ARGO AI

Developing a Self-Driving System You Can Trust

April 2021
Safety Report

LETTER FROM THE CEO

When we established Argo AI in 2016, my co-founder Dr. Peter Rander and I had a clear understanding of the role that safety would play in the development of our self-driving system. It would be the Number One value driving the way we operate as a team, and it would be the Number One reason for building the technology itself.

Throughout our careers, we've seen how robotics and automation can help in myriad industries, from mining to military to railroads to agriculture. We've been lucky enough to aid in the development of technology in each of those sectors. But we've always believed that technology could offer more than just incremental improvements in efficiency or modest corporate profits. We wanted it to transform people's lives for the better.

Our shared experiences at Carnegie Mellon University's National Robotics Engineering Center, followed by separate tenures with other self-driving innovators, gave us first-hand experience with large, industrialized commercial sectors. These collective experiences taught us two major lessons: First, when developing safety-critical technology, it is essential to be process- and data-driven. And second, in order to make a massive societal difference and build for scale, it is critical to collaborate with expert partners.

In terms of process, Argo executes with urgency and commitment. But this is not a race. Our self-driving system will only be deployed when the data tells us it operates safely and reliably, and offers an acceptable quality of service to sustain a business. We will launch driverless commercial operations when our safety case is complete, and demonstrates that our technology can improve peoples' lives, without sacrificing safety.

To achieve scale, we chose to work closely with automakers. Our first partners, Ford and Volkswagen, provide 200 years of combined experience building safe, high-quality vehicles in significant volumes all around the world. Combining our partners' industrial expertise and global reach with our cutting-edge self-driving platform enables the production of a compelling product that meets the tough safety standards and enormous scale of the global transportation industry. The challenge is significant, but by bringing together a team of world-class automotive and robotics engineers, we intend to make this technology available to millions.

Together with our partners, we are conducting real-world validation while working to build societal acceptance, especially within the communities where we plan to first deploy the technology in commercial use. Argo test vehicles are already operating on the streets of six U.S. cities, and we're preparing to launch testing in Europe in the near term. We're doing this because we recognize that trust isn't given—it's earned. As this safety assessment lays out, it's the mission of every employee at Argo to fulfill that objective day in and day out.

But what does Argo's commitment to safety and our technology mean for the average person? We believe our technology has the potential to offer incredible safety benefits, not just for vehicle occupants, but for all road users. The consistently high number of road-traffic fatalities globally, coupled with the even higher number of non-fatal injuries and property damage, make a compelling case that the time for this technology is not in some theoretical future. It is now.

The road ahead is long, and there are further challenges to solve along the way, but we're committed to seeing our vision through to its ultimate destination. This report is just a first step on our journey to inform, educate, and earn the trust of the people we are preparing to serve.

Sincerely,
Bryan Salesky
Founder & CEO, Argo AI

Bryan Salesky, Founder & CEO
Dr. Peter Rander, Co-Founder & President

REPORT SCOPE

We firmly believe in self-driving technology and its profound potential to transform the way we live, ultimately making getting around cities safer, easier, and more enjoyable for all. To that end, this report explains how the team at Argo applies safety principles across all aspects of the engineering and development of our self-driving technology.

We recognize that a number of terms are used to describe vehicles that can operate with varying degrees of automation. The technology that we are developing will enable a vehicle to drive without the need for a human driver, or human intervention in the task of driving, within its operational design domain (which we describe in detail on 24). For those in the industry, our technology is defined by the SAE International as Level 4 automation. To guide the way we talk about the technology to all audiences, we are aligned with the Associated Press Stylebook, which outlines that "autonomous" and "self-driving" can both be used to describe the experience our technology will enable. The term "driverless" will only be used when discussing the experience where there is no human behind the steering wheel, which will come as we near the final phase of development and testing, and begin commercial deployment of our technology.

We are sharing this report to provide vital information to our stakeholders and the communities in which we operate. This document has been written in the spirit of transparency and collaboration, and in support of efforts by the U.S. National Highway Traffic Safety Administration to continually raise awareness and confidence in self-driving technology.

In this report, we frame our corporate safety culture and vision, illustrate how they are supported by the company's testing and validation strategies, and explain how we are forming partnerships with automakers to design for the highest levels of quality, durability, and reliability in self-driving vehicles. We also show how our strict policy of compliance—not only in terms of physical safety, but also data security and privacy safeguards—reflects our foundational commitment to safety.

In addition, this report addresses the 12 elements identified in the U.S. Department of Transportation's Voluntary Safety Self-Assessment guidance. These elements are listed to the right with their page number location for easy reference:

Safety Case

This report is intended as a high-level summary of our safety activities. Much greater detail about all aspects of our safety activities will be provided in our Safety Case, a separate, evidence-based document supporting the commercialization of our self-driving system. The Safety Case is a living document that is currently a work in progress. It is updated regularly based on our internal safety activities, as well as the development of industry guidance and standards.

The Safety Case is a structured argument for acceptable safety throughout the safety lifecycle, and is based on the framework provided by the following categories:

- Safety and security planning
- Organizational policies and procedures
- Safety Architecture
- Functional Safety Analysis, Requirements, and Testing
- Safety of the Intended Functionality (SOTIF) Analysis, Requirements, and Testing
- Product Security Analysis, Requirements, and Testing
- Systems Analysis, Functional and Performance Requirements, and Testing
- Verification and validation plans, specifications, and reports
- Results of self-audits
- Results of independent safety reviews (safety assessments, safety audits, and confirmation reviews)
- Custom rationale to support aspects of autonomous product-specific industry standards such as the Automated Vehicle Safety Coalition (AVSC), International Organization for Standardization (ISO) and others
- Automaker-specific artifacts

The Safety Case provides a comprehensive assessment of safety risks associated with our self-driving system and the controls developed to mitigate those risks, and serves as the basis for independent safety assessments.

To ensure consistent content and thorough evidence, the Safety Case is based on ISO 15026 (Systems and Software Assurance) and our review and assessment of other related industry standards. The Safety Case spans our safety and security engineering work, including work following standards ISO 21448 (SOTIF) and ISO 26262 (Functional Safety), as well as AVSC Best Practices, regulatory requirements, voluntary industry standards, and Fleet Operations safety assurance and controls. For security, Argo AI follows ISO-21434 for product security and ISO-27001 for infrastructure security.

ARGO AI SAFETY CASE FRAMEWORK

The following graphical representation is a snapshot of Argo's three top-level safety claims as well as a sample of sub-claims. The full safety case includes hundreds of sub-claims and supporting evidence. As Argo's development continues, the safety case framework will continue to evolve and mature.

PRODUCT & TECHNOLOGY ARGUMENT

CLAIM 01

The AV is acceptably safe during autonomous operations.

- PERCEPTION SAFETY GOAL
- MOTION PLANNING & CONTROL SAFETY GOAL
- LOCALIZATION SAFETY GOAL
- COMMUNICATION TO OTHER ROAD USERS GOAL
- PASSENGER & ROAD ACTOR INTERACTIONS
- IMPACT RESPONSE
- ODD SELECTION

PROCESS ARGUMENT

CLAIM 02

Argo AI's continuous improvement process ensures the proactive and continued advancement of safety.

- SAFETY MANAGEMENT
- TRAINING
- PROCESSES

PROCESS ARGUMENT

CLAIM 03

Argo AI fosters a safety culture throughout the entire safety lifecycle.

- SAFETY CASE PROCESSES
- SAFETY CULTURE PROCESSES
- INDEPENDENT SAFETY REVIEWS
- QUALITY MANAGEMENT PROCESSES
- FUSA PROCESSES
- SOTIF PROCESSES
- REGULATORY SAFETY PROCESSES
- COMMUNICATIONS CHANNELS
- SELF AUDITS

Safety: Our Foundational Value

Safety is the number one value at Argo AI. It is ingrained in our culture, it dictates the way we work, and it has been developed within our company and our product since our founding.

As a self-driving technology platform company, we do not build self-driving vehicles. We develop the software, hardware, operations infrastructure, and maps that power self-driving vehicles, and we work closely with our automaker partners, Ford and Volkswagen, to integrate this technology into their vehicles.

We recognize that self-driving is a complex technical challenge that requires laser focus and a structured process. Our mission is to build technology that everyone can trust, and to create a product that makes reliable autonomous transport helpful to the greatest number of people. For us, that all starts with the highest-level commitment to safety.

This mission requires not only adhering to rules and regulations on the road, but also thoughtfully integrating our safety principles into every facet of our company and every stage of development, testing, and deployment. We reinforce this company ethos with our employees every day through training, communications, a safety recognition program, and our comprehensive Safety Management System. We also recognize the link between safety and cyber security, and we therefore integrate cyber security training throughout the company, and devote extensive resources to cyber security through every state of development, testing, and deployment.

