Collision Between a Sport Utility Vehicle Operating With Partial Driving Automation and a Crash Attenuator
Mountain View, California
March 23, 2018

Accident Report

NTSB/HAR-20/01
PB2020-100112

National
Transportation
Safety Board

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Notation 59775
Adopted February 25, 2020

Highway Accident Report

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National
Transportation
Safety Board

490 L’Enfant Plaza SW
Washington, DC 20594

National Transportation Safety Board. 2020. ***Collision Between a Sport Utility Vehicle Operating With Partial Driving Automation and a Crash Attenuator, Mountain View, California, March 23, 2018*****. Highway Accident Report NTSB/HAR-20/01. Washington, DC.**

Abstract: On Friday, March 23, 2018, at 9:27 a.m., a 2017 Tesla Model X P100D electric-powered sport utility vehicle (SUV), occupied by a 38-year-old male driver, was traveling south on US Highway 101 (US-101) in Mountain View, Santa Clara County, California. As the Tesla approached a paved gore area dividing the main travel lanes of US-101 from the left exit ramp to State Route 85 (SR-85), the vehicle moved to the left and entered the gore. It continued traveling through the gore and struck a previously damaged and nonoperational crash attenuator at a speed of about 71 mph. The impact rotated the SUV counterclockwise and caused the front body structure to separate from the rear of the vehicle. The Tesla was involved in subsequent collisions with two other vehicles, a 2010 Mazda 3 and a 2017 Audi A4. The Tesla's high-voltage battery was breached in the collision and a postcrash fire ensued. The driver was transported to a local hospital, where he died from blunt-force trauma injuries. The driver of the Mazda sustained minor injuries, and the driver of the Audi was uninjured.

From its investigation of this crash, the National Transportation Safety Board (NTSB) identified the following safety issues:

- Driver distraction
- Risk mitigation pertaining to monitoring driver engagement
- Risk assessment pertaining to operational design domain
- Limitations of collision avoidance systems
- Insufficient federal oversight of partial driving automation systems
- Need for event data recording requirements for driving automation systems, and
- Highway infrastructure issues

On the basis of its findings, the NTSB makes safety recommendations to the US Department of Transportation, the National Highway Traffic Safety Administration, the Occupational Safety and Health Administration, SAE International, Tesla, Apple, and manufacturers of portable electronic devices.

For more detailed background information on this report, visit www.ntsb.gov and search for NTSB accident ID HWY18FH011. Recent publications are also available in their entirety on this website. Other information about available publications also may be obtained from the website or by contacting:

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NOTE: This report was reissued on March 20, 2020, with a correction to page 65, clarifying that Member Jennifer Homendy was joined in her concurring statement by all Board Members (Chairman Robert L. Sumwalt, III; Vice Chairman Bruce Landsberg; and Members Thomas B. Chapman and Michael E. Graham).

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Acronyms and Abbreviations

AAA	American Automobile Association
ADAS	advanced driver assistance systems
ADS	automated driving systems
AEB	automatic emergency braking
CalSTA	California State Transportation Agency
Caltrans	California Department of Transportation
CEA	Consumer Electronics Association (renamed Consumer Technology Association [CTA] in November 2015)
CFR	*Code of Federal Regulations*
CHP	California Highway Patrol
CTA	Consumer Technology Association (formerly Consumer Electronics Association [CEA])
CTIA	Cellular Telecommunications Industry Association
DDT	dynamic driving task
DOT	US Department of Transportation
EDR	event data recorder
FCW	forward collision warning
FHWA	Federal Highway Administration
GPS	global positioning system
HAZMAT	hazardous materials
HOV	high-occupancy vehicle
I-405	Interstate 405
KB	kilobyte
MAIT	Multidisciplinary Accident Investigation Team

MASH	*Manual for Assessing Safety Hardware*
MB	megabyte
MCU	media control unit
mph	miles per hour
MVFD	Mountain View Fire Department
NCAP	New Car Assessment Program
NCHRP	National Cooperative Highway Research Program
NETS	Network of Employers for Traffic Safety
NHTSA	National Highway Traffic Safety Administration
NSC	National Safety Council
NTSB	National Transportation Safety Board
ODD	operational design domain
ODI	Office of Defects Investigation (NHTSA)
OEDR	object and event detection and response
OTA	over-the-air
OTS	California Office of Traffic Safety
PED	portable electronic device
RCM	restraint control module
SAE	SAE International (formerly Society of Automobile Engineers)
SD	secure digital (card)
SMFD	San Mateo Fire Department
SR-85	State Route 85
SUV	sport utility vehicle
TACC	Traffic-Aware Cruise Control
UNECE	United Nations Economic Commission for Europe
US-27A	US Highway 27A

US-101	US Highway 101
US-441	US Highway 441

Terminology Related to Driving Automation Systems

In June 2018, SAE International (SAE) issued an updated *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles* (SAE 2018).[1] The taxonomy includes functional definitions for levels of driving automation. As shown in Table 1 on the next page, SAE lists six levels of automation ranging from Level 0 (no driving automation) to Level 5 (full driving automation). The generic term "driving automation system" refers to any 1–5 level system. Individually, Tesla Autopilot subsystems—such as Traffic-Aware Cruise Control (TACC), which provides longitudinal vehicle motion control; and Autosteer, which provides lateral vehicle directional control—are considered Level 1 systems. When Autopilot is active and multiple subsystems like TACC and Autosteer are combined to provide both lateral and longitudinal vehicle motion control, the system is considered Level 2 driving automation.

SAE classifies a Level 2 system like Autopilot as "partial driving automation." In a Level 2 system, it is the driver's responsibility to monitor the automation, maintain situational awareness of traffic conditions, understand the limitations of the automation, and be available to intervene and take full control of the vehicle at all times. Throughout this report, the terms advanced driver assistance systems (ADAS), driving automation systems, and partial driving automation will be used to describe the capabilities of Tesla Autopilot. In the SAE taxonomy table (next page), the operational design domain (ODD) means the operating conditions under which the driving automation system is designed to function. Object and event detection and response (OEDR) includes detecting, recognizing, and classifying events and preparing to respond as needed. The dynamic driving task (DDT) involves all real-time operational and tactical functions required to operate a vehicle. Automated driving systems (ADS) apply to the higher, more fully automated Levels 3–5.

[1] SAE International, initially established as the Society of Automotive Engineers, is a professional association and standards-developing organization. Refer to www.sae.org for additional information about technical standards developed by the association.

Table 1. Summary of SAE taxonomy and definitions of terms related to driving automation systems for on-road motor vehicles. (Source: SAE International J3016, June 2018)

Level	Name	Narrative definition	*DDT*		*DDT fallback*	*ODD*
			Sustained lateral and longitudinal vehicle motion control	*OEDR*		
Driver performs part or all of the *DDT*						
0	No Driving Automation	The performance by the *driver* of the entire *DDT*, even when enhanced by *active safety systems*.	*Driver*	*Driver*	*Driver*	n/a
1	Driver Assistance	The *sustained* and *ODD*-specific execution by a *driving automation system* of either the *lateral* or the *longitudinal vehicle motion control* subtask of the DDT (but not both simultaneously) with the expectation that the *driver* performs the remainder of the *DDT*.	*Driver* and *System*	*Driver*	*Driver*	Limited
2	Partial Driving Automation	The *sustained* and *ODD*-specific execution by a *driving automation system* of both the *lateral* and *longitudinal vehicle motion control* subtasks of the *DDT* with the expectation that the *driver* completes the *OEDR* subtask and *supervises* the *driving automation system*.	***System***	*Driver*	*Driver*	Limited
ADS ("*System*") performs the entire *DDT* (while engaged)						
3	Conditional Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire DDT with the expectation that the *DDT fallback-ready user* is *receptive* to *ADS*-issued *requests to intervene*, as well as to *DDT performance-relevant system failures* in other *vehicle* systems, and will respond appropriately.	*System*	***System***	*Fallback-ready user (becomes the driver during fallback)*	Limited
4	High Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	***System***	Limited
5	Full Driving Automation	The *sustained* and unconditional (i.e., not *ODD*-specific) performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	*System*	**Unlimited**

Executive Summary

Crash Summary

On March 23, 2018, at 9:27 a.m., a 2017 Tesla Model X P100D electric-powered sport utility vehicle (SUV), occupied by a 38-year-old male driver, was traveling south on US Highway 101 (US-101) in Mountain View, Santa Clara County, California. At this location, US-101 has six southbound traffic lanes, including a high-occupancy vehicle (HOV) exit lane to State Route 85 (SR-85) southbound on the far left. As the SUV approached the US-101–SR-85 interchange, it was traveling in the lane second from the left, which was an HOV lane for continued travel on US-101.[2]

While approaching a paved gore area dividing the main travel lanes of US-101 from the SR-85 left-exit ramp, the SUV moved to the left and entered the gore. The vehicle continued traveling through the gore and struck a damaged and nonoperational crash attenuator at a speed of about 71 mph. The crash attenuator was positioned at the end of a concrete median barrier. As a result of the collision, the SUV rotated counterclockwise and the front body structure separated from the rear of the vehicle. The Tesla was involved in subsequent collisions with two other vehicles, a 2010 Mazda 3 and a 2017 Audi A4.

The Tesla's high-voltage battery was breached in the collision and a postcrash fire ensued. On-scene witnesses found the Tesla driver in his seat with his lap/shoulder belt buckled. They removed him from the vehicle before it was engulfed in flames. The driver was transported to a local hospital, where he died from blunt-force trauma injuries. The driver of the Mazda sustained minor injuries, and the driver of the Audi was uninjured.

System performance data downloaded from the Tesla indicated that the driver was operating the SUV using the Traffic-Aware Cruise Control (an adaptive cruise control system) and Autosteer system (a lane-keeping assist system), which are advanced driver assistance systems in Tesla's "Autopilot" suite. As part of this investigation, the National Transportation Safety Board (NTSB) reviewed previous NTSB investigations involving the Tesla Autopilot system in Williston, Florida; Culver City, California; and Delray Beach, Florida, to examine common issues regarding the safety of advanced driver assistance systems that provide partial driving automation (both lateral and longitudinal control).

Probable Cause

The National Transportation Safety Board determines that the probable cause of the Mountain View, California, crash was the Tesla Autopilot system steering the sport utility vehicle into a highway gore area due to system limitations, and the driver's lack of response due to distraction likely from a cell phone game application and overreliance on the Autopilot partial driving automation system. Contributing to the crash was the Tesla vehicle's ineffective monitoring of driver engagement, which facilitated the driver's complacency and inattentiveness. Contributing to the severity of the driver's injuries was the vehicle's impact with a crash

[2] Additional information about this investigation can be found in the public docket for this crash (NTSB case number HWY18FH011) by accessing the Docket Management System at www.ntsb.gov.

attenuator barrier that was damaged and nonoperational at the time of the collision due to the California Highway Patrol's failure to report the damage following a previous crash, and systemic problems with the California Department of Transportation's maintenance division in repairing traffic safety hardware in a timely manner.

Safety Issues

The safety issues identified in this crash and in previous crashes involving partial driving automation include the following:

- **Driver Distraction.** The Tesla driver was likely distracted by a gaming application on his cell phone before the crash, which prevented him from recognizing that Autopilot had steered the SUV into a gore area of the highway not intended for vehicle travel. The driver was using a company-supplied phone, but his employer, Apple Inc., did not have a policy preventing cell phone use while driving. Strong company policy, with strict consequences for using portable electronic devices while driving, is an effective strategy in helping to prevent the deadly consequences of distracted driving. Additionally, an engineering solution to the distracted driving problem is needed. Electronic device manufacturers have the capability to lock out highly distracting functions of portable electronic devices when being used by an operator while driving, and such a feature should be installed as a default setting on all devices.

- **Risk Mitigation Pertaining to Monitoring Driver Engagement.** The Tesla Autopilot system did not provide an effective means of monitoring the driver's level of engagement with the driving task, and the timing of alerts and warnings was insufficient to elicit the driver's response to prevent the crash or mitigate its severity. Requirements are needed for driver monitoring systems for advanced driver assistance systems that provide partial driving automation (SAE Level 2 systems), and Tesla needs to develop applications that more effectively sense the driver's level of engagement and that alert drivers who are not engaged.

- **Risk Assessment Pertaining to Operational Design Domain.** Crashes investigated by the NTSB continue to show that the Tesla Autopilot system is being used by drivers outside the vehicle's operational design domain (the conditions in which the system is intended to operate). Despite the system's known limitations, Tesla does not restrict where Autopilot can be used. Tesla should incorporate system safeguards that limit the use of partial driving automation systems (Autopilot) to those conditions for which they were designed. Additionally, the National Highway Traffic Safety Administration (NHTSA) has failed to develop a method for verifying that manufacturers of partial driving automation systems are incorporating system safeguards that are critical to ensuring the safety of the motoring public.

- **Limitations of Collision Avoidance Systems.** The Tesla's collision avoidance systems were not designed to, and did not, detect the crash attenuator. Because this object was not detected, (a) Autopilot accelerated the SUV to a higher speed, which the driver had previously set by using adaptive cruise control, (b) the forward collision warning did not provide an alert, and (c) the automatic emergency braking did not activate. For partial driving automation systems to be safely deployed in a high-speed operating environment, collision avoidance systems must be able to effectively detect potential hazards and warn of potential hazards to drivers.

- **Insufficient Federal Oversight of Partial Driving Automation Systems.** The US Department of Transportation and NHTSA have taken a nonregulatory approach to automated vehicle safety. NHTSA plans to address the safety of partial driving automation systems through enforcement and a surveillance program that identifies safety-related defect trends in design or performance. This strategy must address the risk of foreseeable misuse of automation and include a forward-looking risk analysis. Additionally, NHTSA should complete a further evaluation of the Tesla Autopilot system to ensure the deployed technology does not pose an unreasonable safety risk.

- **Need for Event Data Recording Requirements for Driving Automation Systems.** Advanced driver assistance systems that provide partial automation collect significant safety-relevant data that can be used for crash analysis and risk assessment. Currently, manufacturers provide limited access to this data and there is no standardization of retrievable data parameters. This report describes the NTSB's previous safety recommendations and the inaction of federal regulators to address this important issue area that is needed to foster system safety improvements.

- **Highway Infrastructure Issues.** As part of this crash investigation, the NTSB issued a safety recommendation report addressing systemic problems related to the timely repair of traffic safety hardware in California. Investigators found that on the day of the collision, the crash attenuator at the US-101–SR-85 interchange was in a nonoperational damaged condition because of a previous crash, which had occurred 11 days earlier, on March 12, 2018. The Mountain View report briefly summarizes the findings of the safety recommendation report and the actions taken by the state of California to address this safety issue.

Findings

1. None of the following were factors in the Tesla driver's actions in this crash: (1) driver licensing or qualification; (2) familiarization with the vehicle and roadway; (3) medical conditions, fatigue, or impairment by alcohol or other drugs; or (4) weather conditions.

2. The emergency response to the crash was timely and adequate.

3. The Tesla electric vehicle postcrash fire and related damage to the lithium-ion battery presented unusual fire and electrical hazards to first responders.

4. The Tesla's Autopilot lane-keeping assist system steered the sport utility vehicle to the left into the neutral area of the gore, without providing an alert to the driver, due to limitations of the Tesla Autopilot vision system's processing software to accurately maintain the appropriate lane of travel.

5. The Tesla's collision avoidance systems were not designed to, and did not, detect the crash attenuator at the end of the gore, nor did the National Highway Traffic Safety

Administration require such capability; consequently, the forward collision warning system did not provide an alert and the automatic emergency braking did not activate.

6. The driver did not take corrective action when the Tesla's Autopilot lane-keeping assist system steered the vehicle into the gore area, nor did he take evasive action to avoid the collision with the crash attenuator, most likely due to distraction caused by a cell phone game application.

7. Distracted driving due to portable electronic device use remains persistently high, and additional countermeasures are needed.

8. A technological solution, such as a lock-out function or application that automatically disables highly distracting features of a portable electronic device while driving, is an effective countermeasure for eliminating portable electronic device distraction while driving.

9. Strong company policy, with strict consequences for using portable electronic devices while driving, is an effective strategy in helping to prevent distracted driving crashes, injuries, and fatalities.

10. Although the Occupational Safety and Health Administration has guidelines for companies to reduce motor vehicle crashes by prohibiting the use of portable electronic devices while driving, the guidelines lack specificity, are not widely adopted by companies, and are seldom enforced—limiting their impact in addressing the hazards of distracted driving.

11. The Tesla Autopilot system did not provide an effective means of monitoring the driver's level of engagement with the driving task.

12. Although the lack of gore area roadway striping at the Mountain View crash location likely did not contribute to the crash, ongoing research led by the Federal Highway Administration can help identify what highway infrastructure changes may be needed in the future to accommodate automated vehicles.

13. The crash attenuator was in a damaged and nonoperational condition at the time of the collision due to the California Highway Patrol's failure to report the damage following a previous crash and systemic problems with the California Department of Transportation's maintenance division in repairing traffic safety hardware in a timely manner.

14. If the crash attenuator at the US Highway 101–State Route 85 interchange had been repaired in a timely manner and in a functional condition before the March 23, 2018, crash, the Tesla driver most likely would have survived the collision.

15. Because monitoring of driver-applied steering wheel torque is an ineffective surrogate measure of driver engagement, performance standards should be developed pertaining to an effective method of ensuring driver engagement in SAE Level 2 partial driving automation systems.

16. If Tesla Inc. does not incorporate system safeguards that limit the use of the Autopilot system to those conditions for which it was designed, continued use of the system beyond its operational design domain is foreseeable and the risk for future crashes will remain.

17. The National Highway Traffic Safety Administration's failure to ensure that vehicle manufacturers of SAE Level 2 driving automation systems are incorporating appropriate system safeguards to limit operation of these systems to the operational design domain compromises safety.

18. In order for driving automation systems to be safely deployed in a high-speed operating environment, collision avoidance systems must be able to effectively detect and respond to potential hazards, including roadside traffic safety hardware, and be able to execute forward collision avoidance at high speeds.

19. The National Highway Traffic Safety Administration's approach to the oversight of automated vehicles is misguided, because it essentially relies on waiting for problems to occur rather than addressing safety issues proactively.

20. It is essential that the National Highway Traffic Safety Administration's surveillance and defect investigation program closely examine issues related to foreseeable misuse of automation and perform a forward-looking risk analysis to identify partial driving automation system defects that pose an unreasonable risk to safety.

21. The National Highway Traffic Safety Administration's Office of Defects Investigation has failed to thoroughly investigate the Tesla Autopilot design regarding the degree to which drivers are currently misusing the system, the foreseeable consequences of continued use by drivers beyond the system's operational design domain, and the effectiveness of the driver monitoring system in ensuring driver engagement.

22. Vehicle performance data associated with activation and engagement of partial driving automation systems on vehicles involved in crashes are not required nor available on most event data recorders.

23. A standardized set of retrievable data is needed to enable independent assessment of automated vehicle safety and to foster automation safety improvements.

Recommendations

New Recommendations

As a result of its investigation, the National Transportation Safety Board makes the following nine new safety recommendations:

To the National Highway Traffic Safety Administration:

Expand New Car Assessment Program testing of forward collision avoidance system performance to include common obstacles, such as traffic safety hardware, cross-traffic vehicle profiles, and other applicable vehicle shapes or objects found in the highway operating environment. (H-20-1)

Evaluate Tesla Autopilot-equipped vehicles to determine if the system's operating limitations, the foreseeability of driver misuse, and the ability to operate the vehicles outside the intended operational design domain pose an unreasonable risk to safety; if safety defects are identified, use applicable enforcement authority to ensure that Tesla Inc. takes corrective action. (H-20-2)

For vehicles equipped with Level 2 automation, work with SAE International to develop performance standards for driver monitoring systems that will minimize driver disengagement, prevent automation complacency, and account for foreseeable misuse of the automation. (H-20-3)

After developing the performance standards for driver monitoring systems recommended in Safety Recommendation H-20-3, require that all new passenger vehicles with Level 2 automation be equipped with a driver monitoring system that meets these standards. (H-20-4)

To the Occupational Safety and Health Administration:

Review and revise your distracted driving initiatives to increase employers' awareness of the need to develop strong cell phone policy prohibiting the use of portable electronic devices while driving. (H-20-5)

Modify your enforcement strategies to increase the use of the general duty clause cited in 29 *United States Code* section 654 against those employers who fail to address the hazards of distracted driving. (H-20-6)

To SAE International:

For vehicles equipped with Level 2 automation, work with the National Highway Traffic Safety Administration to develop performance standards for driver monitoring systems that will minimize driver disengagement, prevent automation complacency, and account for foreseeable misuse of the automation. (H-20-7)

To Manufacturers of Portable Electronic Devices (Apple, Google, HTC, Lenovo, LG, Motorola, Nokia, Samsung, and Sony):

> Develop a distracted driving lock-out mechanism or application for portable electronic devices that will automatically disable any driver-distracting functions when a vehicle is in motion, but that allows the device to be used in an emergency; install the mechanism as a default setting on all new devices and apply it to existing commercially available devices during major software updates. (H-20-8)

To Apple Inc.:

> Develop and implement a company policy that bans the nonemergency use of portable electronic devices while driving by all employees and contractors driving company vehicles, operating company-issued portable electronic devices, or using a portable electronic device to engage in work-related communications. (H-20-9)

Previously Issued Recommendations Reiterated in This Report

As a result of its investigation, the National Transportation Safety Board reiterates the following two safety recommendations (already classified "Open—Unacceptable Response") in sections 2.3.3 and 2.3.2, respectively, in this report:

To the National Highway Traffic Safety Administration:

> Develop and apply testing protocols to assess the performance of forward collision avoidance systems in passenger vehicles at various velocities, including high speed and high velocity-differential. (H-15-4)

> Develop a method to verify that manufacturers of vehicles equipped with Level 2 vehicle automation systems incorporate system safeguards that limit the use of automated vehicle control systems to those conditions for which they were designed. (H-17-38)

Previously Issued Recommendations Reiterated and Reclassified in This Report

As a result of its investigation, the National Transportation Safety Board reiterates and reclassifies the following five safety recommendations:

To the US Department of Transportation:

> Define the data parameters needed to understand the automated vehicle control systems involved in a crash. The parameters must reflect the vehicle's control status and the frequency and duration of control actions to adequately characterize driver and vehicle performance before and during a crash. (H-17-37)

Safety Recommendation H-17-37 is reclassified from "Open—Await Response" to "Open—Unacceptable Response" in section 2.4 of this report.

To the National Highway Traffic Safety Administration:

> Use the data parameters defined by the U.S. Department of Transportation in response to Safety Recommendation H-17-37 as a benchmark for new vehicles equipped with automated vehicle control systems so that they capture data that reflect the vehicle's control status and the frequency and duration of control actions needed to adequately characterize driver and vehicle performance before and during a crash; the captured data should be readily available to, at a minimum, National Transportation Safety Board investigators and National Highway Traffic Safety Administration regulators. (H-17-39)

Safety Recommendation H-17-39 is reclassified from "Open—Acceptable Response" to "Open—Unacceptable Response" in section 2.4 of this report.

> Define a standard format for reporting automated vehicle control systems data and require manufacturers of vehicles equipped with automated vehicle control systems to report incidents, crashes, and vehicle miles operated with such systems enabled. (H-17-40)

Safety Recommendation H-17-40 is reclassified from "Open—Acceptable Response" to "Open—Unacceptable Response" in section 2.4 of this report.

To Tesla Inc.:

> Incorporate system safeguards that limit the use of automated vehicle control systems to those conditions for which they were designed. (H-17-41)

Safety Recommendation H-17-41 is reclassified from "Open—Await Response" to "Open—Unacceptable Response" in section 2.3.2 of this report.

