

The New Era of Mobility

Aurora

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This document addresses the National Highway Traffic Safety Administration (NHTSA) framework for a voluntary safety self-assessment.

Our Mission:

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

Letter from the Founders

When solving a hard problem, sometimes it pays to step back, clear your preconceptions and begin anew. In 2017 we saw an opportunity to reboot self-driving car development. To start fresh on a problem engineers have been tackling in the same general way since 2005. Since then, machine learning has matured from an academic curiosity to a valuable tool solving real-world problems. Cloud computing has emerged as a core technology for reliable, large-scale data management. And the automotive industry has begun a transition from traditional carmaking toward electric vehicles, advanced semi-autonomous safety systems, and the provision of mobility as a service.

So when we founded Aurora, we opted to pursue a strategy that just wasn't previously available—to follow a path that makes sense for the way things are today.

Each of us possesses deep experience as a leader within the industry: Chris led the Google self-driving car team and was technology director for Carnegie Mellon when it won the 2007 DARPA Urban Challenge; Sterling developed MIT's Intelligent CoPilot, then launched Tesla's Model X and Autopilot; and Drew worked for two decades at the intersection of machine learning and robotics across industry and at Carnegie Mellon.

As engineers, we believe that the current solution to mobility can be dramatically improved. The human-operated, gas-powered, personally-owned automobile is dangerous. It's expensive, needlessly resource intensive, and can be damaging to the environment. We founded Aurora because we saw the need for a new mobility system—one that moves people and goods safely and efficiently by converging self-driving with electrification and ride-hailing.

Before we joined forces, each of us worked to solve self-driving using different approaches. Aurora afforded us the opportunity to create a fundamentally new solution. In deciding our direction, we opted to focus on the single task that our team could achieve better than anyone else: to develop the Aurora Driver, the technology at the heart of the transition to self-driving. This overall goal is summed up in our mission statement: deliver the benefits of self-driving technology safely, quickly, and broadly.

Safely: Our primary motivation is reducing accidents, injuries, and fatalities. The status quo is not acceptable and we need to do something about it.

Quickly: Every day this technology is delayed, thousands of people die and billions of dollars in economic resources and time are squandered. We feel great urgency to turn this tide.

Broadly: To truly make a difference at scale, we partner closely with vehicle manufacturers, transportation networks, fleet management companies, and regional and local governments. We do what we do best, as do each of our partners; by working together, we are building a more scalable platform than any one of us could do alone.

Self-driving technology offers an incredible opportunity to save lives, increase safety and efficiency on our roads, and make it less expensive, more accessible, and generally easier to get around. Someday soon, you and your goods will be transported by the Aurora Driver. For you to trust us, we need to help you understand why we're worthy of that trust, how the technology works, and why it's safe.

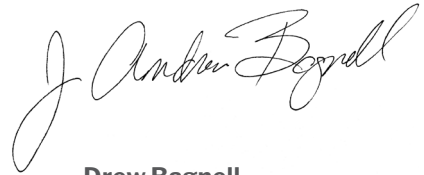
This voluntary safety self-assessment is not only intended to fulfill the suggested requirements of the U.S. Department of Transportation and the National Highway Traffic Safety Administration. We also wrote it to further inform the public about why self-driving vehicles are important to our future, how Aurora is building the technology that will safely drive these vehicles, and what to expect as it all becomes part of our daily lives. We're excited about the potential self-driving technology has to improve transportation safety—and we hope that once you've learned about our approach, you will be, too.



Chris Urmson
Co-founder and
Chief Executive Officer



Sterling Anderson
Co-founder and
Chief Product Officer



Drew Bagnell
Co-founder and
Chief Technology Officer



SAFELY

Ultimately people are going to trust us with their lives. We need to be worthy of their trust.

Culture of Safety

This company exists to create a technology, the Aurora Driver, that will dramatically reduce fatalities and injuries on our roads. A rational corollary of our mission is to develop that technology in a safe manner. Safety has been our first priority since we established the company. It is intrinsic to our development and decision-making process.

From the beginning we've conducted a hazard- and risk-assessment process that evaluates the potential for accidents through every aspect of our operations. Building a safe system is a little like building a boat, in that it doesn't matter if we got things 99% right—a mistake, like a hole in the hull, will still see it sink. The point? Safety isn't something we can do at the end of the process. It needs to be top of mind from the start. Safety engineers need to work closely with design engineers as the system architecture

is developed. Team leads must determine approaches and processes that not only ensure safety but are actually practical and achievable.

But process in and of itself doesn't guarantee safety. We also have to have people who are diligent and take responsibility, and make sure they're not only executing the process, but also understand the reason for the process. We also have to make sure they're motivated by safety.

We've done that. From this point on in the self-assessment we'll aim to describe what the Aurora Driver is and how we're developing it in a responsible manner that increases safety on American roads—and later, on roads around the world. In the following pages, we'll highlight several components that reflect the way safety is core to what we do.

Aurora Values



Operate with integrity: We do the right thing even if it delays us or makes us less money.



Be reasonable: We expect one another to use good judgment with the best interests of the company and our partners in mind.



Win together: We are building a company, and in turn technology, to serve people and communities broadly. We derive strength from the unique perspectives and experiences that reflect the diversity of the world we live in. To benefit from this diversity, we seek to listen as often as we speak and challenge each other to think and act in new ways.



Focus: We're solving one of the most challenging problems of our generation. We get there by cultivating a culture of depth, focus, and rigorous engineering.



Set outrageous goals: We set goals that are outrageous because they require us to focus and make sacrifices. We make trade-offs to set and reach milestones along the way that make each goal attainable, not unreasonable.



No jerks: We debate and solve hard technical problems. We don't waste time battling over personalities and egos.



PEOPLE OF AURORA

Jinnah

Team: Software

Hometown: Kingston, Jamaica and moved to New York City when I was 1

Previous experience: Built high reliability cluster management, load balancing, and content delivery, serving about one-third of all internet traffic. Led software teams in the development of the first reusable orbital-class and multi-core rockets, and an in-house camera-based driver assistance system

Why I work at Aurora: I'm surrounded by peers who are 10x smarter than I am and we all love the mission

First car: Technically, a 1990 Toyota Camry I inherited from my mom. The first car I bought was a 1976 International Harvester Scout II

Favorite road trip: Drove to the Midwest as part of a platoon of vintage trucks. Frequent breakdowns and roadside kludging

What motivates me to work in this industry: Reducing the overall cost of mobility, especially for the most vulnerable members of society

Best memory at Aurora: When we saved a squirrel during one of our rides

Quantifying technology safety

In keeping with our mission to deliver the benefits of self-driving technology safely, quickly, and broadly, we do not believe self-driving vehicles should be generally available to the public until we have confirmed they are safer than a human driver. That requires metrics that quantify the merits of our efforts. We are developing a rigorous process to establish quantitative criteria that allow us to assess the excellence of our system. These metrics will dictate the timing of our commercial deployment.

Limiting safety risk throughout operations

We've executed a strategy to reduce the risk of our endeavor throughout our operations. For example, we've resisted pressure to ramp up the number of on-road testing miles. Instead, we've contained our exposure to the inherent risks of driving by maximizing our processes' ability to benefit from driving simulation and offline testing.

*Our team is solving
a once-in-a-generation
technical challenge.*

Rather than a forum for new development, we treat real-world testing as a mechanism for validating and improving the fidelity of more rapid offline testing. This strategy has allowed us to contain the size of our on-road testing fleet. We limit the distance our test vehicles travel by pursuing mileage quality over quantity; that is, we seek out interesting miles rather than just pursuing large quantities of miles.

Hiring and retaining the best talent as a safety strategy

Aurora is extremely selective with the people we hire. This selectivity has been key to building a lean, high-performing organization where all members contribute meaningfully, which in turn has cemented our desirable reputation in the self-driving industry. We are solving a once-in-a-generation technical challenge, working alongside exceptional colleagues, all led by a leadership team with experience unrivaled in the industry.

Consequently, Aurora is a great place to work. We provide our employees with a supportive and intellectually challenging environment with attractive benefits and compensation, yielding a culture of ownership that sees every employee motivated to diligently work to ensure safety.

Safety in action

When our vehicles are in self-driving mode, the co-pilot uses a laptop display to monitor software performance. The laptop screen shows a model of the vehicle and the way it perceives its surroundings, including depictions of other vehicles, nearby pedestrians or cyclists, road lanes, and traffic lights. If one of our vehicles in self-driving mode approaches a red traffic light, a small red stop-sign icon appears on the display, to show that the vehicle intends to slow down. When that happens, the co-pilot alerts the operator of the vehicle's intent to brake.

We feel this urgency to move, to get the technology into market, and start saving lives. And begin making it easier to get around.