EMPLOYEE RECOGNITION AWARDS

ARGO HIGH FIVE | THE ARGO WAY | SAFETY HIGH FIVE

Argo encourages peer-to-peer recognition, with awards that include the Argo High Five (for outstanding teamwork and collaboration), the Argo Way Forward Award (for teamwork, ethics, and excellence), and the Proactive Safety High Five (for contributions that uphold the Argo safety mindset).

WHY SELF-DRIVING?

We believe that self-driving technology is essential to improving road traffic safety, for a number of key reasons. Self-driving vehicles drive in a consistent manner, and they never get angry, tired, or distracted like human drivers. Capable of learning, a fleet of self-driving vehicles can improve based on the experience of a single vehicle and therefore get even smarter with age.

Based on these capabilities, self-driving technology will enable positive changes in many aspects of society, providing improved safety, accessibility, and mobility. This is especially true for people who live in highly-populated areas where car ownership is expensive and inconvenient. While our development is driven to achieve outcomes rather than deadlines, we still feel a sense of urgency, largely because of the clear societal benefits that will result from self-driving.

Self-driving technology holds the promise to vastly reduce the number of automotive crashes and resulting injuries and fatalities, both for vehicle occupants and for others using the streets, including cyclists, pedestrians, and scooter riders. The World Health Organization estimates that road-traffic crashes account for approximately 1.35 million deaths annually, and that road-traffic injuries are the leading cause of death for children and young adults. The WHO also estimates that pedestrians, bicyclists, and motorcyclists account for more than half of global road-traffic deaths. (*1)

According to the U.S. National Highway Traffic Safety Administration, 36,096 people were killed in motor vehicle crashes in the United States in 2019, the most recent year for which full year data has been published. There were also an estimated 6.76 million police-reported crashes resulting in an estimated 2.74 million injuries. What's more, the number of deaths of vulnerable road users remains high, with 6,205 pedestrians and 846 cyclists killed on U.S. roads in 2019. (*2)

1.35 M Global fatal road traffic crashes annually

36,096 United States fatal motor vehicle crashes in 2019

2.74 M United States non-fatal crashes resulting in injuries in 2019

*1 Source: https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries
*2 Source: https://www.nhtsa.gov/press-releases/roadway-fatalities-2019-fars

In addition to lessening the toll of crashes, self-driving technology has the potential to provide other safety benefits. In a world adjusting to the impact of COVID-19 and bracing for future global events, self-driving technology can help accommodate drastic increases in online shopping and home delivery and the growing demand for contactless ride-hailing services. It has the potential to increase access to transportation, jobs, education, and health care for underserved communities. And it can help fight the effects of global warming by increasing vehicle efficiency and reducing traffic congestion and carbon emissions.

For all of these reasons (safety, access, and mobility), our partnerships with Ford and Volkswagen will first focus on commercialization in complex city and urban environments, where the scale of these challenges is greatest, and the benefits will be most readily recognized.

EXPERIENCE AND PROCESS

At Argo, we believe that applying time-tested engineering processes to self-driving is not just the right way to do it—it's the only way to do it. The company was founded on the principles underlying safety-critical systems in the aviation, military, maritime, and automotive sectors.

Our team has extensive experience commercializing robotics and artificial intelligence products. This includes robotics used for everything from space and deep-ocean exploration to farming and theme parks, and artificial intelligence applications ranging from sports broadcasts to pipe inspections. This deep expertise complements our automaker partners' track record in vehicle integration and manufacturing to produce vehicles at scale.

We have developed robust processes to guide our daily work, including identifying safety issues and elevating their visibility, and managing potential safety risks. As outlined later in this report, our engineering development follows procedures based on international standards agreed upon by experts and approved by the International Organization for Standardization (ISO). These processes support the consistency of safety activities, traceability of all aspects of the safety lifecycle, and successful completion of independent safety assessments, audits, and confirmation reviews. Furthermore, extensive processes, procedures, and training guide the work of our fleet-testing operations to ensure alignment with our Safety Management System.

Prior to allowing the public in or around our self-driving vehicles, we test in a structured and rigorous way to ensure confidence in the safety of the system, and we place a deep emphasis on consistent operations, transparent communications, and ongoing community engagement.

SAFETY CULTURE

We are proud of our culture. At Argo, it is safety—not speed, not profit, and not media hype—that underlies everything we do. We believe that safety is a responsibility of every employee. It drives our approach to development and testing. It guides our technical progress. And it underpins our roadmap to the commercial launch of self-driving vehicles everywhere.

Argo's safety culture is greater than the product; it is driven from the top down, lived bottom up, and rooted in the foundation of our policies, job descriptions, training, communications channels, organizational structure, reporting processes, and behaviors. It envelops not only the product and the people directly developing and testing the product, but also every aspect of our business, from offices to labs and depots to the open road.

All team members are expected to uphold safety standards, identify potential risks and needs, implement organizational improvements to address safety concerns, and advocate for safety in all elements of our work. We even hand out regular safety awards rewarding proactivity and recognizing employee contributions to the advancement of safety in leadership, development, and fleet operations.

International Safety Standards Which Guide Our Development

Our approach to systems engineering is built around two key ISO standards relating to vehicle systems. ISO 26262 defines Functional Safety—that is, requirements to be met by electrical and electronic (E/E) vehicle systems and related software. ISO 21448 addresses the Safety of the Intended Functionality, or SOTIF, and defines a safety standard for driver assistance systems and functions for autonomous vehicles.

We also assessed and considered additional standards that define methods for the construction of the Safety Case for our self-driving system, including ISO 15026 (Systems and Software Assurance). These standards introduce goal structured notation into the safety standards, a powerful tool to organize and understand the logic of a case and the evidence supporting that logic.

We also actively monitor the ongoing development of updates to these standards, the introduction of new relevant standards, and industry guidelines. And we support our automaker partners' involvement in SAE International and the Automated Vehicle Safety Consortium (AVSC) for the development of autonomous product-specific industry best practices.

Contact Us

When we say your voice matters, we mean it sincerely. Whether you're a high school teacher, an automotive enthusiast, a part-time blogger, or a inquisitive road user—we want to hear from you.

General Inquiries
info@argo.ai

Jobs
jobs@argo.ai

Press
press@argo.ai

Our corporate culture values nimble and effective communication throughout the organization. For instance, all Argo employees are empowered and encouraged to identify, track, and escalate any safety-related issues they encounter, and our reporting system allows people to report potential safety issues without fear of reprisals. Our Operations Advisory process enables any employee with a safety concern to recommend that testing stops until a particular safety issue is resolved and verified. Further, at any stage of development, testing, or deployment, any employee can question why and how we make certain decisions and know that they will be heard. We provide simple methods for the public to contact us through our website, and any communication received is promptly reviewed and escalated to leadership as necessary.

Employees are able to take concerns and questions to their direct supervisors, other managers, members of our Global Leadership Team, our Safety and Security Committee, and any member of our People Operations team. To facilitate safety reporting, all employees also have access to Operations Advisories and test-drive data analysis, and the ability to escalate potential safety issues, formally or informally, in person, electronically, or through a confidential 24/7 ethics-reporting hotline.

After each daily test-drive shift, data analysts download test-vehicle data and review the video logs annotated by our Test Specialists. A team of data analysts evaluates disengagements—those events where Test Specialists needed to take back control of the vehicle—and appoints specific development teams to attend to any changes that need to be made to hardware, software, or other infrastructure. The team generates a detailed nightly report which includes a wide range of measurable data, such as miles driven locally and across the fleet, and detailed information about fleet-related performance. Published company-wide, this report provides an additional level of transparency into the development of our system.

In addition to maintaining strong communication channels within the company, we are in constant dialogue about safety standards with external stakeholders, including component suppliers and automaker partners, state and federal government officials, public education and standards committees, and industry consortiums. External engagement ensures that we are continually integrating best practices and cutting-edge research into our safety practices.

Beyond following industry standards throughout the safety lifecycle, we also participate in the development of new standards. In addition, we work with local governments and regulatory bodies developing road-safety rules. We ensure the robustness of our Safety Case by monitoring potential updates to applicable standards and industry best practices.

SAFETY CONCERN REPORTING

Any safety concern raised by an employee enters a structured escalation process and, where appropriate, an Operations Advisory is issued.

Operations Advisories span a broad range of potential actions. At the lower end, operations in a city may be delayed because employees in outlying areas are simply not able to get to work, even if the roads in our test area are clear. A more significant action would be to pause the entire fleet in one city, for example due to extreme weather conditions or major events unfolding across operational areas. Regardless of its breadth, the issuance

of an Operations Advisory to stop autonomous operation requires the personnel in all affected vehicles already in operation to take over manual control immediately and to safely return to their local terminal.

Operations Managers are authorized to issue local Operations Advisories, and Argo engineers can call for fleet-wide Operations Advisories based on their analysis of Test Drive logs or any other mechanism. When an Operations Advisory is issued, it remains active until the root cause is identified, addressed, and validated by leadership representatives.

