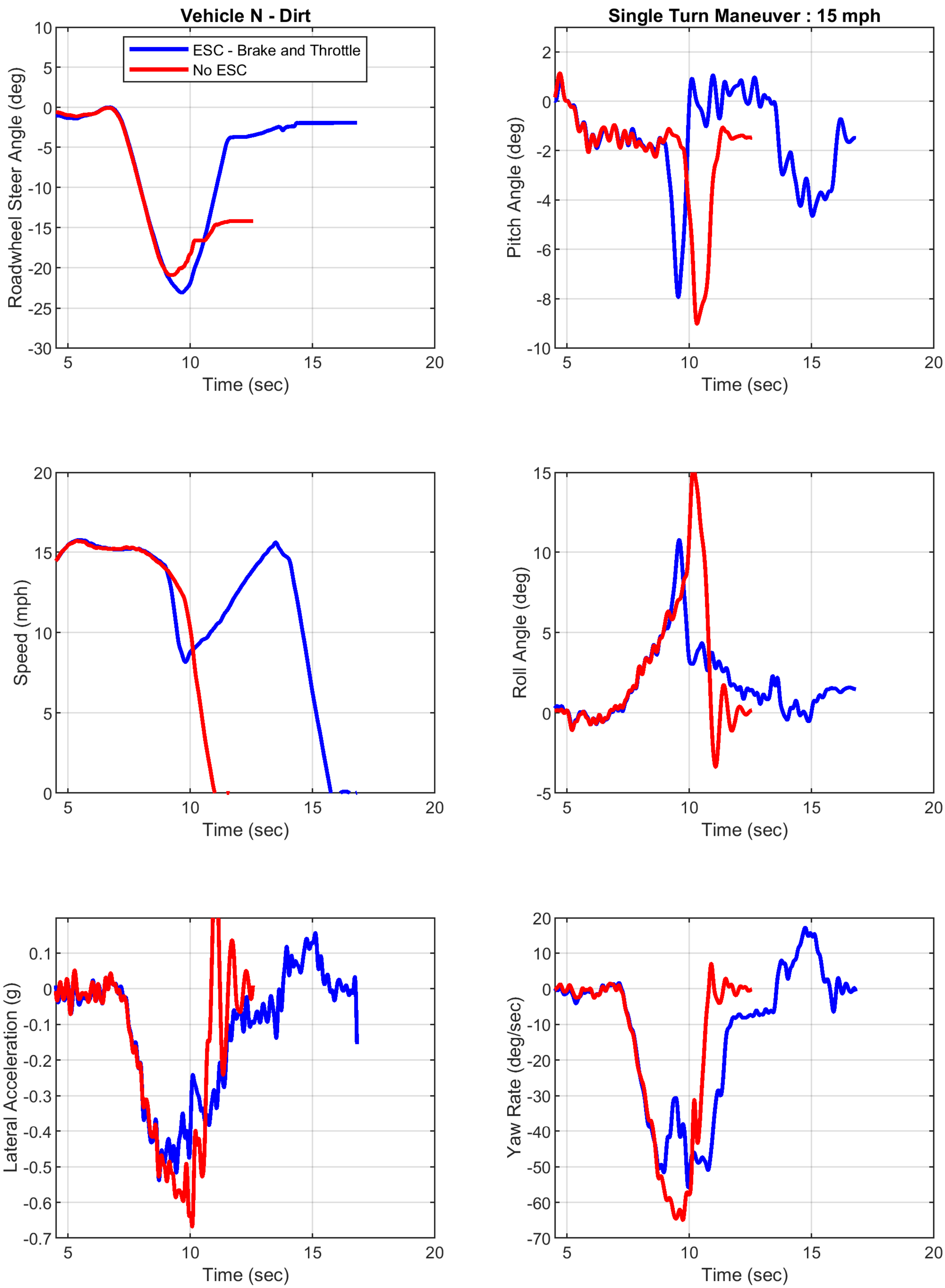
Run N4 – Vehicle N, Asphalt, Avoidance Maneuver, 14 mph – ESC: Brake and Throttle



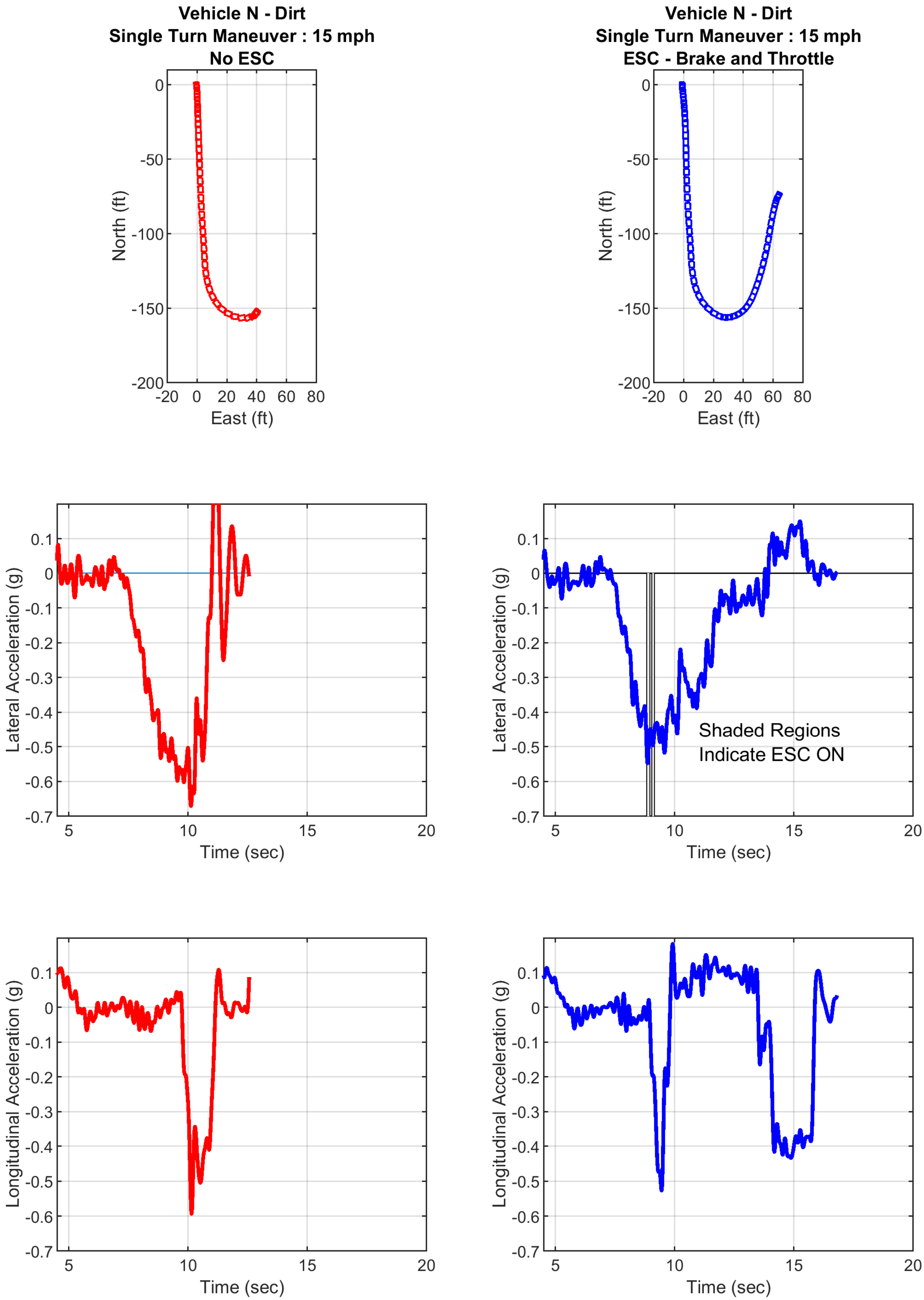




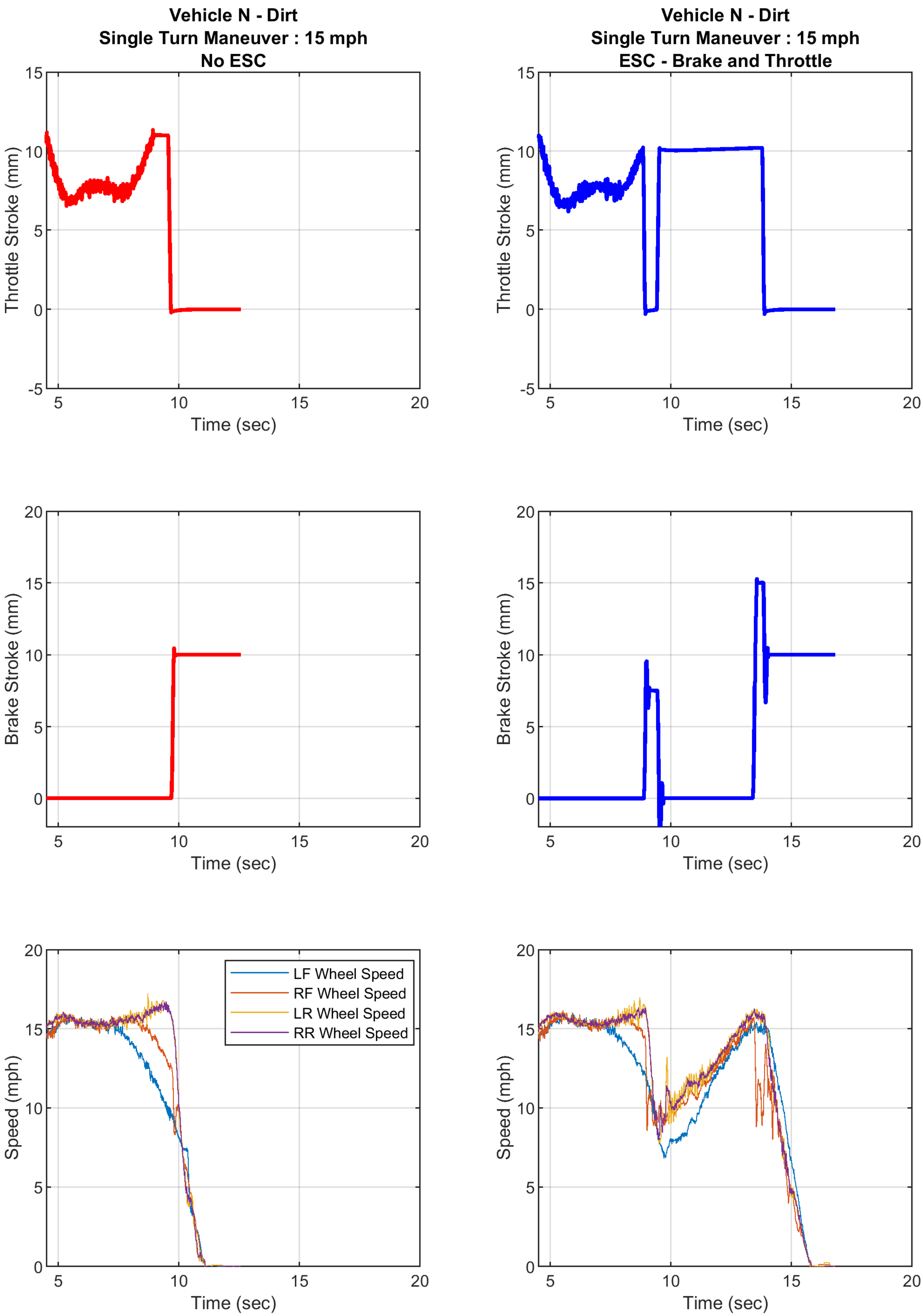
Run N5 – Vehicle N, Dirt, Single Turn Maneuver, 15 mph – ESC: Brake and Throttle



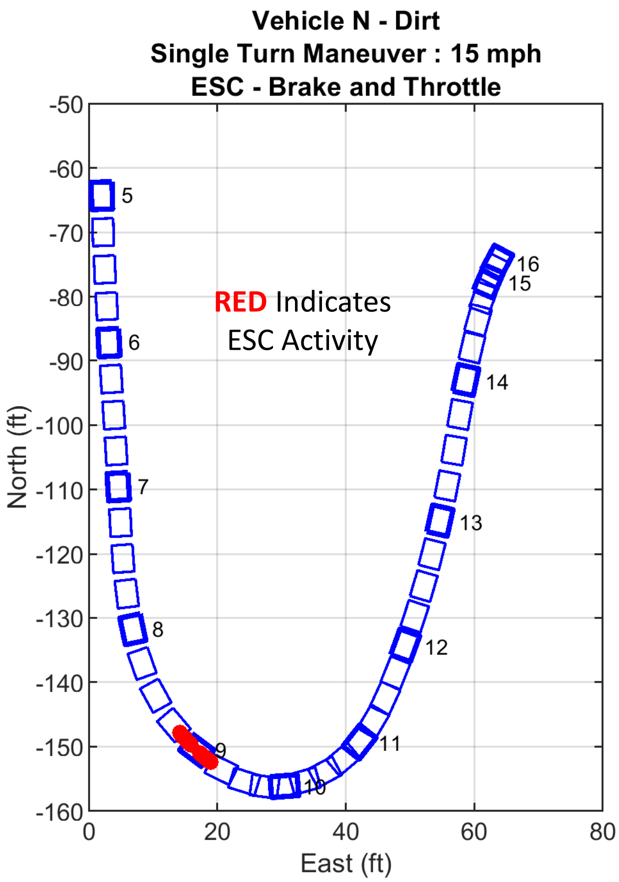
Run N5 – Vehicle N, Dirt, Single Turn Maneuver, 15 mph – ESC: Brake and Throttle

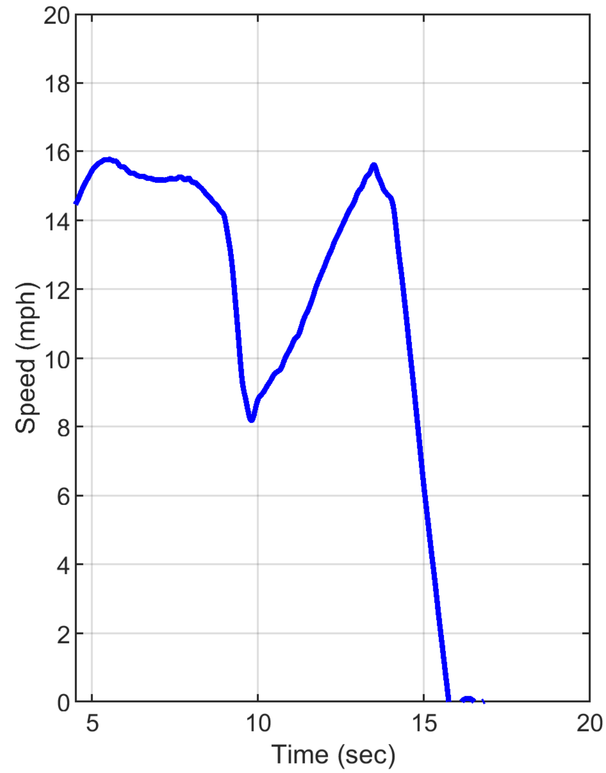


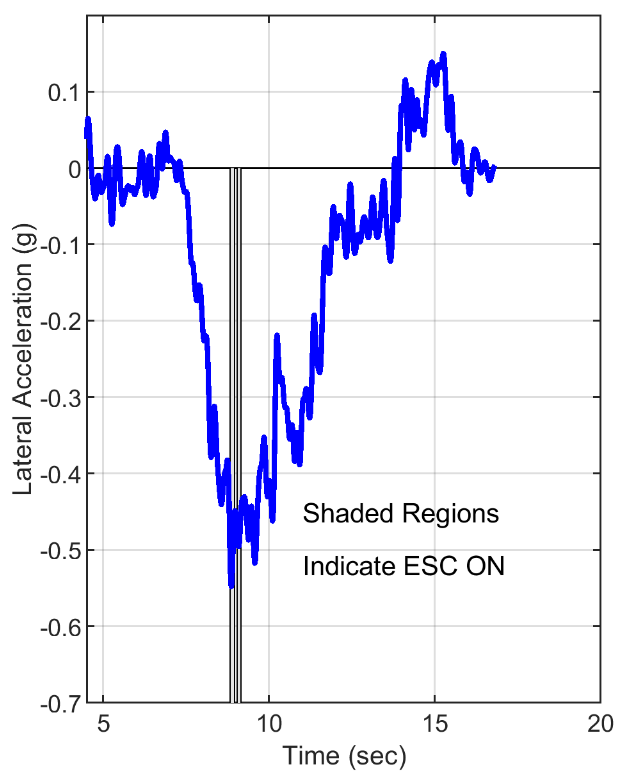
Run N5 – Vehicle N, Dirt, Single Turn Maneuver, 15 mph – ESC: Brake and Throttle



