AUTOMATION AND DATA SUMMARY
FACTUAL REPORT

Mountain View, CA

HWY18FH011

(24 pages)

NATIONAL TRANSPORTATION SAFETY BOARD
OFFICE OF HIGHWAY SAFETY
WASHINGTON, D.C.

AUTOMATION AND DATA SUMMARY
FACTUAL REPORT

A. CRASH INFORMATION

Location:	Southbound US Highway 101 (US-101) south of North Shoreline Boulevard at the exit ramp transition to State Route 85 (SR-85), milepost 48.38, Santa Clara County, Mountain View, California.
Vehicle 1:	2017 Tesla Model X P100D
Vehicle 2:	2010 Mazda 3
Vehicle 3:	2017 Audi A4
Date:	March 23, 2018
Time:	Approximately 9:27 a.m. PDST
NTSB #:	**HWY18FH011**

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C. CRASH SUMMARY

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

D. DETAILS OF THE AUTOMATION AND DATA SUMMARY REPORT

- Section 1 of the report provides a general overview of the driver assistance systems in the Tesla Model X.
- Section 2 of the report provides a description of the Autopilot system.
- Section 3 of the report provides a description of the collision assist systems in the Tesla Model X.
- Section 4 of the report describes data recovery and information related to the operation of the Tesla Model X.
- Section 5 of the report provides a summary of the data pertaining to the dynamics of the Tesla Model X during the 15 seconds preceding the crash.
- Section 6 of the report provides a summary of Tesla Model X Autopilot activation during the trip and warnings provided for hands-off operation.
- Section 7 of the report provides a review of prior drive cycles completed by the driver of the Tesla Model X.
- Section 8 of the report provides a brief summary of changes made by Tesla following the crash to driver assistance systems.

1. General Overview of Tesla Model X

The Tesla Model X was equipped with various Advanced Driver Assistance System (ADAS) that included Autopark, Lane Assist, Speed Assist, Forward Collision Avoidance Systems (CAS) and an Autopilot technology suite. The basic function of the ADAS is to aid drivers in performing driving tasks. This primary focus in this report is on the Autopilot technology suite components which were in use at the time of the crash; the report additionally discusses the Forward CAS.

Tesla updates its Autopilot software (firmware) wirelessly, providing new features as they are developed. At the time of the crash, firmware develop/2018.10-4460-9982610au was installed in the Tesla Model X. The firmware was installed on March 12, 2018, during a service visit at the Sunnyvale Tesla service center. Two days later, a new firmware update was sent out to Tesla owners on March 14, 2018. Between March 14 and the date of the crash, there were 13 attempts to send firmware 2018.10.4 to the accident vehicle via over-the-air (OTA) wireless connection. Each attempt failed because of poor connectivity with the vehicle. Tesla advised that a common cause of connectivity issues is that the home storage environment may be blocking signal reception and lack of adequate Wi-Fi.[1] Tesla was questioned regarding the impact that the new firmware would have had on the crash and the company responded:

[1] The Tesla Model X driver lived in a townhome in Foster City, CA. The garage storage location was separate from the home structure. It is possible this contributed to the lack of wireless connectivity to perform the firmware update.

> *Tesla has not been able to duplicate the driving event in the subject crash, either with the firmware installed at the time of the crash or with newer firmware 2018.10.4. Therefore, we cannot state with any certainty that newer firmware would have made any difference in the crash. Firmware 2018.10.4 did not provide additional cameras or sensor usage, nor did it improve detection abilities. This firmware change updated the vision system processing software to improve overall performance. It improved the way the system determines lanes, providing better lane prediction on pitched and curvy roads, but, again, since we couldn't duplicate the event with either firmware version, we don't know that the update would have changed the outcome.*

Tesla advised that since the Mountain View crash it has enhanced the OTA updating process by also presenting a firmware update window in the Tesla mobile phone application. The application provides push notifications so that owners will be informed in multiple places of updates even when out of the vehicle and can schedule and monitor updates more conveniently.

Tesla advised that OTA firmware installation is extremely successful. As of March 27, 2019, firmware 2018.10.4 had been installed on 99.8% of the U.S. Tesla fleet.

2. Autopilot

2.1 General Information

Tesla's Autopilot technology package is a combination of systems that control vehicle speed and path by automated control of braking, steering and torque to the drive motors. The major subsystems associated with the operation of Autopilot are traffic-aware cruise control (TACC) and Autosteer. TACC provides longitudinal control (acceleration and deceleration) and Autosteer provides lateral control (steering) of the car within the lane. Autosteer can be engaged only after activating TACC; while TACC can be used by itself, Autosteer cannot operate without TACC.

Autopilot consists of a third system—Auto Lane Change which was not used during the trip on which this crash occurred.[2] Autopilot activation is considered an SAE International (SAE) Level 2 automated vehicle system.[3]

2.2 Traffic-Aware Cruise Control (TACC)

TACC uses information from the forward-looking camera and radar sensor to determine if there is a vehicle in front of the Tesla in the same lane. If there is no vehicle in front of the Tesla, TACC maintains a set driving speed selected by the driver. When there is a lead vehicle that is

[2] Auto Lane Change automatically moves the vehicle into adjacent travel lane upon request by a driver. While the system monitor's the vehicle's blind spot to determine lane availability before executing the lane change, the driver is responsible for determining the safety of the maneuver, because while the system has rearward and blindspot detection, these may not work in every situation.

[3] See Surface Vehicle Recommended Practice J3016. The SAE first published SAE J3016, which was developed by the SAE On-Road Automated Driving Committee on January 16, 2014. The 12-page standard provided detailed definitions only for the three highest levels of automation. The revised 30-page standard released on September 30, 2016, provided a taxonomy for all six levels of driving automation.

traveling slower than the Tesla's set speed, the TACC will control motor torques to maintain a selected time-based distance from the lead vehicle.

Drivers using TACC can adjust following distance by choosing a setting from 1 (the closest following distance) to 7 (the longest following distance). Each setting corresponds to a time-based distance that represents how long it takes for the Tesla, from its current location, to reach the location of the rear bumper of the vehicle ahead.

The Tesla Model X owner's manual states that TACC is primarily intended for driving on dry, straight roads, such as highways and freeways and should not be used on city streets.[4] The manual contains numerous warnings regarding the use of TACC related to the limitations of the system, including the following:

- Warning: TACC is designed for your driving comfort and convenience and is not a collision warning or avoidance system. It is your responsibility to stay alert, drive safely, and be in control of the vehicle at all times. Never depend on TACC to adequately slow down Model X. Always watch the road in front of you and be prepared to take corrective action at all times. Failure to do so can result in serious injury or death.

- Warning: Although TACC is capable of detecting pedestrians and cyclists, never depend on TACC to adequately slow down Model X for them. Always watch the road in front of you and be prepared to take corrective action at all times. Failures to do so can result in serious injury or death.

- Warning: Do not use TACC on city streets or on roads where traffic conditions are constantly changing.