> Develop applications to more effectively sense the driver's level of engagement and alert the driver when engagement is lacking while automated vehicle control systems are in use. (H-17-42)

Safety Recommendation H-17-42 is reclassified from "Open—Await Response" to "Open—Unacceptable Response" in section 2.3.1 of this report.

Previously Issued Recommendations Reclassified in This Report

As a result of its investigation, the National Transportation Safety Board reclassifies the following two safety recommendations:

To the Consumer Electronics Association (now the Consumer Technology Association):

> Encourage the development of technology features that disable the functions of portable electronic devices within reach of the driver when a vehicle is in motion; these technology features should include the ability to permit emergency use of the device while the vehicle is in motion and have the capability of identifying occupant seating position so as not to interfere with use of the device by passengers. (H-11-47)

Safety Recommendation H-11-47 is reclassified from “Open—Await Response” to “Closed—No Longer Applicable” in section 2.2.4.3 of this report.

To the California State Transportation Agency:

> Develop and implement a corrective action plan that guarantees timely repair of traffic safety hardware and includes performance measures to track state agency compliance with repair timelines. (H-19-13)

Safety Recommendation H-19-13 is reclassified from “Open—Initial Response Received” to “Open—Acceptable Response” in section 2.2.5.2 of this report.

1 Factual Information

1.1 Crash Summary

On Friday, March 23, 2018, at 9:27 a.m., a 2017 Tesla Model X P100D electric-powered sport utility vehicle (SUV), operated by a 38-year-old driver, was traveling south on US Highway 101 (US-101) in Mountain View, Santa Clara County, California. The driver had departed his home in Foster City, California, at 8:59 a.m. to drive to his work location in Sunnyvale, California (see figure 1).

Figure 1. Map showing crash location and Tesla driver's route of travel on southbound US-101.

Continuing south on US-101, the driver approached the interchange with State Route 85 (SR-85). As shown in figure 2, US-101 southbound at the SR-85 interchange consisted of:

- A single left-exit high-occupancy vehicle (HOV) lane for SR-85 (yellow arrow),
- A single US-101 HOV lane (green arrow; Tesla driver's intended route),
- Three mainline US-101 lanes (red arrows), and
- Two right-exit conventional lanes for SR-85 (blue arrows).

A 630-foot-long paved gore with an unmarked neutral (inside) area separated the left-exit HOV lane for SR-85 from the US-101 HOV lane.[1] The gore widened to about 17.5 feet at the point where a previously damaged and nonoperational crash attenuator was in place ahead of a 3-foot-high concrete barrier (see inset image in figure 2). The barrier separated the left-exit HOV lane for SR-85 from the US-101 HOV lane. At this location, the speed limit was 65 mph.

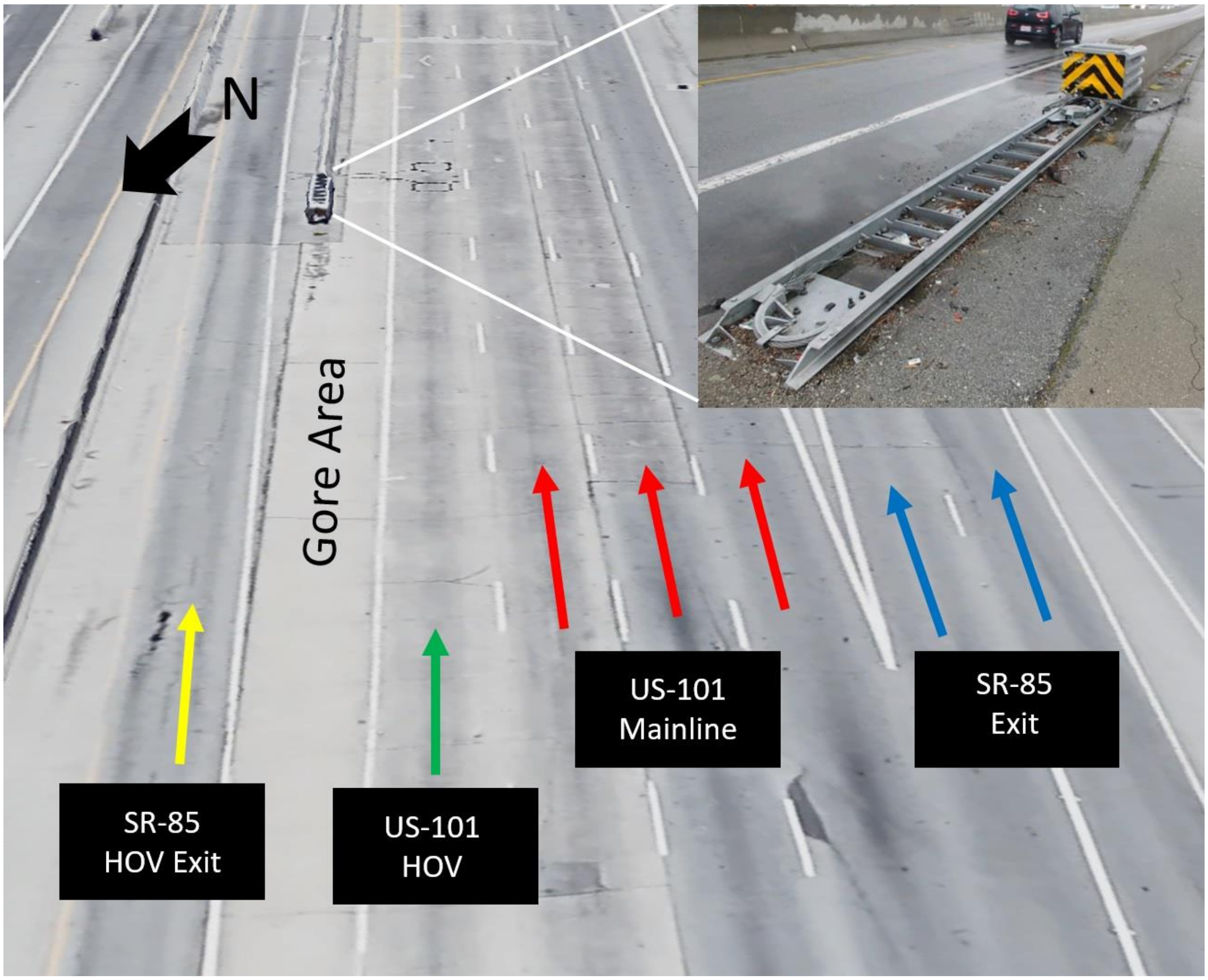

Figure 2. Depiction of travel lanes and gore area at the US-101–SR-85 southbound interchange. Inset photo depicts precrash damaged condition of the crash attenuator. (Source: Google Earth, image date March 2018. Inset photo provided by California Department of Transportation [Caltrans]; image date March 20, 2018).

As the SUV approached the US-101–SR-85 interchange, it was traveling in the second lane from the left with the Tesla's Autopilot system activated (for more detail on the operational performance data, see section 1.2).[2] When the SUV reached the gore dividing the main travel lanes of US-101 from the left exit ramp to SR-85, the vehicle moved to the left. It entered the gore, through which it continued traveling until the front left of the SUV struck the crash

[1] A gore area is a triangular-shaped boundary created by white lines marking an area of pavement formed by the convergence or divergence of a mainline travel lane and an exit/entrance lane. It is not intended for vehicle travel.

[2] In accordance with California Vehicle Code section 21655.5, the California Air Resources Board designated the Tesla Model X as an approved vehicle for single-occupant use in HOV lanes.

attenuator at a speed of 70.8 mph. The impact rotated the SUV counterclockwise and caused the front body structure to separate from the rear of the vehicle. The SUV was subsequently struck by two other vehicles, a 2010 Mazda 3 and a 2017 Audi A4, when it rotated into the lane to the right of the gore (see figure 3).[3]

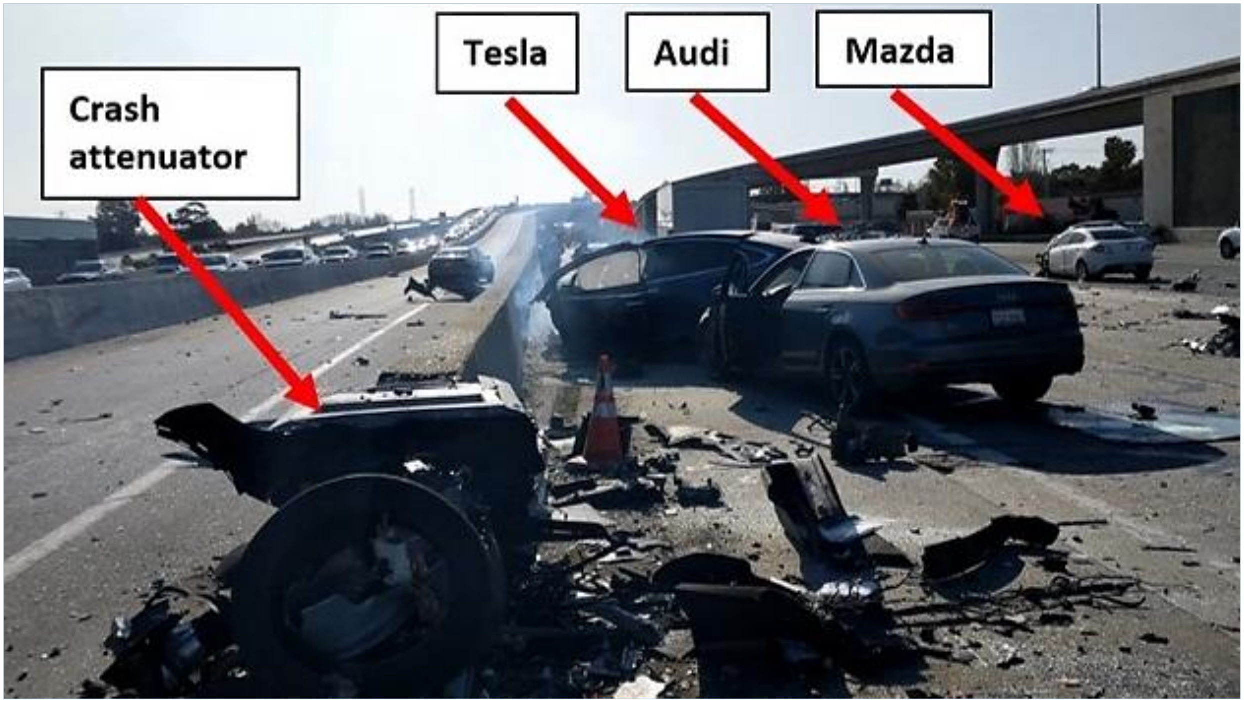

Figure 3. Southbound view of US-101, depicting the Tesla, Audi, and Mazda vehicles at final rest. (Source: witness S. Engleman)

The Tesla's high-voltage battery was breached in the collision and a postcrash fire ensued (see figure 4). After the crash, on-scene witnesses found the driver in his seat with his lap/shoulder belt buckled. They removed him from the vehicle before it was engulfed in flames, and he was transported by ambulance to the hospital for treatment.

The 51-year-old female driver of the Audi was uninjured, and the 25-year-old male driver of the Mazda sustained minor injuries. The Tesla driver died at Stanford Health Care Hospital at 1:02 p.m., 4 hours 35 minutes after the crash. The cause of death was multiple blunt-force injuries that included a fractured pelvis and significant internal injuries.

[3] This investigation focused on the primary collision between the SUV and the crash attenuator. More detailed information related to the precrash motion of the Mazda and the Audi can be found in the public docket for this crash (NTSB case number HWY18FH011).

Figure 4. Northbound view of US-101 depicting Tesla postcrash fire. (Source: witness S. Engleman)

1.2 Operational Performance Data

Autopilot is a combination of Tesla advanced driver assistance systems (ADAS) that control vehicle speed and lane positioning by automating 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 is an adaptive cruise control system that provides longitudinal control (acceleration and deceleration) and Autosteer is a lane-keeping assist system that provides lateral control (steering) of the vehicle inside the lane.

The SUV stored operational data in its event data recorder (EDR) and in non-volatile memory in its media control unit (MCU).[4] The MCU data were continually recorded onto a secure digital (SD) card in the vehicle's Carlog.[5] After examining the Carlog data, National Transportation Safety Board (NTSB) investigators developed a time-position diagram (figure 5) depicting the

[4] The EDR captured the vehicle's dynamic time-series data for the period just before and during the crash event. The EDR was located in the restraint control module (RCM) designed to control the car's airbag system and other supplemental restraints.

[5] Detailed information regarding the recovery of data from the SUV can be found in the Automation and Data Summary factual report in the public docket for this crash (NTSB case number HWY18FH011). Tesla refers to the data stored on the non-volatile memory SD card in the MCU as "Carlog" data. Parameters of data recorded included vehicle speed, steering angle, lateral and longitudinal acceleration, accelerator position, driver-applied brake pedal application, lead vehicle distance, and Autopilot technology features.

motion of the SUV during the 10 seconds leading up to the crash.[6] The time-position diagram is divided into two images. The left image shows the position of the SUV 9.9 to 4.9 seconds precrash and the right image depicts the final 4.9 seconds leading to the crash with the attenuator.

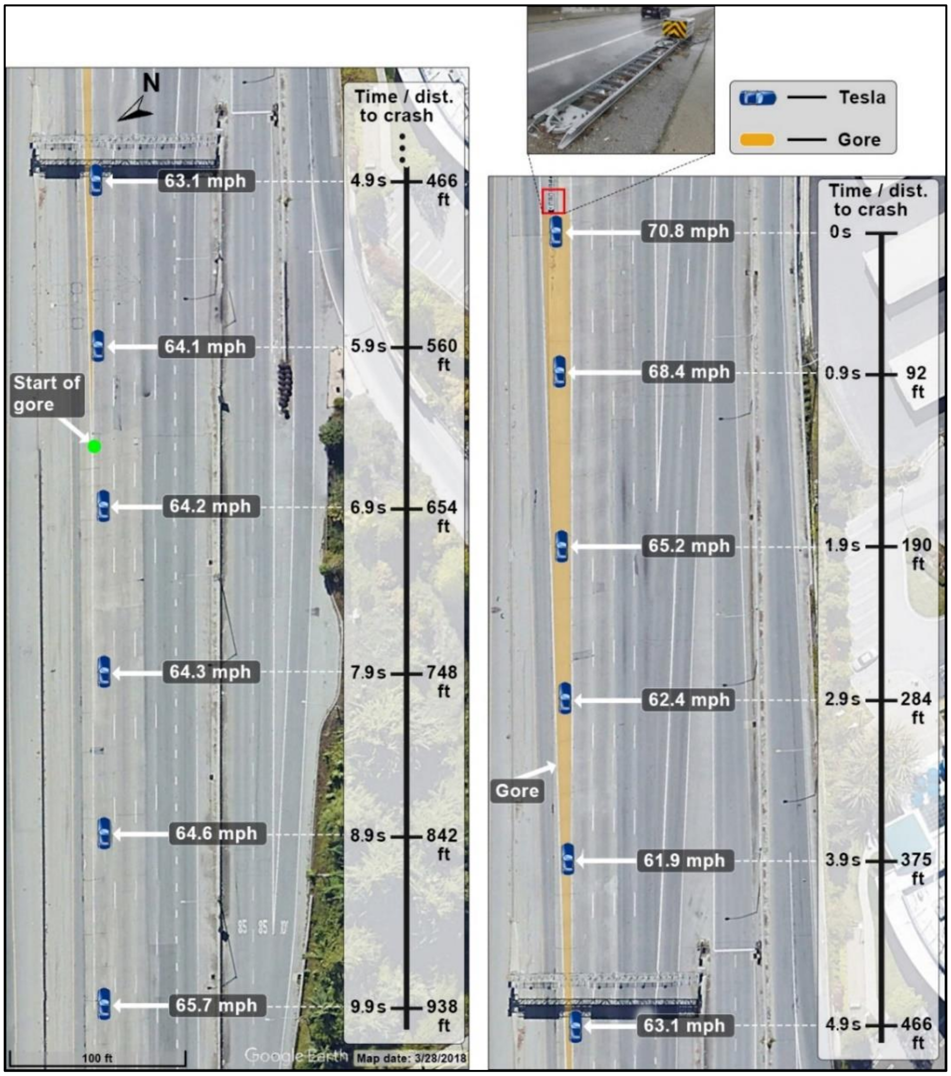

Figure 5. Movement of the Tesla SUV (blue vehicle) during the 10 seconds leading up to the crash with the attenuator. (The gore is highlighted yellow in this graphic for better clarity.)

The Carlog data also showed that during the last 10 seconds before impact:

- Autopilot was active and the TACC was set to a cruise speed of 75 mph.
- Between 10 and 6 seconds prior to the crash, the SUV was traveling between 64 and 66 mph and following another vehicle at a distance of about 83 feet. The Tesla driver had set the TACC to position 1, which maintained the closest possible following

[6] Appendix A gives details of the NTSB investigation. Appendix B contains the tabulated data extracted from the Carlog used to create figure 5.

distance behind the lead vehicle immediately ahead (time-based following distance of about 0.9 seconds).[7]

- 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 of the gore. At the time of the steering movement, no driver-applied steering wheel torque was detected by Autosteer.[8] It is possible that hands can be resting on the steering wheel and no torque is registered. However, a lack of steering wheel torque indicates to the vehicle system that the driver's hands are not on the steering wheel. This hands-off steering indication continued up to the point of impact with the crash attenuator.

- When the SUV was about 3.9 seconds and 375 feet from the crash attenuator and fully inside the neutral area of the gore, the TACC no longer detected a lead vehicle ahead and the SUV began accelerating from a speed of 61.9 mph to the preset cruise speed of 75 mph.[9]

- 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 crash attenuator.

- The data indicated that the SUV driver did not apply the brakes and did not initiate any steering movement to avoid the crash.

1.3 Emergency Response

A multiagency response consisted of the California Highway Patrol (CHP) and the Mountain View Fire Department (MVFD). The first emergency 911 call was received at 9:28 a.m. and the MVFD was dispatched at 9:31 a.m., arriving at the crash location at 9:36 a.m. The MVFD responded with three engine units, one rescue unit, and a truck for patient care, fire suppression, and equipment/personnel recovery.

After emergency personnel extinguished the flames by using water and foam, they noted intermittent popping noises accompanied by smoke, at which time they applied additional water. Because of concerns regarding high voltage and energy issues associated with the Tesla's lithium-ion battery, the MVFD incident commander contacted Tesla Inc. regarding additional actions needed to make the SUV safe. A Tesla battery engineer advised that the vehicle was not safe because of the extent of the damage and that all personnel should stay away from the SUV until Tesla representatives could evaluate it.

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[7] 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.

[8] Torque is force applied to an object to make it rotate about an axis (in this case, the steering wheel to rotate about the steering column).

[9] A dashcam mounted in a vehicle traveling north on US-101 captured the Tesla before the crash. The video showed a sedan in front of the Tesla—a lead vehicle—continuing south in the second lane from the left (the US-101 HOV lane) as the SUV traveled south in the gore area not intended for vehicle travel.

When the Tesla engineers arrived at the crash site, they immediately began removing damaged cells from the battery. Shortly thereafter, they heard three consecutive popping sounds and saw a shift in the vehicle's floorboard. The Tesla engineers determined that further attempts to remove damaged battery parts would be unsafe. Because the SUV could not be made completely stable on scene, it was loaded onto a flatbed tow truck and escorted by the CHP and the MVFD to an impound facility in San Mateo, California. About 20 minutes after the SUV arrived, the San Mateo Fire Department (SMFD) was dispatched to the impound facility because of venting sounds emanating from the Tesla wreckage.[10] The SMFD crew monitored the vehicle with thermal cameras but made no further attempts at fire suppression.

At 7:01 p.m. on March 28 (5 days after the crash), the SMFD was dispatched to the impound facility because of a report of a fire. On arrival, the SMFD crew observed flames about 8–12 inches high emanating from the Tesla's front passenger side. Approximately 300 gallons of water were applied intermittently during a 40-minute period, but because the fire continued to burn, Tesla engineers advised the SMFD to apply foam. At 8:50 p.m., after about 5 minutes of foam application, the fire was extinguished. A hazardous materials (HAZMAT) unit of the SMFD responded to test the run-off water and determined it to be toxic. The HAZMAT unit ordered public works to vacuum water, foam, and vehicle fluids from the storm drain. About 9:50 p.m., the HAZMAT unit declared the scene safe.

Lessons learned from the emergency response to the Tesla fire will be incorporated into a separate NTSB report on electric vehicle battery fires.

1.4 Occupant Restraints

The Tesla driver was restrained with a lap/shoulder belt equipped with a pretensioner that worked in conjunction with airbag systems in a severe frontal collision (figure 6 shows the airbag positions). The pretensioner automatically retracted both the seat belt anchor and the seat belt webbing, reducing slack in both the lap and shoulder portions of the belt.

[10] A damaged lithium-ion battery can cause battery cells to enter "thermal runaway," which is a loss of electrical isolation between the cathode and anode, making the cell overheat and combust. Thermal runaway events are often accompanied by a combination of flames, venting of gases, and popping or other noises resulting from the venting. This reaction may stop at one cell or propagate to adjacent cells.

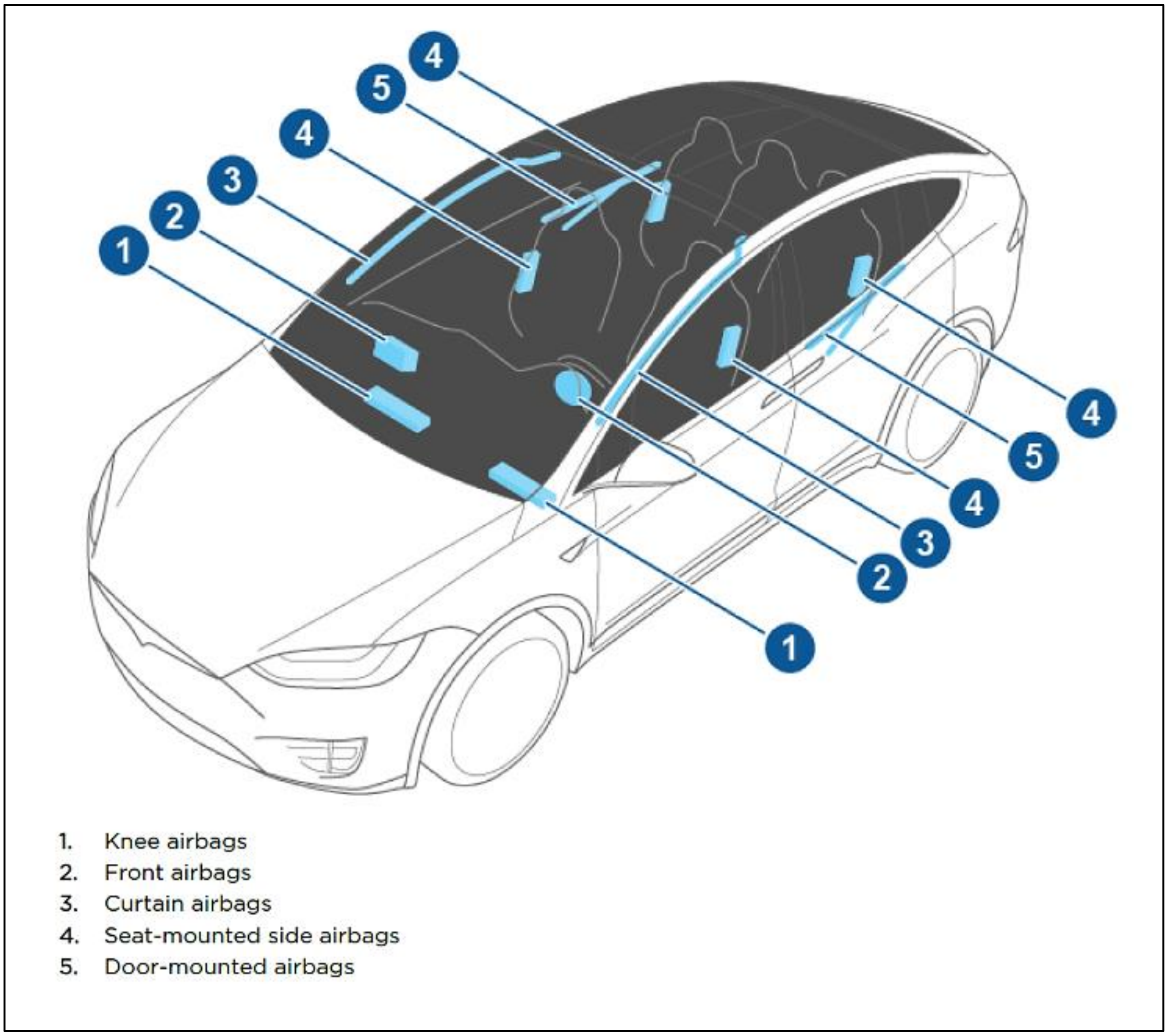

Figure 6. Diagram showing the positions of the SUV's airbags. (Source: *Tesla Model X Owner's Manual*)

Data downloaded from the RCM showed that the following restraint systems deployed during the crash:

- Driver seat belt pretensioners,
- Driver front, knee, and side seat airbags,
- Inflatable curtain airbags on the left and right side,
- Passenger-side seat airbag, and
- Second row left and right curtain and side seat airbags.

