National Transportation Safety Board

Collision Between a Sport Utility Vehicle Operating with Partial Automation and a Crash Attenuator

Mountain View, California
March 23, 2018

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Investigation Overview

Thomas Barth, PhD
Investigator-in-Charge

Crash Overview

- Friday, March 23, 2018
- 9:27 a.m.
- Mountain View, California
- US-101 / SR-85 interchange
- 2017 Tesla Model X SUV
- 38-year-old driver
- Partial automation “Autopilot” engaged

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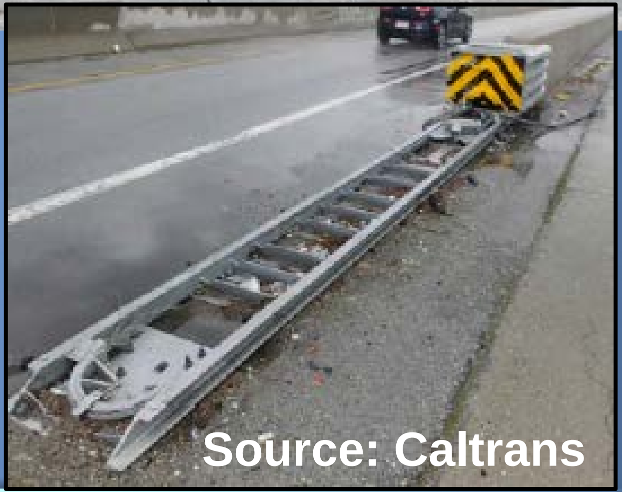
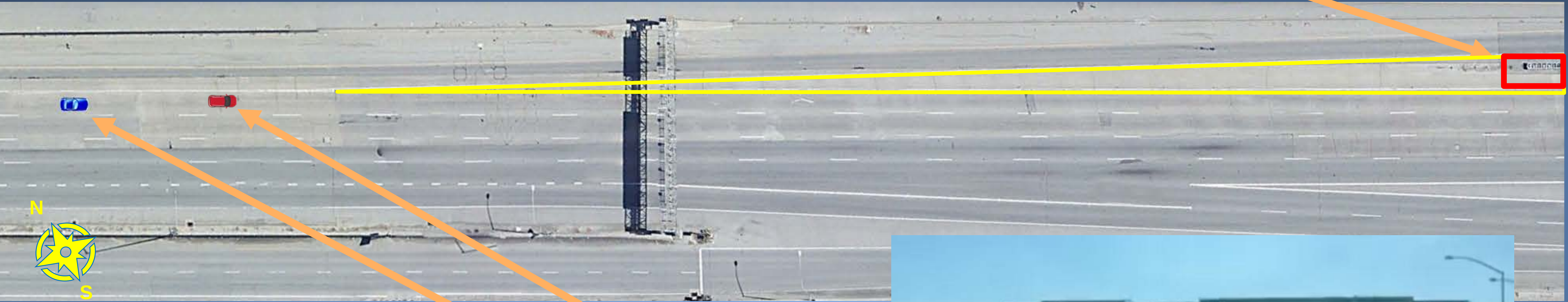
Crash Sequence