A critical part of our Safety Culture and our safety-first approach is our Report Assessment and Issue Resolution process. Per this process, all employees are empowered to proactively identify and raise potential safety concerns, whether they originate from simulation, closed course testing, road testing, or in other operational procedures. Once identified, potential concerns are investigated and managed by a cross-functional team in a transparent and disciplined way to continuously improve the quality and safety of our system.

ARGO SAFETY AND SECURITY COMMITTEE

The Safety and Security Committee oversees and approves policies, and assesses potential risks associated with safety, security, cyber, and IT initiatives, operations, and technology.

This Committee has a number of goals, not least of which is promoting and nurturing our culture of safety. It provides a forum for discussion of potential safety or security-related issues; ensures transparency; provides guidance on best practices, procedures, and standards; and oversees our Safety Management System.

The Committee is comprised of leadership from all cross-functional areas, including, Executive Leadership, Enterprise Information Technology, People Operations, Facilities Operations, Fleet Operations, Systems Engineering, Safety Engineering, Product Security, Product Integration & Test, Hardware Engineering, Software Engineering, Safety Policy & Assurance, Insurance, Compliance, Audit, and Legal.

Any employee concerned about a safety-related matter may raise their concern directly with any member of the Committee.

ARGO VALUES

At Argo, ethics and values are part of our DNA.
We hire people who live, breathe, and embody this ethos.

SAFETY IS NUMBER ONE.
It's our way of working each and every day.

WE BUILD THE FUTURE
street-by-street, block-by-block, going city-to-city.

HONESTY AND HUMILITY
always win over hubris and headlines.

RESPECT
is everyone's responsibility.

EMBRACING DIFFERENCES
delivers superior results.

If in doubt, find a way to
FIGURE IT OUT.

SOLUTIONS
are only as good as the problems they solve.

WE > I.

History is made by those who
NEVER GIVE UP.

SAFETY MANAGEMENT SYSTEM

A Safety Management System (SMS) is a formal, top-down, organization-wide approach to managing safety risk and ensuring the effectiveness of safety risk controls. It includes systematic procedures, practices, and policies for the management of safety risk. Argo's Safety Management System (SMS) defines and reinforces our commitment to putting safety first in all parts of our operations (*3). It consists of four main components, which act as the foundation of all the work we do at Argo:

The safety policy sets forth leadership's commitment to dedicating sufficient resources to building, maintaining, and enforcing our safety culture.

The safety risk management policy explains how we assess risk and design and implement appropriate controls.

The safety assurance policy describes how we routinely evaluate the effectiveness of our controls.

The safety promotion policy describes the steps that we take to achieve the goals set forth in each of these policies and the resources dedicated to supporting our safety culture.

All teams at Argo are expected to adhere to the SMS framework in all activities across the company, from development and testing through fleet operations. Compliance is measured through a mix of intradepartmental reviews and independent audits.

QUALITY AND PERFORMANCE METRICS

At Argo, we utilize multiple metrics and targets to track the quality and performance of our self-driving system (SDS) and drive continuous improvement across the organization and within our vehicle fleet. Our metrics enforce performance and safety parameters on our design. We also develop safety metrics and targets based on vehicle-fleet data, and safety metrics that measure our system's capability and performance.

Fleet performance and safety are measured against three main metrics: Safety, Trip Quality, and Uptime. Within these broad categories, we monitor a number of key data points, including rates of potential collisions found through simulation and their estimated severity; critical failures of key SDS features or systems; violations of road-traffic regulations; and quality and completion of ride. We also monitor the performance of our SDS, from software to sensor suite, to ensure that our automaker partners are able to deliver a viable mobility service.

In addition to these three categories of metrics, our Safety Case includes many more detailed requirements and metrics, all of which are critical for demonstrating that our SDS is acceptably safe. Our testing strategy is holistic and comprehensive, using internally developed safety goals and testing methodologies based on industry best practices and guidance on safety metrics.

While the ultimate measure of our technology's capabilities is its performance during public road testing, one of the challenges of public road testing is that by their very nature, rare events, or "edge cases," cannot be observed repeatedly. In order to ensure sufficient exposure to edge cases, we use repeatable structured testing of these edge cases to validate and verify the whole system. Our fleet data informs the breadth of coverage for those tests, and our systems analysis drives detailed requirements and tests, which we use to validate and verify that identifiable modes of failure have been mitigated.

We test across the spectrum of subsystems, from ensuring that hardware works properly to assessing the outcomes of complex driving decisions. Virtual testing plays a significant role in our assessment of driving functions and complex driving behavior, including various types of simulation to evaluate decisions made by the SDS. Robust testing efforts at our private test track ensures that edge cases are correctly handled. Each of these testing methods is outlined in more detail in the Test and Validation section of this report. Put simply, metrics are essential for making and monitoring progress, and for providing the guidance we believe is essential for commercialization of self-driving technology.

We measure quality and performance against three main categories: Safety, Trip Performance, and Uptime.

*3 *U.S. Federal Aviation Administration, Safety Management System (SMP)
Source: faa.gov/about/initiatives/sms

Systems Safety

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At Argo, our technical development approach is defined by the discipline of systems engineering.

We are developing a system capable of preparing for every interaction that could occur within the environments in which our system will operate. As this report lays out, our strategy of proactively identifying and managing potential faults, functional insufficiencies, and hazards through all aspects of the safety life-cycle, or expected time of product deployment, is planned down to the smallest detail. We develop our SDS to ensure consideration of all aspects of systems safety, from the development of the architecture to the operation of the vehicle, including regulatory, engineering development, and operational safety.

Systems safety starts with the planning process for functional safety, as defined by ISO 26262, and Safety of the Intended Functionality (SOTIF), as defined by ISO 21448.

Thorough planning ensures that every aspect of the safety life-cycle is fully supported. We engineer and rigorously verify to ensure that the SDS is capable of making safe driving decisions at all times. We subject our product to rigorous testing via simulation, resimulation (described in detail beginning on page 38), and closed-course testing. This ensures that the SDS is able to safely execute all driving behaviors, including detecting and responding to unexpected events.

We carry out tests at all levels of systems development. This includes vehicle-level testing, system and subsystem testing, hardware testing, and software unit and integration testing. Many tools are used to identify required tests and scenarios, but this all starts with our hazard analysis and threat identification.

HAZARD AND THREAT IDENTIFICATION

Hazard identification is a key starting point in the systems safety engineering process. Hazard Analysis and Risk Assessment is the approach used to identify hazards and ultimately define safety goals. We utilize an analysis known as Systems Theoretic Process Analysis (STPA) to identify functional insufficiencies and performance limitations in our design (for SOTIF). Our application of STPA identifies the causes of these hazards by reasoning about the vehicle's behavior with respect to a set of scenarios or maneuvers. One example scenario has the vehicle performing an unprotected left turn while reasoning about different stages of traffic-light transitions, various speeds of oncoming vehicles, and pedestrians crossing the road both inside and outside of crosswalks and at a range of speeds. Another key aspect of our SOTIF process includes identifying hazards that occur during fleet-testing operations, and adding those to the STPA-generated hazards and scenarios. Once the hazards are identified, we then design safety mechanisms to ensure that the SDS can safely handle all applicable situations, as well as test scenarios to verify that the safety mechanisms work.

We use a Threat and Risk Assessment strategy to carry out in-depth analysis of all of our assets and the threats they might encounter; we estimate the likelihood of those events and their potential impact; we identify the measures we could take to prevent them; and we then incorporate the results into our verification and validation planning.

SYSTEMS LEVEL SAFETY ACTIVITIES

When we analyze complete systems for potential faults, we use four primary analysis methods: Failure Mode and Effects Analysis, Fault Tree Analysis, STPA, and Dependent Failure Analysis. We also use various other analytical resources and methods such as trade studies, fleet analysis, data collection, literature reviews, empirical data analysis, and rapid prototyping, to help us systematically identify design failures and flaws early in our development lifecycle.

We carry out incremental updates of the systems architecture and requirements based on the results of our systems and safety analyses, subsystem and component analyses, and lower level hardware and software analyses. Through completion of the systems-engineering development phase, we can ensure we have everything we need to develop a system and safety architecture with a high level of integrity.

In addition to analyzing the system for failures and ensuring sufficient fault avoidance, detection, and handling, we analyze the system to ensure that it will mitigate hazardous scenarios even in the event of any system failures.

Using ISO 21448 (SOTIF), we apply STPA and other qualitative and quantitative safety approaches to perform risk assessments and identify design flaws, limitations, and insufficiencies in autonomous vehicle behavior. We systematically identify performance limitations, functional insufficiencies, unexpected behaviors, and ambiguous behaviors that can cause triggering events. We apply our tailored SOTIF process and methodology to provide contextually rich scenario sets. These not only test autonomous driving behavior in common scenarios, but also pressure-test how the SDS responds to other road actors not adhering to road rules and to rare scenarios, or “edge cases.” This includes data analysis to develop scenario-based structured tests and safety-acceptance criteria, to ensure the vehicle performs correctly under a range of conditions. These conditions include identifying objects and events that could affect the system’s ability to detect traffic lights, refining driving policies such as right-of-way assumptions, and developing specific defensive driving behaviors.