The Mazda driver was wearing his lap/shoulder belt at the time of the crash and the Mazda's front airbag deployed. The Audi driver was also restrained with a lap/shoulder belt; the Audi's front airbag did not deploy.[11]

1.5 Vehicle Factors

1.5.1 Tesla SUV

1.5.1.1 Damage. The SUV was extensively damaged in the crash (see figure 7). The front section (everything forward of the leading edges of the front doors) was destroyed and broken into fragments that spread across several traffic lanes at the US-101–SR-85 interchange. Separated components included the front drive motor, front suspension, fenders, and hood. The rear section, including the passenger compartment, sustained thermal damage from the postcrash fire.

Figure 7. Northbound view of the crash scene before the Tesla was engulfed in flames. (Source: witness S. Engleman)

1.5.1.2 Battery Damage. The Tesla electric vehicle was powered by a 400-volt lithium-ion battery. The battery comprised about 8,500 vertically mounted and tightly packed battery cells, divided into 16 modules contained within an aluminum battery pack assembly, extending along the floor of the SUV. The battery pack was breached in the collision and a postcrash fire ensued. Examination of the battery pack found the front edge crushed rearward with the top surface twisted aft and upward, exposing individual battery cells (see figure 8).[12]

[11] A near-deployment airbag event was recorded in the Audi's EDR. The data showed the Audi driver braked about 3 seconds before impacting the Tesla and slowed from a speed of about 63 mph to an impact speed of 16 mph. The impact was not severe enough to trigger an airbag deployment. No data could be imaged from the Mazda because the 2010 model was not supported by crash data retrieval tools.

[12] A detailed discussion of the damaged battery and fire is available in the public docket for this investigation.

Figure 8. Interior view of the Tesla's rear section, with exposed battery cells from the lithium-ion battery (circled in red) in the floorboard. (Source: CHP)

1.5.1.3 Mechanical and Service History. A full examination of the Tesla's mechanical components was not possible due to the fire damage and the extensive damage of the detached components. The condition prohibited an accurate evaluation of the functionality of the throttle, steering, and brake system.[13] Maintenance service records were examined and service personnel at the Tesla Service Center in Sunnyvale were interviewed regarding repairs made to the Tesla SUV between March 6 and March 12, 2018 (11 days before the crash). The March 6 service visit was to diagnose and repair damage to a rear passenger door and to address a complaint about the global positioning system (GPS)/navigation system that caused the cruise control not to function, with an associated alert that read "maps not loaded." The service personnel could not remember the interaction with the driver about the cruise control complaint and wrote on the service records "unable to duplicate concern at this time." A review of the Tesla's Carlog records from the time of the crash showed that the cruise control was functioning, with no alerts about the maps not loading.

[13] A check of the National Highway Traffic Safety Administration (NHTSA) database revealed no relevant recalls or ongoing defect investigations related to the circumstances of the Mountain View crash.

1.5.1.4 Tesla Software Updates. Tesla updates its software (firmware) wirelessly, providing new features as they are developed.[14] Firmware version 2018.10-4460-998269610au was installed on the SUV on March 12, 2018, during the service visit. Two days later, Tesla released a new firmware update to vehicle owners. Between March 14 and the crash on March 23, Tesla made 13 attempts to send firmware version 2018.10.4 to the SUV via over-the-air (OTA) wireless connection. Each attempt failed because of poor connectivity with the vehicle.[15]

Since the Mountain View crash, Tesla has enhanced the OTA updating process by adding a firmware update window in the Tesla mobile phone application. The application provides push notifications so that owners are informed and aware of the availability of updates even when not in the vehicle.[16]

1.5.2 Mazda 3 Car

1.5.2.1 Damage. The 2010 Mazda 3 sustained damage concentrated in the area of the left fender, left front tire and wheel assembly, and driver's door (see figure 9).

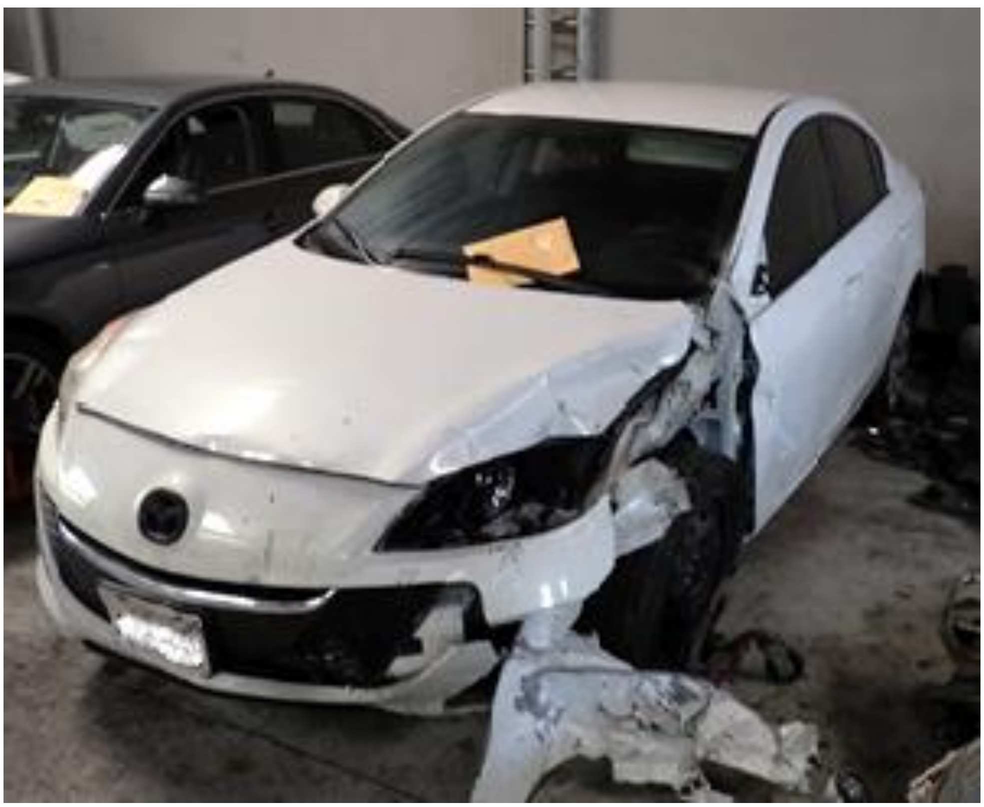

Figure 9. Damage to left front, hood, and left side of the Mazda 3.

[14] Firmware updates occur about every 6 to 8 weeks, but it is not uncommon for there to be 10 weeks between updates. Firmware version numbers reflect the year and week of the release. Any number after the week number is typically a sub-version number, which usually indicates minor fixes to the software.

[15] Firmware 2018.10.4 did not provide additional cameras or sensor usage. The firmware change updated the processing software for the vision system to improve overall performance.

[16] Tesla advised the NTSB that OTA firmware installation is "extremely successful." As of March 27, 2019, firmware 2018.10.4 had been installed on 99.8 percent of the US Tesla fleet.

1.5.2.2 Mechanical Inspection. The CHP Multidisciplinary Accident Investigation Team (MAIT) inspected the Mazda on March 29, 2018, and found no evidence of any mechanical conditions that would have affected the vehicle's safe operation.

1.5.3 Audi A4 Car

1.5.3.1 Damage. The 2017 Audi A4 sustained damage concentrated in the area of the right front bumper, headlamp, and hood (see figure 10).

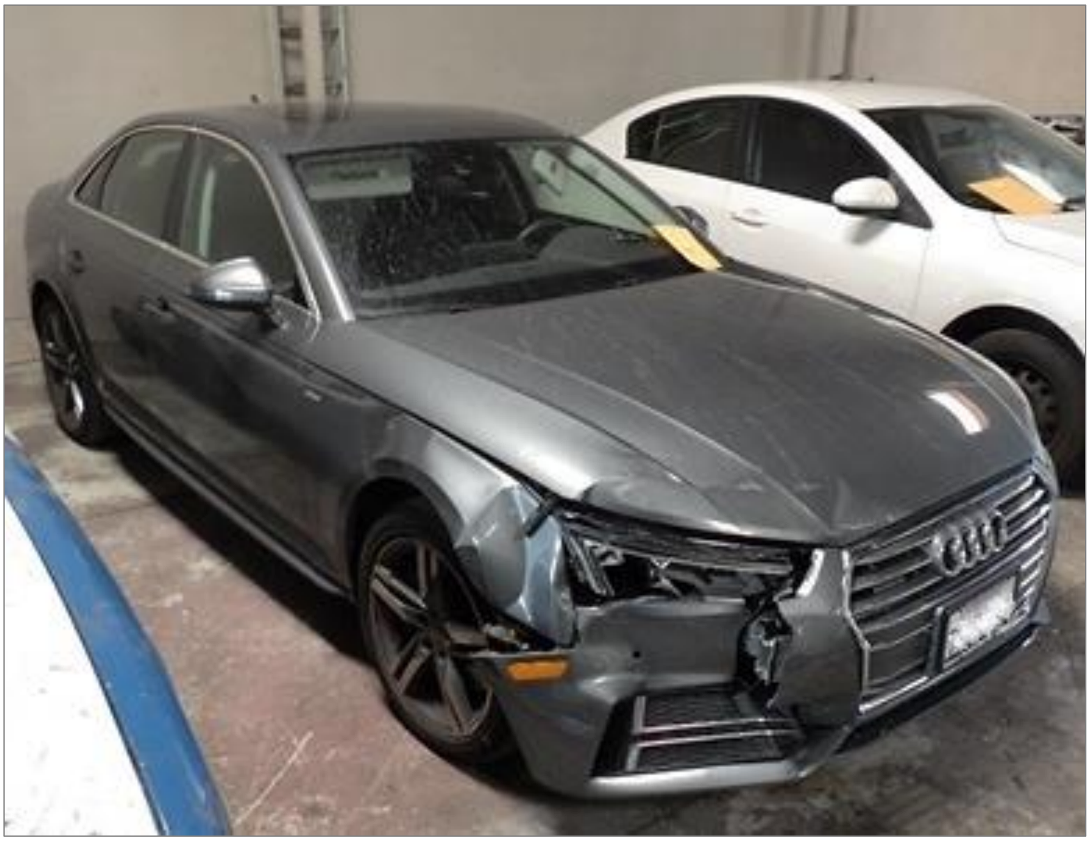

Figure 10. Damage to right front of the Audi A4.

1.5.3.2 Mechanical Inspection. The CHP MAIT inspected the Audi A4 on March 29, 2018, and found no evidence of any mechanical conditions that would have affected the vehicle's safe operation.

1.6 Tesla Autopilot

1.6.1 Autopilot Description

Tesla refers to its suite of ADAS that controls vehicle movement as Autopilot. When Autopilot is active, the system (1) monitors the travel path, (2) maintains the set cruise speed, (3) maintains the vehicle's position in the travel lane, (4) brakes when it detects slower-moving vehicles ahead of the Tesla, and (5) decelerates and follows a slower-moving vehicle in front of the Tesla at a preset following interval.

Autopilot consists of three main subsystems: (1) a sensor and imaging suite (cameras, radar, and ultrasonic sensors) designed to assess the nearby environment (see figure 11), (2) a data-processing suite designed to collect input data from the sensors and compute instructions, and (3) a servo suite designed to send control inputs to the vehicle. Information travels between subsystems using multiple controller area network busses. The performance data associated with Autopilot control systems are stored in non-volatile memory and can be communicated through an OTA network to the Tesla's central computer network. Autopilot is considered an SAE International (SAE) Level 2 partial driving automation system.[17] In a Level 2 system, it is the driver's responsibility to monitor the automation, maintain situational awareness of traffic conditions, understand the limitations of the automation, and be available to intervene and take full control of the vehicle at all times.

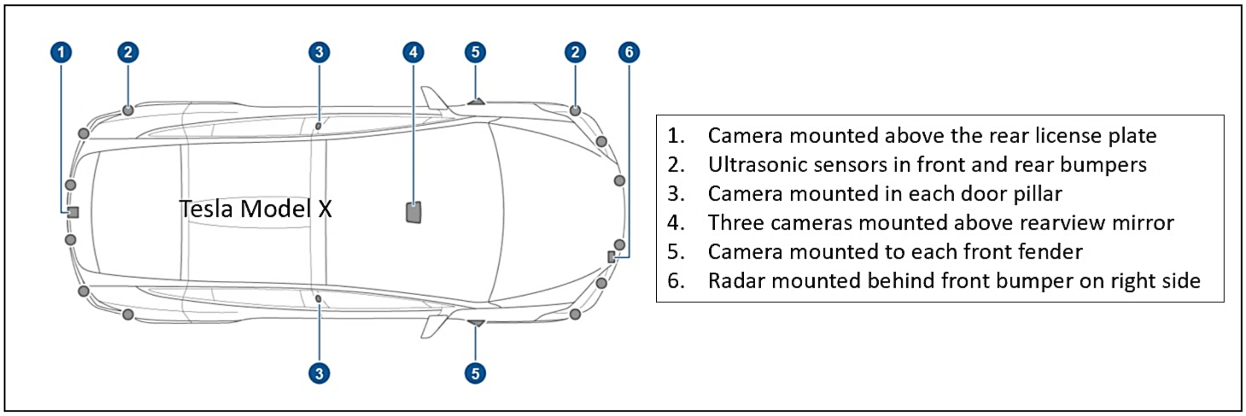

Figure 11. Diagram showing the positions of Autopilot components (cameras, ultrasonic sensors, and radar) for monitoring roadway environment. (Source: Tesla Model X Owner's Manual)

The major Autopilot features that the driver used in the moments leading up to the crash were TACC and Autosteer. TACC uses information from the forward-looking camera and radar sensor to determine whether a vehicle is in front of the Tesla in the same lane. If no vehicle is ahead of the Tesla, TACC maintains a set cruise speed selected by the driver. When a lead vehicle travels slower than the Tesla's set cruise speed, TACC will maintain a selected time interval behind the lead vehicle.

The Autosteer lane-keeping assist system uses information from the forward-looking camera, radar sensor, and ultrasonic sensors to detect lane markings and the presence of vehicles and objects. This information provides automated lane-keeping 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 travel lane. However, if the ultrasonic sensors detect the presence of an adjacent object or large vehicle (for example, a guardrail or a truck), Autosteer may steer the vehicle in a driving path offset from the center of the lane. If Autosteer does not

[17] SAE International, initially established as the Society of Automotive Engineers, is a professional association and standards-developing organization. Refer to www.sae.org for additional information about technical standards developed by the association.

receive adequate data from the camera or sensors, a message displays on the instrument panel indicating that Autosteer is temporarily unavailable.[18]

1.6.2 Autopilot Limitations

Autopilot features are described to Tesla customers as "Beta."[19] The Tesla Model X Owner's Manual (Tesla 2017) includes more than 50 warnings about the limitations of Autopilot features.[20] In addition, before driving with the Autopilot system, the driver must acknowledge several factors. On the display screen inside a Tesla vehicle, the system prompts specifically about Autosteer, although Autosteer requires activating TACC first. The Tesla-provided information states (verbatim):

- Autosteer feature is currently in Beta.
- Autosteer is a driver assistance feature and does not make your vehicle autonomous.
- Please use it only if you will pay attention to the road, keep your hands on the steering wheel, and be prepared to take over at any time. Autosteer is designed for use on highways that have a center divider, clear lane markings, and no cross-traffic. It should not be used on highways that have very sharp turns or lane markings that are absent, faded, or ambiguous.
- Autosteer is currently in Beta, which we say to encourage a higher level of vigilance. If this were a computer or mobile phone, we would not refer to it as Beta, but we believe the standards are considerably higher for vehicle control and want to be clear about the proper use of Autosteer.
- Before using Autosteer, please read the Owner's Manual for instructions and more safety information.
- Do you want to enable Autosteer while it is in Beta?

Drivers also receive an alert every time Autopilot is activated to "Always Keep Your Hands on the Wheel," and "Be Prepared to Take Over at Any Time."

1.6.3 Autopilot Constraints

1.6.3.1 Autopilot Activation. Autopilot (TACC and Autosteer) can be activated on any road on which the system can detect lane markings. To activate Autopilot, a Tesla must be traveling at a speed of at least 18 mph if no lead vehicle is detected. If a vehicle is detected ahead of the Tesla,

[18] If the driver does not respond to visual and audible alerts regarding the unavailability of Autopilot, the vehicle will decelerate in the current travel lane and activate the hazard flashers. (This situation would likely occur only in the event of an incapacitated or completely unresponsive driver.)

[19] In general, Beta means that an application or system is still in the development stages and is not the final version.

[20] Appendix C contains a list of warnings and limitations associated with the use of Autopilot features TACC and Autosteer.

Autopilot can be activated at any speed under 90 mph, even when stationary (if at least 5 feet away from the other vehicle).

1.6.3.2 Restricted Speeds. When Autopilot is active, the system limits the maximum speed at which the vehicle travels. When used on roads without a center divider, Autopilot limits the driving speed to a maximum of 5 mph above the detected speed limit (by reading the speed limit signs). On a road with a center divider, Autopilot allows a maximum travel speed of 90 mph, regardless of the roadway's speed limit. In situations where the Autopilot vision system has not detected a roadway speed limit, Autopilot limits the speed to 45 mph. A driver can manually accelerate above the TACC-limited speed, but when the accelerator pedal is released, Autopilot will slow the Tesla to the limited speed.

If a driver tries to activate Autopilot at a speed that is outside the system's speed restrictions, the instrument panel displays a message indicating that Autopilot is temporarily unavailable.

1.6.3.3 Hands-On Steering Wheel Requirement. When active, Autosteer requires a driver to intermittently hold the steering wheel. The system detects hands on the wheel by recognizing torque on the steering wheel from the driver's manually turning the wheel very lightly (that is, without enough force to retake control).[21] If Autosteer does not detect the driver's hands on the steering wheel for a period of time, a visual warning (flashing white light) appears along the top of the instrument panel and the following message displays: "Apply light force to steering wheel."

If Autosteer does not detect the driver's hands on the steering wheel after the visual warning, the system gives two auditory warnings, the first of which is sounded 15 seconds after the visual warning. If the driver's hands are still not detected on the steering wheel, Autosteer gives a second auditory warning 10 seconds after the first one.

If a driver ignores the second auditory warning and does not apply steering-wheel torque within the next 5 seconds, Autosteer sounds a continuous chime, turns on hazard warning flashers, and slows the vehicle to a complete stop in the current lane of travel. Additionally, if a driver receives any combination of three separate auditory alerts within an hour, Autosteer disengages and remains unavailable until the vehicle has been turned off and then back on.

The time between the detection of hands-off operation and the visual warning depends on (1) vehicle speed, (2) presence of a vehicle ahead, (3) lateral acceleration, (4) type of roadway, (5) detection of system errors (which would prompt an immediate warning), (6) driver application of pedals, and (7) miscellaneous factors, such as the presence of a construction zone. Because the crash Tesla was traveling on a divided highway at a speed greater than 45 mph and following another vehicle, Autosteer would give the first visual alert to the driver 3 minutes after not detecting driver-applied torque on the steering wheel.

[21] Activating a turn signal, using the cruise control lever to adjust the cruise speed or following distance, or using any steering wheel button or scroll wheel is viewed by Autosteer as driver engagement with the system and resets the counting of the hands-off-wheel timing.

1.6.4 Postcrash Changes to Autopilot

After the Mountain View crash, Tesla made design changes to the Autopilot software. The changes included updates to the vision system, more immediate warnings in Autosteer's hands-off-wheel alert timing, and an Autopilot "Drivable Space" forward collision warning and avoidance system. The changes are summarized in appendix D.

1.7 Tesla Collision Avoidance Systems

The SUV was also equipped with collision avoidance assistance features including those for prevention and mitigation of forward collisions. The FCW system provides visual and audible warnings in situations when the Tesla detects high risk of a frontal collision. The AEB is typically engaged after FCW if a driver does not respond, and automatically applies braking to prevent a frontal collision or reduce its impact. The FCW/AEB system is a radar/camera fusion system designed to detect slow, stopped, and decelerating vehicles ahead of the Tesla in the same lane.[22]

During the 5 seconds leading up to the crash, the Tesla SUV accelerated from about 63 mph to nearly 71 mph at impact. During the approach to the crash attenuator, the FCW system did not provide an alert and the AEB did not activate. FCW and AEB are designed and tested to recognize particular types of objects (vehicles) and warn or brake within a particular speed range.

NHTSA has established test protocols and performance specifications for FCW and AEB as part of the agency's New Car Assessment Program (NCAP).[23] Collision avoidance systems that meet the minimum performance specifications are listed as "Recommended Safety Technologies" on NHTSA's NCAP website, but the agency does not rate the overall effectiveness of these systems. Collision avoidance technologies are not currently part of NCAP's 5-Star Safety Ratings program; only vehicle crashworthiness and rollover safety are.

Testing of various collision avoidance systems is also conducted in other parts of the world. Euro NCAP in Europe uses similar testing scenarios to those of NHTSA's NCAP, but there are critical differences. For example, in addition to vehicle crashworthiness and rollover safety, Euro NCAP's overall safety rating includes the effectiveness of the vehicle's collision avoidance technologies.[24] Furthermore, Euro NCAP's testing of FCW and AEB is conducted at speeds up to 50 mph and includes targets representing not only motor vehicles but also pedestrians and bicyclists. On the other hand, NHTSA's NCAP testing of FCW and AEB is conducted at speeds up to 45 mph and uses only motor vehicle targets.

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[22] The FCW and the AEB remain available at all times and in all domains. Although these systems use some of the same sensors as Autopilot, they are not part of the partial driving automation system, which consists of TACC and Autosteer.

[23] See NHTSA's NCAP website (accessed February 4, 2020). The FCW and AEB systems on the 2017 Tesla Model X met NHTSA's performance criteria, and the vehicle model is listed as having these recommended safety technologies.

[24] See Euro NCAP website (accessed February 4, 2020).

1.8 Tesla Driver Factors

1.8.1 Background

This report focuses only on human performance issues related to the Tesla driver. Interviews with the Mazda and Audi drivers, in addition to other background information, can be found in the public docket.