Crash attenuator was collapsed and nonoperational prior to the crash



Crash Sequence

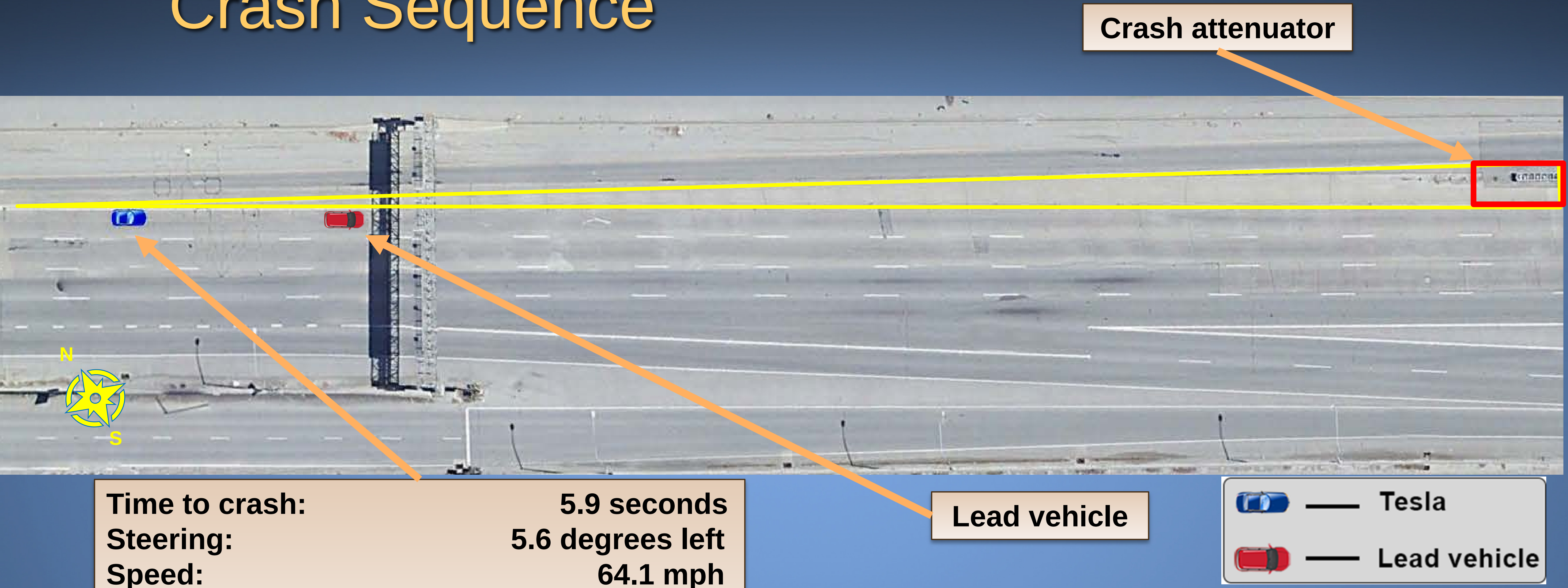


Tesla

Lead vehicle

Time to crash:	7.9 seconds
Speed:	64.3 mph
Lead vehicle:	83.7 feet
Distance to crash:	748 feet

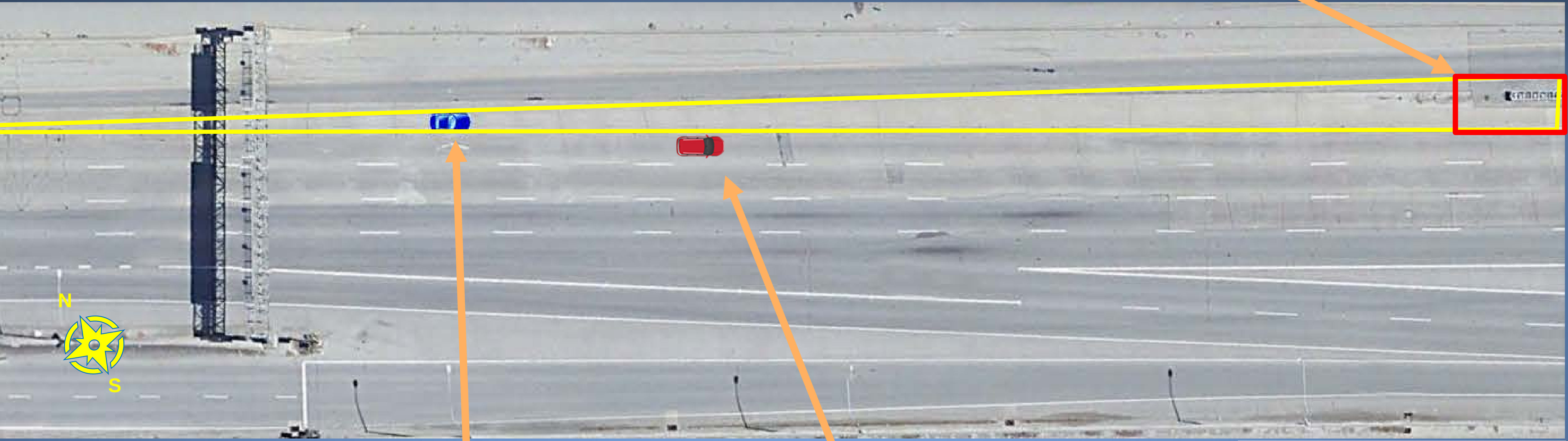
Crash Sequence



Time to crash:	5.9 seconds
Steering:	5.6 degrees left
Speed:	64.1 mph
Lead vehicle:	82 feet
Distance to crash:	560 feet
Indication:	Hands-off steering wheel

