Voluntary Safety Self-Assessment

Aurora

2021

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A Letter from CEO and Co-Founder Chris Urmson

Our goal at Aurora is to transform transportation — to make it more democratic, more productive, more dependable, and — crucially — much safer than it is today. The teams we create, the work that we do, and the partnerships we build all serve this mission: To deliver the benefits of self-driving technology safely, quickly, and broadly.

We see incredible opportunities for the Aurora Driver to positively impact transportation. We can save lives while also increasing safety and efficiency on our roads. We can make the movement of people and goods both less expensive and more accessible. We can serve communities and industries in mutually beneficial and transformative ways.

But all of these opportunities depend on one concept: trust. Our technology needs to be trustworthy. Our company needs to be trustworthy. And so our task is to build trust, one step at a time, by making safety the foundation of everything we do.

We released our last Voluntary Safety Self-Assessment (VSSA) in 2019, and since then Aurora has grown — in company size, in the strength of our partnerships, and in our capacity to build a robust safety infrastructure. We have also continued to develop innovative self-driving software and hardware technologies that will safely accelerate the deployment of the Aurora Driver. As you will read in these pages, we continue to define, refine, and document our safety policies and procedures. We empower our team members to be responsible for making our company's work as safe and, therefore, as trustworthy as possible.

At Aurora, we are committed to continually strengthening our safety culture, and, ultimately, demonstrate ourselves to be trustworthy agents of radical change in transportation.

Chris Urmson
CEO & Co-Founder

Safely

Our primary motivation behind Aurora's work is to reduce crashes, injuries, and fatalities. Over 100 people a day die in car-related crashes in the United States alone — the status quo is not acceptable and we are committed to doing something about it.[1]

Quickly

Every year self-driving technology is delayed, not only are thousands of lives lost, but billions of dollars are squandered. We feel great urgency to turn this around.

Broadly

The benefits of self-driving vehicles apply in a wide variety of contexts, from long-haul trucking to local goods delivery and people moving. Our technology is designed to adapt to these varied use cases, and more.

Executive Summary

Safety is at the core of everything we do at Aurora — we integrate safety into all facets of our business, from initial concept to deployment.

The U.S. Department of Transportation (U.S. DOT) and it's National Highway Traffic Safety Administration (NHTSA) have developed voluntary guidance for autonomous vehicle developers to consider as they develop, test, and deploy self-driving products.

This Voluntary Safety Self-Assessment (VSSA) is intended to inform NHTSA and the public about how we are building the Aurora Driver to safely drive vehicles, and it addresses and expands upon NHTSA's safety design elements. We describe our culture of safety and our systems engineering approach to the safe development and deployment of the Aurora Driver. We also detail our enterprise safety approach to developing and deploying our products, showing how we incorporate safety throughout our culture, processes, programs, training, partnerships, and technology.

This report reflects our current programs and policies and the current capabilities of the Aurora Driver. This document will be updated as our technology and processes evolve.

Here is what you will find in our VSSA:

Architecting our Safety Approach: We introduce our safety case approach, Safety Management System (SMS), emphasis on safety concern reporting, and how we empower all Aurora employees to ground our fleet if they have any safety concerns. We also discuss our strong commitment to integrating cybersecurity within the safety case, the hardware and software of the Aurora Driver, and across Aurora writ large.

Developing the Aurora Driver: We describe how the pieces of our platform are developed — from vehicle-integrated hardware that delivers data inputs to the Aurora Driver computer, to the software modules that use these data inputs to perceive, plan, and control the vehicle's movement.

Testing the Aurora Driver: We provide details about where our vehicles operate, how our software is released, and how we test the Aurora Driver — virtually, on closed tracks, and on public roads. We also discuss how we work closely with our partners to install the Aurora Driver into vehicles in a safe and thoughtful manner.

Operating the Aurora Driver: We provide details about our vehicle operations, vehicle operators, and vehicle equipment inspections.

Delivering the Aurora Driver: We describe our market approach to commercializing the Aurora Driver, including our plans to first deploy our technology in Class 8 trucks, followed closely by passenger vehicles in a ride-hail format.

Building Trust & Transparency: We provide a summary of how we engage with partners and the public on consumer education, and with our peers on industry standards development.

Our mission is to

deliver the benefits of self-driving, safely, quickly, and broadly.

1

Architecting our Safety Approach

Safety is our first priority when it comes to developing the Aurora Driver. Our technology is continuously evolving, and we are simultaneously expanding and refining our safety case, safety management system, and safety culture and working actively with the industry to develop consensus standards and best practices.

Establishing Enterprise-Wide Safety

Achieving a successful approach to safety requires a holistic view. Though much of the early dialogue on automated vehicle technology centers around the safe performance of the vehicle and the automated system, we believe that an enterprise-wide view is necessary to ensure our systems operate safely on all levels. To ensure that safety risk is managed as an organization, we consider the safety of the technology and the safety of our employees, all of which comprise our Safety Culture.

We leverage a disciplined and thoughtful approach with the right team to deploy time-tested industry best practices in an explicit, deliberate manner. Our team of safety experts and leaders bring together expertise from self-driving and automotive companies as well as from industries like aerospace, medicine, and nuclear power. Building a team with depth and breadth of experience and drawing from this wealth of multidisciplinary expertise is paramount because safety is not something we bolt on at the end or check a box to complete. This work requires ingenuity, attention to detail, humility, and a deep understanding of how to approach safety-critical systems.

Our holistic approach ensures that safety is ingrained throughout the entire process, from initial concept to deployment. Guidance from the U.S. Department of Transportation (U.S. DOT) and its National Highway Traffic Safety Administration (NHTSA) have identified 12 safety elements, or core areas of consideration with respect to safety in the self-driving space. Aurora's safety management approach encompasses all of these elements: each is represented in at least one, if not more, elements of our development and operational efforts, which we discuss in more detail throughout this report.

Building our Safety Case

Developing and operating a self-driving vehicle that can operate safely on public roads is a complicated endeavor. Perhaps equally challenging is effectively communicating to the public how we know that a vehicle is safe to operate on public roads. To achieve both aims, Aurora has adopted a safety-case-based approach.

A safety case is a structured argument, supported by evidence, intended to justify that a system is acceptably safe for a specific application in a specific operating environment. This mechanism is used to communicate and manage complex safety concepts across many industries, including oil and gas, military, aerospace, rail, food and drug, and nuclear power.[3] A successful safety case communicates to stakeholders that the risk of harm from a system has been reduced to an acceptable level.[4]

Our Safety Case Framework combines guidance from government organizations, best practices from safety-critical industries, voluntary industry standards and consortia, academic research, and what we have learned in our own work.

As our technology, development, operations, and policies evolve, so will our Safety Case Framework and we will continue to document this evolution in future VSSAs.

The scope of our Safety Case Framework applies to both the development and full-scale operation of Aurora's self-driving vehicles. We tailor our safety case depending on the specifics of the system and the intended uses, such as whether it's a delivery service on our trucking platform or a ride-hailing solution with a partner. For example, depending on the different scenarios outlined below, we leverage different evidence to substantiate safety claims for when the Aurora Driver:

- Is supervised by a vehicle operator versus when it is not
- Is transporting passengers versus goods
- Is operating in different operational design domains (ODD), meaning the specific conditions in which the Aurora Driver can safely operate
- Is deployed in different geographic regions

Organizational Approach to Safety Management

We are committed to a formal and systematic approach to manage safety that will, among other benefits, allow us to build a holistic culture of safety. This robust organizational approach to safety management is based on the International Civil Aviation Organization (ICAO) principles — generally referred to as Safety Management System (SMS). Such an organizational approach allows us to improve performance by proactively managing safety risk while providing safety assurance oversight of its many programs and processes.

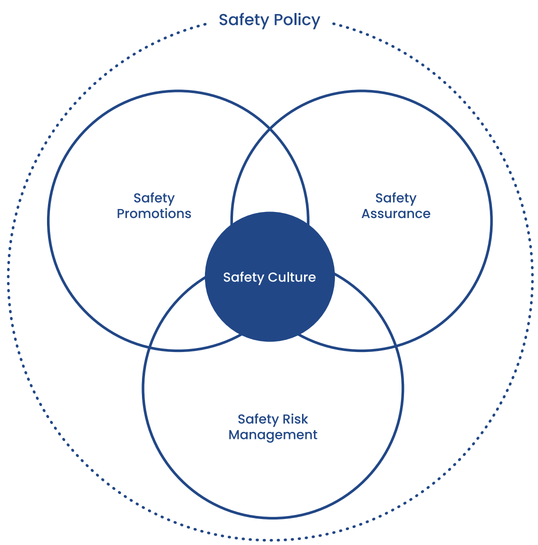
Our organizational approach to safety management is built on four key pillars — a detailed Safety Risk Management structure, a robust Safety Assurance program, disciplined Safety Policy documentation, and Safety Promotions and Education. These four pillars are supported by leadership, reflected in our values, and implemented so that our employees know how to engage with them. Critically, they also form the foundational framework of our engineering decisions. Each pillar plays an important role in cultivating a strong and effective organization-wide safety program and is necessary to enable a high-functioning organization.

Pillars of Safety Management:

- **Safety Risk Management**: Provides a framework for making risk-based organization decisions that enables us to effectively manage the complexity inherent in developing and operating self-driving technology. It also allows us to identify hazards, and to characterize, assess, analyze, and control risk.
- **Safety Assurance Program**: Enables us to proactively and reactively identify safety risk and understand the effectiveness of existing safety risk controls, thereby providing actionable intelligence to continually improve safety. A comprehensive Safety Assurance program ensures proper safety oversight through regular and ongoing monitoring and evaluation of safety performance.
- **Safety Policy Documentation**: Establishes a clearly defined commitment to safety throughout the organization. It also defines the methods and processes to drive responsibility and accountability.
- **Safety Promotion and Education**: Creates and reinforces a Just Culture, which includes open and fair processes to empower anyone within Aurora to voluntarily and confidentially report safety concerns and issues without fear of reprisal. Through training and communication, we can ensure that everyone recognizes their role in promoting safety, and how to fulfill it.

