U.S. Department
of Transportation

**National Highway
Traffic Safety
Administration**

Memorandum

Vehicle Research and Test Center P.O. Box B37
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(937) 666-4511

Subject: FINAL REPORT: PE10-038 "BMW Mini Cooper Electric Power Steering"

Date: 4/11/2011

From: Roger A. Saul
Director
Vehicle Research and Test Center

Reply to Attn. Of: NVS-310

To: Frank Borris
Director
Office of Defects Investigation

Attached is a pdf of the final report titled "BMW Mini Cooper Electric Power Steering." This report completes the requirements for this program.

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Memorandum Report
PE10-038
BMW Mini Cooper Electric Power Steering

Background

Subject vehicles for this program are equipped with an electro-hydraulic power steering system (EHPS). Rather than having a conventional hydraulic power steering pump that is driven by a belt from the vehicle's engine, this system utilizes an electric motor to drive the hydraulic power steering pump. The motor, pump, and an electronic control unit, (ECU) that controls the operation of the electric motor, are all in one unit that is mounted low in the engine compartment, between the engine and the firewall. A small cooling fan is utilized to draw air from underneath the vehicle and blow it across the EHPS unit to help cool it. Figure 1 shows the EHPS unit and the cooling fan mounted in the vehicle.

Figure 1
Power Steering Unit and Cooling Fan Mounted in Vehicle

The Office of Defect Investigations has received complaints and field reports alleging an unexpected loss of power steering assist while driving the subject vehicle. The complainants state that when power steering assist is lost, increased force is required to steer the vehicle. Some drivers reported experiencing difficulty while trying to steer or control the vehicle. The reports indicate that the loss of power steering assist may be related to a power steering pump failure. Several of the complaints allege repeated failures of the second and third power steering units to be installed in their vehicle.

The Vehicle Research and Test Center (VRTC) was asked to perform an analysis of the power steering system failure, to quantify the steering efforts with and without power assist, and to perform limited human factors testing in order to determine driver reaction to a loss of steering assist at low speeds.

Test Vehicle

A 2004 BMW Mini Cooper (VIN: WWMRC33424[redacted]) was leased from a complainant for testing. The odometer registered 55,594 miles when delivered and the EHPS was inoperative. The receiving inspection at VRTC showed that the vehicle was equipped with Bridgestone Potenza G009 tires, size 205/50R16, set to 25 psi. The vehicle manufacturer's recommended tire pressure is 35 psi. The tire manufacturer's maximum allowable inflation pressure is 44 psi. After allowing the tires to cool overnight, the inflation pressure in all four tires was adjusted to the recommended 35 psi. Various vehicle parameters were measured or calculated at this time. Figure 2 shows the test vehicle used for this program.

Figure 2
Subject Test Vehicle

Objective Testing

Instrumentation was installed in the vehicle that allowed the monitoring and recording of vehicle speed, hand wheel (steering wheel) force, and lateral acceleration.

Instrumented testing consisted of sinusoidal steering inputs while driving at steady speeds between 5 mph and 40 mph in 5 mph increments. Steering inputs were approximately 180 degrees left and right or approximately 0.7G lateral acceleration, whichever limit was reached first. Lock-to-lock hand wheel forces were also recorded with the vehicle stopped. After performing these tests with the inoperative EHPS unit that came on the vehicle, a new EHPS unit and cooling fan were installed and the tests were repeated.

Disassembly and Inspection of Power Steering Unit

After the original, non-functional EHPS unit was removed, it was disassembled for inspection and limited testing.

Human Factors Testing

Human factors testing was performed to document the reaction of each test subject when power steering assist was lost without warning while attempting to negotiate a turn. Although participants were chosen from VRTC contractor personnel, the screening process for participants eliminated anyone who claimed to have knowledge of the purpose of the test. Each participant was given a verbal explanation of what to expect[1] prior to the test and a short questionnaire[2] to fill out at the conclusion of the test.

The test course consisted of driving the vehicle on a short section of 2-lane roadway, then through a 90º left turn in a simulated intersection onto another simulated 2-lane road[3] and then through a 180º right turn. After allowing the test driver to become somewhat familiar with the vehicle, the electrical circuit to the power steering pump was interrupted, and thus power steering assist was lost, just as the test subject entered the simulated intersection for the left turn. Traffic pylons were erected on the outside of the simulated intersection to simulate pedestrians waiting to cross the street or a parked vehicle. The test subjects were instructed to avoid striking all pylons.

Test Results

Vehicle Parameters

Table 1 lists the vehicle parameters that were measured, calculated, or found in published data. The tire contact area was determined by spreading ink on a front tire, lowering the tire (mounted on the vehicle) onto a piece of paper, and measuring the area of the resultant contact patch.[4]

[1] A copy of the Explanation to the Driver is provided in Appendix I.
[2] A copy of the driver's questionnaire is provided in Appendix II.
[3] A dimensioned diagram of the simulated intersection is shown in Appendix III.
[4] A front tire contact patch is provided in Appendix IV.

Table 1
Vehicle Parameter Data

Vehicle Data		
Fr.Wheel Arc lock-to-lock: (deg.)	66.75*	
Str. Wheel lock-to-lock: (turns)	2.56*	
Steering Ratio:	13.8:1	
Front Tire Contact Area: (in²)	36	
Tire Size:	P175/65R15	
Turning Radius: (ft.)	17.5*	
Veh. Wt. as tested: (lb)	**LF**	**RF**
	898	833
Total Front (lb)	1731	
	LR	**RR**
	578	553
Rear Total (lb)	1131	
Total (lb)	2862	

* = published data

Objective Testing

Table 2 lists the ranges of measured hand wheel forces, with and without power steering assist, for the nine test conditions that were tested.

Table 2
Results of Objective Testing

Test Description Nominal Speed (mph)	Measured Force Range Without Assist (lb)	Measured Force Range With Assist (lb)
Stationary (asphalt)	50-55	7-8
5 mph	20-25	7-8
10 mph	20-25	7-8
15 mph	25-30	7-8
20 mph	25-30	No Data
25 mph	25-35	6-7
30 mph	25-30	6-8
35 mph	25-27	7-8
40 mph	27-30	6-7

Figure 3 shows the lateral acceleration vs. steering wheel force data for all testing and highlights the difference in required force between assisted and non-assisted steering effort. The blue line represents average unassisted steering effort while the red line represents average assisted steering effort.

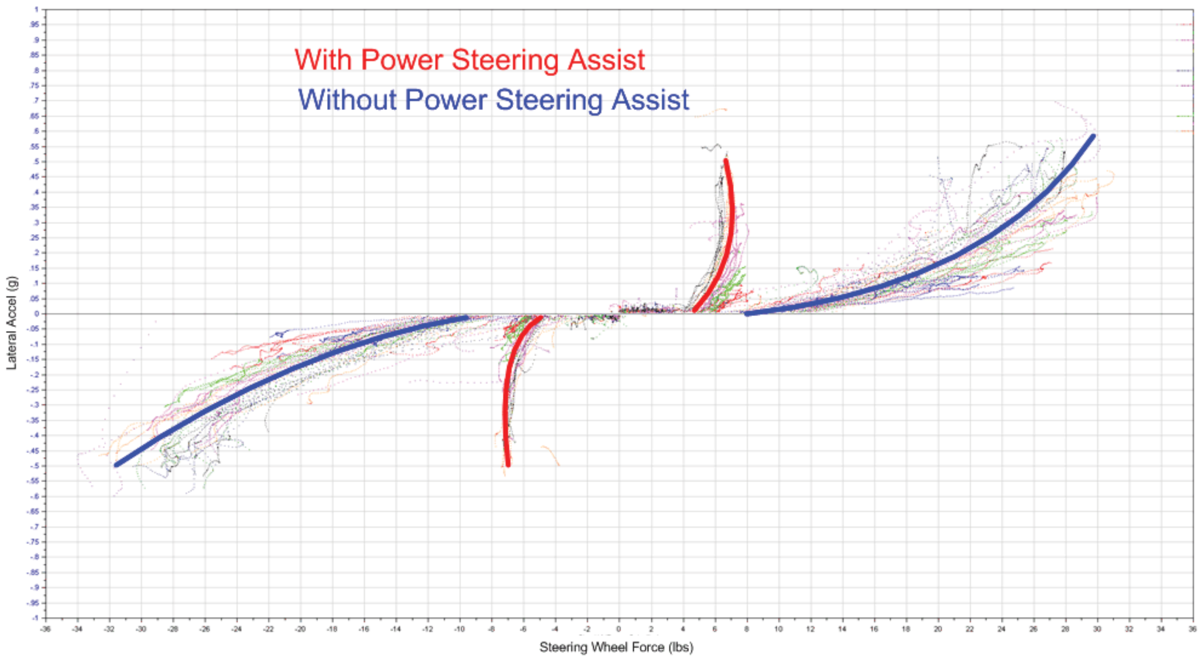


Figure 3
Lateral Acceleration vs. Assisted and Unassisted Steering Effort

<u>Power Steering Unit Inspection</u>

The ECU for the EHPS is physically located between the motor and the pump and is subjected to heat from the engine, the exhaust, and the power steering fluid. Through a process of elimination, it was determined that the failure of the EHPS on the test vehicle was due to an unspecified failure of the ECU. This conclusion was reached after performing the following actions:

1) Disassembly of the EHPS motor showed that a significant amount of fine, black powder and dust were present in the motor. This material was found in the motor can, within the armature windings, and on the brush plate. Because there was no visible corrosion anywhere inside the motor, it was thought that the powder/dust was likely carbon brush material since it was electrically conductive.

2) After finding no mechanical reason for the motor not to run, the motor and ECU were reassembled without the pump. The assembly was then reconnected to the vehicle through the standard electrical connections into the control module. When the vehicle was started, the EHPS continued to be inoperative.

3) Holes were then drilled in the motor housing that allowed wires to be connected directly to the motor brushes, bypassing the ECU. This scenario caused the motor to run when the proper voltage was applied from a non-vehicle power source.

4) The pump portion of the unit was then reattached to the pump and ECU. When the motor was energized by bypassing the ECU, as described above, the pump generated flow and pressure.

5) The cooling fan was then connected directly to a non-vehicle power source and was determined to be functional.

6) Since the new, replacement EHPS and cooling fan both worked properly when mounted in the vehicle, it was determined that the vehicle wiring was not an issue.

Figure 4 shows a portion of the dust and powder found within the motor after disassembly. Figure 5 shows the armature and electrical connections. Figure 6 shows the brush plate and additional dust from inside the motor. Figure 7 shows the condition of the armature and the commutator.

Figure 4
Dust in Motor after Disassembly

Figure 5
Armature and Electrical Connections

Figure 6
Brush Plate and Internal Dust

Figure 7
Armature and Commutator

Human Factors Testing

A summary of the human factors testing is presented in Table 3. Data plots from individual tests are presented in Appendix V.

Seventeen test subjects participated in the human factors testing. Each participant was asked to volunteer their height and weight but the information that was provided was not verified. The subjects ranged in reported height between 5’3” and 6’1” and in reported weight between 112 lb and 240 lb. Two of the female subjects declined to volunteer their weight although they are both well under 240 lb. The maximum hand wheel force that was exerted by the test subjects during the simulated left turn ranged between 20 and 31 lb. (For comparison, driving the vehicle through the simulated intersection with functional power steering required a maximum of 7 lbs of force) All but one test subject was able to negotiate the left turn without contacting the delineating pylons. Most slowed the vehicle so that it was almost stopped, and then proceeded slowly through the turn. Video documentation of the testing has been provided under separate cover.