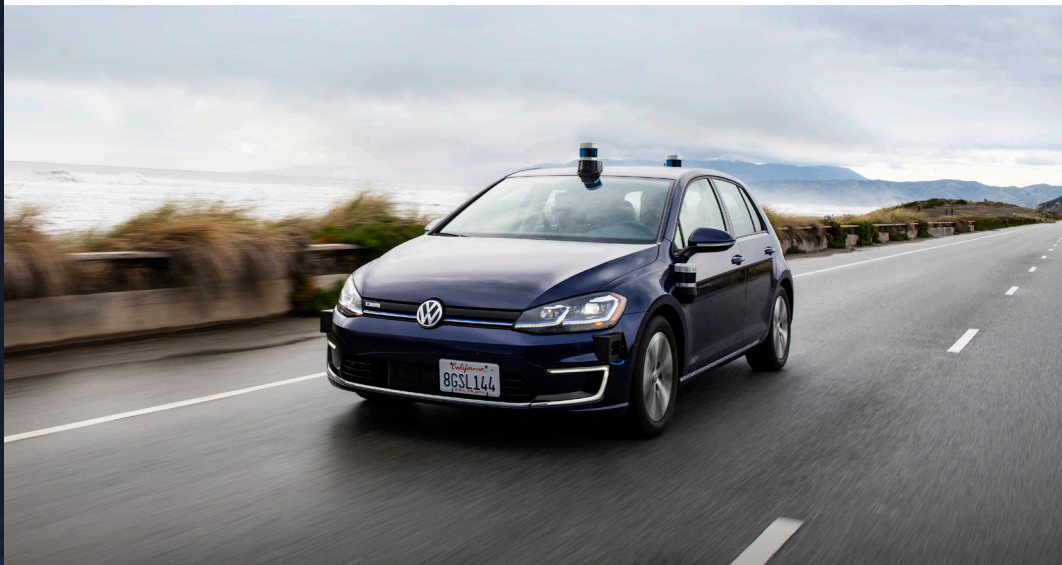
While testing one day, one of our co-pilots noticed the stop-sign icon didn't seem to be appearing. The vehicle was braking normally when it approached a red light, but the stop-sign icon didn't appear. The co-pilot alerted her vehicle operator of the issue, and flagged it in the annotation software. The vehicle operator disengaged the self-driving software and manually piloted the vehicle back to its base. A discussion with colleagues from the operations team led to a consensus that the bug probably was in the visualization software. Nevertheless, the team concluded that it was wise to ground the fleet, and resolve the bug quickly. The order to ground the fleet went out soon after the co-pilot noticed the problem.

Grounding events are rare (you can learn more about grounding events in *Grounding the fleet* on p. 24). Once a grounding event happens, at least two of our founders must authorize the decision to resume self-driving operations on public roads. In the above example, software engineers determined the cause of the bug and fixed it within

hours of the fleet's grounding. (The bug occurred when approaching complex intersections, featuring left-hand turn lanes, where the vehicle's intended path split from one dictated by the main traffic light.) The next step involved testing the new software on a closed course, with video of the confirmed fix distributed to the team. Ultimately, after a review and completion of a written report, the grounding order was lifted. This cost a few hours of operating time, but ensured we understood why this unusual event was occurring.

All Aurora employees, from founders to assistants, are empowered to ground the fleet if they identify something they consider a safety risk. While we provide guidance on what is considered a candidate for a grounding event, we encourage everyone to use their own judgment, and err on the side of caution. Indicative of a poor safety culture is a grounding policy that employees aren't willing to exercise. It means that schedule pressure or production pressure is taking precedence over safety. We don't see this at Aurora. This case is just one among many that are emblematic of Aurora's strong safety culture, and we're proud that our operations team takes the steps necessary to ensure our fleet conducts safe testing on public roads.

Aspects of the Aurora Driver



The Aurora Driver

We are focused on building the technology required to drive vehicles safely through the world. We call that technology the Aurora Driver.

The Aurora Driver will operate at the center of the mobility ecosystem. It comprises the sensors that perceive the world around it, the computer that connects them, and the software that makes sense of the world and plan a safe path through it. The Aurora Driver's hardware, software, and data services tie together the vehicles it powers with the people it serves, the transportation networks it supports, and the fleet-management apparatus it requires.

We recognize that we are not the best in the world at building vehicles. There's an industry that has formed over the last 100-plus years that is far better than we'll ever be at that. We also are not the best suited to deliver a transportation network, or to empower consumers to purchase goods.

That's why we're not designing and assembling cars, deploying ride-hailing networks, or managing the procurement of goods. Similar logic explains why we're not inventing electric vehicles. Companies exist that have mastered each of those sectors, and who—when connected around a common platform—can do far more together than they can apart.

Instead, we're focusing on the single thing that Aurora will do better than anyone else: Create self-driving technology. At first, we envision partnerships with automakers, who can develop vehicle platforms suited for being operated by the Aurora Driver. Later, that network will expand to



Powering the Aurora Driver

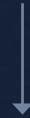
In 1900, the typical American traveled much less than we do today. Average annual mobility amounted to about 3,000 miles—and most of that was by foot. Farmers, factory laborers, townfolk—many passed their entire lifespans never having traveled farther than a day’s walk from home. Then, with the introduction of the Model T, Henry Ford transformed the automobile from an expensive curiosity into a practical method of transportation priced reasonably for all to use. By providing low-cost personal mobility to a large segment of the population, the automobile has reshaped our cities, unlocked economic opportunities, improved access to health care and employment, and facilitated social interaction at a scale never previously enjoyed by mankind. Today, the average American drives more than 13,000 miles per year. Without a doubt, the mass-produced automobile has revolutionized our world.

Those benefits come at a significant cost. We ask distractible humans to do something boring—driving—while within easy reach of compelling diversions. Accidents result, many of them deadly. Around the world, car crashes kill two-and-a-half people every minute. These tragic events extract an emotional and economic toll. According to one NHTSA estimate, costs associated with automobile accidents represent an \$836 billion annual burden on the U.S. economy.¹

How Aurora Approaches Innovation

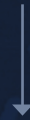
Attract

the best talent in the industry



Design

self-driving technology with a fresh approach



Fuse

rigorous engineering with state-of-the-art machine learning



Invest

early and build for the long-term



Develop

for extensibility and scalability



Embed

safety and testability throughout both design and process

Goals of the Aurora Driver



Increase safety
with technology that never gets tired or distracted



Expand access
for the eleven million people with a disability in the U.S. who have difficulty accessing transportation²



Improve lives
as we liberate drivers from their average 50-minute daily commute³



Revitalize cities
as shared mobility makes garages and parking lots unnecessary, returning vitality to the urban landscape

The next revolution in transportation

It's timely, then, that we're entering a new era. Over the next few years, we expect most people will take their first rides in self-driving vehicles that they've hired through ride-hailing networks. We believe this for several reasons:

- Operators of transportation networks will be able to amortize the cost of self-driving hardware over far more miles than the owners of personally owned vehicles.
- Ride-hailing networks provide the opportunity to feather in the introduction of these vehicles for specific trips whose origin and destination are known when the vehicle is hired.
- Aurora can make a judgment call in advance—whether the self-driving vehicle is capable of fulfilling that trip given the time of day, environmental conditions, and required route.

Consequently, we see transportation networks that provide mobility with self-driving vehicles as the fastest and best way to democratize safety technology.

That, however, is only one part of Aurora's vision. Empowered by the Aurora Driver, we predict a future with fleets of all sorts of driverless vehicles ferrying people and goods around cities for a fraction of the cost of current transportation options, more safely, and consuming fewer resources, than any comparable mobility option today.

If we're able to deliver the benefits of self-driving technology safely, quickly, and broadly, parents won't have to worry about their kids crossing the street. Cities will look and feel different because the streets aren't full of congestion, and we'll be able to dedicate more space for parks, plazas, and people. Our elderly and people living with disabilities will gain access to the economic opportunities and services they need.

More than a century ago, Henry Ford's Model T democratized transportation. Now, we believe self-driving vehicles will trigger a second democratization—one that's safer, more reasonably priced, and more convenient. All of it made possible by fleets of ultra-safe ride-sharing vehicles equipped with autonomous technology—like the Aurora Driver.

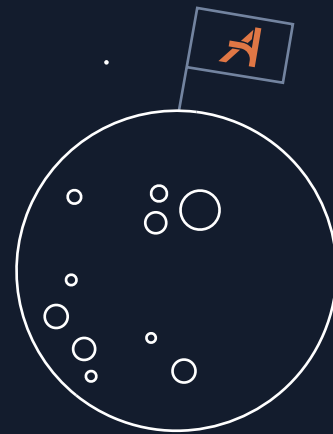
Developing the Aurora Driver

How does one build the technology that powers a driverless car? At Aurora, we took our singular experience in the self-driving industry and began fresh on development in early 2017. Refinement continues—and will continue long after we've made our system safer than a human driver.

Throughout our efforts we've been guided by a development philosophy that counsels against attempting to build a ladder to the moon.