1.8.1.1 Licensing and Experience. The Tesla driver held a California class C noncommercial driver's license with no restrictions. His record showed no traffic-related violations or prior crashes, and his license had never been suspended, revoked, or denied. The driver resided in Foster City and worked as a software engineer for Apple at a facility in Sunnyvale. He was very familiar with this travel route on US-101 because he drove through the area where the crash occurred several times a week on his way to work.

1.8.1.2 Health and Toxicology. The driver's family, friends, and coworkers told investigators that he was good physical condition. He did not smoke, did not take any prescription medications, and did not have any known health issues. He did see a physician in the weeks before the crash for a cough, but the symptoms had subsided by the time of the crash. The driver exercised regularly and had no current major life stressors. He had had laser vision correction surgery about 3 years before the crash, and his vision was 20/20. His hearing was also reportedly good. A postmortem toxicology test did not detect alcohol or other tested-for drugs in his system.[25]

1.8.1.3 Precrash Activities. The below table lists the Tesla driver's activities from March 21 to March 23. The information is based on interviews with family and coworkers, Apple building entry/exit data, cell phone records, and the Tesla's Carlog data. The driver had about 6.5 to 7.5 hours of sleep opportunity per night in the 3 days leading up to the crash. The driver's wife reported that her husband would usually fall asleep immediately and would not wake up during the night. She said that he snored occasionally but that he had never been diagnosed with a sleep disorder such as obstructive sleep apnea.

Table 2. Precrash activities of Tesla driver, March 21–23, 2018.

Time	Activity	Source
Wednesday, March 21		
7:00 a.m.–7:15 a.m.	Awakens	Family interview
8:51 a.m.	Departs home to transport son to preschool	Carlog data
9:01 a.m.	Arrives at preschool in Foster City	Carlog data
9:07 a.m.	Departs preschool to drive to work	Carlog data

[25] The tested-for drugs included amitriptyline, amobarbital, bupropion, bupropion metabolite, butabarbital, carisoprodol, chlorpheniramine, cocaine, desipramine, dextromethorphan, diazepam, diphenhydramine, doxepin, doxylamine, EDDP (metabolite of methadone), BMDP (benzylone), fluoxetine, glutethimide, ibuprofen, imipramine, ketamine, lidocaine, meperidine, meprobamate, methadone, methaqualone, nordiazepam, norpropoxyphene, nortriptyline, pentazocine, pentobarbital, phencyclidine, phenobarbital, phenytoin, propoxyphene, secobarbital, sertraline, and venlafaxine.

Time	Activity	Source
9:44 a.m.	Arrives at work in Sunnyvale (Apple facility)	Carlog data
11:10 a.m.	Departs work to drive home	Carlog data
11:37 a.m.	Arrives home in Foster City	Carlog data
2:30 p.m.	Hires ride-share vehicle for transport to San Francisco to attend game developer's conference	Family interview
11:00 p.m.–midnight	Work colleague drives him home from conference; goes to bed	Family interview
Thursday, March 22		
7:00 a.m.–7:15 a.m.	Awakens	Family interview
8:54 a.m.	Departs home to transport son to preschool	Carlog data
9:04 a.m.	Arrives at preschool in Foster City	Carlog data
9:09 a.m.	Departs preschool to drive to work	Carlog data
10:07 a.m.	Arrives at work in Sunnyvale	Carlog data
10:12 a.m.	Enters Apple facility	Apple building entry data
5:43 p.m.	Departs Apple facility	Apple building exit data
5:45 p.m.	Departs work to drive home	Carlog data
6:12 p.m.	Arrives home in Foster City	Carlog data
7:07 p.m.	Incoming cell phone call from work supervisor	Cell phone records
7:22 p.m.–10:35 p.m.	Text message exchange with supervisor	Cell phone records
11:30 p.m.–12:30 a.m. (Friday)	Goes to bed	Family interview
Friday, March 23		
7:00 a.m.–7:15 a.m.	Awakens	Family interview
8:45 a.m.	Departs home to transport son to preschool	Carlog data
8:53 a.m.	Arrives at preschool in Foster City	Carlog data
8:59 a.m.	Departs preschool to drive to work	Carlog data
9:27 a.m.	Crash – Mountain View	Carlog data

1.8.2 Cell Phone Usage

1.8.2.1 Cell Phone General Information. The CHP recovered two cell phones at the crash scene. One of them, an Apple iPhone 8 Plus, was found among the debris on the highway and sustained major structural damage. The second phone, an Apple iPhone 10, was undamaged and found among the driver's personal belongings. The CHP inspected the phones and returned them both to the driver's family, who in turn forwarded the phones to Apple Inc. Apple advised that the iPhone 8 Plus was a development fused model used primarily for business purposes. The iPhone 10 was provided to the driver for personal use.

1.8.2.2 Cell Phone Inspection and Data Recovery. The NTSB retrieved unencrypted CrashReporter logs from the Tesla driver's Apple iPhone 8 Plus.[26] Each of the three recovered logs showed that a game application was active during the driver's trip to work and was the frontmost application on his phone when the crash occurred. Although the game (a world-building strategy game with multiplayer capability) appears to require manual manipulation, the log data are not specific enough to ascertain whether the Tesla driver was holding the phone at the time of the crash.

Historical CrashReporter logs recovered from the driver's device show a pattern of active game play every day from Monday, March 19, 2018, to Friday, March 23, 2018, between 9:00 a.m. and 10:00 a.m. when the driver was en route to work.[27] NTSB investigators asked his wife (through the family attorney) whether she was aware that her husband played games on his phone. She responded that her husband loved to do so but that he never did while driving.

1.8.2.3 Cell Phone Records. Cell phone records also showed that the Tesla driver was using the Apple-owned iPhone 8 Plus on the morning of the crash. Although the records showed no incoming or outgoing calls or text messages during his trip to work, they did show evidence of data transmissions while the vehicle was in motion. In the 12 hours preceding the crash, the highest data usage (204 kilobytes [KB] per minute average) was recorded in the 11.5 minutes immediately preceding the crash.[28] This level of data usage is consistent with online game activity. When the phone was not in use during the overnight hours when the Tesla driver was asleep, the average data usage was less than 1 KB/minute.

1.8.2.4 Cell Phone Laws and Policy. California state laws prohibit the holding and operating of a cell phone while driving. California Vehicle Code section 23123.5 (a) reads:

> A person shall not drive a motor vehicle while holding and operating a handheld wireless telephone or an electronic wireless communications device unless the wireless telephone or electronic wireless communications device is specifically designed and configured to allow voice-operated and hands-free operation, and it is used in that manner while driving.

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[26] See the Cell Phone Records and Data Recovery report in the public docket for this crash. The recovered CrashReporter logs are available to cell phone application developers for diagnostic purposes. When an application on a phone crashes, a crash report is created and stored on the device. Users of Apple iPhones can access CrashReporter logs on their device by going to Settings/Privacy/Analytics/Analytics Data.

[27] Logs show that the game application was active on March 19, 2018, at 09:03:21; March 20, 2018, at 09:18:53; March 21, 2018, at 09:37:53; and March 22, 2018, at 09:21:31. Tesla Carlog data show that Autopilot was active during these time periods.

[28] Data activity shown in cell phone records can include the network updating software and phone applications, sending and receiving emails, internet usage, upload and download of photos, streaming of videos, and online game playing. Estimated data usage for a specific phone activity includes: one email (no attachments) – 20 KB, one email (with standard attachments) – 300 KB, 1 minute of "surfing" the web – 250 KB, one song download – 4 megabytes (MB), one photo upload to social media – 5 MB, 1 minute of streaming standard-definition video – 11.7 MB, 1 minute of streaming high-definition video – 41 MB, and 1 minute of online game playing – 200 KB.

Because the Tesla driver was an employee of Apple Inc. and was supplied with Apple cell phones for business and personal use, investigators inquired about company policy regarding cell phone use while driving. Apple advised the NTSB that it did not have any company policy regarding cell phone use while driving.

1.8.3 Warnings for Hands Off Wheel

Tesla Carlog data showed that the crash trip lasted 28 minutes 33 seconds. Autopilot was active more than 75 percent of the time and during the final 18 minutes 55 seconds. According to the data, driver-applied torque to the steering wheel was not detected 34.4 percent of the time that Autopilot was active. Figure 12 depicts the last Autopilot segment, during which the system issued two visual alerts for hands-off driving. Because the system continued not to detect driver-applied torque to the steering wheel, one of these visual alerts progressed to the second alerting stage, with an audible warning.

About 6 seconds before the crash, no driver-applied steering wheel torque was detected by Autosteer.[29] This lack of driver input on the steering wheel continued until the impact with the crash attenuator.

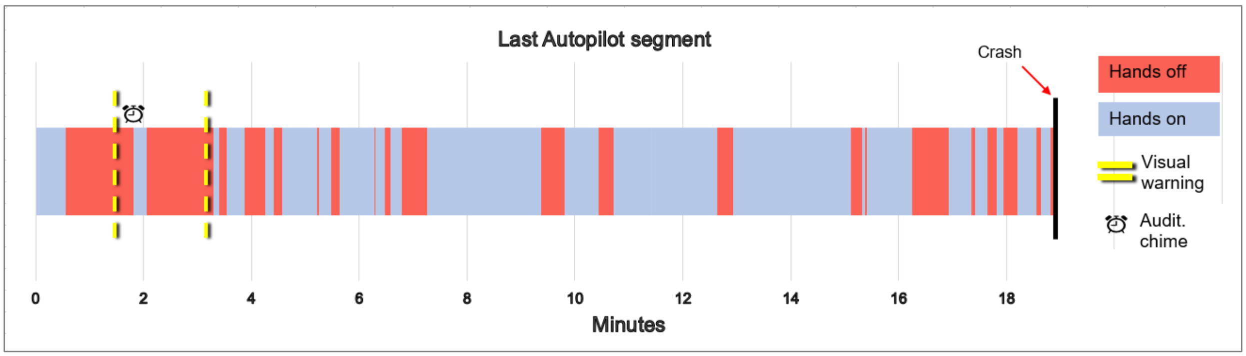

Figure 12. Last Autopilot segment of the crash trip, including warnings for hands-off driving operation.

1.8.4 Vehicle Familiarity and Handling

1.8.4.1 Familiarity with Vehicle. The driver purchased the vehicle in October 2017, and received the vehicle at the Fremont, California, Tesla dealership in November 2017. His family did not recall whether he received any training on the use of the Tesla ADAS features, but his wife remembered him being informed that he needed to keep his hands on the steering wheel while using Autopilot. She told investigators that he became very familiar with the use of the system and would watch YouTube videos related to the Autopilot feature in his spare time. She also stated that the SUV would emit an audible signal if the driver did not have his hands on the steering wheel when in Autopilot mode. The driver belonged to a Facebook group called "Tesla Model X Owner's Club" and would occasionally post about the vehicle's features.

1.8.4.2 Vehicle Handling. Reports reviewed by the NTSB, originating from the driver's family and friends, described issues with the vehicle handling erratically when the driver was traveling in the vicinity of the US-101–SR-85 interchange at the gore area. Investigators interviewed the

[29] The hands-off-wheel detection occurred about the time the SUV entered the gore area.

driver's family and a friend who reported that the driver experienced issues with the Autopilot system steering to the left into the gore area on numerous occasions.[30] One month of Tesla Carlog data was reviewed for the time when the driver was making his morning trip to work. Although GPS information was not available in the Carlog data, the NTSB—using information about the driver's daily patterns and routes—identified two similar incidents that occurred on March 19, 2018, and on February 27, 2018. The data showed that during both incidents, Autosteer induced a steering action to the left, which appeared to be in the vicinity of the gore. The Autosteer action was followed within 2 seconds by a driver-induced steering correction to the right, overriding Autopilot functionality. During these two previous incidents, the driver's hands were detected on the steering wheel.[31]

1.9 Highway Factors

1.9.1 Description and General Characteristics

The crash occurred in the gore area of the US-101–SR-85 interchange, at milepost 48.38, south of the North Shoreline Boulevard overcrossing. The highway is operated and maintained by the California Department of Transportation (Caltrans). US-101 is designated as a north-south roadway, but at the crash location it is aligned in a northwest-southeast direction. As shown earlier in figure 2, the southbound roadway consists of seven traffic lanes. The width of the traffic lanes varies between 11.5 and 12.9 feet.

The speed limit on US-101 in the vicinity of the crash is 65 mph. The average daily traffic for this segment of US-101 is 245,000 vehicles, with a peak hourly total of 17,600 vehicles.[32]

1.9.2 Gore Area

1.9.2.1 Left-Exit Lane and Gore Delineation. Roadway delineation of the left-exit HOV lane for SR-85 southbound begins about 1,540 feet from the crash attenuator, with 8-inch-wide painted broken white lane drop markings designating the left lane as an exit lane. The lane drop markings transition to an 8-inch-wide solid white line 940 feet from the crash attenuator.[33] The apex of the gore area begins about 630 feet from the attenuator where the solid white line bifurcates into two 8-inch-wide white channelizing lines, which form the gore. Before the crash, the gore's neutral (inside) area was not marked with optional diagonal cross-hatching or chevrons.

1.9.2.2 Condition of Roadway Pavement Markings. The lane markings delineating the gore area from the left-exit HOV lane for SR-85 were worn at the time of the crash. On March 27, 2018 (4 days after the crash), NTSB investigators drove through the crash location at about

[30] A friend of the Tesla driver provided the NTSB with a copy of a text message he received on March 19, 2018. The text message(s) from the Tesla driver reported Autopilot "almost led me to hit the median again this morning" at the "85 separation." (Note: the text message was translated from Mandarin Chinese to English.)

[31] The NTSB examined 15 days of Carlog data. Data from March 6 to March 12 were excluded from the review because the vehicle was being serviced at that time. Additionally, investigators looked only at the time period between 9:00 a.m. and 10:00 a.m. on days when the Tesla driver was en route to work. It is possible that other gore area incursions occurred during the month outside the focused review.

[32] The traffic volume information is based on Caltrans 2016 data and reflects total traffic for both directions of travel.

[33] According to the *California Manual on Uniform Traffic Control Devices*, the function of a solid white line is to discourage or prohibit crossing.

9:30 a.m. to approximate the lighting conditions (sun position) that had been present at the time of the collision. As shown in figure 13, the right edge line of the gore was worn and faded in the initial half of the gore. Since the crash, Caltrans has repainted the lane lines at the crash location.

Figure 13. Southbound US-101 view from a video drive-through at 685 feet from crash attenuator. The 8-inch-wide solid white line marking the left side of the gore area (designated with red arrows) was more prominent and visible than the right side of the gore. (Source: NTSB video drive-through, March 27, 2018)

In July 2018, 4 months after the crash, Caltrans added chevron-shaped striping to the neutral area of the gore at the Mountain View crash location (see figure 14). The NTSB asked Tesla whether diagonal cross-hatching or chevron striping would have been effective in preventing the Tesla from entering the gore area. Tesla responded as follows:

> . . . for the firmware installed on the vehicle at the time, gore point striping would not have affected the Autosteer behavior in this crash. In more recent firmware and future firmware, gore point striping may have helped our vision system to discriminate the gore from lanes.

Figure 14. Aerial view of US-101 at the crash location, depicting chevrons (cross-hatching) added to the gore area in July 2018, 4 months after the crash. (Source: Google Earth, image date of August 8, 2018)

1.9.3 Crash Attenuator

1.9.3.1 Background Information. The end of the concrete barrier that separates the left-exit HOV lane (which leads to SR-85) and the HOV lane on US-101 was shielded by a proprietary crash attenuator.[34] The crash attenuator was an SCI Smart Cushion® 100GM crash cushion, manufactured and marketed by Work Area Protection Corporation.[35] The crash attenuator uses a hydraulic cylinder and cable assembly to provide a variable stopping force based on vehicle impact speed.[36] In a frontal impact, the attenuator telescopes rearward to absorb impact energy. Once the crash attenuator has been crushed by an impact, it must be replaced or repaired in order to regain operational status. The crash attenuator is intended to protect motorists by reducing collision forces as it gradually slows a colliding vehicle and helps to absorb the impact energy.

On the day of the crash, the crash attenuator was in a nonoperational, damaged state due to a previous crash that occurred on March 12, 2018. During the March 12 crash, which happened at 10:30 p.m., a 2010 Toyota Prius, operated by a 31-year-old male driver, was southbound on US-101 when it entered the gore area and struck the crash attenuator at a speed in excess of 75 mph. The lap/shoulder-belted Toyota driver survived the crash and was transported to the hospital with injuries.

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[34] In this report, the terms "crash attenuator" and "crash cushion" should be considered synonymous and are used to describe the traffic safety hardware shielding the concrete median barrier on US-101.

[35] See Work Area Protection website (accessed May 28, 2019).

[36] The crash attenuator was tested to the requirements of Test Level 3 found in the American Association of State Highway and Transportation Officials' Manual for Assessing Safety Hardware (MASH).

The CHP responded to the March 12 crash but did not notify Caltrans of the damage to state property as required by policy and interagency operational agreements.[37] On March 20, 2018, two Caltrans maintenance workers patrolling the area discovered that the crash attenuator was damaged. Caltrans inspected the attenuator and determined that it was damaged beyond repair and had to be replaced with a new attenuator. No date was scheduled for the replacement because the Caltrans maintenance supervisor had to locate a replacement attenuator, and maintenance crews were required to be on 12-hour storm patrol shifts due to inclement weather. The maintenance supervisor directed that traffic cones and a Type 1 sawhorse-style plastic barricade be placed in advance of the damaged attenuator until it was replaced. Figure 15 depicts the precrash condition of the attenuator and the location of the displaced barricade and traffic cones.[38]

Figure 15. Southbound US-101 view depicting the precrash damaged condition of the crash attenuator, orange traffic cones, and a displaced Type 1 sawhorse-style barricade on March 22, 2018. (Source: CHP photo provided by passerby)

1.9.3.2 Crash History. Crash and maintenance records show that the attenuator at the crash location was damaged or repaired more frequently than any other left-exit crash attenuator in Caltrans District 4—it had more than double the repairs of any other location.[39] Traffic collision data show that in the 3 years before the fatal March 23, 2018, crash, the attenuator was struck at

[37] For more information, see the CHP/Caltrans Joint Operational Statement and the Caltrans Traffic Incident Management Guidelines in the public docket for this investigation.

[38] Several witnesses provided the CHP and the NTSB with dashcam videos showing the precrash condition of the attenuator and the location of traffic control devices. One video was taken on the morning of March 23, 2018, less than 2 hours before the crash. The image shows the plastic sawhorse barricade lying on the ground immediately north of the attenuator and two orange traffic cones near the white line bordering the left side of the gore, with another cone lying on its side near the end of the concrete barricade.

[39] Between January 2006 and the fatal March 23, 2018, collision, the crash attenuator was damaged at least 12 times. Caltrans District 4 is headquartered in Oakland, California, and provides services to Sonoma, Napa, Solano, Marin, San Francisco, Contra Costa, Alameda, San Mateo, and Santa Clara counties.

least five times, including one collision that resulted in fatal injuries.[40] The crash attenuator at this location was struck again on May 20, 2018, about 2 months after the crash involving the Tesla.

1.9.3.3 Maintenance of Traffic Safety Devices. The NTSB reviewed Caltrans' maintenance procedures and identified systemic problems related to the timely repair of traffic safety hardware. Similar problems were identified during the NTSB investigation of a fatal crash in San Jose, California, that occurred on January 19, 2016, and involved a motorcoach colliding with a crash attenuator on US-101 (NTSB 2017a). Similar to the Mountain View case, the San Jose crash attenuator had been damaged in a previous collision (in this case, 44 days earlier). The NTSB determined that an inadequate work order tracking system contributed to Caltrans' not completing the necessary repairs to the San Jose crash attenuator, and recommended that Caltrans take the following action:

> H-17-4
>
> Modify your work order tracking system to show completion status and to include a means of providing reminders when work orders, particularly those for proprietary devices, are overdue or incomplete.

The status of Safety Recommendation H-17-4 is "Open—Await Response." In meetings with the NTSB, Caltrans has communicated that the agency will officially respond once ongoing litigation pertaining to the San Jose crash permits. In the meantime, Caltrans has developed a dashboard to track overdue service requests and work orders, which is generated and shared daily with maintenance personnel.

In August 2019, the NTSB adopted a safety recommendation report that concluded that the Caltrans maintenance and repair program has been ineffective in ensuring the timely repair of traffic safety hardware (NTSB 2019b). As a result, the NTSB issued the following safety recommendation to the California State Transportation Agency (CalSTA)[41]:

> H-19-13
>
> Develop and implement a corrective action plan that guarantees timely repair of traffic safety hardware and includes performance measures to track state agency compliance with repair timelines.

On December 10, 2019, the secretary of CalSTA updated the NTSB on actions that CalSTA had taken to implement Safety Recommendation H-19-13. First, CalSTA outlined steps that the CHP had taken to enhance reporting of damage to traffic safety hardware. These steps included a revised statewide traffic crash report to include additional data elements to assist with notification procedures, revised CHP policy directives about the reporting of highway conditions, and development of an additional training module for officers regarding appropriate notification

[40] The fatal crash occurred on November 14, 2015, and involved a previously damaged and nonoperational crash attenuator. For additional detail, refer to the Highway Factors factual report in the public docket for this crash investigation.

[41] CalSTA is a cabinet-level state agency that focuses on addressing the state's transportation issues. CalSTA provides oversight of Caltrans, the CHP, the California Transportation Commission, the Office of Traffic Safety, and the Department of Motor Vehicles.

procedures. Caltrans has also taken substantive action to facilitate timely repair of traffic safety hardware. The department will have emergency on-call contractors in place who, within 48 hours of notification, can repair or replace damaged traffic safety hardware when regular maintenance personnel cannot immediately respond. In addition, Caltrans has developed performance measures to monitor overdue service requests and work orders, which will be shared with the maintenance divisions daily. Finally, as a long-term effort, Caltrans is researching deployment-ready technologies that can alert Caltrans directly through electronic notification about impacts to traffic safety devices.

1.10 Weather and Illumination

Data from the weather station at Moffett Federal Airfield in Mountain View, about 1.3 miles north of the crash site, indicate that on March 23, 2018, at 8:56 a.m. (31 minutes before the crash), the weather was clear, the temperature was 49°F, and the wind was from the southeast at 9 mph. According to the US Naval Observatory, at 9:27 a.m. at the crash location, the sun altitude was 26.5 degrees (angle up from the horizon) and the sun azimuth was 110.6 degrees (angle east of true north along the horizon).[42]

Based on the Tesla's headway angle (117 degrees east of north), the sun at the time of the crash was about 6 degrees to the left of the driver's and forward-facing camera's view and 26.5 degrees above the horizon. NTSB investigators completed a drive-through of the crash location several days after the crash to examine the impact of sun position on a driver's view. Investigators determined that although the sun position resulted in minor glare, the lane lines and lines delineating the gore were visible.

1.11 Other NTSB Investigations of Tesla Crashes with Autopilot Activated

Between May 2016 and March 2019, the NTSB investigated three other crashes involving Tesla vehicles with Autopilot activated. This section of the report summarizes those crashes.

1.11.1 Williston, Florida (May 7, 2016)

At 4:36 p.m. on Saturday, May 7, 2016, a 2015 Tesla Model S 70D electric-powered car, traveling east on US Highway 27A (US-27A), west of Williston, Florida, struck a refrigerated semitrailer powered by a 2014 Freightliner Cascadia truck-tractor (NTSB 2017b). At the time of the collision, the truck was making a left turn from westbound US-27A across the two eastbound travel lanes onto NE 140th Court, a local paved road. The car struck the right side of the semitrailer, crossed underneath it, and then went off the right side of the road. The driver, who was the sole occupant of the car, died in the crash; the commercial truck driver was not injured (see figure 16). System performance data downloaded from the car indicated that the driver was operating it using the Autopilot system features TACC and Autosteer.