- Warning: Do not use TACC on winding roads with sharp curves, on icy or slippery road surfaces, or when weather conditions (such as heavy rain, snow, fog, etc.) make it inappropriate to drive at a consistent speed. TACC does not adapt driving speed based on road and driving conditions.

- Warning: Due to limitations inherent in the onboard GPS, you may experience situations in which TACC slows down the vehicle, especially near highway exits where a curve is detected and/or you are actively navigating to a destination and not following the route.

- Warning: TACC cannot detect all objects and may not brake/decelerate for stationary vehicles, especially in situations when you are driving over 50 mph and a vehicle you are following moves out of your driving path and a stationary vehicle or object is in front of you instead. Always pay attention to the road ahead and stay prepared to take immediate corrective action. Depending on TACC to avoid a

[4] See the 2017 Tesla Model X Owner's Manual 8.0. Tesla Inc. updates the owner's manual on a regular basis. The owner's manual cited in the report is the manual available to the accident driver when he purchased the vehicle in November 2017.

collision can result in serious injury or death. In addition, TACC may react to vehicles or objects that either do not exist or are not in the lane of travel, causing Model X to slow down unnecessarily or inappropriately.

- Warning: TACC may be unable to provide adequate speed control because of limited braking capability and hills. It can also misjudge the distance from a vehicle ahead. Driving downhill can increase driving speed, causing Model X to exceed your set speed. Never depend on TACC to slow down the vehicle to prevent a collision. Always keep your eyes on the road when driving and be prepared to take corrective action as needed. Depending on TACC to slow down enough to prevent a collision can result in serious injury or death.

- Warning: TACC may occasionally brake Model X when not required or you are not expecting it. This can be caused by closely following a vehicle ahead, detecting vehicles or object in adjacent lanes (especially on curves), etc.

- Warning: TACC can cancel unexpectedly at any time for unforeseen reasons. Always watch the road in front of you and stay prepared to take appropriate action. It is the driver's responsibility to be in control of Model X at all times.

- Limitations: TACC is particularly unlikely to operate as intended in the following types of situations: 1) the road has sharp curves; 2) visibility is poor (due to heavy rain, snow, fog, etc.); 3) bright light (oncoming headlights or direct sunlight) is interfering with the camera's view; 4) the radar sensor is obstructed (dirty, covered, etc.); 5) the windshield area in the camera's field of view is obstructed (fogged over, dirty, covered by a sticker, etc.).

2.3 Autosteer

Autosteer lane keeping assist uses information from the forward-looking camera, radar sensor, and ultrasonic sensors to detect lane marking and the presence of vehicles and objects to provide an automated lane-centering steering control based on the lane markings and the vehicle directly in front of the Tesla if present. In most cases, Autosteer attempts to center the Tesla in the driving lane. However, if the sensors detect the presence of an obstacle (such as a vehicle or guardrail), Autosteer may steer the vehicle in a driving path offset from the center of the lane. If Autosteer does not receive adequate data from the camera or sensors, a message displays on the instrument panel indicating that Autosteer is temporarily unavailable.

To initiate Autosteer, a driver must be traveling at least 5 mph on a roadway with visible lane markings. If a vehicle is detected ahead, a driver can initiate Autosteer at any speed, even when stationary. When Autosteer is used on residential roads, a road without a center divider, or a road where access is not limited, Autosteer limits the driving speed. The maximum driving speed is calculated based on the detected speed limit plus 5 mph. In situations where the speed limit cannot be detected, speed is limited to 45 mph. When Autosteer is engaged in these situations, the driving speed is reduced to be within these limits. A driver can manually exceed the limited speed, but when the accelerator pedal is released, Autosteer will slow the Tesla to the limited speed.

When active, Autosteer requires a driver to hold the steering wheel. The system detects hands on the wheel by recognizing light resistance as the steering wheel turns or from manually turning the steering wheel very lightly (i.e., without enough force to retake control). If Autosteer does not detect driver's hands on the steering wheel (torque) for a prolonged period, the system disengages after a series of warnings.

If it does not detect hands on the steering wheel for a period of time, a flashing white light appears around the instrument panel and the following message is displayed:

If the system still does not detect driver's hands on the steering wheel after the presentation of the visual alert, the system presents two auditory warnings. The first auditory warning is presented 15 seconds after the visual warning. If the driver's hands on the steering wheel are still not detected, the system presents the second auditory warning 10 seconds after the first one.

If a driver ignores the second auditory warning and does not resume manual control in the next 5 seconds, Autosteer sounds a continuous chime, turns on the warning flashers, and slows the vehicle to a complete stop. At the same time, a visual alert is presented on the instrument panel that shows:

If driver receives any combination of three separate auditory alerts within an hour, Autosteer disengages. For example, three separate occurrences of level one auditory warning disengage the Autosteer. Also, a single third level auditory warning (during the slowdown phase) also disengages the Autosteer (first two levels of auditory warning have to occur first).

The timing of Autosteer hands on wheel alerts is based upon whether the roadway is a divided roadway, vehicle speed, and other factors. Figure 1 depicts the Autosteer hands-off-wheel triggers for the Tesla Model X at the time of the crash. Figure 2 depicts firmware updates introduced in version 2018.23 (June 2018). There are other conditions, such as hardware errors, not represented here in these figures.

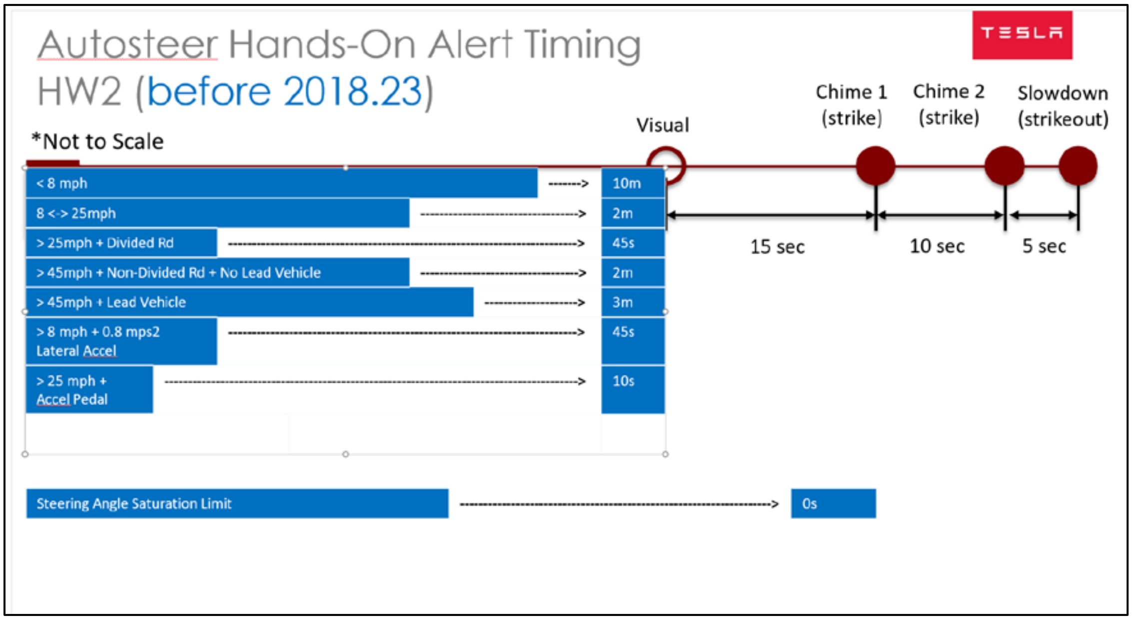

Figure 1. Autosteer hands-on alert timing for the Tesla Model X with firmware develop/2018.10.4-4460-998269610au present at the time of the crash.[5]