That may sound obvious—who would try to build a ladder to the moon? But bear with us. If you're trying to get to the moon, building a ladder is a method that would be gratifying. You could make progress each day by laboring on a structure that is incrementally higher than the day before. The problem is, that method would never reach the moon. The real solution is much less gratifying in the short term. It requires constructing a rocket that appears to make no progress at all day after day because it sits on the pad for a long time—and then, once it's launched, breaks out of Earth's atmosphere and crosses the quarter-million miles in a matter of days.

In our development of the Aurora Driver, we aim to build and launch the rockets.



Hardware

To develop the hardware required to ensure the Aurora Driver's safe operation, we stepped back and conceived of the problem from first principles. Using our experience, we developed a set of guiding tenets: We buy where available, customize where necessary and build where required. We design for extensibility and scalability. That means, from the beginning, we designed the Aurora Driver with future evolution in mind. We're creating a set of hardware components that can be applied to numerous different vehicle platforms, whether we're talking about the various sizes and shapes of passenger vehicles or freight-transporting tractor-trailers, each of which should be easily scaled to a wide variety of environments and weather conditions.

Computer

We based our computing platform on an enterprise-class server architecture designed to meet the needs of our automotive application. That entailed custom-designing several components that enhance the computer's ability to centrally manage all power, communications, and networking. The platform employs general purpose processors, complemented by silicon designed specifically for machine-learning acceleration and camera-signal processing.



PEOPLE OF AURORA

Cam

Team: Hardware

Hometown: Victoria, British Columbia, Canada

Previous experience: Developed driver assist and self-driving hardware

Why I work at Aurora: Because I am inspired by our leadership

First car: 1989 Mazda B2200 lowrider mini truck, AKA the Mazdog

Favorite road trip: San Francisco, California, to Victoria, British Columbia, with the top down on Christmas Eve in an Audi convertible

What motivates me to work in this industry: When cars don't take up valuable real estate, we can use those spaces for pedestrians or parks

Best memory at Aurora: Company events and team happy hours

Aurora Driver Sensor Suite

360° of surrounding coverage:



Automotive-grade imagers
with Aurora-designed optics



Custom-designed,
high-performance lidar



State-of-the-art
imaging radar

Sensors

We designed our sensing architecture to employ three complementary ways of perceiving the world.

- **Cameras** see the world much like people do—they observe the visible light reflected off of objects.
- **Radar** sensors emit radio waves, and “see” the world by measuring how long it takes for the emitted beam to bounce back from different directions, building up a coarse model of the world.
- **Lidar** sensors are much like radar but instead of using radio waves, they use waves of infra-red light and can see the world more crisply.

Each mode suffers from its unique limitations. Cameras have difficulty seeing the world in the dark, or resolving images with high dynamic range (instances when brightness within a single image varies drastically). Radar sensors only provide a relatively coarse view of the world and have problems in environments that are highly radar reflective (like tunnels, or bridges with lots of metal). Lidar sensors can be foiled by snow and dust in the air, both of which can partially absorb or reflect their light. By combining data from all three modalities, it’s possible to combine the strengths of each sensor, without being crippled by their failure modes.

To further identify the specific mode, number, and position on the vehicle of each individual component in the sensor suite, Aurora conducted a comprehensive assessment of target operational design domains, that is, the environments in which our test vehicles will be driving. We assessed the complexities of the roads traveled, such as speed limits and pathway curvature. We assessed the hours of operation and the weather conditions our vehicle should handle, and numerous other factors. From this list we came up with a series of boundary scenarios, essentially, the edge cases our car would have to handle in order to safely navigate its operational design domain. The scenarios helped us develop a list of required capabilities, such as the minimum permitted braking distance at a given speed. In turn, those targets allowed us to establish sensing requirements, such as sensor range and field of view, for each of the boundary scenarios generated. If the sensors were able to meet the requirements for the boundary scenarios, they would also be able to meet the requirements of other, less challenging scenarios that involved lower speeds, larger targets, and less road curvature.

We then evaluated the capability of each sensor modality and specific sensor hardware configuration to meet those general requirements, which in turn allowed us to populate the vehicle’s sensor suite. The requirements, and our sensor suite, will evolve as the operational design domain expands, along with our experience and data.

Sample Boundary Scenarios

To help design the sensors on our vehicles, we've painstakingly assembled a series of boundary scenarios that the Aurora Driver must be able to safely manage. The boundary scenarios we study include:



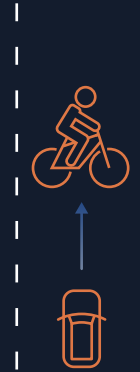
Large objects



Small objects



Traffic lights



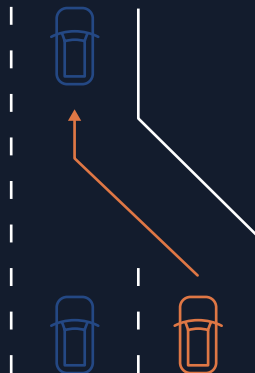
Near-field people



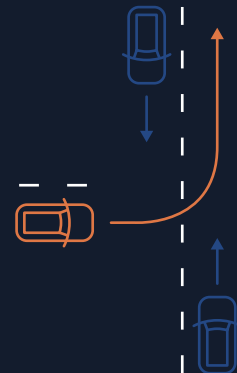
Near-field objects



Emergency vehicles



Merges



Unprotected turns

QUICKLY

The technology we're developing will have an enormous impact. It will save a great deal of lives, so it's imperative for us to work as quickly as safety allows.



Software

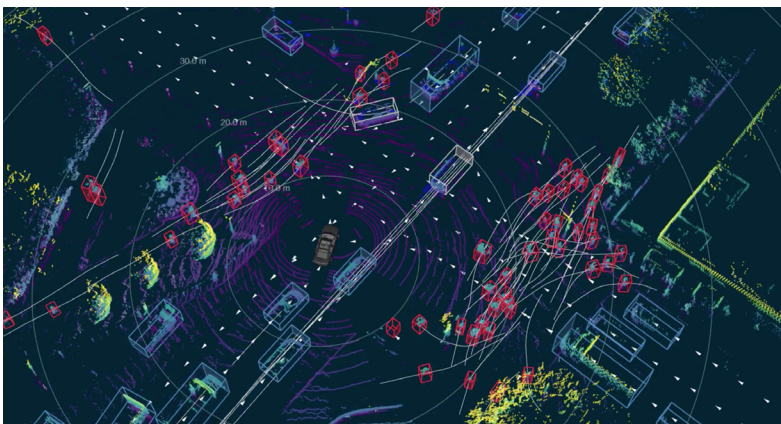
The Aurora Driver must understand its environment, reason about other actors in it, determine the appropriate course of action through it, and execute that action in a safe way. We've constructed our system with a rigorous engineered approach that relies on formal invariants—rules, essentially—to constrain operating decisions and ensure the system functions in a safe, rational, and consistent fashion. Then, within that engineered framework, we've applied machine learning to specifically defined problems. This approach reduces the amount of data we require to validate the choices made by the Aurora Driver. It also reduces the amount of data we must acquire before we're able to safely apply the Aurora Driver to new domains, such as higher-speed driving or more inclement weather conditions.

Localization

The job of the localization module is to determine the precise physical location of the vehicle as well as its position relative to nearby objects. Since many environments, such as urban canyons and tunnels, complicate the vehicle's ability to use GPS signals, we've opted to avoid taking a GPS-dependent approach. Our software uses map data to determine the vehicle's position even in environments that deny or deceive GPS, localizing all six degrees of freedom to within 10 centimeters and 0.1 degree of accuracy.

Perception

Perception is the process of observing the world through various sensors, and analyzing this data to build a detailed model of the state of the world and the actors in it.



Multi-modal. At Aurora, we believe that perception is ultimately a matter of statistics, which requires that we drive error rates as low as possible. Different sensor modalities (or ways of seeing the world) have different strengths and weaknesses. Using different types of sensors improves by several orders of magnitude the system's ability to perceive the world.



PEOPLE OF AURORA

Asta

Team: Perception

Hometown: Los Angeles, California

Previous experience: A perception engineer for self-driving systems

Why I work at Aurora: I have incredible confidence in our founders to carve out a path for self-driving and put these vehicles on the road

First Car: Volvo S60

Favorite road trip: Family road trip from Los Angeles to Michigan. We hiked in Glacier National Park, snorkeled in Utah, and picked blueberries. The whole way, we sang along with The Beatles. We still know "Hey Jude" by heart!

What motivates me to work in this industry: The power of automation is giving people time and freedom. No one should have to spend hours stuck in traffic instead of with their loved ones

Best memory at Aurora: I squeezed into the middle during an on-road traffic light test. Though we had proven the system offline, the whole car burst into cheers when we came to a gentle stop at a red light

Design for learnability. In the last two decades, it has become increasingly clear that there is no credible approach to perception that isn't deeply rooted in machine learning. While required, machine-learning techniques alone are far from sufficient to enable effective self-driving. A key piece of our approach is to integrate machine-learning components into an engineered framework that can accommodate the realities of working with real sensors in a reliable way. This approach features extremely high accuracy requirements for the shape and velocity of objects tracked by the system, as well as the best-practices of modern statistical estimation. Integrating this "top-down" statistical signal-processing approach allows us to boost perception performance well beyond the state of the art achieved by naive machine-learning approaches.