Comments that the test participants provided included: “not a feeling of total control,” “could go into oncoming traffic in a slow speed turn,” “could cause an accident when turning a corner,” “surprised at the required effort,” “thought something broke,” and multiple variations of “hard to turn the wheel.”

Driver #	Gender	Hgt.	Wgt	Feel Safe with P/S	Feel Safe w/o P/S	Reaction to P/S loss	Written Comments	Braking	Handling	Compare to Others	POV	Verbal Comments	Max Force Exerted (lb)
1	M	5'8"	240	Yes	No	Used more force	Not a feeling of total control	Normal	Normal	Same	Ford F-150	Something blocking the steering	23
2	F	5'6"	180	Yes	Yes	Turned harder	None	Normal	Normal	No basis for comp	Dodge Avenger	P/S went out	23
3	F	5'3"	112	Yes	No	Extra stregth to complete	Steering was very difficult	Normal	Normal	No basis for comp	Honda Accord	N/A	23
4	M	5'4"	115	Yes	No	Pulled harder to complete	Could go into oncoming traffic in slow speed turn	No Opinion	Normal	Same	Ford F-150	P/S wasn't working	20
5	F	5'8"	-	Yes	No	Thought something broke	Difficult to turn the wheel	Normal	Normal	Same	Dodge Caliber	Hard to turn	21
6	M	5'5"	130	Yes	No	Slowed & used more force	Difficult to control	Normal	Normal	Better	Subaru Outlook	N/A	21
7	M	5'10"	218	Yes	No	Turned harder	Could cause accident turning a corner	Normal	Normal	Same	Ford F-150	N/A	23
8	M	5'11"	215	Yes	No	Hit brakes harder to slow	Very hard steering force	Normal	Normal	Same	Pontiac Grand Prix	N/A	22
9	M	6'1"	180	Yes	Yes	More torque to S/W	None	Normal	Better	Worse	Honda Accord	N/A	23
10	M	6'0"	185	Yes	Yes	Slowed but still in control	None	Normal	Normal	Same	Chev. Metro	N/A	26
11	F	5'6"	135	Yes	Yes	Tried to steer while braking	None	Normal	Normal	Same	Subaru Legacy GT	Wheel is hard to turn	27
12	F	5'4"	158	Yes	Yes	Startled first, then steered	None	Normal	Normal	Same	Chrysler Concorde	N/A	24
13	M	5'4"	145	Yes	Yes	Applied more force	None	Normal	Normal	Same	Chev S-10 & K1500	Lost the P/S	27
14	M	5'10"	210	Yes	No	Could barely turn wheel	Surprised at req'd effort	Normal	Normal	Worse	Honda Fit	N/A	26
15	F	5'5"	-	Yes	Yes	Braked and then turned	Hard to turn	Normal	Normal	Same	Honda Odyssey	N/A	26
16	F	5'5"	-	Yes	Yes	Slowed and used more forc	None	Normal	Normal	No basis for comp	Saab 900S	N/A	22
17	M	5'8"	165	Yes	Yes	Steered harder	None	Normal	Better	Better	Honda Accord	N/A	31
18	Functional Power Steering												7

Table 3
Summary of Human Factors Driver's Questionnaires

Appendix I
Explanation to Driver

Explanation to driver:

The test vehicle has been instrumented to monitor various driver control functions. Although most of the instrumentation is hidden, the most obvious is steering wheel input. We ask is that you follow instructions and operate the vehicle normally. Our intent is to measure driver reactions and vehicle control forces in various slow-speed driving conditions. Traffic pylons have been erected in several locations throughout the test course. The goal is to avoid striking any of the pylons. The test should take about 15 minutes. Feel free to make any comments about the drivability of the vehicle during the test. You will be asked to complete a brief questionnaire at the conclusion of the test.

Appendix II
Driver's Questionnaire

Questionnaire

1) Did you feel that the vehicle was safe to drive when the power steering was active?

Yes ________ No _______

If no, please explain. ____

2) Did you feel that the vehicle was safe to drive when the power steering failed?

Yes ________ No _______

If no, please explain. ____

3) How did you react to the failure of the power steering?

____

____

4) How would you classify the braking ability of the car?

Below normal____ Normal_____ Better than normal_____ No opinion______

5) How would you classify the handling of the car?

Below normal____ Normal _____ Better than normal_____ No opinion______

6) Have you owned, leased, or otherwise driven a Mini Cooper for an extended period before?

No _____ Yes ______ If yes, how does this Mini compare?

____

7) How would you compare the steering system of the car compared to other cars this size that you have driven?

Better than others_________ Worse than others________

Same as others________ No basis for comparison______

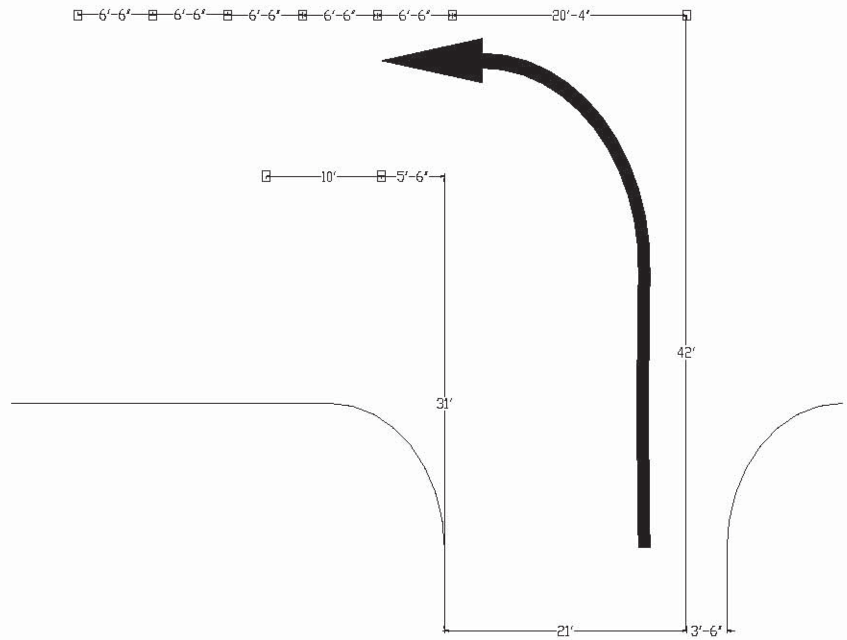
8) Please list the make, model, and year of your personal vehicle that you drive the most?

____

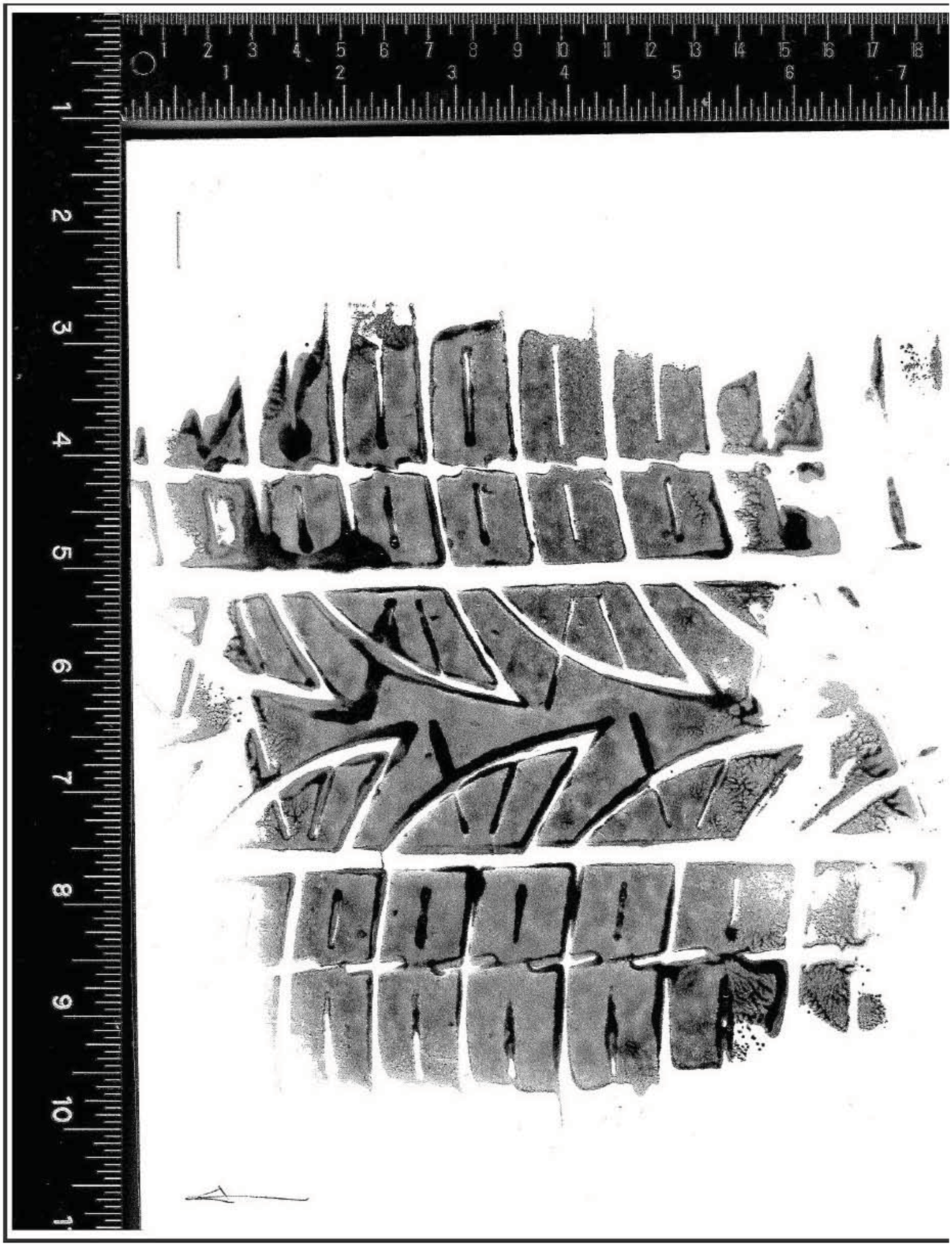
Additional comments: ____

Thank you for completing this survey. Please return the completed form to the person who conducted your test or to Bob Esser.

