

Collision Between Vehicle Controlled by Developmental
Automated Driving System and Pedestrian
Tempe, Arizona
March 18, 2018



Accident Report

NTSB/HAR-19/03
PB2019-101402



**National
Transportation
Safety Board**

Highway Accident Report

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Automated Driving System and Pedestrian
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490 L'Enfant Plaza, S.W.
Washington, D.C. 20594

National Transportation Safety Board. 2019. *Collision Between Vehicle Controlled by Developmental Automated Driving System and Pedestrian*. Highway Accident Report NTSB/HAR-19/03. Washington, DC.

Abstract: On the evening of March 18, 2018, an automated test vehicle struck and fatally injured a 49-year-old pedestrian crossing N. Mill Avenue, outside a crosswalk, in Tempe, Arizona. The Advanced Technologies Group of Uber Technologies, Inc., had installed a proprietary developmental automated driving system in the test vehicle (a modified 2017 Volvo SC90 sport utility vehicle), which was active at the time of the crash. The 44-year-old operator had been operating the vehicle for about 19 minutes before the crash. The National Transportation Safety Board (NTSB) investigation focused on the inadequate safety culture of the Uber Advanced Technologies Group and the need for safety risk management requirements for testing automated vehicles on public roads. As a result of its investigation, the NTSB issued recommendations to the National Highway Traffic Safety Administration, the state of Arizona, the American Association of Motor Vehicle Administrators, and the Uber Technologies, Inc., Advanced Technologies Group.

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Acronyms and Abbreviations

AAMVA	American Association of Motor Vehicle Administrators
ACC	adaptive cruise control
ADAS	advanced driver assistance system
ADOT	Arizona Department of Transportation
ADS	automated driving system
AEB	automatic emergency braking
ATG	Advanced Technologies Group (Uber)
CFR	<i>Code of Federal Regulations</i>
DMV	Department of Motor Vehicles
ERR	electrical reversible retractor
Euro NCAP	European New Car Assessment Programme
FCW	forward collision warning
FMVSSs	<i>Federal Motor Vehicle Safety Standards</i>
<i>g</i>	acceleration due to gravity
GPS	global positioning system
HMI	human-machine interface
lidar	light detection and ranging
m/s ²	meters per second squared
ms/s ³	meters per second cubed
µg/mL	micrograms per milliliter
ng/mL	nanograms per milliliter
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
ODD	operational design domain
PDOT	Pennsylvania Department of Transportation
SAE	SAE International (formerly Society of Automotive Engineers)
SMS	safety management system
SR-202	State Route 202
SRS	supplemental restraint system
SUV	sport utility vehicle
THC	tetrahydrocannabinol
TPD	Tempe Police Department

Executive Summary

Crash Summary

On March 18, 2018, at 9:58 p.m., an automated test vehicle, based on a modified 2017 Volvo XC90 sport utility vehicle (SUV), struck a female pedestrian walking across the northbound lanes of N. Mill Avenue in Tempe, Arizona. The SUV was operated by the Advanced Technologies Group of Uber Technologies, Inc., which had modified the vehicle with a proprietary developmental automated driving system (ADS). A female operator occupied the driver's seat of the SUV, which was being controlled by the ADS. The road was dry and was illuminated by street lighting.¹

The SUV was completing the second loop on an established test route that included part of northbound N. Mill Avenue. The vehicle had been operating about 19 minutes in autonomous mode—controlled by the ADS—when it approached the collision site in the right lane at a speed of 45 mph, as recorded by the ADS. About that time, the pedestrian began walking across N. Mill Avenue where there was no crosswalk, pushing a bicycle by her side.

The ADS detected the pedestrian 5.6 seconds before impact. Although the ADS continued to track the pedestrian until the crash, it never accurately classified her as a pedestrian or predicted her path. By the time the ADS determined that a collision was imminent, the situation exceeded the response specifications of the ADS braking system. The system design precluded activation of emergency braking for collision mitigation, relying instead on the operator's intervention to avoid a collision or mitigate an impact.

Video from the SUV's inward-facing camera shows that the operator was glancing away from the road for an extended period while the vehicle was approaching the pedestrian. Specifically, she was looking toward the bottom of the SUV's center console, where she had placed her cell phone at the start of the trip. The operator redirected her gaze to the road ahead about 1 second before impact. ADS data show that the operator began steering left 0.02 seconds before striking the pedestrian, at a speed of 39 mph. The pedestrian died in the crash. The vehicle operator was not injured. Toxicological tests on the pedestrian's blood were positive for drugs that can impair perception and judgment.

Probable Cause

The National Transportation Safety Board determines that the probable cause of the crash in Tempe, Arizona, was the failure of the vehicle operator to monitor the driving environment and the operation of the automated driving system because she was visually distracted throughout the trip by her personal cell phone. Contributing to the crash were the Uber Advanced Technologies Group's (1) inadequate safety risk assessment procedures, (2) ineffective oversight of vehicle

¹ For more information, see the factual information and analysis sections of this report. Additional information about the investigation of this crash (NTSB case number HYW18MH010) can be found by accessing the [Docket Management System](https://www.nts.gov/docket-management-system) at www.nts.gov. For more information on our safety recommendations, see the [Safety Recommendation Database](https://www.nts.gov/safety-recommendation-database) at www.nts.gov.

operators, and (3) lack of adequate mechanisms for addressing operators' automation complacency—all a consequence of its inadequate safety culture. Further factors contributing to the crash were (1) the impaired pedestrian's crossing of N. Mill Avenue outside a crosswalk, and (2) the Arizona Department of Transportation's insufficient oversight of automated vehicle testing.

Safety Issues

The investigation identified the following safety issues:

- [Uber Advanced Technologies Group's inadequate safety culture.](#) At the time of the crash, the Uber Advanced Technologies Group had an inadequate safety culture, exhibited by a lack of risk assessment mechanisms, of oversight of vehicle operators, and of personnel with backgrounds in safety management. Since the crash, the company has made changes in organizational, operational, and technical areas. The report explores the deficiencies that led to the crash, the potential countermeasures, and the extent to which the postcrash changes made by the Uber Advanced Technologies Group affect the safe testing of ADSs.
- [Need for safety risk management requirements for testing automated vehicles on public roads.](#) Although the National Highway Traffic Safety Administration has published three iterations of an automated vehicles policy, that summary guidance does not provide a means of evaluating an ADS. The absence of safety regulations and detailed guidance has prompted some states to develop their own requirements for automated vehicle testing. The report explores the roles of federal agencies, industry, and individual states in supporting the development of automation and ensuring public safety during ADS testing.

Findings

- [None of the following were factors in the crash: \(1\) driver licensing, experience, or knowledge of the automated driving system operation; \(2\) vehicle operator substance impairment or fatigue; or \(3\) mechanical condition of the vehicle.](#)
- [The emergency response to the crash was timely and adequate.](#)
- [The pedestrian's unsafe behavior in crossing the street in front of the approaching vehicle at night and at a location without a crosswalk violated Arizona statutes and was possibly due to diminished perception and judgment resulting from drug use.](#)
- [The Uber Advanced Technologies Group did not adequately manage the anticipated safety risk of its automated driving system's functional limitations, including the system's inability in this crash to correctly classify and predict the path of the pedestrian crossing the road midblock.](#)

- The aspect of the automated driving system's design that precluded braking in emergency situations only when a crash was unavoidable increased the safety risks associated with testing automated driving systems on public roads.
- Because the Uber Advanced Technologies Group's automated driving system was developmental, with associated limitations and expectations of failure, the extent to which those limitations pose a safety risk depends on safety redundancies and mitigation strategies designed to reduce the safety risk associated with testing automated driving systems on public roads.
- The Uber Advanced Technologies Group's deactivation of the Volvo forward collision warning and automatic emergency braking systems without replacing their full capabilities removed a layer of safety redundancy and increased the risks associated with testing automated driving systems on public roads.
- Postcrash changes by the Uber Advanced Technologies Group, such as making Volvo's forward collision warning and automatic emergency braking available during operation of the automated driving system (ADS), added a layer of safety redundancy that reduces the safety risks associated with testing ADSs on public roads.
- Had the vehicle operator been attentive, she would likely have had sufficient time to detect and react to the crossing pedestrian to avoid the crash or mitigate the impact.
- The vehicle operator's prolonged visual distraction, a typical effect of automation complacency, led to her failure to detect the pedestrian in time to avoid the collision.
- The Uber Advanced Technologies Group did not adequately recognize the risk of automation complacency and develop effective countermeasures to control the risk of vehicle operator disengagement, which contributed to the crash.
- Although the installation of a human-machine interface in the Uber Advanced Technologies Group test vehicles reduced the complexity of the automation-monitoring task, the decision to remove the second vehicle operator increased the task demands on the sole operator and also reduced the safety redundancies that would have minimized the risks associated with testing automated driving systems on public roads.
- Although the Uber Advanced Technologies Group had the means to retroactively monitor the behavior of vehicle operators and their adherence to operational procedures, it rarely did so; and the detrimental effect of the company's ineffective oversight was exacerbated by its decision to remove the second vehicle operator during testing of the automated driving system.
- The Uber Advanced Technologies Group's postcrash inclusion of a second vehicle operator during testing of the automated driving system, along with real-time monitoring of operator attentiveness, begins to address the oversight deficiencies that contributed to the crash.

- [The Uber Advanced Technologies Group’s inadequate safety culture created conditions—including inadequate oversight of vehicle operators—that contributed to the circumstances of the crash and specifically to the vehicle operator’s extended distraction during the crash trip.](#)
- [The Uber Advanced Technologies Group’s plan for implementing a safety management system, as well as postcrash changes in the company’s oversight of vehicle operators, begins to address the deficiencies in safety risk management that contributed to the crash.](#)
- [Mandatory submission of safety self-assessment reports—which are currently voluntary—and their evaluation by the National Highway Traffic Safety Administration would provide a uniform, minimal level of assessment that could aid states with legislation pertaining to the testing of automated vehicles.](#)
- [Arizona’s lack of a safety-focused application-approval process for automated driving system \(ADS\) testing at the time of the crash, and its inaction in developing such a process since the crash, demonstrate the state’s shortcomings in improving the safety of ADS testing and safeguarding the public.](#)
- [Considering the lack of federal safety standards and assessment protocols for automated driving systems, as well as the National Highway Traffic Safety Administration’s inadequate safety self-assessment process, states that have no, or only minimal, requirements related to automated vehicle testing can improve the safety of such testing by implementing a thorough application and review process before granting testing permits.](#)

Recommendations

To the National Highway Traffic Safety Administration:

[Require entities who are testing or who intend to test a developmental automated driving system on public roads to submit a safety self-assessment report to your agency. \(H-19-47\)](#)

[Establish a process for the ongoing evaluation of the safety self-assessment reports as required in Safety Recommendation H-19-47 and determine whether the plans include appropriate safeguards for testing a developmental automated driving system on public roads, including adequate monitoring of vehicle operator engagement, if applicable. \(H-19-48\)](#)

To the state of Arizona:

Require developers to submit an application for testing automated driving system (ADS)-equipped vehicles that, at a minimum, details a plan to manage the risk associated with crashes and operator inattentiveness and establishes countermeasures to prevent crashes or mitigate crash severity within the ADS testing parameters. (H-19-49)

Establish a task group of experts to evaluate applications for testing vehicles equipped with automated driving systems, as described in Safety Recommendation H-19-49, before granting a testing permit. (H-19-50)

To the American Association of Motor Vehicle Administrators:

Inform the states about the circumstances of the Tempe, Arizona, crash and encourage them to (1) require developers to submit an application for testing automated driving system (ADS)-equipped vehicles that, at a minimum, details a plan to manage the risk associated with crashes and operator inattentiveness and establishes countermeasures to prevent crashes or mitigate crash severity within the ADS testing parameters, and (2) establish a task group of experts to evaluate the application before granting a testing permit. (H-19-51)

To the Uber Technologies, Inc., Advanced Technologies Group:

Complete the implementation of a safety management system for automated driving system testing that, at a minimum, includes safety policy, safety risk management, safety assurance, and safety promotion. (H-19-52)

1 Factual Information

1.1 Crash Events

On Sunday, March 18, 2018, at 9:58 p.m. mountain standard time, an automated test vehicle, based on a modified 2017 Volvo XC90 sport utility vehicle (SUV), struck a pedestrian walking midblock across the northbound lanes of N. Mill Avenue in Tempe, Arizona.¹ The SUV was operated by the Advanced Technologies Group (ATG) of Uber Technologies, Inc., which had modified the vehicle by installing a proprietary developmental automated driving system (ADS). The ADS was active at the time of the crash.

The SUV, occupied by a 44-year-old female operator, was completing the second loop on an established test route that included a section of northbound N. Mill Avenue. The SUV had been operating for about 19 minutes in autonomous mode (controlled by the ADS) when it approached the vicinity of the crash site, traveling in the right lane, at a speed of 45 mph. The 49-year-old female pedestrian started to walk east across N. Mill Avenue, pushing a bicycle at her left side (see figure 1). The location had no crosswalk.

According to ADS data, the system first detected the pedestrian 5.6 seconds before the crash. It initially classified the pedestrian as a vehicle, and subsequently also as an unknown object and a bicyclist. Although the ADS continued tracking the pedestrian until the crash, it did not correctly predict her path or reduce the SUV's speed in response to the detected pedestrian.² By the time the system determined that a collision was imminent and the situation exceeded the response specifications of the ADS braking system to avoid the collision—1.2 seconds before impact—the design of the system relied on the vehicle operator to take control of the vehicle. In such situations, the design of the ATG ADS precluded emergency braking for crash mitigation alone.³

Video from an ATG-installed inward-facing camera shows that the operator was glancing away from the roadway for extended periods throughout the trip. Specifically, she was looking down toward the bottom of the center console where she had placed her cell phone at the start of the trip.⁴ According to her phone records, the operator was streaming a television show using an application on her phone. About 6 seconds before the crash, she redirected her gaze downward, where it remained until about 1 second before the crash.

¹ See the appendix for additional information about this National Transportation Safety Board (NTSB) investigation.

² The vehicle was gradually decelerating because it was approaching an intersection and the system had planned a right turn. For details on the route and vehicle motion planning, see section 1.5.

³ For additional details on the ADS and the detection of the pedestrian, see section 1.5.

⁴ For additional information about the vehicle operator's use of a cell phone during the trip, see sections 1.5.6.2 and 1.7.2.3.

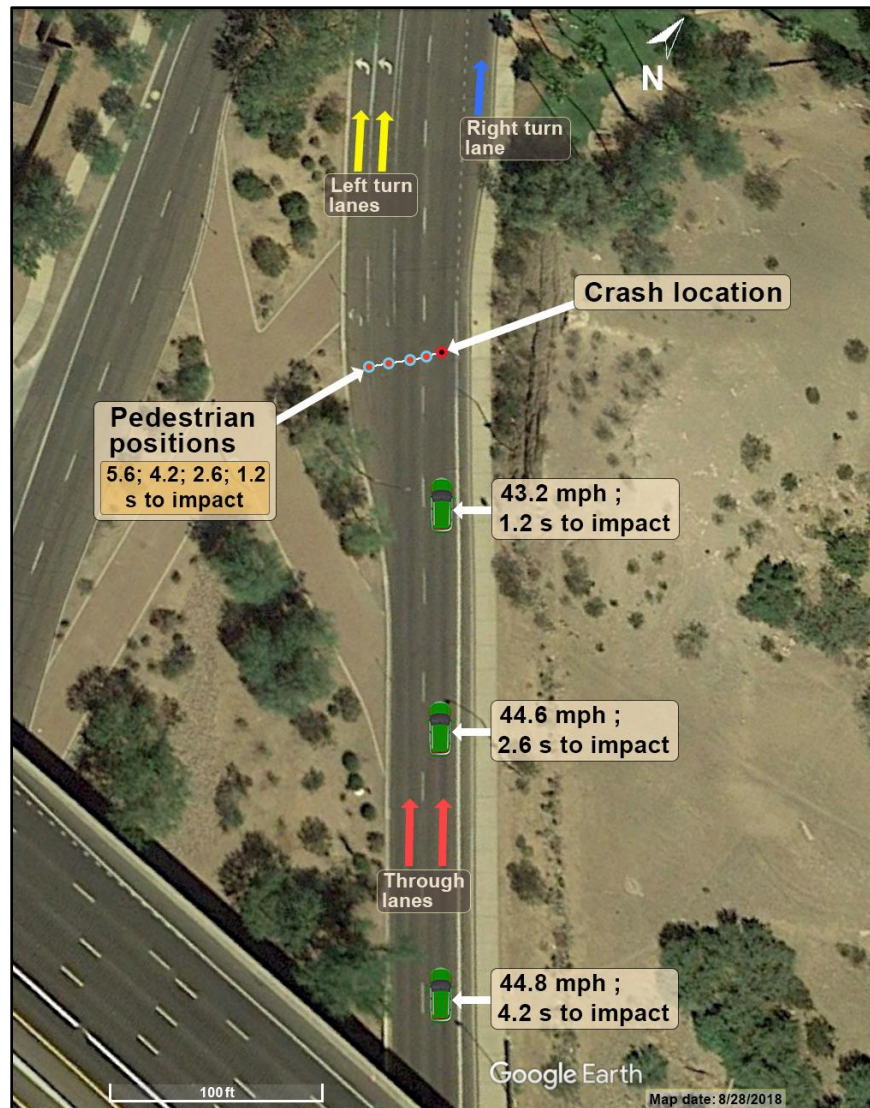


Figure 1. Aerial view of crash location showing path of pedestrian as she attempted to cross N. Mill Avenue and movement and speed of SUV at three points before impact. Pedestrian's path shows her position from initial detection (5.6 seconds before impact) until impact; SUV's position is shown at corresponding times beginning 4.2 seconds before impact. (Source: Adapted from Google Earth)

ADS data show that the operator began steering left 0.02 seconds before striking the pedestrian, at a speed of 39 mph. The video from the ATG-installed forward-facing camera shows that the pedestrian was struck by the SUV's front end at a near-perpendicular angle. The impact pushed the pedestrian under the SUV, which carried her with it. She came to rest 75 feet to the north, in the right-turn lane. The bicycle came to rest 105 feet north of the point of impact. The rest position of the SUV was 189 feet north of the point of impact, in the right-turn lane.

The city of Tempe emergency communication center received a 911 call about the crash at 10:00 p.m. The dispatcher immediately notified the Tempe Police Department (TPD). The Tempe Fire Department received notification 1 minute later. The TPD responded with 11 units, the first

of which arrived on scene at 10:04 p.m. The fire department responded with one engine and one medical unit, both of which arrived on scene at 10:08 p.m. At the time of the crash, it was nighttime, the road surface was dry, and the road was illuminated by street lighting.⁵

1.2 Location

1.2.1 Roadway

The crash occurred in the northbound lanes of N. Mill Avenue, about 400 feet south of its intersection with Curry Road and about 310 feet north of a State Route 202 (SR-202) overpass. The impact occurred along a 311-foot-long tangent—a straightaway section of the roadway. North of the crash site, the horizontal alignment consists of a 328-foot-long, 955-foot-radius curve to the right in the northbound direction of travel. South of the crash location, the horizontal alignment consists of a 3,000-foot-long, 3,280-foot-radius leftward curve. The crash occurred about 244 feet into the straightaway section of N. Mill Avenue, 67 feet before the start of the north curve.⁶ The posted speed limit on this section of N. Mill Avenue is 45 mph.

Near the crash site, the northbound roadway contains two through lanes, each 13.6 feet wide, and one 4-foot-wide bicycle lane along the right shoulder. The road widens for the formation of two left-turn lanes, so that at the crash site, the road is 51 feet wide (refer to figure 1). The vehicle lanes are separated by 4-inch-wide broken white lines, with a solid white line defining the bicycle lane. Raised curbing runs along the side of the road.

Safety lighting in the area of the crash includes six light poles along northbound N. Mill Avenue. The light poles are positioned within about 600 feet of the crash site, four on the right and two on the left side of the road. The light closest to the crash site on the right side of the road is 47 feet south of the impact area. On the left side of the road, the nearest light is 57 feet south of the crash site. According to the TPD, five of the lights were operational when officers arrived. The light on the left side of the road, 158 feet north of the crash site, was not operating.⁷

The average daily traffic northbound on N. Mill Avenue obtained shortly after the crash was 16,800 vehicles. At the request of NTSB investigators, the city of Tempe obtained a daily count of pedestrians (66) and bicyclists (12) in June 2018.⁸ The 10-year crash history of the area between the SR-202 overpass and Curry Road listed no pedestrian fatalities or injuries.

⁵ The temperature was 56°F, the wind was from the west-southwest at 12 mph with gusts to 21 mph, and there was no precipitation. The records are from the weather station at Phoenix Sky Harbor International Airport, 3.8 miles west of the crash site.

⁶ Figure 1 depicts the straightaway section of N. Mill Avenue and about 70 feet of the end segment of the south curve. Considering the length and the large radius of the south curve, the curvature of the roadway might not be easily perceptible when viewing only a limited segment of the curve.

⁷ For more details regarding the installation and performance of the safety lighting, see the [public docket](#) for this investigation (HWY18MH010).

⁸ The pedestrian and bicyclist count was conducted during a 24-hour period on a Tuesday, along N. Mill Avenue between the SR-202 overpass and about 175 feet south of Curry Road, covering a distance of about 500 feet. No sidewalks are present along this segment of N. Mill Avenue. A musical event occurred at a nearby business during the count, which suggests that the average daily count is smaller, possibly considerably smaller.