To implement and promote these four pillars, we have created a Safety Review Board (SRB) to be chaired by our CEO, who has been designated as the Accountable Executive for safety. The SRB provides the highest level of safety risk deliberation, decision making, and safety performance oversight for the Company. While managers and directors are empowered to make decisions surrounding safety risk to certain identified risk levels, the SRB reviews the high level risks to determine whether proposed actions are acceptable or whether additional controls are necessary to bring the risk to an acceptable level. The SRB meets regularly to review data-driven metrics on safety performance.

We believe that adapting industry practices appropriately and systematically will help position us to deliver our products safely. Applying these four key pillars of our organizational safety approach is critical for the responsible development and eventual full-scale operation of self-driving vehicles.



Safety Concern Reporting

Our approach to safety is aligned with the concept of Just Culture, a philosophy that encourages organizations to perform fair investigations, allows employees to openly communicate without fear of reprisal, and to review processes, procedures, and training objectively. Our Just Culture policies empower managers to focus on holistic organizational factors instead of individual human errors. One of the most visible implementations of Just Culture is a Safety Concern Reporting System.

Our Safety Concern Reporting System provides a clear and easily accessible mechanism for reporting potential safety issues to our safety team, and can be used by any employee, contractor, or vendor at Aurora, regardless of level or tenure. Team members can also report their concerns to their lead, manager, or supervisor on duty, encouraging open and transparent communication throughout the organization.

We educate our employees on the protections offered by the Safety Concern Reporting system to minimize any fear of retribution. Each concern is taken seriously and assessed for potential safety risk. Then it is analyzed, reviewed, and resolved with appropriate corrective actions.

The senior leadership team regularly reviews metrics on the usage of the Safety Concern Reporting System, key findings, and organizational trends and, where appropriate, systemic fixes are instituted.

Grounding the Fleet

The phrase "grounding the fleet" refers to the act of ceasing vehicle test operations. All Aurora employees are empowered to ground the fleet for safety reasons, at any time, an important policy we teach all new employees during their first week. Closely aligned with the Just Culture principles, anything that gives a team member concern about safety is a sufficient reason to ground the fleet, without fear of reprisal. Because of our approach to fleet groundings, we have found most of our groundings are proactive, ceasing operations before any unsafe outcome can occur.

We have defined a methodology to stipulate exactly what happens after a grounding event. Immediately upon the issue of a grounding order, our vehicle operators disengage from self-driving mode in any test vehicles that are out in the field.

A grounding order also triggers a cascade of rigorously defined investigatory steps within multiple departments across the company (e.g., operations, safety, engineering). The cause is identified, immediately contained, and permanently addressed. This approach ensures all employees feel responsible and empowered to protect and support Aurora's safety culture.

Cybersecurity

The rapid evolution of autonomous vehicles has created new threat profiles. Our security teams are actively engaged in identifying and mitigating these real and potential threats across Aurora, and our self-driving systems and vehicle platforms, using cybersecurity industry best practices[6] that recommend elimination of risks through design when possible[7] as well as risk-reducing architectures.[8]

We consider all functional areas of our technology to be potential targets with different threat models,[9] and, therefore, a potential vehicle safety concern. In order to robustly address concerns across such a diverse ecosystem, our security teams follow a risk management methodology based on multiple industry best practices[10] to identify, assess, and evaluate risks.

Our self-driving vehicles are built on base vehicles designed for human drivers, so our security technology must work with the vehicle manufacturer's security measures. However, we are continually improving our security primitives (i.e., low-level cryptographic algorithms) to enable the Aurora Driver's ability to identify, protect, detect, respond, and recover from potential threats safely when operating within those vehicles.[11]

Generally, a self-driving vehicle needs to be able to communicate with any remote systems on which the vehicle relies for autonomy support. Our security controls ensure that these communications employ best-practice secure protocols to protect the channel and transmitted data from interception and modification.

Finally, our fleet managers, vehicle operators, and co-pilots also serve as a line of defense in mitigating cyber threats. These professionals are trained to detect, annotate, and diagnose any potential irregularities in system and vehicle performance.

We seek continuous improvement in managing cybersecurity threats. By exploring risks, investing in solutions, and collaborating with our industry partners, we constantly incorporate security upgrades across our vehicle platforms. We are dedicated to developing new security features and capabilities within all components, to improve the security posture for future self-driving vehicles across the industry.

Industry Best Practices and Standards

Our world-class systems engineering team works in parallel with our safety engineers to develop actionable safety standards and promote a culture of safety within Aurora. We leverage industry best practices and standards that have significantly raised the bar in automotive safety, and we are committed to ensuring the relevant principles are embedded within our internal policies, procedures, and approaches in developing the Aurora Driver.

The U.S. DOT Comprehensive Plan[12] identified a set of twenty automotive best practices and standards, which individually address different components or processes for a self-driving system or enterprise. Further, standards such as SAE J3016, SAE J3018, UL 4600, International Organization for Standardization (ISO) 26262, and ISO 21448, as well as the best practices from the Automated Vehicle Safety Consortium (AVSC), are applicable to self-driving technology.

In addition, standards from other industries have utility in the development and deployment of self-driving vehicles. However, as many of these standards were not written specifically to apply to self-driving, they must be interpreted to apply in the self-driving vehicle context. We will continue to review, interpret, and apply relevant best practices and standards across our organization.

2

Developing the Aurora Driver

To truly deliver the benefits of self-driving technology safely, quickly, and broadly, the Aurora Driver needs to move people and goods across all vehicle platforms, from Class 8 trucks to passenger vehicles. Developing a self-driving system with this flexibility is challenging and requires a deep investment in foundational hardware and software design to seamlessly integrate across vehicle platforms. At Aurora, we have prioritized these critical investments knowing that focusing on this foundational technology will ultimately enable us to accelerate the deployment of the Aurora Driver.

Operational Design Domain

The operational design domain (ODD) refers to the conditions in which the Aurora Driver is intended to function — including environment, weather, driving conditions, actor behavior, traffic density, and other considerations. The location of operation and performance capabilities of the Aurora Driver determine the characteristics of the ODD.

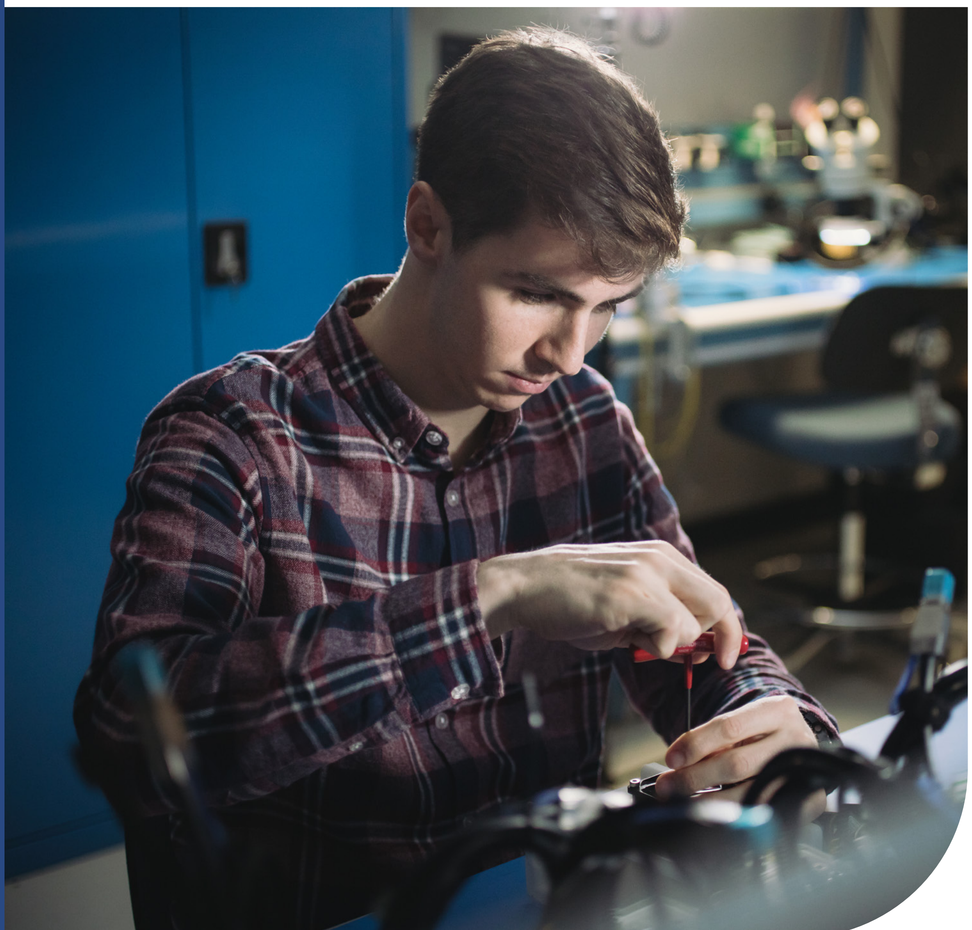
We select ODDs to achieve goals in product strategy, development, and vehicle platform capabilities, among other factors. We operate in cities including Pittsburgh, Pennsylvania, Dallas-Fort Worth, Texas, and the California Bay Area, specifically to give our teams access to the diverse road, traffic, and weather conditions that exist in each area. To date, testing in various ODDs has demonstrated that the Aurora Driver can safely handle multiple challenging situations. This includes varied road environments (urban, suburban, and highway), changing lighting conditions (day, night, dawn, dusk); and myriad weather conditions (clear, fog, rain, and snow).

Once an ODD is identified, we map the area and begin running simulations of scenarios within the ODD. Meanwhile, our trained vehicle operators drive the new roads manually with our system in observer mode. Our engineers then review the collected data and make any software modifications before our vehicle operators operate the system in self-driving mode within the ODD.