Appendix III
Diagram of Simulated Intersection Used for Human Factors Testing

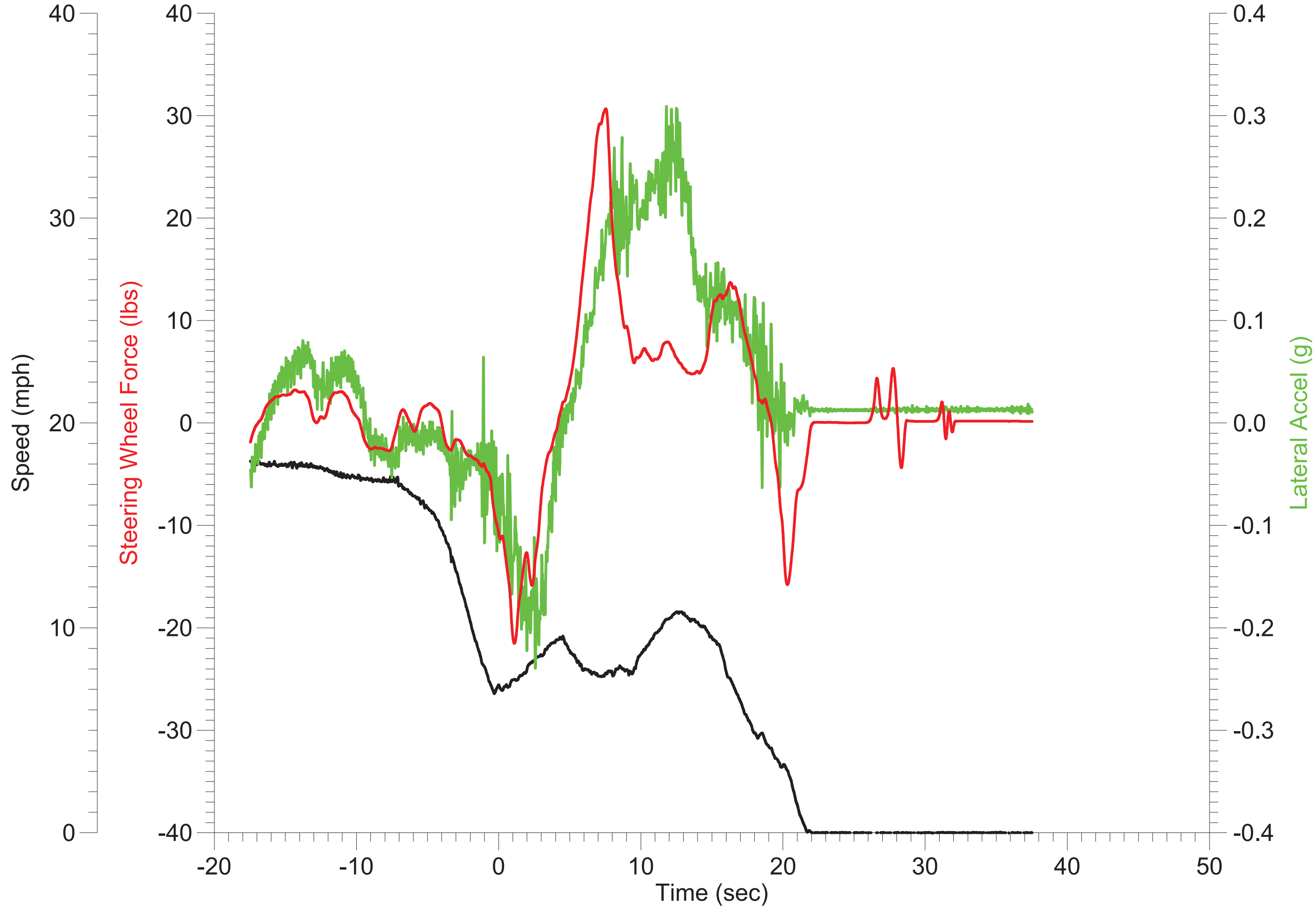

6'-6"
6'-6"
6'-6"
6'-6"
6'-6"
20'-4"
10'
5'-6"
42'
31'
21'
3'-6"

Appendix IV
Front Tire Contact Patch



Appendix V
Data Plots from Human Factors Testing

Driver No. 1


Speed (mph)
Steering Wheel Force (lbs)
Lateral Accel (g)
Time (sec)
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30
20
10
0
-10
-20
-30
-40
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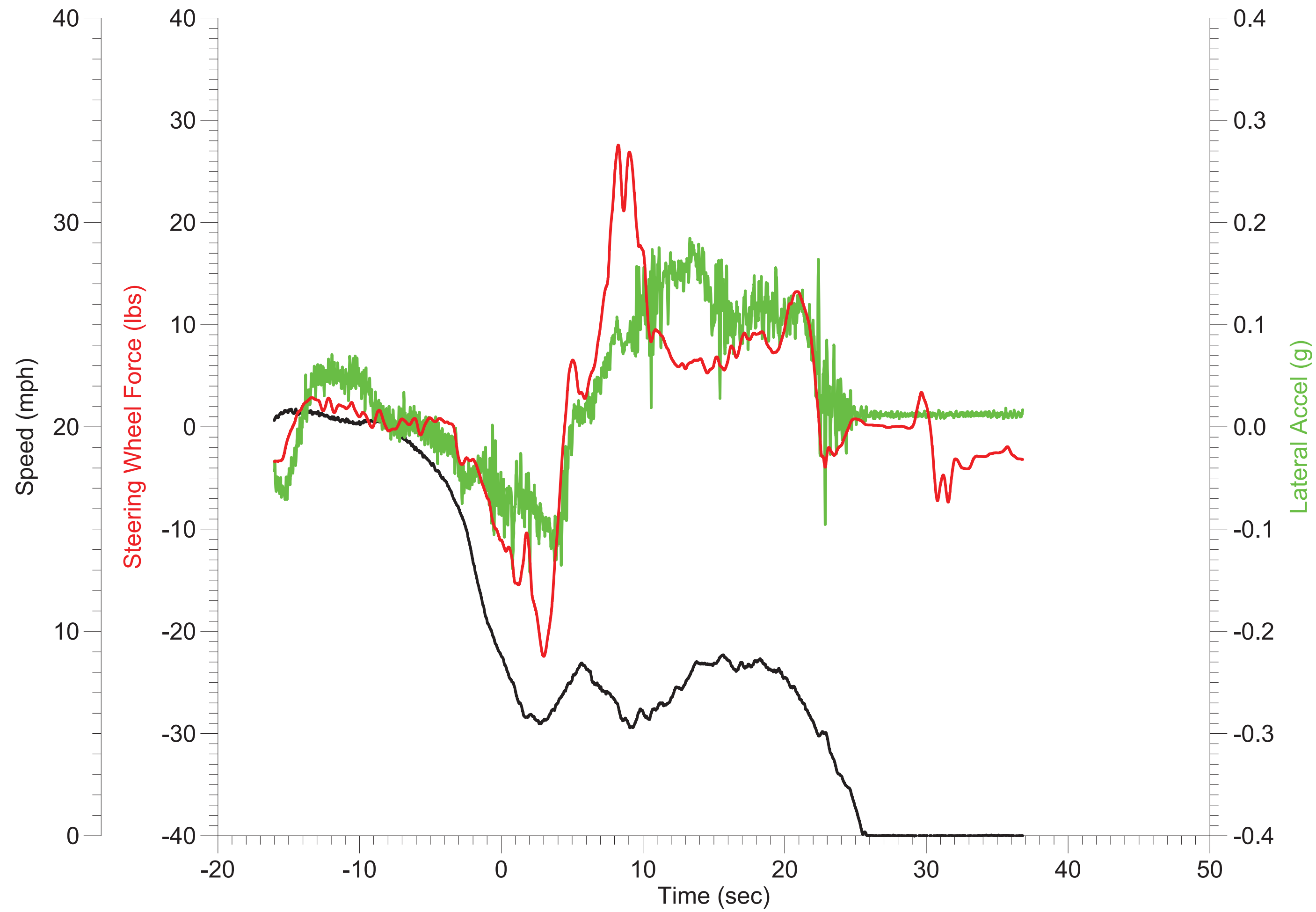
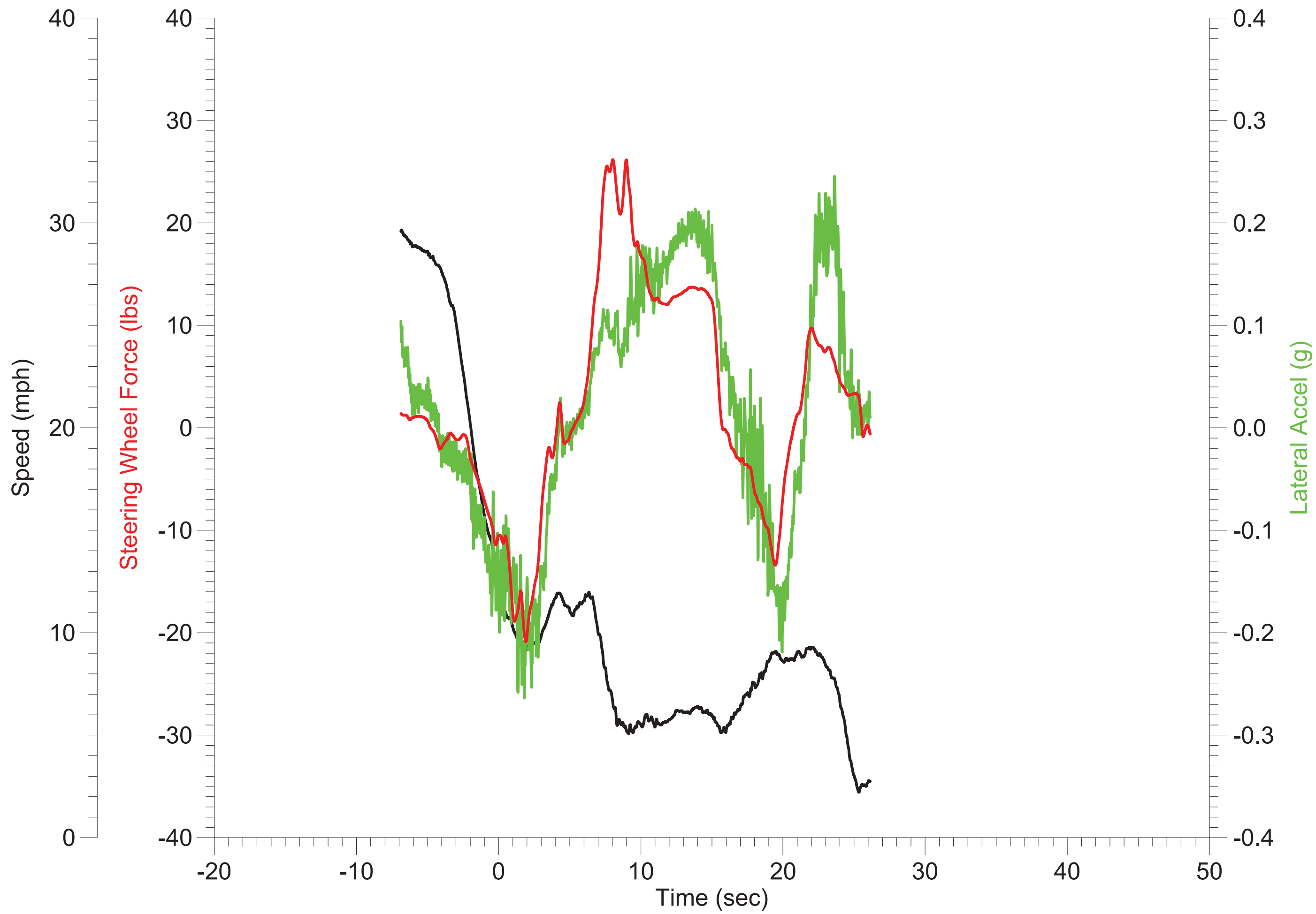
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
50

Driver No. 2



Speed (mph)
Steering Wheel Force (lbs)
Lateral Accel (g)
Time (sec)
40
30
20
10
0
-10
-20
-30
-40
-20
50
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4