1.2.2 Median

The northbound and southbound travel lanes on N. Mill Avenue are separated by a landscaped median. Next to the crash site, the median is about 71 feet wide and includes an X-shaped, red-brick configuration, which at the time of the crash had the appearance of a pathway (figure 2). Also at the time of the crash, the median contained four signs prohibiting pedestrian crossing. Each consisted of a no-pedestrian-crossing symbol with an accompanying USE CROSSWALK plaque (see figure 2).⁹ Two of the signs were on the median's east edge and faced the northbound roadway, about 30 feet north and 130 feet south of the crash site.



Figure 2. Configuration of median on N. Mill Avenue at time of crash (left image) and postcrash changes (right images). Aerial view in left image shows X-shaped configuration, location of signs prohibiting pedestrian crossing, and insets illustrating signs. Right image shows rocks placed postcrash on median (top) and double-sided signs prohibiting pedestrian crossing (bottom). (Sources: Left image adapted from Google Earth; top right image from *Arizona Republic*; bottom right image from city of Tempe)

⁹ The no-pedestrian-crossing symbol was a regulatory sign measuring 18 by 18 inches. The use-crosswalk plaques were also regulatory signs, each measuring 18 inches wide and 12 inches high.

The nearest crosswalks to the crash site are 380 feet north, at the intersection with Curry Road, and 2,700 feet south, at the intersection with Rio Salado Parkway. The north tip of the median—where its width narrows to 6 feet—ends at the crosswalk at the intersection with Curry Road. There is no established walkway from that crosswalk to the brick configuration on the median. The south end of the median ends below the SR-202 overpass. NTSB investigators could not determine how the pedestrian arrived at the median, or whether she reached it by crossing N. Mill Avenue midblock, outside a crosswalk.

After the crash, the city of Tempe added four signs to the existing signposts prohibiting pedestrian crossing, resulting in four double-sided prohibition signs that are visible from both the median and the roadway. The city also removed the X-shaped decorative brick path and replaced it with rocks, creating a terrain unsuitable for walking (refer to figure 2).

1.3 Injuries and Occupant Protection

The pedestrian died on scene from multiple blunt force injuries. The vehicle operator was not injured. The driver's seat of the SUV was equipped with a lap/shoulder belt, which was found attached at its anchor points after the crash. The belt's webbing showed cupping with abrasions and load marks, indicating that it had been worn at the time of impact.

The front seats of the SUV were equipped with electrical reversible retractors (ERRs), seat belt pretensioners that tighten seat belts, keeping occupants closer to their seats in anticipation of a crash. Although the SUV's air bags did not deploy during the crash, the ERR on the driver's seat was triggered after the impact with the pedestrian. For a further description of the ERR, see section 1.6.2.¹⁰

1.4 Vehicle Factors

1.4.1 Sport Utility Vehicle

1.4.1.1 General Description. As noted earlier, the SUV had been modified and equipped with an ADS (see section 1.5). It was also factory-equipped with advanced driver assistance systems (ADASs), including ones designed to avoid or mitigate collisions with pedestrians or bicyclists (see section 1.6).¹¹

The vehicle involved in the crash was a factory-built 2017 Volvo XC90 Inscription model, equipped with a 2.0-liter gas/electric hybrid 400-horsepower engine and an 8-speed automatic transmission. The vehicle had light-emitting-diode headlights of the bending-beam type.¹² It had five passenger seats, two in the front and three in the second row. The vehicle was factory-equipped

¹⁰ Section 1.6 discusses the SUV's design and its collision mitigation systems that affect other roadway users, specifically pedestrians and bicyclists.

¹¹ At the time of the crash, the ADAS was not active because it was designed to deactivate during ADS testing. The interaction between the ATG ADS and the Volvo ADAS is discussed in section 1.6.3.

¹² Bending-beam headlights turn from side to side as the steering wheel turns, helping to illuminate curves.

with a third row of seats, but ATG removed it to create space for computers and other ADS-related equipment.

1.4.1.2 Damage. The SUV sustained damage to the front end. Contact damage on the front bumper, grille, and hood was concentrated in an area slightly offset toward the passenger side (see figure 3). Both bicycle tires left impressions on the SUV's bumper cover. Scrape marks were visible on the lower left corner of the SUV's front spoiler, caused by the bicycle's rear sprocket assembly. The headlights were intact, and there was no other external damage. The vehicle's interior was unaffected by the crash.

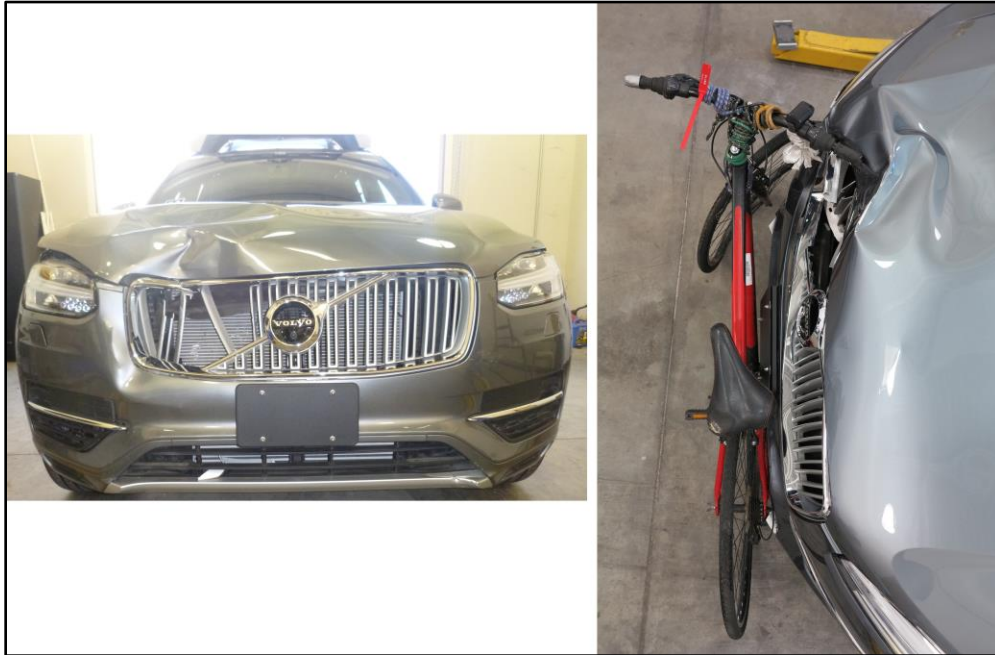


Figure 3. SUV postcrash showing damage to front end (left image) and overhead view of bicycle's position at impact (right image).

1.4.1.3 Mechanical Inspection. NTSB investigators examined the function of the vehicle's factory-equipped components, including the braking, lighting, suspension, and electrical systems. They also examined the wheels and tires. They found no damage or defects in any major mechanical system that could have affected the SUV's performance. No noncollision defects were found on any of the vehicle's tires or wheels.

1.4.1.4 Data Recorder Sources. The SUV was equipped with numerous systems and modules capable of recording data. The various sources recorded information pertaining to vehicle dynamics, occupant protection systems, and autonomous operation of the vehicle (such as detection of other objects in the environment and video of the environment around and inside the SUV). Relevant recorded information captured by the ATG-installed systems is discussed in section 1.5.6. Relevant recorded information captured by the factory-equipped systems—the standard Volvo data-recording components—is discussed in section 1.6.2.

1.4.1.5 Maintenance and Safety Recalls. The vehicle records show regular mechanical maintenance, the last taking place on January 23, 2018.¹³ Based on video from an ATG-installed inward-facing camera, before starting her shift on the day of the crash, the vehicle operator conducted a regular pretrip inspection—examining the SUV’s exterior and interior and verifying the status of the equipment supporting autonomous operation.¹⁴ The SUV was not subject to any federal or Arizona mechanical inspection requirements.¹⁵ It was also not subject to any safety recalls.¹⁶

1.4.2 Bicycle

The bicycle was a 2017 700c Hyper SpinFit manufactured by Hyper Toy Company. As a result of the crash, the bicycle’s front wheel was twisted, and the front fork was misaligned with the handle bars (figure 4 shows the bicycle’s position at impact).

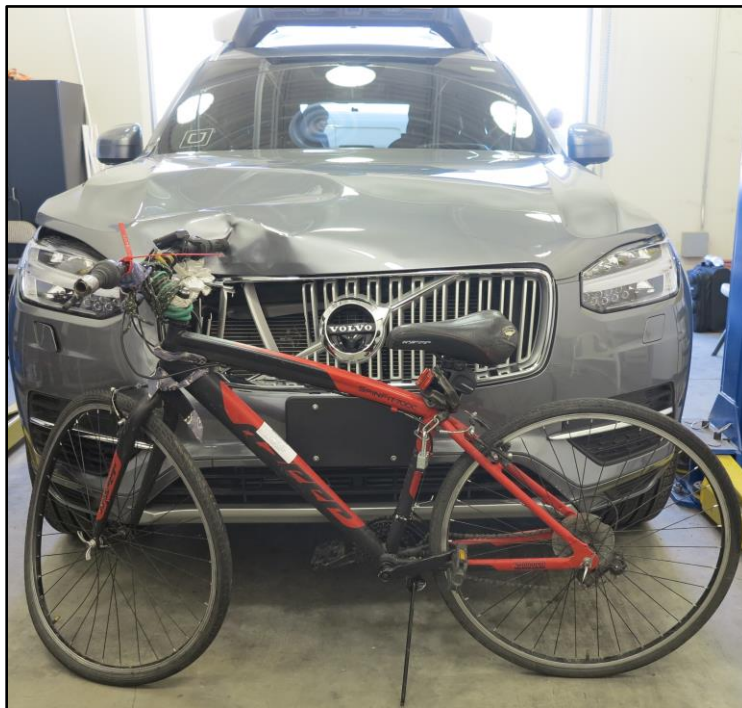


Figure 4. Approximate position of bicycle at impact.

¹³ Maintenance consisted of changing the oil and oil filter, rotating tires, and checking fluids, brakes, and suspension. All four tires were replaced on March 15, 2018.

¹⁴ Among other items, vehicle operators were required by ATG to inspect the ADS disengagement button, the sensors pod, and the functionality of the dash cameras and the tablet through which operators interacted with the system. See the Operations factual report in the NTSB public docket for this investigation (HWY18MH010) for additional details on the pretrip inspection.

¹⁵ Arizona has a requirement for emissions inspection (Arizona [vehicle code 49-542](#)) but not for mechanical vehicle inspection. For a description of ATG operations, see section 1.8.

¹⁶ NTSB investigators searched the National Highway Traffic Safety Administration (NHTSA) [safety recall database](#) on March 29, 2019, and found no recalls relating to the vehicle.

The bicycle had a reflector on the stem and two reflectors on either side of both pedals. The reflectors faced forward of and behind the bicycle, but not in the direction of the approaching SUV. According to video from the ATG-installed forward-facing camera, the bicycle did not have side-facing reflectors on the spokes of either wheel.¹⁷

1.5 Uber ATG Developmental Automated Driving System

1.5.1 Overview

The ATG developmental ADS installed on the SUV was designed to operate in autonomous mode only on premapped, designated routes. When the ADS was active, it performed all driving tasks, including changing lanes, overtaking slow-moving or stopped vehicles, turning, and stopping at traffic lights and stop signs. Although the system was designed to be fully automated along a specific route, a human operator inside the vehicle was tasked with overseeing the system's operation, monitoring the driving environment, and if necessary, taking control of the vehicle and intervening in an emergency.¹⁸

At the time of the crash, the SUV was operating on a designated route for ADS testing, an 11.2-mile loop that included downtown Tempe. Unless stated otherwise, the ADS discussed in this report refers only to the Krypton platform that was installed on the SUV at the time of the crash.¹⁹ After the crash, ATG made numerous changes to the ADS (see sections 1.9 and 2.2).

1.5.2 Structural Components

The ADS that controlled the SUV at the time of the crash consisted of multiple systems for monitoring and analyzing the vehicle's performance and the surrounding environment. Each system had hardware components and software analysis and data-recording elements. As shown in figure 5, structural components included (1) a lidar (light detection and ranging) system, (2) a radar system, (3) a camera system, and (4) telemetry, positioning, monitoring, and telecommunication systems.²⁰

As part of development of the ADS, ATG equipped the SUV with a supplementary fleet-monitoring dash-camera system that included a forward-facing camera and an inward-facing camera for monitoring the vehicle operator. ATG also installed a human-machine interface (HMI)—a tablet computer—that enabled interaction between the vehicle operator and the ADS

¹⁷ Title 16 *Code of Federal Regulations* (CFR) 1512.16 requires newly sold bicycles for roadway use to have reflectors on the front, rear, and pedals, and to have side reflectors on a sidewall of the wheels or on the wheel spokes. This bicycle was not new, and investigators were unable to determine when the pedestrian obtained it.

¹⁸ For additional details regarding operator responsibilities and training, see section 1.8.4.

¹⁹ The software installed on the crash vehicle was version 2018.071.3pl. The rest of the ATG fleet of 2017 Volvo XC90 vehicles at the time of the crash used the same system.

²⁰ For additional information about the ADS components and its functionality, see the Vehicle Automation factual report in the docket for this investigation (HWY18MH010).

(see section 1.5.7 for details).²¹ A regularly scheduled recalibration of the ADS components, primarily the sensors, was conducted on March 13, 2018.

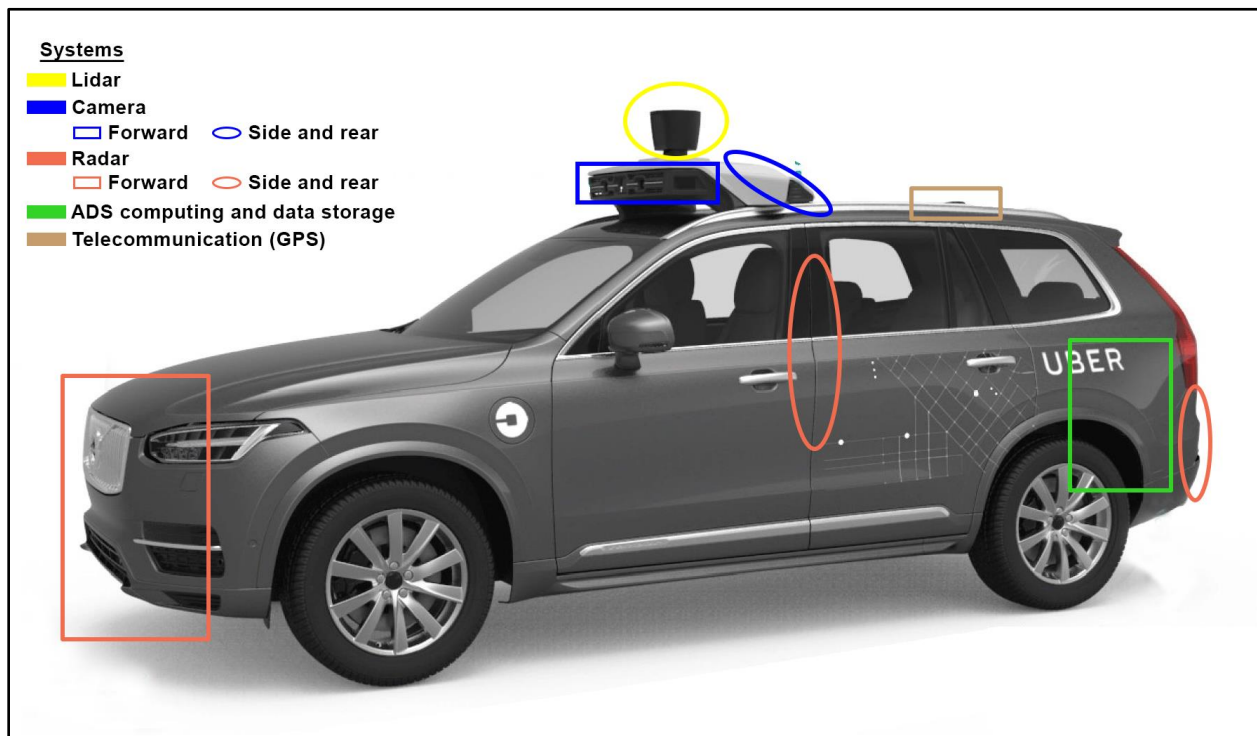


Figure 5. Location of sensor components on 2017 Volvo XC90 equipped with ATG's ADS. (Not all locations of sensor components are shown)

1.5.2.1 Lidar System. The lidar system consisted of a single lidar unit mounted on the forward half of the SUV's roof, as shown above (figure 5).²² The lidar, which was manufactured by Velodyne, had a range of over 100 meters (328 feet) and could detect objects in a 360-degree radius. Initial processing of lidar data was done by the Velodyne processing unit. The ADS then used the data to build a representation of the surrounding environment, which was continually updated as the system detected new objects.

The ADS's primary use of lidar data was for object detection and classification of detected objects. Data from the lidar system were also used to create a map of the designated route and to verify the vehicle's position along that route.

1.5.2.2 Radar System. The radar system consisted of eight radars with dual ranging capabilities—alternating between narrow, long-range scanning and wider, medium-range scanning—positioned around the vehicle to provide a 360-degree view of the surrounding

²¹ An HMI is any type of interface—such as a display, a keypad, or a button—that allows a user to interact with a machine.

²² Lidar uses laser light to detect and measure distance to objects by directing light and receiving it back upon its reflection from an object. Time of flight between the pulsing of the laser light and the reception of its return upon reflection from an object is used to compute distance.

environment.²³ Two radars were placed on the front of the vehicle for forward scanning, two radars were placed on each side for lateral scanning, and two radars were placed on the rear for rearward scanning.

The long-range radar scan had an observational range of up to 180 meters (591 feet), with a 20-degree field of view. The medium-range radar scan had an observational range of up to 65 meters (213 feet), with a 90-degree field of view. The radar system initially processed the data, which the ADS then used to build and update its representation of the environment. The ADS used data from the radar system primarily for detection and classification of objects.

1.5.2.3 Camera System. The camera system consisted of eleven cameras that gave a 360-degree view of the surrounding environment. The system included (1) two cameras with narrow fields of view for long-range forward stereo imaging, (2) one single-lens camera with a wide field of view for medium-range forward imaging, (3) two single-lens cameras with wide fields of view for medium-range imaging of lateral areas, (4) two single-lens cameras with wide fields of view for imaging the area behind the vehicle, and (5) four surround-view cameras positioned for close-range imaging.

The range at which an object could be detected depended on its size and visibility. The ADS processed the optical data from all cameras. The primary use of the imaging data from the forward camera was in the detection of obstacles and the classification of detected objects. The forward camera was also used to recognize traffic signs and the status of traffic lights.²⁴ In addition to monitoring and real-time analysis of perceived objects, the cameras continually recorded the driving environment. ATG regularly reviewed segments of recorded video from the eleven cameras as part of ADS development.

1.5.2.4 Other Systems. A global positioning system (GPS) was used to determine the SUV's position at ADS engagement (described in section 1.5.4.1).²⁵ The SUV was also equipped with a long-term evolution antenna for securing mobile data traffic and authenticating cloud communication.²⁶ Twelve ultrasonic sensors with a range of 5 meters (16 feet) were integrated around the vehicle. They were used primarily to detect other vehicles during lane changes and to identify pedestrians, curbs, and other obstacles when the vehicle was parking or collecting passengers. The vehicle was also equipped with an inertial measurement unit, an electronic device that measures acceleration and angular velocity. The device contained accelerometers and gyroscopes and was used to refine the position of the SUV along its route.

²³ Radars use super-high-frequency radio waves to detect and measure distance to objects. Time of flight between the broadcast of the waves and the reception of their return on reflection from an object is used to compute distance. Super high frequency is defined by the International Telecommunications Union as the band of frequencies ranging from 3 to 30 gigahertz, where 1 gigahertz represents 1 billion cycles per second.

²⁴ The camera system also supported near-range sensing of people and objects within 5 meters (16 feet) of the SUV during lane changes and parking, and when collecting passengers.

²⁵ The GPS was not used to verify the vehicle's position along the premapped routes. Vehicle path verification, as described in section 1.5.3, was done primarily by the lidar system.

²⁶ Long-term evolution, or LTE, is a wireless communication standard for the 4G telecommunication network.

1.5.3 Route Mapping, Path Guidance, and Verification

ATG developed high-definition maps for the designated routes where the ADS operated autonomously. The routes could be considered the ADS geographical operational design domain (ODD)—the roadways on which an automated system is designed to operate.²⁷ Routes were mapped by manually driving an ADS-equipped vehicle along a route while the lidar, camera, and other sensor systems recorded all aspects of the environment. The resulting high-definition map included road markings, curbs, traffic signals, signage, roadway grade and curvature, and pertinent nontraffic static objects, such as buildings. The sensors also recorded vehicle dynamics—velocity, angle, and yaw rate.

The ADS can be initiated only when a vehicle is on a designated premapped route. This system-based restriction precludes operators from engaging the ADS outside the premapped route. Operators are nevertheless responsible for adhering to other ODD conditions, such as operation during inclement weather (see below for operational restrictions).

As the vehicle travels along its route, the sensors continually scan the environment and monitor vehicle dynamics, which are then analyzed to verify the vehicle's position. The environmental features and roadway characteristics detected by the system, along with the monitored vehicle dynamics, are matched to the features and characteristics along the premapped route at those specific locations. The process of continuous and redundant verification of vehicle position is designed to eliminate the possibility of a vehicle venturing outside its designated path. It also allows the system to adapt to slight deviations in the environment and adjust the ADS motion plan accordingly.

1.5.4 Operation

1.5.4.1. Engagement and Restrictions. ADS engagement is a two-step process that can be completed only when an ATG test vehicle is on a designated route. An operator engages the ADS by (1) pulling up a red knob on the center console to the right of the shift lever, and (2) pushing a silver button behind the red knob (see section 1.5.7 for illustration). ADS testing in the Tempe area was restricted by ATG to (1) a maximum vehicle speed of 45 mph; (2) urban and rural roads, excluding highways; (3) most weather conditions, except heavy rain and snow; and (4) most roadway conditions, including dry and wet but excluding accumulated snow. ATG did not restrict ADS testing on the basis of lighting conditions (daytime, nighttime, or twilight).