Operation within the ODD can be constrained at both software and operational levels. For example, in software, the Aurora Driver is prevented from driving in areas outside of the ODD via geofencing techniques that impose a system prohibition on self-driving across the geofence. These constraints can also restrict routing of the Aurora Driver at the lane level based on a set of configurable ODD elements, such as road speed, road type, and traffic-control devices.

Operational constraints are enforced by our vehicle operators, who monitor road and weather conditions while operating in the field. These operators are trained on the governing ODD characteristics, and are prepared to take manual control of the vehicle when presented with a scenario or conditions not included in the relevant ODD.

The combination of the various ODD constraints in any given ODD serve as important controls to reduce unacceptable safety risks at any stage of development, testing, or operation.



Hardware

From Aurora's earliest days, we have adhered to a set of guiding tenets for hardware development: we buy where available, customize where necessary, and build where required. We design for extensibility and scalability, meaning every sensor we develop must support the Aurora Driver across all use cases, whether on a Class 8 truck or a passenger vehicle.

Our self-driving software requires carefully-crafted hardware to power, synchronize, and ingest the data from dozens of high-bandwidth sensors in and around the vehicle. Our approach to design customization in hardware is to use industry technology where it meets our needs (e.g., cameras and near-field lidar), customize where required (e.g., computer design and radar), and develop new technology where doing so differentiates Aurora (e.g., FirstLight lidar) from our competitors.

Because our hardware platform is vehicle agnostic, we are designing our computer and sensors as a tightly-integrated and self-sufficient suite that maintains its safety and performance guarantees even when incorporated into vehicles of various makes, models, and classes. From a small battery-electric sedan to a Class 8 truck, our hardware will enable the Aurora Driver to operate any vehicle, provided the platform meets a minimum set of interface requirements.

Our hardware operates as a central, largely self-sufficient hub. It conditions and distributes its own power, coordinates and synchronizes its own sensors, communicates with the vehicle over a simple umbilical, and will communicate with transportation networks over a common network. This centralization of critical functions makes Aurora's hardware system highly adaptable.

Computer

The Aurora computer is based on architecture and processors designed specifically for machine learning acceleration and high-speed data capture. This custom-designed computer acts as the central hub across all Aurora Driver hardware, managing power, communication, and networking. It:

- Conditions and distributes power;
- Measures and controls the electric and thermal loads of all elements of the system; and
- Ingests, synchronizes, and processes all sensor and vehicle telemetry data required to operate the vehicle.

Inside this computer, a custom Aurora networking switch uses an advanced networking chip and a unique combination of next-generation, high-bandwidth automotive physical layers to efficiently move data between nodes, duplicate data packets, provide redundant pathways, and synchronize our sensors to the microsecond.

The computer controls the vehicle through a vehicle interface module. This is an independent module that is designed for a high level of safety. Upon identification of interface failures with the computer, this module will safely bring the vehicle to a controlled stop.

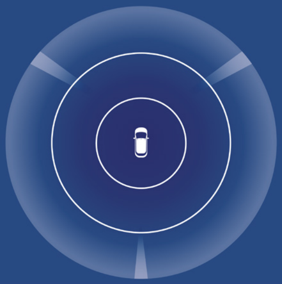
Sensor Suite

We use lidar, cameras, and radar to ensure we have 360° views of surrounding areas. When developing our sensor suite, we simulate placements to ensure there are no blind spots or other issues that could result in failures of the perception system before we place our sensors on our vehicles. Our sensor suite is designed to work across a variety of ODDs and is continuously refined as new capabilities become available.

Sensor Suite

Cameras

Cameras help the Aurora Driver recognize traffic light colors, identify stop signs, and classify objects that are far away. We've custom-designed the lenses, layout, and cleaning solution to ensure that they can see far enough ahead to drive safely on high-speed highways and provide a clear view all around our vehicles.



FirstLight Lidar

Our FirstLight Lidar provides huge advantages over even the most advanced traditional lidar systems available today, especially when it comes to long-haul trucking. It's a self-driving game-changer that allows the Aurora Driver to identify and track objects farther, faster, and with greater precision than ever before.

Radar

Radar helps ensure our perception system can operate in a wide range of weather conditions. We use custom imaging radar solutions that provide far greater range and resolution than traditional automotive radar.

Traditional Lidar

Currently, we also use conventional lidar to help the Aurora Driver identify and track objects that are closer to the vehicle.

Cameras

Our cameras observe the visible light reflected off surfaces, much like people do. We have custom designed the lensing, layout, and cleaning solution for our cameras to meet the demands of the broad set of use cases in which the Aurora Driver will operate. Our cameras' high resolution sensors and quality optics ensure we have adequate range to drive safely on high-speed highways, and sufficiently broad field of view to operate in congested urban settings.

Radar

These sensors emit radio waves, measuring how long it takes for the emitted waves to bounce back from different directions. These sensors also measure the Doppler shift imparted by relative motion between the sensor and objects in the scene. We use cutting-edge imaging radars to provide both elevation and azimuth data, helping the Aurora Driver quickly and accurately perceive the objects around it. When coupled with our cameras and FirstLight Lidar, our radars provide maximum overlap on the sensor inputs we can provide to the Aurora Driver. Radar also works well in most weather, so it can "see" in some circumstances where cameras or lidar cannot. We are working to develop custom-imaging radar solutions that provide for greater range and resolution than a traditional automotive radar.

Lidar

We have invested a considerable amount of time and resources in deeply understanding how perception needs change at high speeds, and putting in place technologies that will allow us to meet them. Using FirstLight, our industry-leading Frequency Modulated Continuous Wave (FMCW) lidar, the Aurora Driver can detect and track objects more quickly, at greater distances, and with greater precision than traditional lidar.

Lidar sensors are much like radar, but instead of using radio waves, they use waves of infra-red light. FMCW lidar sends out a constant stream of light ("continuous-wave") and changes the frequency of that light at regular intervals ("frequency-modulated"). FMCW lidar is powerful because the sensors have the following features:

- **Single photon sensitive**: Allows for detection of the smallest amount of light possible
- **Immune to solar and lidar-to-lidar interference**: Allows for longer range operation and less artifacts
- **Velocity measurement on every single point**: Provides additional information to the perception systems for tracking and detection

FirstLight provides significantly better range performance when compared to traditional pulsed time of flight lidar systems, allowing the Aurora Driver to see beyond 300 meters. Even fractions of a second can make a huge difference in safety and comfort, especially with heavy vehicles driving at highway speeds. Unlike traditional lidar, FMCW lidar provides a very accurate velocity measurement for each data point. This helps our perception system process incoming data faster because it no longer has to estimate velocity from changes in object position observed over a period of time. Instantaneous velocity measurements also make it easier for the perception system to recognize distant and sparse data points as objects and track how those objects are moving over time. This means the Aurora Driver has more time to react to unexpected obstacles.

Traditional lidar systems are often affected by interference, which can occur for example, when there is bright sunlight, when other sensors' light pulses are perceived, or when a lidar receives its own previous pulses at unexpected times. These events can cause errors in the data that result in "ghost" objects that do not exist or objects that are reported in the wrong location. FMCW lidar does not typically experience these problems because each sensor is designed to respond only to its own light. That means FMCW lidar enables more accurate object detection while saving hardware, software, and computational power. Less interference means smoother and safer driving.

In addition to our FirstLight lidar, we also partner with industry-leading third-party lidar developers to source and integrate mid- and short-range lidar on our vehicles. This helps us capture data all around the vehicle at all times.

We are also developing a groundbreaking solid-state scanning mechanism. This lidar-on-chip method replaces bulky, unreliable, and expensive mechanical parts and increases the reliability of our hardware and the uptime of the Aurora Driver. This means we will handle more rides and deliver more goods quickly, safely, and more efficiently.

The Power of FirstLight

Purpose-built by Aurora, for Aurora

FirstLight has been purpose-built to meet the needs of the Aurora Driver, on Aurora's timeline. Rather than catering to the needs of other companies and industries, we're building FirstLight so we can deliver autonomous vehicles to market safely, quickly, and broadly.

Performance, then scalability

While there is an industry push to optimize lidar sensors for cost first, that's not the Aurora way. We focus on performance first, and then scalability.

Beyond 300 meters

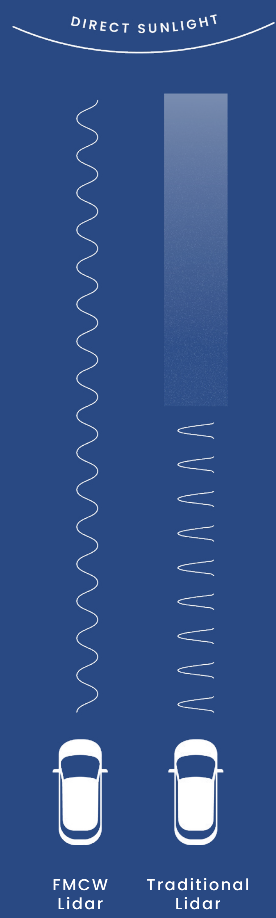
Farther and faster, FirstLight allows the Aurora Driver to see well beyond 300 meters even on targets that don't reflect much light. And it measures velocity instantaneously.

Less interference

FMCW lidar has less static and isn't typically impacted by interference from the sun or other lidars because each sensor is designed to respond to only its own light.

Gamechanger for moving goods and people

We're investing in lidar-on-chip capabilities that increase the reliability of our hardware and the uptime of the Aurora Driver. Faster, more compact lidars will allow us to pull more loads and transport more people safely and quickly.



Hardware Quality Processes

We employ several quality processes to address potential issues with the physical hardware components of the Aurora Driver.