[42] The altitude and azimuth values are for the center of the apparent disk of the sun.

Figure 16. The 2015 Tesla after striking the side of a semitrailer in Williston, Florida.

The NTSB determined that the probable cause of the Williston crash was the truck driver's failure to yield the right of way to the car, combined with the car driver's inattention due to overreliance on vehicle automation, which resulted in the car driver's lack of reaction to the presence of the truck. Contributing to the car driver's overreliance on the vehicle automation was its operational design, which permitted his prolonged disengagement from the driving task and his use of the automation in ways inconsistent with guidance and warnings from the manufacturer.

1.11.2 Culver City, California (January 22, 2018)

At 8:40 a.m. on Monday, January 22, 2018, a 2014 Tesla Model S P85 electric-powered car was traveling behind another vehicle in the HOV lane of southbound Interstate 405 (I-405) in Culver City, California (NTSB 2019a). Because of a collision in the northbound freeway lanes that happened 25 minutes earlier, a CHP vehicle was parked on the left shoulder of southbound I-405, and a Culver City Fire Department truck was parked diagonally across the southbound HOV lane. The emergency lights were active on both the CHP vehicle and the fire truck. The vehicle ahead of the Tesla changed lanes to the right to go around the fire truck, but the Tesla remained in the HOV lane, accelerated, and struck the rear of the unoccupied fire truck at a recorded speed of 31 mph (see figure 17).[43] The Tesla driver did not report any injuries. System performance data downloaded from the car indicated that the driver was operating it using the Autopilot system features TACC and Autosteer.

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[43] About 0.49 seconds before the crash, the FCW system detected a stationary object in the Tesla's path. A visual and audible warning was provided to the driver; however, the AEB system did not activate.

Figure 17. Overhead view of the 2014 Tesla and fire truck on I-405 in Culver City, California. (Source: CHP)

The NTSB determined that the probable cause of the Culver City crash was the Tesla driver's lack of response to the stationary fire truck in his travel lane, due to inattention and overreliance on the vehicle's ADAS; the Tesla's Autopilot design, which permitted the driver to disengage from the driving task; and the driver's use of the system in ways inconsistent with guidance and warnings from the manufacturer.

1.11.3 Delray Beach, Florida (March 1, 2019)

At 6:17 a.m. on Friday, March 1, 2019, a 2018 Tesla Model 3 electric-powered car was traveling south in the right lane of the 14000 block of US Highway 441 (US-441), also known as State Road 7, in Delray Beach, Palm Beach County, Florida (NTSB 2020). At the same time, a 2019 International truck-tractor in combination with a semitrailer was eastbound in a private driveway belonging to an agricultural facility. The truck driver intended to cross the US-441 southbound lanes and turn left into the northbound lanes. The combination vehicle entered the highway without stopping and was subsequently struck by the southbound Tesla. The car struck the left side of the semitrailer and crossed underneath it, shearing off the roof (see figure 18). The driver, who was the sole occupant of the car, died in the crash; the commercial truck driver was not injured.

Figure 18. The 2018 Tesla after striking the side of a semitrailer in Delray Beach, Florida.

The NTSB determined that the probable cause of the Delray Beach crash was the truck driver's failure to yield the right of way to the car, combined with the car driver's inattention due to overreliance on automation, which resulted in his failure to react to the presence of the truck. Contributing to the crash was the operational design of Tesla's partial automation system, which permitted disengagement by the driver, and the company's failure to limit the use of the system to the conditions for which it was designed. Further contributing to the crash was the failure of NHTSA to develop a method of verifying manufacturers' incorporation of acceptable system safeguards for vehicles with Level 2 automation capabilities that limit the use of automated vehicle control systems to the conditions for which they were designed.

2 Analysis

2.1 Introduction

The Mountain View crash involved a 2017 Tesla Model X P100D electric-powered SUV. The 38-year-old driver, traveling south on US-101, was using the Tesla Autopilot system. As the Tesla approached the paved gore area dividing the main travel lanes of US-101 from the SR-85 left-exit ramp, the SUV steered to the left and entered the gore area. The Tesla continued traveling through the gore area and struck a nonoperational crash attenuator at a speed of about 71 mph. The Tesla was subsequently struck by two other vehicles, a 2010 Mazda 3 and a 2017 Audi A4.[44]

During the collision sequence, the Tesla's high-voltage battery was breached and a postcrash fire ensued. After the crash, on-scene witnesses found the driver in his seat with his lap/shoulder belt buckled. They removed him from the vehicle before it was engulfed in flames. The driver was transported to a local hospital, where he died from blunt-force trauma injuries.

Section 2.2 of the analysis focuses on the safety issues found in the Mountain View crash related to the Tesla Autopilot performance, collision avoidance system performance, driver distraction, and highway infrastructure issues.

Section 2.3 expands the analysis to include a review of three other Tesla crashes in which vehicles were operating with Autopilot activated, as well as an evaluation of partial driving automation systems in the following contexts:

- Risk Mitigation Pertaining to Monitoring Driver Engagement (section 2.3.1),
- Risk Assessment Pertaining to Operational Design Domain (section 2.3.2),
- Limitations of Collision Avoidance Systems (section 2.3.3), and
- Insufficient Federal Oversight of Partial Driving Automation Systems (section 2.3.4).

Section 2.4 discusses the need for event data recorders for driving automation systems.

Following a comprehensive review of the circumstances that led to the Mountain View crash, the NTSB established that the following factors did not contribute to the cause of the crash:

- **Driver licensing, qualification, or familiarization with the vehicle and roadway:** The Tesla driver was properly licensed and familiar with the vehicle driving automation systems. He was also very familiar with the roadway and route of travel at the crash location.
- **Medical conditions, impairment, or fatigue:** The Tesla driver had no known health issues and did not take any medications. A postmortem toxicology test did not detect

[44] The analysis and findings will only address issues related to the Tesla driver and vehicle.

alcohol or other tested-for drugs in his system. He routinely slept between 6.5 and 7.5 hours a night, including the night before the crash.

- **Weather conditions:** The weather was clear with no precipitation at or near the time of the crash, and the roadway was dry.

The NTSB, therefore, concludes that none of the following were factors in the Tesla driver's actions in this crash: (1) driver licensing or qualification; (2) familiarization with the vehicle and roadway; (3) medical conditions, fatigue, or impairment by alcohol or other drugs; or (4) weather conditions.

Fire department, law enforcement, and emergency medical personnel arrived at the crash location within 10 minutes of the collision. Initial fire suppression efforts were successful in extinguishing the flames. However, occasional popping noises were emitted from the Tesla, accompanied by smoke. Due to concerns regarding the high voltage of the Tesla's lithium-ion battery, which was breached during the crash, the fire department incident commander requested Tesla Inc. assistance in helping to make the vehicle safe. About 6 hours after the crash, the vehicle was able to be transported to an impound facility, and the highway was reopened for travel. The NTSB concludes that the emergency response to the crash was timely and adequate. Additionally, the NTSB concludes that the Tesla electric vehicle postcrash fire and related damage to the lithium-ion battery presented unusual fire and electrical hazards to first responders.

2.2 Mountain View Crash Discussion

2.2.1 Crash Sequence

As the Tesla approached the US-101–SR-85 interchange, it was traveling on US-101 in the second lane from the left with the Autopilot system engaged, at a speed of between 64 and 66 mph, and following a sedan at about 83 feet of distance. When the Tesla was 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 of the gore not intended for vehicle travel. The Autopilot system did not detect driver-applied steering wheel torque at the time when the vehicle steered into the gore and did not provide any type of warning (visual, audible, or haptic) that the vehicle was traveling through the gore.

As the SUV closed to within 375 feet of the crash attenuator—3.9 seconds from impact—the Tesla was about centered in the gore area between the left and right 8-inch-wide channelizing lines and the Autopilot system no longer detected a lead vehicle. The TACC began accelerating from a speed of 61.9 mph to the preset cruise speed of 75 mph. The FCW did not provide an alert, the AEB did not activate, and the Tesla struck the nonoperational crash attenuator at a speed of 70.8 mph. The driver did not take evasive action (braking or steering) to prevent the crash or mitigate its severity.

2.2.2 Autopilot Performance

Autopilot navigates roadways by detecting lane markings and predicting the path of the vehicle's travel lane. These predictions are made by the vehicle's imaging system: the cameras and the computing software. Tesla's Autopilot technology package is a combination of systems that control the vehicle speed and path by automated control of braking, steering, and torque to the drive motors. All actions of predicting the lane and actuating steering are determined by the vehicle's vision system. NTSB investigators attempted to determine the exact reason Autosteer directed the SUV into the neutral area of the gore, which was not intended for vehicle travel. As acknowledged by Tesla in published information, including the owner's manual, Autosteer is subject to circumstances that can impair system operation. Autosteer is described as particularly unlikely to operate in situations when unable to accurately determine lane markings, or when bright light is interfering with the cameras' view, visibility is poor, or the windshield area in the cameras' view is obstructed.

The lane markings delineating the gore area from the left-exit HOV lane for SR-85 were worn at the time of the crash, with the right edge line of the gore being worn and faded in the initial half of the gore where Autosteer directed the SUV left. In correspondence, Tesla engineers surmised that the Autosteer system likely momentarily lost its lane line prediction and/or identified a stronger lane line on the left side of the gore. Also, at the time of the crash, bright sunlight was shining toward the Tesla's forward-facing camera at an angle of 6 degrees to the left of the vehicle's center and 26 degrees above the horizon. Although the effect of the bright light on the Tesla vision system cannot be determined with certainty, investigators determined that the sunlight presented no more than discomfort glare to the human eye and the lines delineating the gore were readily visible. Although an exact reason is not known, a steering movement into the gore was associated with the vision system's processing software not accurately predicting the path of the current lane of travel. Therefore, the NTSB concludes that the Tesla's Autopilot lane-keeping assist system steered the SUV to the left into the neutral area of the gore, without providing an alert to the driver, due to limitations of the Tesla Autopilot vision system's processing software to accurately maintain the appropriate lane of travel.

Since the crash, Tesla has changed the vision system processing software with firmware updates designed to improve overall performance. According to Tesla, the revised processing software improves the way the system determines lanes and provides better lane prediction on pitched and curvy roads. In June 2018, Tesla also released firmware version 2018.23, which added an immediate alert for no hands on the steering wheel if unusual lane lines are detected or if no valid lane is detected when no lead vehicle is present. It is unknown whether these software changes would have prevented the Mountain View crash or to what extent the new software would have been able to accurately and consistently detect unusual or worn lane markings.

2.2.3 Collision Avoidance System Performance

The FCW and AEB features in Tesla's collision avoidance system use camera and radar information to provide warnings to the driver and to activate braking to prevent or mitigate an imminent crash if the driver does not respond. The system is designed to recognize and detect slow, stopped, and decelerating vehicles when they are traveling ahead of the Tesla in the same lane. The Tesla Carlog data showed that on the approach to the crash attenuator, the FCW system did not provide an alert and AEB did not activate. Tesla's FCW/AEB, like most manufacturer systems, are designed and tested primarily to detect and provide warnings for some vehicle profiles, not targets such as a crash attenuator. Additionally, current NHTSA testing protocols for FCW and AEB are limited to a maximum speed of 45 mph and use only vehicle profile targets. Therefore, the NTSB concludes that the Tesla's collision avoidance systems were not designed to, and did not, detect the crash attenuator at the end of the gore, nor did NHTSA require such capability; consequently, the FCW system did not provide an alert and the AEB did not activate. Section 2.3.3 further discusses collision avoidance systems in reference to all four Autopilot-related crash investigations.

2.2.4 Driver Distraction

The Tesla was more than 500 feet from the crash attenuator when the SUV first entered the gore area of US-101. When the Tesla was 375 feet from the attenuator the vehicle was centered between the two lines delineating the gore with no vehicles ahead to impede the driver’s view of the approaching hazard. Additionally, forward of the attenuator were two orange traffic cones marking the left side of the gore, and a plastic sawhorse-style barricade was lying on the ground directly in front of the Tesla’s path of travel.

During the final 4 seconds of travel prior to impact, the Tesla accelerated toward the crash attenuator and the driver took no evasive braking or steering action to avoid a collision. This level of inaction, given the numerous visual cues of a hazard ahead and unobstructed view, indicates that the driver was inattentive to his forward view and was not appropriately supervising the Autopilot vehicle control system.

The driver was an avid gamer and game developer who routinely used gaming applications on his cell phone. A review of cell phone records and data retrieved from his Apple iPhone 8 Plus cell phone showed that a game application was active during his trip to work. It was also determined that the game was the frontmost open cell phone application on his phone when the crash occurred and data rate usage was consistent with gaming activity. Although the data could not be used to ascertain whether the driver was holding the phone during the final seconds before the crash, the Carlog data showed that his hands were not detected on the steering wheel and that he made no evasive steering or braking input before the crash.

The driver’s lack of evasive action as the Tesla steered to the left into the gore area and traveled more than 500 feet toward the crash attenuator, combined with data indicating that his hands were not detected on the steering wheel, is consistent with a person distracted by a portable electronic device (PED). Therefore, the NTSB concludes that the driver did not take corrective action when the Tesla’s Autopilot lane-keeping assist system steered the vehicle into the gore area, nor did he take evasive action to avoid the collision with the crash attenuator, most likely due to distraction caused by a cell phone game application.

2.2.4.1 A National Problem. Eliminating distraction in transportation has been an issue on the NTSB Most Wanted List of Transportation Safety Improvements for several years. NHTSA reports that 3,166 people died in crashes involving distracted drivers in 2017; of those, 434 died in crashes where cell phone use was cited as a distraction (NHTSA 2019a).

According to a 2018 National Occupant Protection Use Survey, which provides the only nationwide probability-based observed data on driver electronic device use in the United States, an estimated 9.7 percent of drivers were using some type of phone, either handheld or hands-free, at a typical daylight moment in 2018 (NHTSA 2019b).

Interacting with a game application, similar to texting while driving, can be highly distracting because it involves the three major types of distraction: visual distraction—taking your eyes off the road; manual distraction—taking your hands of the wheel and manipulating a PED;

and cognitive distraction—taking your mind off driving and instead concentrating on game strategy. Research has shown that both the visual–manual distraction of manipulating PEDs (Hickman and others, 2010) and the cognitive distraction of using hands-free PEDs (Strayer and others, 2013) significantly impair driver performance. An analysis of data from a naturalistic study of more than 3,000 drivers showed that the crash risk was more than three times greater when drivers were manipulating a cell phone compared to when they were not distracted (Dingus and others, 2016).[45]

The NTSB has also found cell phone-related distraction to be a recurring safety issue; for example, distraction was the main factor in a March 18, 2018, fatal crash in Tempe, Arizona. That evening, a modified 2017 Volvo SC90 SUV struck and fatally injured a pedestrian crossing the roadway outside a crosswalk. The Advanced Technologies Group of Uber Technologies, Inc. had installed in the SUV a proprietary developmental ADS, which was active at the time of the collision. During the entire crash trip, the driver was streaming a television show on her cell phone. In addition to cell phone-related distraction, lack of adequate mechanisms for addressing operators' automation complacency was one of the contributing factors in the Tempe crash (NTSB 2019c).

Additionally, following the investigation of a fatal multivehicle collision in Gray Summit, Missouri, on August 5, 2010, the NTSB recommended that all 50 states and the District of Columbia address distraction due to PED use while driving (NTSB 2011):

H-11-39

(1) Ban the nonemergency use of portable electronic devices (other than those designed to support the driving task) for all drivers; (2) use the National Highway Traffic Safety Administration model of high visibility enforcement to support these bans; and (3) implement targeted communication campaigns to inform motorists of the new law and enforcement, and to warn them of the dangers associated with the nonemergency use of portable electronic devices while driving.

The NTSB also concluded that manufacturers and providers of PEDs known to be frequently used while driving should reduce the potential of those devices to distract drivers by developing features that discourage their use or that limit their non-driving- or nonemergency-related functionality while a vehicle is in operation. Accordingly, the NTSB recommended that the Cellular Telecommunications Industry Association (CTIA) and the Consumer Electronics Association (CEA) take the following action:

H-11-47

Encourage the development of technology features that disable the functions of portable electronic devices within reach of the driver when a vehicle is in motion; these technology features should include the ability to permit emergency use of the device while the vehicle is in motion and have the capability of identifying occupant seating position so as not to interfere with use of the device by passengers.

[45] The naturalistic driving study, completed by researchers at the Virginia Tech Transportation Institute, found that the overall crash risk when interacting with a handheld cell phone was 3.6 times higher.

Crash statistics for 2013–2017 show that fatal collisions involving cell phone use remain persistently high and have not changed significantly, averaging more than 420 deaths per year (NHTSA 2019a).[46] Although many states have enacted legislation that restricts cell phone use by drivers, no state completely bans all forms of cell phone use while driving. Currently, 15 states prohibit drivers from using handheld cell phones while driving and 48 states, the District of Columbia, Puerto Rico, Guam, and the US Virgin Islands ban text messaging for all drivers (NHTSA 2019b).[47]

California has enacted some of the strongest state laws in the nation banning handheld cell phone use while driving and supports these bans with high-visibility law enforcement campaigns. In April 2019 (the year's National Distracted Driving Awareness Month), the CHP participated in law enforcement efforts across the state to crack down on drivers distracted by PEDs. During the month, the CHP issued 19,850 citations to drivers who violated laws pertaining to hands-free cell phone use (California Office of Traffic Safety [OTS] 2019). This total represented a 3.6-percent increase over a similar campaign in April 2018. In addition, an observational study showed that distracted driving due to PED use among California drivers increased from 3.58 percent in 2017 to 4.52 percent in 2018 (OTS 2018).[48]

Efforts to combat distraction have focused primarily on a combination of education, legislation, and enforcement. Based on statistics showing that PED distraction in fatal crashes has not decreased, it is clear that more needs to be done. Therefore, the NTSB concludes that distracted driving due to PED use remains persistently high, and additional countermeasures are needed.

2.2.4.2 Federal Driver Distraction Guidelines. In 2012, NHTSA proposed a long-term, three-phase approach to combat distracted driving by issuing guidelines to address the distraction potential of in-vehicle equipment and PEDs. Phase 1 of the proposal addressed visual–manual interfaces of devices installed in vehicles as original equipment.[49] Phase 2 focused on guidelines for PEDs and aftermarket devices.[50] The third phase, still in development, will expand the guidelines to include auditory–vocal interfaces. In response to the two sets of guidelines, the NTSB

[46] Safety Recommendation H-11-39 remains in an "Open" status for all state recipients. Refer to the NTSB's safety recommendation database for individual state responses. Safety Recommendation H-11-47 to the CTIA was classified "Closed—Acceptable Action" because the CTIA promotes technological solutions at events and through media campaigns. Safety Recommendation H-11-47 was also issued to the CEA; it responded to the recommendation but did not provide details regarding efforts to develop technologies to mitigate distraction from PEDs. Note: The CEA was renamed the Consumer Technology Association (CTA) in November 2015.

[47] See also https://www.ghsa.org/state-laws/issues/distracted%20driving (accessed February 4, 2020).

[48] The authors of the study emphasize that the value indicates that at any one time, the number of people distracted by an electronic device was 4.52 percent, but the number of people engaging in this behavior across their time on a given trip is likely much higher. A person may have been on a phone or sending a text message 5 minutes before they were observed, and these cases are not included in the distracted driving figures (OTS 2018).

[49] See 77 *Federal Register* 11200 (February 24, 2012), "Visual–Manual NHTSA Driver Distraction Guidelines for In-Vehicle Electronic Devices."

[50] See 81 *Federal Register* 87656 (December 5, 2016), "Visual–Manual NHTSA Driver Distraction Guidelines for Portable and Aftermarket Devices."

expressed concern that NHTSA's Driver Distraction Program underemphasized the role of cognitive distraction.[51]

Phase 1 guidelines permit operating in-vehicle equipment—even for non-safety-related purposes—as long as the driver can complete the tasks with glances away from the roadway of 2 seconds or less and a cumulative time spent glancing away from the roadway of 12 seconds or less.[52] In addition, Phase 1 includes lock-out requirements prohibiting certain activities while driving, including displaying video not related to driving; displaying certain graphical or photographic images; displaying automatically scrolling text; manual text entry for the purpose of text-based messaging or internet browsing; and displaying text for reading from books, publications, text-based messages, or other written content.

Phase 2 guidelines call for the pairing of PEDs with in-vehicle equipment to use the built-in displays and controls. The NTSB expressed concern about pairing personal smartphones, tablets, or music devices with original equipment interfaces unless the pairing supports the driving task (for example, GPS navigation). Encouraging the use of PEDs while driving—as pairing does—sends the wrong message to the driving public and may mislead drivers to believe that the use of devices for non-driving tasks while driving is safe if paired with in-vehicle systems.

For devices that do not pair with in-vehicle equipment, NHTSA Phase 2 proposed guidelines call for PEDs to be equipped with a "Driver Mode" that conforms with the Phase 1 glance and lock-out requirements.[53] NHTSA's preferred option is for automatic (as opposed to manual) activation of a PED's Driver Mode when a vehicle is in motion.[54]

In response to NHTSA Phase 2 guidelines, the CTIA called on NHTSA to withdraw the proposed guidelines and re-establish an approach to distracted driving that concentrates on public outreach and educational efforts.[55] The CTIA also challenged NHTSA's authority to issue regulations, or even voluntary guidelines, for PEDs. The CTA (formerly CEA) also questioned NHTSA's regulatory authority to dictate the design of smartphone applications and other devices used in cars, claiming that NHTSA's legal jurisdiction begins and ends with motor vehicle equipment. The CTA pointed to a January 20, 2017, White House Chief of Staff memorandum calling for the withdrawal or delay of all pending regulations.[56] Since issuing the proposed guidelines in 2017, NHTSA has not taken any substantive action and is still considering whether to issue a final set of visual–manual driver distraction guidelines for PEDs.

The NTSB's response to the federal driver distraction guidelines maintained our firm belief that until PEDs can be designed to have no effect on safe driving—or to improve safe driving—they should be disabled in the driving environment.

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[51] See NTSB public comments to Phase 1 and Phase 2 guidelines in docket nos. NHTSA-2010-0053 and NHTSA-2013-0137.

[52] NHTSA research cited in 77 *Federal Register* 11200 found that glances away from the forward road scene greater than 2 seconds at a time are associated with increased crash risk.

[53] Driver Mode was modeled after the similar feature "Airplane Mode," which, when activated, disables all voice, text, telephone, and other signal-transmitting technologies such as Wi-Fi and Bluetooth.

[54] Driver Mode does not activate when the device is being used by a non-driver (such as a passenger).

[55] See CTIA letter dated February 3, 2017, in Docket No. NHTSA-2013-0137.

[56] See CTA letter dated February 13, 2017, in Docket No. NHTSA-2013-0137.