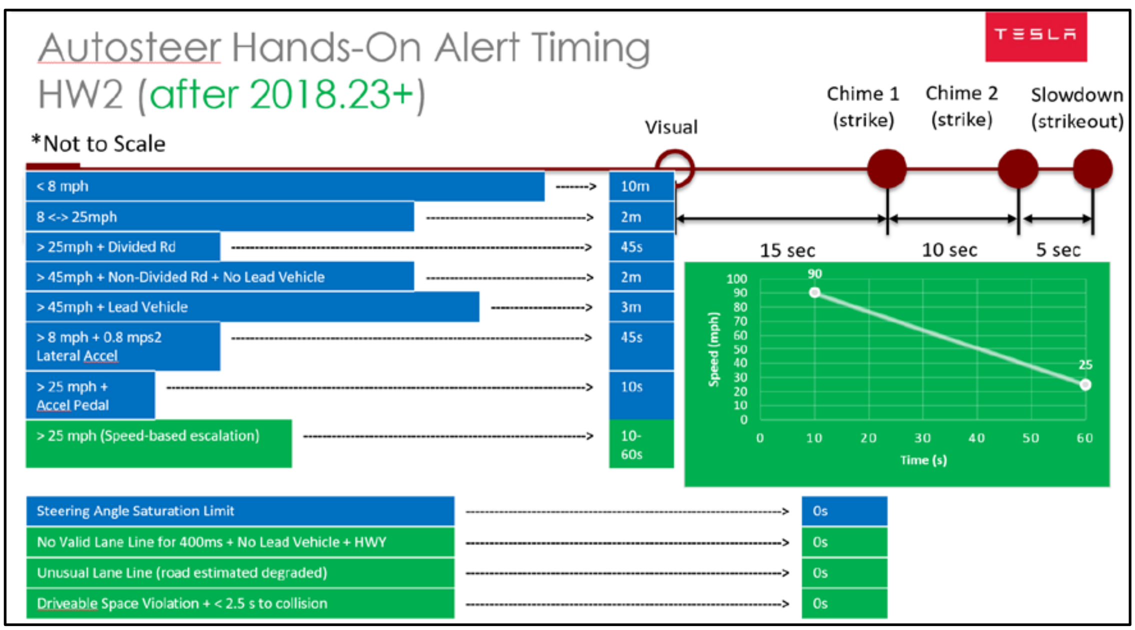

Figure 2. Autosteer hands-on alert timing (shown in green) for the Tesla Model X after firmware version 2018.23 was introduced in June 2018.

[5] Tesla provided permission to the NTSB to display figures 1 and 2 in this factual report of investigation.

In situations where Autosteer is unable to steer the Tesla, Autosteer sounds a warning chime and displays the following message on the instrument panel:

The Tesla Model X owner’s manual lists the following warnings regarding Autosteer:

- Warning: Autosteer is a hands-on feature. You must keep your hands on the steering wheel at all times.

- Warning: Autosteer is intended for use only on highways and limited-access roads with a fully attentive driver. When using Autosteer, hold the steering wheel and be mindful of road conditions and surrounding traffic. Do not use Autosteer on city streets, in construction zones, or in areas where bicyclists or pedestrians may be present. Never depend on Autosteer to determine an appropriate driving path. Always be prepared to take immediate action. Failure to follow these instructions could cause serious property damage, injury or death.

- Warning: Many unforeseen circumstances can impair the operation of Autosteer. Always keep this in mind and remember that as a result, Autosteer may not steer Model X appropriately. Always drive attentively and be prepared to take immediate action.

- Limitations: Autosteer is particularly unlikely to operate as intended in the following situations: 1) when unable to accurately determine lane markings due to poor visibility (heavy rain, snow, fog, etc.), or an obstructed, covered or damaged camera or sensor; 2) when driving on hills; 3) when approaching a toll booth; 4) the road has sharp curves or is excessively rough; 5) bright light is interfering with the camera’s view; or 6) the sensors are affected by other electrical equipment or devices that generate ultrasonic waves.

3. Tesla Model X Collision Avoidance Assist

3.1 Overview

Tesla's collision avoidance assist features include Forward Collision Warning (FCW) and Automatic Emergency Braking (AEB). FCW provides visual and audible warnings in situations when the Tesla detects that there is a high risk of a frontal collision. AEB automatically applies braking to reduce the impact of a frontal collision. The system is a radar/camera fusion system that is functional when the vehicle is turned on, regardless of the Autopilot status. The driver can switch FCW on or off on the DAS page accessible on the media control unit (MCU) touchscreen mounted near the center of the dashboard. The FCW is default "On" for each new drive cycle. The driver can select the timing of FCW alerts with four options: Early, Medium, Late, or Off. Adjusting the timing of the FCW alert does not affect the activation timing of the Tesla AEB system. AEB is always on and cannot be deactivated.

3.2 Forward Collision Warning

The forward-looking camera(s) and the radar sensor in front of the Tesla Model X looks for the presence of an object such as a vehicle, bicycle, or pedestrian. If a collision is considered likely unless the driver takes corrective action, FCW is designed to sound a chime and highlight the vehicle in front in red on the instrument panel. Warnings cancel automatically when the risk of collision has been reduced (for example, the driver has decelerated or stopped the vehicle, or the object in front of your path has moved out of the driving path).[6]

Separate and in addition to FCW, there is a collision warning that can occur only when engaged in TACC mode. These warnings alerts the driver when the system detects a possible frontal collision with a closing distance too great to avoid a collision with the standard TACC deceleration limits (of up to 0.6 g). The alert is identical to the FCW alert, they cannot be distinguished by a driver. TACC collision warning activates even if FCW is turned off by a driver.

The Tesla Model X owner's manual has warnings concerning the FCW system. These warnings include:

- Warning: FCW is for guidance purposes only and is not a substitute for attentive driving and sound judgment. Keep your eyes on the road when driving and never depend on FCW to warn you of a potential collision. Several factors can reduce or impair performance, causing either unnecessary, invalid, inaccurate, or missed warnings. Depending on FCW to warn you of a potential collision can result in serious injury or death.