Crash Sequence

Crash attenuator

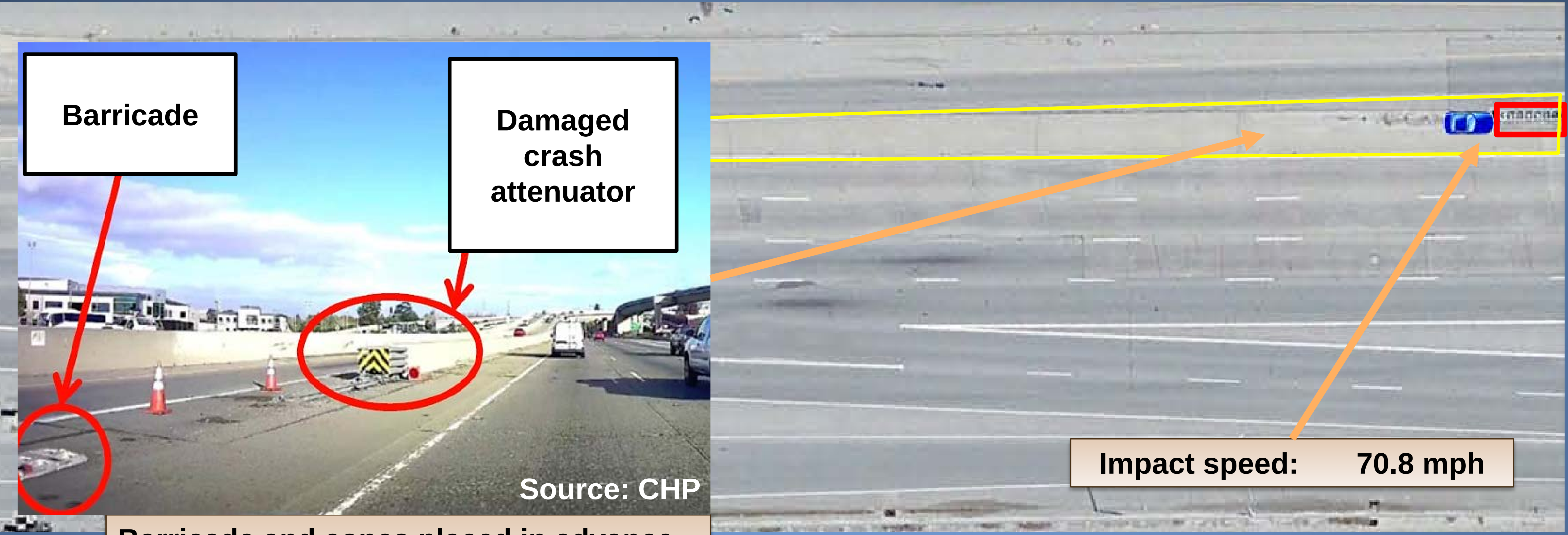


Time to crash: 3.9 seconds
Speed: 61.9 mph
Lead vehicle: None detected
Distance to crash: 375 feet
Vehicle begins to accelerate
Hands-off steering wheel indicated

Lead vehicle
(no longer followed)