Driver No. 3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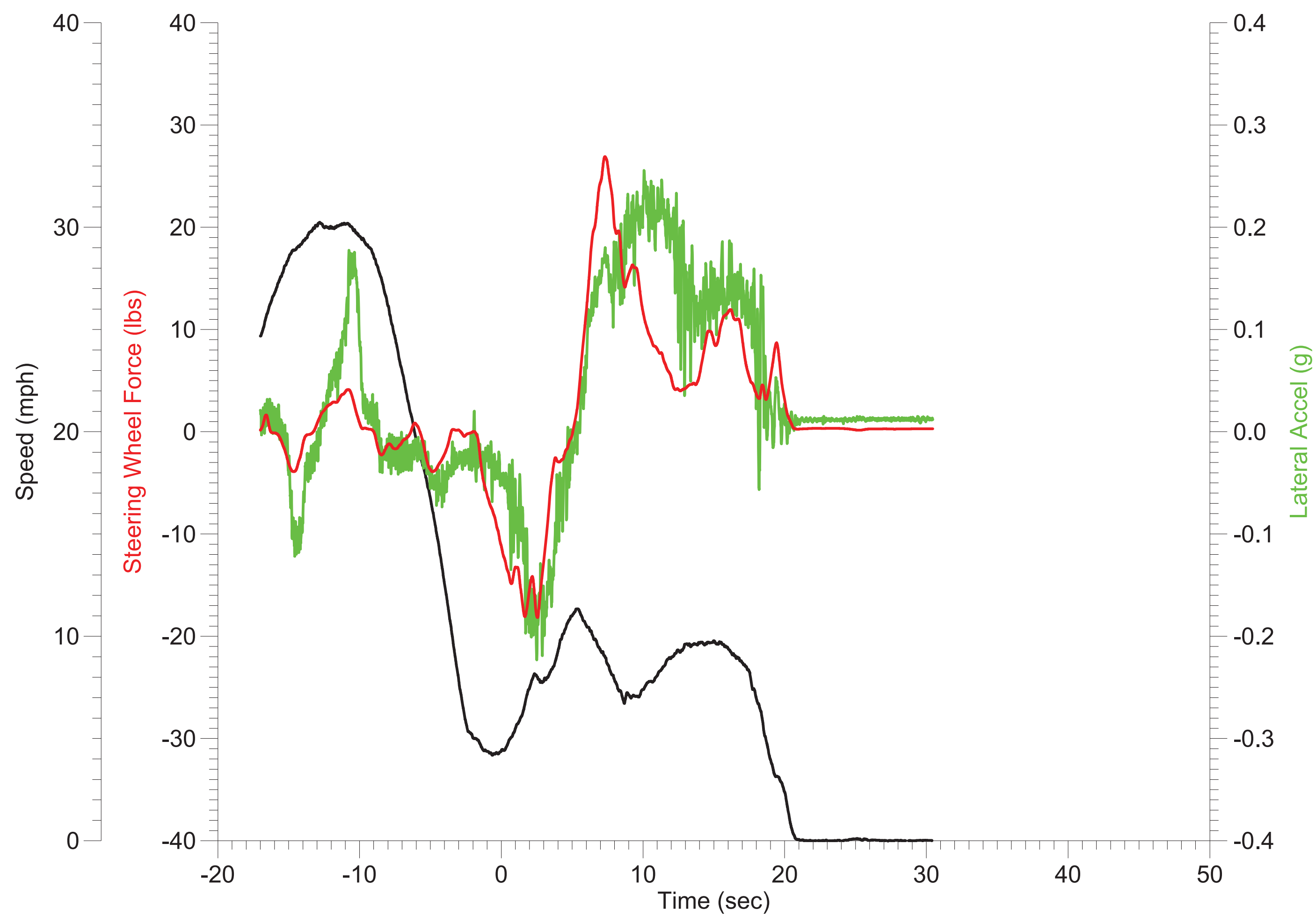
30
20
10
0
Steering Wheel Force (lbs)
40
30
20
10
0
-10
-20
-30
-40
Lateral Accel (g)
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-20
-10
0
10
20
30
40
50
Time (sec)

Driver No. 4



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Steering Wheel Force (lbs)
Lateral Accel (g)
Time (sec)
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30
20
10
0
-10
-20
-30
-40
0.4
0.3
0.2
0.1
0.0
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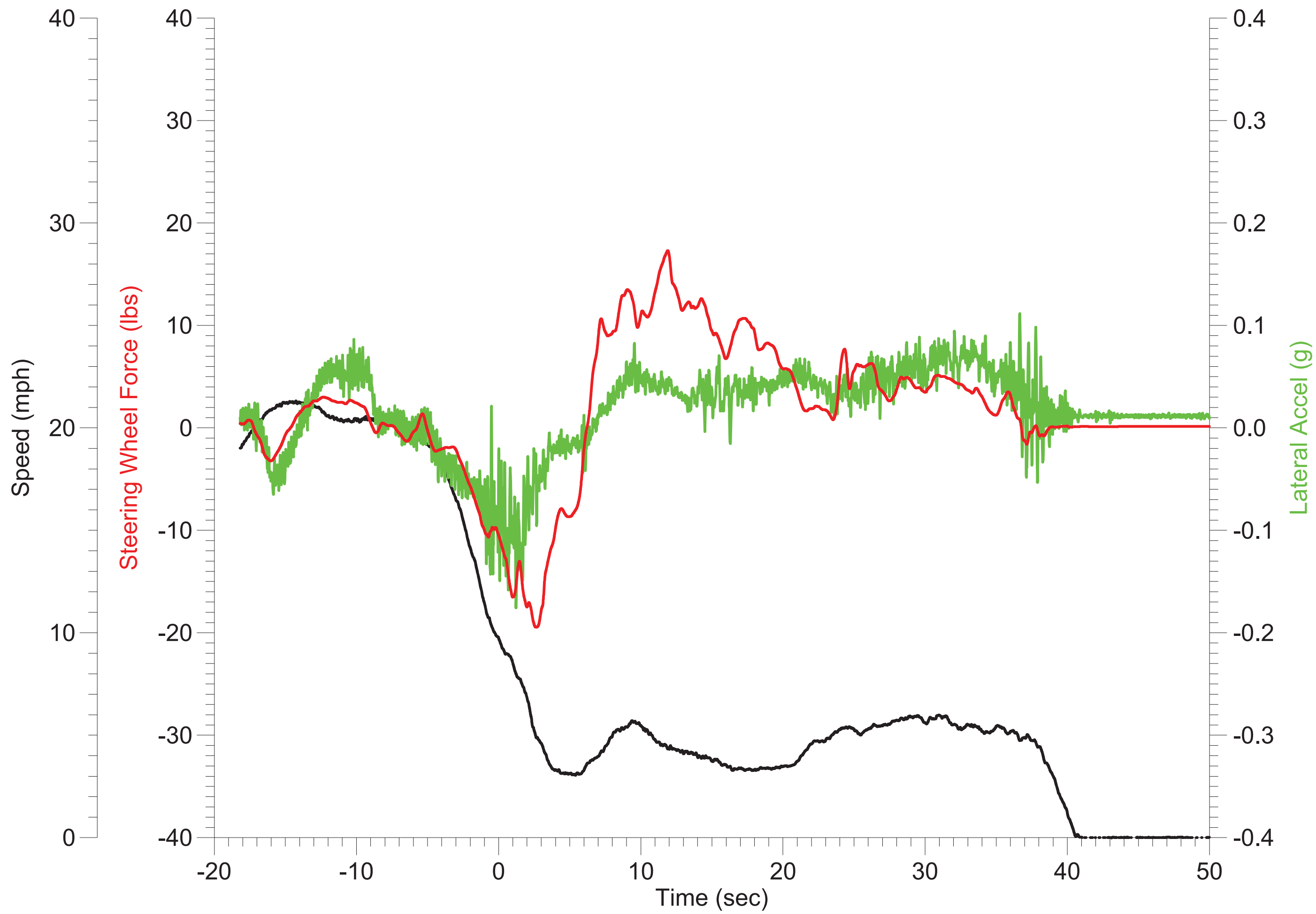
-0.2
-0.3
-0.4
-20
-10
0
10
20
30
40
50

Driver No. 5



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10
20
30
40
Steering Wheel Force (lbs)
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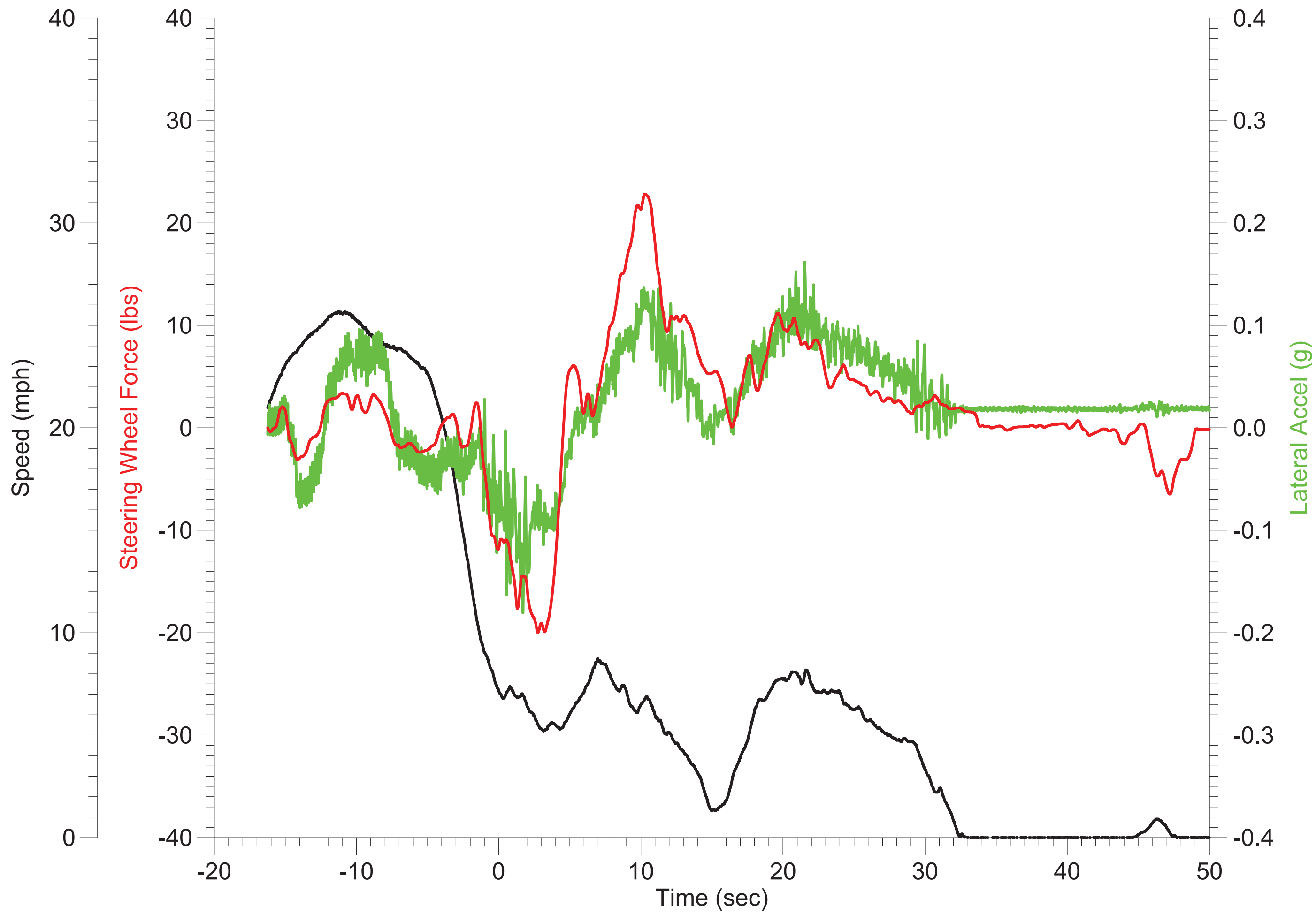
-30
-20
-10
0
10
20
30
40
Lateral Accel (g)
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
-20
-10
0
10
20
30
40
50
Time (sec)