1.5.4.2. Disengagement and Operator Takeover. The ADS can be disengaged by a vehicle operator or by the system itself. An operator can immediately disengage the ADS by taking control of the vehicle—by braking, steering, or accelerating—or by pushing down the red disengagement knob on the center console.²⁸

²⁷ The concept of ODD was introduced in the first [Federal Automated Vehicles Policy](#) published by the US Department of Transportation in September 2016 (accessed December 6, 2019). Based on that policy, a defined ODD should include the speed range, roadways, geographic area, and environmental conditions under which an automated vehicle is designed to operate.

²⁸ Unlatching a lap/shoulder belt would also result in immediate ADS disengagement.

Depending on the circumstances, ADS disengagement initiated by the system can be anticipated or sudden. An anticipated disengagement, such as when the vehicle is exiting a premapped area (geographical ODD), is preceded by an early auditory alert—before disengagement begins—to the operator to take control of the vehicle.²⁹ If the operator fails to take control, at the time of disengagement the system sends the operator another auditory alert and simultaneously starts a gradual vehicle slowdown. Sudden disengagement can follow an operational error in a sensory system or a system fault, such as a problem with data recording. At the time of sudden disengagement, the system sends an auditory alert to the operator.

1.4.5.3 Operator Protocols. At the time of the crash, ATG tested with one vehicle operator inside a vehicle. The company's operating procedures required vehicle operators, after initiating the ADS, to (1) monitor the driving environment and the operation of the ADS; (2) take control of the vehicle and intervene in emergency situations to avoid collisions; (3) hover with their hands above the steering wheel and their foot above the brake pedal to ensure fast takeover of vehicle control; and (4) detect and report any unusual events in the environment or in ADS functioning by interacting with the HMI—as described in section 1.5.7.³⁰

1.5.5 Motion Planning: Object Detection and Hazard Avoidance

A premapped designated route serves as the ADS initial motion plan. As the ADS navigates and controls the vehicle along the route, the system continually monitors the environment for objects, moving or stationary, on or outside the roadway. The detected objects are incorporated into the virtual environment, and the system dynamically updates the vehicle's motion plan to avoid potential conflicts. Changes to the motion plan are usually gradual enough to allow smooth changes in vehicle speed or heading. However, sudden hazardous situations, or their late detection by the system, can require abrupt changes to the motion plan. This section describes the processes by which the ADS operating at the time of the crash detected, classified, and determined the path of potential obstacles, and the design governing ADS actions in emergency situations.

1.5.5.1 Object Detection and Classification. Objects were detected primarily by the lidar, radar, and camera systems. When an object was detected, it was tracked, its heading and velocity were calculated, and it was classified by the ADS. Detected objects could be classified as vehicles, pedestrians, or bicyclists. A detected object could also be classified as "other," indicating unknown object. The perception process of the ADS classified detected objects by relying on the fusion of the three sensor systems. The ADS used a prioritization schema that promoted tracking by certain sensory systems over others and that was also dependent on the recency of an observation.³¹

1.5.5.2 Path Prediction. Once the ADS perception process classified a detected object, the ADS generated multiple possible trajectories—path predictions—based on the typical goal

²⁹ A system-based restriction precluded autonomous operation outside the designated premapped area. If a final destination was outside that area, the ADS would initiate an anticipated disengagement protocol before exiting the area.

³⁰ For details about vehicle operator training, see section 1.8.3.

³¹ A more recent detection of an object received a higher tracking prioritization in the ADS classification schema.

of the detected object and its tracking history. For example, an object detected in a travel lane and classified as a vehicle would generally be assigned a goal of traveling in the direction of traffic in that lane. The system then incorporated the previously detected locations of that object—its tracking history—before generating a possible trajectory. The path predictions were continually updated to incorporate each object's latest detected location.

If the perception process changed the classification of a detected object, it no longer considered the tracking history of that object when generating a new trajectory. For newly reclassified objects, the predicted path depended on its goal. For example, a detected object that was in a travel lane and that was newly classified as a bicycle could be assigned the goal of moving in the direction of traffic in that lane, independent of the object's lack of tracking history.

Certain object classifications ("other") were not assigned goals.³² Their currently detected location was viewed as static, and unless the location was directly on the path of the test vehicle, the object was not considered a possible obstacle. Pedestrians outside the vicinity of a crosswalk were also not assigned an explicit goal. However, a midblock crossing trajectory might be predicted for them based on the observed velocities, when they were continually detected and classified as pedestrians.

If the predicted path of a detected object intersected that of the test vehicle, the ADS would modify its motion plan or initiate hazard avoidance (described below). Since the crash, ATG has changed the way the system fuses sensor information and predicts possible trajectories so that it retains tracking history even if detected objects are reclassified (see section 1.9).

1.5.5.3 Hazard Avoidance and Emergency Braking. As the ADS detected, classified, and tracked objects, it modulated the vehicle dynamics—steering and throttle—to maintain smooth movement, without abrupt changes in motion. In certain situations, such as the sudden hard braking of a vehicle ahead or an initially obscured pedestrian darting in front of the test vehicle, gradual changes in vehicle trajectory might be insufficient to avoid a collision.

As a developmental system, the ATG ADS was designed with a specific engagement protocol for emergency situations. An emergency was defined as a situation requiring braking at a deceleration greater than 7 meters per second squared (m/s^2) (0.71 g) or rate of deceleration (jerk) greater than ± 5 meters per second cubed (m/s^3) to prevent a collision.³³ When the system detected an emergency situation, it initiated action suppression. That was a 1-second period during which the ADS would suppress braking while (1) the system verified the nature of the detected hazard and calculated an alternative path, or (2) the vehicle operator took control of the vehicle.

No alert was given to the operator when action suppression was initiated. ATG stated that it implemented action suppression because of concerns about false alarms—the ADS

³² Since "other" objects were viewed as unknown, their general direction of travel—their potential goals—would also have been unknown.

³³ Acceleration due to gravity is denoted as g . Although the ADS limited maximum automated braking to 0.71 g , the vehicle's maximum braking capacity, with optimal roadway surface friction, was 1 g . The TPD determined, on the basis of the vehicle's capabilities and the road surface friction, that the SUV was capable of decelerating at an average of 0.92 g in the crash area.

identifying a hazardous situation when none existed—that would cause the vehicle to engage in unnecessary extreme maneuvers. The primary countermeasure in an emergency situation was the vehicle operator, who was expected to recognize the hazard, to take control of the vehicle, and to intervene appropriately.³⁴

If a vehicle operator did not take control of the vehicle in an emergency and the situation remained hazardous after action suppression, the ADS response depended on whether a collision could be avoided with a maximum braking of 7 m/s^2 and a maximum deceleration rate of 5 m/s^3 . If a collision could be avoided with the maximum allowed braking and jerk limit, the system executed its plan and engaged braking to the maximum allowed. If a collision could not be avoided with the application of maximum allowed braking, the system was designed to send an auditory alert to the vehicle operator while simultaneously initiating gradual vehicle slowdown. In such circumstances, the ADS was not designed to apply maximum braking only to lessen the severity of a collision.

Since the crash, ATG has changed the way the ADS responds in an emergency situation. The system will now activate maximum allowed braking for crash mitigation as well (see section 1.9).

1.5.6 Data Recorded During Crash Trip

ATG provided NTSB investigators with a comprehensive dataset covering trip preparation in the ATG terminal and the approximately 39-minute operation of the crash vehicle on public roads, as recorded by both the ADS and the supplementary fleet-monitoring system. This section focuses on events leading to the crash but also includes events earlier in the trip. Sources are the quantitative data recorded by the ADS and the video recorded by the cameras, including the supplementary monitoring system. Data pertaining to the operator's interaction with the HMI—the tablet computer—are discussed in section 1.5.7.

1.5.6.1 ADS Data. The ADS data included the time the system detected the pedestrian, how the system classified and assigned predicted paths to the pedestrian, various vehicle dynamics, and the ADS's planned and executed actions. At the request of NTSB investigators, ATG provided a playback of sensor and vehicle dynamics information showing the events leading up to the crash. Investigators examined the output from the sensor systems to create a timeline of the events (see the table). The ADS did not report any sensor or system failures during the crash trip.

³⁴ The vehicle operator was expected to intervene only if circumstances were truly collision-imminent, rather than related to system error or object misclassification.

Table. Selected parameters recorded by vehicle's ADS.

Time to Impact (seconds)	Speed (mph)	Classification and Path Prediction ^a	Vehicle and System Actions ^b
-9.9	35.1	--	Vehicle begins to accelerate from 35 mph in response to increased speed limit.
-5.8	44.1	--	Vehicle reaches 44 mph.
-5.6	44.3	<u>Classification:</u> <i>Vehicle</i> —by radar <u>Path prediction:</u> <i>None</i> ; not on path of SUV	Radar makes first detection of pedestrian (classified as vehicle) and estimates speed.
-5.2	44.6	<u>Classification:</u> <i>Other</i> —by lidar <u>Path prediction:</u> <i>Static</i> ; not on path of SUV	Lidar detects unknown object. Object is considered new, tracking history is unavailable, and velocity cannot be determined. ADS predicts object's path as static.
-4.2	44.8	<u>Classification:</u> <i>Vehicle</i> —by lidar <u>Path prediction:</u> <i>Static</i> ; not on path of SUV	Lidar classifies detected object as <i>vehicle</i> ; this is a changed classification of object and without a tracking history. ADS predicts object's path as static.
-3.9 ^c	44.8	<u>Classification:</u> <i>Vehicle</i> —by lidar <u>Path prediction:</u> Left through lane (next to SUV); not on path of SUV	Lidar retains classification <i>vehicle</i> . Based on tracking history and assigned goal, ADS predicts object's path as traveling in left through lane.
-3.8 to -2.7	44.7	<u>Classification:</u> alternates between <i>vehicle</i> and <i>other</i> —by lidar <u>Path prediction:</u> alternates between <i>static</i> and left through lane; neither considered on path of SUV	Object's classification alternates several times between <i>vehicle</i> and <i>other</i> . At each change, tracking history is unavailable; ADS predicts object's path as static. When detected object's classification remains same, ADS predicts path as traveling in left through lane.
-2.6	44.6	<u>Classification:</u> <i>Bicycle</i> —by lidar <u>Path prediction:</u> <i>Static</i> ; not on path of SUV	Lidar classifies detected object as <i>bicycle</i> ; this is a changed classification of object and object is without a tracking history. ADS predicts bicycle's path as static.
-2.5	44.6	<u>Classification:</u> <i>Bicycle</i> —by lidar <u>Path prediction:</u> Left through lane (next to SUV); not on path of SUV	Lidar retains <i>bicycle</i> classification; based on tracking history and assigned goal, ADS predicts bicycle's path as traveling in left through lane.

Time to Impact (seconds)	Speed (mph)	Classification and Path Prediction ^a	Vehicle and System Actions ^b
-1.5	43.8 ^d	<u>Classification:</u> <i>Other</i> —by lidar <u>Path prediction:</u> <i>Static</i> ; partially on path of SUV	<ul style="list-style-type: none"> - Lidar detects unknown object; because this is an unknown object, it lacks tracking history and is not assigned a goal. ADS predicts object's path as static. - Although detected object is partially in SUV's lane of travel, ADS generates motion plan around object (maneuver to right of object); motion plan remains valid—avoiding object—for next two data points.
-1.2	43.2	<u>Classification:</u> <i>Bicycle</i> —by lidar <u>Path prediction:</u> Travel lane of SUV; fully on path of SUV	<ul style="list-style-type: none"> - Lidar detects bicycle; although this is a changed classification and without a tracking history, it is assigned a goal. ADS predicts bicycle to be on SUV's path. - ADS motion plan (generated 0.3 seconds earlier) for steering around bicycle no longer possible; situation becomes hazardous (emergency situation). - Action suppression begins.
-0.2	40.5	<u>Classification:</u> <i>Bicycle</i> —by lidar <u>Path prediction:</u> Travel lane of SUV; fully on path of SUV	<ul style="list-style-type: none"> - Action suppression ends 1 second after it begins. - Situation remains hazardous; ADS initiates plan for gradual vehicle slowdown. - Auditory alert indicates that ADS is engaging and controlled slowdown is initiating.^e
-0.02	39.0	--	Vehicle operator takes control of steering wheel, disengaging ADS.
Impact			
0.7	37	--	Vehicle operator brakes.
^a Table reports only changes in object classification and path prediction. Last reported values persist until a new one is reported. ^b Process of predicting path of detected object is complex and relies on examination of numerous factors, beyond details given in this column, as described in section 1.5.5. ^c Vehicle was about 243 feet from impact location at this time. ^d Vehicle started decelerating due to approaching intersection, where preplanned route included right turn at Curry Road. Deceleration plan was generated 3.6 seconds before impact. ^e Slight communication delay made it unclear whether implementation of slowdown plan started before operator took control.			

The ADS first detected the pedestrian 5.6 seconds before impact, when she was about 10 feet east of the median curb—approximately in the middle of where the northbound road's two left-turn lanes begin to form (refer to figure 1). The system never classified her as a pedestrian—or correctly predicted her path—because she was crossing N. Mill Avenue at a location without a crosswalk, and the system design did not include consideration for jaywalking pedestrians. The

ADS changed the pedestrian's classification several times, alternating between vehicle, bicycle, and other. Because the system never classified the pedestrian as such, and the system's design excluded tracking history for nonpersisting objects—those with changed classifications—it was unable to correctly predict the pedestrian's path.

Only when the ADS determined that the pedestrian's detected location was in the path of the SUV, 1.2 seconds before impact, did the system recognize an emergency situation—an imminent collision. Because preventing the collision would have required braking beyond the ADS braking design specifications, the system initiated action suppression of its motion plan. One second later, the vehicle was still on a collision path with the pedestrian and the operator had not taken control of the vehicle. Preventing the collision still required braking beyond the ADS design specifications. In accordance with its design, the system did not engage emergency braking, but instead sounded an auditory alert to the vehicle operator as it initiated a plan to gradually slow the vehicle.

1.5.6.2 Camera Recordings. In addition to the ADS camera system that detected obstacles and monitored the environment, the SUV was equipped with Janus V3, a fleet-monitoring device consisting of three cameras: one facing forward, one facing rearward, and one facing inward. NTSB investigators examined video from both the ADS and the Janus cameras.³⁵

Janus Forward-Facing Camera. The first time the pedestrian is visible on the recording is about 2 seconds before the collision. Her shoes are the first objects to become visible, followed by the wheel rims of the bicycle she is pushing. About 1 second before the collision, the pedestrian is seen looking over her right shoulder toward the SUV. She appears to be wearing white shoes, blue jeans, and a dark coat. Her bicycle is red and does not have side reflectors on either wheel. At the time of impact, the bicycle and the pedestrian are perpendicular to the SUV. While a small headlight mounted on the front of the bicycle appears to be on, it is barely visible because the headlight beam is directed perpendicular to the roadway.

Because of the nighttime conditions, as well as the resolution and the quality of the camera lens, the recording from the Janus forward-facing camera is unlikely to depict exactly what the vehicle operator might have seen at the time of the crash. Furthermore, according to NTSB investigators who examined the crash site in the days after the crash and during the same hours as the crash, the nighttime visibility in the area was considerably greater than depicted on the video recording.

ADS Forward Camera. As in the video from the Janus forward-facing camera, the pedestrian becomes visible about 2 seconds before impact. The details in the rest of the recording match those recorded by the Janus forward-facing camera.

Janus Inward-Facing Camera. While the SUV was parked in the ATG garage, about 15 minutes before the drive started, the vehicle operator is seen removing a cell phone from a backpack and placing it in the bottom of the center console, below the HMI tablet and out of the

³⁵ See the Onboard Image and Data Recorder report in the NTSB public docket for this investigation for a complete description of the camera recordings (HWY18MH010).

camera's view (see next section for illustration).³⁶ Before entering the public road, the operator appears several times to be gazing toward and interacting with an object in the bottom of the center console.

The NTSB analyzed the operator's glances during the almost 39 minutes that the SUV was traveling on a public road before the crash. During the 31.5 minutes when the SUV was moving—after entering the public road—the operator spent 34 percent of her time gazing down toward the bottom of the center console.³⁷ The maximum continuous duration of the operator's downward gaze was 26.5 seconds. That occurred on the same section of N. Mill Avenue where the crash occurred but about 23.5 minutes earlier, while the operator was completing the first loop of the route.

During nearly 3 minutes before the crash, the vehicle operator looked toward the bottom of the center console 23 different times. Seven glances lasted at least 3 seconds, with the longest lasting 6.9 seconds. The operator began glancing down toward the bottom of the center console 6 seconds before impact, where she retained her gaze for the next 5 seconds. She returned her gaze to the road about 1 second before impact. According to the ADS data listed in the previous section, the operator initiated a steering maneuver 0.02 seconds before impact.

1.5.7 Human-Machine Interface

ATG mounted a tablet on the center stack, covering Volvo's infotainment screen, to serve as an HMI between the vehicle operator and the ADS (figure 6). While the vehicle was in motion, the tablet displayed the route and the vehicle's movement. The tablet's interactive function was limited to events related to ADS operation. The operator could "tag" (make note of) three types of events: (1) an outside event of interest, such as a stopped school bus; (2) an unusual ADS action, such as incorrectly reacting to a situation that should have been within its capacity; or (3) an issue with equipment inside the vehicle.

When the vehicle was in motion, the system restricted HMI tagging to events that required only one or two screen touches. Operators were instructed to tag an event as soon as possible after its occurrence, safe driving conditions permitting. In case of operator-initiated ADS disengagement, two icons, indicating the criticality of the event, would appear on the tablet for 10 seconds.³⁸ Operators were instructed to press one of the two icons if possible and pull over or complete the route before reporting the disengagement event to their supervisor.

³⁶ While examining the vehicle, NTSB investigators noticed a slot behind the disengagement button, just below the HMI tablet. They determined that the slot could serve as a stable mount for a cell phone and afford a good view from the driver's seat. However, due to the position of the inward-facing camera, the recording does not show that the vehicle operator's cell phone was mounted in the slot.

³⁷ The SUV was stopped in traffic for 7.5 minutes of the total travel time.

³⁸ The two icons were labeled "Critical" and "Autonomy." The "Critical" icon would be selected if the operator took over as a result of a potentially hazardous situation. The "Autonomy" icon would be selected if the operator took over during a nonhazardous situation, usually as a result of unusual ADS behavior.



Figure 6. SUV interior showing locations of slot that could mount a cell phone (yellow region in center console), ADS engagement/disengagement knob (red), ADS engagement button (blue), and HMI (with inset illustrating image on tablet).

HMI data show that 19 minutes 25 seconds before the crash, the system alerted the operator that the ADS was disengaging. That prompted the operator, 3 seconds later, to take manual control of the vehicle. ADS disengagement would have followed the process described in section 1.5.4.2.³⁹ The operator tagged the disengagement on the tablet. Ten seconds later, 19 minutes 12 seconds before the crash, the operator reengaged the ADS. For the rest of the crash trip, the operator did not interact with the tablet, and the HMI did not present any information that required the operator's input on the tablet.

1.5.8 ATG Fleet of Test Vehicles

The route where the SUV was operating at the time of the crash was one of five in the Tempe area on which ATG tested the ADS. At the time of the crash, the company's fleet of test vehicles had traveled that route about 50,000 times. Tempe was one of five locations where ATG conducted ADS testing. The others were Toronto, Canada; Scottsdale, Arizona; San Francisco, California; and Pittsburgh, Pennsylvania.

ATG records show that between September 2016 and March 2018 (excluding the Tempe crash), 37 crashes and incidents involved ATG test vehicles operating in autonomous mode. Most (33) involved another vehicle striking the test vehicle: 25 were rear-end crashes, and in 8 crashes, the ATG test vehicle was sideswiped by another vehicle. In two incidents, the ATG test vehicle was the striking vehicle. In one, the ATG test vehicle struck a bent bollard in the bicycle lane that partly encroached on the vehicle's travel lane. In the other, the operator took control to avoid an

³⁹ ATG provided HMI data in both quantitative and video format. The video showed everything that was displayed on the tablet and every action by the operator.

oncoming vehicle that had entered the test vehicle's lane of travel; the operator steered away and struck a parked car. In the remaining two incidents, the ATG test vehicle was vandalized by a passing pedestrian while the vehicle was stopped.

1.6 Volvo Advanced Driver Assistance Systems

1.6.1 Collision Avoidance

The SUV was factory-equipped by Volvo with several ADASs, including those for the prevention and mitigation of rear-end crashes. A system that warns a driver of an imminent forward collision is called a forward collision warning (FCW) system; one that automatically initiates braking to prevent or mitigate a forward collision is called an automatic emergency braking (AEB) system. Because ATG disengaged the Volvo ADASs during ATG ADS operation, the Volvo ADASs were not active at the time of the crash (the interaction is further explored in section 1.6.3). Investigators nevertheless examined the capabilities of the forward collision mitigation ADAS relative to the crash.

One of the systems, marketed under the name City Safety, is a rear-end-crash warning and mitigation system. It has the capacity to prevent forward collisions with moving or stationary vehicles with a velocity differential of up to 31 mph and to mitigate crashes with a higher velocity differential.⁴⁰ The system alerts a driver when approaching a slow-moving or stopped vehicle. If the driver does not respond by braking or steering away, the system automatically brakes to prevent or mitigate a rear-end crash.

