NATIONAL TRANSPORTATION SAFETY BOARD
Vehicle Recorder Division
Washington, D.C. 20594

March 7, 2017

Driver Assistance System

Specialist's Factual Report
By Joseph A. Gregor

1. EVENT SUMMARY

Location: Williston, Florida
Date: May 7, 2016
NTSB Number: HWY16FH018

For a summary of the crash, refer to the Crash Summary Report in the docket for this investigation.

2. GROUP

A Group was formed composed of the following individuals:

Chairman: Joseph Gregor
Vehicle Recorder Specialist
National Transportation Safety Board

Member: Corporal Daphne P. Yuncker
Troop B
Florida Highway Patrol

Member: Matthew Schwall
Director, Field Performance Engineering
Tesla Motors, Inc.

3. DETAILS OF INVESTIGATION

The NTSB received raw data and image files stored within the Gateway Electronic Control Unit (ECU) of the Tesla Model S (VIN 5YJSA1S26FF[redacted]) together with parametric data based on this raw data that was obtained via database query from Tesla company servers.

3.1. Tesla Driver Assistance System

The Tesla Model S comes equipped with a suite of driver assistance system (DAS) features that includes features such as adaptive cruise control (ACC), lane keeping assistance, and automatic emergency braking (AEB). The Tesla Autopilot feature fuses data obtained from optical, radar, and ultrasonic sensors on the vehicle to build an internal model of the nearby surroundings including both stationary and non-stationary objects. Using this information, together with parametric data concerning the current position[1] and motion[2] of the Tesla vehicle, Autopilot's Autosteer and Traffic-Aware Cruise Control features are designed to work together to compute the wheel torque, wheel braking, and steering inputs required to keep the vehicle in its driving lane when cruising at a set speed on highways that have a center divider and clear lane markings.

3.2. Overall Description of the Tesla Driver Assistance System

The Tesla Model S driver assistance system is composed of three main subsystems: a) a sensor suite designed to assess the nearby environment, b) a servo suite designed to provide thrust, braking, and steering inputs, and c) a data processing suite designed to collect input data from the sensors and compute instructions to deliver to the servos. Information travels between these three subsystems using multiple Controller Area Network (CAN)[3] busses.

These three subsystems provide the functions of *performance monitoring*, *processing*, and *control* required to implement the Tesla Autopilot Driver Assistance System (DAS). *Performance monitoring* refers to functions related to quantifying the actual performance of the vehicle. Examples of performance variables include vehicle speed, acceleration, and direction of travel. *Control* refers to functions related to modifying the future performance of the vehicle. Examples of control variables include steering angle and motor torque. *Processing* refers to functions related to building a model of the external environment and, together with servo commands specified by the driver, deriving servo instructions used to control the vehicle.

The Tesla Model S uses three types of sensors for measuring the relative position of objects in the nearby environment - two electromagnetic-based (radar and visible light) and one sound-based (ultrasonic). CAN busses are used to move data between the various electronic control units (ECU) servicing these and other automobile subsystems (such as motor control, airbag, etc.). Each ECU forms a 'node' on the CAN bus, and messages can be sent asynchronously from any node to any other node.[4] A central node, the Gateway (GTW) ECU, serves as a communications hub distributing messages between the various CAN busses.

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[1] Position information includes mapping data together with the vehicles GPS location.

[2] Motion information includes longitudinal and transverse accelerations, together with vehicle speed and direction of motion.

[3] The Controller Area Network (CAN) bus is a Society of Automotive Engineers (SAE) defined vehicle bus standard designed to allow microcontrollers and devices to communicate without need for a host computer. It is a message-based protocol, similar to the TCP-IP protocol used to support internet communications, which was designed originally for multiplexing signals across the electrical wiring within an automobile.

[4] This is known as asynchronous communications. A node will generally add 'envelope' information including the ID of the message and error correction information along with the data being transferred. All other nodes will 'listen' to the message and respond as appropriate. Physically, communication between nodes is accomplished using a two-wire twisted pair connecting all of the ECUs together.

3.2.1. Bosch Radar System

The Tesla Model S radar system, manufactured by Bosch, is an active system that uses super high frequency (SHF)[5] radio waves broadcast and received using a multi-channel radar transceiver mounted behind the front grille of the vehicle. Time of flight between the broadcast of a series of electromagnetic impulses and the reception of the reflected energy from nearby objects is used to compute a range vector. Radar sensing is limited to a fan-shaped region forward of the vehicle with a specified range of 160 m (525 ft) under ideal conditions.

The Bosch radar system is capable of performing fault analysis and reporting certain faults to the Autopilot system. These faults include messages related to: sensor adjustment/alignment, ECU failure, CAN bus failure, message handshaking problems, invalid external system/sensor data, and parameter values out-of-range.