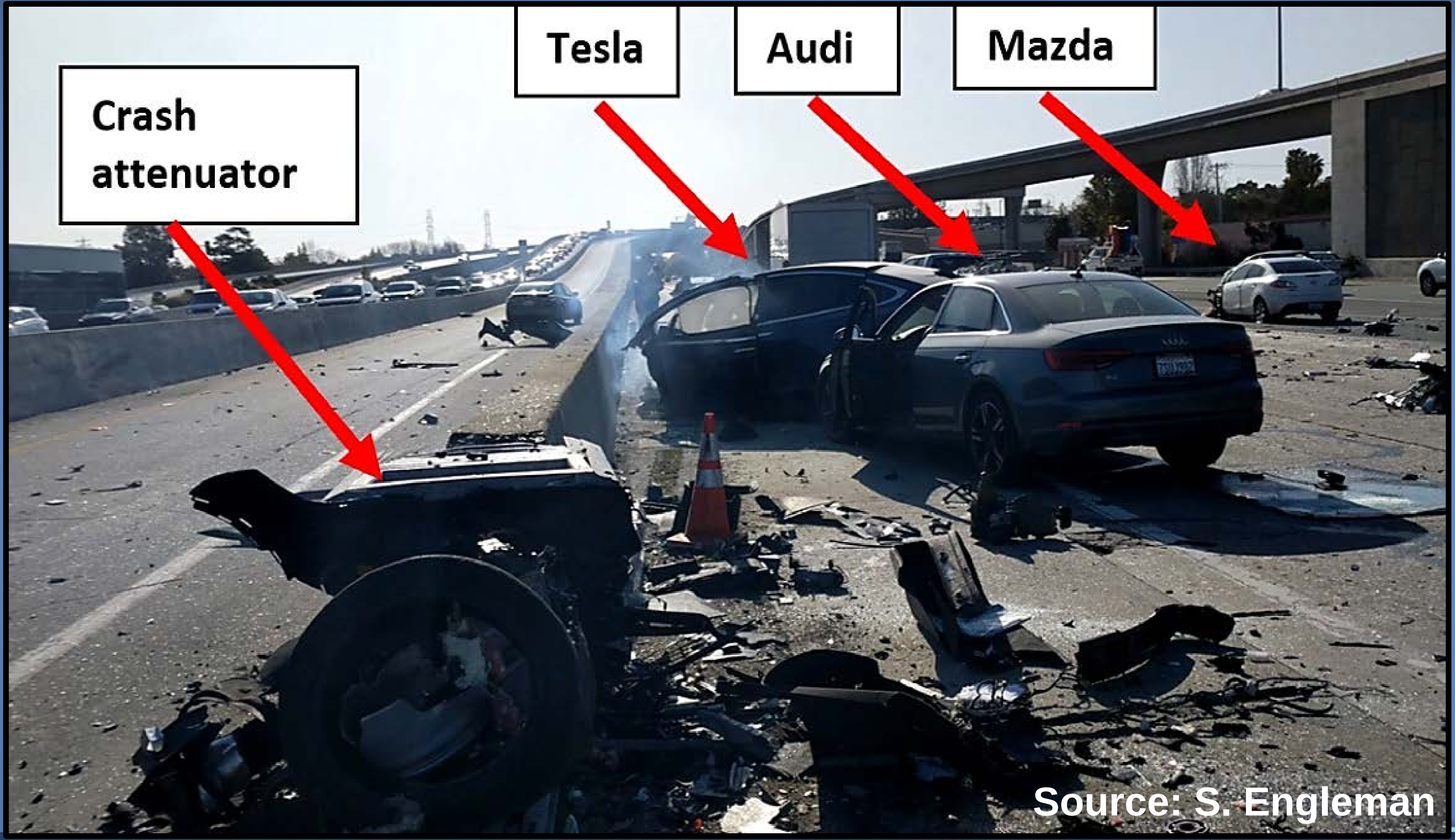
— Tesla
— Lead vehicle

Crash Sequence



Barricade and cones placed in advance of attenuator prior to crash

Crash Sequence



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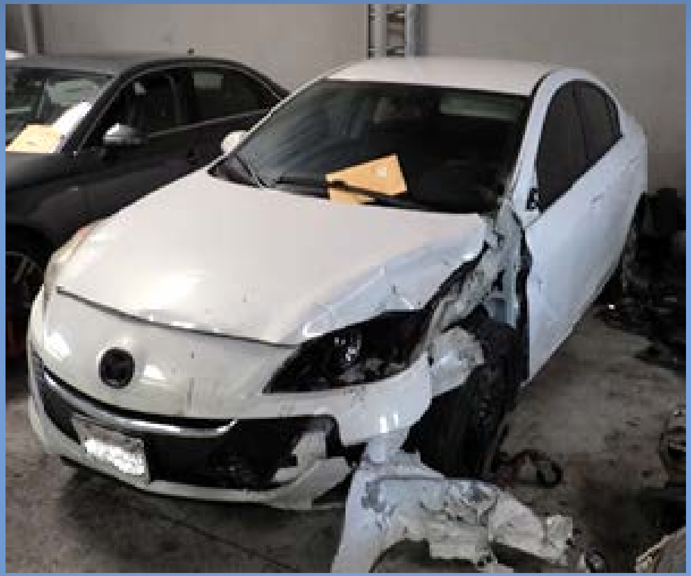
Vehicle Damage and Occupant Injuries

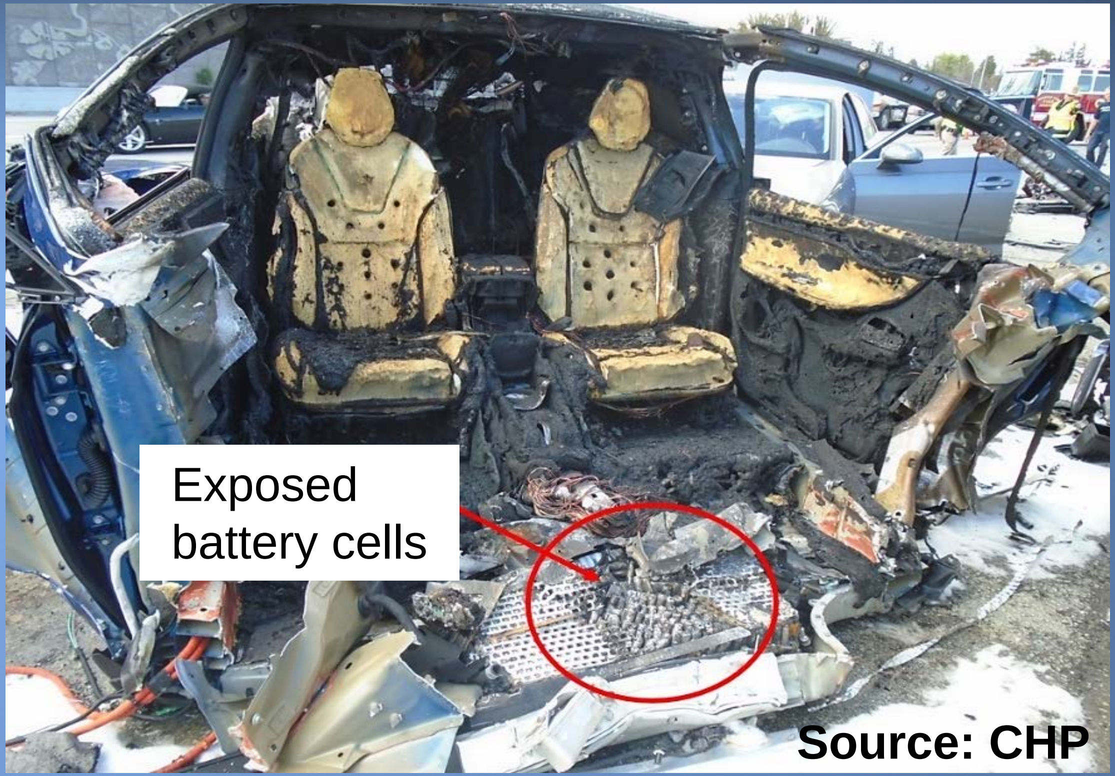
2017 Tesla Model X
- 38-year-old driver
- Fatal injuries



2010 Mazda 3
- 25-year-old driver
- Minor injuries

2017 Audi A4
- 51-year-old driver
- No reported injuries

Emergency Response



Emergency response and electric vehicle fire issues will be covered in a future report

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Investigative Staff

- Tom Barth, PhD – IIC / Vehicle and Survival Factors Investigator
- Don Karol – Project Manager / Highway and Human Performance Investigator
- Bob Swaim* – Tesla Battery Examination

* Denotes staff who are no longer NTSB employees

Report Development Staff

- Ensar Becic, PhD – Human Performance and Automation
- Bob Squire – Reconstruction
- Monica Mitchell – Writer / Editor
- Charlotte Cox – Writer / Editor
- Dan Horak, PhD – Data Analysis
- Ivan Cheung, PhD – Mapping
- Chris O'Neil – Media Relations
- Julie Perrot – Safety Recommendations
- Jane Foster* – Vehicle Recorders
- Ryan Cudemus-Brunoli* – Intern

* Denotes staff who are no longer NTSB employees

Parties to Investigation

- California Department of Transportation (Caltrans)
- California Highway Patrol (CHP)

Noncontributing Factors

- Driver licensing or qualification
- Driver familiarization with the vehicle and roadway
- Medical conditions
- Fatigue
- Impairment by alcohol or other drugs
- Weather conditions

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
- Highway infrastructure issues (safety recommendation report issued in August 2019)

