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

VEHICLE FACTORS GROUP CHAIRMAN'S FACTUAL REPORT

A. CRASH INFORMATION

Location:	Northbound Mill Avenue, approximately 400 feet south of the intersection with Curry Road, in Tempe, Maricopa County, Arizona
Vehicle:	2017 Volvo XC90, being operated by Uber ATG in autonomous mode
Pedestrian:	49-year-old female, walking a bicycle across Mill Avenue
Date:	March 18, 2018
Time:	9:58 p.m. Mountain Standard Time (MST)
NTSB #:	**HWY18MH010**

B. VEHICLE FACTORS GROUP

David Pereira, Vehicle Factors Investigator, Group Chairman
NTSB Office of Highway Safety
490 L'Enfant Plaza East, S.W., Washington, DC 20594

C. CRASH SUMMARY

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

D. DETAILS OF THE VEHICLE FACTORS INVESTIGATION

This report details the mechanical examination of the subject vehicle involved in this crash. The examination included: the steering, braking, tires, suspension, and collision avoidance systems. Overall accident damage, and subsequent damage or anomalies within major vehicle mechanical systems were documented. Supporting photographs, vehicle specifications, maintenance records and other supporting documents were collected. The vehicle inspection was conducted at Tempe Police Department, located at: Apache Substation 1855 E. Apache Blvd. Tempe Arizona. On March 20, 2018. The vehicle components will be described in greater detail in the corresponding sections of this report. *See Vehicle Automation Report* for structural components of the automation system and Autonomous operations of the Uber test vehicle, based on a 2017 Volvo XC90, equipped with Uber developmental automated driving system.

1.1. Vehicle 1: 2017 Volvo XC90[1]

VIN:	YV4BC0PL5H1149667
Date of Manufacture:	November 2016
Model:	T8 eAWD Plug-In Hybrid 7-Passenger
Trim:	Inscription
Body Style:	Sport Utility
Drivetrain:	All Wheel Drive
Additional Technology:	Autonomous self-driving test vehicle
Headlights:	Light-emitting-diode headlights of the bending-beam type[2]
GVWR:[3]	6635 lbs.
GAWR[4] Front Axle:	3139 lbs.
GAWR Rear Axle:	3590 lbs.
Curb Weight:	5059 lbs.
Mileage:	24552
Engine Type:	Turbo/Supercharger Gas/Electric I-4
Displacement:	2.0 L/120
Fuel System Gasoline:	Direct Injection
SAE Net Horsepower:	400 @ 5700 RPM / 87 horsepower electric motor
Trans Description:	Eight-speed Geartronic Automatic Transmission
Brake Type:	Front/Rear disc
Wheelbase:	117.5”
Length, Overall:	194.9”
Width, Max w/o mirrors:	79.1”
Height, Overall:	69.9”
Track Width, Front:	66”
Track Width, Rear:	66.1”
Fleet Number:	014536

1.2. Vehicle Description

The Uber test vehicle is one of a fleet of 2nd generation Uber Advanced Technologies Group (ATG), test vehicles, equipped with the Krypton developmental self-driving system, operated in the Tempe Arizona area.

The vehicle was designed to operate in manual and autonomous (computer controlled) mode along a reference/predetermined test route.

[1] Factory Specifications, prior to modifications and additional equipment added by Uber Advanced Technologies Group
[2] Bending-beam headlights turn from side to side as the steering wheel turns, thereby helping to illuminate curves
[3] Gross Vehicle Weight Rating (GVWR) is the total maximum weight that a vehicle is designed to carry when loaded, including the weight of the vehicle itself, plus fuel, passengers, and cargo
[4] Gross Axle Weight Rating (GAWR) is the maximum distributed weight that a given axle is designed to support

1.3. Damage Description

The vehicle sustained collision damage, to the front end, not affecting any major mechanical systems, as shown in **Figure 1**. Damage specific to any of the vehicle components will be described in greater detail in the -applicable sections of this report.

For uniform description, “left” will refer to the driver’s side, and “right” will refer to the passenger side of the vehicle.

Contact damage to the front of the vehicle was concentrated in an area slightly offset from the vehicle’s centerline toward the passenger side. Contact damage was noted on the vehicle’s front bumper, grille, and hood. The most significant contact damage was concentrated on the hood.