Component-Level Design Verification

Hardware modules for our Aurora Driver undergo testing to identify performance limits and confirm they are meeting specifications. Once we have confirmed the appropriate function, individual components are validated via environmental qualification testing. This testing provides comprehensive coverage of thermal, vibrational, electromagnetic, and other environmental factors beyond what is expected during normal operation. In addition, components undergo extensive reliability testing to ensure proper functionality throughout the intended product lifecycle. This testing exposes components to accelerated wear and tear, namely to simulate lifetime exposure and to understand degradation of function or performance.

Subsystem-Level Design Verification

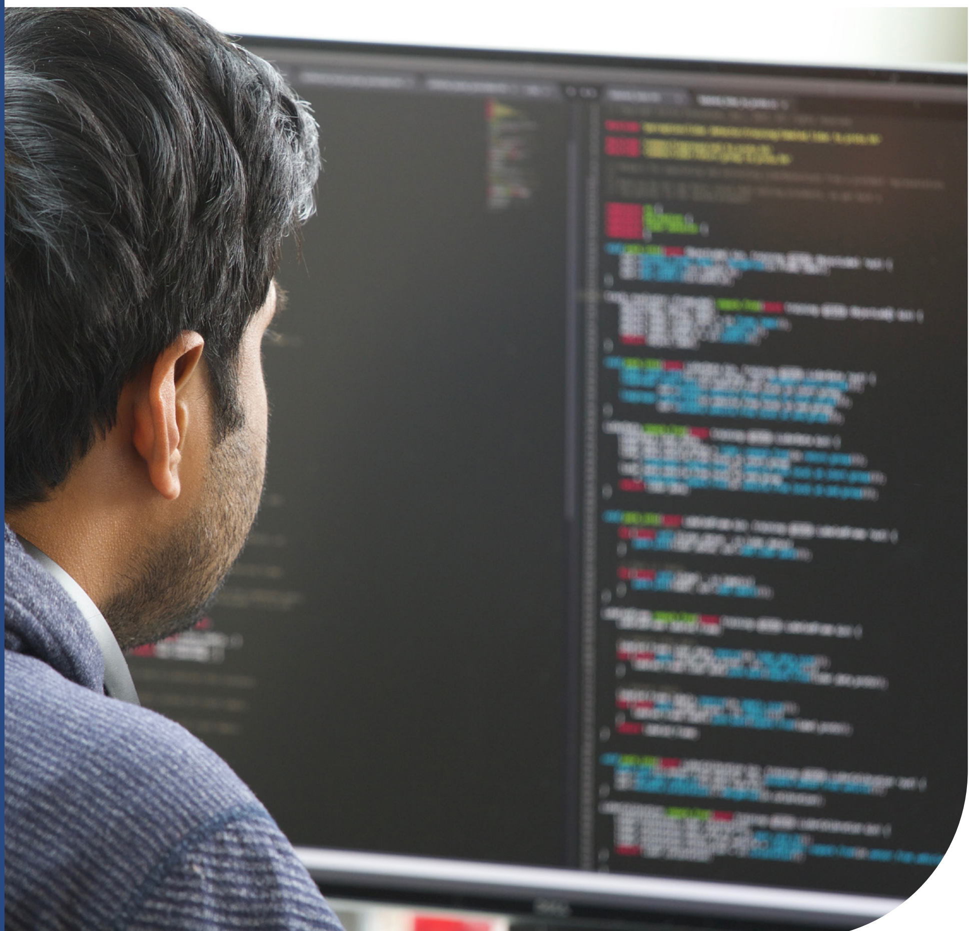
We test certain subsystems in order to confirm effective interactions between components. This stage of testing leverages hardware in the loop (HIL) and simulation testing across hardware and software interfaces in a controlled environment. We also perform fault injection testing at this level. Our tests are automated, allowing us to conduct highly repeatable structured testing of hardware and software interfaces. This subsystem-level design verification is required before track and road testing.

System-Level Design Verification

Self-driving hardware and software components are integrated into the vehicle and tested to confirm performance of:

- **Mechanical interfaces** - including thermal and structural integration into the base vehicle
- **Electrical interfaces** - including integration into the base vehicle power distribution
- **Control path interfaces** - including Application Programming Interfaces (APIs) to provide base vehicle platform motion (e.g., steering, braking, and acceleration) as well as other key actuations (e.g., turn signals and gear changes).

These quality processes are an integral part of the hardware design and development process. Using component-level, subsystem-level, and system-level design verification helps to ensure all facets of our hardware are performing optimally and are, thus, contributing to the safe operation of the Aurora Driver.



Software

The Aurora Driver uses data from its suite of sensors to observe and categorize actors and objects in the environment, predict the actions of the actors and objects it finds, and plan a safe path for the vehicle based on the rules of the road. In addition to sensor data, the Aurora Driver relies on high-definition maps to navigate various ODDs. Each software module serves a distinct function and also feeds data and decisions into the others.

Mapping & Localization

An accurate map helps the vehicle in many ways — allowing the Aurora Driver to locate itself precisely in the world, know the locations of traffic lights, and understand speed limits, one-way streets, and traffic circles. By storing precise road information in a virtual map, the vehicle does not need to expend as much real-time effort decoding the built environment using real-time sensor data. For example, using a detailed map, the vehicle can be aware of an upcoming tight turn before sensors would perceive it, allowing it to anticipate the need to slow down or otherwise optimize its motion plan, thus improving the safety of our vehicles.

Our proprietary high definition map for the Aurora Driver is called the Aurora Atlas. The Aurora Atlas contains information about static scenery and road infrastructure, reducing the amount of data the Aurora Driver has to process in real time. For example, we build stop signs into the Aurora Atlas so the Aurora Driver always knows they are coming, even when hidden behind a parked car. Together, the static scenery and road infrastructure data layers support almost every part of the Aurora Driver's software system.

The Aurora Atlas design maximizes our ability to place content very accurately relative to the self-driving vehicle while still enabling frequent, fast, and efficient updates. A key element of our strategy is keeping the Aurora Atlas locally, rather than globally, consistent. In globally consistent maps, all data is laid out in relation to a single frame (e.g., the center of the Earth), whereas the Aurora Atlas is laid out in relation to multiple frames. The data inside certain geographical areas will use the same frame (locally consistent), but the data between those areas will not (not globally consistent).

Using locally consistent maps allows us to update the Aurora Atlas on a granular scale, without impacting the map as a whole. For example, a driving lane segment is not defined in relation to the entire world, just to its predecessor and successor segments. This means that we can update small portions of maps quickly, ensuring that our maps are up-to-date and true to the roads encountered by vehicles traveling along them.

Our localization system, which determines the vehicle's location within the Aurora Atlas, can reliably determine the vehicle's position and orientation relative to content near the vehicle within centimeters of its location — much more accurately than GPS. We can rapidly build accurate, lightweight maps in new areas and push updates from the Aurora Cloud to the on-vehicle Aurora Atlas in near-real time. We are investing now in a robust system because we know that our success hinges on producing a high-quality Aurora Atlas at scale.

Perception

The Aurora Driver's sensor suite allows it to take in information about the world around each vehicle, including the actors in it. Our perception capabilities allow the Aurora Driver to understand the sensor input so that decisions can be made about how to interact with each actor. Using machine learning and best practices for modern statistical estimation, we carefully track all sensor measurements to ensure the vehicle is immediately aware of any unusual or unknown object, and ready to respond.

For example, if a box falls off of the back of a moving truck in front of us, the Aurora Driver will receive sensor data indicating an object and will track its movement. Regardless of the size of the box or the contents inside it, the vehicle can stop for the projected position of the object without needing to know specifically what the object is.

Planning

The Aurora Driver is designed to act safely around others on the road — to be predictable and human-like, and to be testable and automatically tuned (to perception system improvements). We fuse machine learning with formal rules to create a robust planner that smoothly navigates situations, while retaining the ability to operate in a safe and predictable manner. For example, if another vehicle behaves in a way that results in a shorter than desired following distance, our vehicle is designed to slow until it returns to a nominal state (i.e., reestablishes specified following distance and continues on its route).

Vehicle Control

This software module executes the vehicle's trajectory through the vehicle's interfaces (e.g., steering, acceleration, and braking) using information from the perception and planning modules. Vehicle control monitors the current vehicle position and orientation, and adjusts the vehicle's interfaces to keep the vehicle following the desired trajectory.

Vehicle control also monitors the interface to the computer. When it identifies failures, the vehicle control software will safely bring the vehicle to a controlled stop.

Object and Event Detection and Response

Object and Event Detection and Response (OEDR) refers to the detection of any object or event that is relevant to the driving task, as well as the implementation of the appropriate response to such circumstances.[13] A robust systems engineering approach to ODD selection and characterization, along with OEDR, serve as a crucial foundation to safely developing and deploying the Aurora Driver.

By limiting our vehicles to a specific ODD, we can mitigate risk from preventable harmful events. Additionally, by appropriately detecting and responding to actors and objects in the built and natural environment, we can ensure the Aurora Driver is operating and responding as intended to a variety of inputs.

Our sensor suite and perception software detect and track individual actors and objects to generate estimates of their positions and velocities and to register other attributes that may inform their future motion. Our planning module incorporates perceived actors and objects with the desired route to determine decisions that need to be made. For each decision, the planning module considers the potential actions of other actors, then creates a motion plan that moves the vehicle safely and coherently through the perceived situation. This motion plan is executed by the control module.

We are investing now in a robust system because we know that our success hinges on producing a high-quality Aurora Atlas at scale.

3

Testing the Aurora Driver

We take a rigorous approach to testing the Aurora Driver. We have heavily invested in our Virtual Testing Suite, allowing us to quickly turn on-road events into multiple opportunities for us to learn and advance. We also have multiple testing sites, known as Aurora's Test Site Network, which allows us to physically test and validate the progress of our hardware and software safely and efficiently.