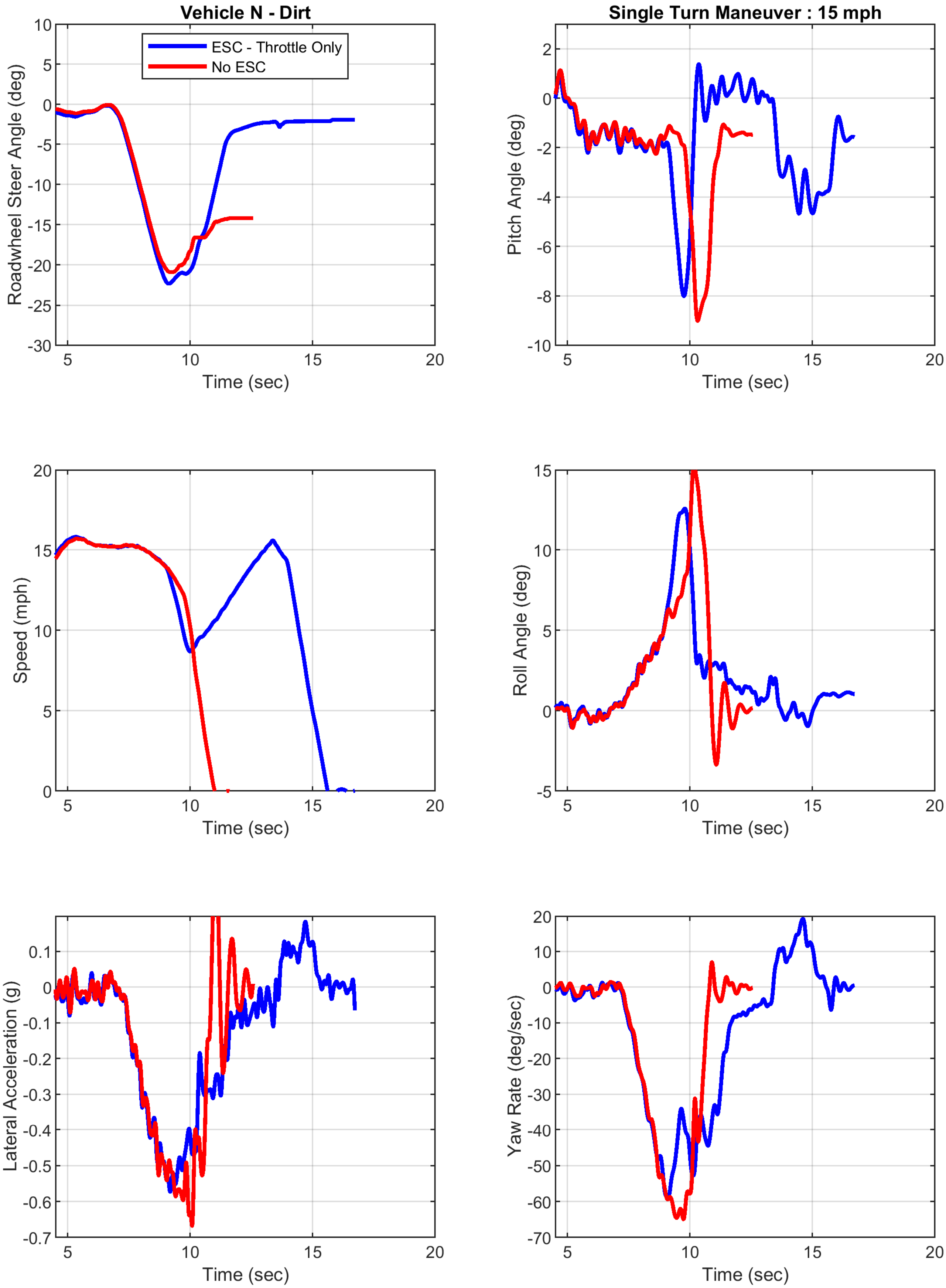
Run N5 – Vehicle N, Dirt, Single Turn Maneuver, 15 mph – ESC: Brake and Throttle



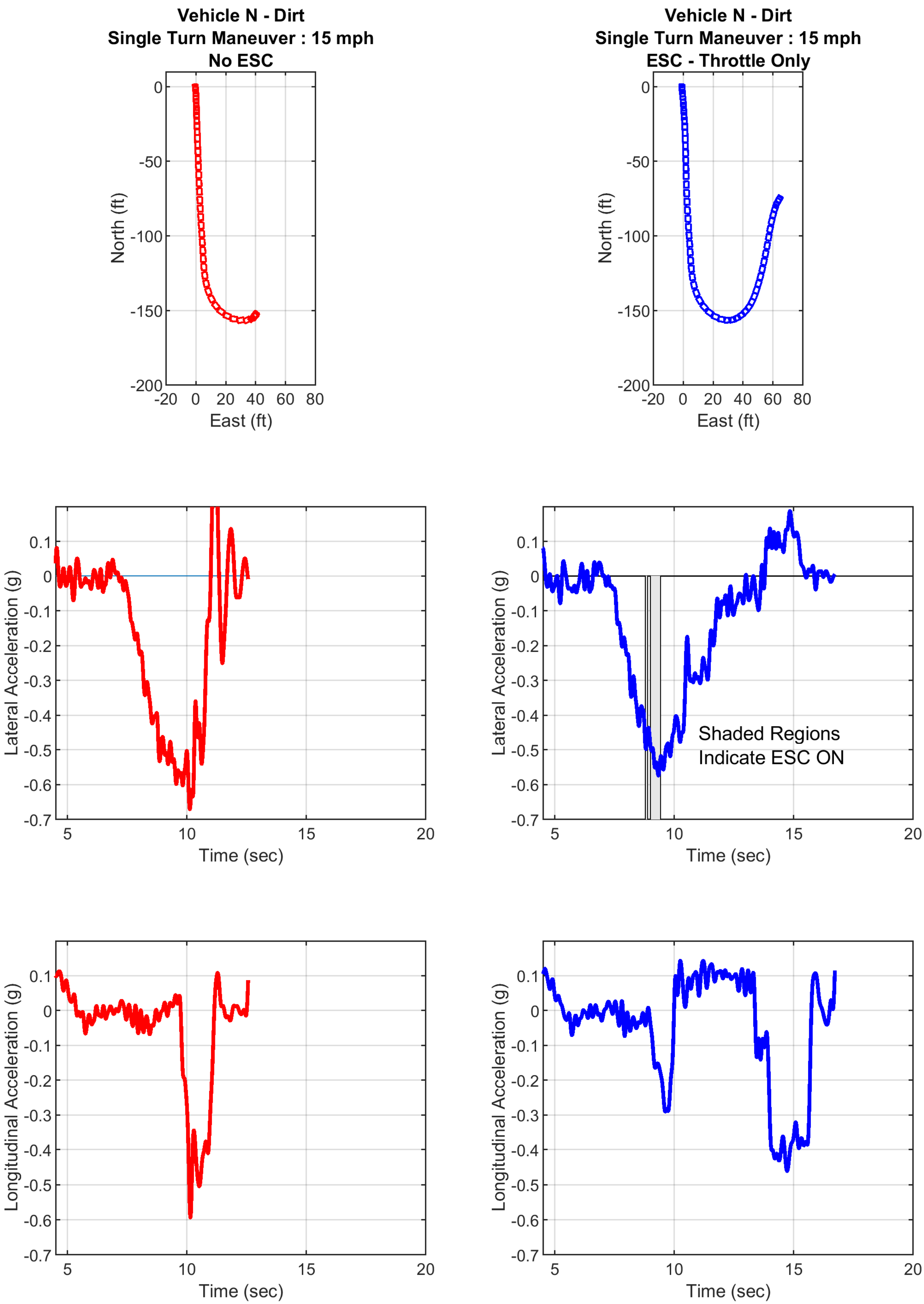




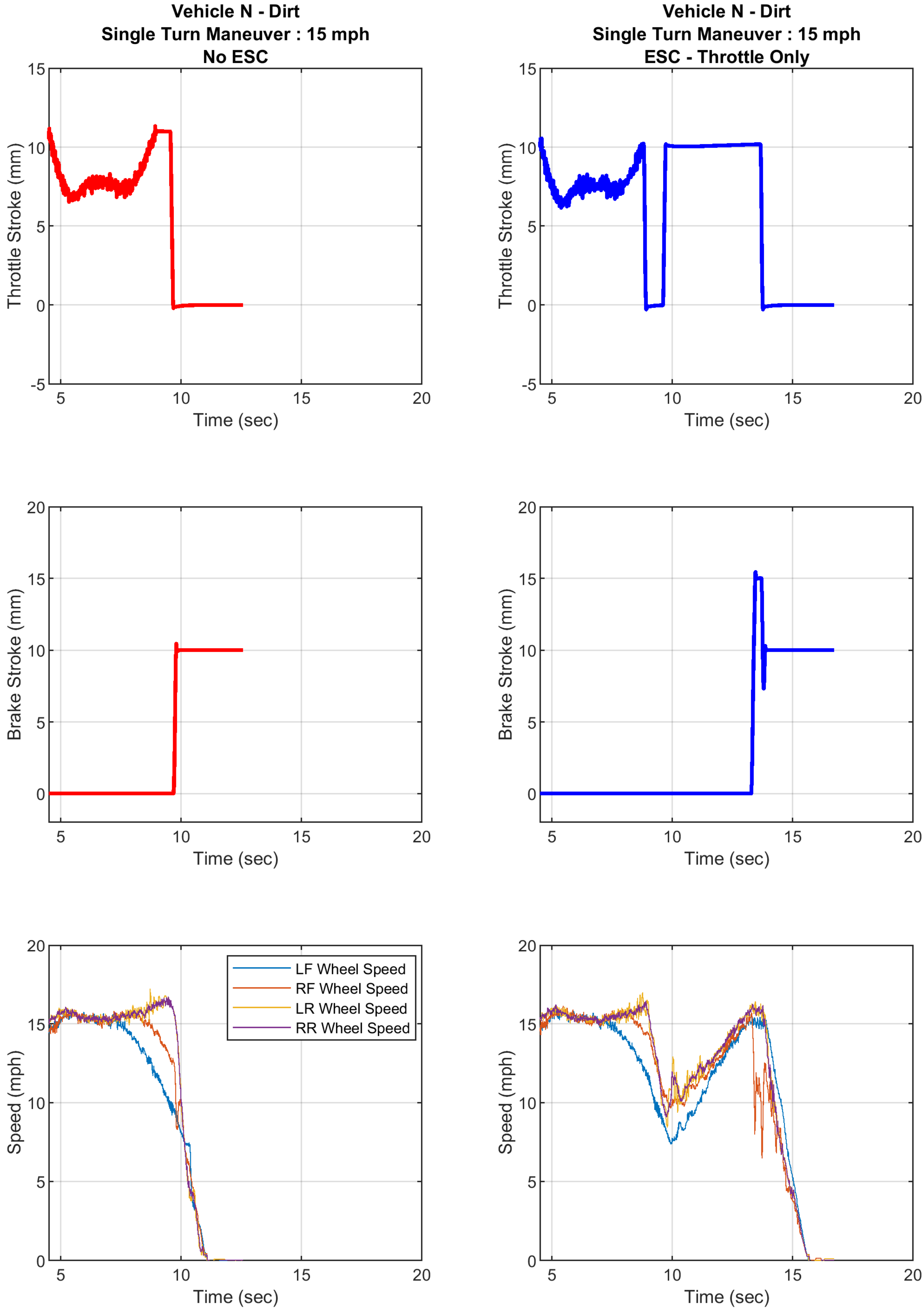
Run N6 – Vehicle N, Dirt, Single Turn Maneuver, 15 mph – ESC: Throttle Only



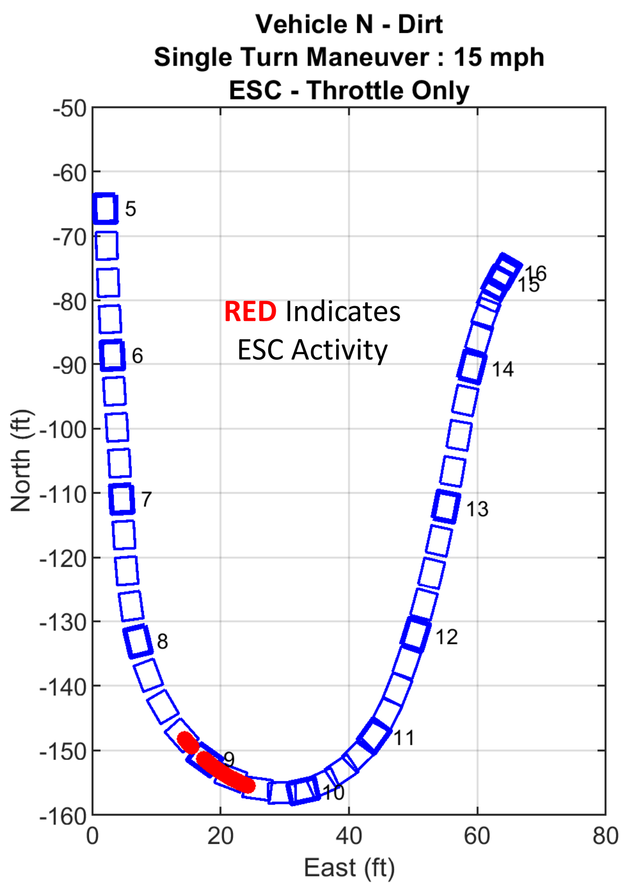
Run N6 – Vehicle N, Dirt, Single Turn Maneuver, 15 mph – ESC: Throttle Only

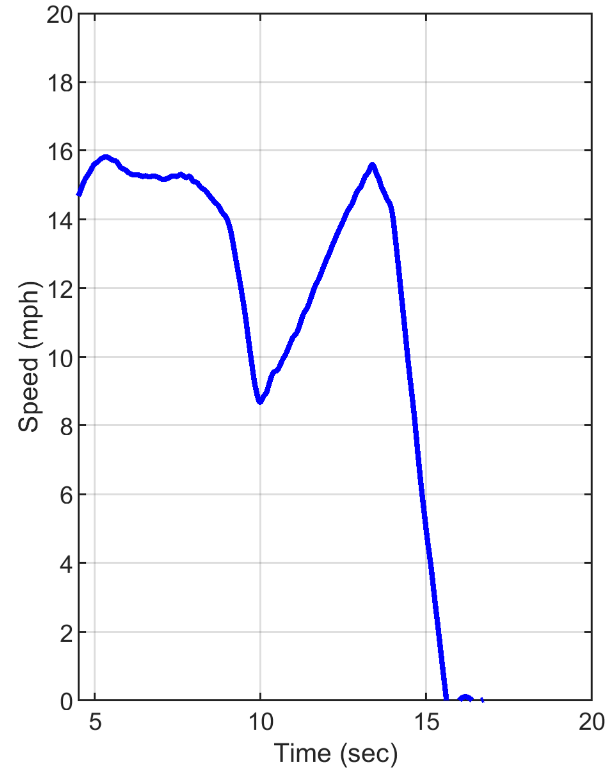


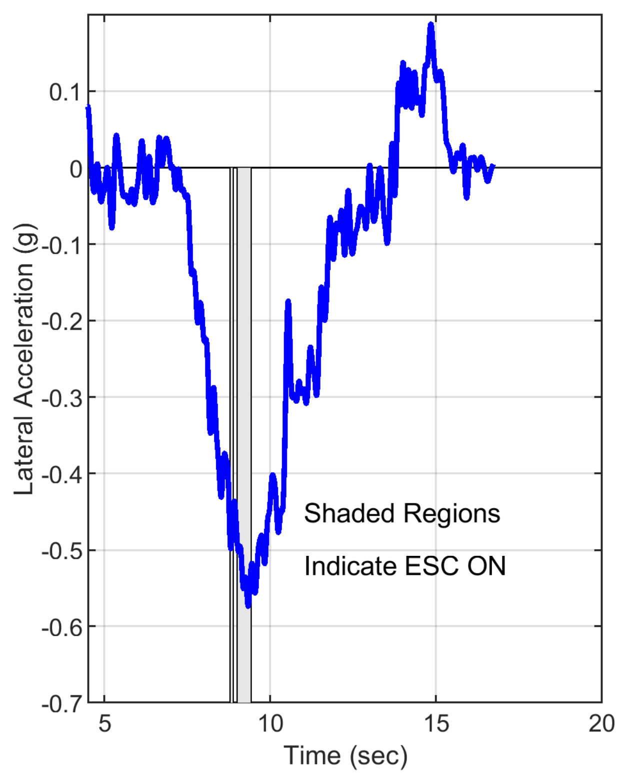
Run N6 – Vehicle N, Dirt, Single Turn Maneuver, 15 mph – ESC: Throttle Only



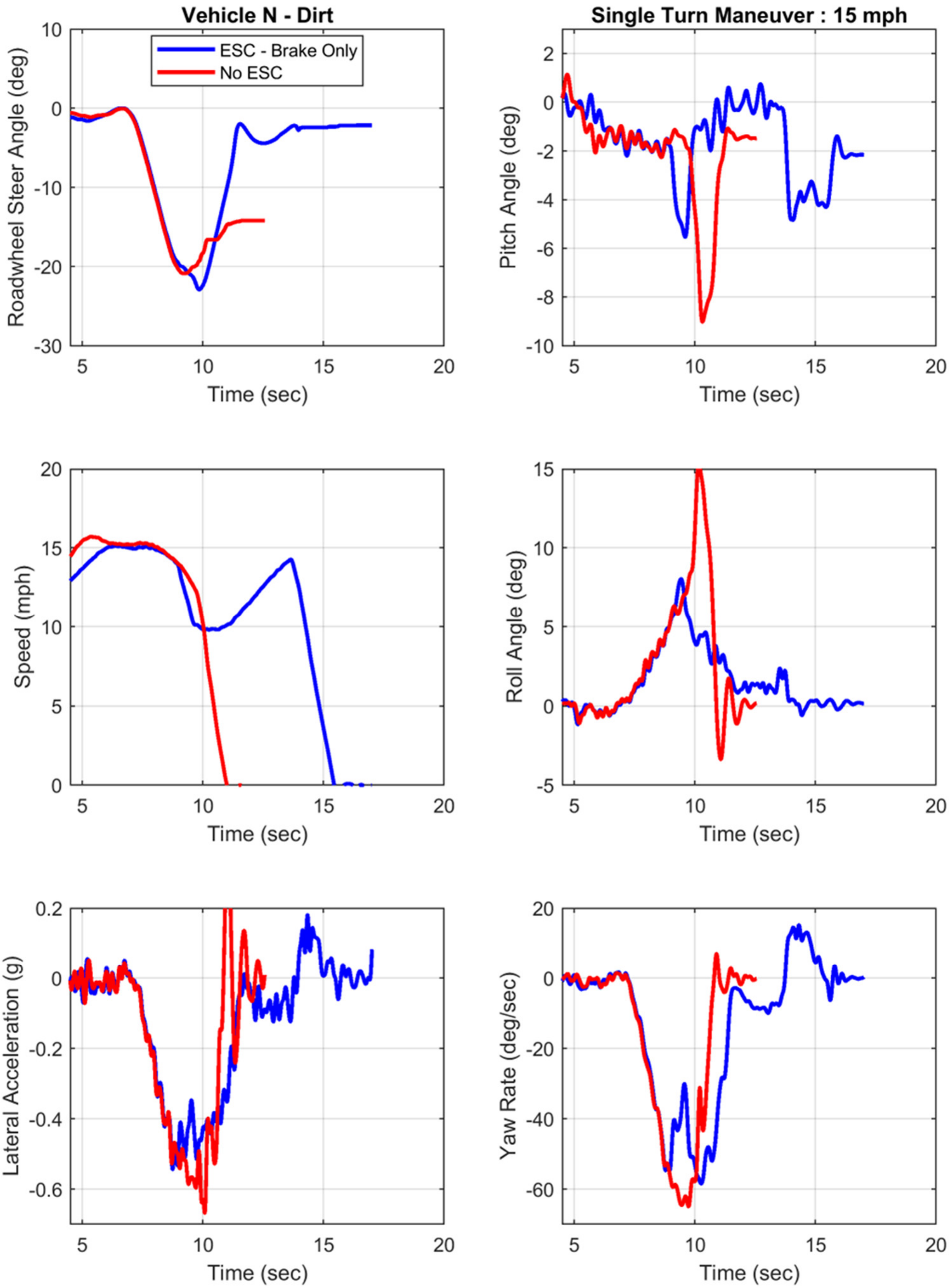
Run N6 – Vehicle N, Dirt, Single Turn Maneuver, 15 mph – ESC: Throttle Only