Other NTSB Investigations

Lessons learned from three other Tesla crashes were incorporated into the Mountain View crash investigation:

- Williston, Florida
- Delray Beach, Florida
- Culver City, California

Williston, Florida (May 7, 2016)

Delray Beach, Florida (March 1, 2019)

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Culver City, California (January 22, 2018)

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Autopilot Performance and Cell Phone Distraction

Don Karol

Overview

- Autopilot system performance
- Driver performance
- Portable electronic device distraction
    - Need for technological solutions
    - Employers' role in combating cell phone distraction

Levels of Automation

No Automation | Driver Assistance | **Partial Automation** | Conditional Automation | High Automation | Full Automation

Partial Automation:
- Supervise automation
- Maintain awareness
- Understand limitations
- Intervene when needed

Autopilot Description

- Monitors travel path
- Maintains set cruise speed
- Maintains vehicle’s position in travel lane
- Brakes when detecting slower-moving vehicles ahead
- Decelerates and follows vehicles ahead at a predetermined following interval

Autopilot Description

- Traffic-Aware Cruise Control (TACC)
  - Longitudinal control (acceleration and deceleration)
- Autosteer lane-keeping assist system
  - Lateral control (maintains lane position)
  - Inadequate sensor input: "Autosteer is temporarily unavailable"

Autopilot Performance

- Autosteer lane prediction and steering
  - Determined by vehicle's vision system, containing cameras and computing software
- Autosteer operation can be hindered if:
  - System cannot determine lane markings
  - Bright light is interfering with cameras' view
  - Visibility is poor
  - Cameras are obstructed

Autopilot Performance

- Lane markings were worn
- Autosteer vision system likely lost lane line prediction
- Identified stronger lane line
- Steering movement likely due to vision system limitations

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Driver Performance

- Driver had unobstructed view
- Numerous visual cues of hazard ahead
- Driver took no evasive braking or steering action
- Level of inaction indicates inattention to forward roadway
- Driver not supervising Autopilot

Portable Electronic Device Distraction

- Driver used game application on phone
- Cell phone game application active during crash
- Cell phone data consistent with gaming activity
- Unknown if driver was holding phone
- Tesla Carlog data – hands likely off steering wheel

Portable Electronic Device Distraction

- Interacting with a game application – highly distracting
- Involves 3 major types of distraction:
  - Visual
  - Manual
  - Cognitive
- Significantly impairs driver performance
- Crash risk is higher

Combating Portable Electronic Device Distraction

- Efforts have focused on:
  - Legislation
  - Enforcement
  - Education
- Mobile device distraction not decreasing
- Additional countermeasures needed

Technological Solution: Lock-Out Distraction

- Applications that block distraction are available
  - Voluntary activation
  - Not widely used
- Cell phone manufacturers can eliminate distraction
- Lock-out mechanism should be installed as default setting
- Automatically lock out distraction when vehicle is in motion

Employers' Role in Combating Distracted Driving

- Tesla driver was an Apple employee driving distracted
- Apple, Inc. has no policy prohibiting cell phone use while driving
- Strong policy is an effective strategy
- OSHA can do more to educate employers
- OSHA can increase enforcement

Summary

- Tesla Autopilot vision system limitations
- Driver's lack of response likely due to cell phone distraction
- Cell phone distraction countermeasures needed
- Distracted driving lock-out mechanism shows promise
- Strong employer cell phone policies needed
- OSHA can do more to educate employers and increase enforcement

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Partial Driving Automation and Collision Avoidance Systems

Ensar Becic, PhD

Overview

- Operational design domain (ODD)
- Monitoring driver engagement
- Collision avoidance system (CAS)

Operational Design Domain

- Conditions in which an automated system is designed to operate
  - Geographic location, roadway type and markings, speed range, weather conditions
- ODD constraints are designed to reduce the effect of Level 2 limitations

ODD Constraints

- Autopilot, stated in vehicle manual, is
  - *Not for use* on city streets, in constantly changing traffic conditions, on winding roads with sharp curves
  - *For use only* on divided highways with limited access
- The system allows a driver to use Autopilot outside its ODD
- Level 2 system limitations are industry-wide

Geographic ODD: Mountain View

- Crash location
  - Highway with center median divider
  - Limited access (no cross-traffic)
  - Major interchange (changing traffic conditions)
- Tesla stated ODD does not apply to Level 2 systems

Geographic ODD: Williston and Delray Beach

- Williston crash location
  - Outside ODD of Autopilot
- Delray Beach crash location
  - Highway with center median divider
  - Not limited access (has cross-traffic)
  - Outside ODD of Autopilot