Virtual Testing

We believe a mature self-driving effort is deeply focused on the ability to analyze system performance offline — that is, with the software stack running in response to synthetic or historical data rather than in real time in the physical world. Our Virtual Testing Suite provides repeatable measures of improvement, speeds development, and lowers the risk inherent to all real-world driving activities. With robust virtual testing in place, road time can be allocated to data collection of complex events and expert human navigation of these scenarios, as well as validation of simulation and offline test suites, and analysis of the autonomy system in the presence of complex second-order effects that may not be viable in simulation.

Our approach employs a suite of tools that are run to analyze the performance of both the current development system and all proposed changes to the code-base. These tools include:

- **Detailed unit and regression tests:** We have a rigorous and robust software engineering culture. It prioritizes considered design, extensive testing, peer review, and continuous integration.

- **Statistical analysis:** To test new changes to self-driving software, we present the build with simulated data generated procedurally or collected during previous bouts of on-road vehicle driving. We then analyze the system performance for everything from localization to perception to planning. While these tests are currently made from real-world data, we are also developing highly-realistic sensor simulations so that we can generate tests for uncommon and high-risk scenarios without needing to first experience them in the real world.

- **Scenario Fidelity Control:** A core feature of our simulation software design is the ability to tune the fidelity of our scenarios to meet the exact testing use case. This is necessary because different modules require different simulation tools. For example, testing the motion planning system requires different simulation tools than testing the perception system. We simulate every variable of the autonomy system, starting with sensor inputs and resulting in motion profiles outputs for the autonomy system. Our sensor simulation suite is capable of simulating any of our sensors on any of our vehicle platforms. The validation system we run alongside our simulation engine allows us to capture nuanced autonomy failures and provide high-signal feedback to developers before the code ever touches a physical vehicle.

Software Release Process

Aurora employs a rigorous verification and validation process, from an initial software change through real-world testing. Deviations from expected operation during offline, test track, and on-road testing and data collection are recorded and shared with self-driving system development teams. These events are tracked from discovery to resolution. For example, we may re-simulate software changes to evaluate their impact on these key events, to confirm issues are resolved as intended, and to confirm that we are not introducing new or old failures. Many events are incorporated into datasets for machine-learning algorithms, while others are utilized as challenging test cases. Once issues are resolved, the resolution factors into every new software change with an eye to preventing the accidental re-introduction of previous behaviors.

This allows us to consistently make progress ensuring we are constantly improving and teaching the Aurora Driver to do new things and handle more complex scenarios safely while optimizing our time on public roads.

Simulation Design

A broad suite of simulations based on real-world interaction and careful design by engineers is critical to ensuring the system makes intelligent, safe decisions. We source these scenarios from diverse channels. Many of the scenarios we run in simulation have their origins in encounters our vehicle operators experience during on-road testing. From a moderately-sized set of field operations tests, millions of scenarios can be generated via such techniques as monte-carlo and procedural variation for evaluation in simulation.

A view of Aurora's virtual highway. High-fidelity synthetic worlds allow us to create accurate and nuanced sensor simulations.

We use descriptive taxonomies as a common language to relate data collected on the road with offline information. These taxonomies allow us to match online experience with relevant offline tests based on capability, operational domain, or failure mode. By leveraging log analysis tools, teams are able to quickly and efficiently classify experiences. By correlating online and offline scenarios, autonomy engineers are better able to understand aggregate performance and more rapidly iterate to a solution by leveraging existing tests.

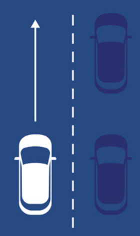
We augment these cases with carefully constructed interactions found in naturalistic driving studies and crash databases.[14] For example, if we are aiming to improve the way our software handles pedestrian crosswalks, we can pull from our database of interactions where our self-driving system encountered a pedestrian at a crosswalk. Then in simulation, we can replay those interactions and evaluate how the new code would handle not only this situation, but permutations of it changing the parameters of the encounter. Are there two adult pedestrians? An adult and a child? Is it a group of pedestrians? This allows us to test the Aurora Driver against a diverse set of use cases without needing to drive this scenario again in the real world.

A subset of our simulation experiments run for long periods in order to detect bugs that may be associated with long run times. However, the vast majority of simulation experiments are short and aim to test specific interactions. Focusing on short simulations to test specific interactions simplifies the task of validation and enables us to efficiently cover a huge number of effective testing miles.

We use a metric-driven approach to analyze and understand our autonomy development trends. We compile key metrics into safety and performance dashboards that allow development teams to understand performance trends at multiple levels of detail. Weighting test results by exposure probability and severity allows Aurora to make informed, prioritized decisions for next steps.

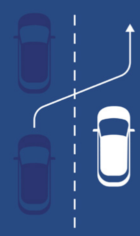
A Snapshot of our Simulation Database

We run complex simulation experiments to check that the self-driving software has behaved as expected. A tiny selection of our simulation database of experiments include:



Highway lane keeping

Lane changes

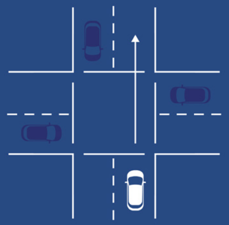


Highway interactions with other vehicles, such as cut-ins and contested lane changes

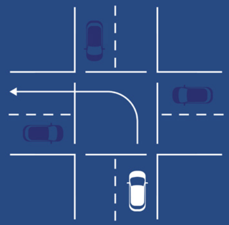
Correct position in lane

Appropriate speed and distance from other actors

Urban interactions with other actors, such as jaywalkers, cyclists, lane-hogging vehicles



Four-way stop traversal



Signalized intersection traversal

Stopping behavior at traffic lights

Go/no-go decision making at amber lights

Passenger comfort metrics

Timely execution of planned maneuvers

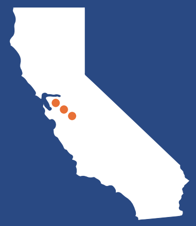
Track Testing

As we develop the Aurora Driver, we need to continually test and validate our progress safely in the physical world. With half a dozen locations and counting, the closed-course Aurora Test Site Network allows us to efficiently test and validate new software on our vehicles in a broad range of environments and conditions, including higher speed truck testing and fault injection testing, as well as conduct vehicle operator training.

These facilities provide an ideal environment to evaluate tolerance to fault injection. For example, we can perform an accelerated course of stress testing by producing one fault after another. We can also confirm our proper handling of foreseeable rider misuse by opening doors, or physically manipulating the vehicle controls, and then confirming that the appropriate safety response is initiated at the self-driving system/vehicle-platform level.

Another advantage of track testing is that it provides us with greater control over interactions with other actors. This enables us to safely assess how our system would handle a diverse array of edge cases, equating to faster and more efficient development, without having to expose the public or our vehicle operators to risky interactions. Scenarios like a cyclist darting into our lane to avoid a car door swinging open rarely occur in real life, but a closed course gives us the opportunity to safely create, test, and iterate these situations.

Aurora Test Site Network



San Francisco, CA
Mountain View, CA

Pittsburgh, PA

Dallas/Ft. Worth, TX

On-Road Testing

Testing on the road, in the physical world, is a mechanism for validating and improving the fidelity of more rapid, offline testing, rather than a forum for new development. Another objective is to shake out any subsystem malfunctions or calibration degradations that arise in the course of nominal operation. We can also confirm our system behaves as expected given varied environmental circumstances like weather, dust and pollen, glare, and smog.

To ensure safety, we require that there be two people in the car at all times while the system is being tested. Our vehicle operators are trained to engage and disengage the self-driving system as needed for both reactionary and policy disengagements.

Reactionary Disengagements

These are situations where a vehicle operator disengages the Aurora Driver because they believed there was a chance that an unsafe situation might occur, or they believed the vehicle was not behaving as designed. For example, if the Aurora Driver planned to conduct a lane change at an inappropriate time, the vehicle operator would quickly disengage.

Policy Disengagements

Vehicle operators proactively disengage anytime the Aurora Driver faces an on-road situation that is out of scope for the software — that is, any situation that the system has not yet been taught to handle. For example, our vehicle operators currently disengage the system any time construction impacts the lane of travel.

Rather than measure progress by the miles we have driven or the disengagements we have avoided, we measure our progress by technical or engineering velocity, which we think of as progress made on our core technology.

When it comes to disengagements, we aim to not repeat the same mistakes. Once we experience an issue (e.g., via an on-road disengagement), we dig in to understand it and correct it. The Aurora Driver system tracks disengagements, as does the co-pilot. We then use the data collected during disengagements to guide development.

These on-road disengagement events can be an incredible learning opportunity. In particular, comments from our vehicle operators provide a firsthand account of the in-vehicle experience. On-road testing and our vehicle operators play a key role in the development of the Aurora Driver and are essential to the feedback loop that exists between software, hardware, operations, and safety teams.

We know we are making progress because we are constantly retiring or refining policy disengagements, and we are passing virtual tests inspired by reactionary disengagements. We have built pipelines that allow us to continuously label, evaluate, and make virtual tests from scenarios we see on the road. When new versions of the software can pass those tests, we know they are performing better than their predecessors.

While we try to maximize the efficiency of our on-road testing by exposing the Aurora Driver to challenging events when it is safe to do so, it is a greater priority to safely complete each on-road mile.

Achieving a Minimal Risk Condition

No system is immune from abnormal conditions that interfere with its ability to function as intended. As such, we have designed the Aurora Driver to anticipate failures and to retain certain safety-relevant functionality even when such a failure occurs. Today, we primarily rely on the vehicle operator to resume control of the vehicle in the presence of a safety-relevant failure. We ensure that the vehicle operators are able to do this by providing robust training on system limitations, and alerting them via audio and visual cues when a failure is detected or when the Aurora Driver stops sending data to the vehicle.

At some point in the future, the Aurora Driver will operate without a human vehicle operator or co-pilot in the vehicle. We are designing the system to support strategies that enable the system to achieve a minimal risk condition[15] — essentially, a stable, stopped condition for a vehicle to reduce the risk of a crash when the vehicle cannot or should not continue — even without human intervention in the event of a crash, unforeseen failure, or other event.