The version of City Safety installed on the crash-involved SUV could also detect pedestrians, bicyclists, or large animals.⁴¹ If the system detected an impending collision, it would alert the driver or automatically brake. The pedestrian- and bicyclist-detection component could avoid or mitigate collisions with pedestrians or bicyclists when the vehicle was traveling up to 43 mph.⁴²

1.6.2 Data and Simulation

1.6.2.1 Control Modules. Investigators examined data from the modules of the SUV's standard control, recording, and storage systems. The control modules recorded only data

⁴⁰ The SUV was factory-equipped with several other ADASs, including roadway departure warning, adaptive cruise control, and lane-keeping.

⁴¹ In 2018, the NTSB published a special investigation report on pedestrian safety that explored vehicle-based countermeasures (such as improved headlights), passive protections built into vehicle designs (such as lower or softer bumpers), collision avoidance systems (such as automatic braking), and roadway designs (such as crossing islands) that can improve pedestrian safety (NTSB 2018). The report analyzed 15 fatal pedestrian crashes from 2016 and made 11 safety recommendations. More recently, the NTSB published a research report on bicyclist safety that examined the nature and scope of bicycle crashes, identified underused countermeasures, and discussed emerging issues (NTSB 2019b).

⁴² City Safety could reduce vehicle speed by up to 30 mph to prevent or mitigate a collision with a bicyclist and by up to 28 mph to prevent or mitigate a collision with a pedestrian.

immediately before and after the impact. Depending on the module, the recorded data spanned 8 to 15 seconds.

Most data from the Volvo control modules were duplicated in the data recorded by the ATG ADS. NTSB investigators examined the overlapping data and verified the consistency of vehicle dynamics data between the two sources. Investigators also examined data from the Volvo supplemental restraint system (SRS), which controlled and stored information about air bag deployment and nondeployment events triggered by sudden velocity changes.⁴³ Another SRS feature detected potential roadway departures by monitoring vehicle dynamics.⁴⁴

Data from the SRS module showed that air bags were not deployed in the crash. The SRS road runoff function, however, detected a potential roadway departure, which triggered the SUV's ERR to tense the driver's seat belt. The ERR activated 1.7 seconds after impact. The timing of the detection of a possible road runoff indicates that it was not due to the initial impact, but rather to the SUV's secondary contact with the pedestrian.

The vehicle was also factory-equipped with an Active Safety Domain master module that controlled and recorded activation of the ADAS. Since the ADASs were deactivated during the crash trip, the master module did not record any data on the operation of the vehicle's various ADASs.⁴⁵

1.6.2.2 Volvo Simulation. Volvo ran simulation tests to demonstrate how its ADAS would have responded to circumstances like those of the Tempe crash. The simulation model assumed ideal sensor operation. Volvo developed 20 variations of the pedestrian's precrash movement—basing variations in her walking speed and crossing angle on videos from the forward-facing cameras—to account for a range of precrash scenarios. The variations in the pedestrian's movement affected the time when City Safety would have detected and identified the pedestrian as being on a collision path with the SUV. While the known trajectory of the pedestrian's movements—based on ADS sensor information—was within the crossing angle parameter of the simulation, each variation in the simulation assumed that the pedestrian moved along a linear path and at a constant walking speed.

Based on the known position and speed of the SUV, for each of the 20 variations of pedestrian movement, the simulation modeled when the forward collision mitigation ADAS would have detected and classified the pedestrian as being on a collision path with the SUV. In the simulation, the pedestrian was detected as being on a collision path when fully within the radar sensor range and the camera's field of view—which occurred at a distance of 50 meters (164 feet).

The simulation next estimated the time when the FCW and the AEB would have activated. The simulation showed that the FCW would have alerted the driver 2.5 seconds before impact, and that the AEB would have activated 1.4 seconds before impact. Assuming no response from the

⁴³ The threshold for triggering a sudden deceleration event was a 7-mph deceleration in 1 second.

⁴⁴ Using an algorithm for detecting rough road, the road runoff function was triggered when a vehicle's roll rate and lateral, longitudinal, and vertical acceleration oscillated three times beyond a threshold value within a short time.

⁴⁵ For additional details pertaining to data recorded by the Volvo systems, see the Vehicle Factors factual report in the NTSB public docket for this investigation (HWY18MH010).

driver, and considering only AEB activation, the SUV was predicted to avoid a collision with the pedestrian in 17 out of 20 variations of pedestrian movement. In the avoidance cases, the reduced speed of the SUV increased the time to collision and allowed the pedestrian to move past the point of intersection with the SUV. In the other three variations, AEB activation reduced the impact speed to less than 10 mph.

1.6.3 Interaction with Uber ATG Automated Driving System

When the SUV was operated in manual mode (controlled by a vehicle operator), all the Volvo ADAS components were active. When the SUV was operated in autonomous mode (controlled by the ATG ADS), all the Volvo ADAS components were automatically deactivated. Volvo's passive safety technologies, such as the seat belt pretensioners and air bag deployment systems, remained active, however.⁴⁶

Volvo enabled ATG to design its test vehicle so that the Volvo ADAS would deactivate when the ATG ADS was engaged. According to both Volvo and ATG, simultaneous operation of the Volvo ADAS and the ATG ADS was viewed as incompatible because (1) there was a high likelihood of signal misinterpretation by the Volvo and ATG systems' radars because they operated on the same frequencies, and (2) the SUV's brake module had not been designed to assign priority if it were to receive braking commands from both the Volvo AEB and the ATG ADS.

1.7 Human Factors

1.7.1 Pedestrian

The pedestrian was a 49-year-old female who, according to the Tempe Fire Medical Rescue Department, did not have a home address. NTSB investigators were unable to obtain additional information about the pedestrian's history or her activities in the days and hours before the crash.

At the request of NTSB investigators, the Federal Aviation Administration Forensic Sciences Laboratory performed toxicological tests on a sample of the pedestrian's blood. The results were negative for alcohol, but the tests identified 2.126 micrograms per milliliter ($\mu\text{g/mL}$) of methamphetamine, 0.25 $\mu\text{g/mL}$ of amphetamine (the primary metabolite of methamphetamine), and 3.1 nanograms per milliliter (ng/mL) of tetrahydrocannabinol (THC) carboxylic acid, an inactive metabolite of THC.⁴⁷

1.7.2 Vehicle Operator

1.7.2.1 Licensing, Training, and Driving History. The vehicle operator was a 44-year-old female who had been working as an automated vehicle operator for ATG since June 2017. She

⁴⁶ According to ATG, all the systems required by the *Federal Motor Vehicle Safety Standards* (FMVSSs) remained operational during ADS operation.

⁴⁷ Methamphetamine is a central nervous system stimulant. The laboratory also detected 7.6 nanograms per gram of THC in the pedestrian's lung tissue. THC is the main psychoactive compound in marijuana. A complete list of substances tested for can be found on the Federal Aviation Administration [website](#) (accessed December 6, 2019).

held an Arizona class D driver's license that had no restrictions, most recently reissued in July 2016.⁴⁸

According to ATG records, the operator had completed a 3-week training program as well as subsequent recurrent training classes (for a description of the training—which included driving skills and ADS operation—see section 1.8.4). She was familiar with the section of N. Mill Avenue where the crash occurred and had traveled on it while operating ATG test vehicles in autonomous mode. She had completed the designated route 73 times in autonomous mode since completing her training. Records show that she had not been reprimanded at any time during her employment. She received a reward for her overall performance in fourth quarter 2017.⁴⁹

Arizona motor vehicle records show that in the 10 years before the crash, the vehicle operator had four traffic violations, the last of which was in April 2016, for speeding.⁵⁰ She had no reportable crashes on her record.

1.7.2.2 Health and Toxicology. No toxicological tests of the vehicle operator were performed. A drug recognition expert from the TPD examined her on scene immediately after the crash and found no probable cause to obtain a blood sample for testing or to conduct other tests for alcohol and other drugs.⁵¹ Although ATG had a policy requiring vehicle operators to submit to drug testing after a crash, the policy was not followed (for more information on ATG policies, see section 1.8.2). In an interview with NTSB investigators, the operator reported having no health issues that would have affected her driving performance.

1.7.2.3 Activities Before Crash. NTSB investigators used information from interviews with the vehicle operator, cell phone records, and ATG employee records to reconstruct the vehicle operator's activities before the crash. She did not work between March 14 and March 16. The records show that she had more than a 12-hour opportunity for sleep on the night of March 15–March 16.⁵² On March 17, after more than a 12-hour sleep opportunity, the vehicle operator arrived at the ATG facility. She started her shift at 8:00 p.m. She completed the shift and arrived home at 3:15 a.m. on March 18.

About noon on the day of the crash, after a 7-hour sleep opportunity, the vehicle operator traveled to Tucson, Arizona, to visit her family. She returned to Tempe in the evening and began

⁴⁸ A class D Arizona driver's license allows the holder to operate any vehicle that does not require a motorcycle or commercial license.

⁴⁹ According to ATG, the vehicle operator's performance reward was based on three criteria: professionalism, collaboration, and initiative/ownership.

⁵⁰ The vehicle operator was cited for "Violation of maximum speed limit outside urbanized area" in April 2016. Other violations include (1) "Reasonable and prudent speed violation" in July 2015, (2) "Operation of vehicle without current registration" in March 2008, and (3) "Driving while license suspended/revoked/canceled" in March 2008.

⁵¹ (a) A drug recognition expert is a law enforcement officer trained in recognizing impairment in drivers due to drug use. (b) Arizona does not have a mandatory requirement for alcohol and other drug testing for drivers involved in fatal crashes.

⁵² Although the vehicle operator was scheduled to work on March 16, she called in sick because of a headache.

her shift at 7:30 p.m.⁵³ At the time of the crash, the operator had been on duty driving—manually in the ATG terminal and in autonomous mode on public roads—about 45 minutes.⁵⁴ Figure 7 shows the vehicle operator’s activities in the 3 days before the crash and on the crash day.

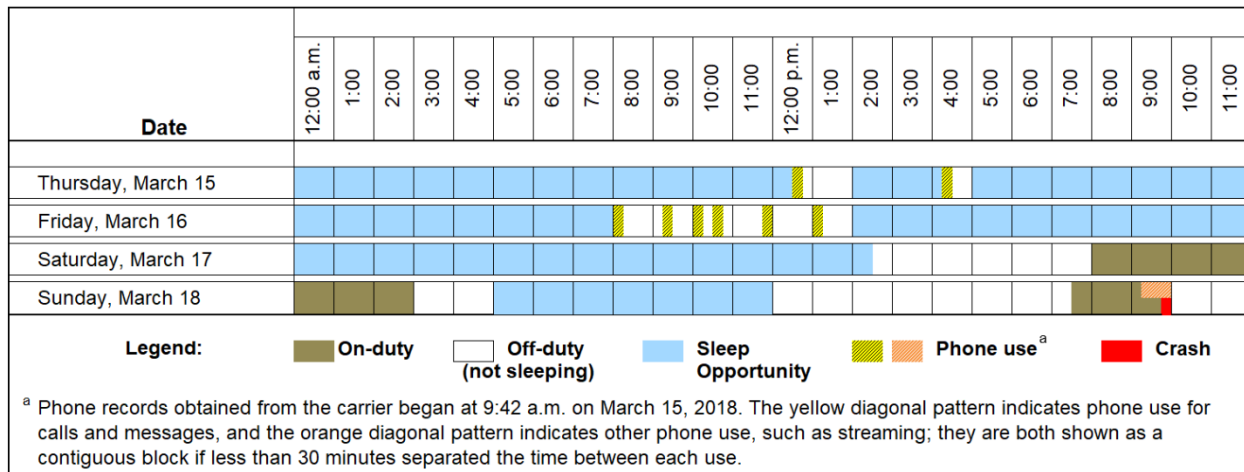


Figure 7. Precrash activities of vehicle operator, March 15–18, 2018.

The vehicle operator told NTSB investigators that she had placed a personal phone in her purse before driving, and that her company phone was on the passenger seat at the time of the crash. She also said that moments before the crash, she was attending to and interacting with the HMI.⁵⁵

The vehicle operator’s personal cell phone held several video-streaming applications. NTSB investigators examined the records that the TPD obtained from the content providers. The records showed that the account belonging to the vehicle operator was continually streaming a television show between 9:16 p.m. and 9:59 p.m. on March 18. That period covered the entire crash trip, which included 39 minutes on a public road.

1.7.3 Postcrash Observation of Sight Distance

On March 22, 2018, the TPD conducted observations at the crash site to determine the distance at which the vehicle operator would have been able to see the pedestrian. The observations started at 10:00 p.m. and were conducted under the same lighting conditions as existed at the time of the crash. NTSB investigators were present during the observations. One officer—of a similar height as the crash-involved pedestrian and wearing a similar dark outfit—was positioned at different locations along the pedestrian’s likely path across N. Mill Avenue. The officer held a bicycle at her left side. At the same time, another officer drove the crash-involved SUV at 5 mph toward the crash area. Although the observation did not reproduce the relative positions of the

⁵³ Tempe is about 109 miles from Tucson. The operator reported arriving in Tucson about 1:30 p.m. and leaving for Tempe by 5:00 p.m.

⁵⁴ As noted earlier, before operating a test vehicle, vehicle operators inspect the vehicle and the ADS.

⁵⁵ Section 1.5.7 describes the data extracted from the HMI. The data showed no tags presented on the tablet near the time of the crash and that the operator did not interact with the HMI during that period.

SUV and the pedestrian in the crash, the TPD examined the maximum distance at which the officer driving the SUV could detect a pedestrian near the northbound travel lane. When the SUV was 637 feet from the impact site, the officer reported being able to see the exemplar pedestrian, who was positioned just off the median curb, at the edge of the left-turn lane.

NTSB investigators who were at the crash location when the TPD made its visibility observations found that the streetlights would have sufficiently illuminated the path of the pedestrian, allowing the vehicle operator to detect her movements. The investigators conducted a sight-distance analysis to determine whether any physical obstructions could have prevented the vehicle operator from seeing the pedestrian while she was attempting to cross N. Mill Avenue. According to ADS data, 5.6 seconds before impact, the pedestrian was about 10 feet east of the median curb and 350 feet north of the SUV. Considering the known positions of the pedestrian and the vehicle operator—based on ADS data—and the height of the SUV’s driver seat, no obstructions would have been present, and the vehicle operator would have had a clear line of sight of the pedestrian 5.6 seconds before impact. The line-of-sight evaluation further showed that the vehicle operator would have continually had a clear line of sight of the pedestrian until impact.

1.7.4 Arizona Statutes on Pedestrian and Driver Responsibilities

Arizona statutes 28-793 and 28-794 govern pedestrian movement and driver responsibility on the state’s roads.⁵⁶ The statute pertaining to pedestrian movement states,

Between adjacent intersections at which traffic control signals are in operation, pedestrians shall not cross at any place except in a marked crosswalk.

And also,

A pedestrian crossing a roadway at any point other than within a marked crosswalk or within an unmarked crosswalk at an intersection shall yield the right-of-way to all vehicles on the roadway.

The Arizona statute regarding driver responsibilities states, among other provisions, that drivers shall “Exercise due care to avoid colliding with any pedestrian on any roadway.” The statute regarding image displays and drivers states,⁵⁷

While a person is driving a motor vehicle . . . the person shall not view a broadcast television image or a visual image from an image display device

⁵⁶ The Arizona statutes governing [pedestrian](#) roadway crossing and [driver](#) responsibility are accessible on the state legislature’s website (accessed December 6, 2019).

⁵⁷ Arizona statute 28-963 sets prohibitions and exceptions pertaining to the use of [image display devices](#) (accessed December 6, 2019).

1.8 Company Operations

1.8.1 Overview

Uber was founded in 2009 as a ride-sharing company that matched drivers with people seeking transportation. At the time of the crash, Uber consisted of six divisions, including ATG.⁵⁸ ATG was established in 2015, with headquarters in Pittsburgh and a core function of developing an automated vehicle platform. At the time of the crash, ATG employed over 1,000 personnel in five locations.⁵⁹ The purpose of the operations center in Tempe was to test the ADS and provide data for improving the system. The Tempe operations center garaged 40 ATG test vehicles—of the same Volvo model as the crash-involved SUV—and employed 254 vehicle operators and 16 supervisors, plus administrative staff.

The 2017 XC90 Volvo vehicles in the ATG fleet of automated test vehicles each had a gross vehicle weight rating of below 10,001 pounds. Under 49 CFR 390.5, such vehicles do not meet the definition of a commercial motor vehicle, so the people operating them did not require a commercial driver's license.⁶⁰ Under Arizona state law, transportation services provided by Uber or ATG were not classified as a taxi, livery, or limousine operation, but rather as a "transportation network company."⁶¹ Arizona state law defines a transportation network company as an entity that uses a digital network or software application to connect passengers to company drivers but may not necessarily own or operate the vehicles used for transportation. Therefore, the Arizona statutes did not require ATG vehicle operators to have a commercial driver's license.

At the time of the crash, ATG did not allow passengers to be picked up or transported while test vehicles were operating in autonomous mode. However, the company had offered free rides during earlier testing. In November 2017, ATG stopped transporting passengers in its test vehicles to focus on ADS development and testing.

1.8.2 Safety Culture and Policies

At the time of the crash, ATG did not have a corporate safety division or a dedicated safety manager responsible solely for assessing the risk of testing the ADS on public roads.⁶² The head of operations was tasked with the duties of a safety manager. ATG also did not have a formal safety plan or a standardized operations procedure—a document outlining the roles and

⁵⁸ For additional information regarding Uber's history and company structure, see the Operations factual report in the public docket for this investigation (HWY18MH010).

⁵⁹ ATG had offices and staff in Tempe; Pittsburgh; Detroit, Michigan; San Francisco; and Toronto. For further details regarding ATG operations in these five locations, see the Operations factual report in the public docket for this investigation (HWY18MH010).

⁶⁰ For more detailed information on how a commercial motor vehicle is defined, see 49 [CFR 390.5](#) (accessed December 6, 2019).

⁶¹ Taxi, livery vehicle, and limousine, as defined in Arizona Revised Statutes section 28-101, pertain to combinations of seating capacity, routes, fixed rates, and other variables. See the Arizona Department of Transportation (ADOT) [website](#) for additional information (accessed December 6, 2019).

⁶² The typical duties of a safety manager include conducting safety briefings, assessing operational risks and loss prevention, and maintaining the safety culture.

responsibilities of departments and personnel tasked with risk assessment. ATG had a list of core values, which were statements of intent that described the company's philosophy.⁶³

ATG's safety-related policies for vehicle operators included (1) no cell phone use and no texting; (2) mandatory seat belt use; (3) drug testing—preemployment, random, reasonable suspicion, and postaccident; (4) maximum driving time of 10 hours; and (5) professional conduct and maintenance of driver qualifications.⁶⁴ ATG policies also pertained to hiring standards and training requirements (described in section 1.8.4).

The company did not have a dedicated fatigue risk management policy. ATG provided NTSB investigators with a memo sent to the supervisors of vehicle operators in February 2018. The memo was intended as a reminder to supervisors that vehicle operators who felt fatigued should, if necessary, go home to get adequate rest, without disciplinary consequences. The content of the memo was the extent of ATG fatigue-related communications with vehicle operators.⁶⁵

Although ATG had a drug-testing policy in place at the time of the crash, it was sporadically implemented. The vehicle operator in the crash had not submitted to any preemployment, random, or reasonable-suspicion drug testing. Further, despite its policies, ATG did not require the operator to submit to a drug test after the crash. Although the operator's supervisor arrived on scene immediately after the crash and had an opportunity to ask her to submit to a drug test, the supervisor—or other ATG management staff—never did.

ATG had a rewards program based on overall job performance. ATG also had a tiered (three-level) disciplinary program for infractions.⁶⁶ The most grievous level—critical—included infractions that put people at risk, such as taking drugs or using a phone while operating a vehicle. Critical infractions resulted in termination. The vehicle operator involved in the Tempe crash had not been subject to any disciplinary actions during her ATG employment before the crash. She was suspended after the crash and was laid off after ATG ceased Tempe operations in May 2018.

ATG encouraged vehicle operators to self-report violations of ATG policies and to report infractions by their peers. ATG stated that terminal managers randomly examined videos from the inward-facing cameras as a spot-check on vehicle operators' adherence to company policies. However, ATG could not document the frequency of spot-checks (only records noting an

⁶³ An organization's safety culture refers to a collection of individual and group values, perceptions, attitudes, and competencies that reflect the organization's approach to safety management. Section 2.2 of the analysis discusses the importance of a safety culture in the context of this investigation.

⁶⁴ (a) The cell phone policy was reviewed with vehicle operators during their first week of training. It was also described in a policy booklet provided to operators. However, employees did not sign or receive a copy of a policy pertaining specifically to cell phone use. (b) The drug-testing policy was modeled on the US Department of Transportation's drug-testing requirements (49 CFR Part 382). (c) Vehicle operators were mandated to take 20- to 40-minute breaks after a maximum of 4.5 hours of sustained driving, and were recommended to take 20-minute breaks after every 2.5 hours of sustained driving.

⁶⁵ Typical fatigue policies, such as those based on the [North American Fatigue Management Program](#), contain mechanisms for adhering to federal and state regulations—including hours on duty, provisions for driving at night, inverted sleep schedules, company wellness programs, and training to minimize the risks of fatigue.

⁶⁶ Like the cell phone policy, the infraction policy was not a standalone policy, which meant that the employees did not sign or receive a copy of a policy pertaining specifically to infractions.

infraction were kept) and stated that the spot-checks were infrequent and usually occurred only after a possible infraction was reported. According to documents provided to NTSB investigators, between April 2017 and February 2018, after examining videos from the inward-facing cameras, ATG identified 18 vehicle operators who had violated the company's cell phone policy. Nine were given remedial training, and nine were terminated.