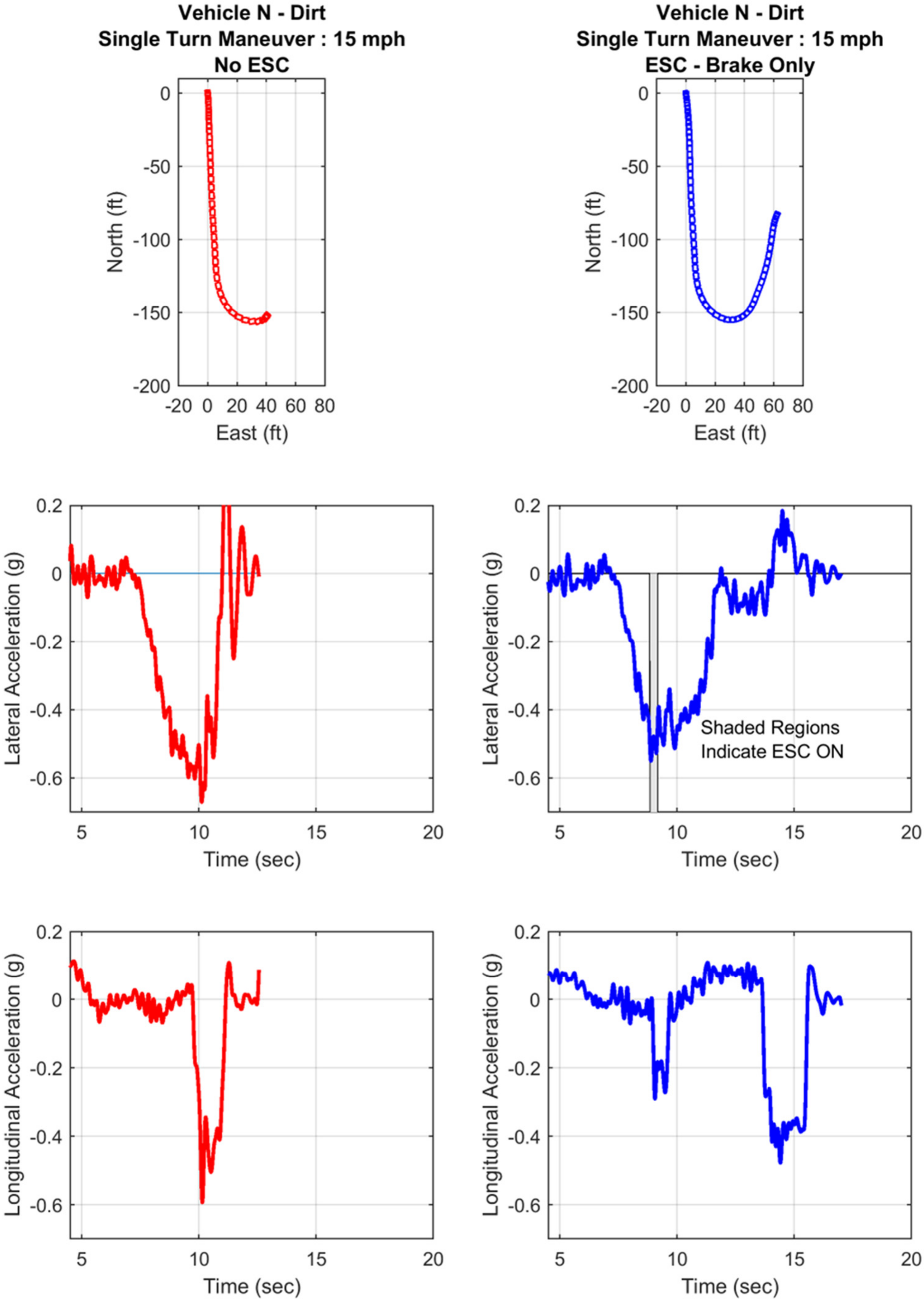




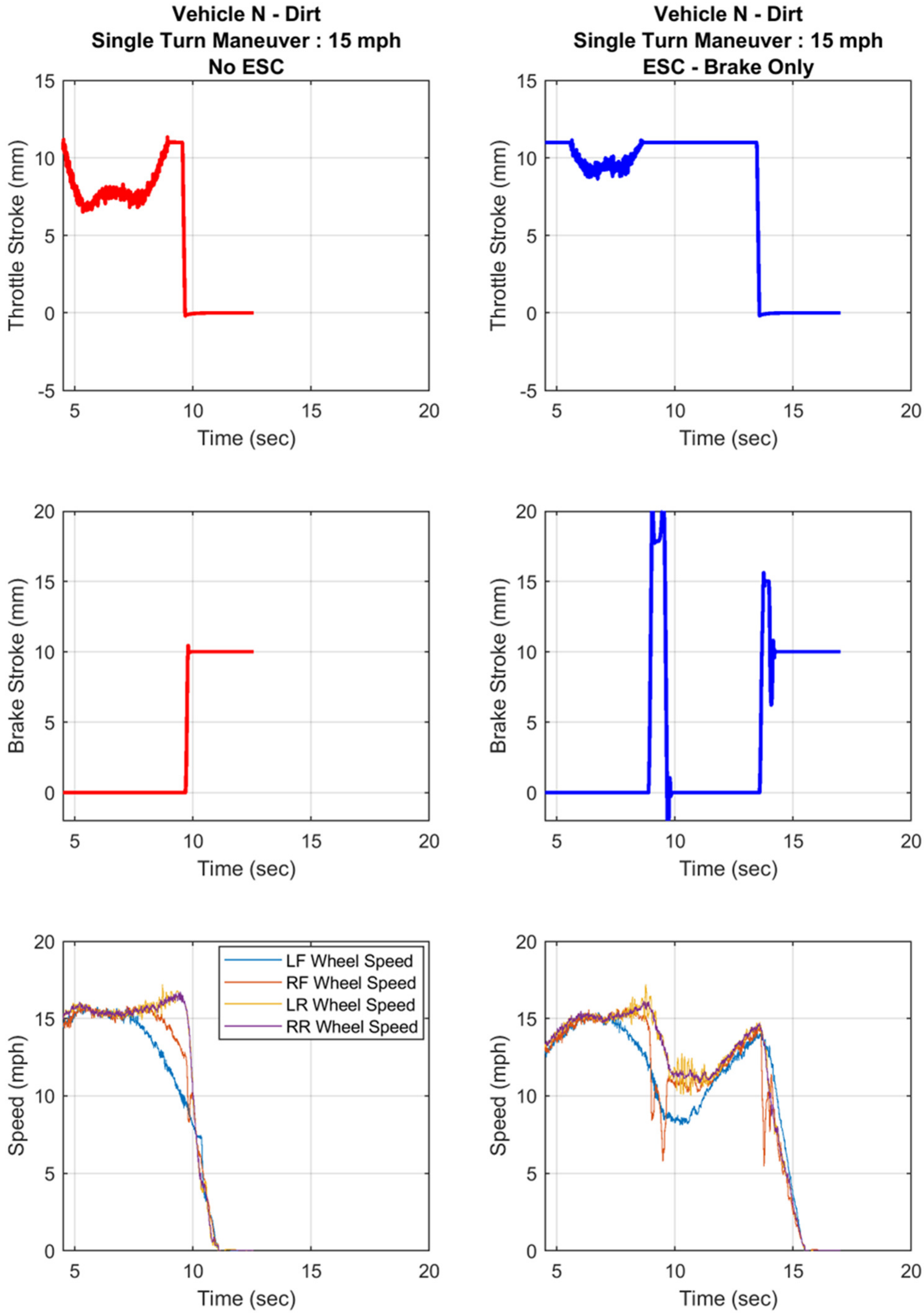
Run N7 – Vehicle N, Dirt, Single Turn Maneuver, 15 mph – ESC: Brake Only



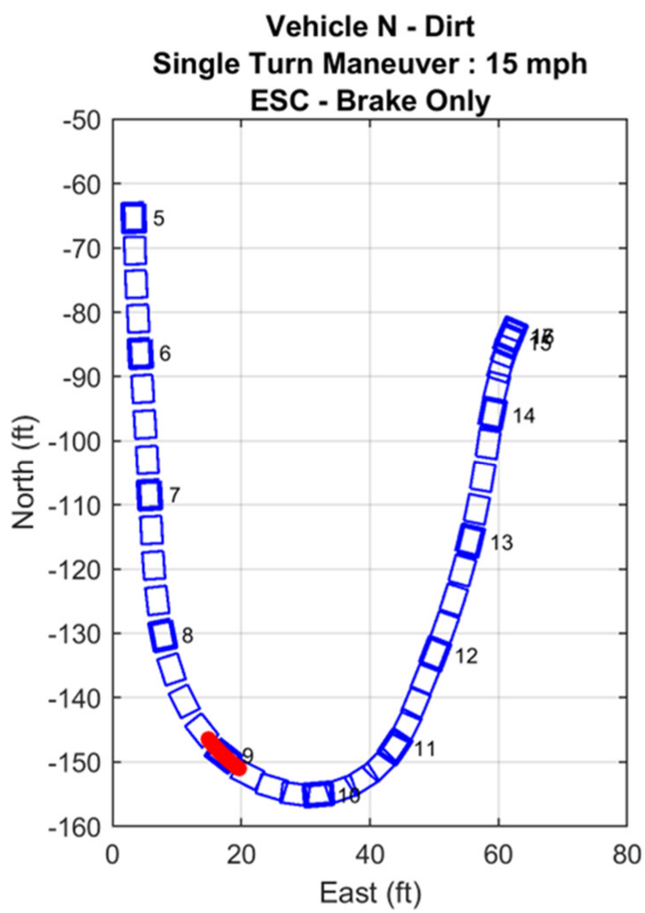
Run N7 – Vehicle N, Dirt, Single Turn Maneuver, 15 mph – ESC: Brake Only

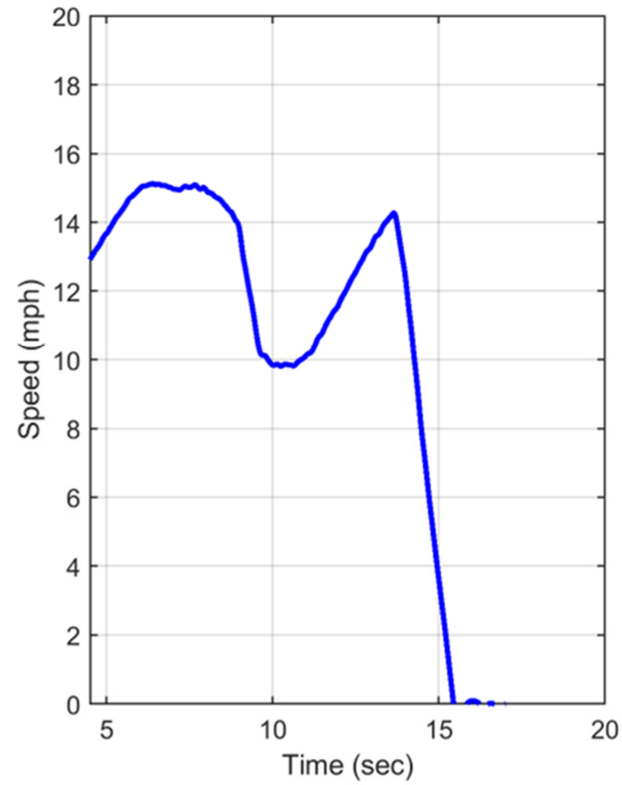


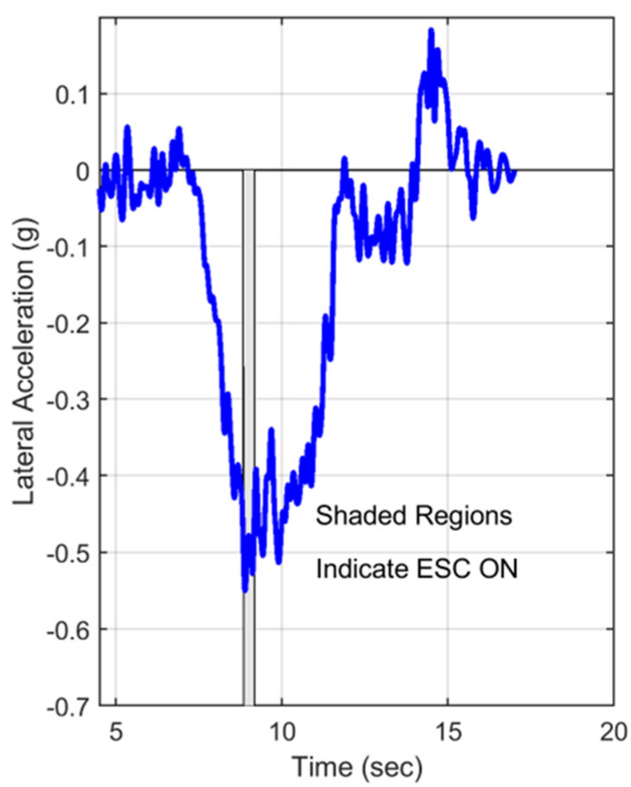
Run N7 – Vehicle N, Dirt, Single Turn Maneuver, 15 mph – ESC: Brake Only



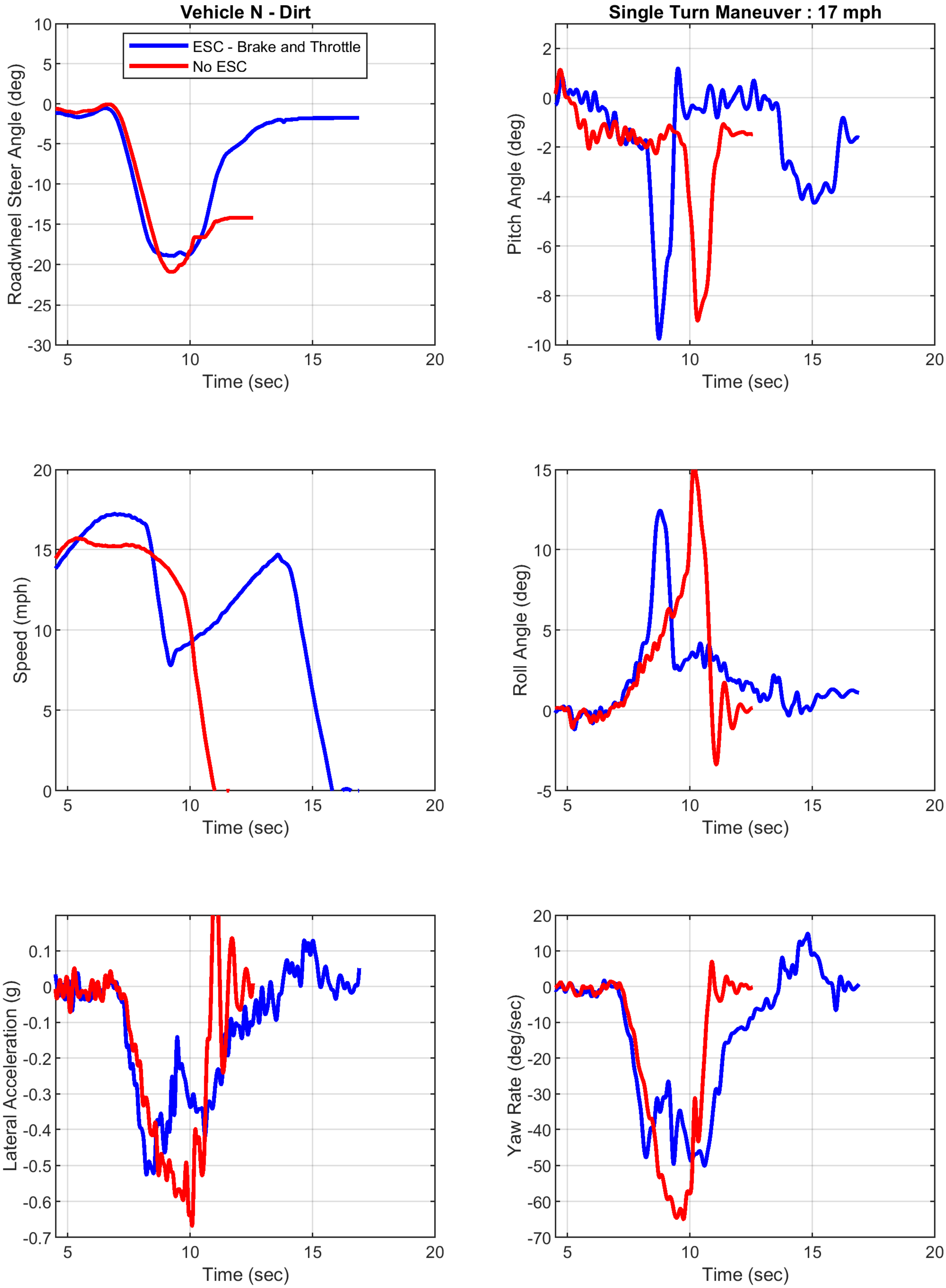
Run N7 – Vehicle N, Dirt, Single Turn Maneuver, 15 mph – ESC: Brake Only