[6] NHTSA's New Car Assessment Program (NCAP) FCW testing is conducted up to 45 mph—with velocity differential up to 45 mph—using a vehicle target. European NCAP testing is conducted up to 80 kph (50 mph)—with the velocity differential up to 80 kph—using vehicle, pedestrian, and bicyclist targets. Both groups conduct FCW testing in three different rear-end crash scenarios in which the test vehicle (1) approaches a stationary lead vehicle, (2) approaches a slow moving lead vehicle, (3) follows a lead vehicle at a constant distance for a period of time, after which the lead vehicle suddenly decelerates. The testing by Euro NCAP that includes pedestrians and bicyclists involves somewhat different scenarios.

- Warning: The cameras and sensors associated with FCW are designed to monitor an approximate area of up to 525 feet in your driving path. The area being monitored by FCW can be adversely affected by road and weather conditions. Use appropriate caution when driving.

- Warning: FCW is designed to provide visual and audible alerts. It does not attempt to apply brakes or decelerate the Tesla Model X. When seeing and/or hearing a warning, it is the driver's responsibility to take corrective action immediately.

- Warning: FCW may provide a warning in situations where the likelihood of collision may not exist. Stay alert and always pay attention to the area in front of the Tesla Model X so the driver can anticipate whether any action is required.

- Warning: FCW does not operate when the Tesla Model X is traveling less than 4 mph.

- Warning: FCW does not provide a warning when the driver is already applying the brake. .

3.3 Automatic Emergency Braking

When a frontal collision is considered unavoidable, AEB is designed to apply the brakes to reduce the severity of the impact. When AEB applies the brakes, the instrument panel displays a visual warning and a chime will sound. When AEB has reduced the driving speed by 25 mph the brakes are released. Such reduction may mitigate the impact or avoid the collision completely in situations when the velocity differential is not greater than 25 mph.

AEB operates only when driving between 5 mph and 85 mph. AEB does not apply the brakes or stops applying the brakes when the steering wheel is turned sharply, the accelerator pedal is pressed or a vehicle, bicycle, or pedestrian is no longer detected ahead. Additionally, current AEB systems developed by manufacturers are not designed or tested to brake for crossing path collision scenarios.[7]

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[7] (a) See NHTSA Office of Defect Investigation PE 16-007 (Automatic Vehicle Control Systems) dated January 19, 2017.
(b) NHTSA developed testing procedures for AEB in 2011 and updated them in 2014. They include the three rear-end crash scenarios and test up to 40 mph velocity differential (the protocols from 2011; the testing conducted in 2014 included velocity differentials up to 25mph). Although in the 2011 report NHTSA described testing scenarios involving cross traffic, cut-in situations and pedestrian intrusions, none of them were validated. Although the update in 2014 includes testing for false alarms and new conditions such as light rain, the update does not include cross-traffic testing protocols or new target types, such as pedestrians.
c) Insurance Institute for Highway Safety (IIHS) also conducts AEB testing, performed only with a stationary vehicle at speeds up to 40 kph (25 mph); this test was developed in 2013. In 2019, IIHS developed an AEB test for a pedestrian target; this test involves three distinct scenarios (including a pedestrian crossing) and testing at speeds up to 60 kph (37 mph).
(d) The Euro NCAP testing protocols for AEB share most of the FCW protocols, and include testing up to 80 kph (50 mph).

The Tesla Model X owner’s manual has warnings concerning the AEB system. These warnings include:

- Warning: AEB is not designed to prevent a collision. At best, it can minimize the impact of a frontal collision by attempting to reduce the driving speed. Depending on AEB to avoid a collision can result in serious injury or death.

- Warning: It is strongly recommended that you do not disable AEB. If you disable it, Tesla Model X does not automatically apply the brakes in situations where a collision is considered likely.

- Warning: Several factors can affect the performance of AEB, causing either no braking or inappropriate or untimely braking. It is the driver’s responsibility to drive safely and remain in control of the vehicle at all times. Never depend on AEB to avoid or reduce the impact of a collision.

- Warning: AEB is designed to reduce the impact of frontal collisions only and does not function when the Tesla Model X is in reverse.

- Warning: AEB is not a substitute for maintaining a safe traveling distance between you and the vehicle in front of you.

- Warning: The brake pedal moves downward abruptly during AEB events. Always ensure that the brake pedal can move freely. Do not place material on top to the Tesla-supplied driver’s floor mat (including an additional mat) and always ensure the driver’s floor mat is properly secured. Failure to do so can impede the ability of the brake pedal to move freely.

- Limitations: Collision avoidance assist features cannot always detect vehicles, bikes, pedestrians, and you may experience unnecessary, inaccurate, invalid, or missed warning for many reasons, particularly if: 1) the road has sharp curves; 2) visibility is poor; 3) bright light is interfering with the camera’s view; 4) the radar sensor is obstructed; or 5) the windshield area in the camera’s field of view is obstructed.

4. Tesla Model X Data Recovery and Summary

4.1 Overview

The NTSB, working with the California Highway Patrol, retrieved data from the Tesla Model X’s 1) restraint control module (RCM); 2) media control unit (MCU); and 3) attempted to image data on the Autopilot HW 2.5 electronic control unit (ECU) module. Information relating to data recovery efforts from these systems is described later in this section of the report.

In the disclaimer section of the Tesla Model X owner’s manual, Tesla provides the following information to owner’s regarding vehicle telematics and data recorders. Tesla states the following:

This vehicle is equipped with electronic modules that monitor and record data from various vehicle systems, including the motor, battery, braking and electrical systems. The electronic modules record information about various driving and vehicle conditions, including braking, acceleration, trip and other related information regarding your vehicle. These modules also record information about the vehicle's features such as charging events and status, the enabling/disabling of various systems, diagnostic trouble codes, VIN, speed, direction and location. The data is stored by the vehicle and may be accessed, used and stored by Tesla service technicians during vehicle servicing or periodically transmitted to Tesla wirelessly through the vehicle's telematics system. This data may be used by Tesla for various purposes, including, but not limited to: providing you with Tesla telematics services; troubleshooting; evaluation of your vehicle's quality, functionality and performance; analysis and research by Tesla and its partners for the improvement and design of our vehicles and systems; and as otherwise may be required by law. In servicing your vehicle, we can potentially resolve issues remotely simply by reviewing your vehicle's data log.

Tesla's telematics system wirelessly transmits vehicle information to Tesla on a periodic basis. The data is used as described above and helps ensure the proper maintenance of your vehicle. Additional Model X features may use your vehicle's telematics system and the information provided, including features such as charging reminders, software updates, and remote access to, and control of, various systems of your vehicle.

Tesla does not disclose the data recorded in your vehicle to any third party except when:

- *An agreement or consent from the vehicle's owner (or leasing company for a leased vehicle) is obtained.*
- *Officially requested by the police or other authorities.*
- *Used as a defense for Tesla in a lawsuit.*
- *Ordered by a court of law.*
- *Used for research purposes without disclosing details of the vehicle owner or identification information.*
- *Disclosed to Tesla affiliated company, including their successors or assigns, or our information systems and data management providers.*
- *In addition, Tesla does not disclose the data recorded to an owner unless it pertains to a non-warranty repair service and in this case, will disclose that data that is related to the repair.*

4.2 Restraint Control Module (RCM)

The RCM is part of the Tesla's supplemental restraint system. The module was capable of recording data when triggered by a crash or near-crash event, such as an airbag event. The Event Data Recorder (EDR) is part of the vehicle's RCM and met the data recording requirements of Title 49 CFR Part 563.