Driver No. 6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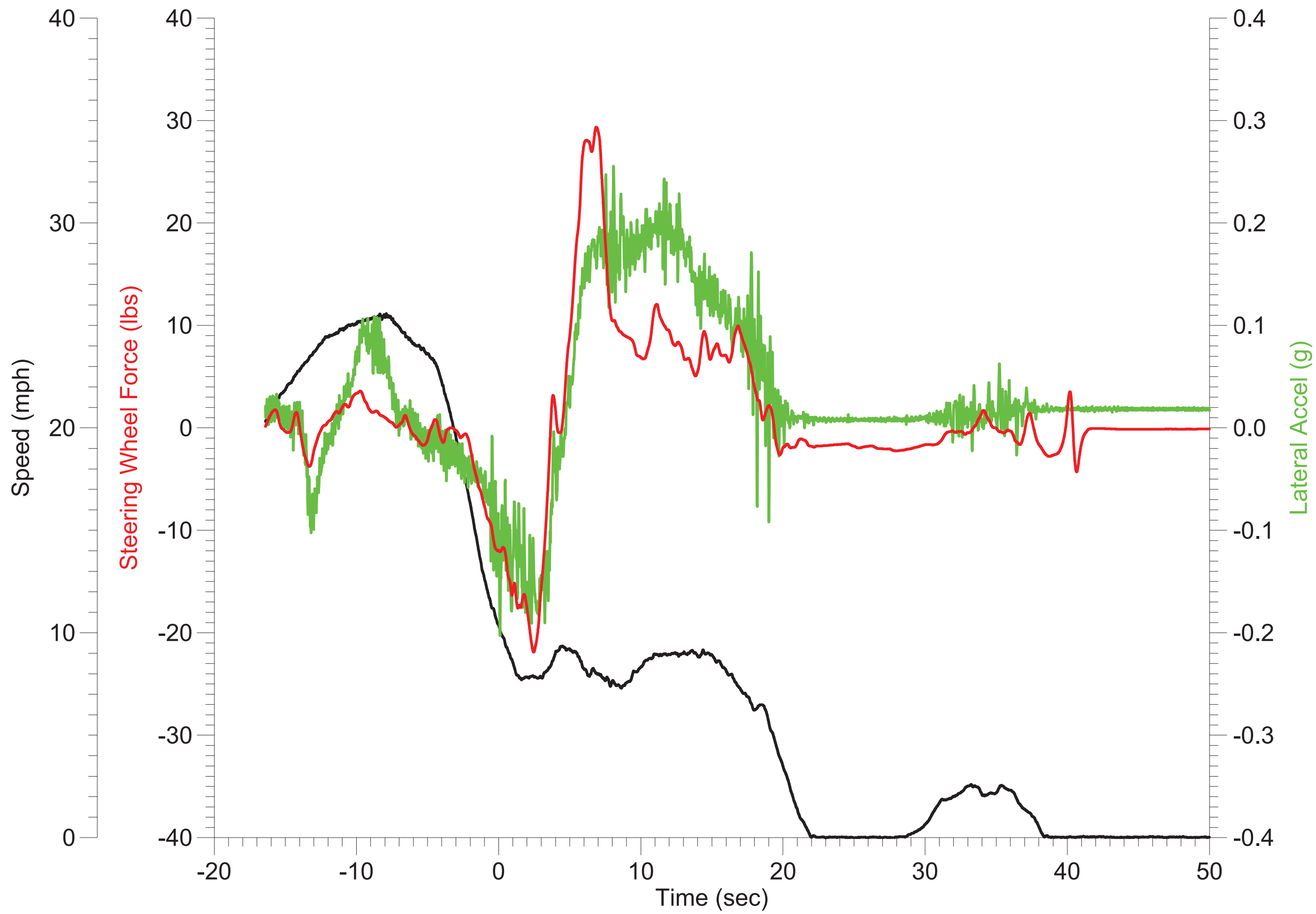
Steering Wheel Force (lbs)
Lateral Accel (g)
Time (sec)
40
30
20
10
0
40
30
20
10
0
-10
-20
-30
-40
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-20
-10
0
10
20
30
40
50

Driver No. 7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30
20
10
0
Steering Wheel Force (lbs)
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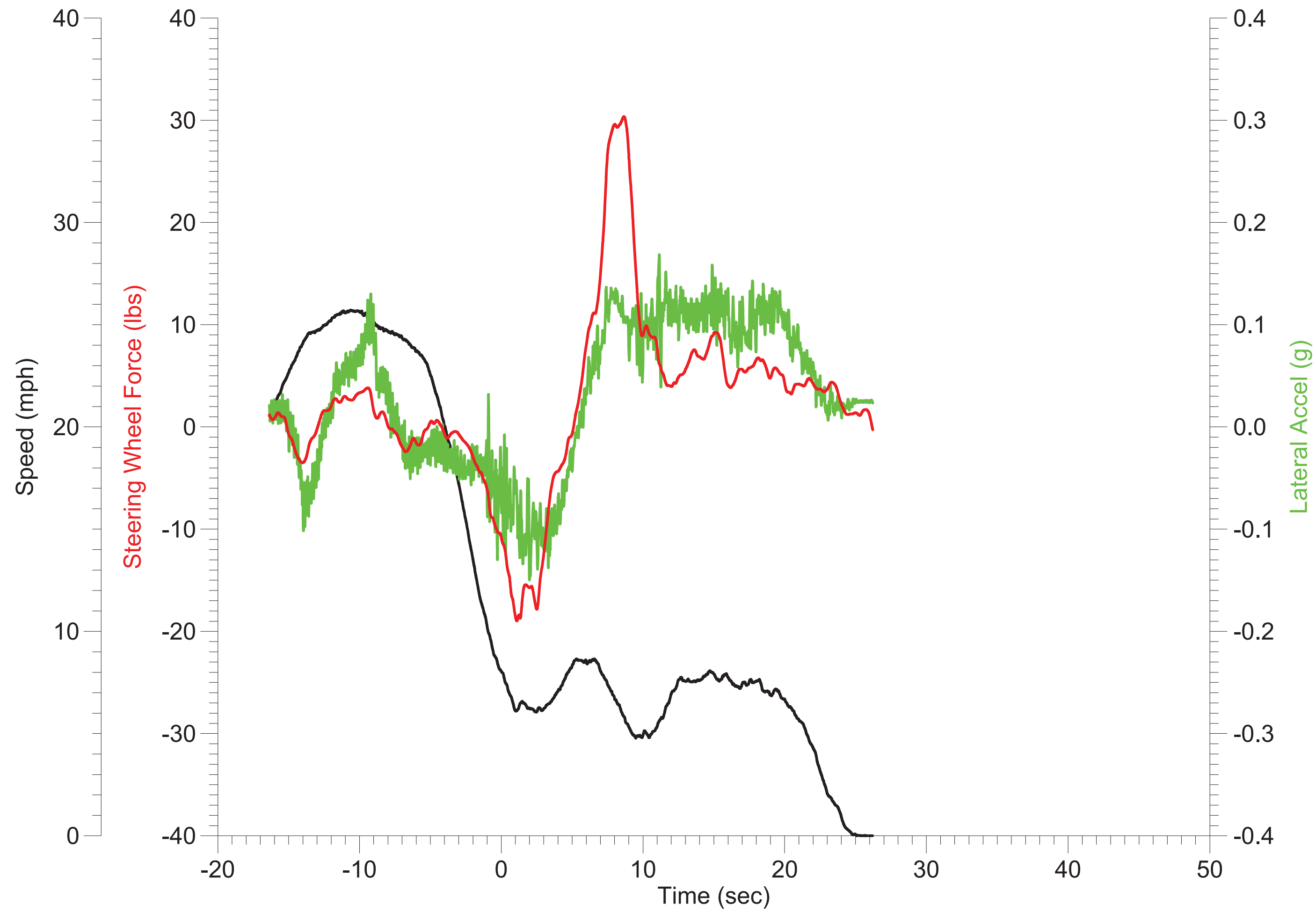
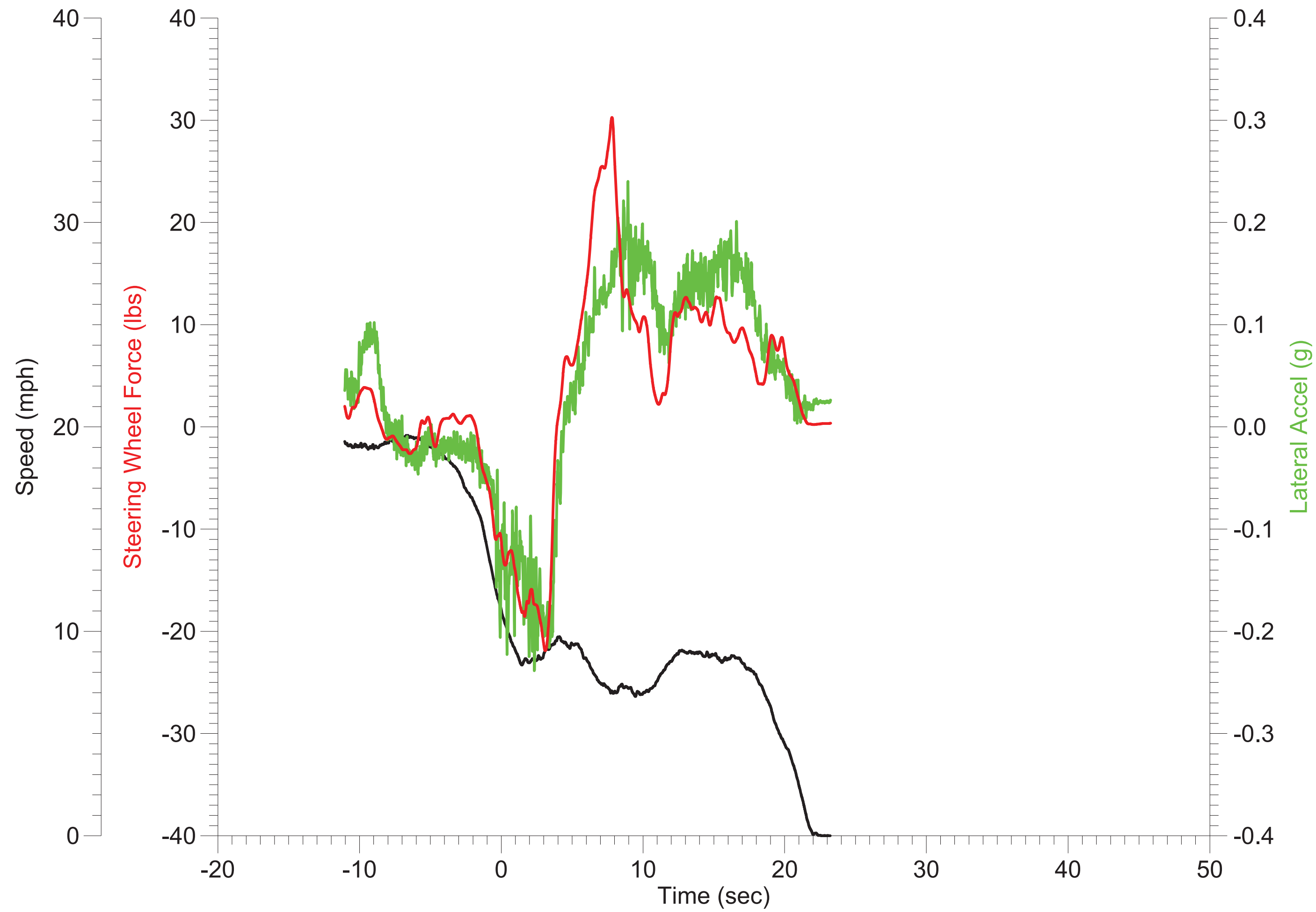
30
20
10
0
-10
-20
-30
-40
Lateral Accel (g)
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-20
-10
0
10
20
30
40
50
Time (sec)