Needed ODD Improvements

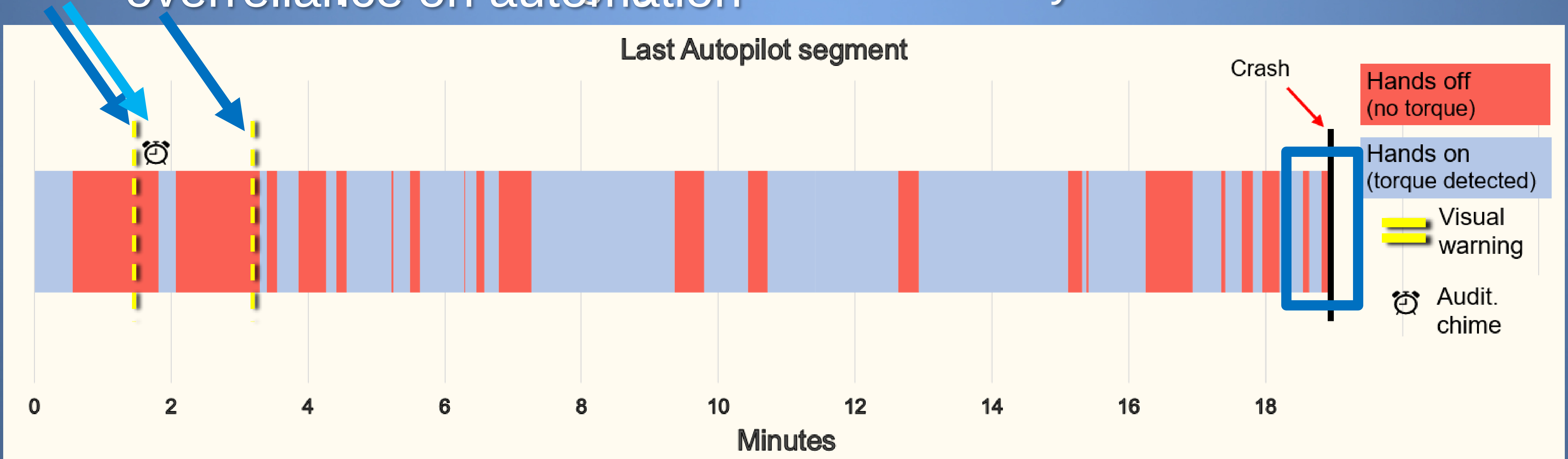
- Manufacturers should include system safeguards to limit the use of Level 2 systems to conditions for which they are designed (H-17-41)
- NHTSA should verify that manufacturers are incorporating the safeguards (H-17-38)
  - Lack of guidance on identifying ODD

Monitoring Driver Engagement

- Driver monitors environment in Level 2 systems
  - Tesla stated that Autopilot can be used on undivided roads with an *attentive* driver
  - Risk of automation complacency and misuse
- Tesla's method of monitoring driver engagement
  - Driver-applied steering wheel torque
  - System provides series of warnings to driver (visual, 3 stages of auditory warnings)

Driver Engagement: Mountain View

- The crash trip lasted 28.5 minutes
  - Autopilot was engaged for the last nearly 19 minutes
- Two visual warnings, one auditory warning
- Lack of responsiveness indicates distraction and overreliance on automation



Driver Engagement: Other Level 2 Crashes

- Williston and Delray Beach, Florida; Culver City, California
  - Driver-applied steering wheel torque not detected at time of impact
  - Prolonged inattentiveness by drivers
  - Drivers were ineffective monitors
- Humans are poor monitors of automation
- Monitoring of steering wheel torque is a poor surrogate measure of driver engagement

Needed Driver Monitoring Improvements

- Manufacturers should implement more effective means of monitoring driver engagement when using Level 2
- NHTSA and SAE should develop performance standards for driver monitoring systems to address automation complacency
- An engaged driver remains a critical component even with advanced driver assistance systems

Forward Collision Avoidance Systems

- FCW and AEB
  - Designed to prevent / mitigate rear-end crashes
  - Not required equipment on vehicles
- NHTSA testing protocols developed for NCAP
  - Maximum speed of 45 mph
  - Using only specific vehicle profile targets
  - No requirements to detect non-vehicles

Forward CAS: Mountain View

- Forward CAS are standard equipment on Tesla
  - FCW and AEB have passed NHTSA's testing protocols
- Mountain View
  - Tesla traveling > 65 mph
  - Approaching an object the system is not designed to detect
  - FCW and AEB did not activate

Forward CAS: Other Level 2 Crashes

- Williston and Delray Beach, Florida
  - Tesla traveling > 65 mph
  - Struck a cross-traffic combination vehicle
  - FCW and AEB did not activate
- Culver City, California
  - Struck a fire truck (vehicle profile not designed or tested for)
  - FCW activated too late for driver to respond (490 msec)

Needed Forward CAS Improvements

- NHTSA should expand testing protocols to include highway speeds and various target profiles, including roadside hardware (H-15-4)
- Improve the effectiveness in domains in which partially automated vehicle systems operate

Summary

- Level 2 systems have limitations, but can improve
  - Defining their ODD and limiting the use to domains for which they are designed
  - Due to risk of automation complacency, effective monitoring of driver engagement is critical
- Forward CAS have limitations, but can improve
  - Broader and challenging testing protocols can incentivize manufacturers to accelerate development

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Federal Oversight of Partial Driving Automation Systems

Don Karol

Overview

- DOT and NHTSA oversight
- NHTSA enforcement of safety-related defects

Nonregulatory Approach to Automation

- Removing unnecessary barriers to innovation
- Voluntary guidance rather than regulations
- Guidance focused on Level 3 – 5 systems
- Action based on safety-related defect trends
- Requires robust defect investigation program

NHTSA Enforcement and Defect Investigations

- Evaluate new technology for "unreasonable risk to safety"
- Manufacturers must account for foreseeable misuse
- Systems must account for foreseeable driver inattention
- Forward-looking risk analysis required in investigations

NHTSA Investigation of Tesla Autopilot System

- NHTSA ODI evaluation of Tesla Autopilot found no defects
- Evaluation did not thoroughly assess:
  - Effectiveness of driver monitoring system
  - Foreseeable future misuse of system
  - Risk of future use of system outside ODD
  - Risks associated with system limitations
- NHTSA further evaluation of Tesla Autopilot needed