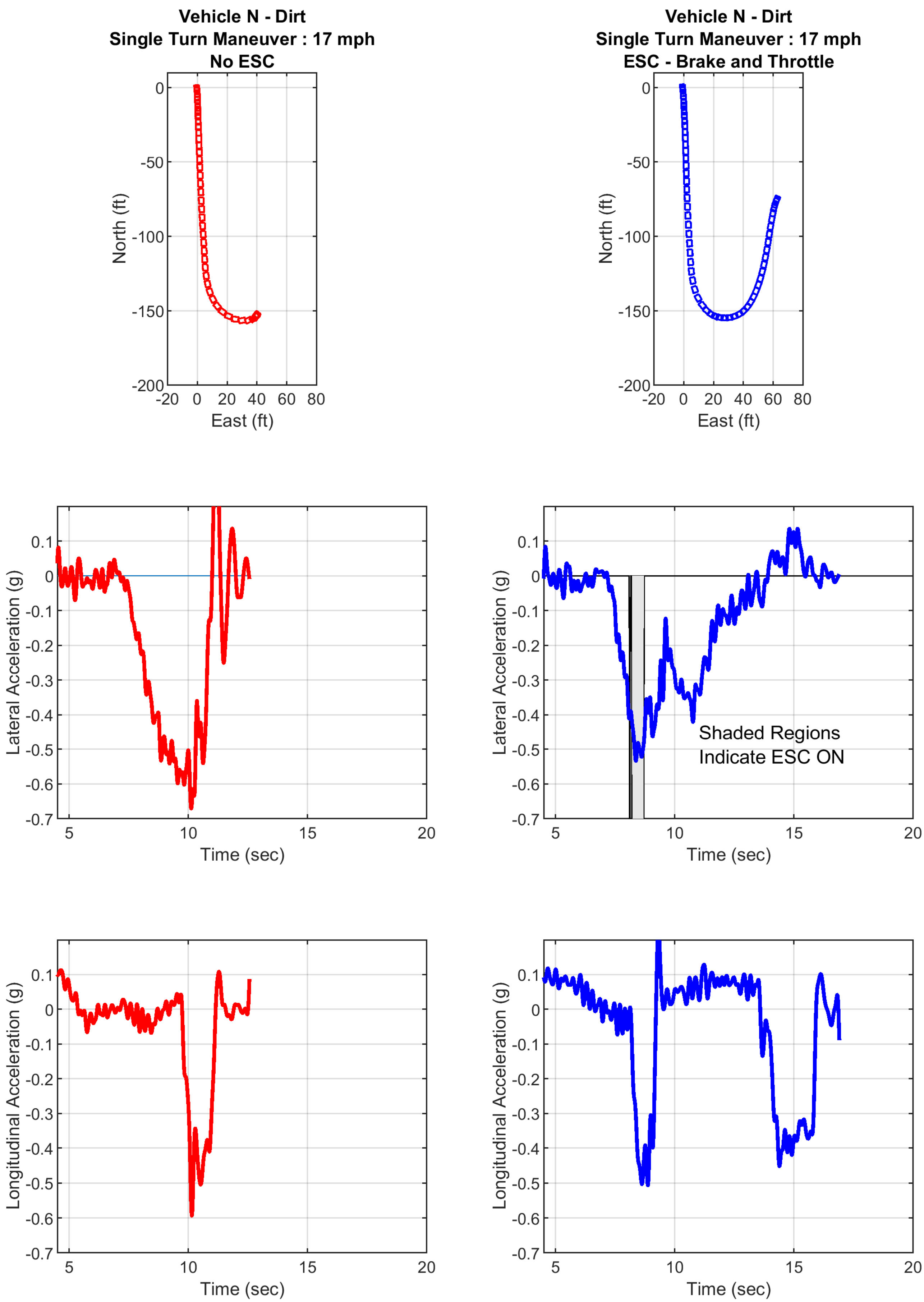




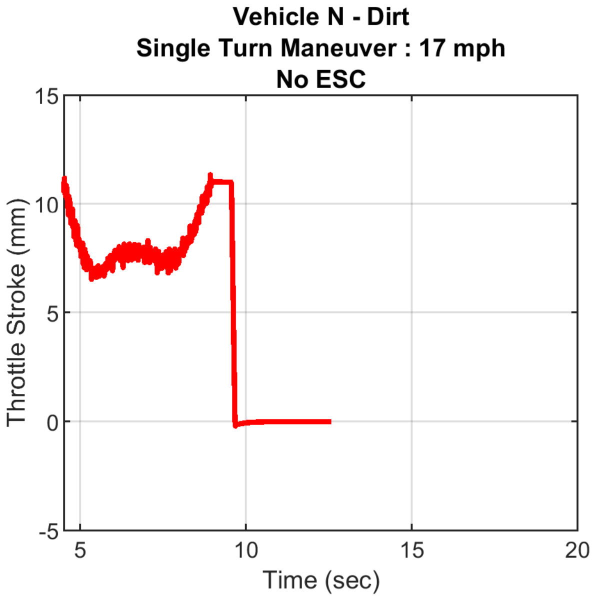
Run N8 – Vehicle N, Dirt, Single Turn Maneuver, 17 mph – ESC: Brake and Throttle

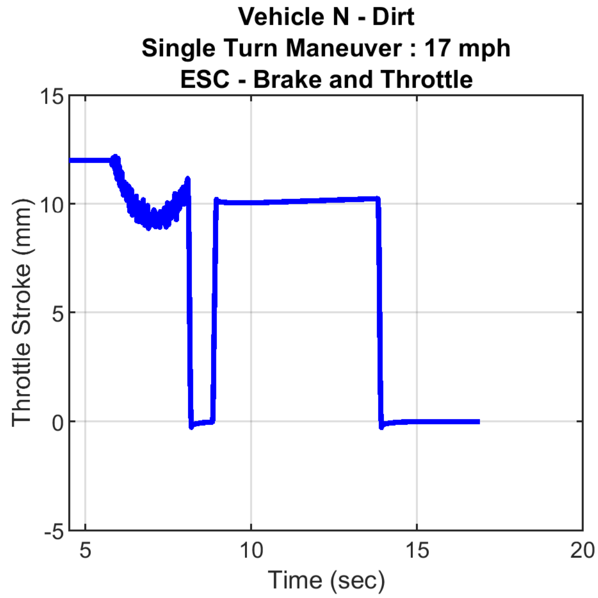


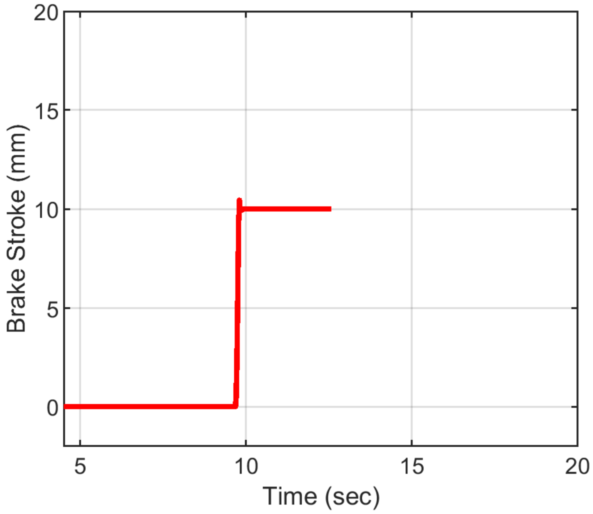
Run N8 – Vehicle N, Dirt, Single Turn Maneuver, 17 mph – ESC: Brake and Throttle

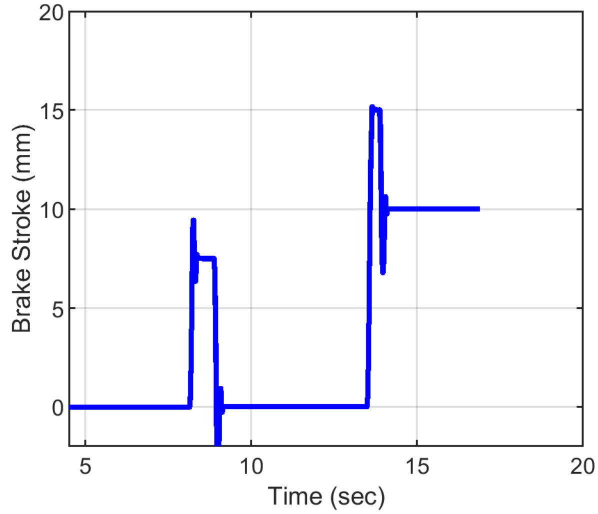


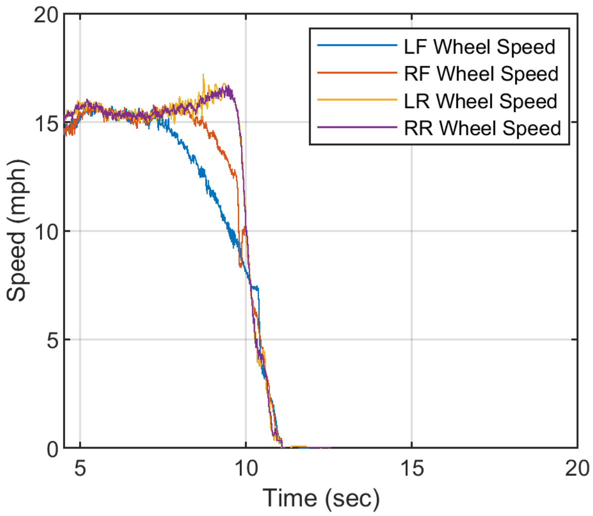
Run N8 – Vehicle N, Dirt, Single Turn Maneuver, 17 mph – ESC: Brake and Throttle

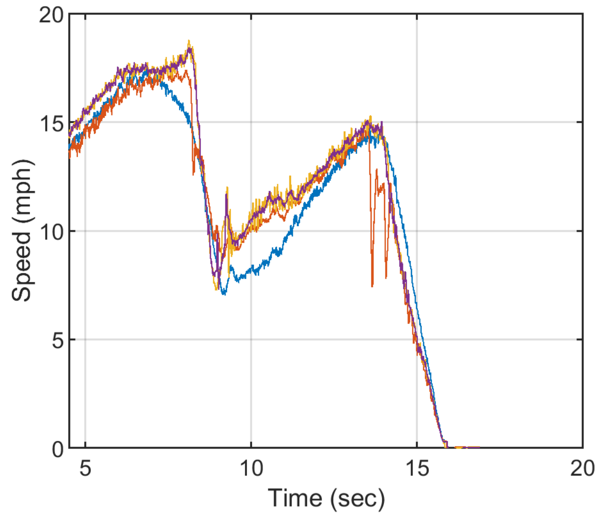




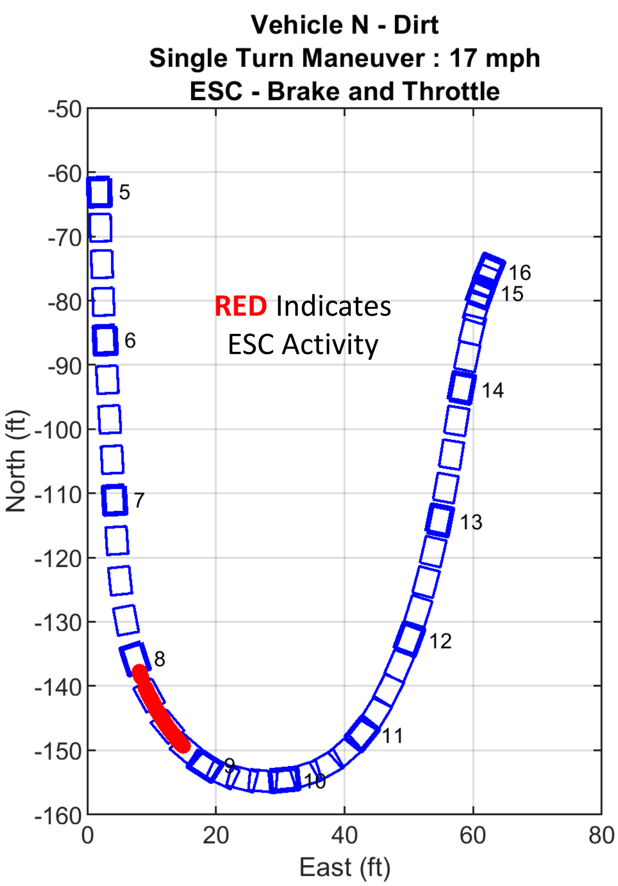


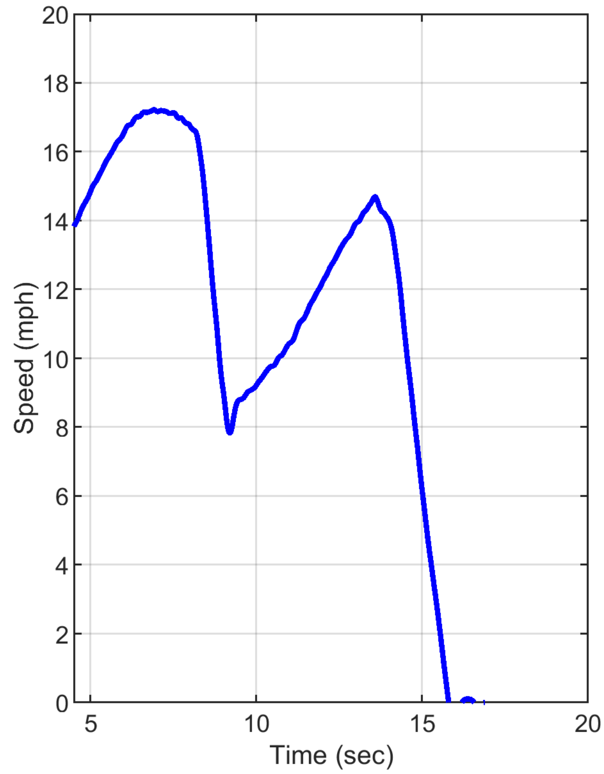


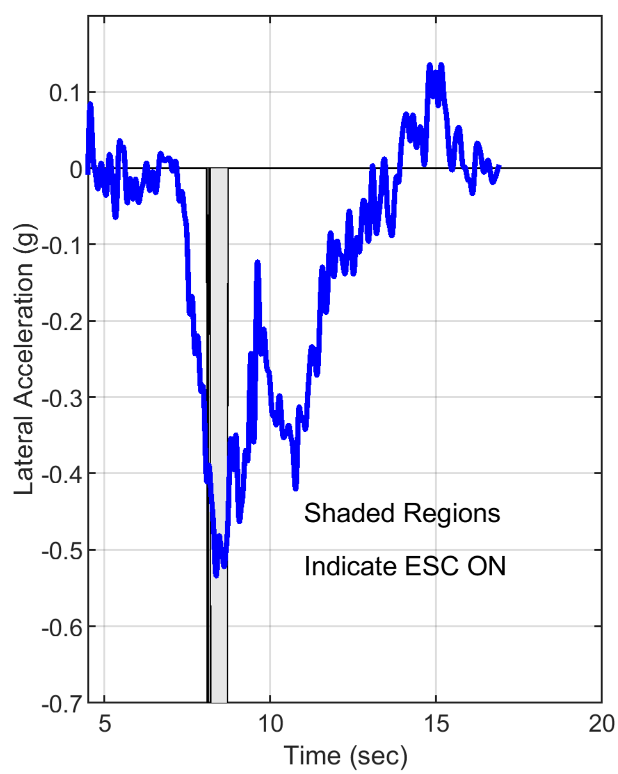




Run N8 – Vehicle N, Dirt, Single Turn Maneuver, 17 mph – ESC: Brake and Throttle







Vehicle G

	Curb	Driver	Driver Plus Instrumentation (DPI)	Gross Vehicle Weight (GVW)
VIMF Test Number		5783	5784	5848
Total Vehicle Weight (lb)	694.0	909.4	928.6	1168.7
Left Front Weight (lb)	174.2	215.4	223.9	253.3
Right Front Weight (lb)	168.1	199.1	219.4	251.0
Left Rear Weight (lb)	175.9	246.6	242.5	332.9
Right Rear Weight (lb)	175.8	248.3	242.8	331.5
Front Track Width (in)	36.35	36.45	36.50	36.45
Rear Track Width (in)	35.60	36.10	36.06	36.60
Average Track Width (in)	35.98	36.28	36.28	36.53
Wheelbase (in)	50.55	50.65	50.60	50.60
CG Longitudinal (in)	25.62	27.56	26.44	28.77
CG Lateral (in)	-0.16	-0.29	-0.08	-0.06
CG Height (in)		24.07	23.34	26.13
Roll Inertia - I_{XX} (ft-lb-s^2)		79	75	109
Pitch Inertia - I_{YY} (ft-lb-s^2)		110	117	198
Yaw Inertia - I_{ZZ} (ft-lb-s^2)		88	96	163
Roll/Yaw - I_{XZ} (ft-lb-s^2)		5	5	17
SSF		0.753	0.777	0.699
KST		0.754	0.777	0.699
Steering Ratio (deg/deg)			1.41	