The rear bicycle tire presented a transfer print, visible on the left edge of the front bumper cover and a front tire print to the right edge of the front bumper cover. Gouging and scrape marks were visible to the lower left corner of the front spoiler that was caused by the rear sprocket assembly on the bicycle. As shown in **Figure 2**.

Figure 1 - Front end damage to the 2017 Volvo XC90

Figure 2– Rear and front bicycle tire transfer print on front bumper cover

1.4. Weight and Measurements

Average vehicle weight measurements taken by Uber of two exemplar XC90 equipped with the Uber self-driving sensor suite are shown in **Table 1**.[5]

Table 1: Average vehicle weights of two exemplar Uber vehicles

Position	Weight (lbs.)		Axle
	Left	Right	Total
Axle 1	1,370	1,357	**2,727**
Axle 2	1,337	1,277	**2,614**
Total			**5,341 lbs.**

1.5. Driver Controls

The driver's seat was not damaged. The seat was fully adjustable, ergonomically designed, with ventilation. The driver's seatbelt was found unbuckled and attached at its anchor points, drivers' seatbelt webbing shows cupping with abrasions and load mark, indicating that it was worn at the time of impact, as shown in **Figure 3.**

Figure 3 – Drivers seatbelt of the 2017 Volvo XC90 showing cupping, circled in red

1.6. Steering

The vehicle's three spoke leather wrapped steering wheel was not deformed and mounted to the steering column that was adjustable for both height and angle. The steering column had two stalk control levers mounted each side. The left lever was the turn signal stalk and included accessory functions for headlights and high and low beam selection. The right stalk controlled the windshield wiper operations. At the time of the examination and not necessarily indicative of pre-

[5] Additional information is contained in Vehicle Factors Attachment – Vehicle Curb Weight Calculations

crash selections, the turn signal stalk was found in the centered in a neutral position, the headlight selector was in the auto on position and the windshield wiper selector was in the off position.

1.7. Suspension

The vehicle was equipped with a standard transverse leaf spring rear suspension with a double wishbone front suspension. No non-collision related defects were found.

1.8. Tires

The tire and weight rating placard mounted inside the door frame of the vehicle suggested that 275/45R20 tires all wheel positions. It also recommended that front and rear tires be inflated to 42 pounds per square inch (psi). Information on the condition of the vehicle tires at the time of inspection is included in **Table 2.**

All of the tires on the vehicle had tread depths that were greater than the minimum recommended 2/32nd of an inch.[6] All of the rims were checked for cracks and elongated lug nut holes, neither of which were found on any of the rims. No collision or non-collision related defects were found on any of the tire or rims.

Table 2- Tire Information for the 2017 Volvo XC90

Axle 1	Left	Right
Make	Pirelli	Pirelli
Model	Scorpion Verde	Scorpion Verde
Size	275/45R20	275/45R20
Max Load	2,337 lbs.	2,337 lbs.
Pressure	41 psi	41
Tread Depth	12/32nd	8/32nd
Tire Identification #	UN 7B TH85 4317	UN 7B TH85 4317
Axle 2	**Left**	**Right**
Make	Pirelli	Pirelli
Model	Scorpion Verde	Scorpion Verde
Size	275/45R20	275/45R20
Max Load	2,337 lbs.	2,337 lbs.
Pressure	42	42
Tread Depth	7/32nd	9/32nd
Tire Identification #	93 7B W651 4216	UN 7B TH85 4317

1.9. Brakes

Vehicle was equipped with 19” front and 18” rear disc brake rotors, Brake pads and rotors were examined and no visible indication of wear or defects.

[6] *https://one.nhtsa.gov/nhtsa/.../9719_S1N_Tires_Nwsltr_June13_062713_v4_tag.pdf*

1.10. Uber Retrofitted Controls

Additional equipment added by ATG to the vehicle operators' compartment are an LCD tablet (Front Seat Control App) mounted above the center console that is hinged for access to factory installed information center. Located on the center console to the right of the shift lever, a red knob has been added to for the vehicle operator (VO) to enable/disable the self-driving mode and a silver momentary push-button to engage the self-driving mode, as shown in **Figure 4**. The VO can also take manual control of the vehicle with inputs to steering, brake or accelerator.