No measurement left behind. Core to our perception approach is the strategy of strict accounting of all sensor returns. We don't allow our perception system to discount any sensor return without explanation—even if that explanation is recognizing the measurement as the result of, for example, exhaust from a truck. This is critical in a system that deeply integrates machine learning, as learning-based approaches can achieve outstanding recognition of some classes of objects and actors but remain inevitably incomplete in their understanding of the world.

Instead, we carefully track all sensor measurements regardless of whether our system can recognize the details of what it is. This is similar to the strategy a human driver might employ when confronted with an unusual or unknown object. For example, consider a wild animal standing near the roadway. The Aurora Driver may not have come across this particular type or breed of animal before, but our system will receive sensor data and indicate occupancy in that location. If the animal then darts out toward the roadway, our system will track its motion as a generic object and can stop for the future-projected position of the animal.

Throughout this scenario, the vehicle will be confident that something is there and will have tracked its movements, even if it doesn't understand specifically what type of object it is. The lack of detailed object knowledge requires the downstream decision-making systems to be conservative in their handling of this object. Additionally, we can test these pathways and generalize this

approach to a broad set of objects, without having to explicitly test against all conceivable wild-animal breeds that might occur in our operational domain. This is at the heart of our approach for dealing with the "long tail" problem all self-driving vehicles must squarely address.

Core to our perception approach is the strategy of strict accounting of all sensor returns. We don't allow our perception system to discount any sensor return without explanation.

Planning

The planning module accepts perception's model of the world and then decides what the vehicle should do to navigate its environment. The planner is conceptually making multiple plans, considering multiple contingencies, and constraining the vehicle's selection of actions to ensure that our behavior is good both in terms of what we expect to happen and in what might happen. This ensures the Driver is responsive to immediate safety threats and exhibits guarding behavior—keeping an appropriate stand-off or modulating speed, for instance.

Our approach to planning is built around a handful of core objectives which are designed to create a system that is:

- Robust to what others do on the road, while acting safely around others on the road
- Predictable and human-like
- Testable and automatically tuned given improvements in the perception system

Traditional approaches to planning are centered around a heavily manually-engineered approach that attempts to specify each decision in advance. A manual approach alone struggles to generate human-like behavior and doesn't adapt well to unanticipated circumstances. More recent approaches attempt a naive, entirely machine-learned approach to decision making. These systems are very difficult to understand, and it's very difficult, if not impossible, to be confident in their performance in new situations.

The Aurora approach is different. We fuse machine learning with an approach that employs formal invariants (or, rules) to create a robust planner able to smoothly navigate the most complex of situations, while retaining the ability to operate in a safe and predictable manner.

Planning invariants. Leveraging decades of research in planning and robust optimization, we attempt to maintain a set of planning invariants, which describe a “safe” basin within the vehicle’s space of planning decisions. These invariants are designed to make certain that the Aurora planner can operate safely given the inevitable and reasonable future trajectories other vehicles and people may take. Two examples of invariants we use:

- Preserve the ability to stop for an actor in our lane who has established right of way
- Preserve the ability to stop for a traffic signal that is not visible to our system

We’ve designed the planner so that it will never choose actions that would violate one of our invariants. If, however, the actions of other drivers or actors suddenly place our system in the position of violating an invariant, we attempt to recover gracefully with an urgency that depends on the severity of the violation. For example, if another vehicle cuts off our vehicle in a way that places our vehicle in violation of a close-following invariant, the system will slow in order to return to a state where it once again retains the ability to avoid collision.

Learned behavior. Planning invariants ensure the system will only make decisions it believes to be safe, but within the realm of safe there remain an infinite number of actions the planner may choose. The challenge is now to

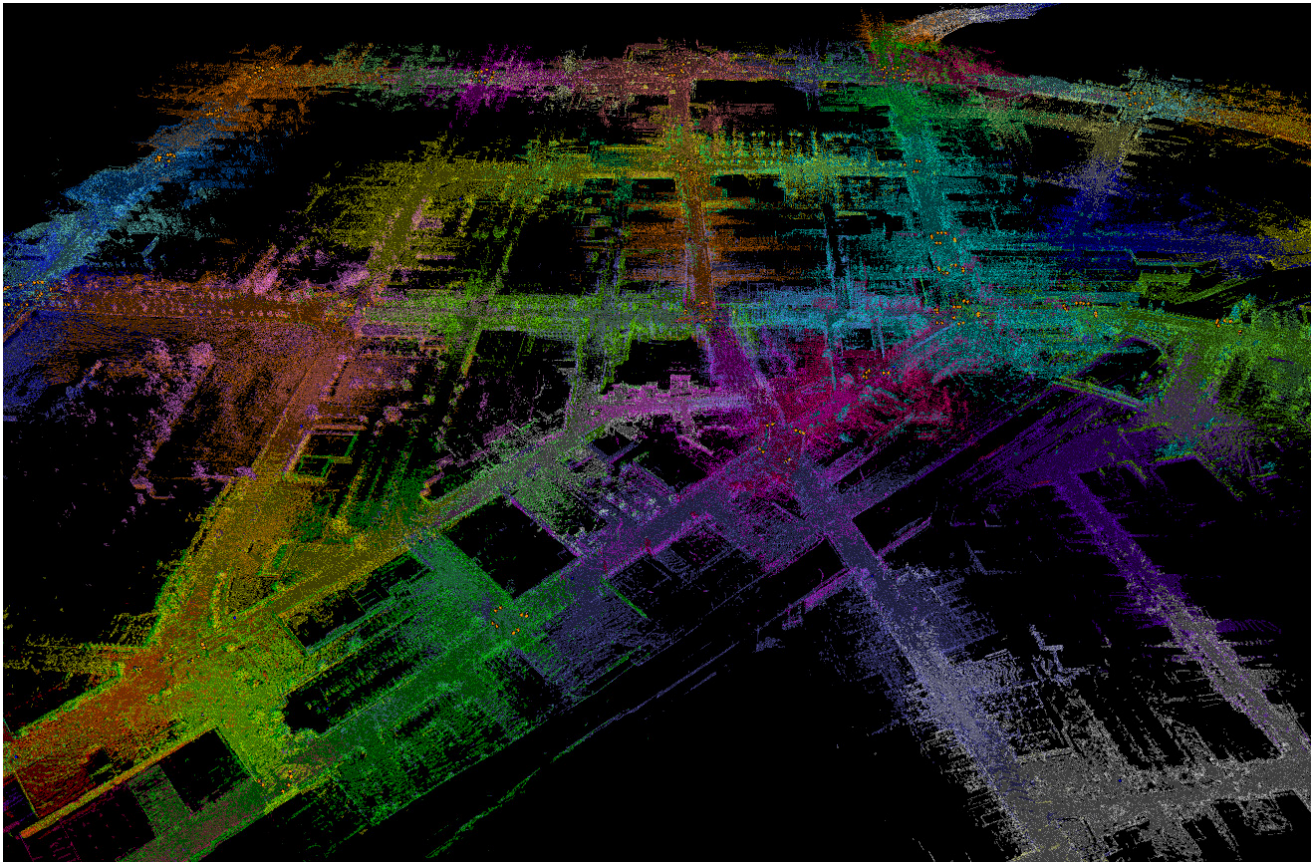
ensure that the planner produces behavior that is natural, interpretable, and thus predictable to other drivers. To ensure this, we learn from our skilled human drivers who implicitly demonstrate the subtleties of human driving; ranging from preferences on lateral acceleration to subtle inferences of which other actors are likely to assert the right of way. To ensure the Aurora Driver is only picking up good habits, we annotate particularly good or bad behavior in detailed simulations.

Control

The control module transforms the planner’s instructions into detailed steering, brake, and throttle commands. Our controls stack is built for automatic calibration at multiple scales. Each vehicle that shares an interface shares a common skeleton of control operation. That skeleton is automatically calibrated by observation of human operators driving the new vehicle platforms to learn the optimal application of throttle, steering, and braking commands to achieve a desired trajectory. This baseline is then fine-tuned for a single vehicle platform during the vehicle’s autonomous operation, enabling rapid deployment across models with consistent results. Sitting separate from the various components of the primary autonomy system is the safety controller. If a module like perception or planning stops working for any reason, or any other significant system failure occurs, the safety controller can return the vehicle to a risk-minimizing fallback state—pulling the vehicle over to the side of the road, for example. (Learn more about fallback strategies on page 32 of “Testing the Aurora Driver.”)