2.2.4.3 Technological Solutions to Combat Distracted Driving. In 2013, CTA initiated a working group focused on addressing portable and aftermarket electronic devices used by drivers in vehicles.[57] The group had the goal of developing industry-based guidelines for PED design that would address driver distraction. In mid-2014, the working group abandoned its work to develop guidelines due to liability concerns. In March 2014, NHTSA hosted a public meeting to bring together vehicle manufacturers and suppliers, portable and aftermarket device manufacturers, cellular service providers, industry associations, application developers, and consumer groups to discuss technological solutions. Additionally, in 2014, the NTSB and NHTSA participated in "Over-Connected and Behind the Wheel: A Summit on Technological Solutions to Distracted Driving."[58]

Many companies have demonstrated technical solutions for aspects of the distracted driving problem. Cell phone providers have begun offering mobile phone applications that disable texting and block nonemergency calls when a vehicle is in motion, and third-party devices are currently available that allow motorists to voluntarily disable nonemergency calls on their cell phones while driving. The two primary methods of detecting driving to activate the blocking software use either GPS information or information directly from the vehicle's on-board diagnostic port. A field test of cell phone filter/blocking technology showed that participants answered fewer incoming calls when the vehicle was in motion and placed more calls when a vehicle was stopped during the blocking period (NHTSA 2013).

In 2017, Apple Inc. introduced a new feature for iPhones called "Do Not Disturb While Driving." This feature is designed to prevent cell phone owners from receiving messages and calls when driving and lets contacts know they are occupied with driving. This application does not automatically lock the cell phone from use but instead permits numerous options to receive notifications and receive calls from certain contacts. Additionally, the feature can be disabled at any time. After Apple released the application, the Insurance Institute for Highway Safety conducted a nationally representative survey of iPhone owners and found that only about one in five had the feature set to activate automatically while driving (Reagan and others, 2018). Because voluntary activation of cell phone lock-out applications is likely to have limited implementation by drivers, automatic activation of technology shows the most promise in combating driver distraction.

Technological approaches have also been developed to identify which vehicle occupant is using a PED. Most approaches use a combination of hardware and software installed in the vehicle and on the PED to determine whether the device user is a driver or passenger. Device-only solutions often use an authentication task approach, whereby a device automatically enters a limited-use state at a speed threshold, and a quick, but challenging task is required to re-enable its full functionality. These authentication tasks are designed to be quick and easy for non-drivers, but nearly impossible for drivers to complete successfully within the short time limit. In April 2014, Apple was granted a patent for technology that would disable all distracting functions on a driver's phone through a lock-out mechanism.[59] In summarizing the invention, Apple

[57] See 81 *Federal Register* 87656 (December 5, 2016), "Visual–Manual NHTSA Driver Distraction Guidelines for Portable and Aftermarket Devices."

[58] This daylong summit featuring three roundtable discussions was held on February 6, 2014, and hosted by Senator John D. (Jay) Rockefeller, IV, the chairman of the US Senate Committee on Commerce, Science and Transportation.

[59] See US Patent no. 8,706,143 B1 ("Driver Handheld Computing Device Lock-Out"), issued April 22, 2014.

described the lock-out mechanism as having the ability to lock out certain functions, such as texting, while a person is driving. The device features a motion analyzer that can detect whether the PED is in motion and beyond a predetermined threshold level, a scenery analyzer that can determine whether the holder of the PED is located in a safe operating area of a vehicle, and a lock-out mechanism that can disable the PED or one or more of its functions based on information from the motion and scenery analyzers.

Apple's patent describes the challenges of combating distracted driving, stating that "texting while driving has become so widespread it is doubtful that law enforcement will have any significant effect on stopping the practice." The NTSB concludes that a technological solution, such as a lock-out function or application that automatically disables highly distracting features of a PED while driving, is an effective countermeasure for eliminating PED distraction while driving.

Cell phone manufacturers have the technological capability and hold the key to eliminating PED driver distraction.[60] Although it may not be feasible or agreeable by manufacturers to completely lock-out all cell phone features while driving, at a minimum, devices should meet per se lock-out requirements described in NHTSA Phase 1 guidelines, including locking out the display of video; displaying graphical or photographic images; displaying text messages; prohibiting manual text entry for the purpose of text-based messaging or internet browsing; and the displaying of text for reading from books, publications, text-based messages, or other written content. Therefore, the NTSB recommends that manufacturers of PEDs (Apple, Google, HTC, Lenovo, LG, Motorola, Nokia, Samsung, and Sony) develop a distracted driving lock-out mechanism or application for PEDs that will automatically disable any driver-distracting functions when a vehicle is in motion, but that allows the device to be used in an emergency; install the mechanism as a default setting on all new devices and apply it to existing commercially available devices during major software updates. Because this recommendation focuses on action needed by individual cell phone manufacturers, Safety Recommendation H-11-47 to CEA (now CTA) is reclassified from "Open—Await Response" to "Closed—No Longer Applicable."

2.2.4.4 Employers' Role in Combating Distracted Driving. The Tesla driver was an Apple employee and was issued two cell phones by the company; one for business and one for personal use. During his trip to work, the driver was most likely interacting with a gaming application on his business-issued cell phone and thereby likely distracted at the time of the crash. Cell phone records and data obtained from the driver's phone also showed that he was most likely using his Apple-supplied phone to play games while driving in the 4 days prior to the crash. Apple does not have a distracted driving or company policy prohibiting the use of company-supplied phones while driving.

Employers should have a responsibility to protect their employees and others with whom they share the road. The National Safety Council (NSC), the Network of Employers for Traffic Safety (NETS), and others have developed best practices and comprehensive tools. The NSC advocates company cell phone policies that prohibit employees from using handheld and hands-free devices while driving any company vehicle, using any company cell phone device

[60] Percentages of US smartphone sales in the third quarter of 2019 were as follows: Apple (42 percent), Samsung (25 percent), LG (12 percent), Lenovo (8 percent), and all others (13 percent). For more information, see www.counterpointresearch.com/us-market-smartphone-share/.

while driving, or participating in any work-related communications while driving (even if in a personal vehicle or on a personal cell phone; NSC 2015). The NSC has also developed a cell phone policy kit that provides in-depth information for safety-conscious employers on how to successfully implement or strengthen company cell phone policy.

NETS conducts studies that analyze the number of crashes per million miles driven and the percentage of fleet vehicles involved in crashes. Regarding distracted driving, NETS data obtained from a 2018 fleet benchmarking study showed that the most effective fleet safety practices are those that include: (1) a strong cell phone policy; (2) procedures to check if and when the policy is violated; and (3) strong enforcement measures in the event of violations.[61] First, regarding cell phone use policies, banning cell phone use resulted in measurably fewer crashes and a lower percentage of vehicles involved in those crashes. When technological steps were introduced to disable cell phone use under the cell phone bans, the crashes were further reduced considerably.

Second, companies that checked cell phone use records after every crash, not just after serious ones, experienced even fewer crashes and lower percentages than those that checked selectively or not at all.

With regard to the third practice concerning enforcement, companies that enforced strong actions following violations—including the possibility of termination—had considerably fewer and lower percentages of crashes than those that just provided warnings, and much lower than those that took no special action.

Although the Tesla driver was operating his personal vehicle on his way to work, the use of his company-supplied PED may have been prevented if a company policy was in place restricting cell phone use while driving with strict consequences for violating the policy. The NTSB concludes that strong company policy, with strict consequences for using PEDs while driving, is an effective strategy in helping to prevent distracted driving crashes, injuries, and fatalities. Therefore, the NTSB recommends that Apple Inc. develop and implement a company policy that bans the nonemergency use of PEDs while driving by all employees and contractors driving company vehicles, operating company-issued PEDs, or using a PED to engage in work-related communications.

Although many companies across the United States have strong programs in place regarding distracted driving—including prohibition against using PEDs while driving—a large majority still have not implemented this safety measure. The Occupational Safety and Health Administration (OSHA) is the federal agency that sets and enforces standards for employees' health and safety. As part of this mission, OSHA provides training, outreach, education, and assistance to private sector employers and employees. Working with NETS and NHTSA, OSHA published guidelines for employers to reduce motor vehicle crashes.[62] The OSHA guidelines, however, are very broad and do not provide employers with specific guidance regarding how to develop a clear and enforceable policy prohibiting the use of PEDs while driving.

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[61] Refer to NETS correspondence in public docket for this investigation.

[62] https://www.osha.gov/Publications/motor_vehicle_guide.html (accessed 10/1/2019).

From an enforcement standpoint, in the absence of federal distracted driving laws for noncommercial drivers, OSHA has authority to issue citations against employers under its general duty clause for failure to address distracted driving hazards.[63] However, a review of statistics pertaining to OSHA's enforcement of the general duty clause identified only a few cases where the agency used this authority against employers for failing to develop and enforce effective distracted driving policies. The NTSB concludes that although OSHA has guidelines for companies to reduce motor vehicle crashes by prohibiting the use of PEDs while driving, the guidelines lack specificity, are not widely adopted by companies, and are seldom enforced—limiting their impact in addressing the hazards of distracted driving. Therefore, the NTSB recommends that OSHA review and revise its distracted driving initiatives to increase employers' awareness of the need to develop strong cell phone policy prohibiting the use of PEDs while driving. The NTSB further recommends that OSHA modify its enforcement strategies to increase the use of the general duty clause cited in 29 *United States Code* section 654 against those employers who fail to address the hazards of distracted driving.

2.2.4.5 Monitoring Driver Engagement. The Tesla driver was likely distracted for at least 5 seconds, as shown by his lack of evasive action as he traveled through the neutral area of the gore and the vehicle accelerated toward the crash attenuator. Tesla Autopilot assesses the driver's level of engagement by monitoring driver interaction with the steering wheel through changes in steering wheel torque.[64] The system uses the driver's interactions with the steering wheel to determine the driver's degree of engagement with the tasks of monitoring the road environment and supervising the Autopilot system's performance. If the system does not detect signs of driver engagement for relatively long periods of time, an escalating series of visual and audible warnings is presented to the driver.

In examining the Tesla Carlog performance data for this crash, investigators noted that the Autopilot system provided two visual alerts and one auditory warning to the driver to put his hands on the steering wheel earlier in the trip. However, during the final 15 minutes before the crash, the system did not provide any visual or audible alerts warning the driver to put his hands on the steering wheel even though his hands came off the steering wheel on multiple occasions for time periods exceeding 10 seconds. At the time of the crash, the system allowed drivers to have their hands off the steering wheel for up to 3 minutes under certain highway driving conditions.

During the last 60 seconds before the crash, the system did not detect driver-applied steering wheel torque 43 percent of the time and provided no warnings to the driver. The system did not provide a hands-off alert to the driver when the system momentarily lost lane line prediction as the vehicle steered to the left into the gore area.[65] The NTSB concludes that the Tesla

[63] The Occupational Safety and Health Act of 1970 general duty clause (29 *United States Code* section 654 [a][1]) states that "each employer shall furnish each of his employees employment and a place of employment which are free from recognized hazards that are causing or are likely to cause death or serious physical harm to his employees." Penalties for willful violations of the general duty clause can range up to $132,598 per occurrence.

[64] According to Tesla, although the weight of the hands on the steering wheel is often enough to register as driver interaction, on some occasions the system will not register torque if the driver is only lightly touching the steering wheel.

[65] Recommendations to address driver monitoring deficiencies are included in section 2.3.1 of this report.

Autopilot system did not provide an effective means of monitoring the driver's level of engagement with the driving task. For further discussion, see section 2.3.1 of this report.

2.2.5 Highway Infrastructure Issues

2.2.5.1 Roadway Markings. A review of the highway environment in the Mountain View crash investigation revealed faded roadway lane markings in the vicinity of where the Tesla Autopilot lane-keeping assist system steered the SUV to the left into the gore. Additionally, the gore was not marked with optional chevrons to designate the area as an off-limits zone for vehicular travel. Although Tesla Inc. indicated that optional gore point striping would not have improved the Autopilot behavior or prevented the crash, the manufacturer stated that in future firmware updates, gore point and roadway striping may help the vision system discriminate the gore from the travel lanes.

The design of highways—from the type and color of pavement used, to the signage, to the lighting, and the speed limit—is based on extensive human performance research. Automated vehicles, starting at even SAE Level 2 driving automation systems, may require that many of these guidelines be revised in the future. In June 2018, the Federal Highway Administration (FHWA) began a *National Dialogue on Highway Automation* to receive input from stakeholders to prepare FHWA programs and policies to incorporate automation considerations. Additionally, the National Cooperative Highway Research Program (NCHRP), funded by state DOTs, began a major research project titled "Impacts of Connected Vehicles and Automated Vehicles on State and Local Transportation Agencies" (NCHRP 20-102). The project looks specifically at infrastructure design and operations, such as:

- Road Markings for Machine Vision (NCHRP 20-102[06]),
- Implications of Connected and Automated Vehicles (NCHRP 14-42), and
- Infrastructure Modifications to Improve the Operational Domain of Automated Vehicles (NCHRP 20-102[21]).

The NTSB concludes that although the lack of gore area roadway striping at the Mountain View crash location likely did not contribute to the crash, ongoing research led by the FHWA can help identify what highway infrastructure changes may be needed in the future to accommodate automated vehicles.

2.2.5.2 Traffic Safety Hardware. As part of the Mountain View crash investigation, the NTSB issued a safety recommendation report on August 12, 2019, addressing systemic problems related to the timely repair of traffic safety hardware in California (NTSB 2019b). Investigators found that on the day of the crash, the crash attenuator at the US-101–SR-85 interchange was in a nonoperational damaged condition due to a previous crash, which occurred 11 days earlier on March 12, 2018. The CHP had responded to the March 12 crash but did not notify Caltrans of the damage to state property. The damaged condition of the crash attenuator went unnoticed by Caltrans—the entity responsible for replacing it—for 8 days until two Caltrans maintenance workers discovered it. Because of prior scheduled work, required storm patrol shifts due to inclement weather, and the need to locate a replacement, the attenuator was not repaired until March 26, 2018, 3 days after the crash that resulted in the death of the Tesla driver.

In the August 2019 safety recommendation report, the NTSB determined that Caltrans did not have a proactive surveillance and inspection program to identify damaged traffic safety hardware, did not have a risk-based maintenance system that prioritizes repairs based on risk factors, was lacking an accurate work order tracking system that provides feedback to maintenance personnel concerning overdue or incomplete work, and did not have an active on-call contract program that augments maintenance forces when necessary repairs cannot be completed in a timely manner. The NTSB concludes that the crash attenuator was in a damaged and nonoperational condition at the time of the collision due to the CHP's failure to report the damage following a previous crash and systemic problems with Caltrans's maintenance division in repairing traffic safety hardware in a timely manner.

Between August and December 2019, CalSTA coordinated substantive actions in response to Safety Recommendation H-19-13, which are described in section 1.9.3.3 of this report. Because of CalSTA's efforts, the NTSB reclassifies the recommendation from "Open—Initial Response Received" to "Open—Acceptable Response."

2.2.5.3 Crash Survivability. The NTSB evaluated the potential survivability of the crash if the Tesla had collided with an operational crash attenuator rather than the fully compressed damaged attenuator. As part of the analysis, investigators reviewed data from crash testing of an operational SCI Smart Cushion® 100GM crash cushion. Several crash tests were completed at an FHWA-approved test site, using a range of light trucks and cars tested at a nominal impact velocity of 60 mph.[66] The purpose of a crash attenuator is to decelerate a vehicle more gradually, over a longer distance and greater duration of time, thus reducing the crash forces on the occupant. The SCI Smart Cushion® crash tests measured what the manufacturer calls the "ride-down acceleration" of the occupant, which represents the average acceleration of the crash test dummy relative to the deceleration of the vehicle in a collision.[67] The tests, with roughly similar conditions as the Mountain View crash, demonstrated that a functional attenuator increases stopping distance and greatly reduces crash forces. The tests showed no penetration of the occupant compartment or deformation of the vehicle, and the occupant risk values were within survivable limits.

The NTSB also examined the circumstances of the March 12, 2018, crash responsible for damaging the crash attenuator before the Tesla collision. NTSB investigators inspected the crash-involved Toyota Prius and downloaded the airbag control module, which had EDR capability. Data obtained from the EDR showed that the Toyota was traveling in excess of 75 mph when it collided with the crash attenuator. Although the data showed that the driver experienced a longitudinal speed change greater than the Tesla driver experienced, the ride-down time was much longer, resulting in lower collision forces and thus greater survivability.

Based on the NTSB analysis of crash test data and a comparison of the crash data from the Toyota Prius and Tesla collisions, the NTSB concludes that if the crash attenuator at the

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[66] Refer to the Crash Attenuator MASH Eligibility and Crash Test Data report available in the public docket for this crash investigation. The vehicle types ranged from sedans lighter than the Tesla to pickup trucks of about the same mass as the Tesla, and with impact orientations similar to the crash.

[67] Note that as the car is being decelerated in a crash, the occupant is being accelerated in his or her seat and then decelerated by the restraint system. The forces acting on the occupant can be somewhat higher than the forces acting on the vehicle, depending on the effectiveness of the restraint system.

US-101–SR-85 interchange had been repaired in a timely manner and in a functional condition before the March 23, 2018, crash, the Tesla driver most likely would have survived the collision.

2.3 Safety Issues Found in Partial Driving Automation Crashes

This section of the report incorporates lessons learned from multiple NTSB crash investigations involving vehicles operating with SAE Level 2 partial driving automation systems. Between May 2016 and March 2019, the NTSB investigated four crashes involving Tesla vehicles operating with Autopilot activated and identified several areas of concern, including: (1) ineffective driver monitoring to ensure driver engagement; (2) use of Autopilot outside the conditions the system was designed for and intended to be operated in, and (3) limitations of the collision avoidance systems to avoid certain crash scenarios. These areas of concern will be discussed in detail in the following report subsections, which include safety recommendations aimed at reducing crashes involving partial driving automation systems.

2.3.1 Risk Mitigation Pertaining to Monitoring Driver Engagement

2.3.1.1 Tesla Driver Monitoring System. Based on system design, in an SAE-defined Level 2 partial driving automation system, it is the driver's responsibility to monitor the automation, maintain situational awareness of traffic conditions, understand the limitations of the automation, and be available to intervene and take over for the driving automation system at all times. In practice, however, drivers are poor at monitoring automation and do not perform well on tasks requiring passive vigilance (Parasuraman and Riley 1997; Moray and Inagaki 2000; and Parasuraman and Manzey 2010). Research shows that drivers often become disengaged from the driving task for both momentary and prolonged periods during automated phases of driving (Banks and others, 2018).

Driver disengagement from supervising Autopilot's partial automation was a critical factor in the four Tesla crashes the NTSB investigated.[68] In the Mountain View and Culver City crashes, the drivers were found to be distracted and not supervising Autopilot's performance or monitoring the driving environment (detecting and recognizing roadway hazards) leading up to the crash. Likewise, in the Williston and Delray Beach crashes, the drivers were inattentive and did not take any evasive action in response to semitrailer vehicles crossing the paths of their cars. Autopilot assesses a driver's level of engagement by monitoring his or her interaction with the steering wheel through changes in steering wheel torque. However, because driving is a highly visual task, a driver's touch or torque on the steering wheel is an ineffective method to determine whether he or she is fully engaged with the driving task. Simply checking whether the driver has placed a hand on the steering wheel gives little indication of where the driver is focusing his or her attention.

Following the investigation of the Williston crash, the NTSB concluded that the way the Tesla Autopilot system monitored and responded to the driver's interaction with the steering wheel was not an effective method of ensuring driver engagement. As a result, the NTSB

[68] SAE Level 2 features are capable of performing only part of the dynamic driving task (DDT) and thus require a driver to perform the remainder of the DDT, as well as supervise the feature's performance when the system is activated. A driver may disengage from the responsibility of supervising the performance of the automation for a variety of reasons such as inattention, driver distraction, fatigue, alcohol or drug impairment, medical incapacitation, and so on.

recommended that six manufacturers of vehicles equipped with Level 2 driving automation systems take the following action:

> H-17-42
>
> Develop applications to more effectively sense the driver's level of engagement and alert the driver when engagement is lacking while automated vehicle control systems are in use.

Of the six automakers, Tesla was the only company that has not officially responded to Safety Recommendation H-17-42.[69] The NTSB continues to maintain that the operational design of Tesla's automated vehicle control systems requires an attentive driver as an integral system element. Therefore, the NTSB reiterates Safety Recommendation H-17-42 to Tesla and reclassifies the recommendation from "Open—Await Response" to "Open—Unacceptable Response."

2.3.1.2 Development of Standards for Driver Monitoring Systems. SAE Level 2 partial automation systems require that the driver monitor the highway and remain able to take control of the vehicle at any time. The success of a Level 2 system depends on a driver completing a monitoring task that requires sustained attention; however, humans generally perform poorly in the role of monitors. Additionally, if a system behaves in a consistent and reliable manner for prolonged periods, the user of that system can become complacent in its operation and may not respond appropriately when required (Parasuraman, Molloy, and Singh, 1993; Lee and See, 2004; Hollnagel and Woods, 2005).

Because driver attention is an integral component of partial automation systems, a driver monitoring system must be able to assess whether and to what degree the driver is performing the role of supervisor of the automation. As seen in the four recent NTSB Tesla Autopilot crash investigations, drivers were able to disengage for prolonged periods of time. The type and timing of alerts are vital components of an effective monitoring system (NHTSA 2018). Studies have been performed to examine the most effective alerting approaches to maintain a driver's attention. A NHTSA study found that a 2-second prompt of disengagement compared to a 7-second prompt increased the driver's level of attentiveness. Additionally, it was found that bi-modal alerts (that is, visual and auditory, visual and haptic) were more effective than unimodal alerts at getting drivers to regain control of the vehicle when an unexpected lane change occurred (NHTSA 2015).

In the United States, no standards or regulations for driver monitoring system design are currently in place, and the type and timing of alerts varies widely among manufacturers. Most manufacturers' owner's manuals state that the automated systems "require" hands-on-wheel operation. At the same time, active warnings provided by manufacturers, like Tesla, may not occur until more than 3 minutes of hands off the wheel have passed. Following the Williston and Mountain View crashes, Tesla released firmware updates that changed the alert timing to include more immediate alerts when driver-applied steering wheel torque is not detected. As of the publication of this report, the timing of visual alerts varies based on vehicle speed of travel (see figure D-1 in appendix D). For example, at a speed of 25 mph, if the system does not detect

[69] The recipients of Safety Recommendation H-17-42 were BMW of North America, Mercedes-Benz USA, Nissan Group of North America, Tesla Inc., Volkswagen Group of America, and Volvo Car USA. During current investigations, Tesla provided information on its alert timings and other Autopilot system changes that the automaker reported were associated with improving driver engagement. These changes are documented in this report.

driver-applied steering wheel torque for 60 seconds, a visual alert will be provided. Even at 90 mph, it would take 10 seconds for the system to provide an alert, during which time the vehicle would have traveled a quarter of a mile.

Although the alert timing is more immediate than previous Autopilot firmware versions, it is still likely inadequate to prevent most crashes, which occur in a matter of seconds (as seen in the Mountain View, Culver City, and Delray Beach collisions).[70] For example, during NHTSA's evaluation of crash events, the agency's Office of Defects Investigation (ODI) found that most crash events develop in a short time frame and usually provide less than 3 seconds for a driver to detect, observe, and react to a pending collision (NHTSA 2017). Any amount of hands-off-wheel steering time (which is currently the surrogate measure of driver engagement that many manufacturers use) is a safety risk because just a few seconds of inattention has been shown to cause most crashes.