In addition, we identify previously unknown hazardous events through scenario-based testing, which helps to build confidence in the system’s safety and performance. We also make extensive use of fleet data to track occurrences of events in the real world, and to track the performance of the SDS against acceptable thresholds. And our SOTIF process ensures a feedback loop of events that occur both in testing and in the fleet.

We develop our SDS to ensure that all aspects of systems safety are considered.

SOFTWARE- AND HARDWARE-LEVEL SAFETY ACTIVITIES

To ensure the management of hazards and threats, we analyze software- and hardware-level safety activities using the four processes outlined previously (Failure Mode and Effects Analysis, Fault Tree Analysis, STPA, and Dependent Failure Analysis); we also assess hardware using Failure Modes and Effects and Diagnostics Analysis. We then update the software- and hardware-level architecture based on the results of all safety analyses. Utilizing these analyses ensures that when we complete the hardware- and software-engineering development phases, we have a full set of systems and safety requirements, test cases, and thorough safety architecture with a high level of integrity.

Additionally, the goal of these methods is to identify performance limitations, functional insufficiencies, unexpected behaviors, and ambiguous behaviors that can cause triggering events using our SOTIF process and methodology.

Ultimately, we work to establish traceability from top-level hazards to requirements, analysis, and verification and validation at all levels. When future changes occur, we will be able to complete an impact analysis to identify specific aspects of verification and validation that may be affected by the change.

Our systems-safety process also links into the manufacturing and operations processes. We ensure that safety-related checks are in place for end-of-line programming, end-of-line test, and vehicle release.

The Safety Case is progressively compiled through this systems-safety process as the safety argument continues to mature. Because it is a key milestone in development and release for production, the Argo Safety Case is assessed by various third parties, including partner companies.

Safety Architecture

The Argo self-driving system (SDS) is our core technology.

Simply put, the SDS is made up of systems, hardware, and software that allows a vehicle to operate autonomously, without the need for a driver, within a specific geographic area, and in appropriate weather conditions. When a vehicle equipped with our SDS is in autonomous mode, the SDS will have full responsibility for the task of driving, meeting the standards for a Level 4 automated driving system as defined by SAE International.

History is filled with often-tragic consequences of failing to focus on the safety-critical aspects of a system, so it is essential that we maintain a clear view of the safety critical elements of the SDS. Argo addresses this need by maintaining what we call the safety architecture of the system.

The Argo SDS safety architecture weaves together views of the system as a whole, as well as its hardware and software, to ensure we capture all safety-critical aspects of self driving. Our safety engineering practices work to understand how faults can occur, how they can be eliminated, and if not eliminated, then how they can be detected and managed to maintain safety throughout the operation and life of the self-driving vehicle. Our work also examines the boundaries of the safety-critical systems, to understand how best to isolate them from faults occurring outside the system itself. This latter work is directly related to our work on the physical security and cyber security of the self-driving vehicle.

UNDERSTANDING THE CONCEPT OF SAFETY ARCHITECTURE

The safety architecture can be thought of as having three views: the system view, the hardware view, and the software view. Each view helps us understand interactions within the elements visible from that view. These views are so important that we think of them as architectures themselves, leading to the conclusion that the safety architecture is the combination of the system safety architecture, the hardware safety architecture, and the software safety architecture.

The first is systems safety architecture, which is used to ensure that the design is sufficient and safe at a system level. Elements of the architecture at this level are assumed to be complex systems in and of themselves, likely containing both hardware and software components. As noted in the Systems Safety section, we apply FMEA and FTA techniques on the system to understand what can go wrong and how we can ensure that the SDS responds safely. This work includes accounting for adequate fail operational and fail functional mechanisms, and identifying common cause and cascading failures at the system level. Those mechanisms could be implemented in hardware, software, or both—the system analysis looks at the system as a whole.

The second element is hardware safety architecture, which uses hardware to minimize and mitigate safety-critical failures. This is achieved through various design methodologies, including designing hardware redundancy; eliminating or modifying hardware paths with high failure rates that could affect safety-critical functionality; and designing sufficient safety mechanisms and diagnostics mechanisms to detect and respond to safety-critical failures. We not only ensure robust hardware design and architecture, we also focus heavily on hardware diversity to reduce the probability of system failures. This requires the use of various hardware components and diverse suppliers for SDS components.

Software safety architecture encompasses many elements across several software abstraction layers. This includes autonomy software, embedded and infrastructure software, vehicle interface software, foundational operating systems software, and more. For example, we have identified a range of safety requirements on autonomy software which the software safety architecture must achieve. One such item is a requirement for diverse safety-critical detection pipelines, so that the failure of a single sensor does not entirely blind the SDS. Another is a requirement for independent software to monitor the different safety-critical components of the autonomy software to detect a range of malfunctions before they can cause harm. Additionally, we include safety requirements on embedded and infrastructure software such as various hardware and software monitors, safety-critical vehicle interface abstraction layers, and ensuring that operating systems for safety-critical functions are sufficient.

Safety architecture weaves together views of the system as a whole, as well as its hardware and software, to ensure we capture all safety-critical aspects of self driving.

SYSTEMS SAFETY ARCHITECTURE

The SDS is an integrated hardware and software system composed of custom-designed, multi-modal sensing technology, including high-resolution cameras, lidar, radar, microphones, and inertial sensors, as well as custom, power-efficient, high-density ruggedized computing hardware. The SDS computing hardware is composed of a primary computer system, known as the Autonomous Vehicle System (AVS), and a back-up system called the Complementary Autonomous Vehicle System (CAVS); together, they integrate into the automaker's autonomous vehicle platform (AVP), i.e. the vehicle, for Level 4 self-driving capability.

Systems safety architecture also encompasses the holistic design of the vehicle and integration of the SDS. For example, communication interfaces and power architecture are analyzed to protect against common-cause failures. We follow design best practices that recommend power lines and data transfer cables be kept physically separate from each other—not just between different vehicle functions, but also between the AVS and the CAVS components. This approach to design patterns is an essential aspect of our systems safety strategy that mitigates common cause and systematic failures.