Mapping

Maps are integral to robust operation of a self-driving vehicle. Equipping the vehicle with a three-dimensional model of its environment is a little like providing it with the sort of knowledge a human driver acquires after navigating the same route, numerous times. The technique allows the Aurora Driver to effectively benefit from the combined observations of many Aurora-powered vehicles passing through the same areas. An accurate map helps the vehicle to locate itself precisely in the world. It helps the vehicle detect traffic lights, and provides fore-knowledge of speed limits, one-way streets, and traffic circles. The Aurora Driver relies on its lidar and cameras to collect the data required to build a map. Once collected, the data is processed through a combination of automated



and manual production and quality-assurance tooling, and made available to the entire fleet. Aurora maps are designed and built to be updated and pushed to the fleet efficiently.

Safety approach and cybersecurity

In 2011, the International Organization for Standardization (ISO) released ISO26262, a set of guidelines designed to ensure the functional safety of the electrical and electronic components in automobiles. Aurora uses ISO26262 as the foundation of our safety approach, while employing other methodologies in specific instances we've identified as more appropriate than the 26262 standards.

Our cybersecurity approach takes into consideration guidance provided by NHTSA, best practices set forth by the Automotive Information Sharing and Analysis Center's Automotive Cybersecurity Best Practices, and design standards established by the National Institute of Standards and Technology. We are developing a methodology based on the Society of Automotive Engineers' Cybersecurity Guidebook for Cyber-Physical Vehicle Systems

(SAE3061) as well as the ISO26262 standards. These two risk-management documents provide guidance on how to identify, assess, and mitigate unacceptable risks, particularly with respect to protecting electrical and electronic systems. In other words, we use the existing state of the art as a starting point and advance it by adding processes to address the shortcomings of the existing standards as they pertain to autonomy and machine learning. 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 also are developing our own processes to address the safety of machine-learning components. Similarly, Aurora-developed processes will be used to address Safety of the Intended Functionality (SOTIF) hazards.

Testing the Aurora Driver



Our experience has taught us to aim for *quality* of miles over quantity while developing the Aurora Driver. In keeping with this strategy, we develop against a base of tests that are executed off the road, in simulation. When we do test drive on roads we tend to be doing one of two things: Our human vehicle operators are conducting exemplary driving maneuvers to teach the Aurora Driver how best to control a vehicle. Or we're driving in autonomous mode to test the Aurora Driver's improving capabilities. In each case, we follow numerous principles that dictate our operations:

Manual control assurance

During development, the vehicle operator can regain normal operation of the vehicle by turning the steering wheel, applying pressure to the brake or throttle, depressing an easily accessible button on the steering wheel, or using the emergency disconnect. When the emergency disconnect has been pressed, the Aurora Driver cannot control or influence vehicle operation.

Two-person teams in test vehicles

On-road testing occurs with two people in test vehicles at all times. The vehicle operator monitors the local environment and ensures the safe performance of the vehicle. The co-pilot monitors the self-driving system and alerts

the vehicle operator of the vehicle's intentions. "The vehicle is preparing to lane change," the co-pilot might say, so that the vehicle operator knows to conduct shoulder checks. Both the vehicle operator or co-pilot can call for a disengagement.

Autonomous control limits

We limit the amount of control the self-driving system has over the vehicle, to prevent the system from conducting a maneuver to which the pilot could not respond. For example, during early development testing the self-driving system would not be allowed to conduct a hard swerve because such an event would not provide the pilot with enough time to resume control of the vehicle in the event of incorrect action.

Pre-mission vehicle verification

Every day, before a vehicle goes out for a test drive, our operators perform parking-lot tests to verify they can resume control when necessary by the various methods available to them. The testing procedure sees the vehicle operator confirm to the co-pilot that each of the ways they might regain control of the vehicle are functional. Vehicle operator and co-pilot also verify the audio and visual cues are working properly.



PEOPLE OF AURORA

Ethan

Team: Perception and Localization

Hometown: Baltimore, Maryland

Previous experience: I've worked on both simultaneous localization and mapping for autonomous vehicles and worked as a scientist in the mixed-reality space and the robotics industry

Why I work at Aurora: Because the people here are not only exemplary scientists, engineers, operators, and entrepreneurs—but also superb human beings

First car: 1988 Chevy Celebrity wagon I borrowed from my dad

Favorite road trip: A drive from Duke University to San Diego in four days for an underwater robot competition. We traveled in one minivan and I sat next to our robot, putting the finishing touches on the software

What motivates me to work in this industry: Getting to places without having to actually drive there

Best memory at Aurora: Our first autonomous rides on public roads, which were performed simultaneously in California and Pittsburgh

Efficient fleet size

We keep the fleet only as large as our engineering team requires to develop the driver. Others have maximized fleet size in order to maximize number of miles traveled, assuming that such a strategy will maximize their learning. We see such a strategy as an unnecessary expansion of the fleet's driving risk. Such a situation creates an excess of data at little to no value. Consequently, we limit the size of our fleet to ensure our team is able to triage, and learn from, all of our driving data.

Grounding the fleet

The phrase “grounding the fleet” refers to the process of ceasing vehicle test operations throughout our organization. Although such events happen only rarely, we have defined a methodology to stipulate exactly what happens after a grounding event, which reflects how seriously we take these matters. Once a grounding order is issued, our vehicle operators disengage from self-driving mode any test vehicles that are out in the field. Vehicle operators then manually drive the test vehicles back to base.

Anything that gives a team member concern about safety is a sufficient reason to ground the fleet. An example of this policy in practice is featured on page 9, in the “Safety in Action” section of “Culture of Safety.” In general, an order to ground the fleet is issued anytime a vehicle operator discovers an issue that affects the safe operation of a vehicle, a developer discovers a bug that might compromise on-road safety, or a technician or hardware engineer discovers an issue with hardware that would impact the vehicle operator's ability to safely control the vehicle. For example, a software fault that prevents the disengagement mechanism from functioning would require fleet grounding. A curb strike could trigger a fleet grounding as well. Upon the report of any collision, Aurora immediately grounds its entire fleet, regardless of initial interpretation of the cause.

A grounding order triggers a cascade of rigorously defined steps that sees our engineering team investigating the cause of the problem that triggered the grounding. The cause is identified, addressed, and revised by the team. As described in “Culture of Safety,” at least two members of our founding trio must issue the order to resume fleet operation on public roads.

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. Virtual testing provides repeatable measures of improvement, speeds development, and lowers the risk inherent to all real-world driving activities. Road time is best 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: Core to our approach to real-world software development is a rigorous and robust software engineering culture that 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, then analyze the system performance of everything from localization to perception to planning.

Analysis of human driving: A core feature of our system design is the ability to provide a probabilistic model of correct driving behavior. We rerun our system on large swaths of expert human driving data and analyze it. The primary object of this analysis is an assessment of how well the system is able to predict exemplary human driving behavior. A system that is performing well finds good human decisions predictable. In contrast, a system that is performing poorly finds it difficult to predict exemplary human driving decisions. For instance, if an engineer introduces a software change that would cause uncomfortably late braking, the probabilistic model of correct driving behavior would flag this new code as problematic as it does a poor job of predicting the expert human driver's braking profile. This type of analysis drives our entire approach to ensuring predictable, human-like behavior.

Software Development: Offline Verification

Aurora combines diverse tools to achieve comprehensive evaluation



Metrics: A straightforward set of quantitative measures designed to monitor system performance, and ensure that performance improves over time.



Forward simulation: Frequently based on an interaction that triggers a pilot takeover. We build the equivalent scenario in simulation, then run it to determine whether further investigation is required.



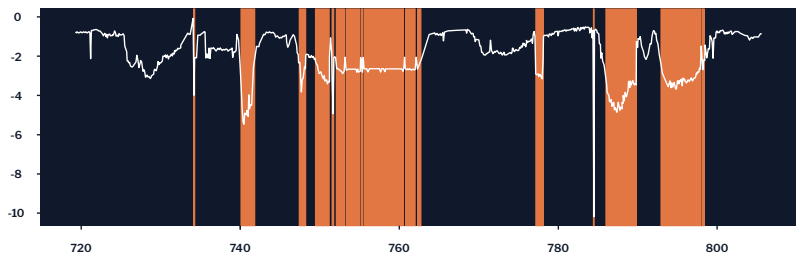
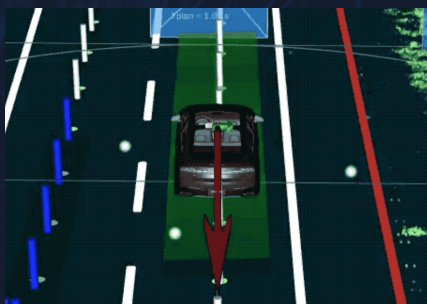
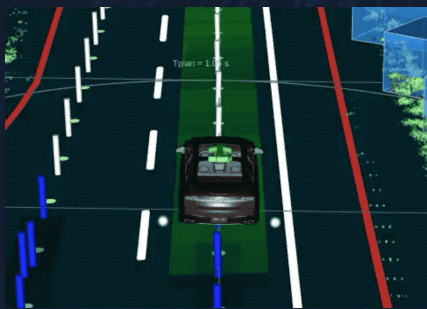
Manual driving evaluation: We run software in the background when operating the vehicle manually to evaluate the software through complex scenarios.