Data Recording

The Aurora Driver features a data-logging system, which stores raw sensor information as well as other vehicular data, including the operating state of the self-driving system. The Aurora Driver also logs vehicle performance, functionality of the sensor suite, and anything else we have concluded could be valuable to reconstruct an event.

We have designed the logging system with protections to secure the data in the event of a crash. If a crash occurs, the data-logging system stores predefined data from the vehicle that allows us to reconstruct the event.

Crashworthiness and Post-Crash Automated Driving System Behavior

As part of our ongoing development of self-driving technology, we have integrated the Aurora Driver into multiple vehicle platforms. When choosing original equipment manufacturer (OEM) partners and specific vehicle platforms, we consider the crashworthiness of each base vehicle platform. We then work closely with our OEM partners and upfitters to install our systems in a safe and thoughtful manner on Federal Motor Vehicle Safety Standards (FMVSS) certified, production-ready vehicles. In some cases, we also work closely with our OEM partners on pre-production vehicles, which allows us to better prepare the Aurora Driver for integration with the production vehicle platform, and follow the protocols our OEM partners use for the development of FMVSS certified vehicles.

In the event of a crash, our trained operations team initiates post-crash procedures, which include communicating with first responders and deploying representatives from our response teams to the location. We are aware of the important role played by public safety officials, including law enforcement, fire and rescue officials, and emergency medical technicians, in the cities in which we operate. We take seriously the imperative to seamlessly integrate our operations into cities so as to not disrupt public safety official activities. We proactively engage with public safety officials in the locations where we are operating, and are committed to publishing a public law enforcement interaction plan.

Safety Metrics

Throughout the industry, a number of system-level metrics have been utilized by self-driving developers as indicators of progress in development. In our view, not all of these metrics are consistently applied, and over-emphasis on some of them may create unintended incentives. Even those metrics that are applied consistently within the efforts of an individual developer, and those that provide some useful information on improvement over time, may be ill-suited for objective, cross-developer safety metrics in deployment.[16]

At Aurora, we utilize a set of safety metrics to track the performance of the Aurora Driver throughout the development and testing processes. We purposefully do not use just one safety metric throughout the entire development and testing process, because we find that the value provided by each metric can vary at different points of the development process as the performance of the system improves and as capabilities are implemented.

Our approach to safety metrics was informed by and aligns with key industry standards.[17] Ultimately the development and utilization of these safety metrics play a critical role in our safety case as they provide evidence to support numerous claims.

At the system level, Aurora's safety metrics and specific performance targets are computed using data collected from all of our testing activities (simulation, track, and road).

High-level examples of the data we may utilize in the formulation of our safety metrics include:

- Scenario Test Pass/Fail Results
- Execution of Behavioral Competencies
- Vehicle Dynamics (Velocity, Jerk, Acceleration)
- Policy & Reactionary Disengagements
- Spatial Separation from Other Road Users
- System Faults & Responses
- System Reaction Times

Finally, the normalization of these performance metrics is critically important. While miles and hours may be useful under very controlled conditions, we (and others[18]) have previously noted the challenges associated with normalizing by miles driven or even hours of operations.[19] We are exploring other normalization factors such as number of interactions with other road users and types of typical and critical scenarios experienced such as cut-in/out, lane changes, and unprotected turns, to name a few.

4 Operating the Aurora Driver

Testing our technology on public roads is a privilege that we take seriously. We employ a range of best practices for our employees, technology, equipment, and facilities to maintain safe operations.

Vehicle Operators

Vehicle operators play a key role in the development of self-driving vehicles and are essential to the collaboration between safety, software, hardware, and product teams. Our vehicle operators are full-time employees of Aurora and play an integral role in the development of our technology and our overall approach to safe testing on public roads. They ensure safe vehicle testing and commercial operations, provide feedback to the development team, execute data collections for mapping and labeling, and represent the single biggest source of public interactions, since they are out in public with our vehicles.

Our vehicle operators are key to understanding and evaluating the performance of our self-driving system. They close the feedback loop for our developers by providing them with actionable insights and data from closed course and road testing. Proper training, continuous education, and open lines of communication with our safety and engineering teams help ensure our vehicle operators are able to do their jobs safely, effectively, and efficiently.

Hiring and Retention Criteria

Our recruiting process for vehicle operators seeks out safe, experienced drivers who have undergone a driving assessment to ensure their ability to operate a motor vehicle in an exemplary manner. We aim to hire candidates with key attributes like decisiveness, adaptability, awareness, and the ability to think critically and communicate clearly under pressure. Our vehicle operators have diverse backgrounds and experiences (e.g., military veterans, pilots, professional truck drivers, educators), which helps ensure we get varied feedback throughout the field-testing process. Every one of our vehicle operators has passed an extensive driving history background check and driving evaluation. Finally, to ensure that all vehicle operators stay current with new policies, they are required to participate in a weekly refresher training program, which includes material on any new process or procedures from the past week.

Policies

Recognizing key distinctions between conventional driving and operating a developmental self-driving vehicle, we have implemented a number of technologies and policies for vehicle operators to assist with the safety of self-driving vehicle operations, which include but are not limited to:

- **Hours of Service**: We implement hours of service policies for all of our vehicle operators and our truck operators adhere to the Federal Motor Carrier Safety Administration (FMCSA) Hours of Service regulation.[20] Our trucks are equipped with Electronic Logging Devices (ELDs) to ensure compliance with these rules. Additionally, vehicle operators are encouraged to use their own discretion to further limit time operating a vehicle in conditions that have a higher cognitive demand, such as roads with high pedestrian and bicycle traffic or nighttime driving.

- **Cell Phone and Smartwatch Use**: Vehicle operators are strictly prohibited from interacting with their mobile devices and/or smartwatch while the vehicle is in motion or the self-driving system is engaged.

- **Monitoring**: All of our self-driving vehicles are equipped with a third-party driver monitoring system.

Training

Our vehicle operators are required to complete a comprehensive training program to prepare them to safely operate a self-driving vehicle and protect its surroundings and occupants from harm. As part of this intensive, multi-level training program, our vehicle operators and co-pilots must complete classroom assignments, undergo defensive-driver education, and be evaluated by driving with an instructor to confirm mastery of both basic and specialized driving skills.

Our training program starts with safe manual driving training to ensure fluency and comfort operating vehicles equipped with non-standard technology features and physical equipment required for self-driving operations. This training begins on a closed course before proceeding to public road training.

In order to move to the next level, vehicle operators must also have demonstrated acute situational awareness for potential nearby hazards, competence in conducting tests to confirm the safety of proposed changes in software, fluency with post-incident procedures, and mastery within each testing type.

In addition to completing our rigorous training program, our truck operators must possess a valid Commercial Driver's License (CDL) in order to pilot a truck.

Vehicle operators play a key role in the development of self-driving vehicles and are essential to the collaboration between safety, software, hardware, and product teams.

Vehicle Operator Responsibilities

Effective communication between the pilot and co-pilot plays an important role in acceptably safe self-driving vehicle operations. Our training program covers guidelines for managing in-vehicle communication. Further, vehicle operators are trained to share relevant information from the co-pilot workspace that can assist the pilot.

Pilot

- The pilot keeps the vehicle, the people in the vehicle, and anyone around the vehicle safe at all times.
- The pilot keeps hands in contact with the steering wheel, and a foot hovering near the throttle and brake pedals, while the system has self-driving engaged, to respond quickly if necessary.
- In the event that the Aurora Driver attempts an action that would violate the rules of the road, the pilot immediately takes over.
- If the Aurora Driver engages in an action that results in a potentially unsafe situation, the pilot immediately takes over.
- If active emergency vehicles are encountered, the pilot immediately takes over.

Co-pilot

- The co-pilot uses a laptop to monitor software performance. The laptop shows a model of the vehicle and the way it perceives its surroundings, including other vehicles, nearby pedestrians and cyclists, road lanes, and traffic lights.
- The co-pilot informs the pilot of anything that looks out of the ordinary as it pertains to software.
- The co-pilot annotates testing logs with useful information designed to provide context to notable testing events, allowing the vehicle operator to focus on the driving task.
- The co-pilot monitors the performance of the Aurora Driver and indicates to the pilot any performance shortfalls of the Aurora Driver.
- The co-pilot monitors and provides feedback to the pilot to ensure the pilot is adequately performing responsibilities.

Transitioning Between Self-Driving and Manual Driving

Transitions to and from manual driving help facilitate safe testing and risk management. These transitions are only completed by vehicle operators who have received the training necessary to understand how and when to do so safely.

Vehicle operators may engage the self-driving system within the ODD only when it is safe to do so and the co-pilot confirms they are ready. Similarly, vehicle operators must be able to easily transition out of self-driving and into manual driving whenever necessary to help ensure safe operation.

We have designed our system to have multiple means of shifting out of self-driving. At any time, the vehicle operator can shift out of self-driving mode by turning the steering wheel, applying pressure to the brake or throttle, or using the emergency disconnect. When the emergency disconnect has been pressed, the Aurora Driver cannot control or influence vehicle operation.

Our vehicle operators are trained on the scope of permissible operating conditions, along with special actors, conditions, or events which the Aurora Driver may not be able to handle performantly and are therefore considered out of scope for self-driving testing. Vehicle operators recognize conditions out of scope for self-driving and preemptively disengage the self-driving system, which returns driving control to the vehicle operator. This information is reinforced during in-vehicle training and fault injection training (FIT) modules, and prepares the co-pilot to inform the vehicle operator of any upcoming events that may require a transition to manual mode.

Human-Machine Interface

Human drivers are constantly receiving new information from the driving environment, processing this information, and making informed decisions. Audio-visual alerts within the vehicle are designed to provide vehicle operators with a quick and easy understanding of the state of the self-driving system. Additionally, the audio and visual indicators improve operator-response time.