Investigators did not find any evidence that ATG had examined video recordings of the crash-involved vehicle operator before the Tempe crash. She was never reported by a peer and did not receive any disciplinary actions during her employment. When interviewed, her supervisor did not report reviewing any videos of the operator. Since the crash, ATG has made changes in its oversight of vehicle operators and in operator training (see section 1.9).

1.8.3 Operator Training

According to ATG, only candidates who met the following qualifications were considered for the vehicle operator training program: (1) at least 21 years old; (2) a minimum of 1 to 3 years of driving experience, depending on age; (3) no more than three minor driving violations in the previous 3 years; (4) no major traffic violations in the previous 3 years; and (5) no serious traffic violations in the previous 7 years.⁶⁷

The training program lasted at least 3 weeks and included instruction in the classroom, on a closed course, and on the road. The first week of training typically took place in Pittsburgh. It included 3 days of classroom training focused on ATG policies, procedures, and company values, and 2 days of familiarization with the dynamics of the test vehicle and manual vehicle operations.⁶⁸

The second week of training, also in Pittsburgh, consisted primarily of closed-course and on-the-road training. The focus was on vehicle-handling skills and decision-making in critical situations, such as encounters with noncompliant or aggressive drivers or with jaywalking pedestrians. While operating a vehicle on the closed course, trainees participated in scenarios where they faced obstacles, including motorized dummies used to simulate pedestrians. The scenarios were designed to train the operators to scan for pedestrians who were on crosswalks or who were jaywalking, as well as to anticipate hazardous situations. In interviews with NTSB investigators, the vehicle operator involved in the crash and other operators stated that they routinely encountered jaywalking pedestrians while operating test vehicles in autonomous mode.

In the second week, candidates also learned how to operate the ADS and about the system's limitations and the operational protocols (required tasks) for operating a test vehicle in autonomous mode. According to ATG, the operational protocols—specifically, operator sitting with hands hovering over the steering wheel and foot hovering above the brake pedal—were designed to promote vigilance and allow operators to quickly take control if necessary. During this time,

⁶⁷ Minor violations involve infractions such as failure to obey traffic lights and speeding; major violations involve infractions such as driving with a suspended license or without insurance; severe violations involve infractions such as driving under the influence or reckless driving.

⁶⁸ The vehicle operator involved in the crash completed the first week of training in Tempe. Although most vehicle operators traveled to Pittsburgh for the first week, because of timing constraints, some operators completed their first week of training at their home stations.

operators were trained in the HMI tagging procedures. At the end of the second training segment, trainees had to pass both a written and a driving test before continuing.

Trainees who successfully completed the second week of training transitioned to another week of training at their home base. Those who completed the final stage in Tempe learned about the routes where they would operate test vehicles. Trainees were paired with a mentor, who further coached them on ADS operations and accompanied them as they gained experience with ADS operation on public roads and with transporting passengers. After the week of training in the final segment, the mentor would grant final approval or make a determination of a need for additional training.

1.8.4 Transition to Single Vehicle Operator

When the operator in the Tempe crash began training, ATG protocols required two people in a test vehicle during ADS operation. One occupied the driver's seat and monitored the environment in preparation for a possible takeover, while the second operator—an “event tagger”—occupied the front passenger seat. The tagger used a laptop to monitor the vehicle's path and to annotate any situations of interest (such as unexpected ADS actions or unusual events in the environment).

During September–October 2017, ATG consolidated the responsibilities of two vehicle operators into that of a single operator. The consolidation occurred after ATG equipped the test vehicles with an HMI tablet that afforded operators a simpler interaction with the ADS. ATG stated that the transition to a single operator was an operational decision that allowed the company to increase the number of test vehicles, and that the HMI tablet had simplified the tagging task so that a single operator could carry out both driving-monitoring and tagging tasks. The vehicle operator in the Tempe crash began her training as an event tagger. Her training switched to that of primary/single operator on October 25, 2017.

1.9 Postcrash Changes

On March 19, 2018, immediately after the crash, ATG stopped testing ADS-equipped vehicles on public roads in all its operational centers. ATG stated that this was a precautionary measure while the company evaluated its testing procedures and overall operational and organizational structure, including its safety culture. On March 26—8 days after the crash—Arizona's governor instructed ADOT to suspend ATG's privileges to test ADS-equipped vehicles in autonomous mode in the state.

On December 20, 2018, after completing internal and external evaluations, ATG resumed ADS testing on public roads. As of the date of this report, ATG testing is self-limited to a 1-mile loop in Pittsburgh near ATG headquarters. The speed limit on the loop is 25 mph, the maximum speed at which ATG now tests ADS-equipped vehicles. At the time of the crash, ATG tested at a maximum speed of 45 mph.

As a part of the process of examining its safety culture and identifying safety deficiencies, ATG conducted an internal assessment and a voluntary external review.⁶⁹ Both reviews made recommendations in technical performance, operational safety (including implementation of safety procedures and oversight of vehicle operators), and organizational structure. During meetings with ATG representatives, NTSB investigators communicated safety issues uncovered during their investigation. When ATG resumed testing on public roads in December 2018, it had implemented changes in (1) technical performance, (2) operational safety, and (3) organizational structure.

1.9.1 Technical Performance

1.9.1.1 Volvo Advanced Driver Assistance System. Since December 20, 2018, when ATG restarted testing, the Volvo forward collision mitigation ADAS remains active during ATG ADS operation. The Volvo FCW and AEB with pedestrian-detection capabilities are engaged during both manual driving and autonomous operation. ATG engineers worked with Volvo to solve the problem of radar signal interference between the two systems. ATG changed the operational frequency of the ATG-installed radars that support ADS so that they do not interfere with the Volvo ADAS, yet maintain functional effectiveness. ATG also worked with Volvo to assign prioritization to one system when both systems issue emergency braking commands. The decision for assigning priority to a system depends on the circumstances.

1.9.1.2 Handling of Emergency Situations. In addition, ATG changed the way the ADS manages emergency situations (as described in section 1.5.5.3) by no longer implementing action suppression. The updated system does not suppress braking after it detects an emergency situation, regardless of whether maximum braking would prevent a crash.⁷⁰ Now, the ATG ADS engages emergency braking even if only to mitigate a crash. ATG also increased the jerk limit (rate of deceleration) to $\pm 20 \text{ m/s}^3$. ATG stated that under the current maximum testing speed of 25 mph, no unintended consequences (increased number of false alarms) have occurred since action suppression was eliminated.⁷¹

1.9.1.3 Path Prediction. ATG also changed the way the ADS calculates possible trajectories (predicts the path) of detected objects (as described in section 1.5.5.2). If the ADS detects a pedestrian outside a crosswalk, it can now assign the person a potential goal of crossing the road midblock. That is, jaywalking is considered a possible pedestrian goal. In addition, the system incorporates previous locations of a tracked object when generating possible trajectories, even when the object's classification changes. It generates trajectories based on both the object's classification (its possible goals) and all its previous locations.

1.9.1.4 Uber ATG Simulation. NTSB investigators discussed with ATG how the postcrash technical changes might have affected the Tempe crash. ATG simulated the circumstances of the

⁶⁹ For a more detailed description of the internal and external reviews, see the Operations factual report in the public docket for this investigation (HWY18MH010), as well as the accompanying attachments.

⁷⁰ The elimination of action suppression was a gradual process. ATG reported that it reduced the action suppression period to less than 1 second—while testing for the effect of such a change—before removing the process entirely.

⁷¹ ATG reported no increase in hard braking resulting from a falsely detected emergency situation or imminent collision.

March 18 crash, including all environmental features and known pedestrian positions and using a September 2018 version of the ADS software. The simulation results showed that the new software would have properly detected and classified the pedestrian as such at a distance of about 88 meters (290 feet), 4.5 seconds before impact. At that distance, according to ATG, based on the new software, the ATG ADS would also have correctly predicted the pedestrian's path as crossing the street midblock on a collision path with the SUV. As a result, the system would have initiated braking more than 4 seconds before the original impact and prevented the crash.

1.9.2 Operational Safety

1.9.2.1 Testing Protocol and Operator Training. When ATG restarted ADS testing on public roads in December 2018, its testing procedure specified that a test vehicle should carry two operators, positioned in the driver's seat and the front passenger seat. It also changed their position description to "mission specialist." In autonomous mode, the primary responsibility of the specialist in the driver's seat is to monitor the driving environment and take driving control in emergency situations. The primary responsibility of the specialist in the passenger seat is to tag relevant information on the HMI and act as a redundant monitor of the environment and ADS operation.

ATG established a new minimum 3-week-long training module for mission specialists that includes 30 hours of instruction and evaluation before a specialist operates a test vehicle (in either manual or autonomous mode). Among other topics, the training covers (1) situational awareness, emergency maneuvering, fatigue management, distracted driving, and ATG policies such as cell phone use; (2) the functionality and limitations of the Volvo ADAS and the ATG ADS; (3) enhanced driving skills, such as defensive techniques, emergency maneuvers, and reversing and parking; and (4) communication between the mission specialists during autonomous operation.

At the end of training, mission specialists must pass a written test and a driving test before being allowed to operate test vehicles, in either manual or autonomous mode, on public roads. ATG implemented remedial and annual recertification training for the mission specialists. Newly hired specialists go through the new training program. Those who transitioned from previous vehicle operator positions were required to complete at least 30 hours of additional training, focused on driving skills and communication.

1.9.2.2 Vehicle Operator Oversight. ATG has equipped its test vehicles with a Nauto fleet management system, consisting of a forward-facing camera and an inward-facing camera that monitors the attentiveness of a mission specialist in the driver's seat. When the system detects that a driver's seat mission specialist has looked away from the road for several seconds, it sounds a chime. At the same time, the system sends a report to the mission specialist's supervisor, who examines the video and determines whether action is needed. ATG told investigators that the company uses the attentiveness-monitoring system as a coaching tool.

1.9.2.3 Other Operational Changes. ATG has developed a fatigue management policy based on the North American Fatigue Management Program.⁷² Mission specialists receive training in fatigue management. ATG has further limited operation in the driver's seat to 4 hours per shift, with a mandatory break after 2 hours.

ATG has enhanced its drug-testing policy for mission specialists (vehicle operators) so that it mirrors the federal standards applicable to commercial drivers (49 CFR Part 382). ATG provided NTSB investigators with documentation showing that regular preemployment and random drug tests are being administered. Policies that were formerly published in one booklet have been separated into standalone documents, including the cell phone and disciplinary policies. Mission specialists acknowledge them individually. ATG has also introduced "concern reporting," according to which any ATG employee can report an issue and request a suspension of testing because of safety concerns.

On November 2, 2018, ATG published a safety self-assessment report describing the company's safety plan for ADS-equipped vehicles and submitted it to NHTSA.⁷³ The company acted in voluntary compliance with NHTSA's automated vehicles policy (see section 1.10 for further discussion).

1.9.3 Organizational Changes

1.9.3.1 Restructuring and Personnel Changes. As a result of the internal and external assessments noted above, ATG has restructured its teams and created new teams and departments. A separate safety department was established, headed by a new employee with an extensive background in safety management. The operational safety and training teams were moved from the operations department to the safety department. An employee with extensive experience in aviation safety management was hired to head the operations safety team. The operational safety and training teams were made independent of the development and testing teams, a restructuring designed to promote checks and balances in ADS development.

1.9.3.2 Safety Management System. ATG has begun establishing a safety management system (SMS). The effort is led by the new head of the operational safety team, who had implemented SMS for a previous employer.⁷⁴ In a meeting with NTSB investigators in May 2019, ATG described its plans for SMS implementation. The company stated that it expects full implementation to take 4 to 5 years.

⁷² As noted earlier, fatigue policies based on the [North American Fatigue Management Program](#) contain mechanisms for adhering to federal and state regulations (hours on duty, driving at night, inverted sleep schedules, wellness programs, training to minimize fatigue risks).

⁷³ Uber ATG's 2018 safety self-assessment report can be viewed on the NHTSA [website](#) (accessed December 6, 2019).

⁷⁴ The aviation industry defines SMS as "a formal, top down, organization-wide approach to managing risk and assuring the effectiveness of safety risk controls. It includes systematic procedures, practices, and policies for the management of risk" (see the Federal Aviation Administration [website](#), accessed December 6, 2019).

1.10 Policies, Standards, and Regulations for Automated Vehicles

1.10.1 Federal Standards and Guidance

At the federal level, NHTSA is responsible for setting motor vehicle safety standards, while the states regulate the operation of motor vehicles on public roads. The FMVSSs set minimum performance standards for all new motor vehicles and motor vehicle equipment.⁷⁵ NHTSA has the authority to enforce the standards and act when safety defects are discovered.

As of the date of this report, NHTSA had not developed any required safety standards for systems such as FCW, AEB, and ADS and had not proposed any testing procedures for evaluating a minimum level of ADS performance. In September 2016, NHTSA released an initial policy document on automated vehicles, the *Federal Automated Vehicles Policy* (NHTSA 2016).⁷⁶ The document gave basic guidance for testing and deploying ADS-equipped vehicles. It also proposed a model state policy focused on removing obstacles to autonomous vehicle use created by requirements for having an operator inside a vehicle.

The first policy document outlined a plan for a process that, after its refinement and adoption, would ask ADS developers to submit a safety self-assessment report to the agency. NHTSA stated that submission of the report was expected to be voluntary, but that in the future, it might be mandated. NHTSA incorporated the SAE International (SAE) taxonomy for vehicle automation systems (SAE International J3016) in this policy document.⁷⁷ The taxonomy, updated with slight modifications in 2018, has six levels of driving automation, from Level 0 (no automation) to Level 5 (full automation).

In September 2017, NHTSA issued its second automated vehicles policy, *Automated Driving Systems 2.0* (NHTSA 2017).⁷⁸ The policy described 12 safety elements and provided summary guidance to manufacturers and others for use in preparing a safety self-assessment report.⁷⁹ It encouraged developers to create a process for accomplishing the goals of each element. However, it gave little specific information about how developers should accomplish those goals. It also did not provide developers or others with a means of assessing their safety processes—of

⁷⁵ The FMVSSs specify the design, construction, performance, and durability requirements for motor vehicles and regulated automobile safety-related components, systems, and design features. The requirements are specified in such a manner “that the public is protected against unreasonable risk of accidents occurring as a result of the design, construction or performance of motor vehicles and is also protected against unreasonable risk of death or injury to persons in the event accidents do occur . . .” (Public Law 89-563, 80 Stat. 718, *National Traffic and Motor Vehicle Safety Act of 1966*).

⁷⁶ See [Federal Automated Vehicles Policy](#) (accessed December 6, 2019).

⁷⁷ Surface Vehicle Recommended Practice J3016 was developed by the SAE On-Road Automated Driving Committee, and the first version was published on January 16, 2014. The revised standard released on September 30, 2016, gave a taxonomy for six levels of driving automation. The [current version](#), from June 2018, retains the six levels of automation with slightly modified descriptions (accessed December 6, 2019).

⁷⁸ See [Automated Driving Systems 2.0](#) (accessed December 6, 2019).

⁷⁹ The safety elements fall into the areas of (1) system safety, (2) ODD, (3) object and event detection and response, (4) fallback (minimal risk condition), (5) validation methods, (6) HMI, (7) vehicle cybersecurity, (8) crashworthiness, (9) postcrash ADS behavior, (10) data recording, (11) consumer education and training, and (12) federal, state, and local laws.

determining whether the safety processes designed to accomplish the goals of the 12 elements were appropriate. The policy did not require developers to adhere to the guidance when developing automated vehicles or to submit a safety self-assessment report. The policy stated that assessment reports, if submitted, were not subject to NHTSA approval.⁸⁰

In October 2018, NHTSA released its third automated vehicle policy (NHTSA 2018). The document slightly expanded the agency's guidance to include other US Department of Transportation modal agencies. The third version retained the focus on vehicles with higher levels of automation—SAE Levels 3, 4, and 5.⁸¹

Both the second and third policies outlined best practices and recommendations for state and local governments concerning ADSs, focusing on technology-neutral systems and legislation that might negatively affect automated systems. The third version also included suggestions to state government to consider implementing requirements for the drivers of test automated vehicles, but it did not give specific examples.

1.10.2 Arizona Requirements

Arizona has limited requirements for the testing of automated vehicles. When ATG began testing in Arizona, the operation of automated vehicles in the state was regulated by Executive Order 2015-09 (effective August 25, 2015). The executive order permitted testing and operation of an automated vehicle regardless of whether a person was inside the vehicle. The only requirement pertaining to ADS operation was that someone—located either inside or outside the vehicle—should direct the vehicle's movement if necessary. The executive order did not instruct ADOT to require applications for the testing of automated vehicles.

On March 1, 2018, the Arizona governor authorized Executive Order 2018-04, which established parameters under which ADS-equipped vehicles could operate in the state; the main parameter was whether a person was inside a vehicle.⁸² Developers testing or operating an ADS-equipped vehicle with a person inside are required by the executive order to

follow all federal laws, Arizona State Statutes, Title 28 of the Arizona Revised Statutes, all regulations and policies set forth by the Arizona Department of Transportation . . .

The order does not contain any other safety-focused requirements for automated vehicles occupied by at least one person.

Developers testing driverless ADS-equipped vehicles—testing without a person inside a vehicle—are required to submit a written statement to ADOT acknowledging that their vehicles (1) are in compliance with the FMVSSs or have received an exemption from NHTSA, (2) can

⁸⁰ According to NHTSA, the voluntary safety self-assessment “is intended to show the public that entities are considering the safety aspects of ADSs; communicating and collaborating with [the Department of Transportation]; encouraging the self-establishment of industry norms for ADSs; and building public trust, acceptance, and confidence through transparent testing and development.”

⁸¹ See [Automated Vehicles 3.0](#) (accessed December 6, 2019).

⁸² See Arizona [Executive Order 2018-04](#) (accessed December 6, 2019).

achieve minimal risk conditions, and (3) meet all registration, licensing, and insurance requirements.⁸³ The statement acknowledging compliance with Executive Order 2018-04 is due to the department within 60 days of the start of testing; however, the department does not have a process for verifying the accuracy of the stated information. The executive order also directs developers and state agencies to instruct law enforcement and other first responders on how to interact with automated vehicles in emergencies or during traffic enforcement. Because Executive Order 2018-04 does not require a statement acknowledging compliance from entities conducting ADS testing with an operator inside a vehicle, ATG did not submit such a statement to ADOT.

On October 11, 2018, the Arizona governor authorized Executive Order 2018-09, which called for establishing an Institute of Automated Mobility to be led by representatives from the state's commerce, transportation, and academic entities.⁸⁴ The order stated that the role of the institute would include conducting research and developing infrastructure for the advancement of automated vehicle technology. The order stated further that the institute would work with the state to develop policy recommendations pertaining to the operation of automated vehicles.

On March 26, 2018, after the fatal crash in Tempe, the governor of Arizona directed ADOT to suspend ATG's ability to conduct ADS testing in the state.

⁸³ A minimal risk condition is 1 of the 12 safety elements NHTSA introduced in *Automated Driving Systems 2.0*. Arizona Executive Order 2018-04 approximates NHTSA's description, defining it as "A low-risk operating mode in which a fully autonomous vehicle operating without a human person achieves a reasonably safe state, such as bringing the vehicle to a complete stop, upon experiencing a failure of the vehicle's automated driving system that renders the vehicle unable to perform the entire dynamic driving task."

⁸⁴ See Arizona [Executive Order 2018-09](#) (accessed December 6, 2019).

2 Analysis

2.1 Introduction

A vehicle operated in developmental autonomous mode was traveling north on N. Mill Avenue in Tempe, Arizona, in the evening when it struck a pedestrian who was pushing a bicycle while walking east midblock across the road. The pedestrian died, and the vehicle operator was uninjured.

2.1.1 Exclusions

As a result of its investigation, the NTSB established that the following did not cause or contribute to the crash:

- *Driver licensing, driving experience, or knowledge of ADS operation:* The vehicle operator had a valid driver's license and considerable driving experience. She had received training and was knowledgeable in the operation and functionality of the ADS.
- *Vehicle operator substance impairment or fatigue:* Although no postcrash toxicology tests were conducted, a TPD drug recognition expert who examined the operator on scene immediately after the crash found no probable cause to test for alcohol and other drugs. Based on interviews, cell phone records, and witness accounts, the NTSB found no evidence of operator fatigue.
- *Vehicle mechanical condition:* NTSB investigators examined the vehicle and found no preexisting mechanical conditions that might have contributed to the crash.
- *Emergency response:* First responders provided appropriate and efficient emergency medical response.

The NTSB therefore concludes that none of the following were factors in the crash: (1) driver licensing, experience, or knowledge of the ADS operation; (2) vehicle operator substance impairment or fatigue; or (3) mechanical condition of the vehicle. The NTSB further concludes that the emergency response to the crash was timely and adequate.

2.1.2 Pedestrian Actions

The 49-year-old pedestrian was pushing a bicycle at her left side while walking east across N. Mill Avenue at a location without a crosswalk. Based on ADS data, the SUV would have been about 350 feet from the pedestrian when the system first detected her—5.6 seconds before impact. At that time, the pedestrian was about 10 feet east of the median curb, in the part of the road where the left-turn lanes began forming. At 350 feet, based on the NTSB sight distance analysis, the SUV and its headlights would have been visible to the pedestrian.