3.2.2. MobilEye Image Capture and Processing System

The Tesla Model S optical system is a passive system that employs a single 1-Megapixel monochromatic camera mounted in the rear-view-mirror area of the front windshield and is designed to accept light information from a region ahead of the vehicle. This data is routed through a dedicated camera ECU which can store images in volatile[6] memory and pass this data on to a visual processing unit produced by MobilEye that performs pre-processing of the incoming optical data and fusion with data received from the Bosch radar system. The results of this data fusion, together with image processing performed to extract features corresponding to objects in the local environment, is communicated to other components of the Tesla Model S Autopilot system including the Gateway ECU.

The MobilEye system is capable of performing fault analysis and reporting certain faults to the Autopilot system. These include messages related to: radar low visibility or misalignment, image quality issues (focus, contrast, etc.), image obstruction issues (blockages, sun blindness, etc.), and image calibration issues.

3.2.3. Ultrasonic Sensor System

The Tesla Model S ultrasonic system is an active system that uses high frequency sound waves broadcast and sensed using an array of twelve ultrasonic transducers arrayed about the front and rear bumpers of the vehicle. Time of flight between the broadcast of a sound impulse and the reception of its return reflected from a nearby object is used to compute short range distance. Data from the ultrasonic sensors are used primarily to track objects travelling at low relative speeds in close proximity to the vehicle.

[5] SHF is defined by the International Telecommunications Union (ITU) as that band of frequencies ranging from 3 to 30 GHz, where 1 GHz represents 1,000,000,000 cycles per second.

[6] Volatile memory is a form of solid state memory that requires the continuous application of power to retain stored data.

3.3. Event Data Recorder Regulations

Federal regulation 49 CFR 563[7] specifies the data collection, storage, and retrievability requirements for vehicles equipped with event data recorders. The regulation does not require that vehicles be equipped with event data recorders. Equipping a vehicle with an event data recorder is completely voluntary. The regulation also specifies vehicle manufacturer requirements for providing commercially available tools and/or methods for accomplishing data retrieval from an event data recorder in the event of a crash. The Tesla Model S involved in this crash did not, nor was it required by regulation, contain an event data recorder. As a result, the data recorded by the ECU was not recorded in accordance with this regulation. Further, there is no commercially available tool for data retrieval and review of the ECU data. NTSB investigators had to rely on Tesla to provide the data in engineering units using proprietary manufacturer software.

3.4. Gateway Electronic Control Unit

The Tesla Model S stores non-geo-located data on the vehicle in non-volatile[8] memory using a removable SD card installed within the Gateway ECU. This SD card is large enough to typically maintain a complete record of all stored data for the lifetime of the vehicle.

One type of data acquired and stored is general vehicle state information. This data is continually written to the Gateway ECU as long as the car is on. Typical parameters include: steering angle, accelerator pedal position, driver applied brake pedal application, vehicle speed, Autopilot feature states, and lead vehicle distance. Some of these parameters are recorded at a 1Hz rate. Other parameters are only recorded when a change of state occurs. All parameters are timestamped with the time of arrival at the Gateway ECU using a GPS derived clock time.

The vehicle also supports the acquisition and storage of data related to forward collision warning (FCW) and automatic emergency braking (AEB) events. Typical parameters include information documenting vehicle, radar, camera, and the internal DAS-state associated with a triggering FCW / AEB event. This data is recorded as a snapshot triggered by a specific event and timestamped with the time of arrival at the Gateway ECU using a GPS derived clock time.

As part of FCW and AEB event data, the vehicle supports the acquisition and storage of image data captured by the forward facing camera. This system can buffer 8 frames of image data sampled at one second intervals centered[9] upon a triggering FCW / AEB event. These frames are initially captured in volatile memory in the Camera ECU and then stored in non-volatile memory at the end of the drive. From there it is transferred via CAN bus to the Gateway ECU where it is stored on the internal SD card. This image data is not timestamped.

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[7] Title 49, Code of Federal Regulations Part 563 outlines the Transportation requirements covering Event Data Recorder requirements for those vehicles containing an event data recorder.

[8] Non-volatile memory is a form of solid state memory capable of retaining previously stored data without an external power source.

[9] The fifth frame in the series coincides with the trigger event.

Data from the SD card is episodically data-linked to Tesla servers using a virtual private network connection established via Wi-Fi, or using the 3G cellular data capabilities of the vehicle. Camera data will only be available after it has been transferred to the Gateway ECU via CAN bus. This process can take over 40 minutes.