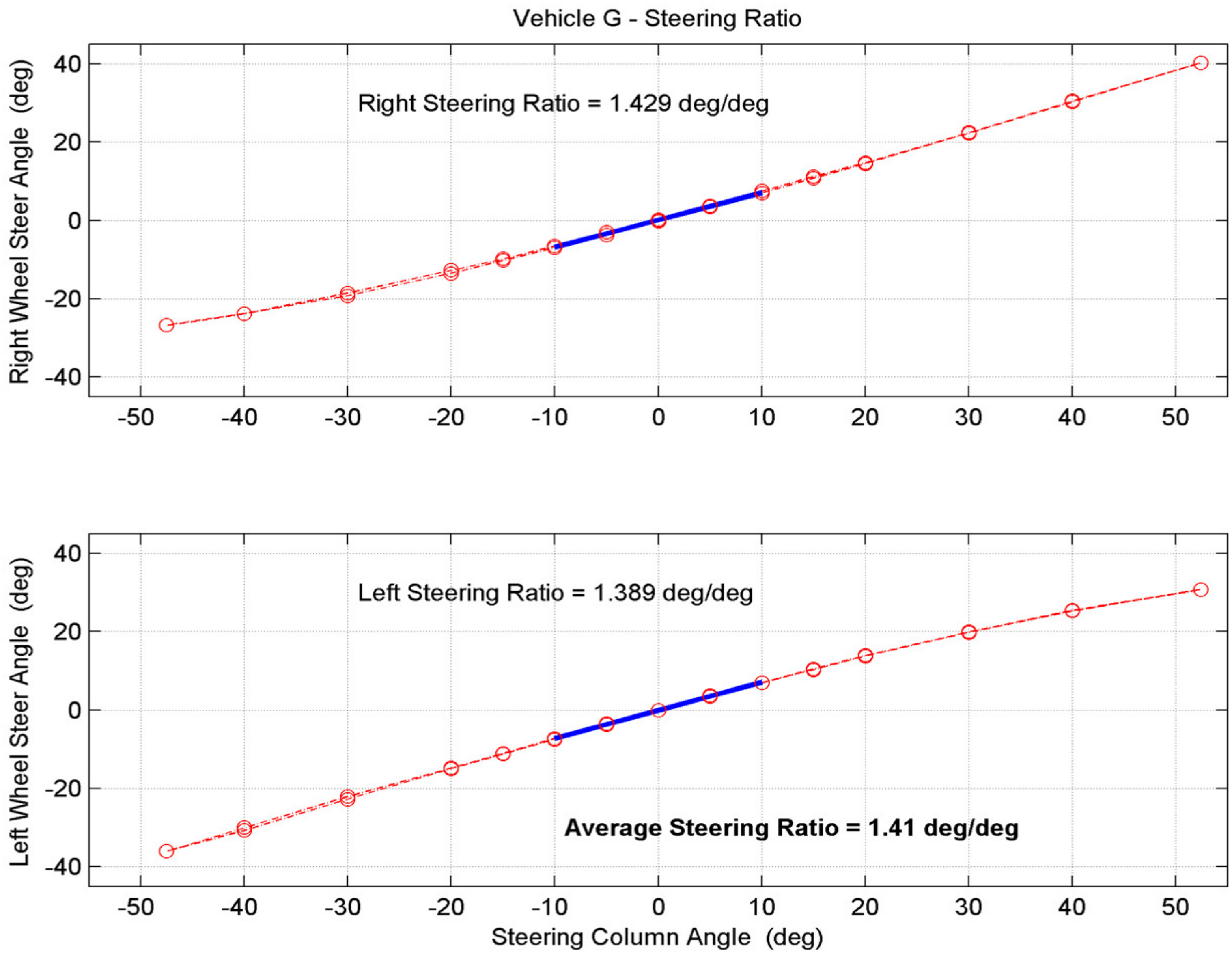
Vehicle G

		Driver	Driver Plus Instrumentation (DPI)	Gross Vehicle Weight (GVW)
Lateral Right Tilt	Right Tilt First Wheel Lift	Rear	Rear	Rear
	Right Tilt Angle (TTA) (deg)	28.2	28.4	24.1
	Right Tilt Ratio (TTR)	0.535	0.540	0.446
Lateral Left Tilt	Left Tilt First Wheel Lift	Rear	Rear	Rear
	Left Tilt Angle (TTA) (deg)	28.8	28.8	24.3
	Left Tilt Ratio (TTR)	0.550	0.551	0.452
	Average Lateral TTA (deg)	**28.5**	**28.6**	**24.2**
	Average Lateral TTR	**0.542**	**0.545**	**0.449**

Longitudinal Front Tilt	Front Tilt First Wheel Lift	Left	Left	Right
	Front Tilt TTA (FTTA) (deg)	49.3	48.1	45.3
	Front Tilt TTR (FTTR)	1.163	1.114	1.011

Longitudinal Rear Tilt	Rear Tilt First Wheel Lift	Left	Right	Left
	Rear Tilt TTA (RTTA) (deg)	43.1	44.1	38.7
	Rear Tilt TTR (RTTR)	0.935	0.969	0.802

Vehicle G



Vehicle G - Steering Ratio
Right Steering Ratio = 1.429 deg/deg
Right Wheel Steer Angle (deg)
40
20
0
-20
-40
-50
-40
-30
-20
-10
0
10
20
30
40
50
Left Steering Ratio = 1.389 deg/deg
Average Steering Ratio = 1.41 deg/deg
Left Wheel Steer Angle (deg)
Steering Column Angle (deg)

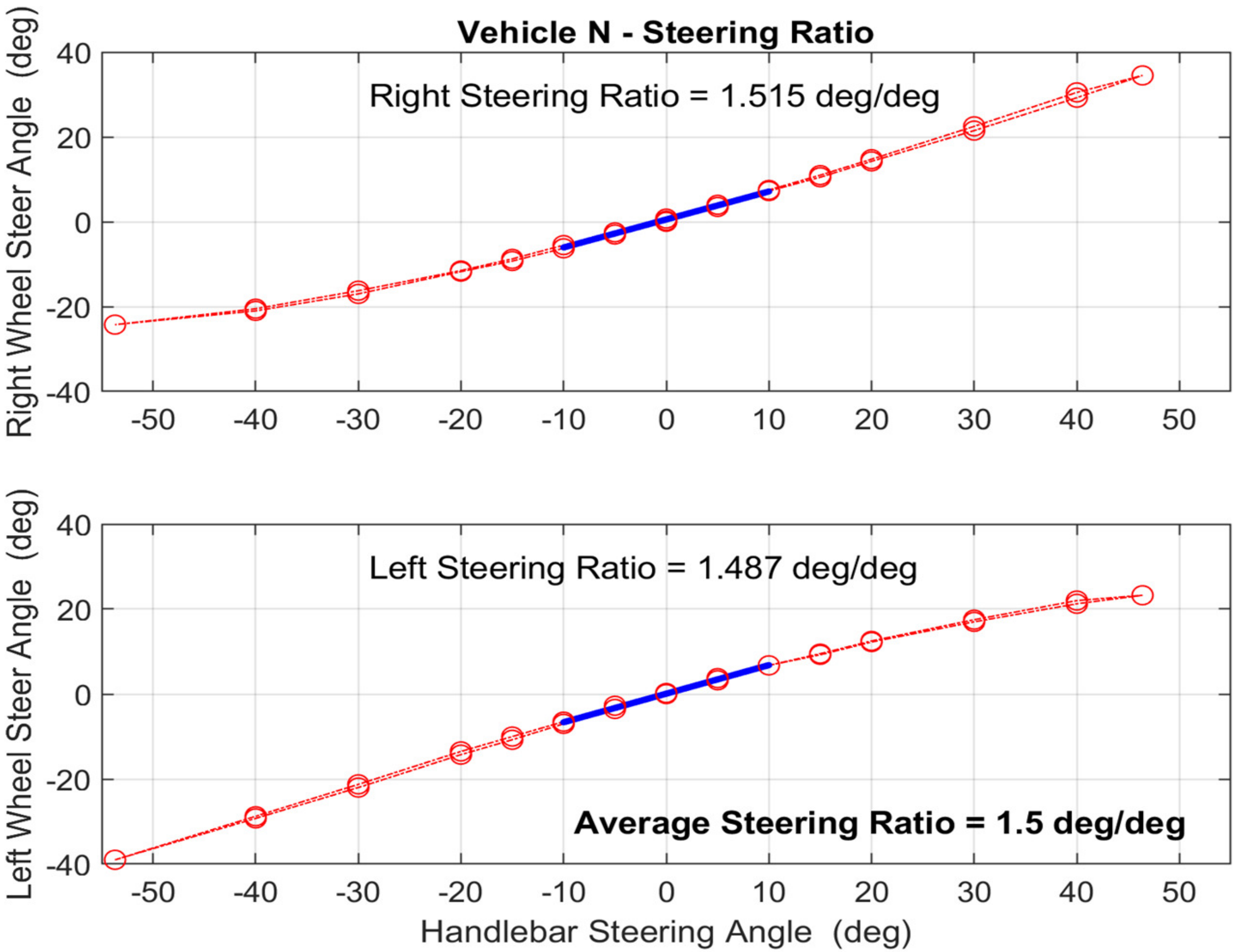
Vehicle N

	Curb	Driver	Autonomous Ballast to Driver Loading	Gross Vehicle Weight (GVW)
VIMF Test Number	7821	7822	7919	7823
Total Vehicle Weight (lb)	951.0	1164.9	1164.2	1463.5
Left Front Weight (lb)	240.3	274.2	273.0	309.1
Right Front Weight (lb)	235.8	271.8	266.9	300.9
Left Rear Weight (lb)	228.4	300.7	299.0	420.2
Right Rear Weight (lb)	246.5	318.2	325.3	433.3
Front Track Width (in)	39.80	39.90	39.90	40.10
Rear Track Width (in)	38.20	38.28	38.28	38.28
Average Track Width (in)	39.00	39.09	39.09	39.19
Wheelbase (in)	50.80	51.10	51.00	51.35
CG Longitudinal (in)	25.37	27.15	27.35	29.95
CG Lateral (in)	0.27	0.25	0.33	0.06
CG Height (in)	20.32	23.12	22.55	25.10
Roll Inertia - I_{XX} (ft-lb-s^2)	41	76	75	100
Pitch Inertia - I_{YY} (ft-lb-s^2)	118	144	181	232
Yaw Inertia - I_{ZZ} (ft-lb-s^2)	123	130	171	206
Roll/Yaw - I_{XZ} (ft-lb-s^2)	2	9	9	21
SSF	0.960	0.845	0.867	0.781
KST	0.960	0.846	0.868	0.784
Steering Ratio (deg/deg)			1.50	

Vehicle N

		Curb	Driver	Autonomous Ballast to Driver Loading	Gross Vehicle Weight (GVW)
Lateral Right Tilt	**Right Tilt First Wheel Lift**	Rear	Rear	Rear	Rear
	Right Tilt Angle (TTA) (deg)	38.6	31.7	33.7	26.5
	Right Tilt Ratio (TTR)	0.797	0.618	0.667	0.498
Lateral Left Tilt	**Left Tilt First Wheel Lift**	Rear	Rear	Rear	Rear
	Left Tilt Angle (TTA) (deg)	39.2	32.9	35.2	27.6
	Left Tilt Ratio (TTR)	0.817	0.647	0.706	0.522
	Average Lateral TTA (deg)	**38.9**	**32.3**	**34.5**	**27.0**
	Average Lateral TTR	**0.807**	**0.632**	**0.687**	**0.510**
Longitudinal Front Tilt	**Front Tilt First Wheel Lift**	Left	Left	Right	Left
	Front Tilt TTA (FTTA) (deg)	52.0	48.1	50.6	45.6
	Front Tilt TTR (FTTR)	1.279	1.113	1.219	1.020
Longitudinal Rear Tilt	**Rear Tilt First Wheel Lift**	Right	Right	Equal	Right
	Rear Tilt TTA (RTTA) (deg)	52.6	44.4	43.3	35.8
	Rear Tilt TTR (RTTR)	1.306	0.979	0.944	0.722

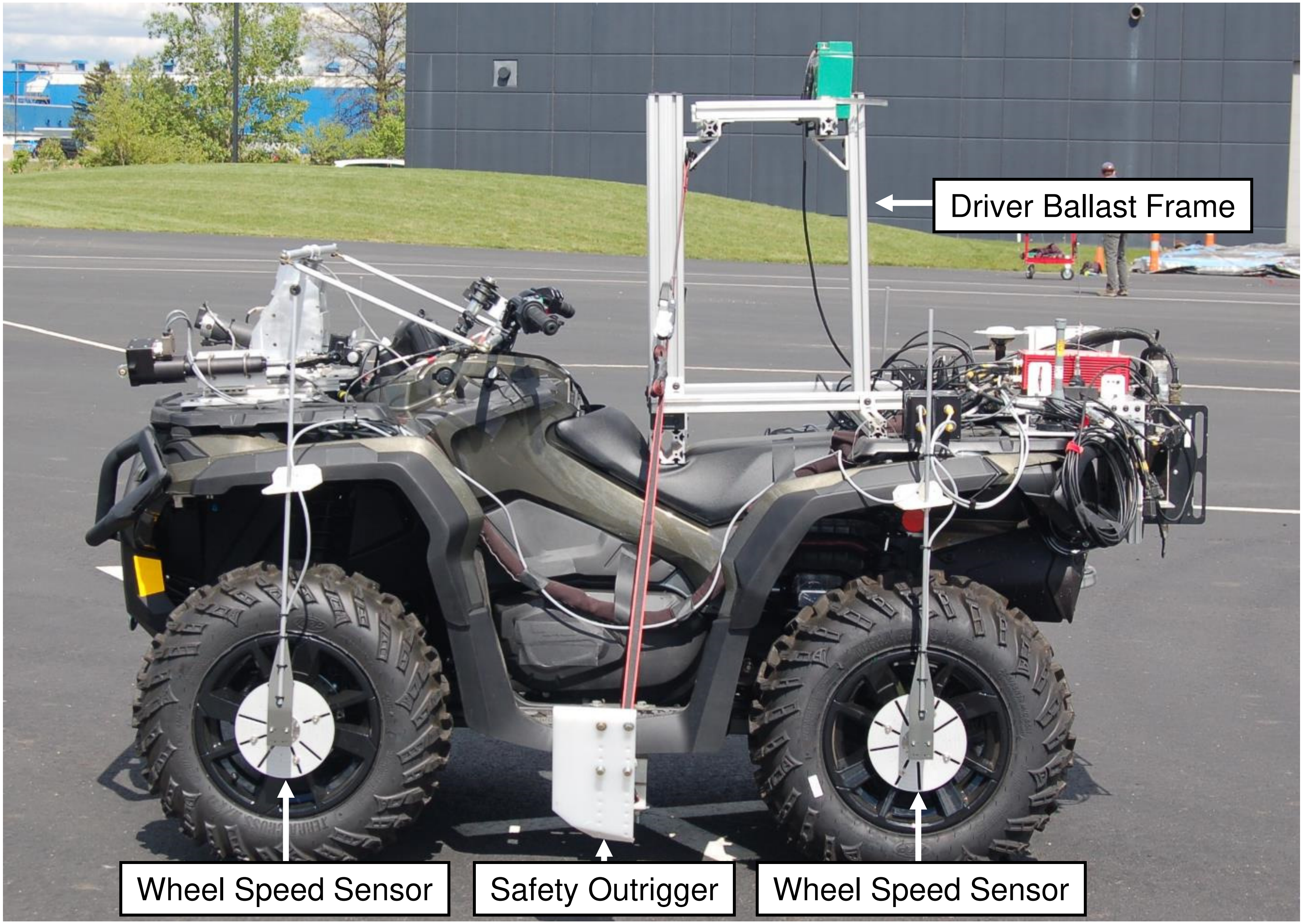
Vehicle N



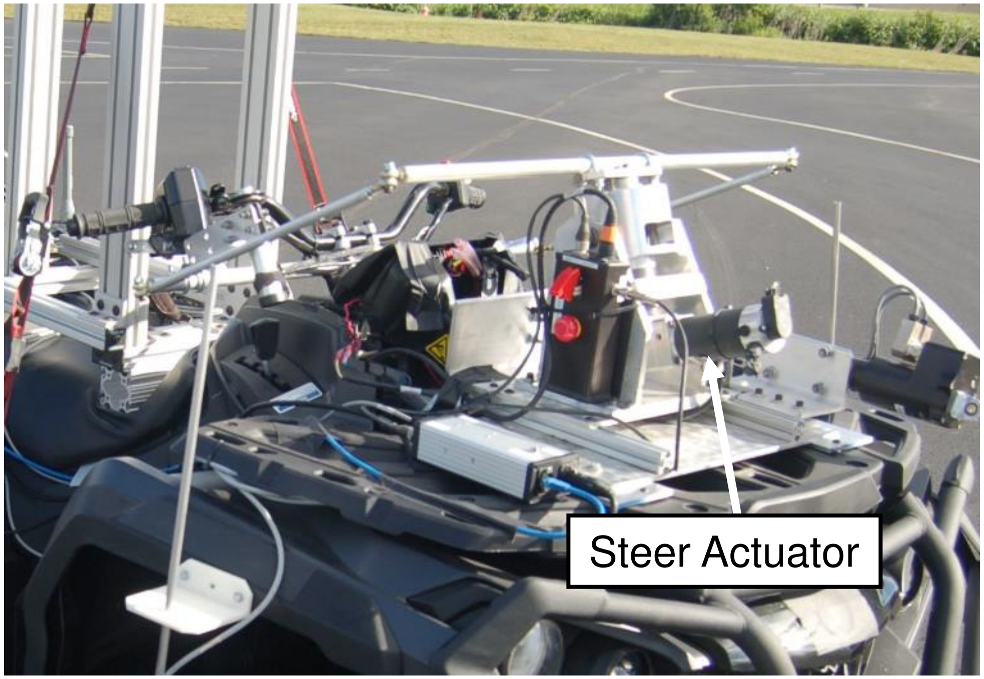
Vehicle N - Steering Ratio
Right Steering Ratio = 1.515 deg/deg
Right Wheel Steer Angle (deg)
40
20
0
-20
-40
-50
-40
-30
-20
-10
0
10
20
30
40
50
Left Steering Ratio = 1.487 deg/deg
Left Wheel Steer Angle (deg)
Average Steering Ratio = 1.5 deg/deg
Handlebar Steering Angle (deg)