On March 28, 2018, NTSB investigator Karol and CHP investigators responded to Atlas Towing facility in San Mateo, California to inspect the Tesla Model X. The RCM was located among the burned remains of the Tesla, under a melted plastic panel between the front seats. The RCM was photographed and then removed by the CHP for further analysis.[8] Later in the day, on March 28th, the RCM was imaged at the CHP Redwood City Area office. Tesla personnel assisted with the imaging of the RCM. Upon retrieving data from the RCM, the data was uploaded to the Tesla EDR report service at https://edr.tesla.com to produce an EDR report.[9] Figure 2 depicts photographs of the module and the imaging process. An excerpt from the EDR report, depicting 5 seconds of data prior to the crash, is shown in Figure 3.

Figure 2. Photograph of RCM following removal from Tesla and imaging process at CHP Redwood City area office.

TESLA

Event Data (Event 1)

Time (sec)	Vehicle Speed (km/h)	Accelerator Pedal (%)	Rear Motor Speed (rpm)	Service Brake	Stability Control	ABS Activity
-5.0	102	0	6799	Off	On	Off
-4.5	101	0	6713	Off	On	Off
-4.0	100	0	6641	Off	On	Off
-3.5	100	0	6612	Off	On	Off
-3.0	100	0	6689	Off	On	Off
-2.5	101	0	6766	Off	On	Off
-2.0	104	0	6937	Off	On	Off
-1.5	107	0	7104	Off	On	Off
-1.0	109	0	7284	Off	On	Off
-0.5	112	0	7433	Off	On	Off
0.0	114	0	7584	Off	On	Off

Figure 3. Excerpt from Tesla EDR report depicting 5 seconds of precrash data.

[8] On March 26, 2018, CHP Sergeant Clarke met with the wife of the Tesla driver who provided consent to the CHP to retrieve electronic data from the vehicle involved in the crash. NTSB authority to retrieve data from vehicles in an accident is contained within Title 49 US Code 1131 and is authorized in the Driver Privacy Act of 2015.

[9] See Automation and Data Summary Attachment 1 – Tesla EDR Report.

4.3 Media Control Unit (MCU) Telematics Data

The Tesla Model X stores non-geo-located data on the vehicle in non-volatile[10] memory using a removable SD card installed within the MCU. The SD card is large enough to typically maintain a record of all stored data for over one year. One type of data acquired and stored is general vehicle information. This data is continually written to the MCU (SD card) and recorded in the vehicle's Carlogs. Typical parameters include steering angle, accelerator pedal position, driver applied brake pedal application, vehicle speed, Autopilot technology features, longitudinal and lateral acceleration, 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 MCU using a GPS derived clock time.

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 cellular data capabilities of the vehicle. 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 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 MCU. 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 onboard the Tesla vehicle.

Following the crash, Tesla informed the NTSB that due to the catastrophic nature of the crash data related to the crash event was not uploaded to Tesla servers. NTSB investigator Karol contacted CHP Sergeant Clarke and requested he retrieve the MCU (infotainment system) from the wreckage so that investigators could access data on the SD card later.

On March 28, 2018, the SD card was removed from the MCU at the CHP Redwood City area office (see figure 4). Tesla personnel copied the data from the SD card so that it could be decrypted and translated at Tesla headquarters. Following the copy of the data, the SD card was returned to CHP evidence storage at the Redwood City area office. Additionally, NTSB retained a copy of the raw data on the SD card which consisted of approximately 1.16 GB of data composed of 156 files organized in 11 folders. Most data, including the vehicle log files containing parametric data was stored in a proprietary binary format that required the use of Tesla in-house software tools for conversion into engineering units.

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

Figure 4. Removal of the SD card from the MCU on March 28, 2018 at the CHP Redwood City area office.

4.4 Autopilot HW 2.5 ECU Module

The Autopilot HW 2.5 ECU module was removed from the Tesla wreckage at the tow impound facility and booked into evidence at the CHP Redwood City area office. The module was transferred to the NTSB to determine if information, such as video imagery, could be retrieved from the module. On August 2, 2018, NTSB investigators responded to the Tesla offices at 3500 Deer Creek Road, Palo Alto, California to work with Tesla engineers to attempt imaging of the module. Due to the power loss sustained during the crash, no information related to the crash could be retrieved from the module. The module was returned to the CHP to be booked into evidentiary control at the Redwood City area office.

5. Tesla Model X Carlog Data

The table below depicts 14.9 seconds of data obtained from the SD card (Carlogs) immediately prior to the crash.[11]

Time	Time to Crash	Speed	Distance from Attenuator	Lead Vehicle Distance	Steering (L or R)	Lateral Acceleration
9:27:12.5	14.9 secs	69.5 mph	1437.9 feet	98.4 feet	1.6 deg. L	0.046 g's
9:27:13.5	13.9 secs	69.6 mph	1335.9 feet	95.1 feet	0.8 deg. L	0.010 g's
9:27:14.5	12.9 secs	69.4 mph	1234.7 feet	93.5 feet	0.4 deg. L	.005 g's
9:27:15.5	11.9 secs	68 mph	1133.9 feet	88.6 feet	0.2 deg. L	0.020 g's
9:27:16.5	10.9 secs	66.75 mph	1035.1 feet	86.9 feet	1.4 deg. L	0.020 g's
9:27:17.5	9.9 secs	65.65 mph	937.9 feet	83.7 feet	1.3 deg. L	0.010 g's
9:27:18.5	8.9 secs	64.6 mph	842.3 feet	82 feet	0.8 deg. L	0.005 g's
9:27:19.5	7.9 secs	64.3 mph	747.8 feet	83.7 feet	0.3 deg. L	0.010 g's
9:27:20.5	6.9 secs	64.2 mph	653.6 feet	83.7 feet	1.6 deg. L	0.025 g's
9:27:21.5	5.9 secs	64.05 mph	559.6 feet	82 feet	5.6 deg. L	0.122 g's
9:27:22.5	4.9 secs	63.1 mph	466.3 feet	80.4 feet	0.8 deg. L	.005 g's
9:27:23.5	3.9 secs	61.9 mph	374.6 feet	NA	0.3 deg. R	-.005 g's
9:27:24.5	2.9 secs	62.35 mph	283.5 feet	NA	1.1 deg. R	-.026 g's
9:27:25.5	1.9 secs	65.25 mph	189.9 feet	NA	1 deg. R	-.031 g's
9:27:26.5	0.9 secs	68.4 mph	91.9 feet	NA	3.8 deg. L	.036 g's
9:27:27.4	0	70.84 mph[12]	0	NA	NA	NA

Based upon a review of the data contained in the Carlog files that includes the entire trip on which the crash occurred, NTSB was able to determine the following:

[11] Distance measurements from the attenuator are approximate and were derived based upon kinematic equations taking into the speed recorded and individual time intervals. Lead vehicle distance was converted from meters to feet. Steering wheel angle is reported by the electronic assisted power steering system. Lateral and longitudinal acceleration values were converted from m per sec per sec to g units.