In general, data stored on-board the vehicle will contain information additional to that contained on Tesla servers. Specifically, any data stored since the last auto-upload event will exist only on the vehicle itself and must be recovered by forcing an over-the-air upload, using maintenance download equipment to connect directly to the vehicle, or by removing and directly accessing the SD card internal to the central primary dash-mounted electronic control panel.

In addition to the aforementioned data, the vehicle supports the upload of anonymized geo-location data to Tesla for mapping and Autopilot feature development efforts. This data is not stored on-board the Tesla vehicle.

3.5. Data Recovery

Approximately 510 MB of data was recovered from the vehicle by removal and duplication of data stored on the GTW internal SD card. This data was composed of 87 files organized in 8 folders and stored on the SD card in a MS Windows readable format. The data included 8 image files representing data from the forward facing camera. A small subset of this data was stored in ASCII format. But the vast majority, including the vehicle log files containing all of the parametric data discussed in this report, was stored in a proprietary binary format that required the use of in-house manufacturer software tools for conversion into engineering units.

The Tesla model S involved in this crash was running firmware version 7.1 (2.17.37). This vehicle was capable of recording hundreds of parameters. Of these, Tesla converted the subset determined by the NTSB to be relevant to this investigation into engineering units for the investigation. This was accomplished by performing a database query on vehicle data on Tesla servers that mirrored the information that was recovered from the SD card. The result of this query yielded parametric data from 53 distinct variables, and text-based information related to 42 distinct error messages, covering a 42 hour period from 04:24:27 UTC (00:24:27 EDT) on May 6, 2016 to 22:15:25 UTC (18:15:25 EDT) on May 7, 2016.[10] Based on timestamps from cascading error message information, and a change of state of the power contactor parameter to OPEN, the crash occurred at 20:36:13 UTC (16:36:13 EDT) on May 7, 2016.

3.6. Data Description

Image data from the vehicle's camera was recovered from the SD card. By design, this data does not contain any timestamp information. The recovered image data did not

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[10] This data indicated that the accident vehicle's Gateway ECU continued to log some data including numerous error messages for 2 hours 9 minutes and 12.4 seconds after the accident event.

contain information consistent with the crash. These images were likely triggered by an earlier FCW / AEB event and written to the SD card prior to the last trip.

Parametric data was also recovered from the SD card. Subsequent to the initial data recovery effort, Tesla provided detailed information regarding a subset of parameters requested by the NTSB (see Appendix 1). The actual data for these parameters, converted into engineering units by Tesla using manufacturer proprietary in-house software tools, is included as Attachment 1 to this report. Figures 1 – 4 provide a detailed graphical depiction of this data.

In the following discussion, ***parameter names*** will be given in ***bold italics***. For discrete parameters – those only taking on a finite list of possible states – the *parameter state* will be given in *italics*. Selected details concerning these parameters and their indicated states is given in Appendix 1.

Certain parameters, such as ***VEHICLE SPEED***, are intended to represent a physical measurement; these are referred to as *continuous* parameters. Other parameters, such as ***CRUISE STATE***, are intended to represent one out of a finite number of possible states; these are referred to as *discrete* parameters.

Figures 1 and 2 illustrate vehicle control and performance parameters plotted over the final trip including the: ***CRUISE STATE***, ***MOTOR TORQUE*** (-***MAIN***[11] and -***SLAVE***[12]), ***CRUISE SETTING***, ***STEERING ANGLE*** sensor reading,[13] and ***VEHICLE SPEED***. Figure 1 shows additional state information[14] related to the Autopilot and the Autopilot hands-on sensing logic, as well as parametric data for the distance in meters to any identified lead vehicle.[15] Figure 2 shows additional state information for the brake pedal, turn indicators, and rear brake light, as well as parametric data measuring the position of the accelerator pedal.

Figures 3 and 4 illustrate the same parameters as figures 1 and 2, respectively. These plots show more detail by displaying only the last 6-1/4 minutes leading up to the crash.

The beginning of the accident drive is indicated by the concurrent initialization of multiple vehicle systems. This occurred at 15:55:23 EDT, at which time the ***BUCKLE DRIVER STATUS*** parameter also transitioned to *BUCKLE LATCHED*. At approximately 15:58 EDT, several parameters transitioned to a state or states consistent with autopilot features being actively engaged and controlling the vehicle. The ***AUTOPILOT STATE*** parameter transitioned to a state of *ACTIVE NORMAL* and remained in either the *ACTIVE NORMAL* or *ACTIVE RESTRICTED* states during the remainder of the trip up to the time of the crash. At the same time, ***CRUISE STATE*** transitioned to *ENABLED*, and remained in this state for the majority of the trip up to the crash. Also, the ***AUTOPILOT HAND ON STATE*** transitioned from