Simulation: A core pillar of testing for self-driving technology. Because parameters are so easily changed in simulation, we can test a diverse set of interactions in a risk-free manner.

Virtual Testing with Historical Data

This sequence of images shows the way simulation safely detects a problem with perception, which in turn triggers corrective measures by our engineering team. The top image displays the simulated vehicle progressing along a simulated two-lane divided road. Most of the time the vehicle is applying a small amount of acceleration, as shown by the small green arrow in the top image. In the bottom image, the system is braking hard, as indicated by the large red arrow, for a false obstacle generated by the perception system. In the top image, the software and human driver agree. In the bottom, the Aurora driver opts to brake but the human driver did not. So we know the object is false. Such examples represent opportunities to improve and we've developed the ability to discover these instances automatically.



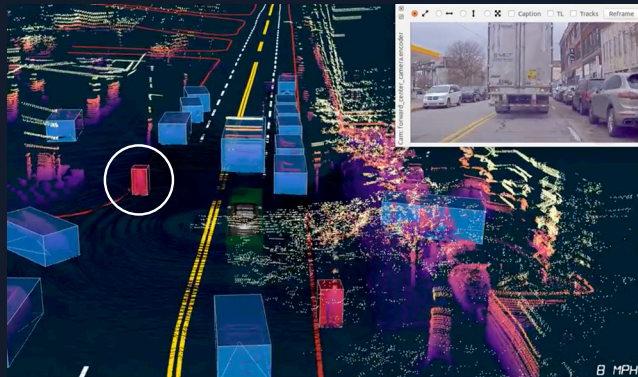
In the above chart, for example, the system is examining how surprising the autonomy system finds exemplary human driving behavior. The red bars indicate regions where the expert human demonstration seemed very improbable to the Aurora driver.

A broad suite of simulations based on real-world interaction and careful design by engineers is critical to ensuring the system performs well in its decision making. 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. We augment these cases with carefully constructed interactions found in naturalistic driving studies and crash databases. (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.)

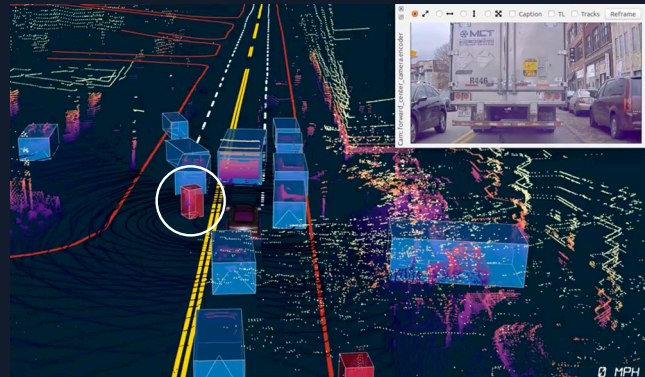
For example, if we're aiming to improve the way our software handles pedestrian crosswalks, we can pull from our database of interactions each occasion that our self-driving system encountered a pedestrian at a crosswalk. Then, in simulation, we can replay those interactions and evaluate how the new code would handle not only this situation, but myriad permutations of it. For instance, we can change 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 Driver against a diverse set of cases without needing to go out and 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.

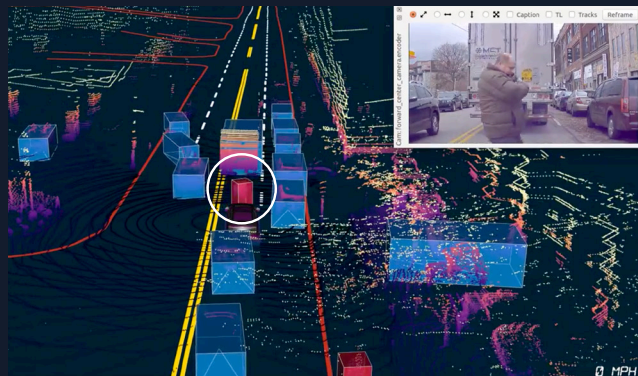
Simulation in Practice



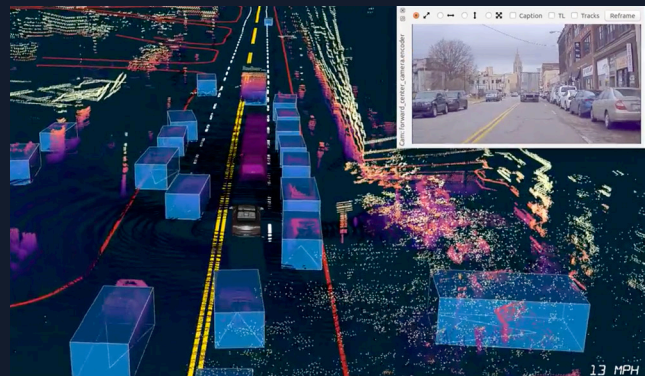
1. Example of the way we use simulation to validate the way a new software build handles particular interactions, in this case, a tough scenario for urban driving in which the Aurora Driver must exhibit the correct end-to-end behavior as the pedestrian (circled) is about to cross the street.



2. In simulation, the Aurora Driver correctly slows for the approaching pedestrian.



3. As the pedestrian crosses directly in front of the simulated vehicle, the vehicle stays halted, validating the safety of the software.



4. The pedestrian has now entered his car. Distance is safe to begin driving. The latest software makes more rapid progress restarting motion and successfully passed the safety- and comfort-critical hurdle of this particular interaction.

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



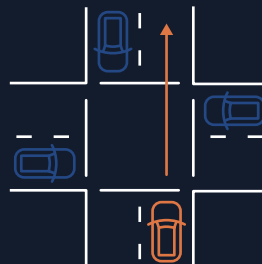
Correct position in lane



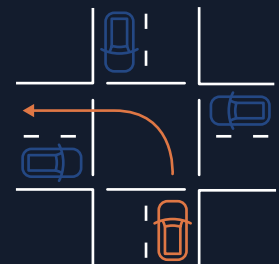
Appropriate speed and distance from other actors



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

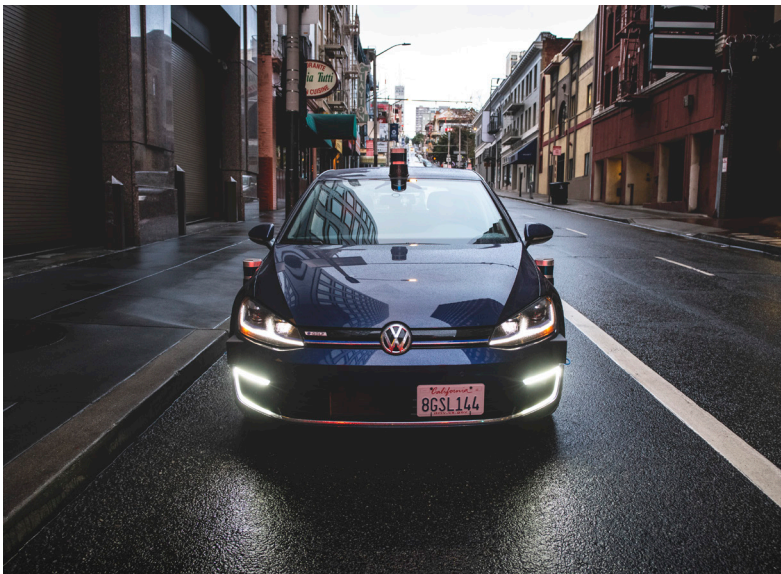
BROADLY

We intend our technology to operate across vehicle makes and models, from the largest tractor-trailer to small cars and anything else that drives on the road.



On-Road Vehicle Testing

As we've outlined, real-world testing is a mechanism for validating and improving the fidelity of more rapid offline testing, rather than a forum for new development. Another objective of such driving is to shake out any subsystem malfunctions or calibration degradations that arise in the course of nominal operation. We also confirm our system behaves as expected for environmental circumstances in our operational domain, including such variables as weather, dust and pollen, glare, and smog, among others.



To maximize the efficiency of our on-road testing, we seek out areas where the Aurora Driver will encounter new relevant situations with relatively high density. By exposing the Aurora Driver to challenging environments and conditions, we compress the time between interesting events and make every mile count. (That said, our conservative disengagement policy sees vehicle operators encouraged to use their judgment, and disengage, if they don't feel comfortable with a situation.)

We test on private tracks. We test in varied Pittsburgh weather, including snow, heavy rain, and heavy fog. We test on roads with tunnels, toll booths, and challenging on- and off-ramp interactions. We test in complex San Francisco urban cases with dense multi-modal traffic, high occlusions, and narrow streets. And we test on a variety of urban, suburban, and highway roadways in California's South Bay Area.