Driver No. 8



Speed (mph)
0
10
20
30
40
Steering Wheel Force (lbs)
-40
-30
-20
-10
0
10
20
30
40
Lateral Accel (g)
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
Time (sec)
-20
-10
0
10
20
30
40
50

Driver No. 9



Speed (mph)
Steering Wheel Force (lbs)
Lateral Accel (g)
Time (sec)
0
10
20
30
40
-40
-30
-20
-10
0
10
20
30
40
-0.4
-0.3
-0.2
-0.1
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0.2
0.3
0.4
-20
-10
0
10
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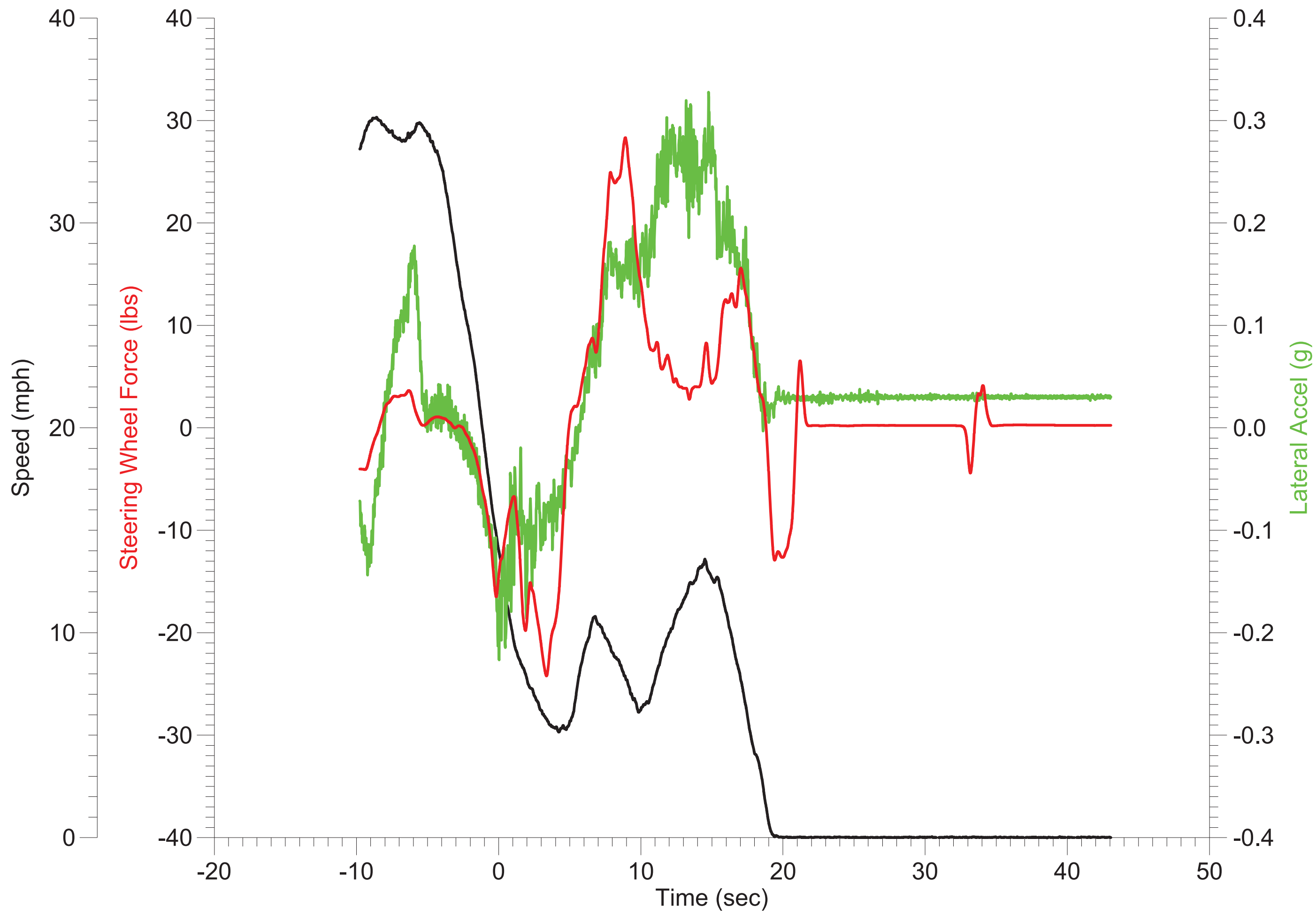
40
50

Driver No. 10



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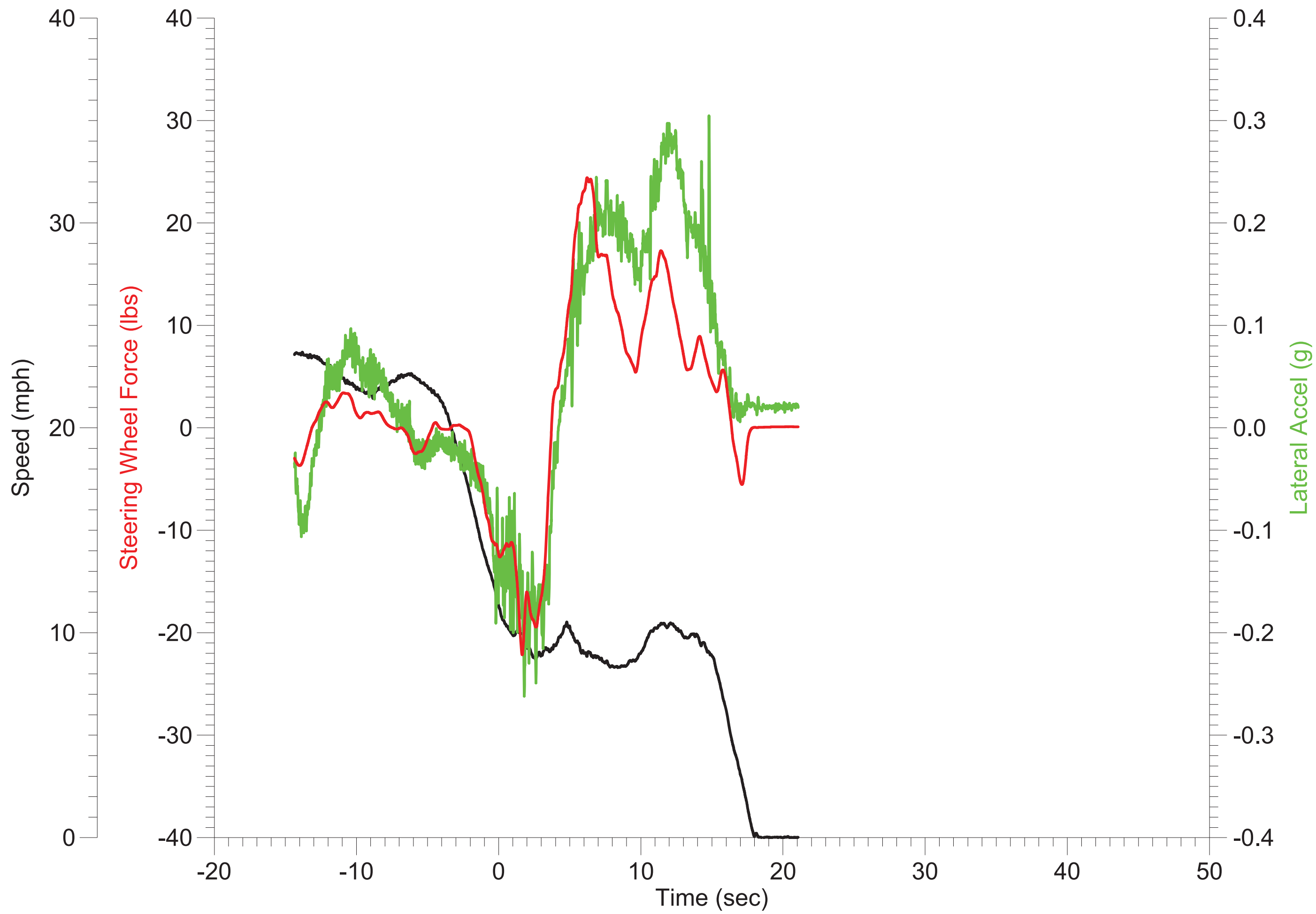