[11] Main motor torque refers to the torque on the main (rear) drive wheels.
[12] Slave motor torque refers to the torque on the slave (front) drive wheels.
[13] Positive values indicate that the steering wheel is positioned to execute a right hand turn.
[14] State information includes discrete data such as engaged or disengaged for control parameters, and illuminated or not illuminated for performance monitoring parameters (indicators). Certain parameters, like the Autopilot state, can assume a larger number of states due to the complexity of the system.
[15] If a lead vehicle has not been identified (e.g. the lane ahead of the vehicle is deemed clear of other vehicles by the Tesla DAS) this parameter will return a constant of 204.6 m.

HANDS NOT REQUIRED to one of several states that correspond with an Autopilot system requirement that torque be applied to the steering wheel as a surrogate for sensing driver engagement.

For the vast majority of the trip, the ***AUTOPILOT HANDS ON STATE*** remained at *HANDS REQUIRED NOT DETECTED*. Seven times during the course of the trip, the ***AUTOPILOT HANDS ON STATE*** transitioned to *VISUAL WARNING*. During six of these times, the ***AUTOPILOT HANDS ON STATE*** transitioned further to *CHIME 1* before briefly transitioning to *HANDS REQUIRED DETECTED* for 1 to 3 seconds. During the course of the trip, approximately 37 minutes[16] passed during which the Autopilot system was actively controlling the automobile in both lane assist and adaptive cruise control. During this period, the ***AUTOPILOT HANDS ON STATE*** was in *HANDS REQUIRED DETECTED* for 25 seconds. For the remainder of this period, the ***AUTOPILOT HANDS ON STATE*** was in *HANDS REQUIRED NOT DETECTED*, or in one of the visual or aural warning states.

Twice during the course of the trip – at approximately 16:19 and 16:30 EDT – the data showed indications consistent with the vehicle coming to a stop or near stop. At these times vehicle speed slowed to below 7 mph, ***CRUISE STATE*** transitioned from *Enabled* to *Standby*, ***AUTOPILOT HANDS ON STATE*** transitioned to *HANDS NOT REQUIRED*, and ***AUTOPILOT STATE*** oscillated between *AVAILABLE* and *UNAVAILABLE*. In both cases, the driver applied accelerator pedal input to manually accelerate the vehicle before the ***AUTOPILOT STATE*** and ***AUTOPILOT HANDS ON STATE*** transitioned to states consistent with Autopilot operation with lane assist. The last stop or near stop occurred at approximately 16:29:52 EDT; 6 minutes 21 seconds before the crash.

After the second stop or near stop, the ***CRUISE SET*** parameter increased in steps from 47 mph, to 65 mph, to 70 mph, and finally to 74 mph, where it remained for approximately two minutes up to and just after the crash. The ***VEHICLE SPEED*** parameter reported 74 mph at the time of the crash. The Lead Vehicle Distance parameter indicated the presence of a lead vehicle on six separate occasions during the accident trip. The last occasion approximately two minutes prior to the crash, where the lead vehicle distance dropped from a constant of 204.6 (indicating no vehicle detected) to 18.6 m (61 feet) and then increased and transitioned back to no vehicle detected over the course of 30 seconds.[17] The lead vehicle distance subsequently remained at 204.6 – consistent with no lead vehicle being detected – for the final 1 minute 35 seconds up to the time of the crash. The ***DRIVER BRAKE APPLY*** parameter remained in the *NOT APPLIED* state up to and after the collision.

The converted data indicates that the headlights were not on at the time of the collision. The ***HEADLIGHT STATUS*** parameter is a discrete parameter that changes state when an activation or deactivation event occurs, and assumes the last known state at all other times. The ***HEADLIGHT STATUS*** parameter transitioned to *ON* at 16:36:14 EDT, one second

[16] More precisely, the Autopilot system was actively controlling the automobile in both lane assist and adaptive cruise control for a total of 36 minutes 43 seconds during the accident drive.
[17] This behavior is consistent with another vehicle ahead of the Tesla changing lanes or 'cutting-in' ahead of the Tesla and accelerating away.

after the crash.[18] The ***HEADLIGHT STATUS*** was previously reported as *OFF* at 09:42:36 EDT, approximately 6 hours prior to the beginning of the accident trip.

In addition to the Tesla database query used to obtain the engineering unit parametric data examined in this investigation, Tesla performed a supplemental database query at NTSB request to determine the presence of any status messages indicating that AEB or FCW were disabled during the accident drive; no such messages were identified. Tesla reported that there was no indication in the recorded data of an FCW event, AEB event, or any other event indicating detection of an in-path stationary object at or just prior to the time of the crash.