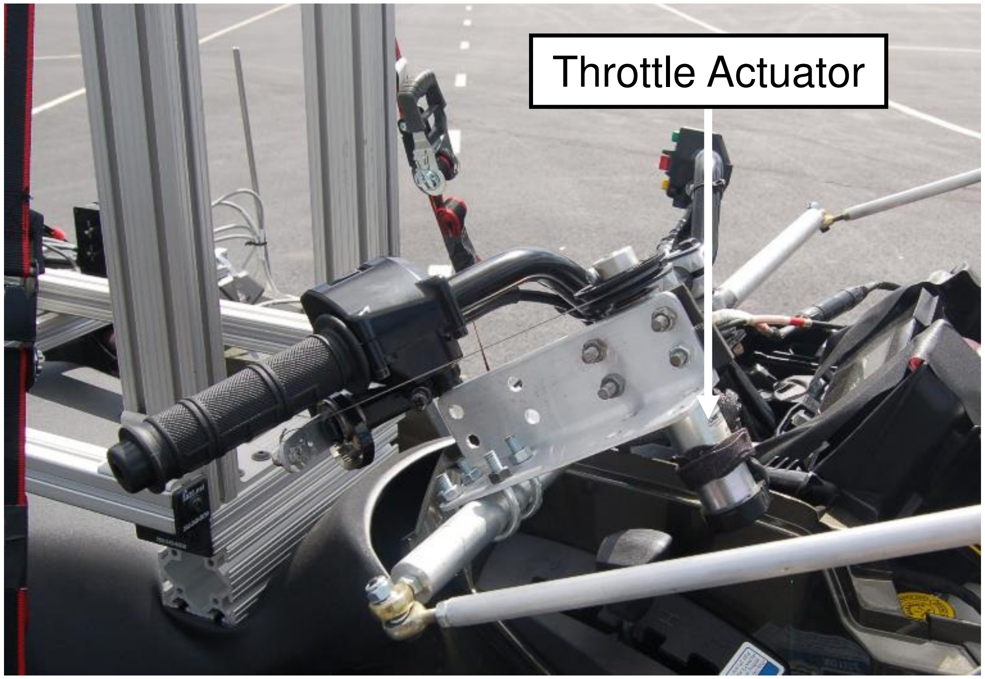
Side View of Vehicle G

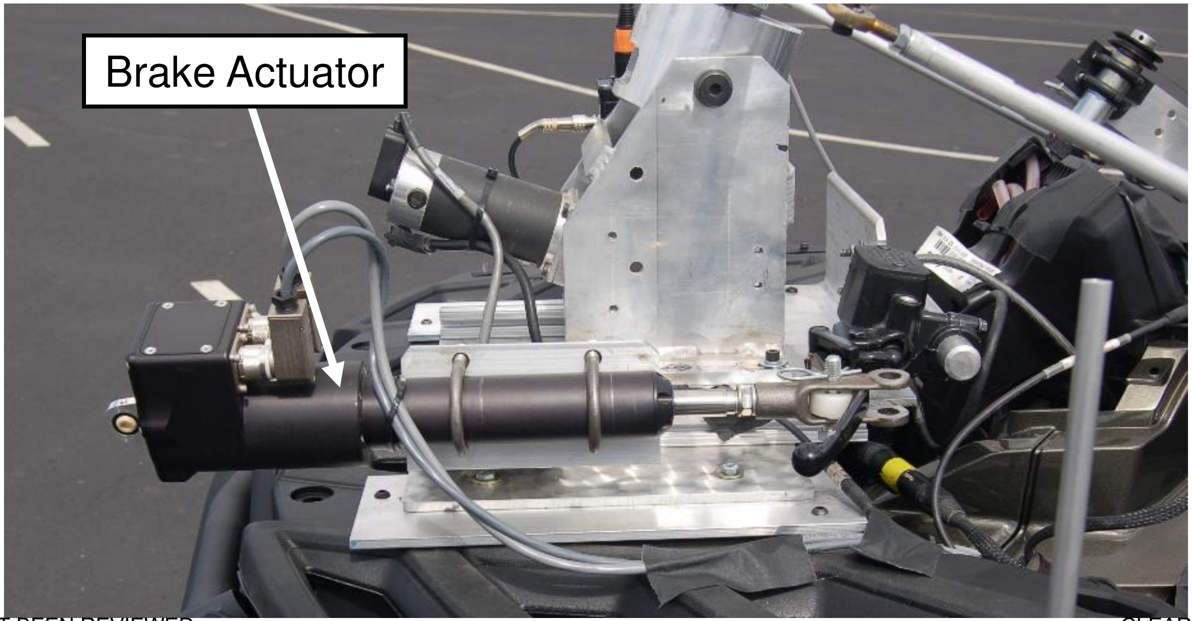
Side View of Vehicle N



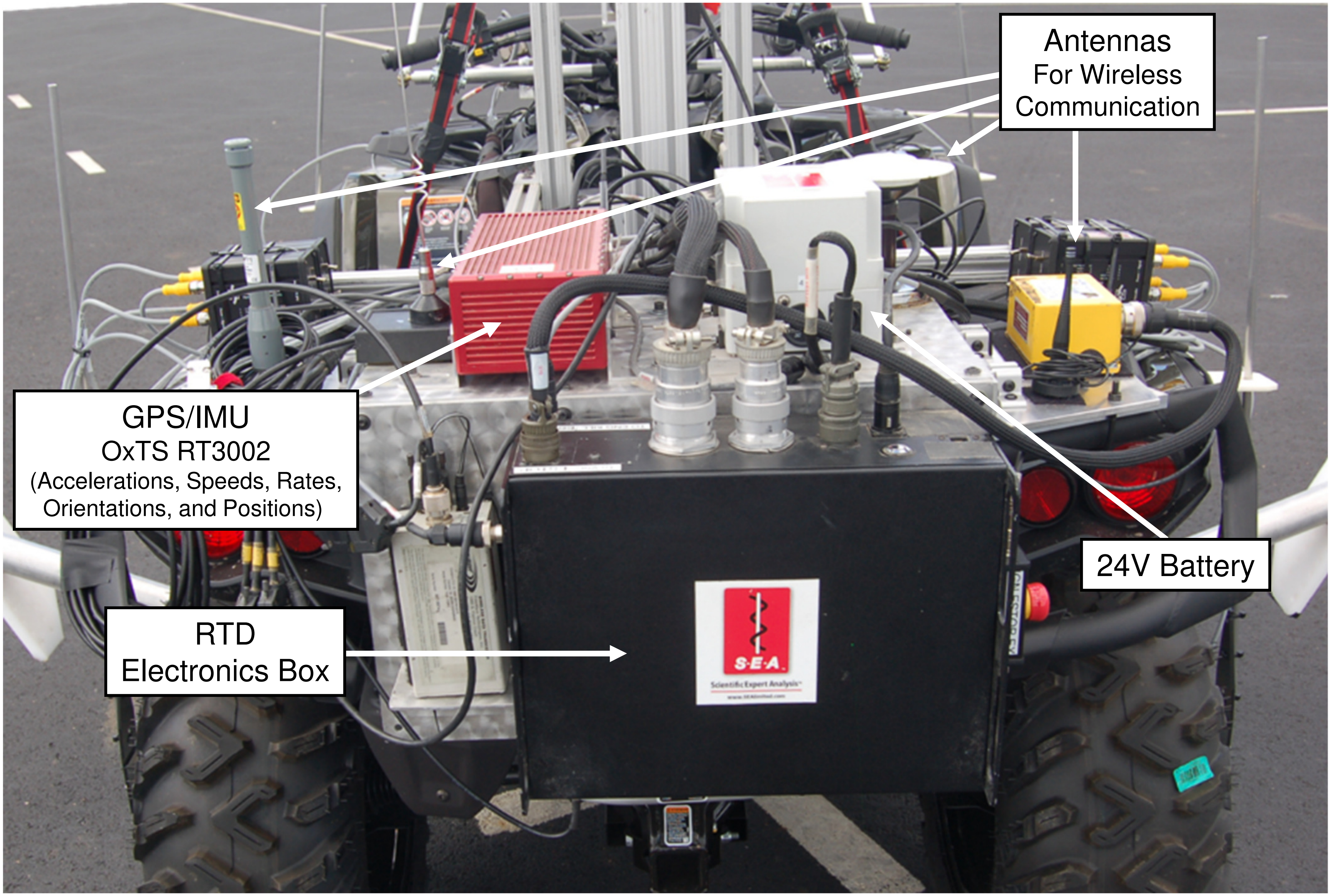
SEA ATV Robotic Test Driver (RTD) Components (Steer, Throttle, and Brake Actuators)



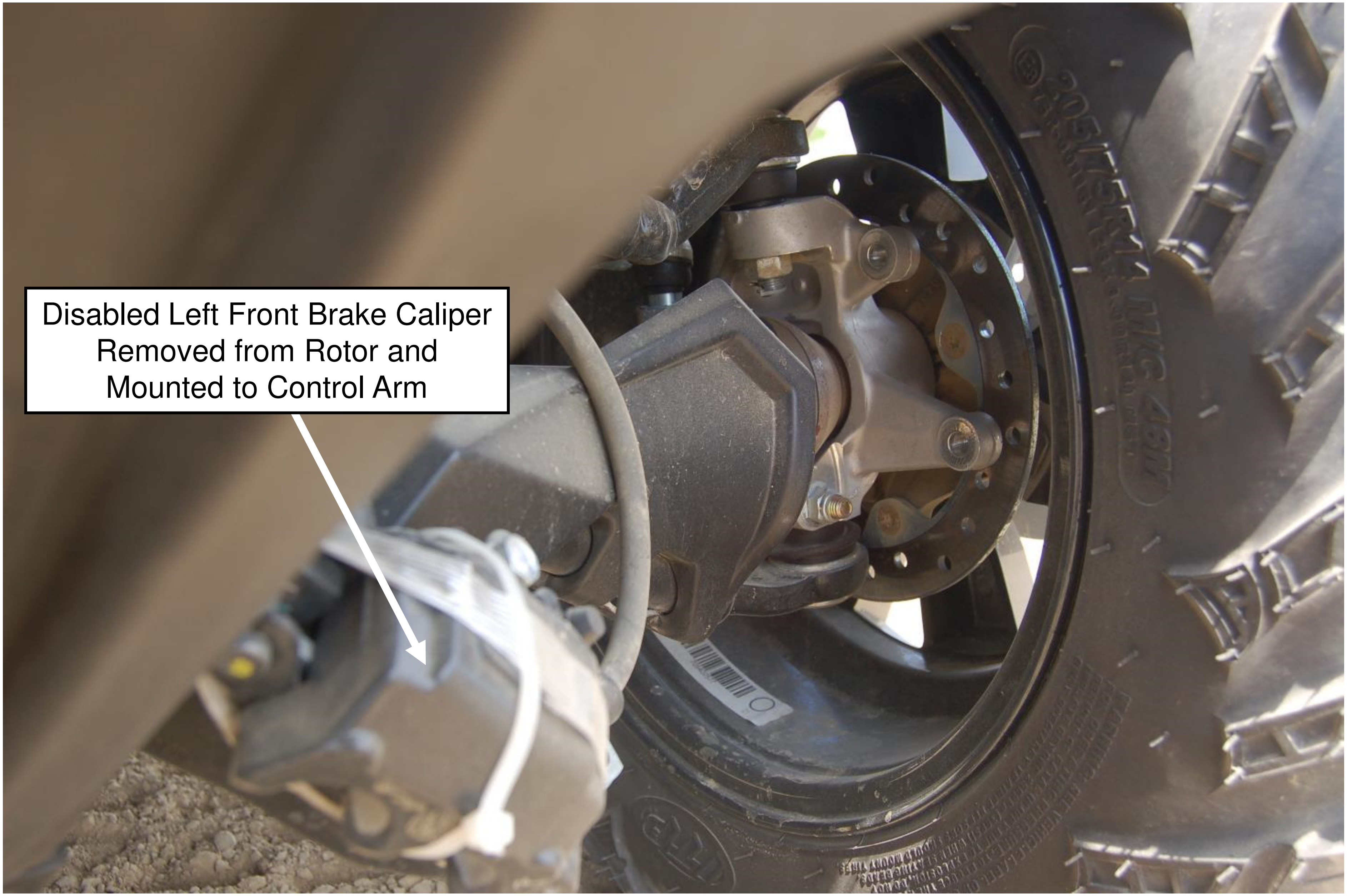




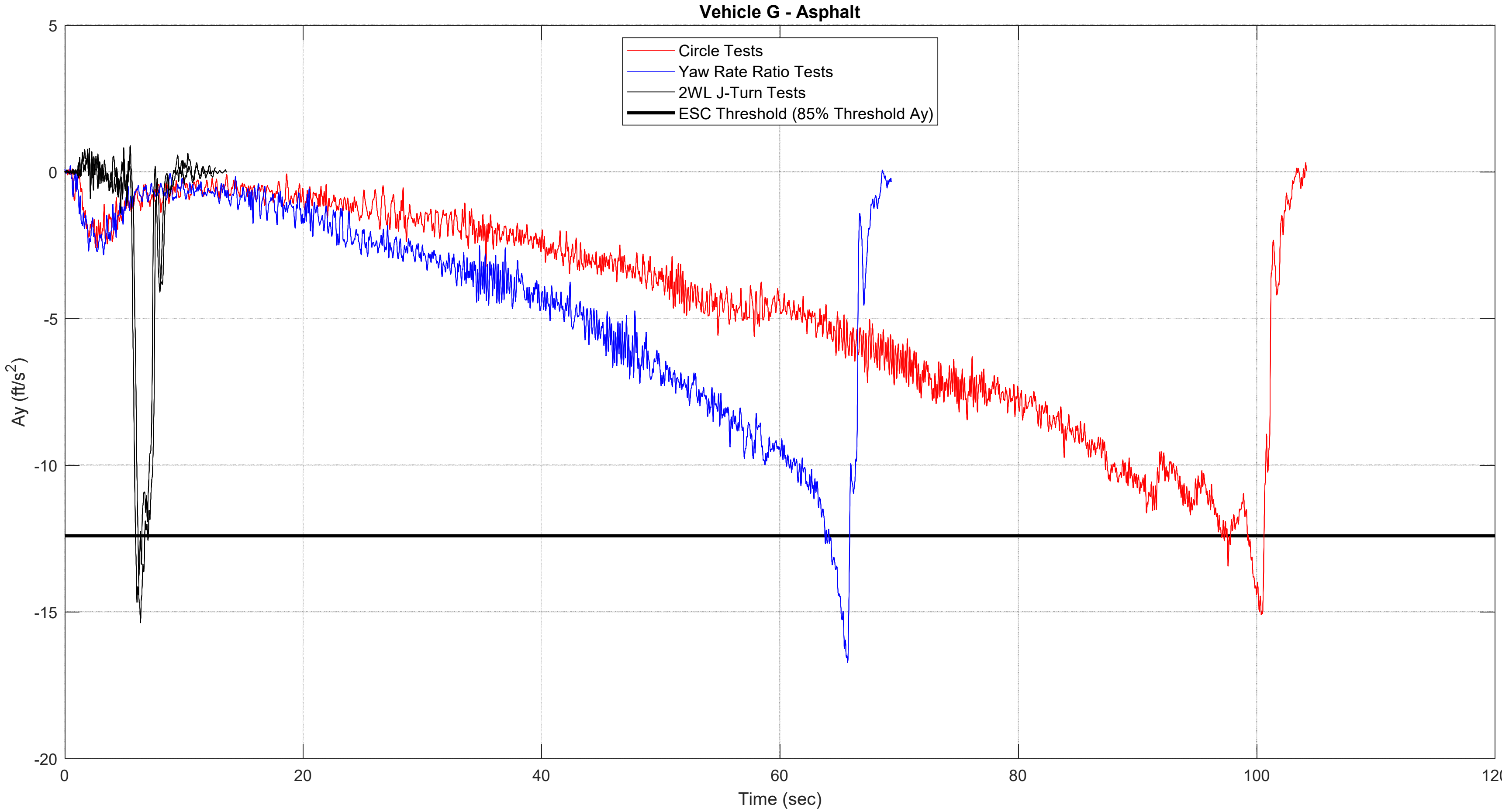
SEA ATV Robotic Test Driver (RTD) Components (GPS/IMU, Control Box, and Antennas)



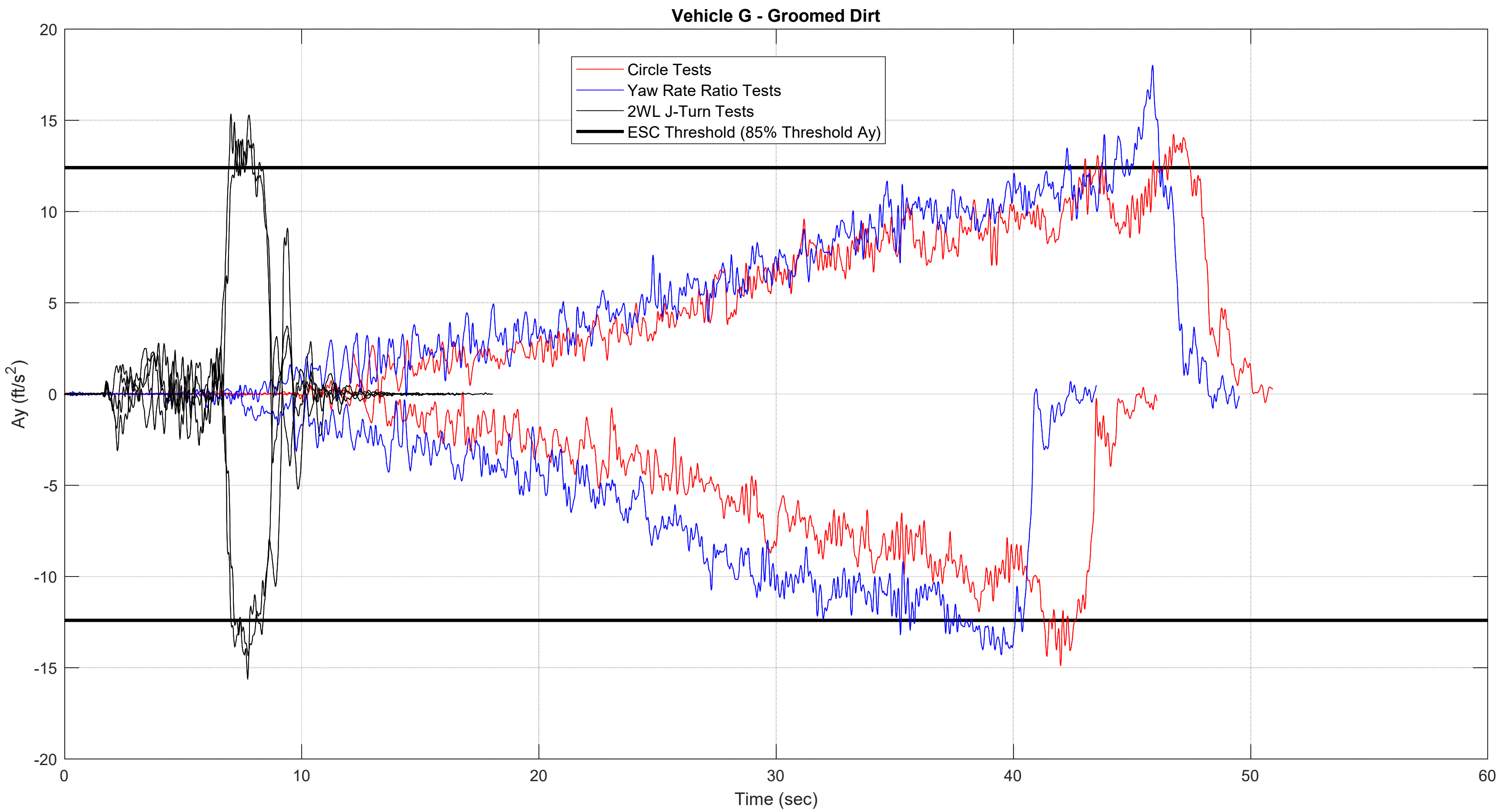
Photograph Showing Left Front Brake Caliper Removed from Brake Rotor and Cable-Tied to the Suspension Control Arm