PEOPLE OF AURORA

Greg

Team: Operations

Hometown: Seattle, Washington

Previous experience: Built global service and drive operations teams at automotive and self-driving vehicle companies, and launched an on-demand valet company that made parking easier in major cities

Why I work at Aurora: To usher in safe mobility and unlock transportation solutions for all, especially those with disabilities

First car: 1965 Ford Mustang 289

Favorite road trip: Seattle to Disneyland as a kid

What motivates me to work in this industry: We have an aging population. With self-driving cars, there will be a day when a son can request a vehicle to bring his father to a doctor's appointment, and ensure he returns home safely. I wish I could have done so for my dad

Best memory at Aurora so far: Our recent funding round; it means we can execute even faster on our vision

Performance Metrics and Disengagement Rates

In the public consciousness, disengagement rates reflect the maturity of the self-driving system, with the lower the rate, the better. In reality, such rates tell only a small part of the story. The focus on disengagement rates complicates a company's ability to keep on-road testing efficient, by seeking out challenging situations that create high intervention rates. Another disadvantage is that disengagement rates fail to include information about the testing environment or the conditions encountered. Consequently, during the development phase, we target efficient on-road learning across a diverse range of operational conditions. We do not prioritize large numbers of miles between interventions.

To extract metrics that reflect the performance of the Aurora Driver, we look deeper into the data. Consider the task of evaluating lane-change capability. In this example, we might measure and track:

- Number of lane changes the fleet has attempted per day
- Which lane changes were contested (forcing the vehicle to reason about vehicles in adjacent lanes)
- Success rate of all lane changes vs. the success rate of contested lane changes

Track testing

One component of our real-world vehicle testing involves running our vehicles at private tracks, which offers several key benefits over public road testing. Private tracks provide a safe setting to induce faults without causing risk to other roadway users. Thus, they offer 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 assess how our system would handle a diverse array of "close call" situations, without having to expose the public or our vehicle operators to risky interactions.

Disengagements

When we deploy our fleet on public roads, we aim to maximize our overall efficiency, and seek out areas where the self-driving system will frequently encounter new relevant situations. Then, as the Aurora Driver improves, we increase the complexity of operating environments and conditions.

Consequently, actualized miles per disengagement—or the number of miles our test fleet drives between disengagements—ideally stays low as we seek to challenge our self-driving system.

Types of disengagements

Our vehicle operators are trained to engage and disengage the self-driving system as needed for both routine and non-routine reasons. We categorize and track each of these disengagements as follows:

Routine disengagements: A vehicle operator will trigger a disengagement anytime the Aurora Driver faces an on-road encounter that is out of scope for the software, that is, that the system hasn't yet been taught to handle. Such disengagements are tracked by the system and noted as such by the co-pilot. Data collected from such routine disengagements are then used by the team to guide development. Other routine disengagements include elective decisions by operators to, for example, stop for gas or end a trip.

Operator interventions: These are situations within the scope of the software that a vehicle operator felt might have led to an unsafe situation if operation of the Aurora Driver was allowed to continue. The co-pilot marks the intervention, and Aurora's triage team then determines in simulation whether, without intervention from the pilot, the vehicle would

have been involved in an unsafe situation. If it is determined that an event would have resulted, the intervention is marked as critical, and could lead to a fleet grounding.

Software kickouts: The Aurora Driver is designed with safeguards in place to detect and alert the vehicle operator to abnormalities or failures in the self-driving system. When such an issue is detected, the vehicle operator and co-pilot are alerted with visual and audible alerts, whereupon they resume manual operation of the vehicle. During development testing we use conservative triggers to flag potential issues early.

Fallback and post-crash automated driving system behavior

While the vehicle operator is the primary fallback strategy during the current phase of development, the Aurora Driver will at some point in the future operate without a human vehicle operator or co-pilot in the vehicle. With that future in mind, we have designed the system from the beginning to support fallback strategies that return the vehicle to a safe state without human intervention in the event of a crash, unforeseen failure, or other event. The fallback action taken will depend on the type of failure or event, using the best available sensors and actuators to execute the action. Such measures include, but are not limited to the following:

Limp state: In the event of a critical failure that affects the vehicle outside of the autonomy system, such as a tire blowout, the Aurora Driver will enter the *limp state*, continuing to execute planning and control maneuvers until the vehicle is able to come safely to a stop. Depending on the nature of the fault, the system may immediately pull over to the side of the road, navigate to a convenient stop that is other than the intended destination, or it may allow continued operation of the vehicle with reduced capability for some period of time until either the destination or a service center can be reached.

Fallback trajectory: In the event of a critical fault of the Aurora Driver that sees the safety controller remain operational, the Aurora Driver will execute the *fallback trajectory*. This action consists of following the last valid trajectory sent to the safety controller by the primary computer. This will happen by default, due to the system design, if the primary computer stops providing trajectory

updates to the safety controller. The fallback trajectory is intended for the vehicle to achieve a state of minimal risk, which ends in a stop.

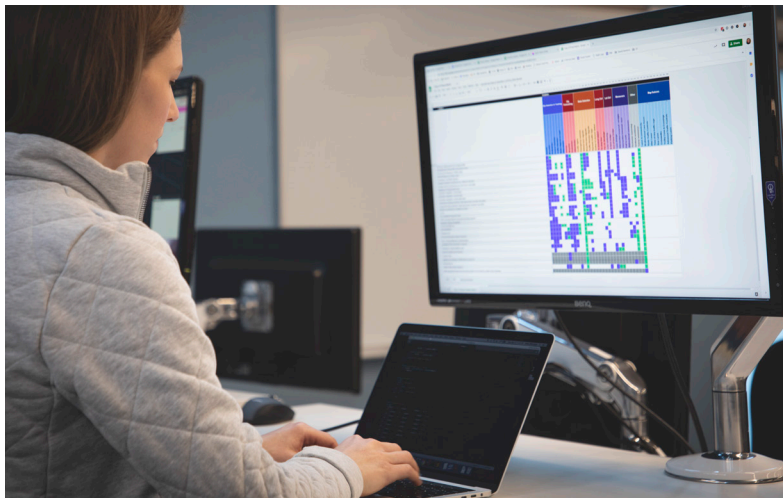
Fallback stop: In the event of a collision, or a critical fault of the safety controller, the vehicle will execute a *fallback stop*. This action brings the vehicle to rest quickly but allows surrounding actors time to respond accordingly, while also avoiding hazards that may result from attempting a rapid stop. The fallback stop enables hazard lights, engages the horn, holds the steering in its last commanded position, and applies a constant deceleration until the vehicle comes to a stop.

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. Vehicle performance and functionality of the sensor suite also is logged, as is anything else we've concluded could be valuable to reconstruct an event. The logging system has been designed 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. Aurora also requires the presence of a human co-pilot in the vehicle at all times while the system is being tested to log and annotate data. For example one of the co-pilot's main responsibilities is to annotate system performance, as well as disengagements and the reasons for such disengagements.

Operational Design Domains

The term *operational design domain (ODD)* refers to the environment, weather, driving conditions, and traffic density, among other factors, presented to a vehicle equipped with a self-driving system. To date, testing has demonstrated that the Aurora Driver can handle multiple challenging situations, in urban, suburban, and highway road environments; various lighting conditions (day, night, dawn, dusk); and myriad weather conditions (clear, fog, rain, and snow). We have been careful to target our on-road tests at the conditions of interest; focusing at times on, for example, traffic light-governed intersections at night or high-speed merging in various weather conditions. This ODD targeting allows us to minimize wasted miles and keep challenging cases flowing to the top of our training and validation funnel. Aurora operates in Pittsburgh, Palo Alto, and San Francisco, specifically to give our test teams access to the diverse road, traffic, and weather conditions that exist in each.



Adding new geographic areas is a multistep process. We map the area first, then run our software through simulations of any new boundary scenarios contained within the expanded ODD. Next, we have our vehicle operators drive the new roads manually with our system in observer mode, to ensure that it responds appropriately given real-world inputs. Only once the Aurora Driver has passed that process do we allow our vehicle operators to operate the system in self-driving mode within the expanded ODD.



PEOPLE OF AURORA

Chethana

Team: Product

Hometown: Hyderabad, India

Previous experience: Have worked in automotive technology, across projects including powertrain controls and suspension systems around efficiency, performance, experience, and safety

Why I work at Aurora: Because of how we balance the industry's best practices with a novel approach to building technology

First car: Honda Accord coupe

Favorite road trip: Hana, Hawaii

What motivates me to work in this industry: I want to contribute to this novel auto transformation, which will make us safer and improve our quality of life

Best memory at Aurora: Seeing all the teams come together as we put the hardware and software into our vehicles to begin road testing

Vehicle Operators



Our vehicle operators are full-time employees of Aurora and represent an integral part of our team. They ensure safe vehicle-testing operations, provide feedback to the development team, execute test data collections for mapping and labeling, and represent the single biggest source of public interactions, since they are out in public with our vehicles.