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[18] The converted and time-stamped engineering unit data indicated that the vehicles DAS continued to log data for 2 hours 9 minutes and 12.4 seconds after the accident event.

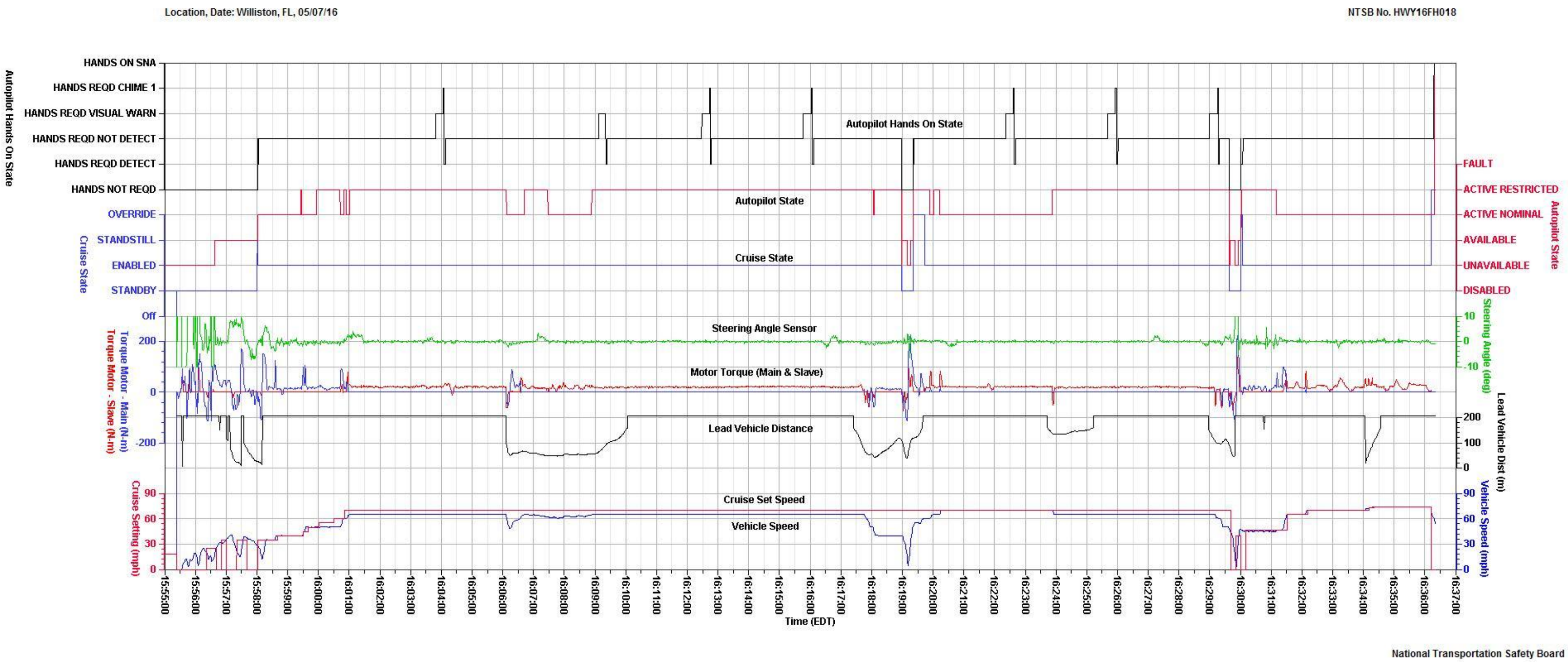

Figure 1. Autopilot vehicle control and vehicle performance information for the accident trip (41 minutes).