Figure 4 – Additional equipment added to the driver's compartment by Uber ATG, circled in red

1.11. Maintenance and Inspection Records

Maintenance records indicate that the vehicle had regularly scheduled services completed Other maintenance included:

- On March 13, 2018, the vehicle had AV sensors scheduled recalibration[7]
- On March 15, 2018 at 23,946 miles the vehicle had 4 new 275/45R20XL Pirelli Scorpion Verde tires installed and a tire pressure monitor system sensor kit that included 4 sensors replaced.[8]

Utilizing the fleet maintenance software Fleetio.[9] The vehicle was inspected by the VO prior to being opertated the morning of the crash, this is 29-point inspection that includes the exterior and interior of the vehicle.[10]

[7] Additional information is contained in Vehicle Attachment - AV Sensors Scheduled Recalibration
[8] Additional information is contained in Vehicle Attachment -Work order #5683, Dated March 15, 2018
[9] https://www.fleetio.com/
[10] Additional information is contained in Vehicle Attachment - Driver Pretrip -Inspection Record

1.12. Collision Mitigation

The SUV was factory-equipped by Volvo with several advanced driver assistance systems (ADAS). One of those systems is "City Safety", a rear-end crash warning and mitigation system that is capable of preventing collisions with moving or stationary vehicles with up to 31 mph velocity differential and mitigating the crashes with higher velocity differential.[11]

This system alerts a driver when approaching a slow moving or a stopped lead vehicle; if the driver does not respond by braking or steering away, the system automatically brakes to prevent or mitigate the rear end crash. In a generic terminology, a system that warns a driver of an imminent forward collision is called forward collision warning (FCW) system and one that automatically initiates braking to prevent of mitigate a forward collision is called automatic emergency braking (AEB) system.

Additionally, the version of City Safety installed on the crash-involved vehicle also included a pedestrian, bicyclist and large animal detection components. If the system detects an impending collision, it would alert the driver or automatically brake to prevent or mitigate such collision. The pedestrian detection component of City Safety has an effective overall speed limit of 43 mph and can avoid collisions with pedestrians with up to 28 mph velocity differential and mitigate the crashes with higher velocity differential.[12]

All the driver support functions hosted by the Active Safety Domain Master (ASDM) are turned off by Uber when the test vehicle is operated in computer control mode and active when the vehicle is in manual mode. The interaction of the Volvo ADAS, Uber ATG's ADS and postcrash changes for collision mitigation are further explored the *Vehicle Automation Report.*

1.13. Event Data Recording

The vehicle was equipped with several standard control, recording and storage systems that were examined for crash data to include additional data provided by the Uber developmental automated driving system (ADS) that is further explained the *Vehicle Automation Report*.

1.13.1. Airbag Control Module

The vehicle was equipped with an airbag control module (ACM) compliant with 49 CFR Part 563.[13] The ACM has an event data recorder (EDR) capabilities as a separate feature.

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[11] (a) While the effectiveness of City Safety for detection of stationary vehicles is reduced when traveling above 43 mph, the effective speed limit or moving vehicles is higher.
(b) The SUV was factory-equipped with several other ADAS, including roadway departure warning, adaptive cruise control, and lane keeping.

[12] City Safety can reduce vehicle speed up to 30 mph to prevent or mitigate a collision with a bicyclist, and up to 28 mph to prevent or mitigate a collision with a pedestrian.

[13] In summary, 49 CFR Part 563 defined the minimum data set that must be collected if a manufacturer decides to voluntarily install an EDR (event data recorder) in their vehicle, along with requirements for the range and accuracy of EDR data. Part 563 is applicable to vehicle manufactured after September 1, 2010 and applies to vehicle with a GVWR of 8,500 pounds or less.