Recruiting, selection, and retention strategies

Our recruiting process for vehicle operators seeks out safe 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 such key attributes as decisiveness, the ability to think critically, adaptability, awareness and perspective. We also seek out candidates with superior communication skills. The vehicle operators we hire come from diverse backgrounds and have diverse experiences, 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 is certified in first aid and CPR. Finally, to ensure that all operators stay current with new policies, we conduct a weekly refresher training program, which includes material on any new process or procedures from the past week.

Operator training

As part of an intensive six-week training program, our vehicle operators and co-pilots undergo defensive-driver education conducted by instructors certified by a professional driver training company.

Week one (onboarding): Introduction to operations, introduction to the vehicle and the self-driving system, observing expert vehicle operators, and classroom work to understand safe operations and map reading. How to set up and shutdown the vehicles. Start-up checklists. How autonomous vehicles work. Incident response training and emergency simulations.

Week two (basics of co-piloting): Material taught includes background on Aurora's software-development cycle, pre-trip setup and inspection, parking lot demonstration and the basics of co-piloting, as well as operator communication, post-trip procedures, trouble-shooting and escalating, groundings, and testing and evaluation.

Week three (third-party safe driver training): Education involving state driver's manuals, vehicle-operator training, vehicle-operation practice in a parking lot with an instructor. New vehicle operators also practice disengaging and engaging autonomy in various scenarios. There's closed-course vehicle operator practice with an instructor, as well as fault-injection practice and third-party defensive driver training.

Week four (detailed co-piloting): Curriculum includes pre-trip procedure and vehicle inspection, post-trip procedure and inspections, calibration procedures, mapping procedures, and evaluations. During week four, our new vehicle operators also receive their autonomous vehicle testing permits.

Week five (public road piloting): New vehicle operators practice operation of self-driving vehicles on public roads, as well as pre-trip inspection and procedures, and post-trip procedures and inspection. Vehicle operators are tested.

Week six (putting it all together): During the final week, training includes pre-trip vehicle operator inspection and procedures, a review of vehicle operator expectations for developer tests, and a review of vehicle operator software procedures. The final evaluation assesses ability to pilot vehicle safely under diverse traffic conditions.



PEOPLE OF AURORA

Daniela

Team: Technical Operations

Hometown: Tijuana, Mexico

Previous experience: Medical Surgeon, Emergency Medical Technician, Fire Service, Safety Supervisor

Why I work at Aurora: I want to contribute in the creation of a safer mode of transportation that will reduce injuries and deaths globally

First car: Ford Thunderbird LX V8

Favorite road trip: Driving on California's Highway 1 and visiting Monterey, Big Sur, and the Lake Tahoe area

What motivates me to work in this industry: Testing and creation of a safer mode of transportation that will benefit the world

Best memory at Aurora: Opportunity to work with brilliant colleagues who share their time and knowledge

Operator pair responsibilities

Our vehicle operators work in pairs, with each member of the partnership possessing separate responsibilities.

Vehicle operator responsibilities:

- The vehicle operator keeps the vehicle, the people in the vehicle, and anyone around the vehicle safe at all times.
- The vehicle operator keeps hands in contact with the steering wheel, and a foot hovering near the throttle and brake pedals, while the system has autonomy 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 vehicle operator immediately takes over.
- If the Aurora Driver engages in an action that results in a potentially unsafe situation, the vehicle operator immediately takes over.
- If active emergency vehicles are encountered, the vehicle operator immediately takes over.

Co-pilot responsibilities:

- The co-pilot informs the vehicle operator 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.
- The co-pilot indicates to the vehicle operator any performance shortfalls of the Aurora Driver.
- The co-pilot monitors and provides feedback to the vehicle operator to ensure the vehicle operator is adequately performing responsibilities.

Human-Machine Interface

Audio-visual alerts 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. On loss of communication with the self-driving system, the light bar automatically turns red (see sidebar).

Audio safety features

Unambiguous audio indications are played for certain state transitions, and when the system is faulted, for example:

- Audio is played continuously when takeover is required.
- Audio is played when engagement is attempted but fails.
- Audio is played when the system disengages, regardless of cause.
- Audio is played when the system engages.

Crashworthiness

Every vehicle operated by Aurora as part of its ongoing development of self-driving technology meets all federal and state safety standards with respect to crashworthiness. All test vehicles used by Aurora have been certified by the original equipment manufacturer as meeting all federal crashworthiness standards. The installation and integration of the Aurora self-driving system with the underlying vehicle platform does not alter, modify, or defeat the occupant-protection systems, including seat belts and airbags, in those vehicles or the performance level of those systems in the event of a crash. Furthermore, the installation and integration process does not materially affect the structural integrity of the vehicle or alter the vehicle seating arrangement.

Light Bar Visual Indicators

White



Indicates not ready
(manual control)

Blue



Indicates ready state
(manual control)

Green



Indicates healthy state
(autonomy engaged)

Red



Indicates unhealthy state
manual takeover required
(autonomy engaged)



PEOPLE OF AURORA

Sonya

Team: Recruiting

Hometown: Sunnyvale, California

Previous experience: I have been connecting with great people and building amazing technical teams at growing companies spanning mobile apps to blockchain

Why I work at Aurora: Our company's approach to self-driving cars is groundbreaking and I respect the focus on safety. I also think everyone should have the right to be independent and mobile

First car: 2005 Black Honda Civic SI Hatchback

Favorite road trip: Driving to Tahoe when the weather was clear, crisp, and the colors were brighter than ever

What motivates me to work in this industry: Tragically, a few weeks into joining Aurora a friend passed away in a motorcycle accident. It was devastating and I'm hoping self-driving cars reduce, or eliminate, these accidents

Best memory at Aurora: Our team is distributed across multiple cities. It's nice when we're all in one spot!

Engaging the Community

While autonomous vehicles have drawn intense interest from the media, regulators, and academics, most members of the public have limited knowledge about the implications of the technology. To educate stakeholders, we hold open houses for students, leaders, and other members of the community. In addition, Aurora and its employees are committed to supporting partnerships and programs that align our strengths as an organization with key social issues to serve as a force for positive change.

- We engage and collaborate with local, state, and federal governments to fulfill our commitment as an industry leader to support the development of standards and regulatory frameworks.
- We serve as industry partner for the Pennsylvania Department of Transportation; Aurora was the first self-driving company to receive an authorization from the state to test autonomous vehicles.
- We lend our expertise to nonprofit organizations that focus on developing the next generation of young pioneers in the fields of science, technology, engineering, and mathematics (STEM). For example, we partner with Pittsburgh's Girls of Steel, an all-girl robotics team made up of 50 teenagers from more than 30 schools.
- We are a founding member of PAVE (Partners for Automated Vehicle Education), a coalition of industry, nonprofit, and academic institutions that helps to inform and educate the public and policymakers on automated vehicles, and their benefits.

Federal, State, and Local Laws

We've taken pains throughout our various operations to ensure that the Aurora Driver is configured to comply with all applicable federal, state, and local laws within its approved operational design domain. In addition, every Aurora Driver vehicle meets all applicable Federal Motor Vehicle Safety Standards. The vehicles also comply with federal laws and regulations relating to fuel economy, emissions, noise, and labeling requirements. Moreover, Aurora ensures that such vehicles are in compliance with all applicable state rules regarding insurance requirements, reporting requirements, registration and titling requirements, and other state-based requirements.

References

¹ See p. 4, National Center for Statistics and Analysis, *Summary of motor vehicle crashes: 2016 data*, Traffic Safety Facts, Report No. DOT HS 812 580, Washington, DC: National Highway Traffic Safety Administration, 2018. Available at <https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812580>.

² Bezyak, Jill L., Scott A. Sabella, and Robert H. Gattis, "Public transportation: an investigation of barriers for people with disabilities," *Journal of Disability Policy Studies*, 28, no.1(2017): 52-60. Available at <https://journals.sagepub.com/doi/full/10.1177/1044207317702070>.

³ Based on rounding one-way mean duration of 26.58 minutes for all modes of travel. Source: Federal Highway Administration, *2017 National Household Travel Survey*, Washington, DC: U.S. Department of Transportation, 2017. Available online: <https://nhts.ornl.gov>.

Appendix

Developing the Aurora Driver satisfies the following NHTSA VSSA recommendations for topics discussed: System Safety, Object and Event Detection and Response, Cybersecurity

Testing the Aurora Driver satisfies the following NHTSA VSSA recommendations for topics discussed: Validation Methods, Operational Design Domain, Human-Machine Interface, Crashworthiness, Fallback, Data Recording, Post-Crash ADS Behavior

Engaging the Community satisfies the following NHTSA VSSA recommendations for topics discussed: Consumer Education and Training; Federal, State, and Local Laws