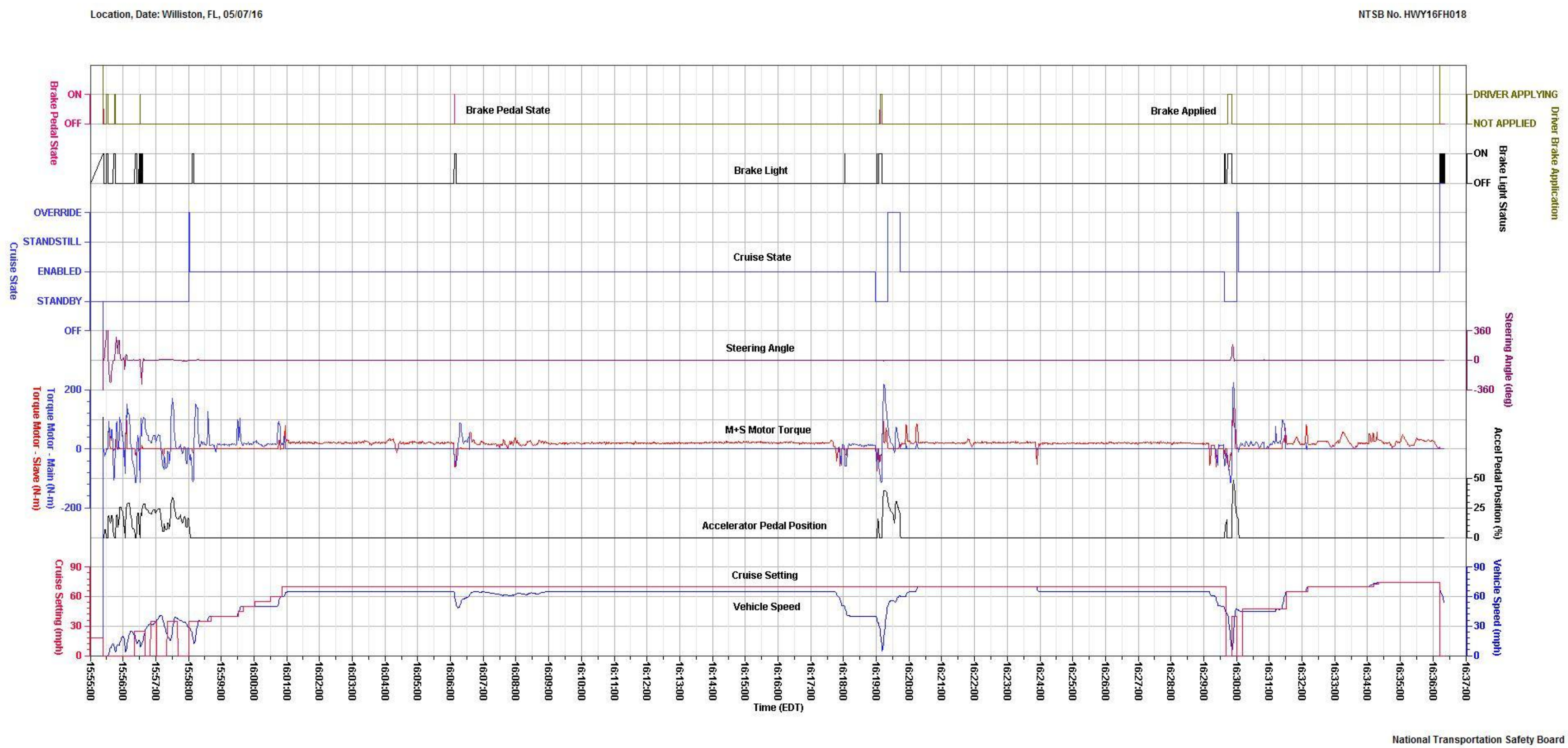

Figure 2. Autopilot, user control, and vehicle performance information for the accident trip (41 minutes).