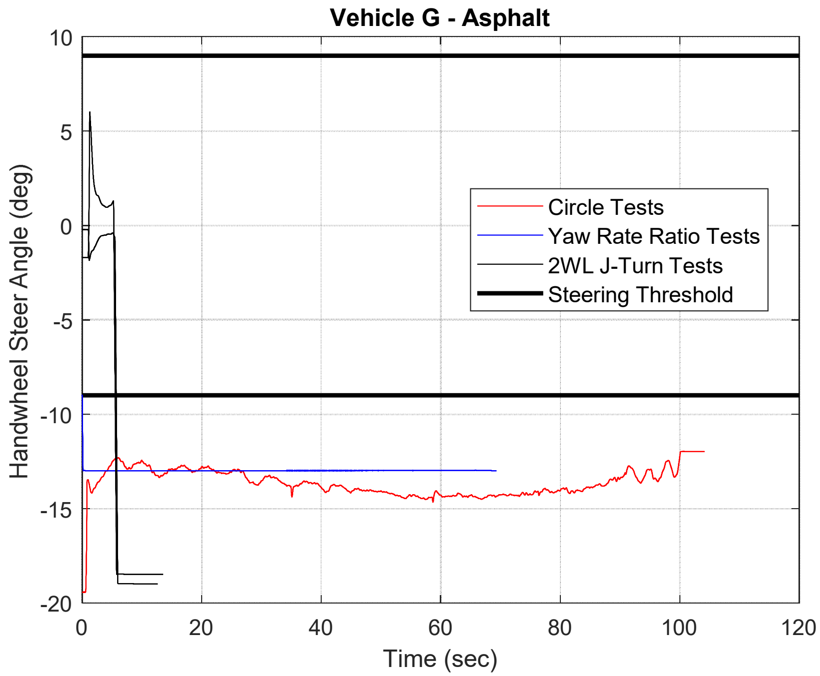


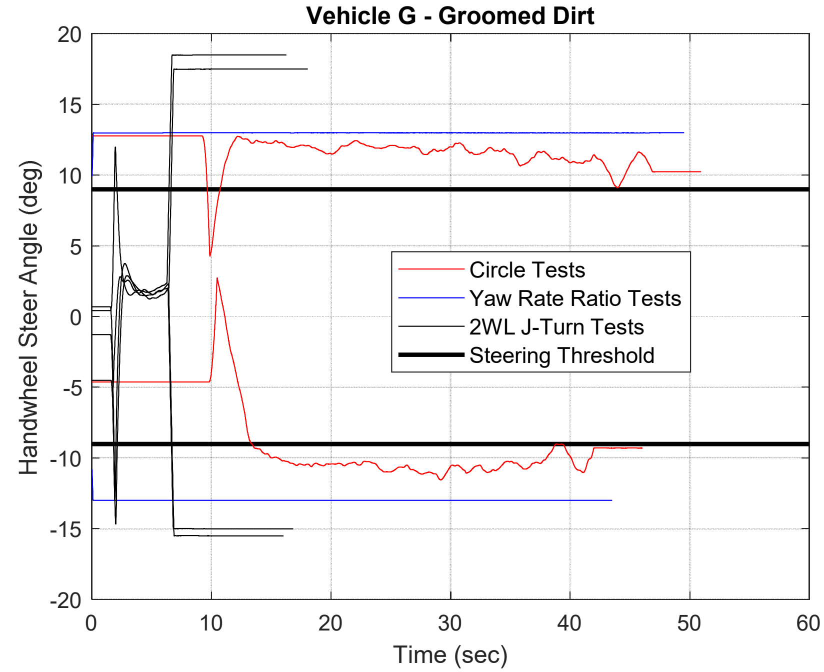
Lateral Acceleration Values Used for ESC Threshold Levels Determined from Threshold Ay Values Measured During Two-Wheel Lift (2WL) Test Outcomes During 20 mph Dropped-Throttle J-Turn Tests ESC Threshold Used = 85% Threshold Ay					
	Threshold Ay Asphalt (g)	Threshold Ay Groomed Dirt (g)	Average Threshold Ay (g)	**ESC Threshold (g)**	**ESC Threshold (ft/s^2)**
Vehicle G	0.459	0.445	0.452	**0.384**	**12.4**
Vehicle N	0.540	0.556	0.548	**0.466**	**15.0**

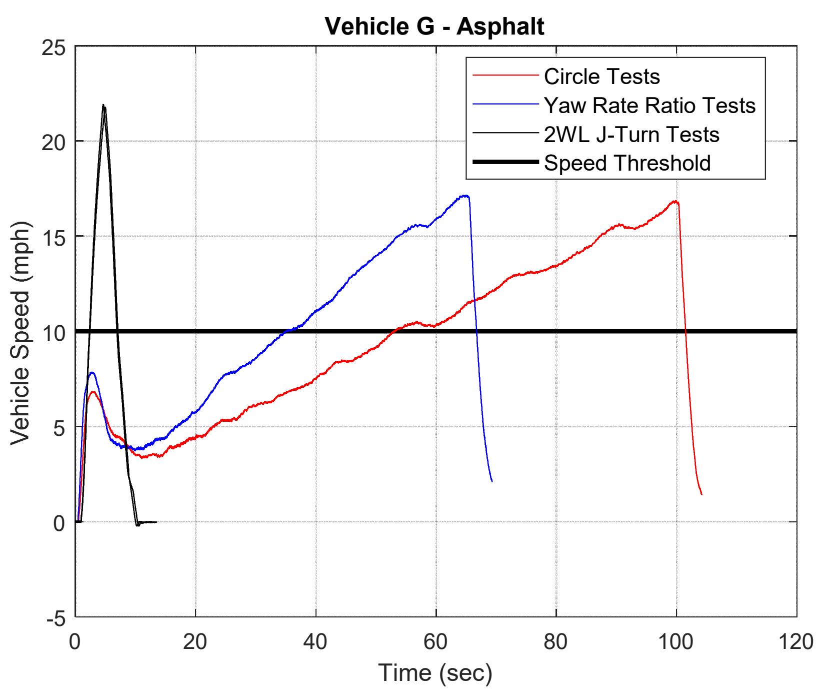


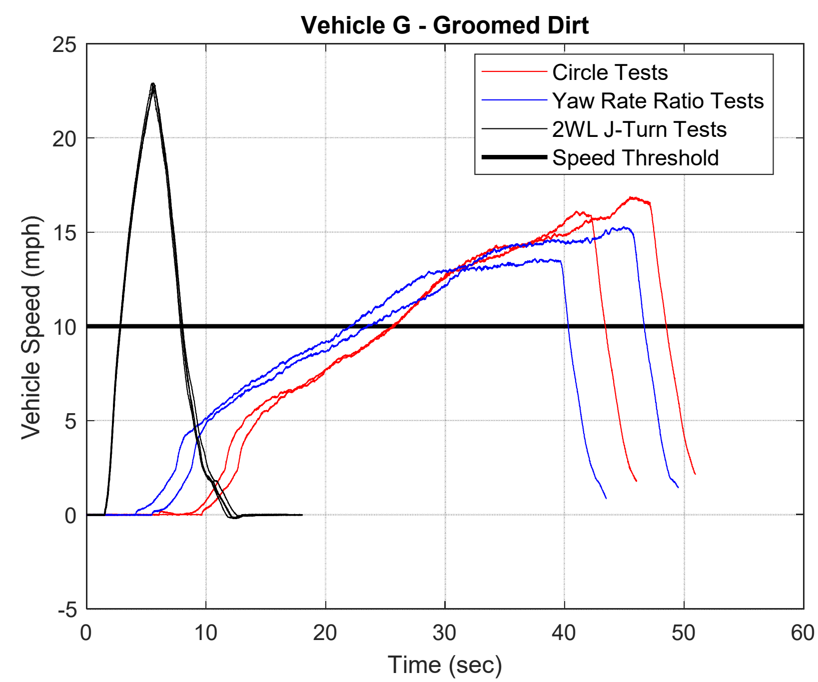
Vehicle G - Asphalt
Circle Tests
Yaw Rate Ratio Tests
2WL J-Turn Tests
ESC Threshold (85% Threshold Ay)
Ay (ft/s^2)
Time (sec)
5
0
-5
-10
-15
-20
0
20
40
60
80
100
120

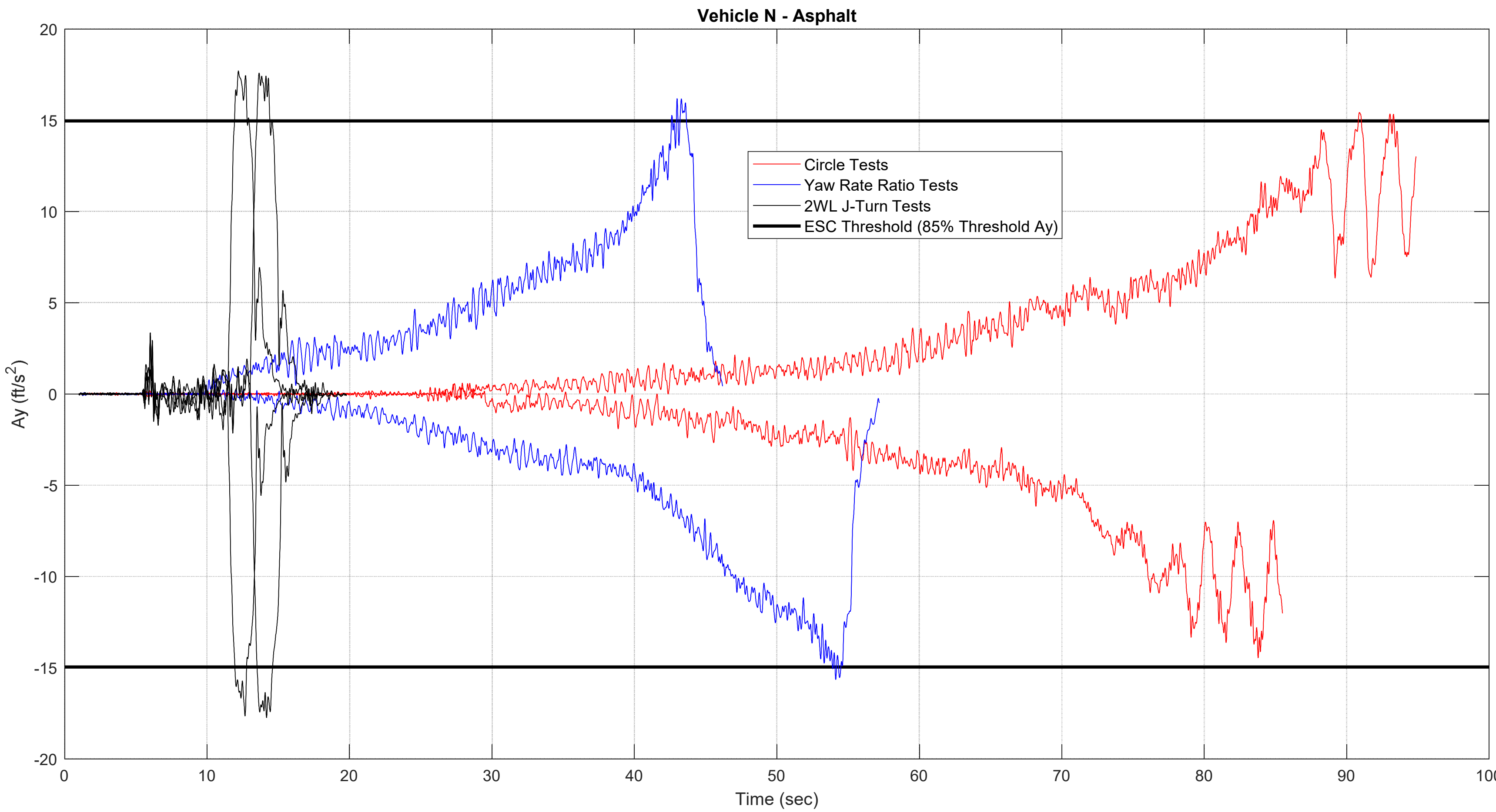

Vehicle G - Groomed Dirt
Circle Tests
Yaw Rate Ratio Tests
2WL J-Turn Tests
ESC Threshold (85% Threshold Ay)
Ay (ft/s^2)
Time (sec)
20
15
10
5
0
-5
-10
-15
-20
0
10
20
30
40
50
60

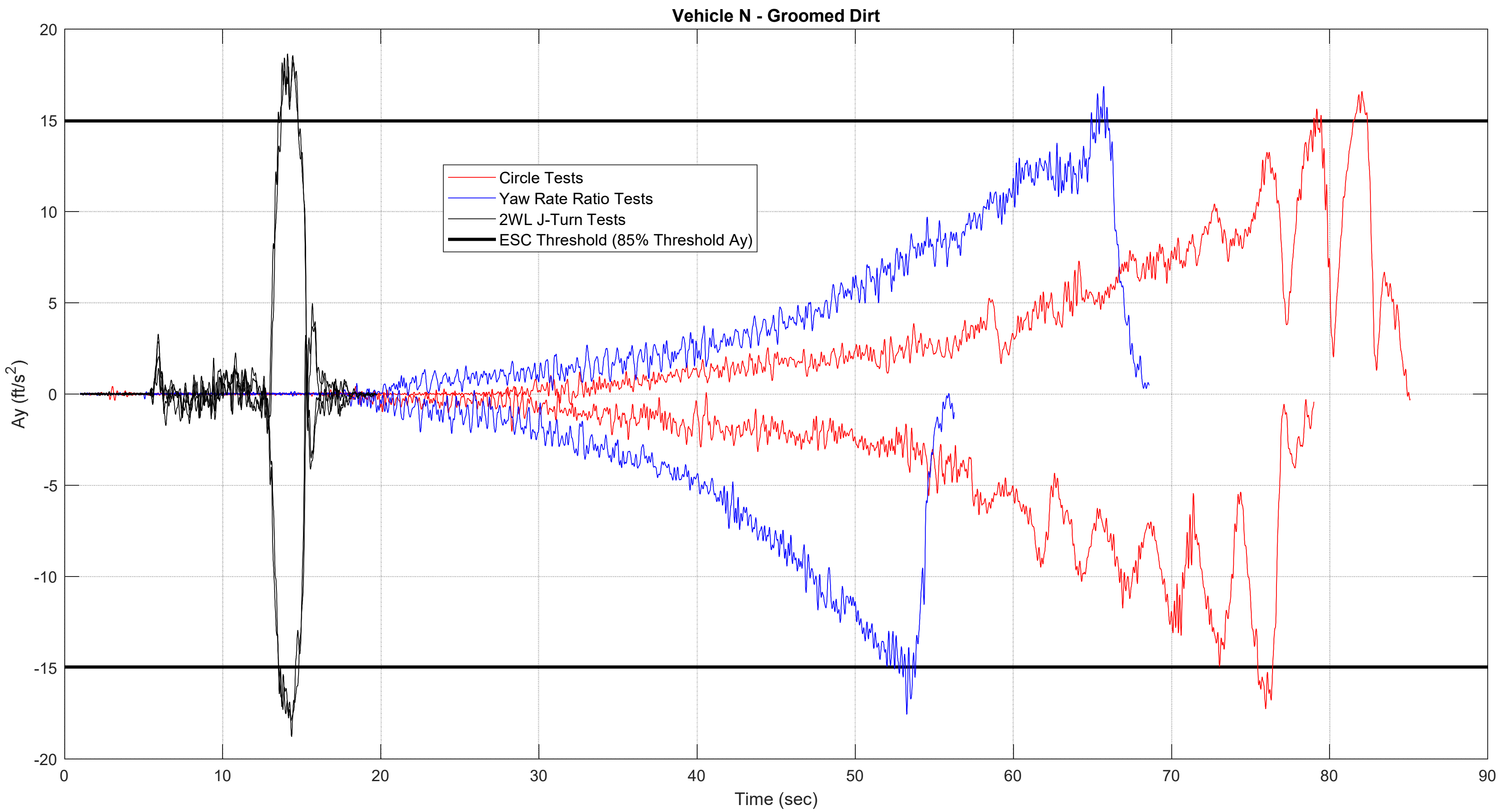

Vehicle G - Asphalt
Handwheel Steer Angle (deg)
Time (sec)
Circle Tests
Yaw Rate Ratio Tests
2WL J-Turn Tests
Steering Threshold