[12] Approximate speed at impact was not recorded in the Tesla Carlogs. The speed was obtained from the EDR report depicted in Figure 3.

- Autopilot was engaged and the TACC was set to a cruise speed of 75 mph.

- The Tesla was traveling between 64 to 66 mph and following a lead vehicle at about 83 feet. According to Tesla, the TACC was set to position 1 which maintains the closest possible following distance behind the lead vehicle (time-based following distance of about 0.9 seconds).[13]

- When the Tesla was about 5.9 seconds and about 560 feet from the crash attenuator, Autosteer initiated a left steering input (5.6 degrees at the steering wheel) toward the neutral area or the gore.

- About 5.9 seconds before the crash, Autosteer did not detect driver-applied steering wheel torque. This indication of no hands-on steering wheel continued until the time of crash.

- The Autosteer lane keeping assist subsystem was tracking both the left and right lane lines until about 5 seconds before the crash, when the Tesla lost acquisition of lane lines and began following the lines into the gore point.[14]

- About 4.6 seconds before the crash, an Autopilot angle rate saturation alert was recorded in the Carlog data. Tesla advised that this alert is set when the steering angle rate desired by the steering controller would be greater than the speed-dependent maximum allowed rate.[15]

- When the Tesla was about 3.9 seconds and 375 feet from the crash location, the TACC no longer detected a lead vehicle ahead and the vehicle began accelerating from a speed of 61.9 mph to the cruise set speed of 75 mph.[16]

- About 3.5 seconds before the crash, the Tesla reacquired a right high confidence lane line and was near centered in the neutral area of the gore tracking the left and right 8-inch wide channelizing lines of the gore area.

- The forward collision warning (FCW) system did not provide an alert and the automatic emergency braking (AEB) did not activate as the Tesla approached the non-operational (already compressed) crash cushion.[17]

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[13] Tesla advised NTSB that TACC position 1 is set to maintain a 1 second following time. This following time is a target and not exact because the controller allows some flexibility to smooth the gap accounting for the relative velocity, acceleration, and distance of the target vehicle.

[14] Vehicle data is not available to confirm this point, however, this is the most likely supposition in discussion with Tesla.

[15] Tesla limits the rate of change of the steering angle command based on the vehicle speed in order to help prevent sudden aggressive steering actions by the steering controller. Tesla advised NTSB that this is a commonly recorded alert and is used for engineering diagnostics purposes only and is not a customer-facing alert.

[16] Witness video showed the lead vehicle – a passenger sedan style vehicle - continuing southbound in the second lane from the left.

[17] FCW and AEB systems are not designed to detect lane-separating barriers such as the non-operational crash cushion nor at high speeds (60 – 70 mph in this crash).

6. Autopilot Activation and Warnings for Hands-off Operation

Carlog data shows that the ignition cycle that preceded the crash lasted about 28 minutes and 33 seconds. Autopilot was engaged for a total of 21 minutes and 53 seconds during the last ignition cycle (see figure 5). During the final Autopilot segment, the system did not detect driver-applied steering wheel torque for 34.4 percent of the time.

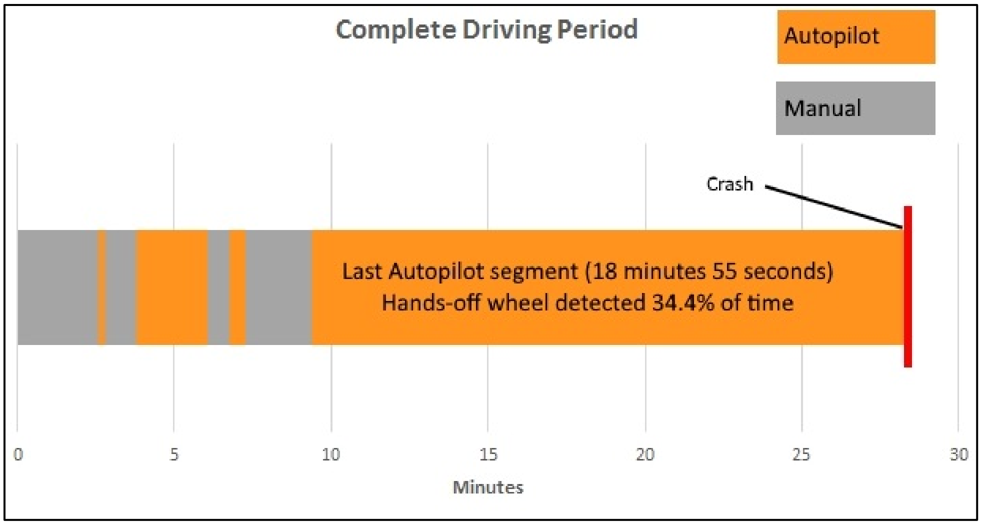

Figure 5. Depiction of manual and Autopilot controlled operation of the Tesla during the crash trip.

The driver had Autopilot engaged continuously for the final 18 minutes and 55 seconds of the crash trip, including the time of the crash. During this last Autopilot segment, the system issued two visual alerts for hands-off driving operation and one first level auditory alert (see figure 6).

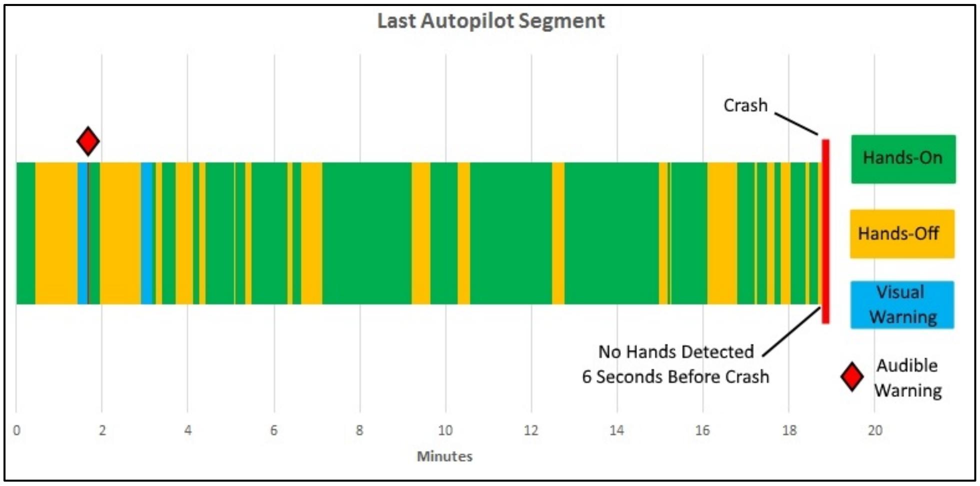

Figure 6. Depiction of the last Autopilot segment of the crash trip, including the warnings for hands-off driving operation.