The timing of hands-off-wheel warning intervals has been addressed in Europe by the United Nations Economic Commission for Europe (UNECE) (Mousel 2018). UNECE regulations require that drivers who misuse lane-keeping assist systems by going "hands off" must be warned by an optical signal (visual warning) after 15 seconds at the latest (see figure 19). Then, after 30 seconds, parts of the optical signal must turn red and an acoustic alert must be triggered. After 30 seconds of acoustic warning, an emergency signal of at least 5 seconds must sound a final warning.[71]

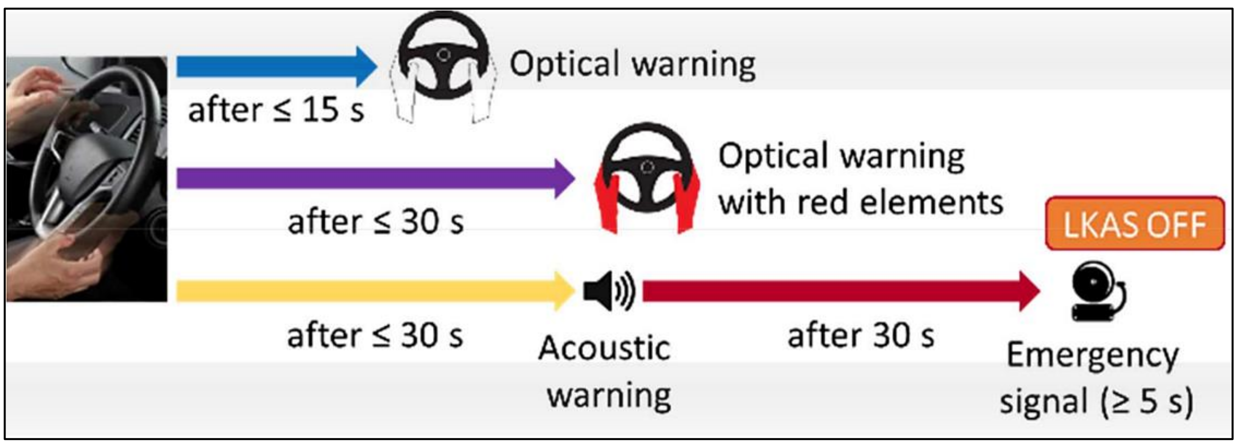

Figure 19. UNECE escalating timing of alerts for hands off wheel. ("LKAS" in the image means "lane-keeping assist system.") (Source: Mousel 2018)

A monitoring system needs to assess whether and to what degree drivers are performing their specified role. SAE J3016 states that monitoring is most frequently deployed as a countermeasure for misuse or abuse, including overreliance due to complacency; however, SAE J3016 is silent on what constitutes effective driver monitoring. Currently, no performance standards exist for the appropriate timing of alerts, the type of alert (visual, auditory, haptic), or

[70] The critical events leading to these four crashes developed in less than 10 seconds. In the Mountain View crash, the Tesla Autopilot lane-keeping assist system steered the SUV to the left into the gore area less than 6 seconds before the collision with the crash attenuator.

[71] Tesla advised the NTSB that Tesla vehicles operating in Europe are designed to meet the timing of alerts criteria set in UNECE regulations.

the use of redundant monitoring sensors to ensure driver engagement.[72] Therefore, the NTSB concludes that because monitoring of driver-applied steering wheel torque is an ineffective surrogate measure of driver engagement, performance standards should be developed pertaining to an effective method of ensuring driver engagement in SAE Level 2 partial driving automation systems. Therefore, the NTSB recommends that NHTSA, for vehicles equipped with Level 2 automation, work with SAE International to develop performance standards for driver monitoring systems that will minimize driver disengagement, prevent automation complacency, and account for foreseeable misuse of the automation. The NTSB issues a corresponding recommendation to SAE International to work with NHTSA. The NTSB further recommends that NHTSA, after developing the performance standards for driver monitoring systems recommended in Safety Recommendation H-20-3 (above), require that all new passenger vehicles with Level 2 automation be equipped with a driver monitoring system that meets these standards.

2.3.2 Risk Assessment Pertaining to Operational Design Domain

SAE J3016 discusses the need for manufacturers to accurately describe ADAS features and clearly define the level of driving automation and its capabilities, but also its operational design domain (ODD)—the conditions in which the driving automation system is intended to operate.[73] Examples of such conditions include roadway type, geographic location, clear roadway markings, weather conditions, speed range, lighting conditions, and other manufacturer-defined system performance criteria or constraints. As shown in appendix C and summarized below, Tesla has outlined many operating conditions and limitations based on the Autopilot system design:

- Designed for use on highways with a center divider,
- Designed for areas with no cross-traffic and clear lane markings,
- Not for use on city streets or where traffic conditions are constantly changing,
- Not for use on winding roads with sharp curves, and
- Not for use in inclement weather conditions with poor visibility.

Despite communicating these operating conditions and limitations to owners and drivers, Tesla Autopilot firmware does not restrict the system's use based on functional road classification. The system can essentially be used on any roads where it can detect lane markings, which allows drivers to activate driving automation systems at locations and under circumstances for which their use is not appropriate or safe, such as on roadways with cross traffic or in areas that do not consistently meet the ODD, such as roadways with inconsistent lane markings. The Mountain View crash occurred in a challenging multi-lane operational environment with exit ramps on both sides of the highway and faded roadway lane markings. To characterize and evaluate the

[72] Some manufacturers have developed different approaches to monitor system performance, such as the use of eye-tracking cameras. The Driver Attention System in the 2018 Cadillac CT6 Super Cruise partial driving automation system uses a small camera located at the top of the steering column; the camera focuses exclusively on the driver and uses infrared light to track the driver's head position.

[73] The ODD discussion applies to the Autopilot partial driving automation system. Although the collision avoidance systems FCW and AEB use some of the same sensors (cameras and radar) as Autopilot, FCW and AEB are designed for, and meant to work in, all domains.

performance of Level 2 systems on public highways and in naturalistic environments, the American Automobile Association (AAA) conducted testing, which found that Level 2 systems performed best on open freeways but were challenged on freeways with moderate traffic and in areas of transitions (AAA 2018).[74] Most Level 2 systems were incapable of staying in their lane on curved portions of freeways, including in freeway transition areas.

SAE J3016 considers the ODD for Level 2 systems to be limited (see table 1). Today's Level 2 systems can assess a vehicle's location and the current roadway type/classification and determine whether the roadway is appropriate for the system's ODD. Despite this capability, Tesla has chosen to permit operation of Autopilot under conditions that do not meet its ODD. Tesla has informed the NTSB that its "operational design domain limits are not applicable for Level 2 driver assist systems, such as Autopilot, because the driver determines the acceptable operating environment." Moreover, Tesla has advised the NTSB that "Autopilot can be safely used on divided and undivided roads as long as the driver remains attentive and ready to take control."

The Williston, Florida, crash involved a 2015 Tesla Model S that collided with a tractor trailer combination crossing an uncontrolled intersection on a nonlimited-access highway.[75] Partial automated vehicle operation on nonlimited-access highways presents challenges in detecting cross-path intrusions, pedestrian and bicycle traffic, and signage at intersections. Additionally, cross-path collisions are challenging for collision avoidance systems. The NTSB concluded in the investigation of the Williston crash that if automated vehicle control systems do not automatically restrict their own operation to those conditions for which they were designed and are appropriate, the risk of driver misuse remains. The NTSB recommended that Tesla and other manufacturers of Level 2 automation take the following action:

H-17-41

Incorporate system safeguards that limit the use of automated vehicle control systems to those conditions for which they were designed.

Five automobile manufacturers responded to this recommendation with steps they were taking to address the issue. Tesla, however, has not responded. As mentioned previously, Tesla has stated that it does not believe ODD limits are applicable to the Autopilot system as long as the driver remains attentive. During the Mountain View investigation, Tesla was queried regarding plans to implement ODD restrictions and indicated that the driver was solely responsible for choosing when to use the SAE Level 2 system. However, Tesla vehicles continue to be involved in crashes where Autopilot is activated and operating outside the intended geographic ODD. In March 2019, in Delray Beach, Florida, a fatal crash involving a 2018 Tesla Model 3 occurred under circumstances very similar to the Williston crash. In the Delray Beach crash, a truck-tractor in combination with a semitrailer was traveling eastbound in a private driveway belonging to an agricultural facility on the west side of US-441. The combination vehicle entered the highway without stopping and was subsequently struck by the southbound Tesla. At the time of the crash,

[74] Vehicles tested included the 2018 Mercedes-Benz S-Class with Active Distance and Steering Assist, the 2018 Nissan Rogue with ProPILOT Assist, the 2017 Tesla Model S with Autopilot, and the 2019 Volvo XC40 with Pilot Assist.

[75] Access control is a key factor in the functional classification of roads. All interstates are "limited-access" roadways, providing no access to abutting land users. Travelers use high-speed entrance and exit ramps to access limited-access roadways (Federal Highway Administration 2013, p. 14).

the Autopilot system was active, and the Tesla was traveling at 68 mph in a 55-mph posted speed limit area. The Autopilot system and collision avoidance systems did not classify the crossing truck as a hazard, did not attempt to slow the vehicle, and did not provide a warning to the driver of the approaching crossing truck. Further, the driver did not take evasive action in response to the crossing truck. At the crash location, the highway was not limited-access and had more than 34 roadways and private driveways intersecting US-441 within the immediate 5-mile area.

The Delray Beach highway operating environment, like the cross-traffic conditions in Williston, was clearly outside the Tesla Autopilot system's ODD. Tesla, however, fails to provide system safeguards to limit the use of Autopilot for the operating conditions for which it was designed. By placing full reliance on the success of its partial automation system on the premise that drivers will be attentive at all times and will be sufficiently knowledgeable to make proper decisions regarding where to operate the system, Tesla has created a system designed to fail because of the foreseeable misuse of the system. The NTSB concludes that if Tesla Inc. does not incorporate system safeguards that limit the use of the Autopilot system to those conditions for which it was designed, continued use of the system beyond its ODD is foreseeable and the risk for future crashes will remain. Therefore, the NTSB reiterates Safety Recommendation H-17-41 to Tesla and reclassifies the recommendation from "Open—Await Response" to "Open—Unacceptable Response."

Without more rigorous standards or guidelines to manufacturers regarding Level 2 emerging automation technology, safeguards will be insufficient to prevent use of Level 2 systems in nondesigned ways. After the Williston crash, the NTSB recommended that NHTSA address this vital safety concern, as follows:

> <u>H-17-38</u>
>
> Develop a method to verify that manufacturers of vehicles equipped with Level 2 vehicle automation systems incorporate system safeguards that limit the use of automated vehicle control systems to those conditions for which they were designed.
>
> In response to Safety Recommendation H-17-38, NHTSA stated the following:
>
> The agency has no current plans to develop a specific method to verify manufacturers of vehicles equipped with Level 2 systems incorporate safeguards limiting the use of automated vehicle control systems to those conditions for which they were designed. Instead, if NHTSA identifies a safety-related defect trend in design or performance of a system, or identifies through its research or otherwise, any incidents in which a system did not perform as designed, it would exercise its authority as appropriate.

In August 2018, the NTSB reclassified Safety Recommendation H-17-38 "Open—Unacceptable Response." If NHTSA had been proactive in response to the recommendation after the Williston crash and verified that manufacturers such as Tesla incorporate ODD safeguards into their systems, the fatal Delray Beach crash might have been prevented. Therefore, the NTSB concludes that NHTSA's failure to ensure that vehicle manufacturers of SAE Level 2 driving automation systems are incorporating appropriate system safeguards to limit operation of these systems to the ODD compromises safety. The NTSB believes NHTSA should reevaluate its position on the importance of verifying that manufacturers incorporate ODD safeguards into their systems, and therefore reiterates Safety Recommendation H-17-38.

2.3.3 Limitations of Collision Avoidance Systems

The four Tesla crashes that the NTSB investigated highlight the limitations of the collision avoidance systems FCW and AEB when vehicles equipped with the technology are traveling at high speed or are faced with vehicle shapes or objects that the system has not been designed to detect. In the Williston, Delray Beach, and Mountain View crashes, the involved vehicles were traveling at speeds in excess of 65 mph. In each crash, the FCW and AEB did not provide a warning and the AEB system did not activate the brakes because the systems are not designed or tested to operate consistently at speeds over 50 mph. Additionally, in each of the four crashes, the Tesla was faced with an object (fire truck, crash attenuator, or side of semitrailer) different from the type of vehicle targets that the system was designed to detect during testing. Yet, these types of objects are common on our roadways.

The NTSB previously addressed FCW and AEB testing and assessment protocols in a special investigation report (NTSB 2015). The report concluded that NHTSA's existing testing scenarios and protocols for the assessment of collision avoidance systems in passenger vehicles do not adequately represent the wide range of velocity conditions seen in crashes, particularly high-speed crashes. Because of this deficiency, the NTSB recommended that NHTSA take the following action:

> H-15-4
>
> Develop and apply testing protocols to assess the performance of forward collision avoidance systems in passenger vehicles at various velocities, including high speed and high velocity-differential.

Since receiving the recommendation, NHTSA has taken no action toward gaining a better understanding of how these lifesaving technologies perform in real-world high-speed crash scenarios. Therefore, in June 2016, the NTSB classified the recommendation "Open—Unacceptable Response." In this report of the Mountain View crash, the NTSB reiterates Safety Recommendation H-15-4 to NHTSA.

Because most manufacturers have designed SAE Level 2 driving automation systems to operate on high-speed, limited-access, divided highways such as interstate freeways, it is important that when the automation or the driver makes an error, that collision avoidance systems act as an additional layer of safety. The NTSB concludes that in order for driving automation systems to be safely deployed in a high-speed operating environment, collision avoidance systems must be able to effectively detect and respond to potential hazards, including roadside traffic safety hardware, and be able to execute forward collision avoidance at high speeds. Therefore, the NTSB recommends that NHTSA expand NCAP testing of forward collision avoidance system performance to include common obstacles, such as traffic safety hardware, cross-traffic vehicle profiles, and other applicable vehicle shapes or objects found in the highway operating environment.

2.3.4 Insufficient Federal Oversight of Partial Driving Automation Systems

2.3.4.1 Nonregulatory Approach. The US Department of Transportation (DOT) and NHTSA have taken a nonregulatory approach to automated vehicle safety as described in policy and in response to NTSB recommendations. The DOT has emphasized that "the right approach to achieving safety improvement begins with a focus on removing unnecessary barriers and issuing voluntary guidance, rather than regulations that could stifle innovation" (DOT 2018). Although the DOT has described how it will address increasing levels of automation (Levels 3–5), few if any vehicle performance regulations or guidelines have been explicitly provided for Level 2 systems in the United States. NHTSA has informed the NTSB that it plans to ensure the safety of Level 2 systems through its enforcement authority and surveillance program aimed at identifying safety-related defect trends in design or performance. The NTSB concludes that NHTSA's approach to the oversight of automated vehicles is misguided, because it essentially relies on waiting for problems to occur rather than addressing safety issues proactively.[76] Additionally, for an acceptable level of safety to be achieved, a robust surveillance program must be present so that vehicle safety-related defects can be identified in a timely manner.

2.3.4.2 NHTSA Enforcement of Automated Vehicle Safety-Related Defects. The National Traffic and Motor Vehicle Safety Act provides the basis and framework for NHTSA's enforcement authority over motor vehicle equipment defects. NHTSA is charged with reducing deaths, injuries, and economic losses from motor vehicle crashes.[77] Part of that mandate includes ensuring that motor vehicles and motor vehicle equipment, including automated vehicle safety technologies, perform in ways that "protect the public against unreasonable risk of accidents occurring because of design, construction, or performance of a motor vehicle, and against unreasonable risk of death or injury in an accident."[78]

The NHTSA enforcement guidance states that when an automated safety technology causes crashes or injuries, or poses other safety risks, the agency will evaluate such technology through its investigative authority to determine whether the technology presents an unreasonable risk to safety.[79] The guidance also states that manufacturers should take steps necessary to ensure that technology introduced on US roadways accounts for any foreseeable misuse that may occur, particularly in circumstances that require driver interaction while a vehicle is in operation.[80]

Included in the enforcement guidance is information directly relevant to the Mountain View crash and other recent Tesla crashes investigated by the NTSB. NHTSA states that "a semi-autonomous driving system that allows a driver to relinquish control of the vehicle while it is in operation but fails to adequately account for reasonably foreseeable situations where a

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[76] Refer to the testimony of NTSB Chairman Robert L. Sumwalt, III, before the US Senate Committee on Commerce, Science and Transportation on November 20, 2019, titled "Highly Automated Vehicles: Federal Perspectives on the Deployment of Safety Technology."

[77] See 49 *United States Code* section 30101.

[78] See 49 *United States Code* 30102(a)(8).

[79] NHTSA Enforcement Guidance Bulletin 2016-02; "Safety-Related Defects and Automated Safety Technologies," 81 *Federal Register* 65705.

[80] NHTSA has defined misuse as an operator, when having knowledge and understanding of the system's limitations and operational use instructions, deliberately chooses not to act according to the intent and design of the automated component. When a driver, having full knowledge of the responsibility to supervise and monitor the roadway, engages in a secondary task that may disrupt or eliminate the capability to effectively perform monitoring duties, such disengagement can qualify as misuse.

distracted or inattentive driver must retake control of the vehicle at any point may also be an unreasonable risk to safety."

In determining whether a vehicle design poses an "unreasonable risk" to safety, NHTSA is charged with answering the question through a forward-looking risk analysis. According to the enforcement guidance, the forward-looking risk analysis "is not to protect individuals from the risks associated with defective vehicles only after serious injuries have already occurred; it is to prevent serious injuries stemming from established defects *before* they occur."

Because NHTSA has determined that oversight of Level 2 driving automation systems will be based primarily on tracking safety-related trends and enforcement authority, the NTSB concludes that it is essential that NHTSA's surveillance and defect investigation program closely examine issues related to foreseeable misuse of automation and perform a forward-looking risk analysis to identify partial driving automation system defects that pose an unreasonable risk to safety.

On June 28, 2016, NHTSA's ODI opened a preliminary investigation to examine the design and performance of Tesla's driving automation systems in use at the time of the Williston crash.[81] The investigation did not identify any defects but added that NHTSA intended to monitor the issues and reserved the right to take further action if circumstances warranted. An NTSB review of the ODI investigation report identified shortfalls in the agency's evaluation of the Tesla Autopilot design. Deficiencies in the investigation include the following:

- ODI described the Tesla hands-on steering wheel system for monitoring driver engagement but did not evaluate the effectiveness of the user monitoring system (type and timing of alerts) in maintaining driver engagement.[82]

- ODI examined steps taken by Tesla in the design process to safeguard against driver misuse but did not evaluate the degree to which drivers are currently misusing the Autopilot system.[83]

- ODI described the Autopilot ODD as highways with a center divider and clear lane markings but did not complete a forward-looking risk analysis to assess the ramifications of continued operation outside the ODD.[84]

Additionally, NHTSA identified numerous limitations of the Tesla Autopilot system but did not evaluate foreseeable consequences of drivers' continued use beyond the system's ODD. Therefore, the NTSB concludes that NHTSA's ODI has failed to thoroughly investigate the Tesla Autopilot design regarding the degree to which drivers are currently misusing the system, the

[81] NHTSA ODI investigation PE 16-007 (Automated vehicle control systems) closed January 19, 2017.

[82] The ODI investigation stated that "driver misuse in the context of semi-autonomous vehicles is an emerging issue and the agency intends to continue its evaluation and monitoring of this topic, including best practices for handling driver misuse as well as driver education."

[83] A review of Tesla historical Carlog data could inform NHTSA of the prevalence of driver misuse of the Autopilot system and address the foreseeability of future misuse needed by investigators to make a defect determination.

[84] ODI reported that the Autopilot system does not prevent operation on any road types. ODI also described that the crash avoidance systems (FCW/AEB) were not designed to detect and brake for cross-traffic and that certain vehicle shapes or objects may delay or prevent the system from classifying various threats. ODI did not complete a review of historical Tesla Carlog data to determine the propensity of drivers to operate outside the ODD.

foreseeable consequences of continued use by drivers beyond the system's ODD, and the effectiveness of the driver monitoring system in ensuring driver engagement. Following the closure of NHTSA's ODI investigation PE-16-007 in January 2017, the agency stated that it would monitor Autopilot's functionality and reserved the right to take further action if circumstances warranted it. During the past 3 years, numerous crashes, injuries, and fatalities have occurred involving Tesla vehicles operating with Autopilot activated.[85] In addition, Tesla has collected a large data set that can be accessed to answer important questions related to how and where Autopilot is being used and the foreseeability of driver misuse.[86] Therefore, the NTSB recommends that NHTSA evaluate Tesla Autopilot-equipped vehicles to determine if the system's operating limitations, the foreseeability of driver misuse, and the ability to operate the vehicles outside the intended ODD pose an unreasonable risk to safety; if safety defects are identified, use applicable enforcement authority to ensure that Tesla Inc. takes corrective action.

2.4 Need for Event Data Recorders for Driving Automation Systems

Title 49 *Code of Federal Regulations* (*CFR*) Part 563 sets forth requirements for data elements, data capture and format, data retrieval, and data crash survivability for EDRs installed in light vehicles manufactured on or after September 1, 2012.[87] The regulation did not mandate installation of EDRs in light vehicles; rather, if the vehicle manufacturer chooses to install an EDR, the regulation defines the format and specifies the requirements for providing commercially available tools and/or the methods for retrieving EDR data in the event of a crash.

On December 13, 2012, NHTSA issued a notice of proposed rulemaking (NPRM) that proposed a new federal motor vehicle safety standard mandating that EDRs meeting 49 *CFR* Part 563 requirements be installed on most light vehicles. On February 8, 2019, NHTSA withdrew the proposed rulemaking because the agency determined that a mandate was not necessary. NHTSA's internal analysis showed that for model year 2017, 99.6 percent of new light vehicles sold were equipped with EDRs that met Part 563 requirements. NHTSA added that given the near-universal installation of EDRs in light vehicles, NHTSA no longer believed that the safety benefits of mandating EDRs justified the expenditure of limited agency resources.

In the withdrawal of the final rule, NHTSA advised that it would continue its efforts to modernize and improve EDR regulations, including fulfilling the agency's statutory mandate to promulgate regulations establishing an appropriate recording duration for EDR data to "provide accident investigators with vehicle-related information pertinent to crashes involving such motor vehicles."[88] Because the data recording requirements codified in 49 *CFR* Part 563 more than a decade ago are very limited, requiring the reporting of only 15 data elements, NHTSA advised

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[85] For example, NHTSA's Special Crash Investigations program has initiated 14 investigations into Tesla crashes with Autopilot activated.

[86] The NTSB requested that Tesla provide any studies, analyses, or reviews that examine driver habits when Autopilot was active. Tesla's legal counsel replied, "we don't have any data analysis on user habits. We form our viewpoints based on review of engineering experience, customer complaints, feedback, social media, service visits, and incident review, but this is subjective and anecdotal and not analytical as you describe."

[87] The EDR requirements apply to "light vehicles" required to have frontal airbags – those with a gross vehicle weight rating of 3,855 kilograms (8,500 pounds) or less and an unloaded vehicle weight of 2,495 kilograms (5,500 pounds) or less.

[88] See the Fixing America's Surface Transportation Act, Public Law 114-94 (December 4, 2015) section 24303.

that it is actively investigating whether the agency should revise the data elements to account for advanced safety features.

In the Mountain View, Culver City, and Delray Beach Tesla crashes, NTSB investigators were able to retrieve data from the RCM EDR, but the data did not address ADAS activation or engagement. As a result, the NTSB used Carlog data to interpret ADAS functionality, but this type of data is not available on many vehicles currently operating with these systems. Further, no commercially available tools are currently able to retrieve and review any non-EDR vehicle recorded data, and other manufacturers of vehicles with driving automation systems similarly control access to the postcrash proprietary information associated with their vehicles. The NTSB concludes that vehicle performance data associated with activation and engagement of SAE Level 2 partial driving automation systems on vehicles involved in crashes are not required nor available on most EDRs.