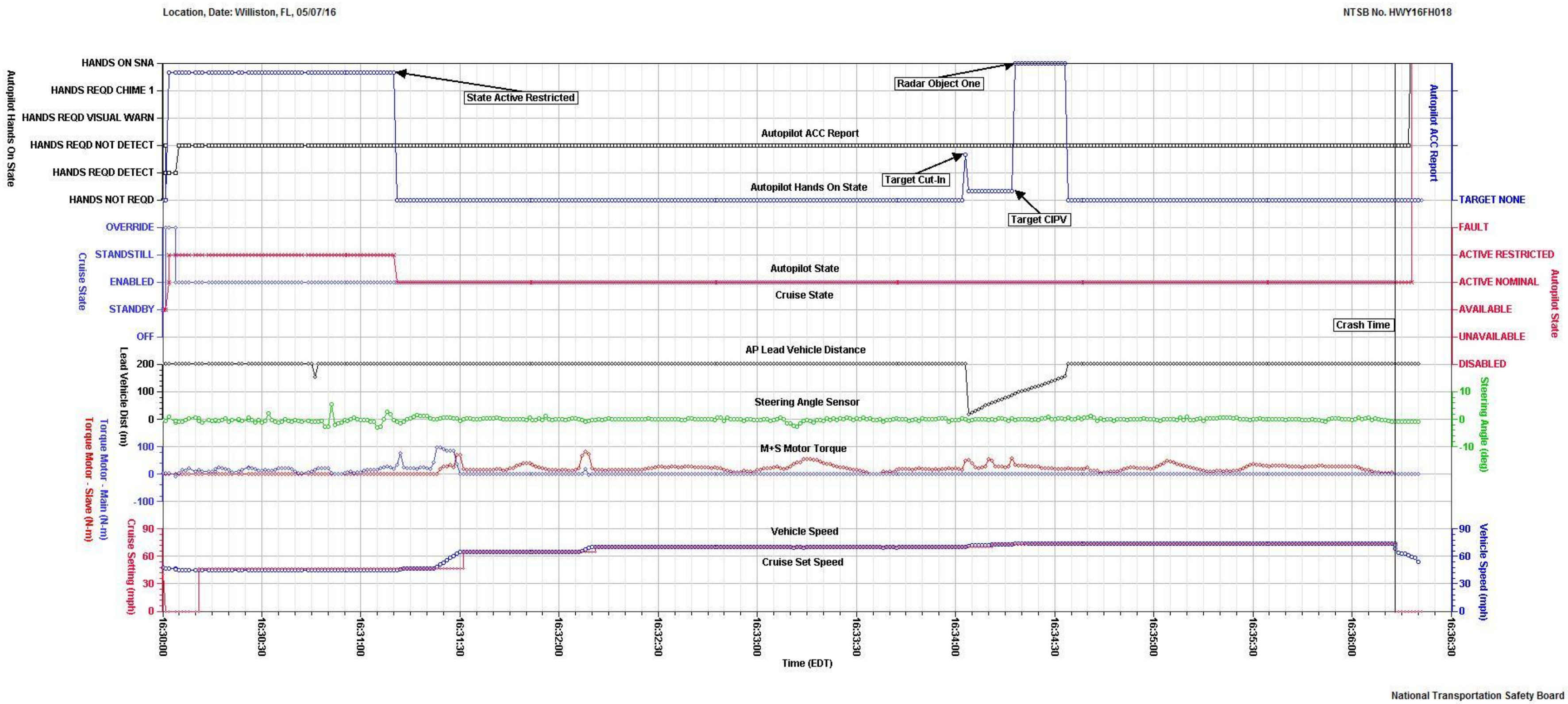

Figure 3. Autopilot vehicle control and vehicle performance information for the last 6 ¼ minutes of the accident trip.