Toxicology tests showed that the pedestrian had drugs in her system, including methamphetamine and an inactive marijuana metabolite. The level of methamphetamine—2.126 µg/mL—strongly indicates impairment and chronic misuse. Methamphetamine particularly can severely affect perception and judgment (Cooper and Logan 2004). In its special investigation

of pedestrian safety, the NTSB (2018) reported that in 6 of the 15 pedestrian crashes it analyzed, the pedestrian's decision-making had been impaired by alcohol or other drugs.⁸⁵

Although pedestrians—impaired or not—regularly cross streets outside a crosswalk, the pedestrian who died in this crash attempted to cross in front of an approaching vehicle, which would have had to decelerate to avoid the collision. The analysis could not determine whether the pedestrian's actions were due to errors of perception—she did not see the SUV or misjudged its approaching speed—or to errors of judgment—she assumed that the vehicle would brake to allow her to cross. Evidence of potential sources of distraction to the pedestrian, such as cell phone use, is lacking; also, the approaching vehicle would have been noticeable. Therefore, the pedestrian's decision to cross the street, and her failure to take evasive action before the collision, could be attributed to the impairing levels of methamphetamine found in her body. The NTSB concludes that the pedestrian's unsafe behavior in crossing the street in front of the approaching vehicle at night and at a location without a crosswalk violated Arizona statutes and was possibly due to diminished perception and judgment resulting from drug use.

2.1.3 Safety Issue Areas

The following analysis examines the hazard detection and collision avoidance functionalities of ATG's ADS; the vehicle operator's actions before the crash and the reasons for not detecting the pedestrian in time to avoid the collision; and whether ATG's testing procedures and overall safety risk management procedures, as well as safety policies, were adequate. In addition, the analysis examines the issue of testing automated vehicles on public roads and the roles of stakeholders. The focus of the analysis is on two main safety issues:

- **ATG's inadequate safety culture.** Considered are deficiencies in safety risk management procedures and safety policies, including oversight of vehicle operators:
 - ATG's safety risk management (section 2.2.1).
 - Operators' supervision of vehicle automation (section 2.2.2).
 - ATG's safety policies, including safety methods, processes, and organizational structure (section 2.2.3).
- **Need for safety risk management requirements for testing automated vehicles on public roads.** Considered are the roles of the federal government, industry, and the states in ensuring public safety during ADS testing (section 2.3).

⁸⁵ Another important factor in the pedestrian crashes was time of day. Six crashes occurred at night and three during the twilight transition between day and night.

2.2 Uber ATG Safety Culture

A safety culture is the collection of individual and group values, perceptions, attitudes, and competencies that reflect an organization's approach to safety management.⁸⁶ A good safety culture is reinforced by a foundation of risk management practices and oversight mechanisms, along with procedures for ongoing assessment to ensure adherence and dynamic adjustment to the safety practices. When oversight mechanisms and risk-managing procedures and practices are established across an organization to provide a systemic approach for achieving an acceptable level of safety risk, the organization can be considered to have the framework of a formal SMS.

The four primary components of an SMS—as advocated by the Federal Aviation Administration and adopted industrywide, including by the ground transportation industry—are (1) *safety policy*, which defines methods, processes, and organizational structure; (2) *safety risk management*, which determines the need for new risk control mechanisms or modification of existing ones; (3) *safety assurance*, which continually examines the efficacy of the current risk control mechanisms and identifies new sources of risk; and (4) *safety promotion*, which incorporates training and communication to create a positive safety culture across an organization.⁸⁷

As this analysis shows, at the time of the crash, ATG lacked several foundational aspects of safety culture. The deficiencies were also exhibited in the four primary components of an SMS:

- *Safety policies*—the framework and mechanisms that create a good safety culture—were frequently lacking or were inconsistently applied. As discussed in section 2.2.3, ATG did not have a corporate safety plan, and some of its existing policies, such as drug testing, were sporadically implemented.
- *Safety risk management*, particularly in ADS development as it pertains to testing on public roads, lacked comprehensiveness. As discussed in section 2.2.1, ATG's ADS had insufficient safety redundancies, which increased the overall risk of testing the system on public roads.
- *Safety assurance*, which is intended to continually assess potential risk, was sporadically implemented, and also lacked appropriate mechanisms for effective implementation. As discussed in section 2.2.2.2, ATG did not provide appropriate oversight of vehicle operators, even though the company had tools for such oversight.
- *Safety promotion*, intended to foster safety culture across the company, was not always effectively communicated. As discussed in section 2.2.3, company policies were not individually acknowledged by employees, and supervisors sporadically implemented some policies.

⁸⁶ Although there is no single definition of safety culture, a version of the one proposed by the United Kingdom's Advisory Committee on the Safety of Nuclear Installations in 1993 is often cited: "The safety culture of an organisation is the product of individual and group values, attitudes, competencies, and patterns of behaviour that determine the commitment to, and the style and proficiency of, an organisation's health and safety management" (ACSNI 1993).

⁸⁷ See Federal Aviation Administration [website](#) (accessed December 6, 2019).

2.2.1 Uber ATG Safety Risk Management

The ADS that controlled the test vehicle at the time of the crash was a developmental system. As of the time of this report, there are no production-level automated vehicles on public roads that do not require the operator to monitor the driving environment or rely on a driver to take over the driving task if necessary.

ADS development, with the reliance on still-evolving technology and machine learning, is an iterative process that is expected to contain errors and failures and to expose limitations. This is also an expectation of a development process for any product or technology. A crucial distinction in ADS development is that the technology is tested on public roads, among other settings. As such, developers must anticipate potential system failures and their effects on safety and implement strategies and countermeasures to minimize the safety risks. Robust mechanisms for managing safety risk would include multiple layers of safety redundancy designed to control potential risks that may exist in the environment where such systems are tested.

2.2.1.1 Precrash ADS Functionality. As a developmental system, the ATG ADS had limitations in several areas, including its ability to detect pedestrians and predict their trajectories and its handling of emergency situations, as described below.

Pedestrian Detection. At the time of the Tempe crash, the ATG ADS did not have the functionality to anticipate pedestrians crossing midblock outside a marked crosswalk; although it could detect and identify pedestrians, it would not assign them an inherent goal of jaywalking. Rather, to predict a pedestrian's trajectory, the system relied on consistent tracking and classification of the pedestrian as such. In the crash, the ADS sensory and imaging systems—lidar, radar, and camera—detected *an* object 5.6 seconds before impact, when the pedestrian was in the middle of where the northbound road's two left-turn lanes began forming. However, the system never correctly classified the pedestrian. The ADS changed the pedestrian's classification several times, alternating between vehicle, bicycle, and other. Furthermore, with each change in object classification, the ADS perceived the pedestrian as a new object without considering its location history. Because (1) the system was unable to correctly identify the pedestrian as such, (2) the ADS design did not rely on tracking history for nonpersisting objects—those with changed classifications—to predict a path, and (3) the system lacked the functionality to assign a goal of jaywalking, the system was unable to correctly predict the pedestrian's path.

At the time of the crash, the ATG fleet of test vehicles had traveled the route on which the crash occurred about 50,000 times. When interviewed, ATG vehicle operators reported occasionally encountering pedestrians crossing a road midblock, and ATG's training of vehicle operators included preparation for hazardous situations such as jaywalking pedestrians. Pedestrians crossing a road midblock should be an anticipated safety risk when testing in urban environments. Because object identification is a challenging task for any ADS, the system was never able to correctly classify the pedestrian as such. However, such limitations should be anticipated and managed by additional layers of safety redundancy. The NTSB concludes that the Uber ATG did not adequately manage the anticipated safety risk of its ADS's functional limitations, including the system's inability in this crash to correctly classify and predict the path of the pedestrian crossing the road midblock.

Collision Avoidance and Mitigation. The ADS detected an emergency situation—determined that a collision with the pedestrian was imminent—1.2 seconds before impact. At the time of the crash, ATG had designed the ADS to suppress braking for 1 second after it detected a hazardous situation and if hard braking—greater than 0.71 *g*—was required to prevent a collision. Action suppression allowed the ADS to abort severe vehicle maneuvers if a hazardous situation resolved itself or was deemed false. It also allowed the vehicle operator to take control if the situation was truly hazardous.

In this crash, emergency braking was suppressed because the situation exceeded the ADS response design specifications for avoiding the collision (it required deceleration greater than 0.71 *g* to avoid the crash). One second later, when suppression ended, the operator had not taken control of the vehicle and the situation remained hazardous. In such situations, when a crash could not be prevented with the application of maximum braking (0.71 *g*), the ADS was designed not to apply maximum allowed braking only to mitigate the crash. Momentarily suppressing a planned motion may be reasonable from a technical perspective because errors, such as false alarms or failing to detect an object, are expected in a developmental system. However, such suppression, particularly when coupled with a decision not to use emergency braking to mitigate a crash, can be viewed as actions that limited the layers of safety redundancy and reduced safety. The NTSB concludes that the aspect of the ADS's design that precluded braking in emergency situations only when a crash was unavoidable increased the safety risks associated with testing ADSs on public roads. The NTSB further concludes that because the Uber ATG's ADS was developmental, with associated limitations and expectations of failure, the extent to which those limitations pose a safety risk depends on safety redundancies and mitigation strategies designed to reduce the safety risk associated with testing ADSs on public roads.

Multiple layers of safety redundancy are needed to reduce the risks of testing automated vehicles on public roads. One possible system-level redundancy available to ATG was the Volvo forward collision mitigation systems. However, to avoid possible radar signal interference, ATG decided to disable the crash vehicle's factory-equipped FCW and AEB during ADS testing. The Volvo FCW and AEB could detect pedestrians and bicyclists and respond to their encroachment into the path of a vehicle. Simulation tests by Volvo suggest that a standard Volvo XC90—equipped with FCW and AEB—might have prevented or at least mitigated the Tempe crash.⁸⁸ The capabilities of the Volvo AEB to detect and respond to a crossing pedestrian are also supported by testing conducted by the European New Car Assessment Programme (Euro NCAP).⁸⁹ In addition, Thatcham Research in the United Kingdom conducted a closed-course test that replicated the conditions of the Tempe crash, including the correct vehicle year/model and speed and using a motorized pedestrian crash dummy crossing a street while pushing a bicycle. The results showed

⁸⁸ The 2017 Volvo XC90 and later models are equipped with FCW and AEB as standard equipment.

⁸⁹ Since Euro NCAP had not yet implemented the pedestrian AEB testing protocol at the time of the last testing of the XC90—the 2015 model year—we examined the testing that Euro NCAP conducted on a 2017 Volvo S90 equipped with the same generation of ADAS technology as the 2017 XC90. The [testing on the S90](#) showed that the pedestrian AEB was able to avoid a collision with a crossing adult pedestrian when traveling up to 60 kilometers per hour (37 mph).

that a standard 2017 Volvo XC90, equipped with AEB, was able to avoid striking the crash dummy or to significantly reduce the vehicle's speed at impact.⁹⁰

Although ATG's decision to disable the Volvo FCW and AEB was a response to technical complexities, that action removed one layer of safety redundancy. Furthermore, the way the ADS was designed to brake in emergency situations—braking applied at less than full braking force (up to 0.71 *g*) and only if it would prevent a crash, not to mitigate an impact—did not match the full capabilities of the Volvo AEB. In some performance aspects, the collision avoidance abilities of the ADS were below those of the system it replaced. The implications of removing a single layer of safety redundancy, for a production-level or a developmental ADS, depend on the existence and capability of other layers of safety redundancy to detect and respond to a potentially hazardous situation. The NTSB concludes that the Uber ATG's deactivation of the Volvo FCW and AEB systems without replacing their full capabilities removed a layer of safety redundancy and increased the risks associated with testing ADSs on public roads.

2.2.1.2 Uber ATG Postcrash Changes. After the crash, ATG conducted internal and external reviews of its safety procedures and of the organization as a whole. As a result of the internal reviews and the continued development of the ADS, ATG also made numerous changes in technical areas. Many of the changes would have affected safety-relevant issues at the time of the Tempe crash.

When ATG restarted ADS testing in December 2018, it modified its ADS so that Volvo's forward collision mitigation ADASs, specifically FCW and AEB with the pedestrian-detection component, would remain active during ATG ADS operation. ATG changed the frequency at which the radars supporting the ADS operated so that they would not interfere with the Volvo FCW and AEB. ATG also changed the ADS design:

- It incorporated the possibility of jaywalking pedestrians. The system can assign a potential goal to a pedestrian of crossing a road outside a crosswalk.
- It modified the way the ADS classifies and tracks detected objects. Previous locations of a tracked object are now incorporated into the decision process when generating possible paths, even when the object's classification changes.
- It gradually eliminated the use of action suppression in emergency situations. The system does not suppress system response after the detection of an emergency situation even when its resolution—prevention of a crash—exceeds the system's design specifications.
- It allowed the system to engage braking in emergency situations even if only to mitigate a crash.

Some of the postcrash changes, as demonstrated in the simulations conducted by Volvo and ATG and the tests of Volvo's AEB by Euro NCAP and Thatcham Research, could have directly affected the outcome of the Tempe crash. The NTSB concludes that postcrash changes by the Uber ATG, such as making Volvo's FCW and AEB available during operation of the ADS,

⁹⁰ Additional information about the testing by Thatcham Research is found in the "Volvo XC90 Testing by Thatcham Research" item in the public docket associated with this investigation (HWY18MH010).

added a layer of safety redundancy that reduces the safety risks associated with testing ADSs on public roads.

2.2.2 Operator Supervision of Vehicle Automation

At the time of the crash, ATG's vehicle operators were responsible for several tasks, including the following:

- Monitoring the driving environment and the operation of the ADS.
- Hovering with their hands above the steering wheel and their foot above the brake pedal for fast takeover of vehicle control.
- Detecting unusual events in the driving environment or in ADS performance and noting them through interaction with the HMI.
- Taking control of the vehicle and intervening in emergency situations to avoid a collision. (As noted earlier, the ADS was designed to suppress braking in potential emergency situations to reduce false positives and allow the vehicle operator to take control.)

In the Tempe crash, when the ADS determined that a collision with the pedestrian was imminent, the design of the system and ATG's mitigation strategy relied on the vehicle operator to take control of the vehicle. That strategy was based on the assumption that an attentive operator would recognize a hazard and take control of the vehicle in sufficient time to minimize the risk. In the Tempe crash, the vehicle operator was not actively engaged in the driving task, and neither the ADS nor the vehicle operator intervened to avoid or mitigate the crash.

2.2.2.1 Operator's Actions. Video from the inward-facing camera shows that the vehicle operator spent nearly a third of the trip looking down toward the bottom of the SUV's center console, where she had placed her personal cell phone at the beginning of the trip. About 6 seconds before impact, the operator again glanced toward the bottom of the center console, where her gaze remained for the next 5 seconds. About 1 second before the impact, the operator returned her gaze to the road, but only in time to try to steer away, 0.02 seconds before striking the pedestrian. Examination of the operator's cell phone and records from a video-streaming application on her phone show that the operator was streaming a video for the entire trip, including the moments before the crash.

In a postcrash interview, the operator told investigators that moments before the crash, she was interacting with the HMI tablet, located in the center stack. However, HMI data show that immediately preceding the crash, the HMI did not present any alerts and that no tags were entered, indicating that the operator was not interacting with the HMI before the crash.

ADS data show that when the autonomous system first detected the pedestrian—5.6 seconds before the impact—she was about 10 feet east of the median curb, approximately in the middle of the road's two left-turn lanes and about 350 feet north of the SUV. Sight distance evaluation shows that no obstructions were present that would have prevented the vehicle operator from seeing the pedestrian, from when the ADS first detected her until the impact. Although the crash occurred at night, streetlights were present in the area. Despite the low level of lighting

portrayed in the video from the forward-facing fleet-monitoring camera, NTSB investigators who observed the crash location at night found that the streetlights would have sufficiently illuminated the road where the pedestrian was crossing.

Because the crash-involved vehicle operator was engaged in visual distraction in the moments leading up to the crash, the NTSB examined how an attentive driver might have responded in that situation. When the ADS initially detected the pedestrian—5.6 seconds before impact—the SUV was traversing the end of a curve before emerging from under the SR-202 overpass. Considering that drivers do not typically scan outside a roadway’s travel lane while negotiating a curve, even an attentive driver in the Tempe crash scenario might not have detected the pedestrian when the ADS detected her (Shinar 1977; Kandil, Rotter, and Lappe 2010; Itkonen, Pekkanen, and Lappi 2015). When the SUV exited the curve—3.9 seconds before impact and about 243 feet south of the crash site—the pedestrian had just entered the left through lane. At that relative distance, the pedestrian would have been within the field of view of an attentive driver’s typical scanning pattern for a straight roadway. Based on braking tests of the SUV at the crash location, an attentive driver would have been able to stop the SUV before the impact location if applying maximum braking within 1.9 seconds of entering the straight section, or within 3.5 seconds of the ADS detecting the pedestrian.⁹¹

Considering the roadway geometry, the sight distance, and the lighting in the crash area, the vehicle operator, had she been attentive, would have had 2 to 4 seconds to detect and initiate a response to the crossing pedestrian to prevent the crash. However, the vehicle operator was visually distracted, and by the time she raised her gaze from her cell phone to the road, she had only about 1 second to detect and respond to the pedestrian. By that time, she could not avoid the collision. The NTSB concludes that had the vehicle operator been attentive, she would likely have had sufficient time to detect and react to the crossing pedestrian to avoid the crash or mitigate the impact.

Earlier in the trip, while passing through the section of N. Mill Avenue where the crash occurred, the operator gazed continuously for 26.5 seconds down toward the bottom of the center console, where she had placed her cell phone. Although this is a clear example of deliberate engagement in visual distraction, it also represents the operator’s failure to perform her primary task, which was to monitor the driving environment and the performance of the ADS.

Research pertaining to automation monitoring and operator interaction with automated systems is comprehensive. Across domains, automation complacency is identified as a critical consequence of automation—a decrement in performance that results from less-than-adequate

⁹¹ (a) The TPD determined, on the basis of the vehicle’s capabilities and the road surface friction, that the SUV was capable of decelerating at an average of 0.92 *g* in the crash area. (b) Based on the initial vehicle speed of 44 mph and the maximum braking of 0.92 *g* (according to TPD roadway friction testing), the SUV would have taken 2.1 seconds to come to a complete stop.

monitoring of an automated system by a human operator (Parasuraman and Manzey 2010; Moray and Inagaki 2000).⁹²

Evidence of automation complacency has been found in settings as varied as simulated multisystem industrial monitoring (Parasuraman, Molloy, and Singh 1993), air traffic control (Metzger and Parasuraman 2001), aviation crashes (Funk and others 1999), and the grounding of a passenger ship (NTSB 1997). While research has shown that the extent of automation complacency depends on task complexity—complacency is lower in simple tasks—it also depends on the rate of automation failure. Detection of automation failure is poorer for systems that have a low failure rate (Davies and Parasuraman 1982). In other words, the better the automation system, the more likely the operator is to become complacent and not detect its failure.

In recent years, the NTSB has examined automation complacency in the operation of vehicles with Level 2 automation capabilities—vehicles that can maintain control and respond to slowing traffic but require constant driver monitoring due to their limited capabilities. The NTSB determined that the probable cause of crashes that occurred in Williston, Florida, in May 2016 and in Culver City, California, in January 2018 included driver inattention and overreliance on vehicle automation (NTSB 2017, 2019a).⁹³

When it comes to the human capacity to monitor an automation system for its failures, research findings are consistent—humans are very poor at this task. The NTSB concludes that the vehicle operator’s prolonged visual distraction, a typical effect of automation complacency, led to her failure to detect the pedestrian in time to avoid the collision. The NTSB further concludes that the Uber ATG did not adequately recognize the risk of automation complacency and develop effective countermeasures to control the risk of vehicle operator disengagement, which contributed to the crash.

2.2.2.2 Uber ATG Oversight of Vehicle Operators. ATG’s oversight of vehicle operators was inadequate. Although the company had installed inward-facing cameras in its test vehicles, supervisors said that they rarely reviewed the camera videos. Regular review could have (1) uncovered critical violations of ATG policy, such as the use of a cell phone; (2) monitored adherence to operational procedures, such as hovering hands over the steering wheel; and (3) served as a coaching tool by monitoring expected challenges, such as maintaining operator attentiveness in the face of likely automation complacency.

⁹² A National Aeronautics and Space Administration report ([Prinzel 2002](#)) defines complacency as “self-satisfaction that can result in non-vigilance based on an unjustified assumption of satisfactory system state.” Based on general automation literature and research by Parasuraman and Manzey (2010), automation complacency can also be viewed as an insufficient attention to the operation of an automated system and its output, typically as a consequence of a low failure rate of such a system.

⁹³ As a result of the Williston investigation, the NTSB issued two safety recommendations to six manufacturers of vehicles with Level 2 automation systems, including Safety Recommendation 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.” The overall status of this recommendation is “Open—Acceptable Response.” Most manufacturers responded with their plans and current efforts to reduce system misuse and maintain driver engagement, including considerations for improving driver monitoring.

About 5 months before the crash, ATG began testing with only one operator in a vehicle. The responsibilities of two vehicle operators—one monitoring the driving environment and the other noting information about the system and the driving environment—were consolidated after ATG equipped its test vehicles with an HMI that made it easier for operators to interact with the ADS. However, by removing the second operator, ATG also removed a layer of safety redundancy. The second operator can be viewed as a mechanism for detecting a potentially hazardous situation and acting to prevent a crash, as well as a reminder of the vehicle operator's responsibilities. The consolidation of responsibilities also increased the task demands on the now-sole operator. Even though the HMI had simplified the notation task, a single vehicle operator was required to do more than before. Specifically, an operator now had to look away from the road to manipulate the HMI, even if infrequently.