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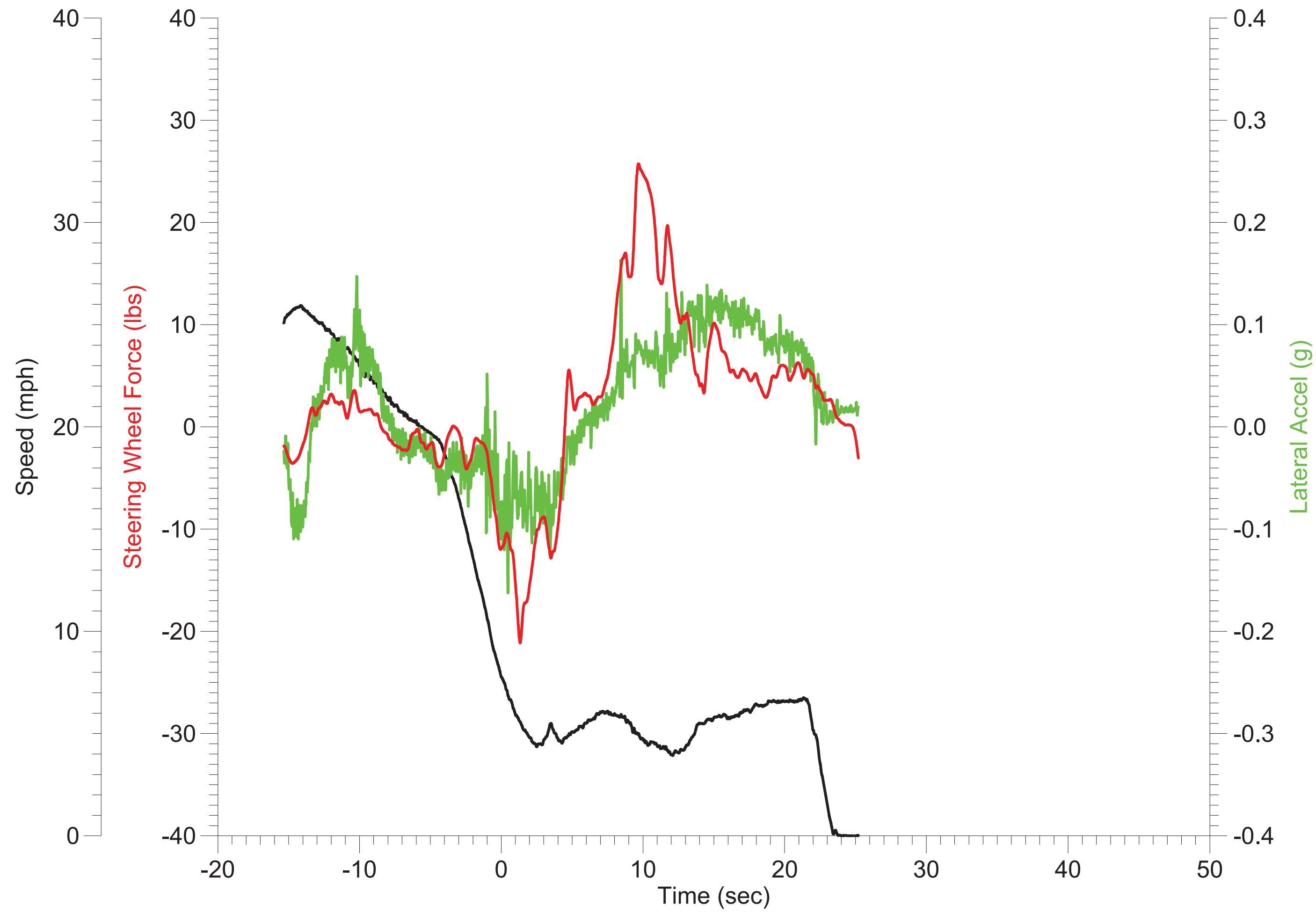
Speed (mph)
Steering Wheel Force (lbs)
Lateral Accel (g)
Time (sec)
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10
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-40
-30
-20
-10
0
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20
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40
0.4
0.3
0.2
0.1
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-0.4
-20
-10
0
10
20
30
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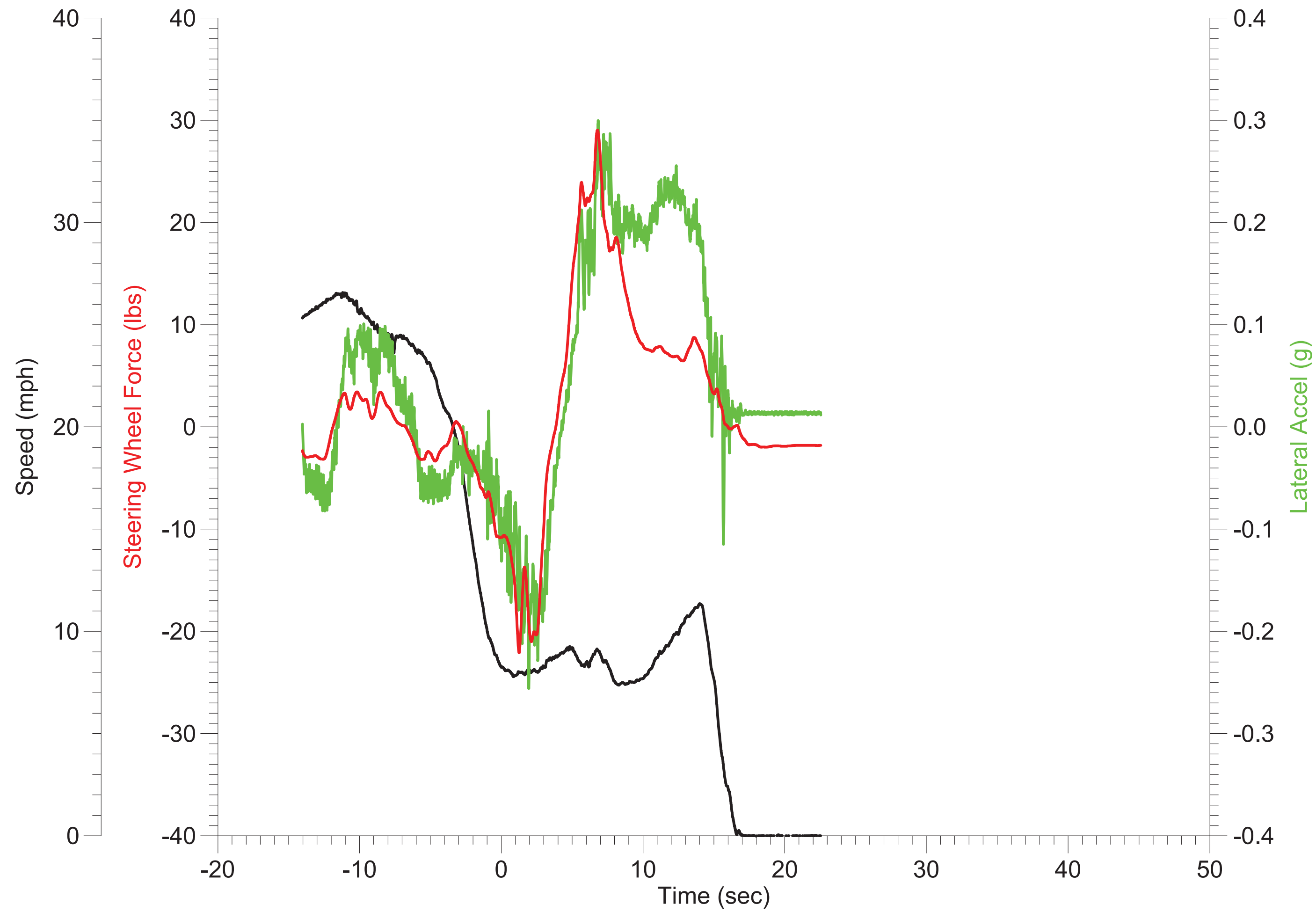
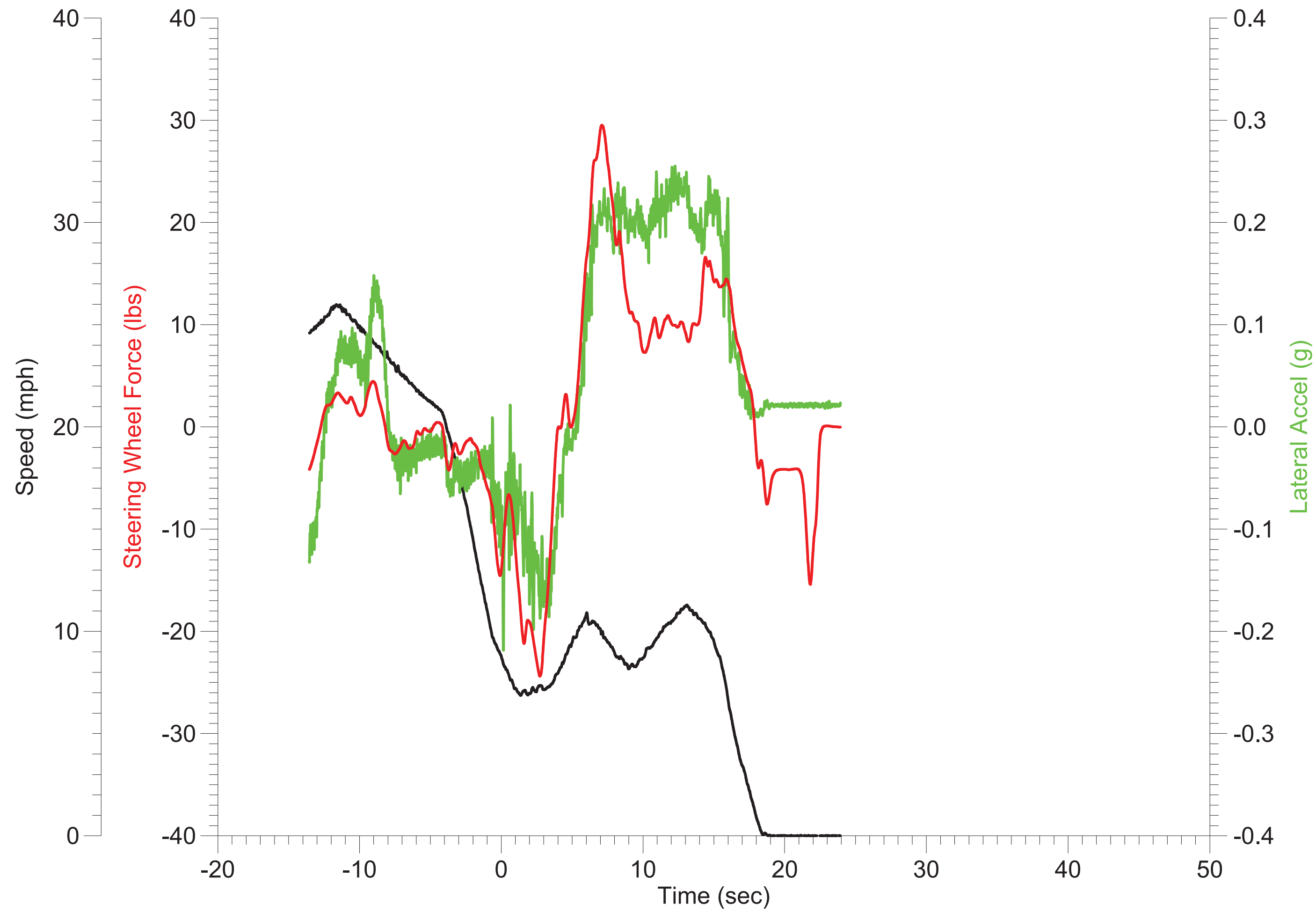
50

Driver No. 13



Speed (mph)
Steering Wheel Force (lbs)
Lateral Accel (g)
Time (sec)
0
10
20
30
40
-40
-30
-20
-10
0
10
20
30
40
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
-20
-10
0
10
20
30
40
50

Driver No. 14


Speed (mph)
Steering Wheel Force (lbs)
Lateral Accel (g)
Time (sec)
0
10
20
30
40
-40
-30
-20
-10
0
10
20
30
40
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
-20
-10
0
10
20
30
40
50