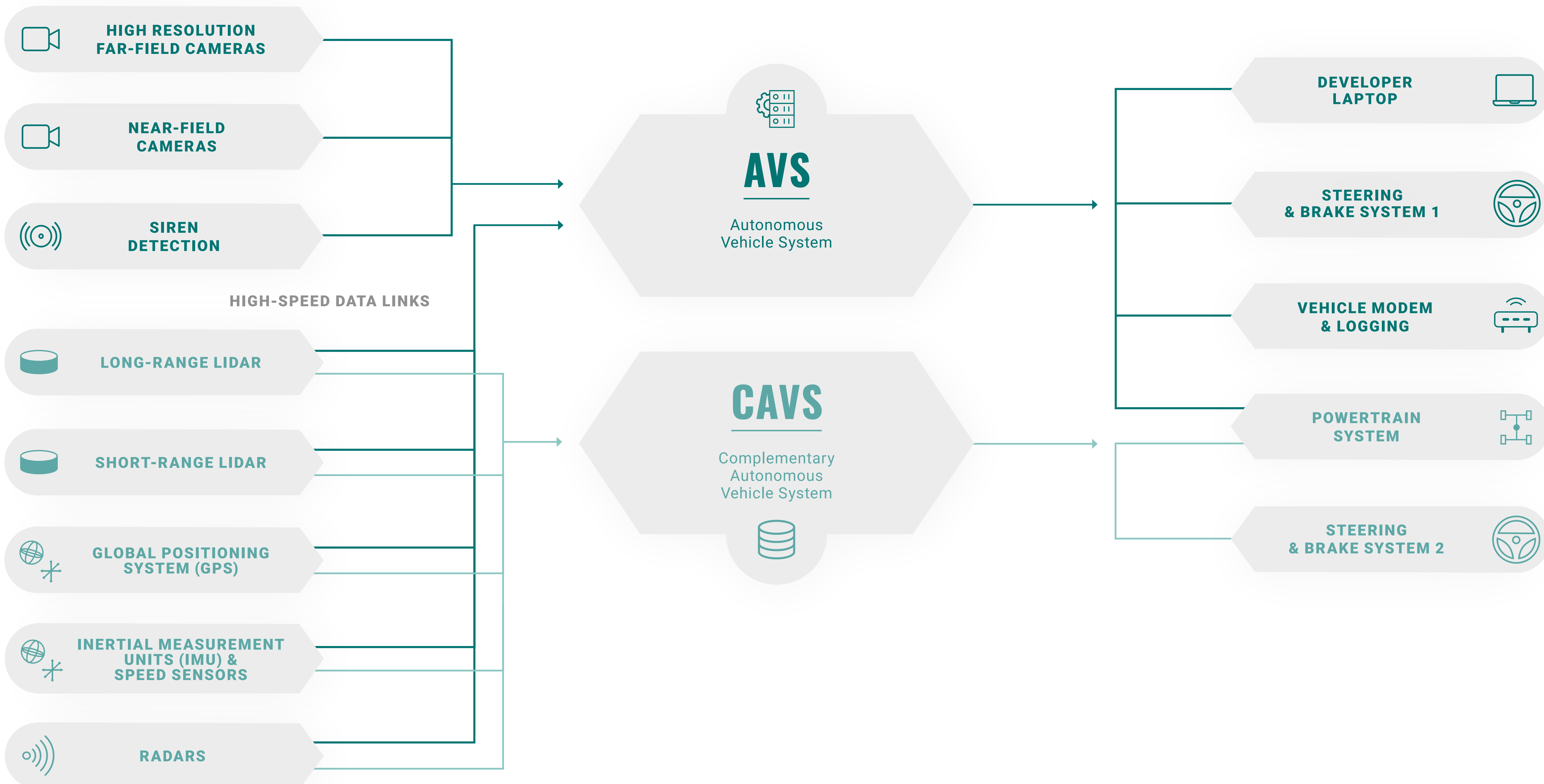
INDEPENDENCE AND SYSTEMATIC DIVERSITY

The Argo SDS safety architecture contains a number of elements added to increase independence and systematic design diversity. We build independence into our safety architecture to ensure that two or more systems that may perform the same function can continue to operate in the event that one of them fails. Systematic design diversity ensures that independent systems are unlikely to fail the same way at the same time.

These concepts arise most obviously when we study the architecture of the entire self-driving vehicle, which contains two main subsystems: the SDS and the AVP. Although Argo is solely

We work closely with each of our automaker partners to integrate our self-driving system (SDS) into their vehicle, which is referred to as the Autonomous Vehicle Platform (AVP). The Ford Escape Hybrid is being phased into our U.S. test fleet in 2021 to replace the Fusion Hybrid sedan. Later in the year, the first test vehicle with Volkswagen Commercial Vehicles based on the upcoming ID.Buzz will begin testing in Munich, Germany.

THE ARGO SELF-DRIVING SYSTEM ARCHITECTURE



and entirely responsible for the SDS, and our automaker partners are solely and entirely responsible for the AVP, different types of failures in the SDS or the AVP can be mitigated only through design elements that impact the other. We work closely with our automaker partners to ensure safety through the whole vehicle.

For example, as discussed elsewhere in this report, both the AVS and the CAVS are independently capable of operating the self-driving vehicle, and are both in the SDS architecture for the unlikely event that either subsystem fails. To prevent a failure in a common power supply causing both the AVS and the CAVS to fail, each runs on a separate source of power.

Within the SDS itself, a crucial aspect of our safety-design architecture is the independent systems and diversity designed into the AVS and the CAVS. This design ensures that the AVS and the CAVS have direct access to enough sensors, power sources, and communications channels that each is independently able to safely control the self-driving vehicle even if the other system fails entirely. The two systems work seamlessly together, but utilize diverse software approaches, different hardware components and processors, and serve fundamentally different purposes.

THE SENSING SYSTEM

The SDS contains a number of different sensors and sensor types to detect objects all around the vehicle. At least two sensor types observe all areas around the vehicle. In safety engineering terms, this sensing architecture provides the properties of independence (more than one observing the same area) and systematic diversity (different types of sensors all detecting objects but in different ways).

These independent and systematically diverse operating modes are vital for handling the rare but not impossible occurrence of a sensor failure. Even more important, though, is a different type of “failure,” namely when the environment gets more complex. Even when the system is operating normally, dust, rain, and even just entering or exiting a dark tunnel on a bright sunny day can be enough to degrade the performance of any sensor type. The use of systemically different sensors types, such as lidar and radar, enables the vehicle to continue driving safely and consistently even when the performance of the vehicle’s cameras is limited.

Finally, sensing systems must be able to operate in poor weather conditions. In wet weather, water and dirt from the road can soil the sensors, degrading their performance and potentially entirely blocking their view. Addressing this type of failure requires the addition of independent vehicle systems designed to prevent the dirt and water from reaching the sensor, clean the sensor, detect the need to clean, and detect any failure to clean.

With our automaker partners, we are engineering all of these capabilities into our self-driving vehicles.

THE PRIMARY COMPUTER SYSTEM: AVS

Constantly scanning 360-degrees around the vehicle as part of its driving task, the autonomous vehicle system (AVS) is fully capable of detecting objects in and around its path and planning an appropriate vehicle response on the move at full capability. The AVS is designed to control the vehicle in a safe manner under both common and rare scenarios, including handling road users who are not adhering to road rules. To help avoid and mitigate potential collision, the SDS is equipped with emergency maneuvering functionality. This helps it select the best possible response even in adverse situations, for example proactively performing defensive driving behaviors, changing lanes, veering, and emergency braking, as needed.

The AVS hardware performs the functions designated by the self-driving software, which include functions such as sensor-data acquisition and processing, detection, tracking, and prediction; localization and mapping; motion planning and control; interacting with Remote Guidance Operators (which we detail on page 34); and diagnostics, logging, and other infrastructure tasks. The AVS is also responsible for safely and correctly communicating with the AVP.

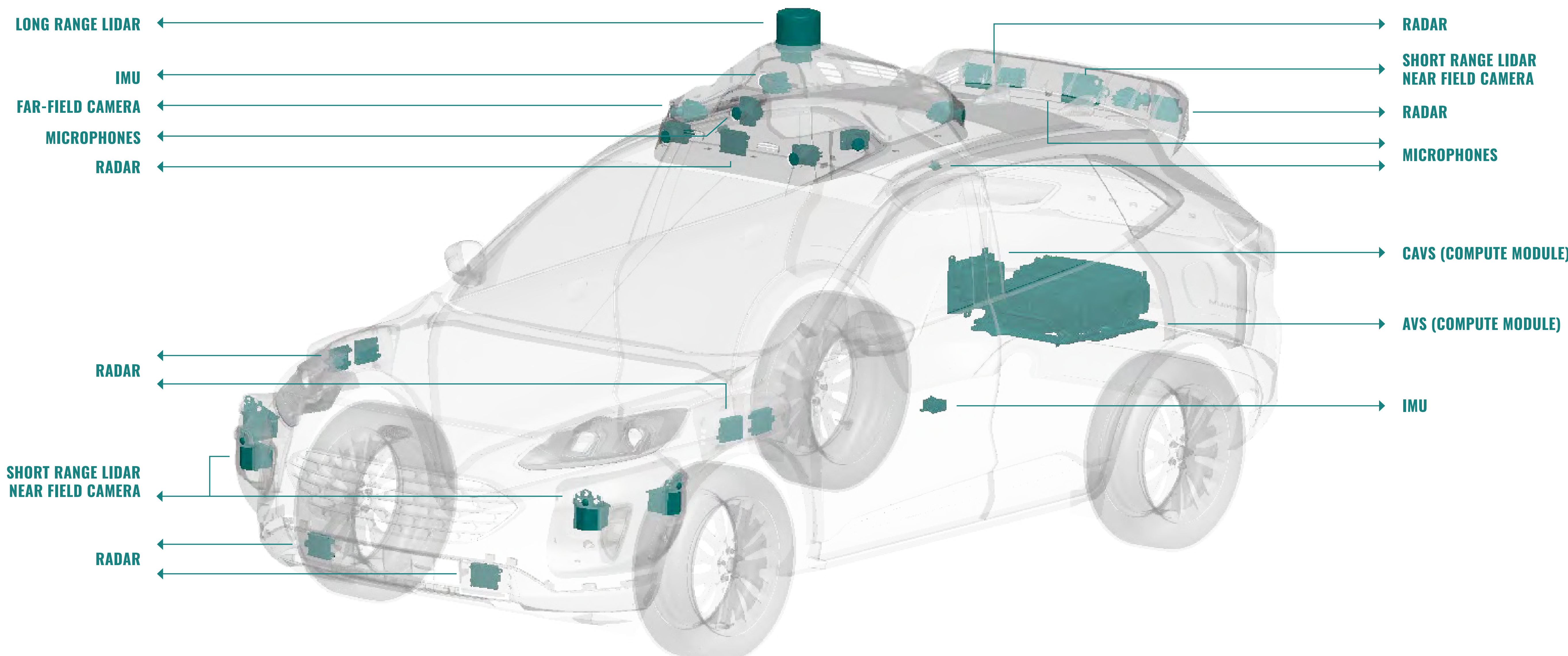
THE BACK-UP COMPUTER SYSTEM: CAVS

Our complementary autonomous vehicle system (CAVS) runs in parallel with the AVS. A robust, purpose-built backup system, the CAVS is designed to take over control of the self-driving vehicle in the event that the AVS enters a degraded state or stops communicating, and to ensure that the vehicle brakes with maximum force if a collision is imminent.