7. Review of Prior Drive Cycle Carlog Data

After the crash, the family of the Tesla Model X driver reported that the driver had complained about prior incidents involving the vehicle pulling to the left toward the gore area. NTSB reviewed one month of Carlog data (February 23, 2018 to March 23, 2018) and identified two prior incidents involving the Tesla Model X being operated in Autopilot mode steering to the left in the vicinity of the gore collision location.[18] A description of the two similar incidents is provided below.

On Monday, March 19, 2018, at about 9:25:42, the Carlog data showed the Tesla traveling at 75.65 mph, following a lead vehicle at about 111 feet (1.5 second following time). The Tesla was being operated with Autopilot activated and the driver's hands were detected on the steering wheel. Autosteer applied a -5.1° steering wheel angle toward the gore area, which was followed a second later by a +2.5° corrective steering wheel angle away from the gore area. As a result of the corrective steering action an override alert was recorded in the Carlog data. This alert is triggered when a driver manually applies enough torque to the steering wheel to disengage Autopilot. The Autopilot disengagement alert is accompanied by a visual indicator and an audible chime.

A graphical representation of a comparison between the March 19 and March 23 data is shown in Figure 7. Figure 7a shows the speeds on the two days. The speed on March 19, 2018 is in blue and the speed on March 23, 2018, is in red. The horizontal axis of the plot is traveled distance in units of miles. Travel distance was determined by integrating the Tesla speed over time. This distance was set to zero at the location where the Tesla exited the curve on US-101 that is located north of the Embarcadero Road interchange. The exit from the curve was determined by the steering wheel angle and the lateral acceleration approaching zero after a period of having elevated values, as seen in Figures 7b and 7c, respectively.

The vertical dotted lines at distance zero in Figure 7 are at the exit from the US-101 curve. The vertical dotted lines at distance 3.8 miles are at the location where Autosteer steering starts being affected by the gore. The data on the day of crash day ended at distance 3.9 miles, where the Tesla impacted the attenuator. The blue curves in Figure 7 corresponds to the trip on March 19, 2018. The Carlog data from that trip was integrated along US-101 and shifted along the traveled distance axis to align the steering wheel angle and the lateral acceleration at the exit from the US-101 curve with the corresponding red curves.

NTSB investigator Don Karol interviewed a friend of the Tesla driver who provided information regarding the Tesla's incursion into the gore area on March 19, 2018. A screenshot of

[18] Tesla advised NTSB that GPS data was not available to correlate the Carlog data to a specific location. NTSB used geographic landmarks coupled with speed, steering angle and time-distance relationships to determine prior day Carlog data relative to the crash location. In toll, the NTSB examined 15 days of data. The dates from March 6 to March 12 were excluded from the review since the vehicle was being serviced at that time. Additionally, investigators only looked at the time period between 9:00 a.m. and 10:00 a.m., days when the Tesla driver was making his morning commute to work. It is possible that other gore area incursions occurred during the month outside of this focused review.

a text message was provided to the NTSB showing that the Tesla driver reported Autopilot steering the Tesla toward the gore area that morning.[19]

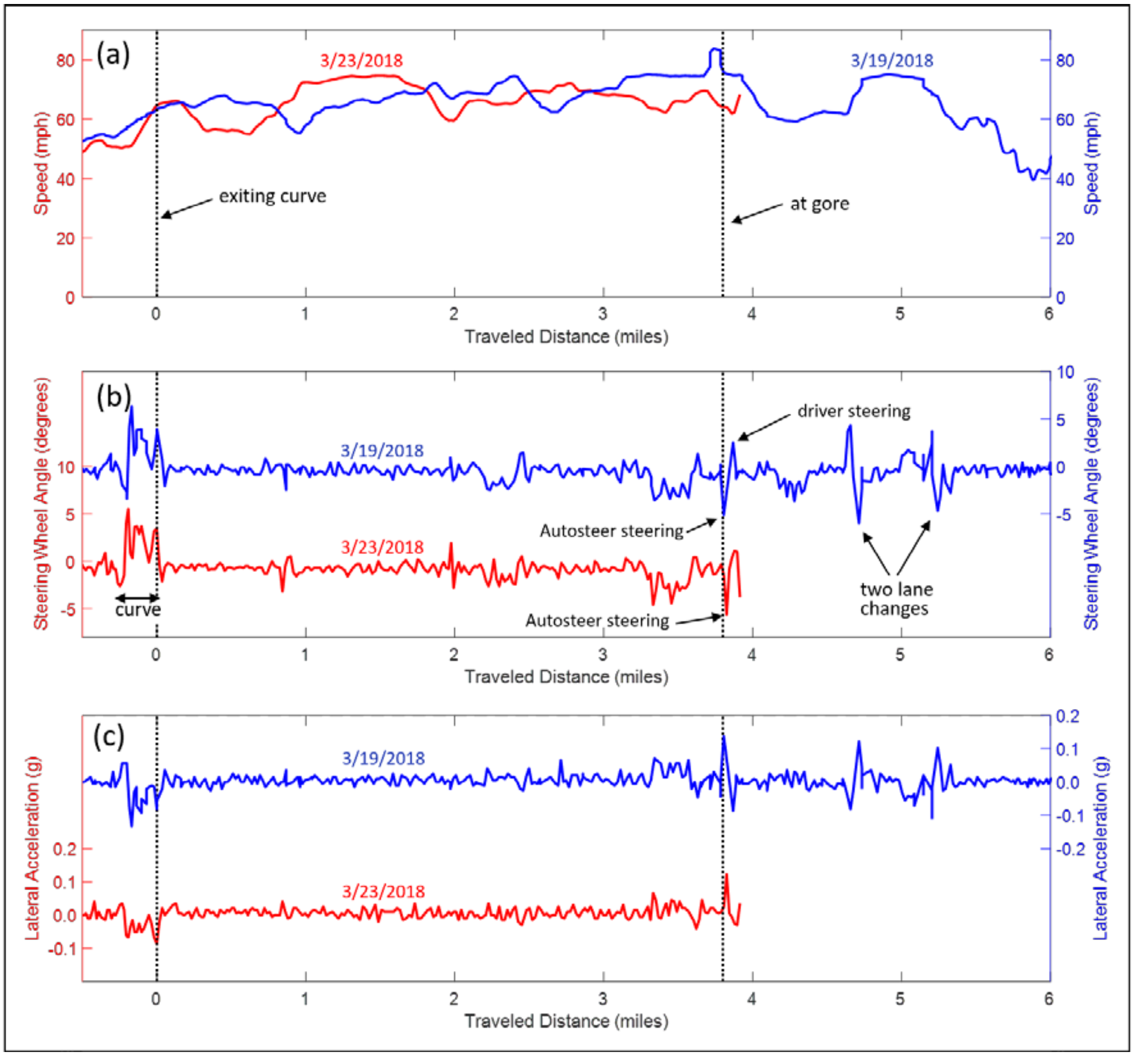

Figure 7. Data from the Tesla Model X Carlogs on March 19 and March 23 showing the similarity between the Autosteer actions while traveling in the vicinity of the gore area.