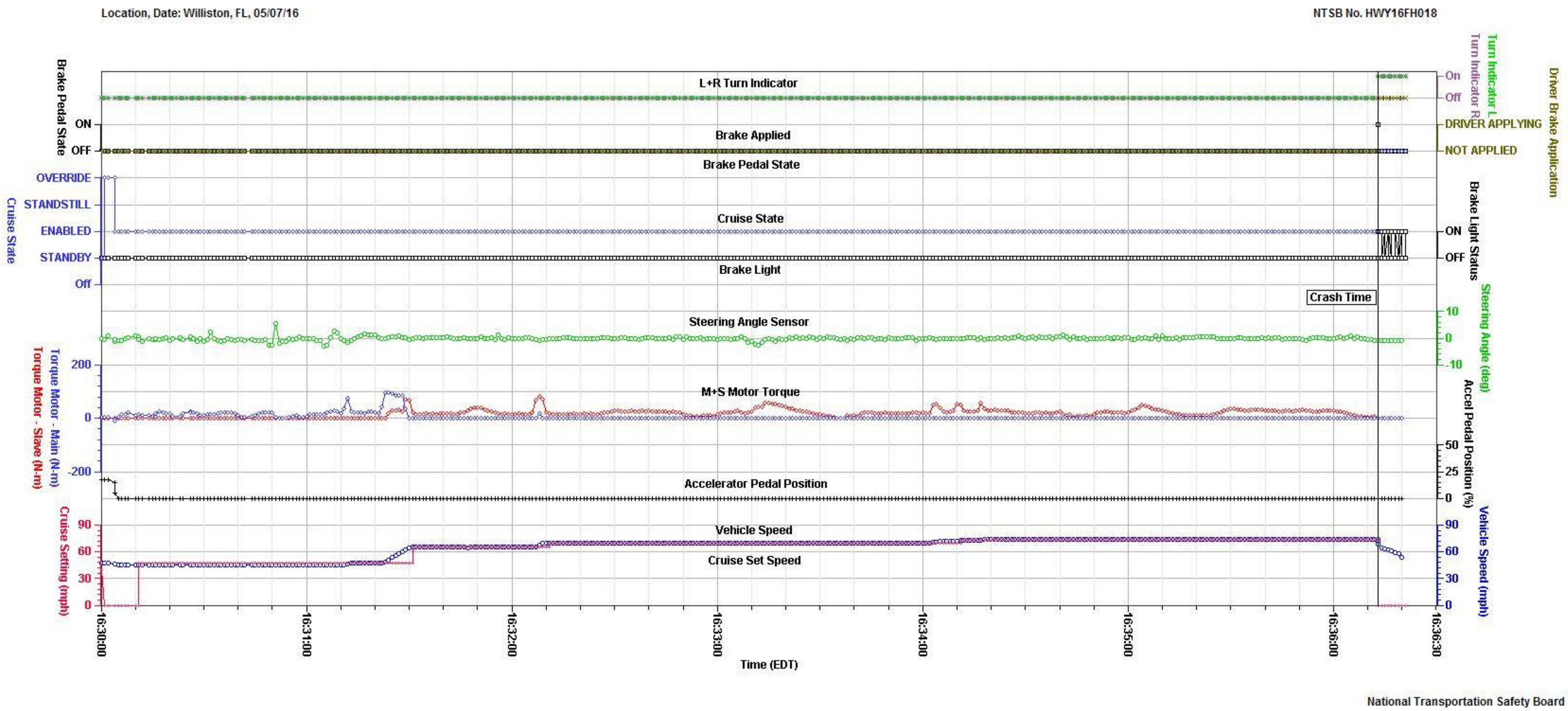

Figure 4. Autopilot, user control, and vehicle performance information for last 6 ¼ minutes the end of the accident trip.

Appendix 1

Parameter Name	Units	Update Rate	Update Logic	Description
AUTOPILOT HANDS ON STATE	discrete	Asynchronous	Upon Change	*HANDS NOT REQD* = Autopilot not controlling vehicle.
				HANDS REQD DETECTED = Steering wheel torque sufficient to detect hands-on.
				HANDS REQD NOT DETECTED = Steering wheel torque insufficient to detect hands-on.
				HANDS REQD VISUAL = Visual warning to driver.
				HANDS REQD CHIME 1 = Stage 1 aural warning to driver.
				HANDS REQD CHIME 2 = Stage 2 aural warning to driver.
				HANDS REQD SLOWING = Autopilot slowing vehicle.
				HANDS SNA = Steering wheel hands-on detection not available.
AUTOPILOT STATE	discrete		Upon Change	*DISABLED* = Autopilot disabled.
				UNAVAILABLE = Autopilot unavailable.
				AVAILABLE = Autopilot available.
				ACTIVE NOMINAL = Autosteer engaged.
				ACTIVE RESTRICTED = Autosteer cruise speed restricted due to detected road class.
				FAULT
				SNA = System state is not available
LEAD VEHICLE DIST	meters	1/s	Periodic & upon alert	Distance to in-lane forward vehicle (when identified). [204.6 = *SNA*]
CRUISE SETTING	mph	1/10s	Periodic & upon alert	Cruise Control Setting
TORQUE MOTOR - MAIN	N·m	1/s	Periodic & upon alert	Commanded rear motor torque
TORQUE MOTOR - SLAVE	N·m	1/s	periodic & upon alert	Commanded front motor torque
STEERING ANGLE	degrees	1/s	periodic & upon alert	Steering angle reported by the electronic assisted power steering system. [Positive right sign convention]
CRUISE STATE	discrete		Upon change	*OFF* = Cruise control deactivated.
				STANDBY = Cruise control available but not controlling the vehicle.
				ENABLED = Accelerator pedal input not overriding cruise control.
				STANDSTILL = Speed = 0 mph.
				OVERRIDE = Accelerator pedal input overriding cruise control.

Parameter Name	Units	Update Rate	Update Logic	Description
				FAULT = Cruise control has entered fault state.
ACCEL PEDAL POSITION	% of full travel	1/s	Periodic & upon alert	Accelerator pedal position [102.4 = SNA]
VEHICLE SPEED	mph	1/s	Periodic & upon alert	Vehicle speed based on integrated wheels rotation rate.
DRIVER BRAKE APPLICATION	discrete		Upon Change	
				NOT APPLIED = BOSCH detecting that driver is not applying brakes.
				DRIVER APPLYING = BOSCH detecting that driver is applying brakes.
				SNA = Brake pedal signal not available.
AIRBAG WARNING INDICATOR	discrete		Upon Change	*OFF* = indicator extinguished.
				ON = indicator illuminated.
				FLASHING = indicator flashing.
BRAKELIGHT STATUS	discrete		Upon Change	
				OFF = indicator extinguished.
				ON = indicator illuminated.
HEADLIGHT STATUS	discrete		Upon Change	
				OFF = indicator extinguished.
				ON = indicator illuminated.
ACC REPORT[19]	discrete		Upon Change	

[19] For a detailed explanation of the Tesla Adaptive Cruise Control system see the *NTSB Human Performance Group Chairman's Supplemental Report: Driver Assistance Systems*, Williston, FL, HWY16FH018.