The AVS is fully equipped with emergency maneuver functionality and capability, and contains internal hardware and software to tolerate many types of failures while continuing to operate safely. If environmental, electrical, or mechanical issues interrupt the operation of the AVS, the CAVS is there to intervene. In these rare situations, the CAVS is designed to execute a fallback maneuver to bring the vehicle safely to a stop.

The CAVS provides an additional layer of protection as well. If the AVS is unable to avoid a potential impact, the CAVS will intervene and apply the brakes to mitigate a potential collision. This functionality does not replace that of the primary computer, the AVS—rather, it is supplementary. The AVS performs an emergency maneuver as required; the CAVS provides a secondary layer of safety and utilizes different hardware components from the AVS, including processors. Additionally, the CAVS uses different autonomy algorithms and perception software than the AVS—all to mitigate potential systematic failures, and to ensure maximum brake force is employed to mitigate the energy of an imminent collision.

ARGO SDS-EQUIPPED FORD ESCAPE HYBRID TEST VEHICLE



Operational Design Domain (ODD)

Operational Design Domain

Domain Constraints

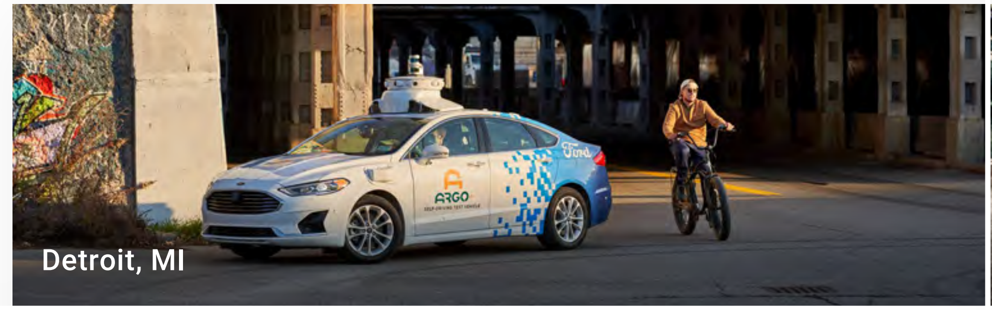
In self-driving, as in the field of intelligence, there are known knowns and known unknowns.

Examples of the former are conditions that are controllable, or avoidable, by design, such as what roads to drive on. Among the latter are unavoidable conditions, such as a car ahead slamming on its brakes, or a pedestrian stepping into the road in an unusual location. Capturing all of this known and unknown information in a structured way is important to ensure the SDS is prepared to safely handle anything it might encounter. This section looks at how all of this information is captured.

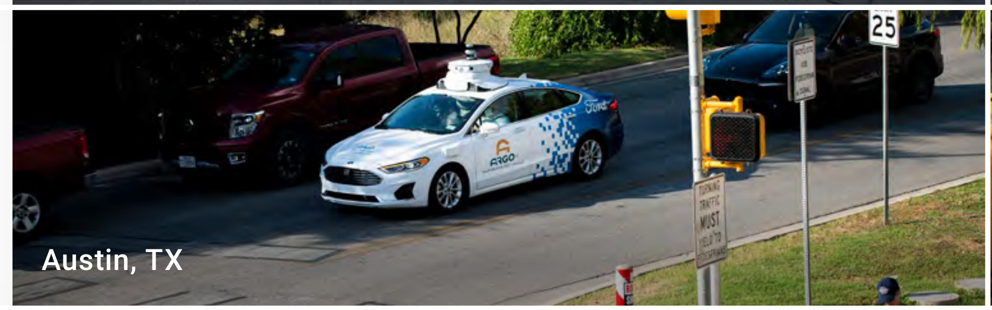
An operational design domain (ODD) describes the geographic, environmental, and technical parameters that define the operating range of a self-driving system (SDS). In our ODD development, we support and review the best-practice guidelines for defining an ODD as published by the Automated Vehicle Safety Consortium.

We use the ODD concept in two ways: to set product goals, and to characterize the capabilities of our system as it evolves. To create the goals, we construct a desired ODD by identifying a specific set of roads and other technical and environmental parameters we want our SDS to handle. These include, but are not limited to:

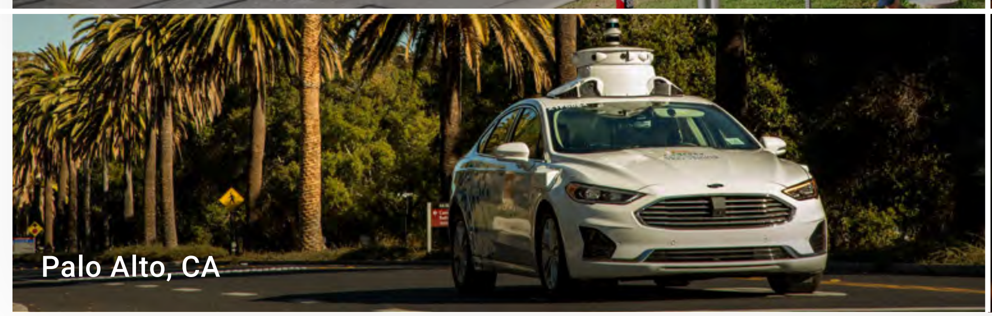
- Ambient operating temperatures for the sensors and compute system
- Maximum levels of precipitation across a variety of precipitation types
- Maximum road grade and curvature
- Specific lane and road geometry
- Daytime and nighttime driving

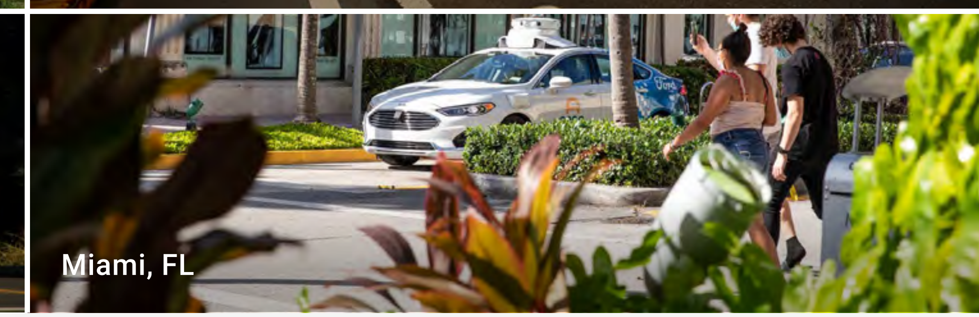

Detroit, MI


Washington, D.C.


Austin, TX


Pittsburgh, PA


Palo Alto, CA


Miami, FL

To evaluate our progress, we construct and run simulation and physical tests that isolate different challenges of operating within our target ODD, and analyze the results. The gap between the two drives our development efforts.

Consider a simple example of structured testing within an ODD. A team may set out to develop an SDS capable of driving at 60 mph on roads with downhill grades of 10%. To achieve this goal, the SDS must see far enough ahead on the downhill slope to detect moving road users or static obstructions in the roadway, and to have time to safely avoid collisions with any of the above. To measure progress toward this goal, we construct simulation and physical tests that reconstruct the ODD—i.e., we test on a closed course at grades of 10% with static objects blocking the road. We then run tests at increasing vehicle speeds to identify when the vehicle is no longer able to consistently avoid the objects. If the vehicle achieves only 55 mph, then we can say that the actual achieved self-driving ODD speed limit is 55 mph, while the development team continues to work to achieve the goal of 60 mph in those same conditions.

For each generation of our test vehicles and eventual production self-driving system, Argo uses key dimensions of the ODD to drive sensor selection, compute hardware, and software algorithms. For example, back in 2017, our first generation SDS sought to drive at 25 mph around a specific set of streets in the Pittsburgh and Detroit metropolitan areas. As we achieved each capability, we set new goals for each succeeding generation, incrementally increasing the top speeds that we could safely drive and broadening the set of streets in which we could test.

Defining the ODD involves capturing the complexity of the driving environment, since no two streets are ever the same and driving on a busy city boulevard is quite unlike driving on a quiet suburban road. Differences in the lane widths, presence of parked cars, frequency of pedestrian and cyclist traffic, aggressiveness of driving, and social norms of interacting with other vehicles are often dramatically different.

We are developing our SDS to tackle a vast range of conditions, not only within the relative calm of suburban streets, but also within complex and sometimes chaotic traffic-jammed urban cores in major cities like Miami, Austin, and Washington, D.C. We use this complexity and variety to ensure we have 360-degree awareness both at long and short distances, anticipating a broad range of behaviors from pedestrians, cyclists, and other road users. Testing in multiple, complex cities at the same time allows us to go beyond verifying conditions that we've planned for: it also validates that the system works in the real world, day and night, rain or shine.

For commercial deployment, the vehicle will operate within a "geonet" of specific streets and turns defined according to topographical features and maximum speed limits. Over time, that geonet will be broadened geographically and technically to expand operations. Within the geonet, our SDS will be able to operate in a variety of special circumstances, including school and construction zones, and areas where there may be temporarily altered circumstances, such as active emergency responders.