An event recording is typically triggered when the ACM experiences a pre-determined acceleration over time threshold or receives a signal from a remote sensor that activates the supplemental restraint system (SRS) deployment algorithm, also known as "algorithm enable" (AE). The recorded event data is classified as either a "deployment" or "non-deployment" depending upon whether an SRS device was commanded to deploy.[14] The type of data acquired varies by vehicle model and model year and have limitations as to the resolution, sampling interval, and time period of the recording, as well as the recorded parameters which was interpreted by the Bosch Crash Data Retrieval (CDR) software.[15]

Police investigators from Tempe and Scottsdale Arizona Police Departments initiated data imaging from the Volvo's EDR stored in the airbag control module. The CDR report conveyed that communication between the ACM and the software had been established and contained SRS status data and event data. The configuration indicated that the module was capable of storing both SRS deployment and non-deployment events. Non-deployment events, of which the ACM will store six, can be overwritten by more severe events or events that result in a deployment command. The data retrieved from the vehicle included a single event that was classified as a non-deployment.

The following is a summary of certain aspects of the electronic data retrieved from the vehicle: The report indicated that the recording was complete, but not locked with no multiple events detected. A total of five (5) ignition cycles had been recorded between the event and the data download. The five (5) ignition cycles are accounted by cycling the ignition during the investigation.

The recorded event was classified as a front impact with a maximum longitudinal change in velocity of 14.9 mph in the forward (negative) direction and a maximum lateral change of velocity of 1.2 mph at following the event trigger, both events occurred greater than 300ms. There was no restraint system deployment command for this event by the ACM. The service brake transitioned from off to on at the time of algorithm start (algorithm enable or "AE"). The vehicle had been slowing during the 5.0 seconds prior to the AE event from a maximum speed of 44.1 mph to 33.6 mph at the algorithm start. Some of this speed loss is accounted by the vehicle slowing down for anticipated right turn in computer control mode. The full report generated by the CDR software is included in vehicle factors attachments.[16]

1.13.2. Active Safety Domain Master.

Volvo's Active Safety Domain Master (ASDM) provided another source of crash data for investigators. While Volvo's collision avoidance ADAS were deactivated at the at the time of the crash, this module still records various vehicle dynamics when triggered.

The ASDM has an additional SRS road runoff functionality, that detects potential roadway departures by monitoring various vehicle dynamics.[17] The vehicle was equipped with an electrical

[14] An SRS device may include any airbag, seat belt pretensioner, rollover sensor or other non-reversible restraint
[15] Software version 17.7 was used for the imaging and interpretation.
[16] Vehicle Factor Attachment - Bosch Crash Data Retrieval Report
[17] The road runoff functionality is provided by an algorithm that detects rough road and is based on vehicle roll rate and lateral, longitudinal and vertical acceleration. The runoff is triggered when the roll rate and the three different accelerations oscillate three times beyond a threshold vehicle within a short span

reversible retractor (ERR) in the front seats, which tenses seat belts, keeping an occupant closer to the seat, in anticipation of a crash. The ASDM module controls and records the activation of Volvo ADAS.

Data provided by Volvo showed that the SRS road runoff functionality detected a potential roadway departure which triggered ERR to tense the driver's seat belt. The activation of the ERR was detected by the ASDM which triggered the ASDM incident recorder.[18]

Comparing Volvo recorder data to data from Uber ADS and the forward-facing video, investigators were able to align the timeline of the road runoff detection and the ERR activation to the time of the impact.

At the time of the impact with the pedestrian, the SUV was traveling at 39 mph; one second later, the speed was reduced to only 36 mph. The ERR was activated approximately 1.7 seconds after the impact; the SUV speed at that time was approximately 29 mph.[19] The delay in the ERR activation was because the detection of possible road runoff was not due to the initial impact, but rather due to the vehicle's secondary contacts with the pedestrian. Further explained in the *Vehicle Automation Report.*

1.14. Volvo Car Corporation Case Analysis Simulation

A simulation series of a "vehicle to pedestrian conflict scenarios" was conducted by Volvo Car Corporation. The purpose of the simulation was to estimate the scenario outcome if the UBER test vehicle would have had the City Safety pedestrian detection functionality enabled during the conflict event.

As described in section 1.12, the City Safety software is designed as a set of driver support functions, including pedestrian detection. If a potential conflict with a pedestrian is detected, and the driver is not acting to resolve the conflict, the function will first issue a Forward Collision Warning (FCW). If the driver does not act on the warning, the vehicle will initiate Automatic Emergency Braking (AEB) to avoid or mitigate a collision. The function is designed to assist the driver in avoiding imminent collisions without intruding during normal driving. The function hence only activates very close in time to an actual collision, when it is deemed difficult for a normal driver to resolve the conflict.