Technical complexities influenced the design of the ADS, resulting in the removal or diminished use of layers of safety redundancy. In that light, ATG's decision to remove a second vehicle operator from its test vehicles—and rely on only one operator as a monitoring mechanism—was even more significant. The unintended adverse consequences of removing the second operator were exacerbated by ATG's inadequate oversight of vehicle operators. The NTSB concludes that although the installation of an HMI in the Uber ATG test vehicles reduced the complexity of the automation-monitoring task, the decision to remove the second vehicle operator increased the task demands on the sole operator and also reduced the safety redundancies that would have minimized the risks associated with testing ADSs on public roads. The NTSB further concludes that although the Uber ATG had the means to retroactively monitor the behavior of vehicle operators and their adherence to operational procedures, it rarely did so; and the detrimental effect of the company's ineffective oversight was exacerbated by its decision to remove the second vehicle operator during testing of the ADS.

2.2.2.3 Uber ATG Postcrash Changes. Among other areas, the ATG-commissioned external review specifically recommended that the company make periodic, unannounced checks on vehicle operators. When ATG restarted ADS testing in December 2018, it went back to having two operators in the test vehicles, positioned in the driver seat and the passenger seat. Before the change, ATG reformed and expanded operator training to include advanced modules on driver distraction, exercises in emergency maneuvering, training in communication between the two operators, and further instruction on the functionality and limitations of the ADS. As a result, the vehicle operator in the driver seat is responsible only for monitoring the driving environment and for taking control of the vehicle and intervening in an emergency.

ATG also made a crucial change in the oversight of vehicle operators during ADS testing. Specifically, ATG installed a new inward-facing camera system that allows real-time monitoring of operator attentiveness. When the system detects that an operator in the driver seat has gazed away from the road for several seconds, it immediately sends an alert to the operator in the vehicle and a report to the supervisor who reviews the recordings. The NTSB concludes that the Uber ATG's postcrash inclusion of a second vehicle operator during testing of the ADS, along with real-time monitoring of operator attentiveness, begins to address the oversight deficiencies that contributed to the crash.

2.2.3 Uber ATG Safety Policies

2.2.3.1 Precrash Safety Plan and Safety Culture Framework. At the time of the crash, ATG did not have a corporate safety plan—a standardized operations procedure that outlines the roles and assigns safety-related responsibilities to departments and personnel to effectively assess risk. ATG did not have a safety division or a dedicated safety manager responsible for risk assessment and mitigation. Although lacking experience in safety management, the ATG head of operations was tasked with the additional responsibility of being the safety manager. Without a safety framework—a safety plan and specialized departments and personnel—an organization cannot implement a safety program that (1) embodies the fundamental principles of safety culture and (2) contains comprehensive guidance for the development of safety countermeasures. The consequences of a lack of such a safety framework are seen in the events that led to the Tempe crash.

A good safety culture is supported by policies and rules that ensure oversight of and adherence to the policies, and by personnel with experience in safety management and risk mitigation. At the time of the crash, many of these elements were inadequate or missing at ATG—specifically, oversight and risk assessment mechanisms and personnel with backgrounds in safety management. The consequences were exhibited in the inadequate oversight of vehicle operators and the failure to implement company policies, such as drug testing.

Although ATG had a policy prohibiting the use of cell phones and a disciplinary policy detailing the consequences of policy infractions, the policies were not individually acknowledged by vehicle operators. The policies were not standalone, as is the typical industry practice, but were part of a larger policy booklet.⁹⁴ ATG also did not have a dedicated fatigue management program, a fundamental component of a good safety culture, particularly in the transportation industry. ATG's drug-testing policy at the time of the crash provides an example of its poor commitment to safety culture. Although ATG's drug-testing policy required preemployment, random, probable cause, and postcrash drug testing, it was sporadically implemented. The vehicle operator in the Tempe crash had not submitted to any drug tests before or during her employment at ATG, including after this crash. Although impairment of the operator was not a factor in the crash, ATG's lack of enforcement of its own drug-testing policy indicates an inadequate safety culture. The NTSB concludes that the Uber ATG's inadequate safety culture created conditions—including inadequate oversight of vehicle operators—that contributed to the circumstances of the crash and specifically to the vehicle operator's extended distraction during the crash trip.

2.2.3.2 Postcrash Changes. The ATG-commissioned external review after the crash yielded recommendations for building a safety culture. Among the recommendations were that ATG do the following:

- Develop an SMS program and seek the services of individuals and organizations who had SMS expertise.
- Appoint senior managers for operational safety and for the training of vehicle operators.

⁹⁴ Industry practices have multiple sources, including 49 CFR 382.601 and the [Occupational Safety and Health Administration's Training Requirements in OSHA Standards](#) (accessed December 6, 2019).

- Designate the head of systems safety and the leaders of training and operational safety to lead SMS development.

Largely as a result of the recommendations from the external review, ATG made numerous changes to the company's organization and operations. ATG created an independent safety department and moved its training and operational safety teams into the safety department. ATG hired personnel with more than 20 years of experience in safety management—including developing and implementing an SMS—to lead the department. In a meeting with NTSB investigators, ATG described a comprehensive plan for putting an SMS in place, with full implementation expected by 2024.⁹⁵

ATG also changed its policies, including the way employees are instructed in them and how adherence is achieved. For example, cell phone use and disciplinary policies are now standalone, individually signed by vehicle operators, and reinforced in recurrent training. Further, ATG implemented technological solutions to ensure adherence to the cell phone policy by means of the new inward-facing camera system, which provides feedback to the vehicle operators and the associated supervisor when attention is diverted from the driving environment. While the main requirements of the company's drug policy remain unchanged, documentation from ATG shows full adherence. ATG also implemented a fatigue management program, modeled after the North American Fatigue Management Program, and now limits operation in the driver's seat to 4 hours per shift.

Although the technical and operator oversight changes that ATG made have potential to improve crash avoidance and mitigation factors, the company's organizational changes could be considered as potentially having the most long-term benefit. The changes ATG implemented postcrash represent a systemic approach to establishing the company's safety culture. All the postcrash changes, including those involving ADS design, vehicle operator oversight, corporate policies, and SMS development, indicate a shift in ATG's approach to safety culture. The NTSB concludes that the Uber ATG's plan for implementing an SMS, as well as postcrash changes in the company's oversight of vehicle operators, begins to address the deficiencies in safety risk management that contributed to the crash. Therefore, the NTSB recommends that the Uber ATG complete the implementation of an SMS for ADS testing that, at a minimum, includes safety policy, safety risk management, safety assurance, and safety promotion.

2.3 Testing of Automated Vehicles

The investigation of the Tempe crash revealed deficiencies in the way ATG tested its ADS on public roads in Arizona, including ineffective oversight of vehicle operators and inconsistent management of safety risk. Although ATG has made, and continues to make, safety improvements in the way it tests ADS-equipped vehicles, ATG is just one of many developers who are conducting such testing. Furthermore, a manufacturer is not the only entity with a role in ensuring the safe testing of automated vehicles on public roads. To establish a robust framework for safely testing ADSs across manufacturers, it is necessary to involve (1) federal agencies—which can establish

⁹⁵ The meeting took place on May 9, 2019.

and mandate ADS performance standards, (2) industry—which manufactures and develops ADSs, and (3) the states—which traditionally regulate drivers and vehicle operation on public roads.

To provide a thorough and constructive discussion about the testing of automated vehicles, it is necessary to parse the terminology that is used in public discourse. Specifically, it is necessary to distinguish the system that controlled the ATG test vehicle involved in this crash from various driver-assist and collision avoidance systems that exist on many vehicles on the roads today.

2.3.1 Terminology of Automation

One of the main sources of confusion in discussions about automated vehicles is the language used in the industry and by researchers and regulators compared to that used by the general public. Industry, regulators, and academics frequently use the six-level SAE automation taxonomy as a reference point when discussing vehicle capabilities and operator responsibilities. However, the SAE automation levels may not be easily relatable to the general public. At the same time, the terms used by vehicle manufacturers to market their driver-assist systems—such as ProPilot (Nissan), Pilot Assist (Volvo), and Autopilot (Tesla)—can add to public confusion about the degree of automation in the production-level vehicles now available (Teoh 2019; McDonald and others 2016).⁹⁶ Although the general public frequently uses *self-driving vehicle* as a term to describe currently available vehicles, it is an incorrect portrayal of the capabilities of production-level vehicles on the roads in the United States today—*no such production-level vehicles currently exist*.⁹⁷

2.3.1.1 Advanced Driver Assistance System. The defining characteristic of an ADAS is that it *assists* a driver in the performance of the driving task. Assistance can consist of (1) maintaining vehicle stability—through a system such as electronic stability control; (2) controlling vehicle speed and following distance—through a system such as adaptive cruise control (ACC); (3) maintaining lane position—through a system such as lane-keeping or lane-centering; or (4) preventing or mitigating collisions—through systems such as FCW, AEB, and roadway departure warning. While a vehicle can be equipped with multiple ADASs—including combining lateral and longitudinal control—a human driver is always responsible for operating the vehicle and detecting and responding to hazards.⁹⁸ In the SAE automation taxonomy, vehicles with Levels 0, 1, or 2 of automation capability are described as equipped with an ADAS.

2.3.1.2 Automated Driving System. The defining characteristic of an ADS is that the system takes full control—even if temporary or constrained—of all aspects of the driving task. While a geographical area, environmental conditions, or a human occupant’s availability may limit

⁹⁶ These exemplar systems are considered ADASs. A description of overall ADAS functionality and limitations is given in section 2.3.1.1.

⁹⁷ ATG also describes its test vehicles as self-driving, but they are not production level. Adding to the complexity with terminology is that some test vehicles equipped with ADSs may be considered self-driving in certain limited circumstances, such as in good weather, with a mapped roadway, and with well-defined lane markings.

⁹⁸ Combining lateral and longitudinal control through lane keeping/lane centering and ACC systems creates Level 2 automation capabilities—partial automation. In such systems, a human driver is still responsible for monitoring the environment and the operation of the system.

the domain where an ADS is operational, the system is entirely responsible for controlling the vehicle and avoiding hazards in that domain.⁹⁹

An ADS can be viewed as a holistic system consisting of many ADASs that are integrated and automated in the ADS, which, because of its advanced sensor and computing capabilities, affords removing a critical layer of safety redundancy—the requirement for constant human monitoring of the driving environment. Within the context of the SAE automation taxonomy, vehicles with Levels 3 to 5 of automation are described as having an ADS. Also, NHTSA’s automated vehicle policy refers to ADS when describing highly automated vehicles—vehicles with Levels 3 to 5 of automation. Considering that the ATG ADS is a developmental system and was being tested on a designated, premapped route, we could say that the intent of the ATG ADS is Level 4 automation.

2.3.2 Federal Approach

2.3.2.1 Safety Standards and Automated Vehicle Guidance. ATG’s developmental ADS can be viewed as a discrete component that adds automation capabilities to a vehicle. The 2017 Volvo XC90 is a production vehicle that meets all applicable FMVSSs. The installation of the ADS on Volvo vehicles in the ATG fleet—including sensors, cameras, and computing equipment—did not invalidate any FMVSSs those Volvo vehicles already met. While the Volvo XC90 is equipped with FCW and AEB, they are not required equipment on a vehicle. As such, ATG’s deactivation of the factory-equipped Volvo FCW and AEB did not invalidate any FMVSS.

Although NHTSA does not have any ADS-related safety standards or even suggested assessment protocols, as of the date of this report, no manufacturers sell or operate ADS-equipped production-level vehicles—those that do not require human monitoring. At the same time, several dozen manufacturers and developers are testing automated vehicles across the country. Further, multiple manufacturers are promising near-term arrival of production-level vehicles with SAE Level 3 automation capabilities.¹⁰⁰

NHTSA has published three iterations of automated vehicle guidance to address those systems. In the second iteration of its automated vehicle policy, NHTSA provided guidance and encouraged ADS manufacturers and developers to submit voluntary safety self-assessment reports describing the safety approach they are taking in the development of their ADSs. The guidance listed 12 safety-related areas but contained little specific information on how to achieve those safety goals—for example, training vehicle operators, ensuring oversight, or evaluating whether an ADS has reached a level of safe functionality. Moreover, submitting a safety self-assessment report is voluntary, and NHTSA does not publish an evaluation of the reports to determine the extent to which developers follow the automated vehicle guidance.

⁹⁹ Depending on the level of automation, a human occupant may be required to be available to take the control of the vehicle after being prompted by the system. That requirement applies to Level 3 automation.

¹⁰⁰ NHTSA has made an initial step toward considering future development of ADS standards. In October 2018, the agency issued an advance notice of proposed rulemaking titled “Pilot Program for Collaborative Research on Motor Vehicles with High or Full Driving Automation” (*Federal Register*, vol. 83, no. 196, October 10, 2018: 50872–50883). The notice focuses on how the agency can encourage and facilitate research needed to inform the development and establishment of ADS standards, if necessary.

While the current iteration—*Automated Vehicles 3.0*—presents a policy architecture that applies across transportation modes, it retains the limiting aspects: cursory guidance, voluntary report submission, and absence of report assessment. The NTSB communicated those views to the US Department of Transportation in response to the publication of *Automated Vehicles 3.0*.¹⁰¹ The NTSB stated that “Among the NTSB’s concerns is that on-road testing by manufacturers of new technology cannot serve to demonstrate safety,” and that “A comprehensive, multipronged approach that defines system safety before on-road pilot testing is needed.”

As of the date of this report, 16 manufacturers and developers have submitted a voluntary safety self-assessment report.¹⁰² By way of comparison, 62 developers have received an ADS testing permit in California.¹⁰³ Further, even those safety self-assessment reports submitted to NHTSA vary considerably in the level of detail they provide, as well as in the topics they discuss. This lack of uniformity is a result of the voluntary nature of the reports, the cursory guidance, and the absence of report assessment.

Based on its latest automated vehicle policy and its other public communications, it appears that NHTSA does not intend to develop ADS safety standards or assessment protocols at the present time. The NTSB recognizes the complexity of developing safety standards for a production-level ADS. Nevertheless, a framework for the primary emphasis of this investigation—testing of ADSs—is attainable, and the basis for the framework is already established in NHTSA’s automated vehicle policy.

2.3.2.2 Recommendations. Since 1995, the NTSB has continually advocated the implementation of ADASs in all highway vehicles and has placed implementation of collision avoidance systems on its Most Wanted List every year since 2016.¹⁰⁴ The NTSB also recognizes that ADASs and other advanced systems, such as ADS, have the potential to mitigate or prevent crashes on our roadways. A promise of the upcoming ADSs is that such systems will be safer than a human driver. Until that promise is realized, the testing of a developmental ADS—with all its expected failures and limitations—requires appropriate safeguards when conducted on public roads.

NHTSA’s automated vehicle policy provides insufficient instructions on how developers should accomplish the safety goals of the 12 safety-related areas. More limiting aspects of the policy pertain to (1) the absence of a NHTSA process for evaluating the adequacy of a safety self-assessment report, and (2) the lack of a mandatory submission requirement. The shortcomings of the policy are exacerbated by the lack of assessment procedures and the difficulties in their development. For example, 1 of the 12 safety areas is “object and event detection and response,” pertaining to the capability of an ADS to detect, classify, and respond to objects and events in the

¹⁰¹ The NTSB submitted comments on *Automated Vehicles 3.0* (Docket No. [DOT-OST-2018-0149](#)) on December 20, 2018.

¹⁰² The list of the entities, along with the safety self-assessment plan they submitted, can be found on [NHTSA’s website](#) (accessed December 6, 2019).

¹⁰³ For further discussion, see section 2.3.4.1.

¹⁰⁴ The NTSB made its first recommendation pertaining to collision avoidance technology in 1995 (Safety Recommendation H-95-44) when it asked the US Department of Transportation to begin testing collision warning systems in commercial fleets.

environment. In this report, we have discussed the significant challenges pertaining to ADS development, particularly system perception—detection, classification, and path prediction. The NTSB recognizes the difficulties in developing a standardized metric for assessing the perception of an ADS. In another of the 12 safety elements of its automated vehicle policy—HMI—NHTSA makes a weak case for monitoring driver engagement. The agency states, “Entities are encouraged to consider whether it is reasonable and appropriate to incorporate driver engagement monitoring” For those reasons, a determination of whether sufficient safeguards exist for the testing of a developmental ADS on public roads requires a holistic assessment of all relevant safety areas, particularly when performance metrics may not exist.

The traditional division of oversight, in which NHTSA controls vehicle safety and the states monitor drivers, may not be easily applicable to developmental automated test vehicles. It might not be immediately apparent who controls the vehicle, or whether vehicle control and supervision are shared between the computer (the vehicle) and the human operator. The lack of a meaningful, or any, policy from the states leaves the public vulnerable to potentially unsafe testing practices. And the lack of a comprehensive policy from NHTSA leaves the states without an effective tool for assessing the safety of an entity’s testing practices. To ensure that testing of automated vehicles on public roads is conducted with minimal safety risk, meaningful action from both NHTSA and the states is critical.

If the process of submission of safety self-assessment reports were mandatory and included evaluation and approval by NHTSA, it could serve as a criterion for judging whether a developer’s approach to ADS development and testing met the minimal intent of the 12 safety areas. NHTSA’s approval of a safety plan could also provide a minimum safeguard for the testing of developmental ADSs on public roads. Furthermore, assessment by NHTSA would provide important support to states when evaluating the appropriateness of a developer’s approach to the testing of automated vehicles.

The NTSB concludes that mandatory submission of safety self-assessment reports—which are currently voluntary—and their evaluation by NHTSA would provide a uniform, minimal level of assessment that could aid states with legislation pertaining to the testing of automated vehicles. Therefore, the NTSB recommends that NHTSA require entities who are testing or who intend to test a developmental ADS on public roads to submit a safety self-assessment report to the agency. The NTSB further recommends that NHTSA establish a process for the ongoing evaluation of the safety self-assessment reports as required in Safety Recommendation H-19-47 and determine whether the plans include appropriate safeguards for testing a developmental ADS on public roads, including adequate monitoring of vehicle operator engagement, if applicable.

2.3.3 Industry Efforts

Without federal ADS standards or state-mandated requirements for testing on public roads (see section 2.3.4), it is up to developers—traditional vehicle manufacturers, technology-based companies, new entities, and associations—to determine the needed safety mechanisms and countermeasures before testing their ADS-equipped vehicles on public roads. Coalitions are forming to address that need.

In March 2015, the SAE's On-Road Automated Driving Committee issued *Guidelines for Safe On-Road Testing of SAE Level 3, 4, and 5 Prototype Automated Driving Systems (ADS)*.¹⁰⁵ While the document does not establish performance criteria or test procedures, it contains an intermediate level of guidance on several issues relevant to the Tempe crash, specifically, operator training and oversight. The guidelines assume that testing would be conducted under the supervision of a person inside a test vehicle. The document also provides guidance on (1) the selection of test routes and graduated road testing—expanding the complexity of a geographical domain, (2) the stages of software development, and (3) the conditions under which, and the methods by which, an operator or the system itself would disengage the ADS.

Industry efforts are also evident in the development of standards for ADS evaluation. Currently in the approval process, UL standard 4600, developed by UL and Edge Case Research, is expected to be approved by the end of 2019.¹⁰⁶ The standard is being created with a goal of establishing safety principles and processes for evaluating automated vehicles. It intends to present a pathway for creating a safety case that would include topics such as risk analysis, evaluation of safety-relevant aspects of the design process, and validation of autonomy. The focus of UL 4600 is on production-level ADSs with Levels 4 or 5 of automation. The standard is not expected to contain comprehensive guidance for testing such systems.

2.3.4 State Approach: Legislating Automated Vehicle Testing

In the absence of federal ADS safety standards or specific ADS assessment protocols, many states have begun legislating requirements for automated vehicle testing. The development of state-based requirements could be attributed to the concerns of many states about the safety risk of introducing ADS-equipped vehicles on public roads. The requirements vary. Some states, such as Arizona, impose minimal restrictions. Other states have established requirements that include a more in-depth application and review process. Below, we discuss the process for approving applications for the testing of ADS-equipped vehicles in three states, including Arizona.

2.3.4.1 California. Before testing or deploying ADS-equipped vehicles on public roads in California, a company must apply for and obtain a permit. In September 2014, the state adopted its first regulations on the testing of automated vehicles, and in April 2018, expanded the regulations to include requirements for driverless operation.¹⁰⁷ The California Department of Motor Vehicles (DMV) issues three types of automated vehicle permits: (1) a testing permit that requires a vehicle operator to be present inside a vehicle; (2) a testing permit that allows testing without an operator inside a vehicle; and (3) a deployment permit—nontesting operation for public use.¹⁰⁸

¹⁰⁵ SAE standard J3018, retrieved from the [SAE website](#) on June 10, 2019.

¹⁰⁶ UL, formerly Underwriters Laboratories, is the world's largest organization that, following established standards, conducts safety and quality testing on a broad range of products; products that pass the tests receive UL certification. UL also works to establish new or consolidate existing global standards.

¹⁰⁷ California Vehicle Code Section 38750 requires the Department of Motor Vehicles to adopt regulations governing both the testing and public use of autonomous vehicles on California roadways. The [code](#) was accessed on December 6, 2019.

¹⁰⁸ See [California DMV](#) for more information. The website was accessed on December 6, 2019.

Conditions for obtaining a permit for testing with an operator inside a vehicle include (1) specialized training of vehicle operators; (2) that an operator be in physical control of the vehicle or actively monitoring the vehicle's operations; (3) completion of previous testing in controlled conditions; (4) prohibition on transporting passengers for a fare; and (5) reporting of crashes, as well as annual submission of the frequency of ADS disengagements, initiated by a vehicle operator or by the system.¹⁰⁹ A permit for testing without an operator has more stringent requirements, including continuous remote monitoring of the vehicle status and previous extensive testing in controlled conditions that closely simulate the ODD in which the testing will be conducted on public roads.