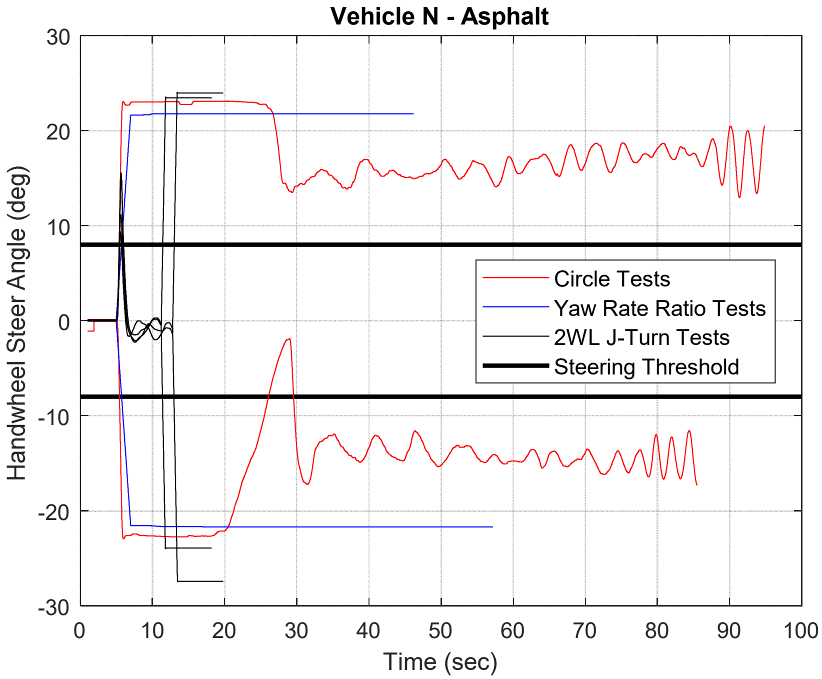

Vehicle G - Groomed Dirt
Handwheel Steer Angle (deg)
Time (sec)
Circle Tests
Yaw Rate Ratio Tests
2WL J-Turn Tests
Steering Threshold

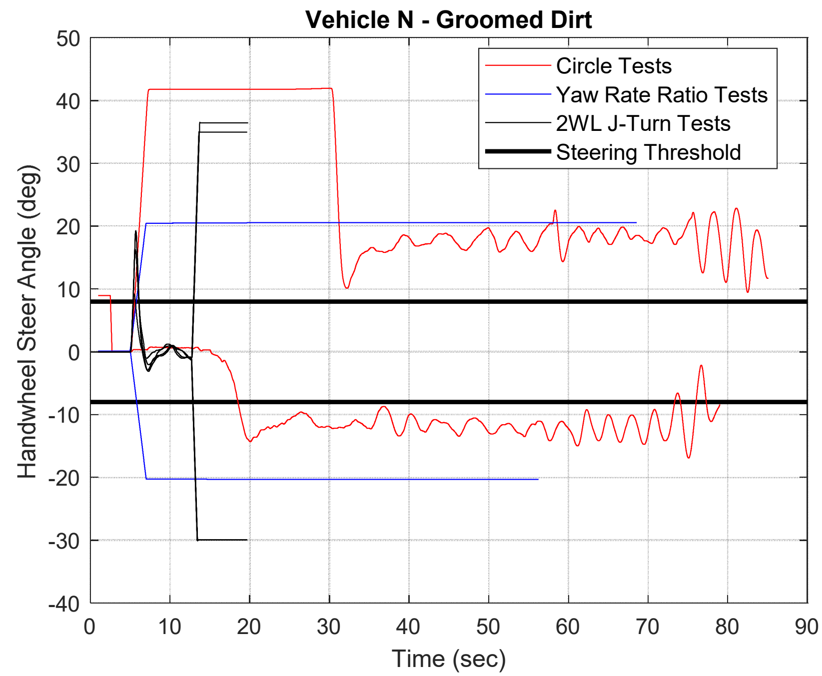

Vehicle G - Asphalt
Vehicle Speed (mph)
Time (sec)
Circle Tests
Yaw Rate Ratio Tests
2WL J-Turn Tests
Speed Threshold

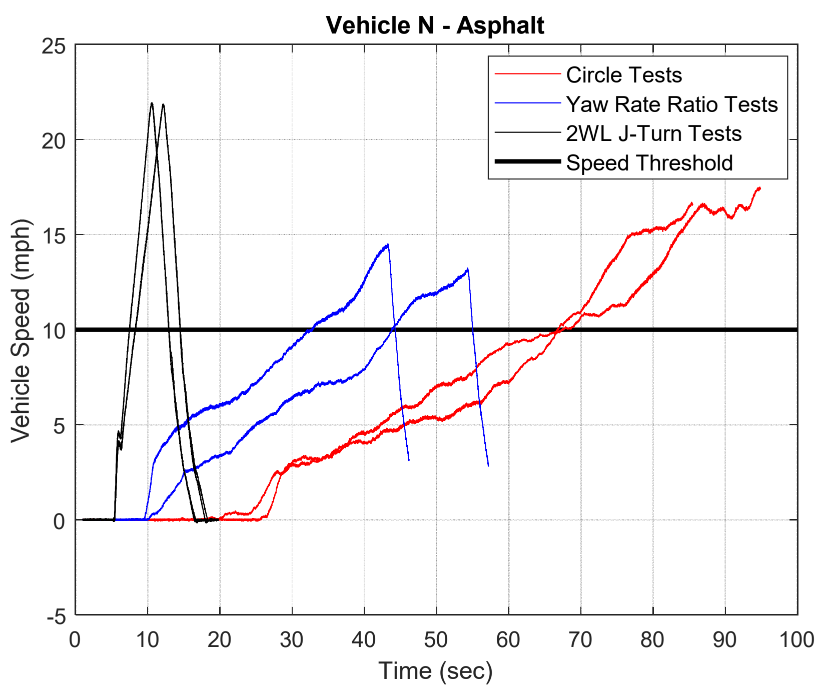

Vehicle G - Groomed Dirt
Vehicle Speed (mph)
Time (sec)
Circle Tests
Yaw Rate Ratio Tests
2WL J-Turn Tests
Speed Threshold

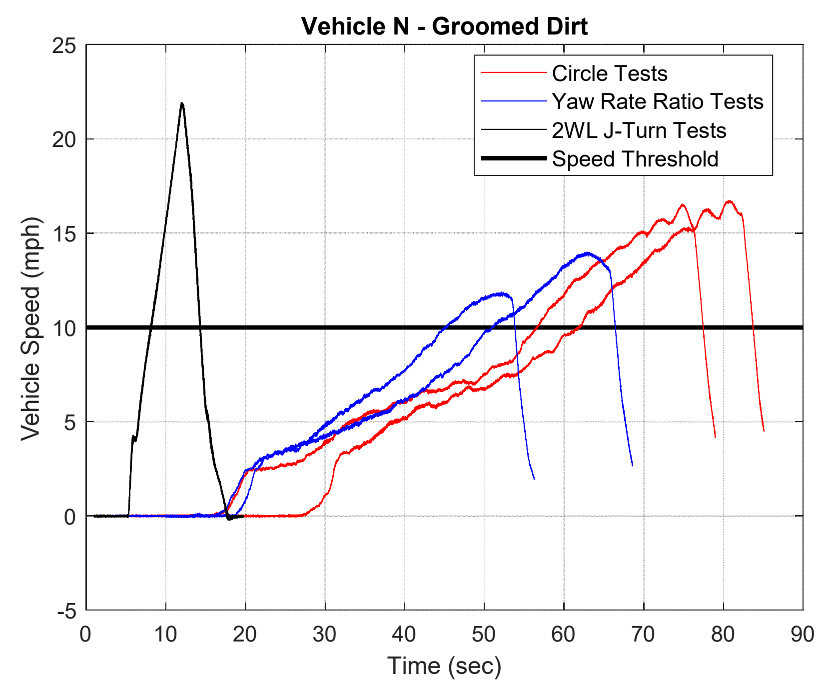

Vehicle N - Asphalt
Circle Tests
Yaw Rate Ratio Tests
2WL J-Turn Tests
ESC Threshold (85% Threshold Ay)
Ay (ft/s^2)
Time (sec)
20
15
10
5
0
-5
-10
-15
-20
0
10
20
30
40
50
60
70
80
90
100


Vehicle N - Groomed Dirt
Circle Tests
Yaw Rate Ratio Tests
2WL J-Turn Tests
ESC Threshold (85% Threshold Ay)
Ay (ft/s^2)
Time (sec)
20
15
10
5
0
-5
-10
-15
-20
0
10
20
30
40
50
60
70
80
90


Vehicle N - Asphalt
Handwheel Steer Angle (deg)
Time (sec)
Circle Tests
Yaw Rate Ratio Tests
2WL J-Turn Tests
Steering Threshold
30
20
10
0
-10
-20
-30
0 10 20 30 40 50 60 70 80 90 100

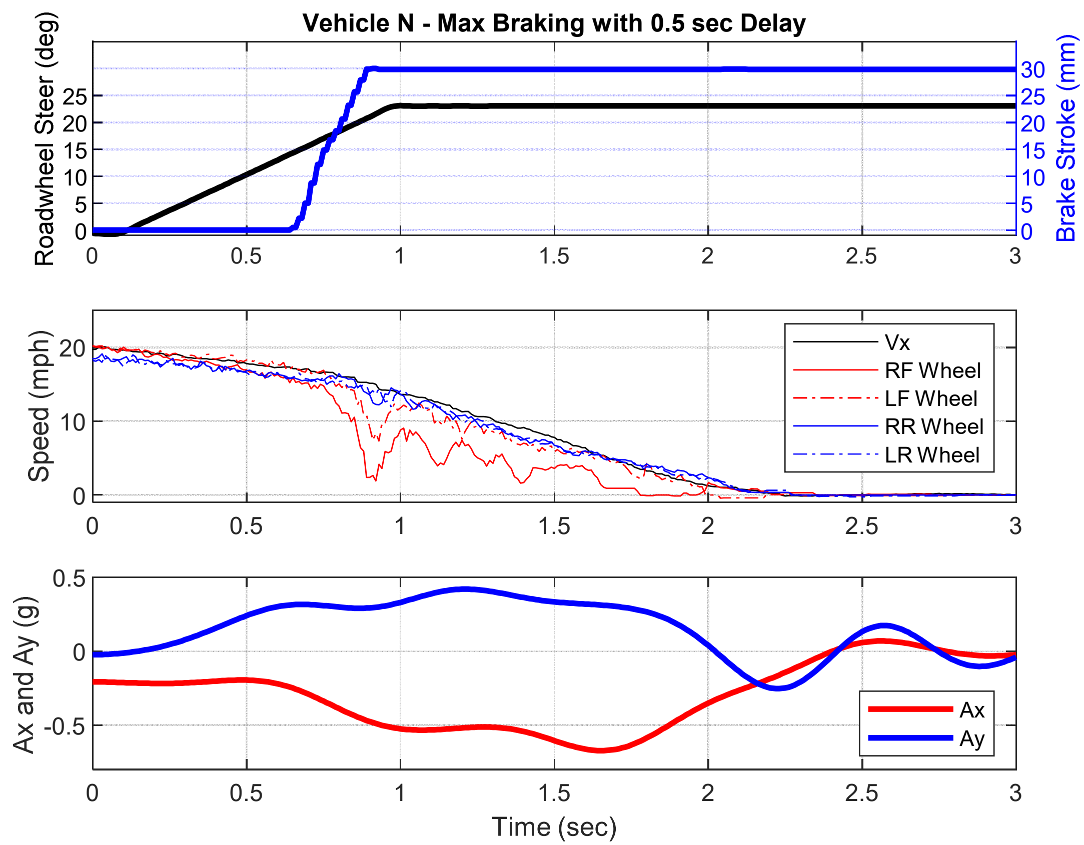

Vehicle N - Groomed Dirt
Handwheel Steer Angle (deg)
Time (sec)
Circle Tests
Yaw Rate Ratio Tests
2WL J-Turn Tests
Steering Threshold
50
40
30
20
10
0
-10
-20
-30
-40
0 10 20 30 40 50 60 70 80 90

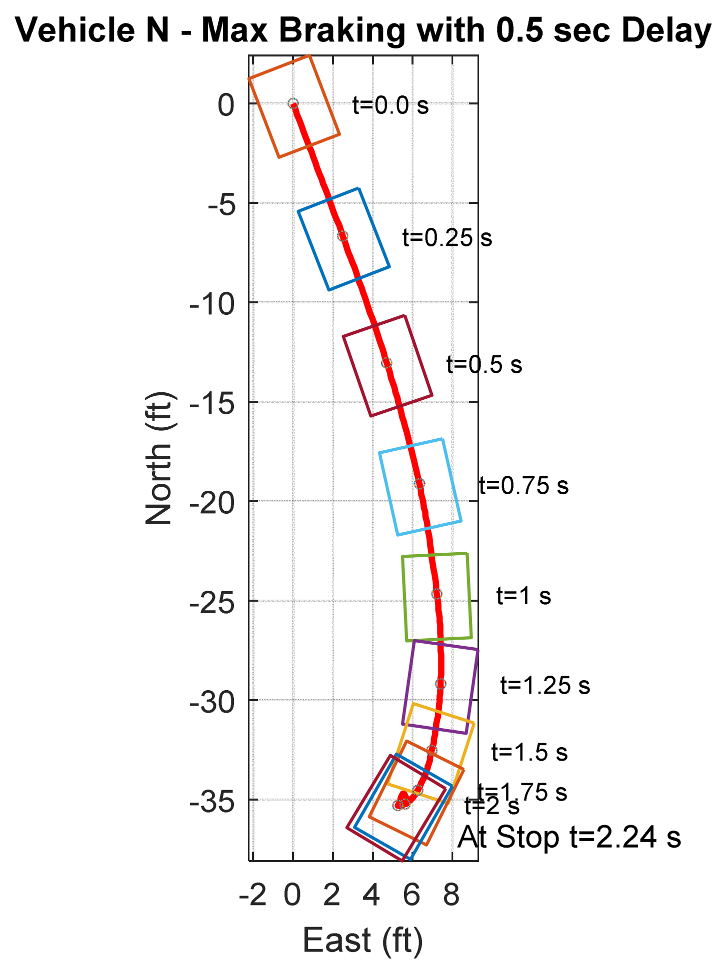

Vehicle N - Asphalt
Vehicle Speed (mph)
Time (sec)
Circle Tests
Yaw Rate Ratio Tests
2WL J-Turn Tests
Speed Threshold
25
20
15
10
5
0
-5
0 10 20 30 40 50 60 70 80 90 100


Vehicle N - Groomed Dirt
Vehicle Speed (mph)
Time (sec)
Circle Tests
Yaw Rate Ratio Tests
2WL J-Turn Tests
Speed Threshold
25
20
15
10
5
0
-5
0 10 20 30 40 50 60 70 80 90

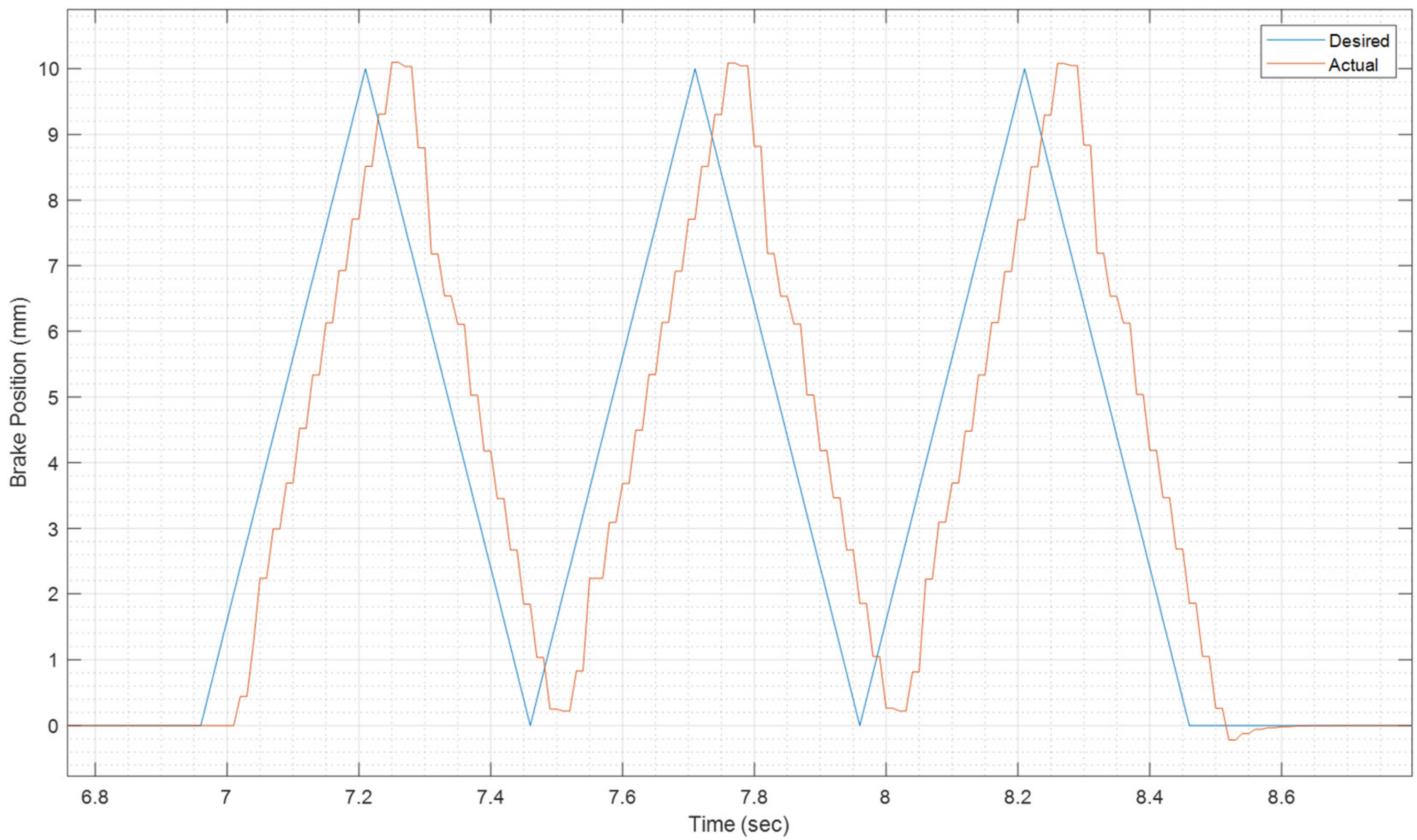
Results Showing Timing of ABS Cycling of Vehicle N

Results from Braking and Turning Maneuver Performed on Wet Grass





Demonstration of Capabilities of Electronic Motor Brake Actuator Used to Cycle Hand Brake to Emulate ABS on Vehicle G



Brake Position 10 mm in 0.25 sec