Visual safety features

Visual alerts and the state of the Aurora Driver are visible to both the vehicle operator and co-pilot via a light bar on the center instrument panel. Only a solid green light indicates that the self-driving system is engaged, actively operating in self-driving. All other light bar colors indicate the self-driving system is disengaged. On loss of communication with the self-driving system, the light bar automatically turns red.

Audio safety features

Unambiguous audio indications are played for certain state transitions and when the system is faulted. Examples of when the audio is played include:

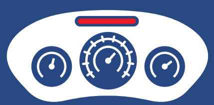
- When takeover is required
- When engagement is attempted but fails
- When the system disengages, regardless of cause
- When the system engages

Light Bar Visual Indicators

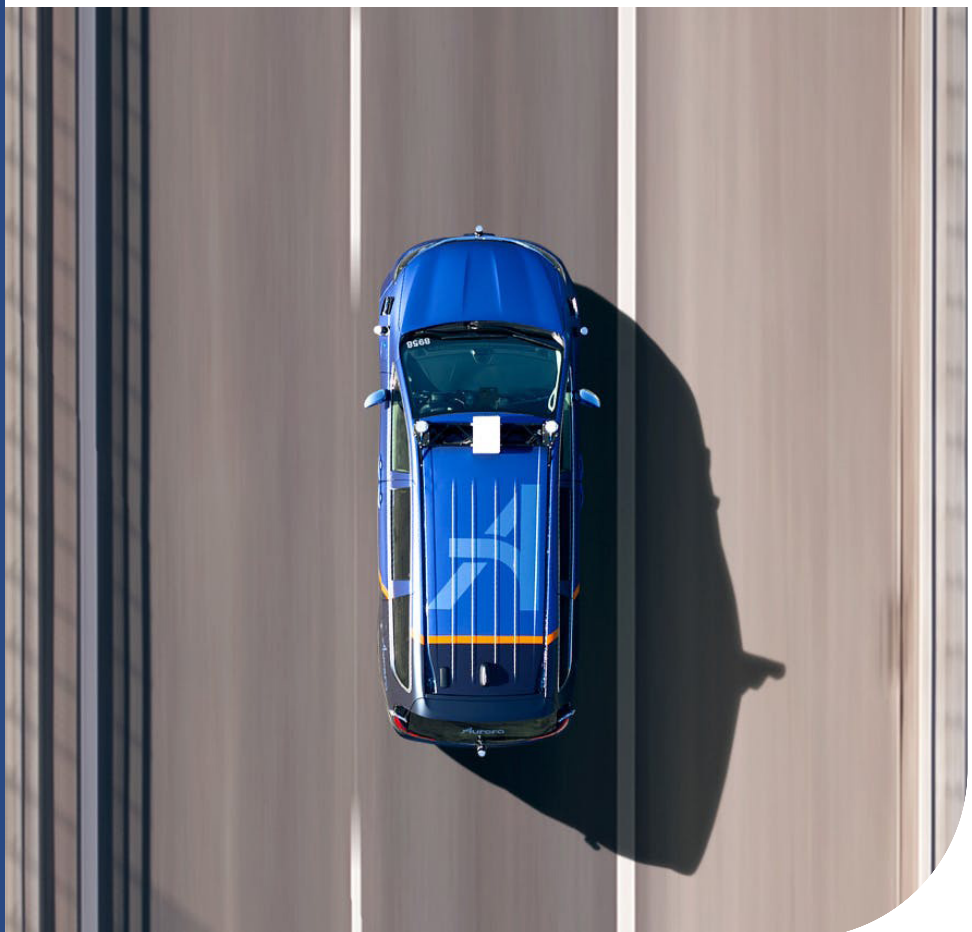
White
Indicates not ready
(manual control)

Blue
Indicates ready state
(manual control)

Green
Indicates healthy state
(self-driving engaged)



Red
Indicates unhealthy state
manual takeover required
(self-driving engaged)



Vehicle Equipment Inspection

Each day, before and after each trip, we extensively inspect vehicles for any internal or external vehicle issues associated with the base vehicle or the self-driving system. We inspect parts and accessories including, brakes, windshield wipers, steering, lighting devices and reflectors, tires, rear vision mirrors, emergency equipment, the sensor suite, and its computers. The inspectors will note any issue which could affect the safe operation of the vehicle, and our maintenance reporting system prohibits operation of the vehicle while such conditions persist. Our service technicians also conduct additional monthly routine maintenance inspections of internal and external vehicle equipment and systems.

In compliance with FMCSA regulations, truck operators also complete daily Driver Vehicle Inspection Reports (DVIRs) during the pre- and post-trip inspection.

5 Delivering the Aurora Driver

The Aurora Driver is a platform that combines the hardware, software, and data services needed to move people and goods safely through the world on autonomy-enabled vehicles. We will bring the benefits of self-driving technology by delivering and scaling the Aurora Driver with a network of manufacturing, mobility, logistics, and fleet management partners.

Commercializing the Aurora Driver

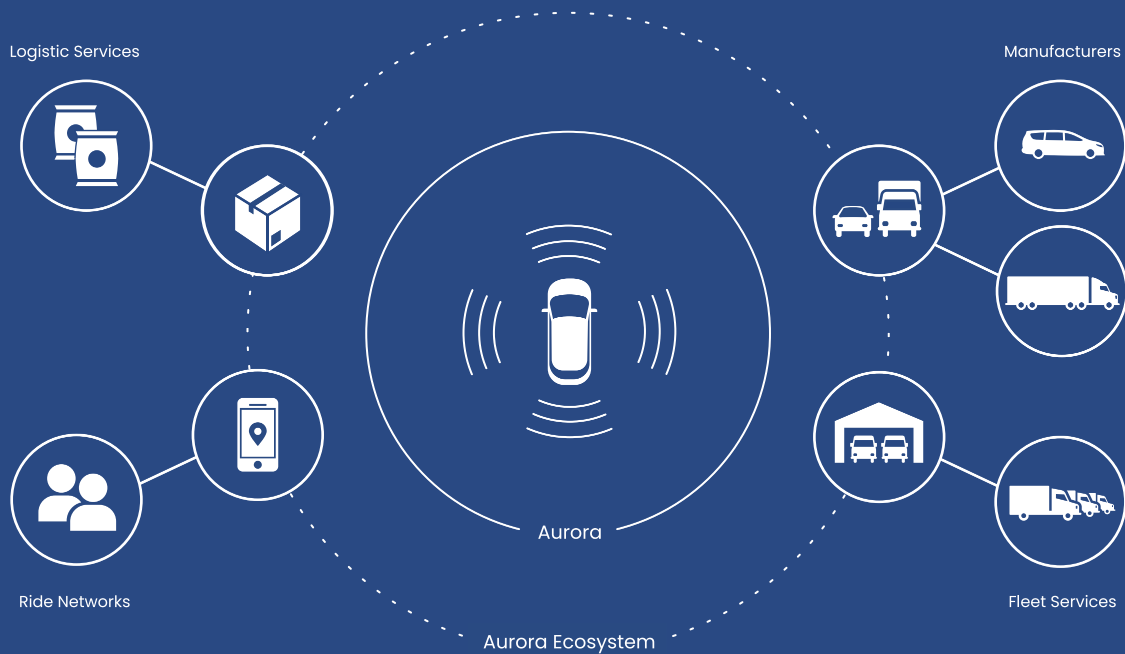
The Aurora Driver is designed to readily adapt between distinct vehicle platforms and diverse use cases. This allows us to rapidly deploy it on a variety of vehicle models from Class 8 trucks to passenger vehicles in various settings. This multi-industry and multi-platform approach to deploying self-driving technology is important: it allows not only for broad application of the fundamental technology, but also for each vehicle and use case to benefit from the broader network of Aurora-powered vehicles. Our cars learn from our trucks and our urban ride-hailing application is informed by the experience our vehicles encounter in other settings.

Trucking will be our first product, and we have formed strategic partnerships with two of the most respected industry leaders, PACCAR and Volvo Trucks, to support the introduction of self-driving trucking solutions for the Class 8 market. These partnerships combine PACCAR's and Volvo's respective expertise in vehicle development, manufacturing, sales, service, and customer support with our deep understanding of self-driving technology to develop, integrate, produce, and support self-driving solutions at scale.

The common core of the Aurora Driver allows our passenger vehicle developments to benefit from our trucking work, and vice versa. In preparation for the Aurora Driver's deployment in ride hailing applications, we have established strategic partnerships with Toyota and Denso, the largest global manufacturers and tier-one automotive suppliers, respectively. Additionally, we have established partnerships with Hyundai Motor Company, Volvo Cars, and Stellantis; each an experienced global manufacturer of passenger vehicles. Our strategic partnership with Uber connects our technology to the world's leading ride-hailing platform and allows us to gracefully introduce Aurora-powered vehicles into passenger mobility in a targeted, highly-efficient, and network-supported way.

The combination of our partnerships, our market-entry sequence, and our industry-leading technology give us a clear path to safely delivering self-driving vehicles.

The Aurora Ecosystem



Vehicle Platforms

To date, we have demonstrated the transferability of the Aurora Driver across ten vehicle platforms, including Class 8 trucks, commercial vans, minivans, and sedans. These experiences have added to our collective understanding of technical integration and the process of effectively developing with manufacturing partners. These collaborations include, but are not limited to, our partnership with PACCAR and Volvo Trucks to develop a driverless Class 8 truck platform, and with Toyota, Denso, and Uber to build and deploy a driverless ride-hailing service.

Our fleet today consists of Class 8 trucks, minivans, and SUVs manufactured by our OEM partners.

Our Fleet

Passenger Vehicles

Class 8 Trucks

At Aurora, we’re moving fast and continue to combine our technical agility with strong partnerships founded on safety that give us the resources and momentum to be the leaders in self-driving.

6

Building Trust and Transparency

Earning the public's trust and confidence is core to our mission. We do this through clear communication, and proactively and voluntarily share information about our technology and safety approach to both our employees as well as to our partners, the public, and the government.