The SDS includes a number of features to prevent operation beyond the ODD. For one, it is prevented from encountering new territory; the SDS will only drive on the map, which encodes the authorized geonet. As another example, the SDS monitors rainfall, and will safely stop the vehicle if rainfall becomes too heavy.

DOMAIN ABILITIES

ATTRIBUTE	CAPABILITY
Road Speed	Operation on roadways with posted speed limits of up to 65 mph.
Road Types	Operation on: • Freeways/highways • City streets • Suburban/rural roads • Parking lots/garages
Lighting & Hours	Operation 24 hours/day in all seasons and lighting conditions.
Weather	Operation in: • Rain

DOMAIN CONSTRAINTS

The following road types are not initially in scope:

- Off-road

The following weather conditions are not initially in scope:

- Snow
- Freezing rain/sleet
- Hail
- Dense fog
- Extreme environmental conditions (including, but not limited to, hurricanes, earthquakes, landslides, etc.)

Why We Test in Multiple Cities

Testing in multiple cities ensures a richness of interactions, and a diversity of complexity that makes the system smarter and safer. This gives the SDS the experience and understanding of city-specific regulations and behaviors that it needs for "naturalistic driving"—that is, the ability to drive like a local. With operations in six U.S. cities, and European testing due to start in 2021, we're driving on thousands of miles of undirected roads, and expanding our map every month. Indeed, our urban testing footprint may be the largest, most diverse active urban-testing footprint of any self-driving vehicle developer. If the initial selection of cities is done well, then each additional city will be similar to where our cars have already operated. For example, when we began testing operations in our sixth location, Austin, in 2019, we were up and running in autonomous mode within a few weeks of having test vehicles on the ground.

A self-driving vehicle that operates safely for many miles on the same roads but never encounters a cyclist weaving through traffic, or a pedestrian walking outside of a crosswalk may make poor decisions when confronted with these difficult interactions. Plus, each new city has its own unique culture, topography, climate, traffic patterns, and driving behaviors.

Our test cities provide a broad array of challenges that are representative of what might be encountered in cities around the world:

- Pittsburgh has its share of hills, narrow streets, bridges, and five-way or other quirky intersections.
- Detroit features wide lanes and boulevards, shared center-turn lanes, as well as four-season weather.
- Palo Alto sees a wide variety of walkers, runners, and cyclists, including those traveling in groups.
- Miami is jammed with the full spectrum of actors: pedestrians, bikes, mopeds, scooters, rollerbladers, hoverboards, cars, buses, and trucks.
- Austin's streets include a variety of manually- and and motor-driven scooters, which are used by riders of widely varying skill levels.
- Washington, D.C has heavy traffic and some of the most complex traffic-control measures found anywhere — including roundabouts.

Safe Operation

Self-driving capability requires the self-driving system (SDS) to be able to detect and track objects, recognize situations, anticipate how other actors will behave, and decide what to do next.

This section describes how the SDS handles normal operations and exceptions, and cases with clear expectations as well as others with more ambiguity; it also addresses how the system detects and responds to failures severe enough to require the execution of special maneuvers to achieve a condition with minimal risk.

HOW OUR SDS WORKS

To understand the full range of SDS operation in all situations, it is important to step back to see all the elements that work together to keep the self-driving vehicle in operation. Argo is focused on developing an SDS for fleets of vehicles that are deployed each day without drivers or any type of operator or monitor in the vehicle. This context helps explain the four main elements of this ecosystem: maps that define and bound the roads on which the SDS can navigate; the self-driving vehicle itself; personnel to remotely assist the SDS when it requests help to understand how to proceed; and fleet-management personnel to deploy and maintain the vehicles.

A Day in the Life of an Argo Autonomous Vehicle

Once we reach commercial readiness, this is how we envisage a typical day (or shift) in the life of one of our self-driving vehicles:

- Before the vehicle leaves the terminal, it is cleaned and prepared in maintenance mode, and the SDS is loaded with the latest software and map. The team then puts the self-driving vehicle into autonomous mode.
- Once in autonomous mode, the SDS uses its sensors (lidar, cameras, and radar) to see around the vehicle, and to determine where it is. This step is called localization. No vehicle leaves the terminal until it clearly knows its own location to within centimeters of accuracy.
- Once localized, the vehicle takes on assignments throughout the day, using the map and its full sensor suite, including inertial sensors and even the vehicle's wheel-motion sensors, as it travels around. Whether moving people or goods, all assignments require safe driving.
- At the same time, the SDS looks around for objects on or near the road as well as traffic controls such as stop signs and traffic lights. It tracks objects and predicts what they will do next, and anticipates the possibility of hidden objects appearing from behind occlusions caused by buildings and other vehicles, or objects on or near the road. This gives the SDS full 360-degree awareness of its environment.
- With a thorough understanding of its environment, the SDS determines the best actions it can take to maintain safety and make progress to its destination. A part of this planning is ensuring that it stops correctly at stop signs; takes its turn fairly at four-way stops; stops for red lights or at traffic lights that have lost power; yields appropriately for unprotected turns when other vehicles should have the right of way; and yields for pedestrians and cyclists who often have priority at different road crossings.
- At any point along its way, if the SDS requires help about how best to proceed, it will contact the Remote Guidance team for assistance. Until that team has clarified the situation, the SDS will keep the vehicle in a safe state, gently slowing and even stopping if necessary.
- All along, the SDS constantly monitors its critical resources; when it requires more fuel, or its battery needs charging, the SDS will stop taking further assignments and return to the terminal. It will also notify the fleet management team that it is returning, so that technicians can be prepared for its arrival.
- Once it returns to the terminal, the fleet management team puts the vehicle into maintenance mode. The day (or shift) is done, and this entire top-to-bottom process is ready to repeat.

MAPS: THE FOUNDATION OF DRIVING AWARENESS

When a person drives, they are almost always more comfortable when they're somewhere they've driven before: they know what to expect. Without that prior experience, the road ahead could be radically different from anything they have experienced before. These observations are analogous to the benefits of using a map in a self-driving vehicle: to gain all the benefits of "been there, done that." Our SDS goes further: It will not venture into any location of which it has no prior knowledge.

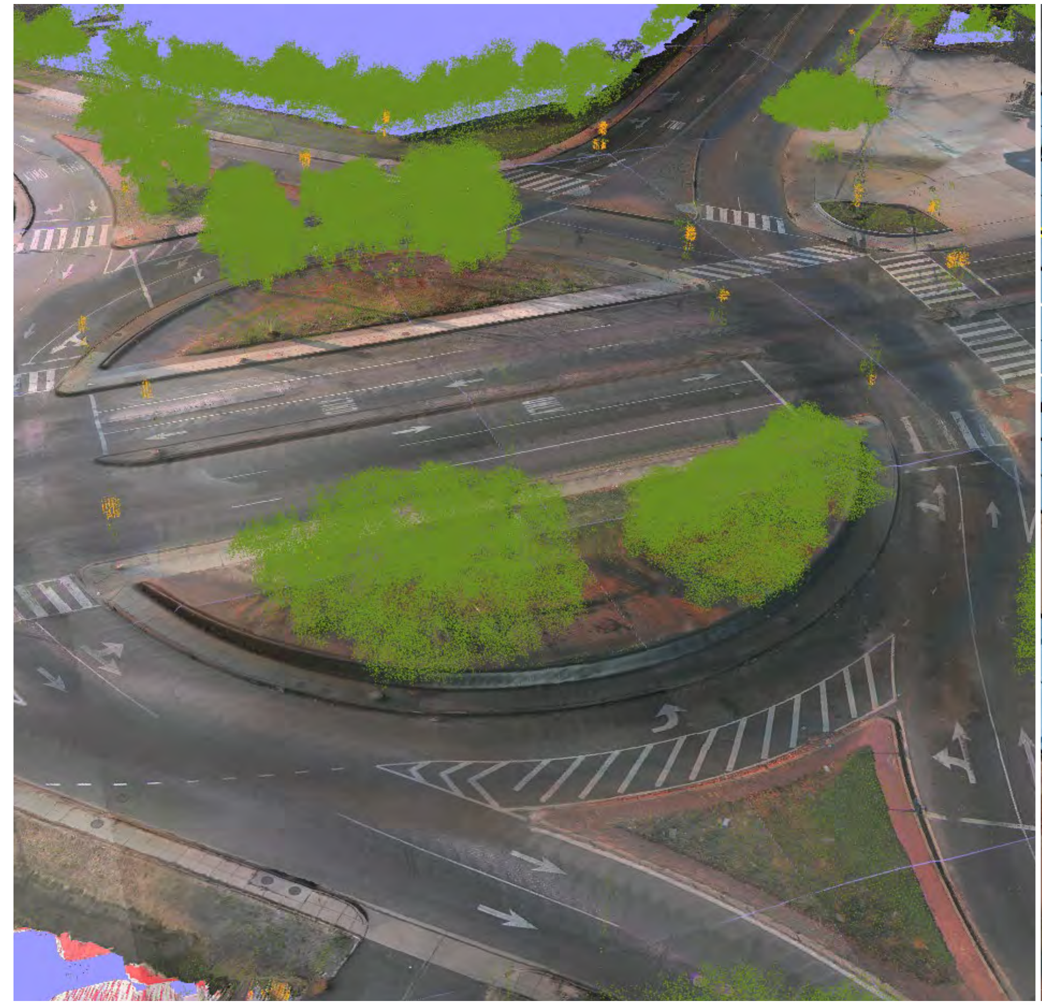
Our SDS uses maps to aid localization, perception, prediction, and motion planning decisions. The high-definition 3D maps we develop are purpose-built for our SDS. While traditional maps are designed only to help humans navigate from point A to point B, Argo's maps do much more, and include a far more granular level of detail than just roads and turns. Because the system maps the world in great detail, it provides rich information to our SDS to enable good decision-making informed not just by what the system sees, but also by the prior knowledge encoded in the map.