Another similar incident was identified in the Carlog data for February 27, 2018. At about 9:31:30, the Tesla was traveling at 66.95 mph, following a lead vehicle at about 83.7 feet (0.85 second following time). The Tesla was being operated with Autopilot activated and the driver's hands were detected on the steering wheel. Autosteer applied a -6º steering wheel angle toward the gore area, which was followed two seconds later by a +1.3º corrective steering wheel angle away from the gore area (see Figure 8).

[19] Tesla provided vehicle repair records and customer contacts and there was no written record showing that the driver (owner) contacted Tesla about any prior gore point incursions.

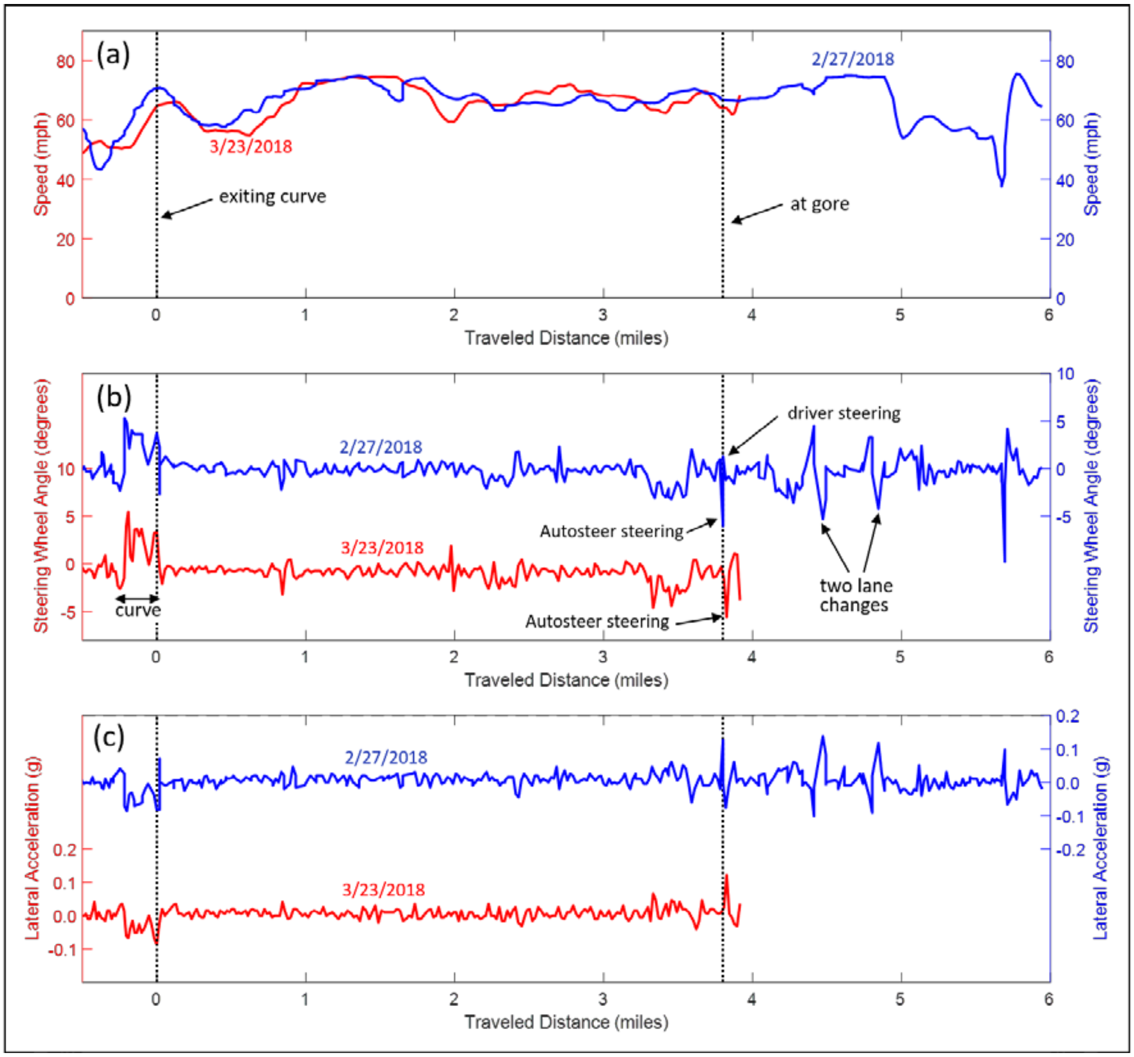

Figure 8. Data from the Tesla Model X Carlogs on February 27, 2018 and March 23, 2018 showing the similarity between the Autosteer actions while traveling in the vicinity of the gore area.

Following the Mountain View crash, Tesla made design changes to Autopilot firmware. The changes included an improved vision system, more immediate Autosteer hands-off wheel alert timing warnings (as shown in figure 2), and an Autopilot "Driveable Space" forward collision warning and avoidance system. These changes are summarized below:

- ***Hydranet Vision System*** (Firmware Update 2018.10.4): The firmware update includes vision system changes designed to improve the ability of the system to recognize poor and faded lane markings, slopes/banks, and higher-curvature roads. A higher fidelity "roadway estimator" was incorporated to improve lane and path prediction. The Hydranet Vision System also includes changes that impact depth detection, vision-radar association, and vehicle detection.

- ***Autopilot Hands-Off Wheel Alert Timing*** (Firmware Update 2018.23): The firmware changed the alert timing to include more immediate alerts when hands are not detected on the steering wheel and there is no valid lane line (plus no lead vehicle) or if an unusual lane line detected. It also includes visual alerts based upon speed-based escalation for travel speeds over 25 mph. For example, at a speed of 25 mph if the vehicle does not detect hands on wheel for 60 seconds, a visual alert would be provided. At 90 mph the alert would be provided after 10 seconds. Tesla advised that more immediate audible warnings are also provided if the system no longer recognizes a lane while hands are not detected on the steering wheel.

- ***Driveable Space Collision Warning*** (Firmware Update 2018.23): The firmware was updated with a forward collision warning and active braking when certain unknown objects are identified in the path of the vehicle. This "Drivable Space" time-to-collision provides warning up to 2.5 seconds based on detection. Since this warning is part of the Autopilot system it cannot be disabled when the Autopilot system is operating. The warning system is determined by the camera vision system without radar fusion and establishes a boundary ahead of the vehicle. When the vehicle approaches the end of the driveable space a chime will sound and maximum braking will be applied. Driveable space provides heavy deceleration but is primarily intended to give drivers an audible warning and reduce impact severity, not to fully prevent all crashes at highway speeds.

E. DOCKET MATERIAL

The following attachments are included in the docket for this investigation:

<u>LIST OF ATTACHMENTS</u>

Automation and Data Summary Attachment 1 – Tesla EDR Report

END OF REPORT

Donald F. Karol
National Resource Specialist