For these simulations, the simulation tool used two modules; one describing the virtual vehicle and the other describing the vehicle surroundings. The vehicle module contains models that describe the vehicle's dynamic responses, the City Safety functionality and the behavior of the external sensors that provide information about the vehicle surroundings. The vehicle surroundings module contains models describing the environment, the conflict situation and any surrounding traffic flow.

[18] Additional information is contained in Vehicle Factor Attachment - Volvo EDR data

[19] Due to different recording rates - ASDM records data at 5 Hz while depending on a variable, the SRS records data at either 10 Hz or 2 Hz- the vehicle speed is accurate within 1-2 mph.

It is important to note that in this simulation series, ideal sensor data and functionality were used. Also, to compensate for uncertainties about the environmental conditions, a series of variations of the pedestrian pre-crash movement were simulated (i.e. altering pedestrian walking speed and crossing angle slightly for each simulation), to account for a greater range of possible pre-crash scenarios.

For each variation of the pedestrian pre-crash movement and starting from the known position and speed of the Uber test vehicle, the simulation modelled when the City Safety software would have detected and classified the pedestrian as being on a collision path. For this to happen, the pedestrian was required to be fully within both radar sensor range and within camera field of view. Since the exact classification moment is difficult to model given the limited data available, a range of different classification times were used to ensure sufficient scenario coverage.

As a next step, the simulation estimated the time of the activation of the FCW and the AEB; the FCW would have alerted the driver at approximately 2.5 seconds time-to-contact (TTC) and the AEB would have engaged at approximately 1.4 seconds TTC.[20] Assuming no response for the driver, and considering only the activation of the AEB, the SUV would have avoided the collision with the pedestrian in 17 out of 20 variations—the pedestrian would have moved out of the path of the SUV. In the remaining 3 variations, the AEB would have reduced the impact speed to less than 10 mph.

1.15. Documented Recall and Warranty Clams

A search of the safety recall database maintained by the National Highway Traffic Safety Administration (NHTSA) revealed no recalls relating to the vehicle.[21]

2. Bicycle

2.1. Bicycle: 700c Hyper SpinFit Men's Hybrid Bike, Red

Serial Number:	TK17C31876
Frame size:	26"
Manufactured:	2017 by Hyper Toy Company of Malaga NJ

2.2. Damage

The bicycle had damage to the front rim, and front fork was not aligned with handle bars as shown in **Figure 5.** The bicycle was missing the side reflectors from the spokes on the front and rear wheels as shown in **Figure 6**. The rear reflector on seat post was turned facing forward. White

[20] (a) TTC indicates time before impact between the pedestrian and the SUV.
(b) At the recorded impact speed of 43 mph, the TTC would have been 2.6 seconds at 50 meters from the point of impact.
[21] A search of the safety recall database on 03-29-2018 that is maintained by the National Highway Traffic Safety Administration (NHTSA) http://www-odi.nhtsa.dot.gov/recalls/recallsearch.cfm.

reflector mounted on stem was correctly facing forward, both pedals had front and rear facing reflectors.[22]

Figure 5 - Hyper 700c SpinFit Hybrid Bike

Figure 6 – Photo of exemplar Hyper 700c SpinFit Hybrid Bike showing reflectors mounted on front and rear wheels circled in red

E. DOCKET MATERIAL

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

[22]According to Title 16 code of Federal Regulations (CFR) part §1512.16 Requirements for reflectors. Bicycles shall be equipped with reflective devices to permit recognition and identification under illumination from motor vehicle headlamps.

LIST OF ATTACHMENTS

Vehicle Factors Attachment -	Vehicle Curb Weight Calculations
Vehicle Factors Attachment -	AV Sensors Scheduled Recalibration
Vehicle Factors Attachment -	Work Order #5683, Dated March 15, 2018
Vehicle Factors Attachment -	Driver Inspection Record
Vehicle Factor Attachment -	Bosch Crash Data Retrieval Report
Vehicle Factor Attachment -	Volvo EDR Data

END OF INFORMATION

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