As more manufacturers deploy driving automation systems on their vehicles, to improve system safety, it will be necessary to develop detailed information about how the active safety systems performed during, and how drivers responded to, a crash sequence. Manufacturers, regulators, and crash investigators all need specific data in the event of a system malfunction or crash. Recorded data can be used to improve the automated systems and to understand situations that may not have been considered in the original designs. Investigators need event data to conduct effective and productive investigations involving vehicles using automated vehicle control systems. Further, data are needed to distinguish between automated control actions and driver control actions. Therefore, the NTSB concludes that a standardized set of retrievable data is needed to enable independent assessment of automated vehicle safety and to foster automation safety improvements.

Following the Williston fatal crash, on September 28, 2017, the NTSB made a recommendation to the US DOT regarding the need to define data parameters necessary to understand automated vehicle control systems, and made two recommendations to NHTSA to define a standard reporting format and to require manufacturers of vehicles equipped with driving automation systems to report incidents, crashes, and vehicle miles operated with the systems enabled:

To the US DOT:

H-17-37

Define the data parameters needed to understand the automated vehicle control systems involved in a crash. The parameters must reflect the vehicle’s control status and the frequency and duration of control actions to adequately characterize driver and vehicle performance before and during a crash.

To NHTSA:

H-17-39

Use the data parameters defined by the U.S. Department of Transportation in response to Safety Recommendation H-17-37 as a benchmark for new vehicles equipped with automated vehicle control systems so that they capture data that

> reflect the vehicle's control status and the frequency and duration of control actions needed to adequately characterize driver and vehicle performance before and during a crash; the captured data should be readily available to, at a minimum, National Transportation Safety Board investigators and National Highway Traffic Safety Administration regulators.
>
> H-17-40
>
> Define a standard format for reporting automated vehicle control systems data and require manufacturers of vehicles equipped with automated vehicle control systems to report incidents, crashes, and vehicle miles operated with such systems enabled.

In response to these recommendations, NHTSA advised that it had communicated with SAE International about developing industry standards but explained that "manufacturers are not currently required to enable vehicles to record data from usage of driving automation systems (SAE levels 1–2) or operation of such systems during crash triggered events. The ability for traditional vehicle manufacturers and other stakeholders to report on automated technology system use and its operation during incidents and crashes is highly dependent on each vehicle's specific recording and downloading technology." Additionally, NHTSA advised that it believes development of recording requirements is best accomplished through voluntary compliance until industry consensus on standard data elements can be established.

NTSB experience with crashes involving different levels of driving automation shows that the amount and availability of recorded data varies widely amongst manufacturers. In the more than 2 years since these important safety recommendations were issued, neither the DOT nor NHTSA has taken any substantive action to address them. Although NHTSA replied on February 7, 2018, the DOT has not responded to Safety Recommendation H-17-37 since issuance. Because it is unlikely that crash investigators and regulators will fully understand the causal factors in a crash without easily accessible data from driving automation systems, the NTSB reiterates Safety Recommendation H-17-37 to the DOT and reclassifies it from "Open—Await Response" to "Open—Unacceptable Response." In addition, the NTSB reiterates Safety Recommendations H-17-39 and -40 to NHTSA and reclassifies them from "Open—Acceptable Response" to "Open—Unacceptable Response."

3 Conclusions

3.1 Findings

1. None of the following were factors in the Tesla driver's actions in this crash: (1) driver licensing or qualification; (2) familiarization with the vehicle and roadway; (3) medical conditions, fatigue, or impairment by alcohol or other drugs; or (4) weather conditions.

2. The emergency response to the crash was timely and adequate.

3. The Tesla electric vehicle postcrash fire and related damage to the lithium-ion battery presented unusual fire and electrical hazards to first responders.

4. The Tesla's Autopilot lane-keeping assist system steered the sport utility vehicle to the left into the neutral area of the gore, without providing an alert to the driver, due to limitations of the Tesla Autopilot vision system's processing software to accurately maintain the appropriate lane of travel.

5. The Tesla's collision avoidance systems were not designed to, and did not, detect the crash attenuator at the end of the gore, nor did the National Highway Traffic Safety Administration require such capability; consequently, the forward collision warning system did not provide an alert and the automatic emergency braking did not activate.

6. The driver did not take corrective action when the Tesla's Autopilot lane-keeping assist system steered the vehicle into the gore area, nor did he take evasive action to avoid the collision with the crash attenuator, most likely due to distraction caused by a cell phone game application.

7. Distracted driving due to portable electronic device use remains persistently high, and additional countermeasures are needed.

8. A technological solution, such as a lock-out function or application that automatically disables highly distracting features of a portable electronic device while driving, is an effective countermeasure for eliminating portable electronic device distraction while driving.

9. Strong company policy, with strict consequences for using portable electronic devices while driving, is an effective strategy in helping to prevent distracted driving crashes, injuries, and fatalities.

10. Although the Occupational Safety and Health Administration has guidelines for companies to reduce motor vehicle crashes by prohibiting the use of portable electronic devices while driving, the guidelines lack specificity, are not widely adopted by companies, and are seldom enforced—limiting their impact in addressing the hazards of distracted driving.

11. The Tesla Autopilot system did not provide an effective means of monitoring the driver's level of engagement with the driving task.

12. Although the lack of gore area roadway striping at the Mountain View crash location likely did not contribute to the crash, ongoing research led by the Federal Highway Administration can help identify what highway infrastructure changes may be needed in the future to accommodate automated vehicles.

13. The crash attenuator was in a damaged and nonoperational condition at the time of the collision due to the California Highway Patrol's failure to report the damage following a previous crash and systemic problems with the California Department of Transportation's maintenance division in repairing traffic safety hardware in a timely manner.

14. If the crash attenuator at the US Highway 101–State Route 85 interchange had been repaired in a timely manner and in a functional condition before the March 23, 2018, crash, the Tesla driver most likely would have survived the collision.

15. Because monitoring of driver-applied steering wheel torque is an ineffective surrogate measure of driver engagement, performance standards should be developed pertaining to an effective method of ensuring driver engagement in SAE Level 2 partial driving automation systems.

16. If Tesla Inc. does not incorporate system safeguards that limit the use of the Autopilot system to those conditions for which it was designed, continued use of the system beyond its operational design domain is foreseeable and the risk for future crashes will remain.

17. The National Highway Traffic Safety Administration's failure to ensure that vehicle manufacturers of SAE Level 2 driving automation systems are incorporating appropriate system safeguards to limit operation of these systems to the operational design domain compromises safety.

18. In order for driving automation systems to be safely deployed in a high-speed operating environment, collision avoidance systems must be able to effectively detect and respond to potential hazards, including roadside traffic safety hardware, and be able to execute forward collision avoidance at high speeds.

19. The National Highway Traffic Safety Administration's approach to the oversight of automated vehicles is misguided, because it essentially relies on waiting for problems to occur rather than addressing safety issues proactively.

20. It is essential that the National Highway Traffic Safety Administration's surveillance and defect investigation program closely examine issues related to foreseeable misuse of automation and perform a forward-looking risk analysis to identify partial driving automation system defects that pose an unreasonable risk to safety.

21. The National Highway Traffic Safety Administration's Office of Defects Investigation has failed to thoroughly investigate the Tesla Autopilot design regarding the degree to which drivers are currently misusing the system, the foreseeable consequences of continued use by drivers beyond the system's operational design domain, and the effectiveness of the driver monitoring system in ensuring driver engagement.

22. Vehicle performance data associated with activation and engagement of partial driving automation systems on vehicles involved in crashes are not required nor available on most event data recorders.

23. A standardized set of retrievable data is needed to enable independent assessment of automated vehicle safety and to foster automation safety improvements.

3.2 Probable Cause

The National Transportation Safety Board determines that the probable cause of the Mountain View, California, crash was the Tesla Autopilot system steering the sport utility vehicle into a highway gore area due to system limitations, and the driver's lack of response due to distraction likely from a cell phone game application and overreliance on the Autopilot partial driving automation system. Contributing to the crash was the Tesla vehicle's ineffective monitoring of driver engagement, which facilitated the driver's complacency and inattentiveness. Contributing to the severity of the driver's injuries was the vehicle's impact with a crash attenuator barrier that was damaged and nonoperational at the time of the collision due to the California Highway Patrol's failure to report the damage following a previous crash, and systemic problems with the California Department of Transportation's maintenance division in repairing traffic safety hardware in a timely manner.

4 Recommendations

4.1 New Recommendations

As a result of its investigation, the National Transportation Safety Board makes the following nine new safety recommendations:

To the National Highway Traffic Safety Administration:

Expand New Car Assessment Program testing of forward collision avoidance system performance to include common obstacles, such as traffic safety hardware, cross-traffic vehicle profiles, and other applicable vehicle shapes or objects found in the highway operating environment. (H-20-1)

Evaluate Tesla Autopilot-equipped vehicles to determine if the system's operating limitations, the foreseeability of driver misuse, and the ability to operate the vehicles outside the intended operational design domain pose an unreasonable risk to safety; if safety defects are identified, use applicable enforcement authority to ensure that Tesla Inc. takes corrective action. (H-20-2)

For vehicles equipped with Level 2 automation, work with SAE International to develop performance standards for driver monitoring systems that will minimize driver disengagement, prevent automation complacency, and account for foreseeable misuse of the automation. (H-20-3)

After developing the performance standards for driver monitoring systems recommended in Safety Recommendation H-20-3, require that all new passenger vehicles with Level 2 automation be equipped with a driver monitoring system that meets these standards. (H-20-4)

To the Occupational Safety and Health Administration:

Review and revise your distracted driving initiatives to increase employers' awareness of the need to develop strong cell phone policy prohibiting the use of portable electronic devices while driving. (H-20-5)

Modify your enforcement strategies to increase the use of the general duty clause cited in 29 *United States Code* section 654 against those employers who fail to address the hazards of distracted driving. (H-20-6)

To SAE International:

For vehicles equipped with Level 2 automation, work with the National Highway Traffic Safety Administration to develop performance standards for driver monitoring systems that will minimize driver disengagement, prevent automation complacency, and account for foreseeable misuse of the automation. (H-20-7)

To Manufacturers of Portable Electronic Devices (Apple, Google, HTC, Lenovo, LG, Motorola, Nokia, Samsung, and Sony):

> Develop a distracted driving lock-out mechanism or application for portable electronic devices that will automatically disable any driver-distracting functions when a vehicle is in motion, but that allows the device to be used in an emergency; install the mechanism as a default setting on all new devices and apply it to existing commercially available devices during major software updates. (H-20-8)

To Apple Inc.:

> Develop and implement a company policy that bans the nonemergency use of portable electronic devices while driving by all employees and contractors driving company vehicles, operating company-issued portable electronic devices, or using a portable electronic device to engage in work-related communications. (H-20-9)

4.2 Previously Issued Recommendations Reiterated in This Report

As a result of its investigation, the National Transportation Safety Board reiterates the following two safety recommendations (already classified “Open—Unacceptable Response”) in sections 2.3.3 and 2.3.2, respectively, in this report:

To the National Highway Traffic Safety Administration:

> Develop and apply testing protocols to assess the performance of forward collision avoidance systems in passenger vehicles at various velocities, including high speed and high velocity-differential. (H-15-4)

> Develop a method to verify that manufacturers of vehicles equipped with Level 2 vehicle automation systems incorporate system safeguards that limit the use of automated vehicle control systems to those conditions for which they were designed. (H-17-38)

4.3 Previously Issued Recommendations Reiterated and Reclassified in This Report

As a result of its investigation, the National Transportation Safety Board reiterates and reclassifies the following five safety recommendations:

To the US Department of Transportation:

> Define the data parameters needed to understand the automated vehicle control systems involved in a crash. The parameters must reflect the vehicle’s control status and the frequency and duration of control actions to adequately characterize driver and vehicle performance before and during a crash. (H-17-37)

Safety Recommendation H-17-37 is reclassified from “Open—Await Response” to “Open—Unacceptable Response” in section 2.4 of this report.

To the National Highway Traffic Safety Administration:

> Use the data parameters defined by the U.S. Department of Transportation in response to Safety Recommendation H-17-37 as a benchmark for new vehicles equipped with automated vehicle control systems so that they capture data that reflect the vehicle's control status and the frequency and duration of control actions needed to adequately characterize driver and vehicle performance before and during a crash; the captured data should be readily available to, at a minimum, National Transportation Safety Board investigators and National Highway Traffic Safety Administration regulators. (H-17-39)

Safety Recommendation H-17-39 is reclassified from "Open—Acceptable Response" to "Open—Unacceptable Response" in section 2.4 of this report.

> Define a standard format for reporting automated vehicle control systems data and require manufacturers of vehicles equipped with automated vehicle control systems to report incidents, crashes, and vehicle miles operated with such systems enabled. (H-17-40)

Safety Recommendation H-17-40 is reclassified from "Open—Acceptable Response" to "Open—Unacceptable Response" in section 2.4 of this report.

To Tesla Inc.:

> Incorporate system safeguards that limit the use of automated vehicle control systems to those conditions for which they were designed. (H-17-41)

Safety Recommendation H-17-41 is reclassified from "Open—Await Response" to "Open—Unacceptable Response" in section 2.3.2 of this report.

> Develop applications to more effectively sense the driver's level of engagement and alert the driver when engagement is lacking while automated vehicle control systems are in use. (H-17-42)

Safety Recommendation H-17-42 is reclassified from "Open—Await Response" to "Open—Unacceptable Response" in section 2.3.1 of this report.

4.4 Previously Issued Recommendations Reclassified in This Report

As a result of its investigation, the National Transportation Safety Board reclassifies the following two safety recommendations:

To the Consumer Electronics Association (now the Consumer Technology Association):

> Encourage the development of technology features that disable the functions of portable electronic devices within reach of the driver when a vehicle is in motion; these technology features should include the ability to permit emergency use of the device while the vehicle is in motion and have the capability of identifying occupant

> seating position so as not to interfere with use of the device by passengers. (H-11-47)

Safety Recommendation H-11-47 is reclassified from “Open—Await Response” to “Closed—No Longer Applicable” in section 2.2.4.3 of this report.

To the California State Transportation Agency:

> Develop and implement a corrective action plan that guarantees timely repair of traffic safety hardware and includes performance measures to track state agency compliance with repair timelines. (H-19-13)

Safety Recommendation H-19-13 is reclassified from “Open—Initial Response Received” to “Open—Acceptable Response” in section 2.2.5.2 of this report.

BY THE NATIONAL TRANSPORTATION SAFETY BOARD

ROBERT L. SUMWALT, III
Chairman

BRUCE LANDSBERG
Vice Chairman

JENNIFER HOMENDY
Member

THOMAS B. CHAPMAN
Member

MICHAEL E. GRAHAM
Member

Report Date: February 25, 2020

Board Member Statement

Member Jennifer Homendy filed the following concurring statement on March 3, 2020:

The most dangerous way to travel in our country is on the road. In 2018, there were 36,560 fatalities on our nation's roadways. Each and every one of these fatalities is tragic and that tragedy is compounded by the fact that most of these fatal crashes can be traced back to human error. The driver is the most vital part of the safe operation of a vehicle, but they can also be the most dangerous part of operating a vehicle. The appropriate use of proven technologies that support drivers in the safe operation of their vehicle has the potential to prevent crashes, reduce injuries, and save lives.

Nearly 25 years ago, based on the investigation of a multi-vehicle crash in Menifee, Arkansas, the NTSB issued a safety recommendation to the US DOT to begin testing of collision warning systems on commercial motor vehicles. This safety recommendation was "Closed—Unacceptable Action" in 1999 because the DOT failed to take action and the industry had taken the lead in testing the technology. The NTSB has continued to issue safety recommendations related to collision avoidance systems and most have been directed to NHTSA. In fact, increasing the implementation of collision avoidance systems in all new highway vehicles is on our 2019–2020 Most Wanted List of Transportation Safety Improvements. Unfortunately, like the safety recommendation to the DOT in 1995, NHTSA has continued the trend of inaction and has failed to implement many of our safety recommendations related to collision avoidance systems and other vehicle safety technology.

There is no disputing the benefits of vehicle safety technology. As technology matures and becomes more robust and integrated into vehicles across the country, many of the issues on our Most Wanted List could be addressed. Even before we see fully autonomous vehicles on our roads, the variety of technologies being discussed now could help prevent or mitigate speeding-related crashes; eliminate distraction; and recognize fatigue and driver impairment.

While there is tremendous potential for vehicle automation systems, there needs to be strong federal guidance around the testing and application of the technology. Since 2016, the NTSB has investigated four crashes that involved vehicles with varying levels of automation and our investigators are seeing many of the same issues over and over. As a result of our 2016 investigation in Williston, Florida, a safety recommendation was issued to NHTSA specific to Level 2 vehicle automation systems:

> Develop a method to verify that manufacturers of vehicles equipped with Level 2 vehicle automation systems incorporate system safeguards that limit the use of automated vehicle control systems to those conditions for which they were designed. (H-17-38)

This safety recommendation has not been acted on and because of that inaction, NHTSA was identified in the probable cause as contributing to the 2019 crash in Delray Beach, Florida. NHTSA maintains that voluntary standards for manufacturers of vehicles with Level 3–5 automation systems is the best way forward and they completely ignore issues and concerns around Level 2 vehicle automation systems that are on our roads now. Instead, they are choosing to rely on their recall authority to address the safety of Level 2 systems.

The recall authority that NHTSA has is an important part of making sure vehicles in the United States are as safe as they can be, but that recall can only be utilized after a problem has been identified. This often means that lives have been lost while NHTSA is waiting for a problem to present itself. As Finding 19 of this report states, NHTSA's "approach to the oversight of automated vehicles is misguided, because it essentially relies on waiting for problems to occur rather than addressing safety issues proactively."

As a federal agency with the mission to "save lives, prevent injuries, and reduce economic costs due to road traffic crashes through education, research, safety standards, and enforcement activity," the hands-off approach NHTSA is taking to collision avoidance systems and Level 2 vehicle automation systems seems counter to their mission. The latest policy on automated vehicle technologies from the DOT – Ensuring American Leadership in Automated Vehicle Technologies; Automated Vehicles 4.0 – is more focused on protecting innovation rather than promoting safety.

Our investigation of the Tempe, Arizona, automated test vehicle crash found that the lack of leadership has led states to try to fill the safety gaps that are being left by NHTSA. As vehicle technologies are developed and implemented, states have an important role in making sure their roadways are safe, but they shouldn't be doing it alone. The Mountain View crash is an example of how NHTSA needs to first and foremost be focused on the safety of the traveling public and not on promoting innovation. The longer NHTSA decides to not be a safety leader, the longer our roadways will continue to see lives lost from the misuse of vehicle technology by drivers and manufacturers.

Chairman Robert L. Sumwalt, III; Vice Chairman Bruce Landsberg; and Members Thomas B. Chapman and Michael E. Graham joined in this statement.

Appendix A: Investigation

The National Transportation Safety Board was notified of this crash on March 23, 2018, and initially dispatched two investigators to the scene to examine safety issues related to the electric-powered vehicle fire. The investigation was expanded to include the human performance, vehicle automation, and highway safety issues addressed in this report. The NTSB team also included staff from the Office of Aviation Safety and the Office of Research and Engineering.

Parties to the investigation were the California Department of Transportation and the California Highway Patrol.

Pursuant to Title 49 *CFR* section 831, Tesla Inc. was designated as a party to this investigation because the automaker could provide qualified technical personnel who could actively assist in the investigation. On April 11, 2018, the NTSB revoked Tesla's status as a party member because of the company's failure to abide by the terms of the NTSB Party Agreement. After being removed as a party member, Tesla's general counsel office continued to assist the NTSB and provided answers to investigators' technical questions.

Appendix B: Tesla Carlog Data

The table below depicts 14.9 seconds of data recorded immediately before the crash, retrieved from the Tesla's Carlog.[1]

Table 3. Tesla Carlog data.

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[2]	0	NA	NA	NA

[1] Distance measurements from the attenuator are approximate and were derived based on kinematic equations taking into account 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 acceleration values were converted from meters per second to g units.

[2] Approximate speed at impact was not recorded in the Tesla Carlog. The speed was obtained from the Tesla EDR report, which was based on the imaging of the RCM.

Appendix C: Autopilot and Collision Avoidance Limitations

Limitations of Traffic-Aware Cruise Control (TACC):

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. 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 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.).

Limitations of Autosteer

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.

Limitations of Forward Collision Warning (FCW) System

The *Tesla Model X Owner's Manual* lists the following warnings regarding the FCW system:

- 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.

- 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.

Limitations of Automatic Emergency Braking (AEB) System

The *Tesla Model X Owner's Manual* lists the following warnings regarding the AEB system:

- 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 of 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.

Appendix D: Postcrash Changes Made to Tesla Autopilot

After the Mountain View crash, Tesla made design changes to the Autopilot firmware. The changes are summarized below:

- ***Hydranet Vision System*** (Firmware Update 2018.10.4, released March 2018): 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, released June 2018): 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 is detected (see figure D-1). 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.

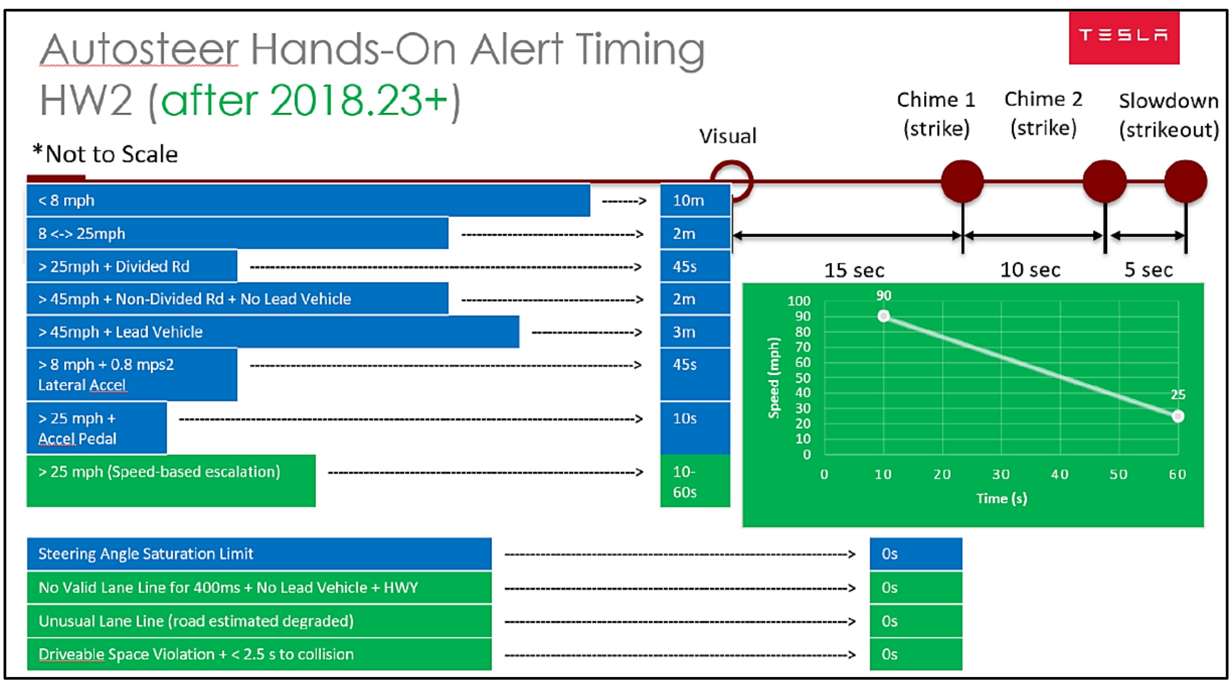

Figure D-1. Autosteer hands-on alert timing for the Tesla after firmware 2018.23 was implemented in June 2018. (Changes are highlighted in green)

- ***Drivable 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 a warning up to 2.5 seconds based on detection. Because 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 drivable space, a chime will sound and maximum braking will be applied. Drivable 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.

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