The California DMV reviews applications and can request clarification or additional documentation before issuing an approval. As of January 28, 2019, the DMV had approved 62 permits for testing with a vehicle operator inside a vehicle, only 1 permit for testing without an operator, and no permits for production-level automated vehicles.¹¹⁰

2.3.4.2 Pennsylvania. Pennsylvania also has an application and review process for testing ADS-equipped vehicles in the state. In June 2016, the Pennsylvania Department of Transportation (PDOT) established an autonomous vehicle policy task force. When ATG was conducting ADS testing in Pittsburgh before the Tempe crash, PDOT did not yet have guidance for testing automated vehicles in the state. In July 2018, the PDOT task force published *Automated Vehicle Testing Guidance*.¹¹¹ In a conversation with NTSB investigators, members of the task force said that the circumstances of the Tempe crash, and the way ATG conducted its testing, significantly influenced PDOT's July 2018 guidance.

Unlike the California DMV, PDOT grants permits only for ADS testing with an operator inside a vehicle. PDOT does not issue permits for ADS testing without an operator inside a vehicle or for public deployment of driverless automated vehicles. In communication with NTSB investigators, PDOT stated that the Pennsylvania vehicle code requires a driver to be inside a vehicle. That regulatory restriction prohibits a vehicle without a driver—a test or a production vehicle—from operating on public roads in Pennsylvania.

To obtain a permit, a developer submits a notice of testing that includes (1) basic information about the applicant, the vehicles, and the drivers; (2) the applicant's acknowledgement that it has met 12 safety-based criteria on data recording, operator training and testing, and ADS operation; and (3) either the NHTSA safety self-assessment report or a PDOT safety risk mitigation plan.¹¹² Some of the conditions for obtaining a PDOT testing permit—as covered in the applicant's acknowledgements and risk mitigation plan—include (1) previous testing in simulated

¹⁰⁹ For more details on the requirements for testing with a driver, see [California DMV testing requirements](#). The website was accessed on December 6, 2019.

¹¹⁰ Waymo is the only company that received a permit for testing without a driver inside a vehicle, but as of the date of this report, the company has not yet begun such testing. The websites for the holders of the [driver](#) and [driverless](#) permits were accessed on June 10, 2019.

¹¹¹ See PDOT [guidance](#) (accessed December 6, 2019).

¹¹² Two of the developers that applied for the permit submitted the safety self-assessment report in lieu of the PDOT application. For a detailed description of the application requirements for an automated vehicle testing permit, see the PDOT automated vehicle testing guidance in the NTSB public docket for this investigation (HWY18MH010).

and closed-course settings; (2) a training plan for vehicle operators that covers driving and hazard-detection skills and a comprehensive understanding of ADS functionality; (3) measures for addressing operator fatigue and inattentiveness; (4) a requirement for an operator to be either in physical control of a vehicle or actively monitoring the vehicle's operation; (5) a description of safety measures in case of ADS disengagement, regardless of the reason; and (6) a prohibition on transporting passengers for a fare. Furthermore, if a developer intends to test at speeds over 25 mph, either a second operator must be in the front seat of the test vehicle or a single operator must undergo enhanced training.¹¹³ As of the date of this report, all developers conducting ADS testing in Pennsylvania have two operators inside their test vehicles.

PDOT evaluates the testing application material and may request additional documentation or clarification before deciding whether to approve a testing permit. As of the date of this report, none of the companies that submitted an application had received immediate permit approval. All six companies were required to submit additional documentation or provide further clarification before a permit was granted.

However, PDOT does not require developers testing ADS-equipped vehicles in the state to obtain a permit. Although the application process is voluntary, PDOT told NTSB investigators that all six developers that test in the state have applied for and received a testing permit. The agency said that obtaining the permit is an incentive in itself, because the permit serves as a stamp of approval by the state.

By the time ATG resumed ADS testing in December 2018, PDOT had established guidance for ADS testing on public roads. ATG applied to test ADS-equipped vehicles and was granted a testing permit from PDOT. Considering that ATG is currently testing at speeds of up to 25 mph, the company's use of two vehicle operators—in excess of PDOT requirements—could be considered a cautious approach and a substantial change from its previous testing procedures in Tempe (where ATG tested with a single operator on a roadway that had a speed limit of 45 mph).

2.3.4.3 Arizona. As of the date of this report, Arizona did not have specific requirements pertaining to the testing of automated vehicles with an operator inside. According to Arizona Executive Order 2018-04, developers testing an ADS *without* a person inside a vehicle are required to acknowledge in writing that their test vehicles meet a few basic requirements—including that they are capable of achieving minimal risk conditions. Developers testing *with* an operator inside are not required to submit a statement or adhere to any conditions other than those that apply to nonautomated vehicles. The executive order does not contain any additional requirements or guidelines for ADS testing. ATG did not submit any statement or application to ADOT before or during its testing in Tempe, because its ADS vehicles always had at least one vehicle operator inside.

Despite the circumstances of the Tempe crash, Arizona has not made any changes to the requirements for ADS testing in the state. Although ADOT revoked ATG's privilege to test its ADS after the crash, it is worth reiterating that as of the date of this report, other developers can

¹¹³ As part of the application process, under "Operational Requirements," PDOT states: "Testers requesting use of a single safety driver for operations on trafficways posted above 25 mph must present evidence of an enhanced performance driver training plan for Department review."

test their ADSs in Arizona in the same way ATG did at the time of the crash. Furthermore, when they are being tested with an operator inside, other ADS-equipped vehicles do not need to meet any conditions beyond those that apply to general traffic vehicles.

The NTSB concludes that Arizona's lack of a safety-focused application-approval process for ADS testing at the time of the crash, and its inaction in developing such a process since the crash, demonstrate the state's shortcomings in improving the safety of ADS testing and safeguarding the public. Therefore, the NTSB recommends that Arizona require developers to submit an application for testing ADS-equipped vehicles that, at a minimum, details a plan to manage the risk associated with crashes and operator inattentiveness and establishes countermeasures to prevent crashes or mitigate crash severity within the ADS testing parameters. The NTSB further recommends that Arizona establish a task group of experts to evaluate applications for testing vehicles equipped with ADSs, as described in Safety Recommendation H-19-49, before granting a testing permit.

2.3.4.4 Statewide Recommendation. As June 2019, 21 states had no regulations pertaining to ADS testing.¹¹⁴ Although 29 states had some type of ADS-related policy, the requirements for testing varied considerably.¹¹⁵ Furthermore, the existence of a regulation is not a sure indication of a comprehensive and safety-driven ADS testing policy. Indeed, Arizona is 1 of the 29 states that had some regulations pertaining to ADS testing.

This report discusses two states—California and Pennsylvania—that have developed safety-driven requirements or guidance for ADS testing. However, no comprehensive studies have examined the efficacy of state regulations—based on safety metrics—and the policies adopted by California and Pennsylvania may not necessarily represent the best approach.

For example, although Pennsylvania's operator-monitoring requirements are more stringent than California's—at least one person is required inside a vehicle—the application process is voluntary. While PDOT stated that all entities that are currently conducting ADS testing in the state have submitted an application and received a permit, a mandatory application process might be necessary elsewhere. The California DMV's requirement for annual reporting of system disengagements has been criticized as having unintended negative consequences (Koopman and Osyk 2019). To reduce the number of disengagements, a developer could decide to modify the system to increase the threshold at which it disengages, potentially increasing risks by operating at the edge of the safety envelope. On the other hand, a developer who approached testing more conservatively, by requiring multiple safety redundancies for an ADS to remain engaged, could experience more disengagements.

Other states, especially those without any regulations for the testing of automated vehicles, would benefit from adopting regulations that require a thorough review of developers' safety plans, including methods of risk management. As described its second automated vehicle policy, NHTSA has worked with stakeholders to develop a model policy for state legislatures pertaining to ADS testing. In its guidance, the agency listed several actions that states should consider adopting,

¹¹⁴ The information was retrieved from the National Conference of State Legislatures [website](#) on June 10, 2019.

¹¹⁵ As of the date of this report, 40 states have some type of ADS-related policy, according to the National Conference of State Legislatures website. However, the policies in many of those states are unrelated to testing

including the creation of an internal process for issuing permits for ADS testing. One of the stakeholders was the American Association of Motor Vehicle Administrators (AAMVA), which has developed numerous model programs for motor vehicle administration, law enforcement, and highway safety in general. The association serves as a clearinghouse for highway safety issues and represents state and municipal officials.

In May 2018, the AAMVA published *Jurisdictional Guidelines for the Safe Testing and Deployment of Highly Automated Vehicles*.¹¹⁶ Although the guidance contains elements of ADS testing (fewer elements than in NHTSA's automated vehicle policy, however), the AAMVA document also lacks specific guidance for developers on how to accomplish the included recommendations. The guidance does include one important element, a recommendation to jurisdictions to identify a lead agency and establish an automated vehicle committee to develop strategies for addressing automated vehicle testing.¹¹⁷ However, the guidance does not include recommendations requiring developers to submit a safety plan and for the automated vehicle committee to review and approve such a plan.

The NTSB concludes that, considering the lack of federal safety standards and assessment protocols for ADSs, as well as NHTSA's inadequate safety self-assessment process, states that have no, or only minimal, requirements related to automated vehicle testing can improve the safety of such testing by implementing a thorough application and review process before granting testing permits. Therefore, the NTSB recommends that AAMVA inform the states about the circumstances of the Tempe, Arizona, crash and encourage them to (1) require developers to submit an application for testing ADS-equipped vehicles that, at a minimum, details a plan to manage the risk associated with crashes and operator inattentiveness and establishes countermeasures to prevent crashes or mitigate crash severity within the ADS testing parameters, and (2) establish a task group of experts to evaluate the application before granting a testing permit.

¹¹⁶ The [guidance](#) was created by the [Autonomous Vehicle Best Practices Working Group](#), a task group created by the AAMVA (accessed December 6, 2019).

¹¹⁷ NHTSA's *Automated Driving Systems 2.0* policy includes a suggestion to the states to consider "new oversight activities on an administration level to support States' roles and activities as they relate to ADSs." NHTSA continues by saying that it "does not expect that States will need to create any particular new entity in order to support ADS activities"

3 Conclusions

3.1 Findings

1. None of the following were factors in the crash: (1) driver licensing, experience, or knowledge of the automated driving system operation; (2) vehicle operator substance impairment or fatigue; or (3) mechanical condition of the vehicle.
2. The emergency response to the crash was timely and adequate.
3. The pedestrian's unsafe behavior in crossing the street in front of the approaching vehicle at night and at a location without a crosswalk violated Arizona statutes and was possibly due to diminished perception and judgment resulting from drug use.
4. The Uber Advanced Technologies Group did not adequately manage the anticipated safety risk of its automated driving system's functional limitations, including the system's inability in this crash to correctly classify and predict the path of the pedestrian crossing the road midblock.
5. The aspect of the automated driving system's design that precluded braking in emergency situations only when a crash was unavoidable increased the safety risks associated with testing automated driving systems on public roads.
6. Because the Uber Advanced Technologies Group's automated driving system was developmental, with associated limitations and expectations of failure, the extent to which those limitations pose a safety risk depends on safety redundancies and mitigation strategies designed to reduce the safety risk associated with testing automated driving systems on public roads.
7. The Uber Advanced Technologies Group's deactivation of the Volvo forward collision warning and automatic emergency braking systems without replacing their full capabilities removed a layer of safety redundancy and increased the risks associated with testing automated driving systems on public roads.
8. Postcrash changes by the Uber Advanced Technologies Group, such as making Volvo's forward collision warning and automatic emergency braking available during operation of the automated driving system (ADS), added a layer of safety redundancy that reduces the safety risks associated with testing ADSs on public roads.
9. Had the vehicle operator been attentive, she would likely have had sufficient time to detect and react to the crossing pedestrian to avoid the crash or mitigate the impact.
10. The vehicle operator's prolonged visual distraction, a typical effect of automation complacency, led to her failure to detect the pedestrian in time to avoid the collision.

11. The Uber Advanced Technologies Group did not adequately recognize the risk of automation complacency and develop effective countermeasures to control the risk of vehicle operator disengagement, which contributed to the crash.
12. Although the installation of a human-machine interface in the Uber Advanced Technologies Group test vehicles reduced the complexity of the automation-monitoring task, the decision to remove the second vehicle operator increased the task demands on the sole operator and also reduced the safety redundancies that would have minimized the risks associated with testing automated driving systems on public roads.
13. Although the Uber Advanced Technologies Group had the means to retroactively monitor the behavior of vehicle operators and their adherence to operational procedures, it rarely did so; and the detrimental effect of the company's ineffective oversight was exacerbated by its decision to remove the second vehicle operator during testing of the automated driving system.
14. The Uber Advanced Technologies Group's postcrash inclusion of a second vehicle operator during testing of the automated driving system, along with real-time monitoring of operator attentiveness, begins to address the oversight deficiencies that contributed to the crash.
15. The Uber Advanced Technologies Group's inadequate safety culture created conditions—including inadequate oversight of vehicle operators—that contributed to the circumstances of the crash and specifically to the vehicle operator's extended distraction during the crash trip.
16. The Uber Advanced Technologies Group's plan for implementing a safety management system, as well as postcrash changes in the company's oversight of vehicle operators, begins to address the deficiencies in safety risk management that contributed to the crash.
17. Mandatory submission of safety self-assessment reports—which are currently voluntary—and their evaluation by the National Highway Traffic Safety Administration would provide a uniform, minimal level of assessment that could aid states with legislation pertaining to the testing of automated vehicles.
18. Arizona's lack of a safety-focused application-approval process for automated driving system (ADS) testing at the time of the crash, and its inaction in developing such a process since the crash, demonstrate the state's shortcomings in improving the safety of ADS testing and safeguarding the public.
19. Considering the lack of federal safety standards and assessment protocols for automated driving systems, as well as the National Highway Traffic Safety Administration's inadequate safety self-assessment process, states that have no, or only minimal, requirements related to automated vehicle testing can improve the safety of such testing by implementing a thorough application and review process before granting testing permits.

3.2 Probable Cause

The National Transportation Safety Board determines that the probable cause of the crash in Tempe, Arizona, was the failure of the vehicle operator to monitor the driving environment and the operation of the automated driving system because she was visually distracted throughout the trip by her personal cell phone. Contributing to the crash were the Uber Advanced Technologies Group's (1) inadequate safety risk assessment procedures, (2) ineffective oversight of vehicle operators, and (3) lack of adequate mechanisms for addressing operators' automation complacency—all a consequence of its inadequate safety culture. Further factors contributing to the crash were (1) the impaired pedestrian's crossing of N. Mill Avenue outside a crosswalk, and (2) the Arizona Department of Transportation's insufficient oversight of automated vehicle testing.

4 Recommendations

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

To the National Highway Traffic Safety Administration:

Require entities who are testing or who intend to test a developmental automated driving system on public roads to submit a safety self-assessment report to your agency. (H-19-47)

Establish a process for the ongoing evaluation of the safety self-assessment reports as required in Safety Recommendation H-19-47 and determine whether the plans include appropriate safeguards for testing a developmental automated driving system on public roads, including adequate monitoring of vehicle operator engagement, if applicable. (H-19-48)

To the state of Arizona:

Require developers to submit an application for testing automated driving system (ADS)-equipped vehicles that, at a minimum, details a plan to manage the risk associated with crashes and operator inattentiveness and establishes countermeasures to prevent crashes or mitigate crash severity within the ADS testing parameters. (H-19-49)

Establish a task group of experts to evaluate applications for testing vehicles equipped with automated driving systems, as described in Safety Recommendation H-19-49, before granting a testing permit. (H-19-50)

To the American Association of Motor Vehicle Administrators:

Inform the states about the circumstances of the Tempe, Arizona, crash and encourage them to (1) require developers to submit an application for testing automated driving system (ADS)-equipped vehicles that, at a minimum, details a plan to manage the risk associated with crashes and operator inattentiveness and establishes countermeasures to prevent crashes or mitigate crash severity within the ADS testing parameters, and (2) establish a task group of experts to evaluate the application before granting a testing permit. (H-19-51)

To the Uber Technologies, Inc., Advanced Technologies Group:

Complete the implementation of a safety management system for automated driving system testing that, at a minimum, includes safety policy, safety risk management, safety assurance, and safety promotion. (H-19-52)

BY THE NATIONAL TRANSPORTATION SAFETY BOARD

ROBERT L. SUMWALT, III

Chairman

JENNIFER HOMENDY

Member

BRUCE LANDSBERG

Vice Chairman

Report Date: November 19, 2019

Board Member Statement

Vice Chairman Bruce Landsberg filed the following concurring statement on November 25, 2019.

The automated vehicle (AV) event that resulted in a fatally injured pedestrian was not an accident. Accidents are unpredictable and unforeseeable. Rather, this was a crash that was predictable and avoidable. Crashes regularly happen on the highways—we know exactly what went wrong and how to prevent them. Driver-error-related crashes typically exceed 90 percent of all crashes. No surprises there. Here, automation played a significant part. Unfortunately, humans, who had the ability to prevent the crash, did not. Automation in vehicles has great potential, but it must be developed and managed carefully. That didn't happen here.

AVs are just now being tested, so one might think this was an “accident.” But the sequence of events was predictable except for the exact time and place. The AV sensing mechanisms and software were, and are, in early development. There remains significant risk despite widespread marketing enthusiasm.

Automation Complacency—Automation complacency occurs when the operator becomes very comfortable with the technology and relaxes the oversight that they are supposed to provide. It's present in many crashes and seen in all modes of transportation. Automation performs remarkably well most of the time and therein lies the problem. Human attention span is limited, and we are notoriously poor monitors.

Driver Inattention—The safety driver knew that cell phone use was prohibited while the vehicle was moving. Distracted driving has reached epidemic proportions and this crash is just one more tragic example. On this trip, the safety driver spent 34 percent of the time looking at her cell phone while streaming a TV show. The longest inattentive period was 26 seconds and in the 3 minutes prior to the crash, she glanced at the phone 23 times! Why would someone do this? The report shows she had made this exact same trip 73 times successfully. Automation complacency!

Pedestrian Inattention—A few more links in the crash sequence include darkness and an impaired pedestrian who elected to cross a divided highway well away from any crosswalk.

According to the NTSB's *Special Investigation Report: Pedestrian Safety*, published in September 2018, the potential for a pedestrian fatality was highly predictable. Nearly 75 percent of pedestrian fatalities occur during hours of darkness, and over 70 percent occur between intersections, away from crosswalks. Arizona law requires pedestrians to yield to motor vehicles between intersections, and there was signage prohibiting crossing in that area. A crosswalk was located about 300 feet away.

About 40 percent of fatally injured pedestrians are under the influence of alcohol. In this event, the postmortem toxicology showed the pedestrian to have about 10 times the therapeutic dose of methamphetamines in her system, which likely would have impaired her judgment and perception of impending threats. As drug use, both legal and illegal, becomes more prevalent, this risk will increase. While some may feel this is victim-blaming, my belief is that everyone has some

responsibility for intentional acts regarding their own safety: exercising good judgment and following the law.

Technology—Uber Advanced Technologies Group (ATG) started its test program in Tempe, Arizona, with two humans aboard—a safety driver and an observer (event tagger) who would document any mistakes the vehicle made and report them back to the engineers to address. But since everything was going so well and the tagging process was made easier, ATG decided that a dedicated observer was not needed. The vehicle was performing as well or better than expected. Automation complacency!

The vehicle, a Volvo SUV XC90, was equipped with driver-assist systems to detect pedestrians by providing alerts and braking. However, concerns about radar frequency interference between the Volvo's and ATG's systems led ATG to deactivate the Volvo system. In hindsight, the Volvo system was better able to detect a pedestrian under the circumstances that fateful night.

Uber ATG management had installed inward- and outward-facing cameras, but no one was monitoring the cameras to see if the no-cell-phone rules were being followed. Trust but verify! The report goes into considerable detail on the company's safety management system, or lack thereof. To Uber ATG's credit, it is taking prompt action to address the shortcomings the NTSB identified.

NHTSA's Inaction—Finally, we chastised the National Highway Traffic Safety Administration (NHTSA) for not providing definitive leadership to the states to manage the expansive growth in AV testing. During the meeting, Member Jennifer Homendy read NHTSA's mission statement, which is to *"Save lives, prevent injuries, and reduce economic costs due to road traffic crashes, through education, research, safety standards and enforcement activity."*

NHTSA would like to advance technology without squelching innovation. This permissive approach, while simultaneously preserving safety, is complex and not without risk. The AV guidance laid out in its documents is advisory only. As such, it's dependent upon either a company's willingness to adopt or a state's desire to better oversee the critical AV safety issues on our public roads.

It's time for NHTSA to live up to its stated goals and create appropriate safety regulation in this developmental area. Regulations can change as technology evolves and experience grows. It's a dynamic environment, but evolution in nature and in technology where lives are at stake is a brutal process. Natural processes are unavoidable, but NHTSA is working in a controllable environment. It should work with the stakeholders to put safety first and technology advancement second.

The more sophisticated the automation, the more complex the software and hardware programming. There are hundreds of thousands or millions of lines of code, and bugs can be extremely difficult to eliminate when buried deeply in a system. Ultimately, it will get better, but the development process matters. Aviation automation, an area much in the news lately, is child's play compared to surface vehicles, and we're still debugging aircraft software, some 70 years later! Bringing automated vehicles beyond the driver-assisted level is going to take a while, and collectively we need to be on guard!

Appendix: Investigation

The National Transportation Safety Board (NTSB) received notification of the crash in Tempe, Arizona, on March 19, 2018, and launched investigators from the Office of Highway Safety to address highway and vehicle factors, motor carrier operations, human performance, and onboard recorders. The team also included staff from the NTSB's Office of Research and Engineering.

The Volvo Car Group, Volvo Car USA LLC, the Uber Advanced Technologies Group, and the Arizona Department of Transportation were parties to the investigation.

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