Internal Safety Communications

Safety is not just the focus of the safety team – it is a critical part of the work everyone at Aurora does, and we are committed to keeping all employees informed and engaged on matters of safety. We value open, transparent, and regular communication with all of our employees with the end goal of increasing awareness around company safety policies, objectives, and processes.

On a routine basis, we provide promotional and educational material on safety, such as presentations from safety leadership (including during new-hire orientation and company-wide all hands), bulletins and alerts that showcase safety metrics or processes, and immersive employee events, campaigns, and workshops around safety.

Public Engagement

Developing self-driving technology is our core work, but not our only focus. We also see a need to educate the public on the work we are doing, and what the future of self driving looks like. We believe in proactively and voluntarily sharing information about our technology and safety approach. Given this commitment to transparency and engagement, we publicly share information about our operations in current and planned cities through accessible channels such as our website, local meetings and events, and the media. We also work to inform all levels of government, including law enforcement, about our development, including both existing and intended operations in the public space.

Consumer Education and Training

At Aurora, we proactively seek to educate consumers and other stakeholders about our technology, testing, and safety approach. We do so in a variety of ways, including blog posts, direct exposure to our self-driving vehicles, and collaborative platforms, like the NHTSA AV TEST initiative.[21]

We engage with the public by organizing community events, providing notices of operation in communities where we operate, and collecting feedback to facilitate impactful collaboration. By partnering with nonprofits and groups like Partners for Automated Vehicle Education (PAVE),[22] which Aurora helped found, we will continue these conversations outside of these communities as well.

Impactful collaboration also means engaging the right stakeholders at each level of government. We strongly believe that governments are our partners when it comes to safely and successfully deploying self-driving vehicle technology. Through proactive information sharing and ongoing dialogue that takes external views into account, we can both educate and learn from our stakeholders and others in the self-driving community.

Voluntary Safety Self-Reporting

We believe that the voluntary safety report is an important platform for self-driving technology developers to communicate consistently and regularly regarding progress in development, remaining challenges, and plans for deployment. This safety report is part of a series of regular updates, released at key points of transition and development of our self-driving system.

Safety Advisory Board

At Aurora, we have established a Safety Advisory Board of outside experts charged with reviewing, advising, and suggesting changes to Aurora's self-driving enterprise, including inputs on organizational goals and priorities. The Board consists of recognized experts in a variety of relevant fields, drawing from aviation safety, insurance, emergency/trauma medicine, automotive safety, and academia meeting approximately quarterly to:

- Advise on our self-driving program approach to safety;
- Advise and guide on broader industry topics, such as readiness for driverless operation
- Provide guidance and recommendations to manage identified safety risks in our approaches;
- Review our approach to improving widespread consumer understanding and acceptance of self-driving vehicles;
- Provide input and direction to help ensure we are positively directed for the future of self-driving technology; and
- Work collaboratively with internal leadership and teams to ensure strong oversight of the self-driving development program.

The Board's independent advice is utilized as we lead the safe development and deployment of self-driving technology.

Industry Standards Development

When it comes to safety at Aurora, we also strive to push the entire industry forward.

We have reviewed the best practices and standards of other safety-critical industries, the existing automotive standards, U.S. DOT guidance in preparing for the Future of Transportation: Automated Vehicles 3.0[23], and Ensuring American Leadership in Automated Vehicle Technologies: Automated Vehicles 4.0[24], to identify those relevant to our system and operations.

As self-driving technologies advance, we are focused on collaborative technical efforts to rapidly develop and publish consensus best practices and standards, to drive the safe development and deployment of the technology. We are an active participant in multiple industry efforts to establish these best practices and standards.

Leading Through Transparency and Collaboration

As an industry, we must continue to work together.

We are committed to sharing our safety work and expertise by participating in and providing technical contributions to efforts focused on the development, understanding, and education of industry safety standards and best practices. We currently participate in various roles in a number of standards development organizations including AVSC, Institute of Electrical and Electronics Engineers (IEEE), UL, LLC., and SAE International. Our technical contributions to these activities include:

- Safety Driver Training and Oversight Procedures
- System Level Safety Metrics Concepts
- Operational Design Domain Concepts and Lexicon
- Safety Management System Implementation Lessons Learned
- Behavioral Competency Testing and Evaluation Approaches
- Safety Related Model Assumptions and Attributes
- Safety Principles for Development and Testing

It’s not enough to forge new ground when it comes to safety at Aurora, we are pushing the entire industry forward.

7 Appendix

Acronyms

API
Application Programming Interfaces

AVSC
Automated Vehicle Safety Consortium

CDL
Commercial Driver's License

DVIR
Driver Vehicle Inspection Report

ELD
Electronic Logging Device

FIT
Fault Injection Training

FMCSA
Federal Motor Carrier Safety Administration

FMCW
Frequency Modulated Continuous Wave

FMVSS
Federal Motor Vehicle Safety Standards

HIL
Hardware In The Loop

ICAO
International Civil Aviation Organization

IEEE
Institute of Electrical and Electronics Engineers

ISO
International Organization for Standardization

NHTSA
National Highway Traffic Safety Administration

OEDR
Object and Event Detection and Response

OEM
Original Equipment Manufacturer

PAVE
Partners for Automated Vehicle Education

SMS
Safety Management System

SRB
Safety Review Board

U.S. DOT
United States Department of Transportation

VSSA
Voluntary Safety Self-Assessment

NHTSA Safety Elements

Architecting our Safety Approach addresses the following NHTSA Safety Elements: System Safety, Cybersecurity, and Consumer Education & Training

Developing the Aurora Driver addresses the following NHTSA Safety Elements: System Safety, Operational Design Domain, Object & Event Detection & Response, Fallback, Validation Methods, and Federal, State, & Local Laws

Testing the Aurora Driver addresses the following NHTSA Safety Elements: System Safety, Operational Design Domain, Object & Event Detection & Response, Fallback, Validation Methods, Crashworthiness, Post-Crash ADS Behavior, Data Recording, and Federal, State, & Local Laws

Operating the Aurora Driver addresses the following NHTSA Safety Elements: System Safety, Operational Design Domain, Object & Event Detection & Response, Fallback, Validation Methods, Human Machine Interface, Consumer Education & Training, and Federal, State, & Local Laws

Delivering the Aurora Driver addresses the following NHTSA Safety Element: System Safety

Building Trust and Transparency addresses the following NHTSA Safety Elements: System Safety, Consumer Education & Training, and Federal, State, & Local Laws

[1] NHTSA, 2019, 'https://www.nhtsa.gov/press-releases/roadway-fatalties-2019-fars.'

[2] NHTSA, 2017, 'https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/13069a-ads2.0_090617_v9a_tag.pdf.'

U.S. DOT, 2018, 'https://www.transportation.gov/sites/dot.gov/files/docs/policy-initiatives/automated-vehicles/320711/preparing-future-transportation-automated-vehicle-30.pdf.'

U.S. DOT, 2020, 'https://www.transportation.gov/sites/dot.gov/files/2020-02/EnsuringAmericanLeadershipAVTech4.pdf.'

[3] The concept of a safety case was first introduced in the early 90's following the Piper Alpha tragedy in the Oil and Gas industry. Cullen, 1990, 'https://www.hse.gov.uk/offshore/piper-alpha-public-inquiry-volume1.pdf.'

[4] Kelly, 2004, 'https://doi.org/10.4271/2004-01-1779.'

[5] ICAO, 2021, 'https://www.skybrary.aero/index.php/ICAO_Safety_Management_Manual_Doc_9859.'

[6] SAE International, 2020, 'https://www.sae.org/standards/content/iso/sae21434.d1/.'

[7] NHTSA, 2020, 'https://www.nhtsa.gov/sites/nhtsa.gov/files/documents/vehicle_cybersecurity_best_practices_01072021.pdf.'

[8] NHTSA, 2017, 'https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/13069a-ads2.0_090617_v9a_tag.pdf.'

[9] NIST, 2016, 'https://csrc.nist.gov/publications/detail/sp/800-154/draft.'

[10] NIST, 2018, 'https://www.nist.gov/cyberframework.'

SAE International, 2020, 'https://www.sae.org/standards/content/iso/sae21434.d1/.'

[11] NIST, 2018, 'https://www.nist.gov/cyberframework.'

[12] U.S. DOT, 2021, 'https://www.transportation.gov/sites/dot.gov/files/2021-01/USDOT_AVCP.pdf.'

[13] NHTSA, 2017, 'https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/13069a-ads2.0_090617_v9a_tag.pdf.'

[14] In this context, the term "interaction" refers to discrete events where the vehicle has to do something other than drive within the lane at a steady speed. Interactions present the main challenges and risks in self driving.

[15] SAE, 2021, 'https://www.sae.org/standards/content/j3016_202104/.'

[16] RAND Corporation, 2018, 'https://www.rand.org/pubs/research_reports/RR2662.html.'

[17] AVSC, 2021, 'https://www.sae.org/standards/content/avsc00006202103/.'

UL, 2020, 'https://ul.org/UL4600.'

[18] RAND Corporation, 2018, 'https://www.rand.org/pubs/research_reports/RR2662.html.'

[19] RAND Corporation, 2016. 'https://www.rand.org/pubs/research_reports/RR1478.html.'

[20] FMCSA, 2017, 'https://www.fmcsa.dot.gov/regulations/hours-service/summary-hours-service-regulations.'

[21] NHTSA, 2020, 'https://www.nhtsa.gov/automated-vehicles-safety/av-test.'

[22] PAVE, 2021, 'https://pavecampaign.org/.'

[23] U.S. DOT, 2018, 'https://www.transportation.gov/sites/dot.gov/files/docs/policy-initiatives/automated-vehicles/320711/preparing-future-transportation-automated-vehicle-30.pdf.'

[24] U.S. DOT, 2020, 'https://www.transportation.gov/sites/dot.gov/files/2020-02/EnsuringAmericanLeadershipAVTech4.pdf.'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