Summary

- “Hands-off” approach to oversight
- Safety depends on strong defect investigation program
- Shortfalls found in NHTSA’s defect investigation
- Further evaluation of Tesla Autopilot needed

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Crash Event Data Recorders

Robert Squire

Overview

- Continuously recorded electronic vehicle data
- Crash event data recorders (EDR)
- Data integration for vehicles equipped with advanced driver assistance systems (ADAS)
- Previous recommendations

Continuously Recorded Data

- Records engagement and status of ADAS
- Potentially stored on board vehicle with periodic wireless submission to manufacturer
- Proprietary naming convention and data format requires interpretation by manufacturer

Crash Event Data Recorders

- EDR is a function in the airbag or restraint control module
- Recording begins with crash event or trigger threshold
- EDR is not required by regulation

Crash Event Data Recorders

- If an EDR is installed, 49 CFR Part 563 defines purpose, application, and data-recording requirements
  - Recording of time-series data just prior to and during an event
  - Specifies format of data
  - Minimal survivability requirements for data
  - Data retrievable and interpretable through commercially available means

Crash Event Data Recorders

- Minimum 15 data elements
- Guidance for 30 additional data elements
- Guidance for survivability
- Commercial accessibility

EDR Report

File Information	Value
VIN	5YJXCAE28HF
Retrieval Date	2018/03/28 19:41:44 (UTC)
Retrieval User Comments	MX MM2
Retrie	
EDR	
Repo	
Repo	
Numb	
Time	
Igniti	

Event 1 Data Record

Data Element	Value
Maximum Delta-V, Longitudinal (km/h)	-92
Time To Maximum Delta-V, Longitudinal (ms)	275.0

Deployment Summary (Event 1)

Device	Status	Deployment Command Time (ms)
Driver Front Airbag Stage 1	Deployment Commanded	4
Driver Front Airbag Stage 2	Deployment Commanded	9
Driver Knee Airbag	Deployment Commanded	4
Driver Retractor Pretensioner	Deployment Commanded	4
Driver Lap Pretensioner	Deployment Commanded	9
Driver Switchable Load Limiter	Deployment Commanded	4
Driver Side Seat Airbag		
Passenger Front Airbag Stage 1		
Passenger Front Airbag Stage 2		
Passenger Active Vent		
Passenger Knee Airbag		
Passenger Retractor Pretension		
Passenger Lap Pretensioner		
Passenger Switchable Load Lim		
Passenger Side Seat Airbag		
Inflatable Curtain Airbag Left		
Inflatable Curtain Airbag Right		
Second Row Retractor Pretensi		
Second Row Left Curtain Airbag		
Second Row Side Seat Airbag L		
Second Row Retractor Pretensi		
Second Row Right Curtain Airb		
Second Row Side Seat Airbag Right	Deployment Commanded	9
HV Battery Disconnect	Deployment Commanded	4

Event Data (Event 1)

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

Automated System Data Challenges

- Crash data recorded in airbag control modules contain no ADAS performance information
- ADAS data is not accessible to investigators without manufacturer assistance
- Standard set of parameters is needed to assess driver and vehicle performance

Previous Recommendations

Issued to the US DOT and NHTSA

- Define data parameters for automated vehicles (H-17-37)
- Apply these data parameters as benchmarks for new vehicles (H-17-39)
- Define standard format for reporting system data (H-17-40)

Summary

- Data is crucial for crash investigations
- ADAS data is not recorded by typical EDR functionality
- ADAS data parameters need to be defined
- ADAS data needs to be readily accessible and interpretable by crash investigators

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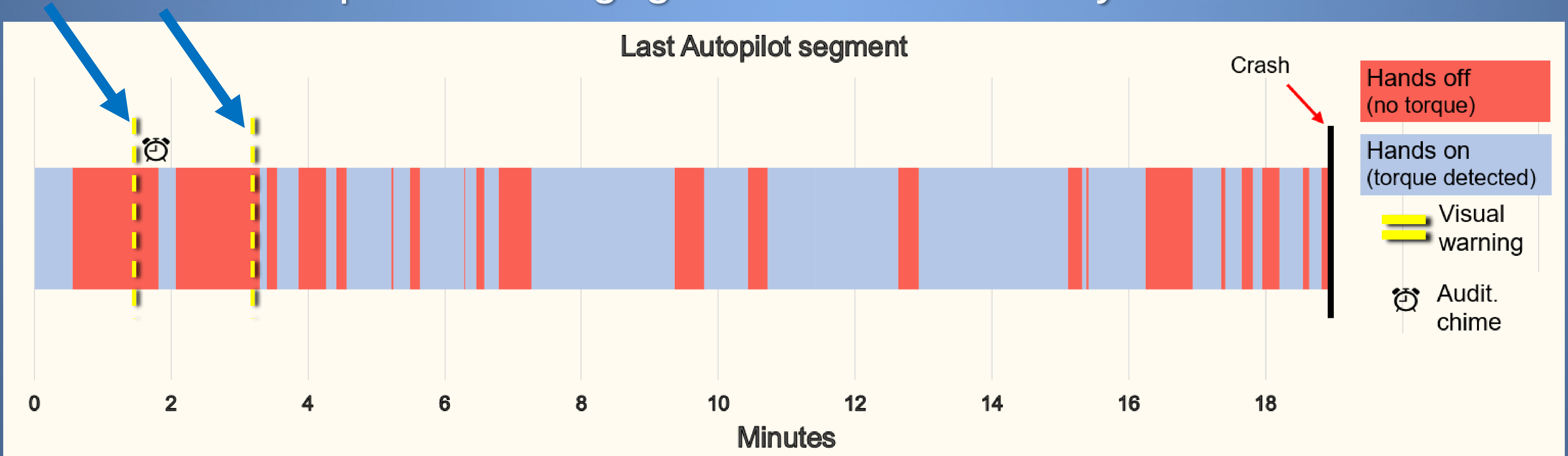
Driver Engagement: Mountain View