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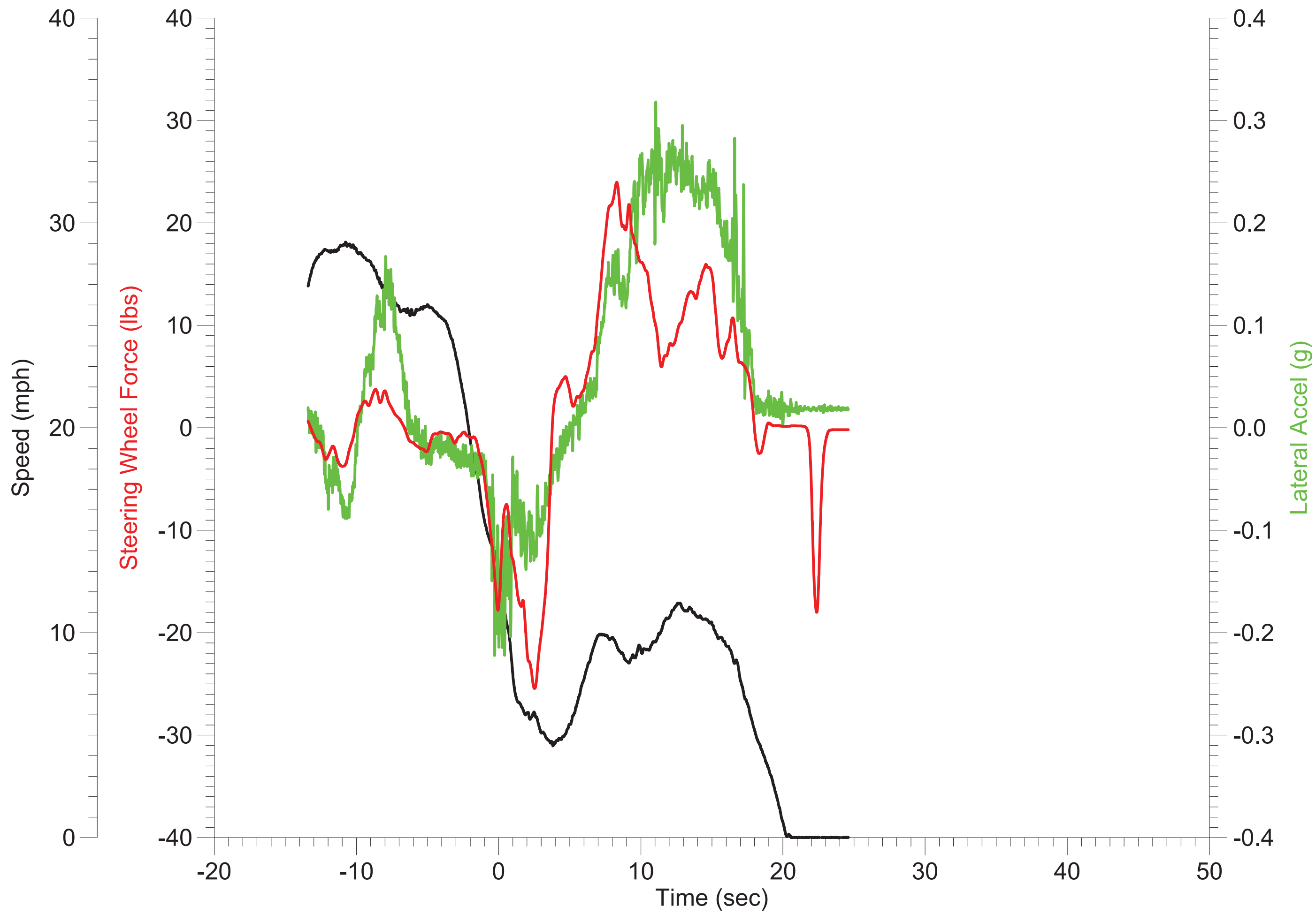

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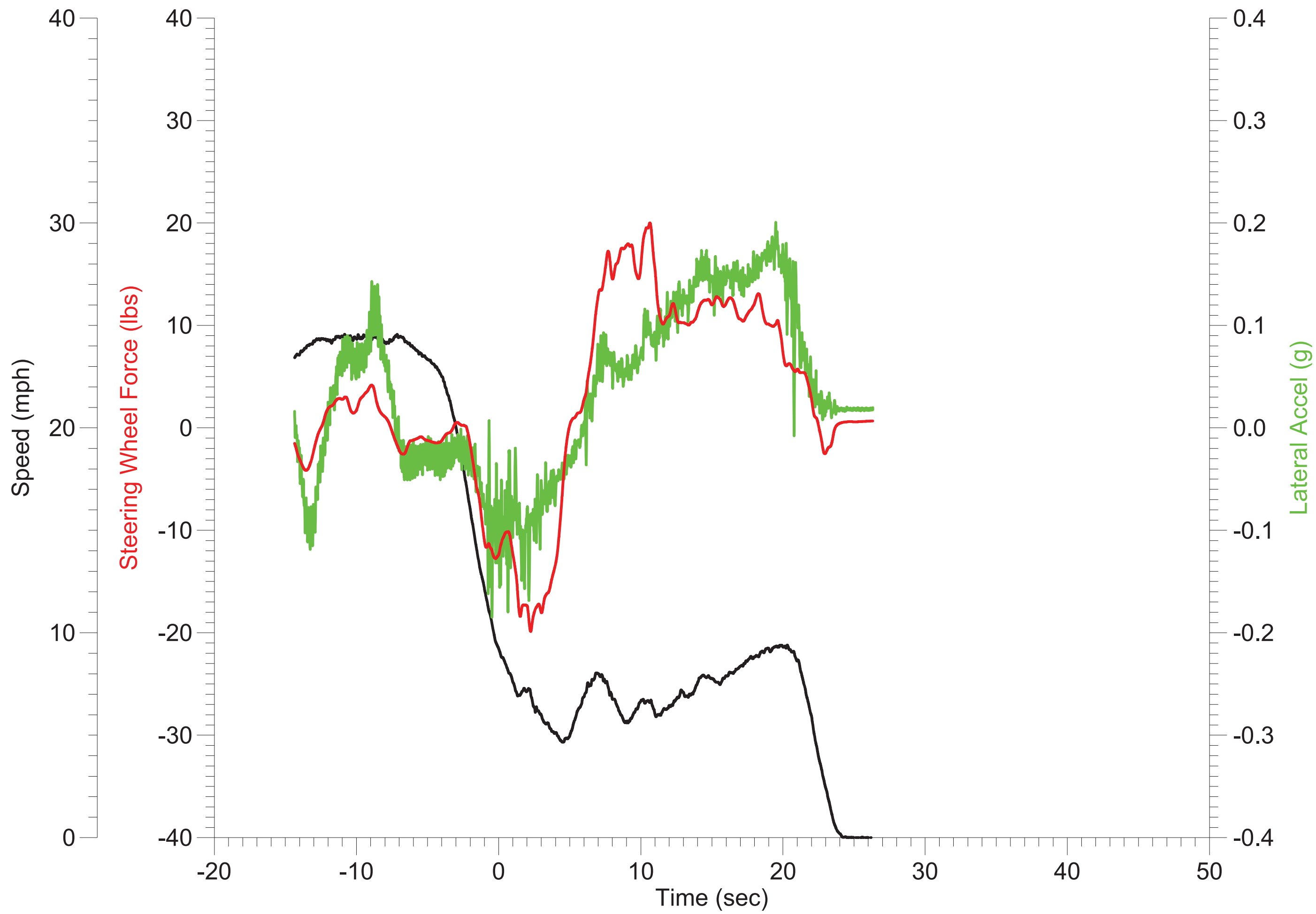
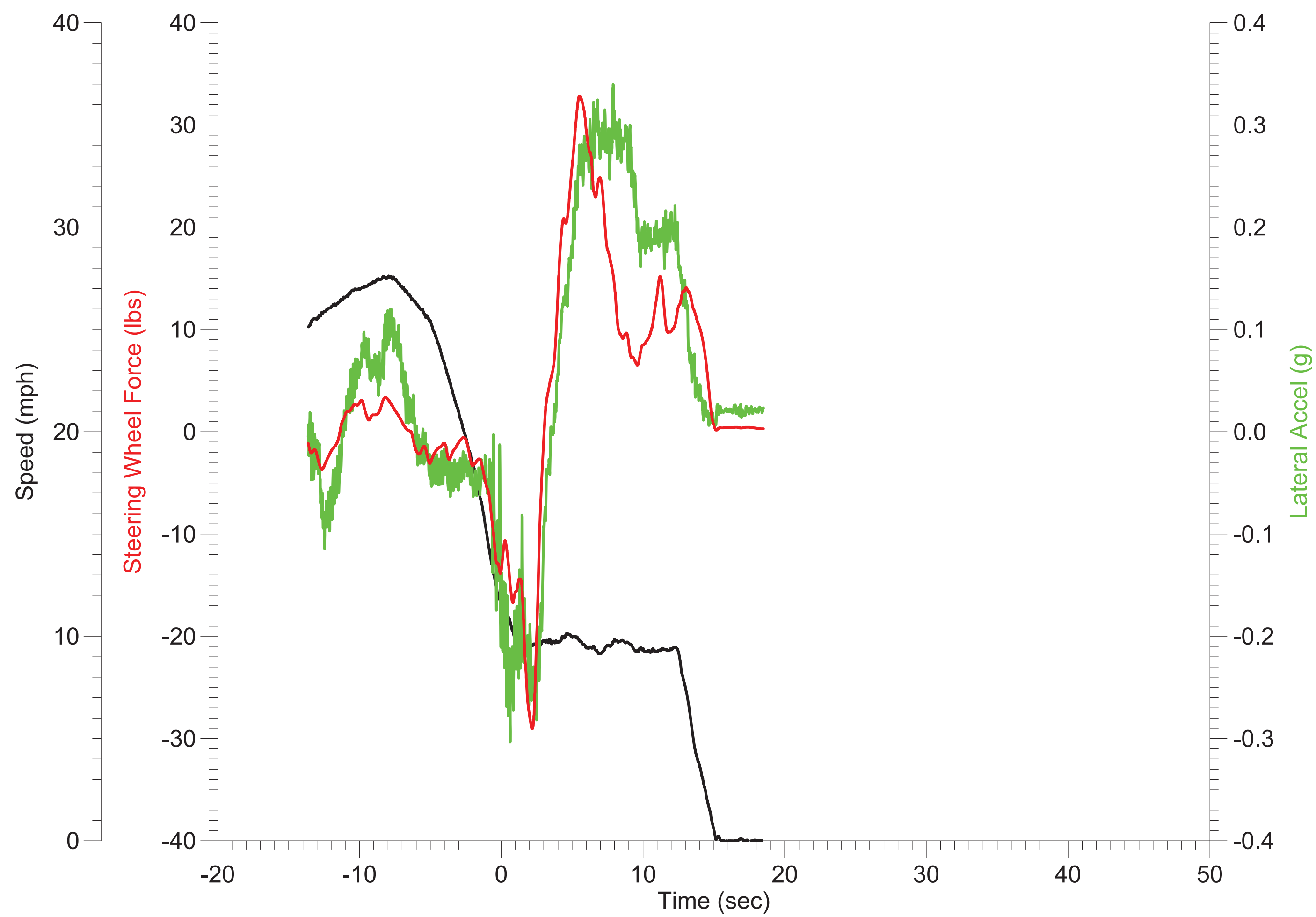

Speed (mph)
0
10
20
30
40
Steering Wheel Force (lbs)
-40
-30
-20
-10
0
10
20
30
40
Lateral Accel (g)
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
-20
-10
0
10
20
30
40
50
Time (sec)

Driver No. 17



Speed (mph)
40
30
20
10
0
Steering Wheel Force (lbs)
40
30
20
10
0
-10
-20
-30
-40
Lateral Accel (g)
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-20
-10
0
10
20
30
40
50
Time (sec)