- The crash trip lasted 28.5 minutes
  - Autopilot was engaged for the final nearly 19 minutes



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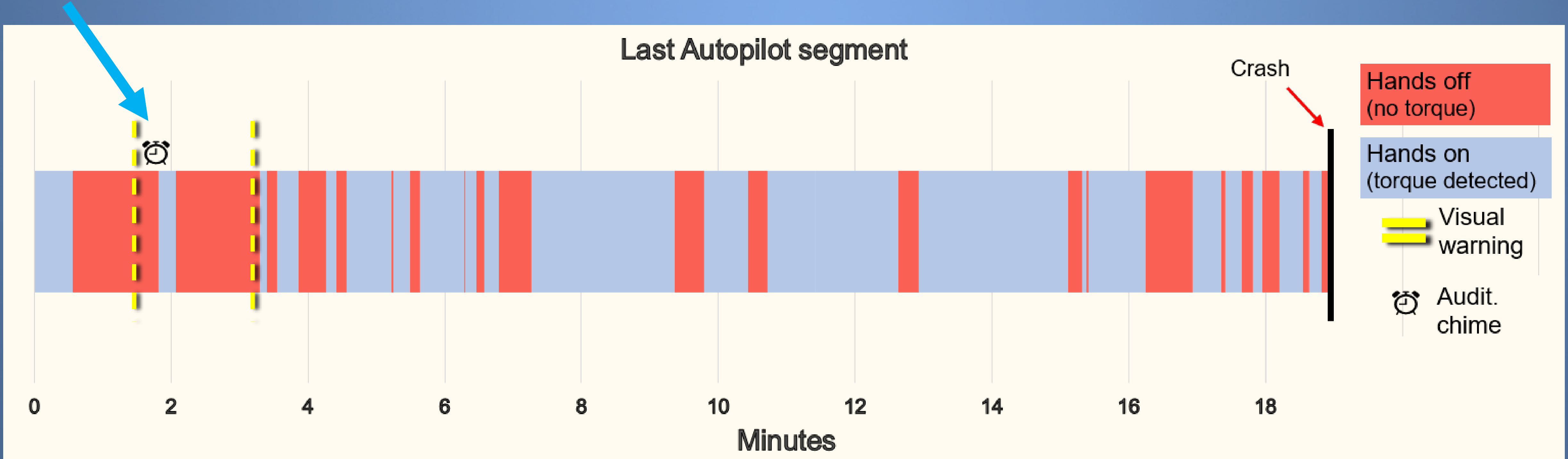

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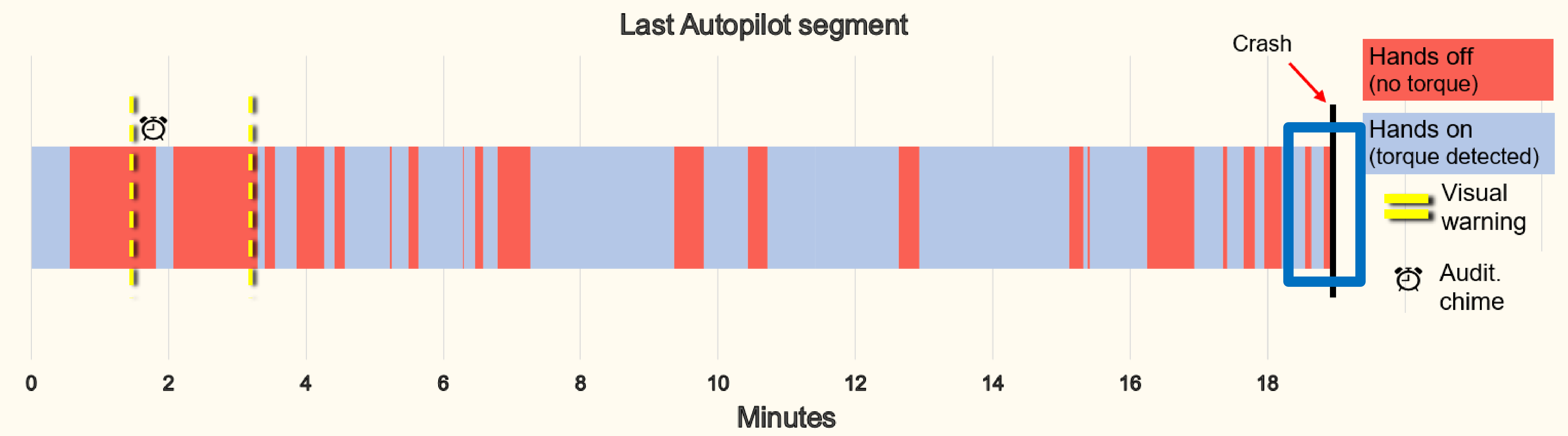

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