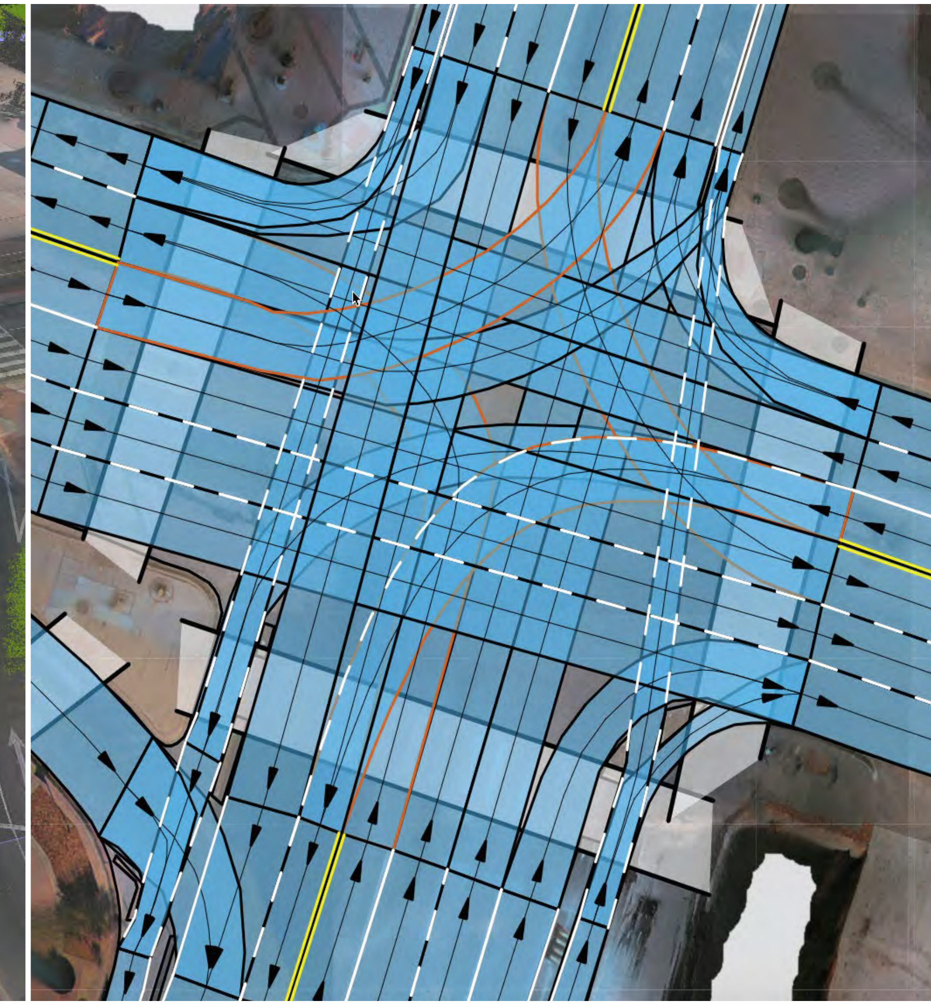
The map itself contains a variety of information. To support localization, the map contains a 3D model derived from the same lidar, cameras, and radar that are part of the SDS. This model is compactly stored yet also highly accurate, containing a rich representation of the entire road network, including the junctions, turns, intersections, and other road features that can impact driving, such as lane segments, street signs, crosswalks, rights of way, and traffic lights that control each lane. As noted previously, all map information is loaded onto the vehicle, rather than streaming over the air.

Our approach to mapping represents a street-by-street process designed to ensure the accuracy of this fundamental information. Creating our own maps gives us the flexibility to quickly make changes as the operational environment changes, such as the introduction of temporary construction projects or new permanent road layouts. New traffic signals and signs can be installed or removed; lanes, pedestrian crossings, and stop lines can change when roads are re-striped; and new barriers and bollards can be installed. For these and other reasons, our SDS only treats maps as an aid, and checks whether the real world matches its expectations. When those expectations are not met, the SDS either adapts to the new reality or takes a safe action, such as slowing to a stop or pulling over, and requests help from Remote Guidance. In this way, the SDS stays safe regardless of recent real-world changes.

OBJECT AND EVENT DETECTION AND RESPONSE (OEDR)

The primary objective of the SDS is to drive safely to move people and goods. To do this, the SDS must always be aware of its environment, from the vehicle, pedestrian, and cyclist traffic sharing the road, to those nearby who might enter the road. The SDS is designed to respond to all road users, from the very well behaved to those who are distracted, drowsy, or, for whatever reason, are no longer adhering to legal and social etiquette of safely sharing the road. It must also reason about its own motion, complying with all traffic laws, yielding the right of way appropriately, and anticipating and avoiding both normal as well as reasonably foreseeable and avoidable deviations from road rules and etiquette by others.





The SDS has prior knowledge of the areas where we test based on highly detailed maps we first build, including such features as ground surface imagery (left) showing a 3D representation of a complex traffic “roundabout,” and vector mapping (right) showing the direction of each lane of traffic at a major intersection.

We have already discussed how we accomplish these goals with the basic architecture of our SDS, seeing the world through multiple types of overlapping sensors, as well as designing and incorporating redundant AVS and CAVS compute systems. We now look more closely at the software within these systems and how they accomplish the driving function, i.e., how our system performs object and event detection and response. We decompose the problem into three parts:

- Perception: the process of using sensor data to understand what is happening around the vehicle, and tracking that behavior over time.
- Prediction: the process of anticipating what could happen next, and how the vehicle's own actions might alter the behavior of others.
- Motion Planning and Controls: the process of selecting actions for the vehicle to take next, both to preserve safety and to make progress toward its next destination.

PERCEPTION

The perception system's job is to process sensor data to generate a comprehensive situation report for the prediction and planning systems. Perception must detect, track, and classify everything in the scene. Of course, the world is highly complex, and no perception system will ever recognize everything it sees. In those situations, the perception system must still detect it, track it, and report that its class is unknown. If the SDS observes a three-headed monster (on Halloween, for example), it may not know what it is, but the perception system can still report that it sees an unknown object at a particular position and moving at a particular speed in a particular direction. More formally, this is known as an open-world problem, and Argo's perception system is prepared to handle that world.

The perception system detects and tracks different classes of vehicles, from small to very large, those with four wheels and a fixed body as well as those with many wheels and articulated bodies, such as a Class 8 tractor-trailer or a "bendy bus." It detects and tracks lights and various signals (e.g. turn signals, brake lights) from those vehicles. It detects a variety of cyclists, motorbikes and mopeds, along with pedestrians, animals, strollers, and more. It perceives specialized vehicles such as school buses and emergency vehicles, including when they are active with signs, lights, or sirens. It detects a variety of construction equipment—cones, barriers, bollards, fences, jersey barriers, etc.— that are frequently found on roads, as well as several specialized workers (e.g. construction and road-maintenance crew). The perception system even reasons about different types of vegetation found alongside the road.

To perform all of these functions, the perception system processes all the sensor data. For example, several cameras are able to observe traffic lights. The perception system processes the video looking where the map reports a traffic light should be, and looks for the structure of the signal—from simple three-bulb signals with red, yellow, and green lights, to complex signals that add multiple arrows and may also blink to communicate the presence of pedestrians. The SDS also actively looks for the addition of temporary traffic lights, as are commonly used in special construction zones. Multiple cameras observe traffic lights as the vehicle approaches an intersection, and so the perception system can operate even with the loss of one camera's video (due to anything from power loss, to camera failure, to mud on the lens).

For object detection and tracking, the perception system again uses multiple sensors, not only cameras, but also radar and lidar. All of these sensors overlap, so the perception system actually runs several different types of detection, generating a more accurate and stable report of what it sees. In more technical terms, we say that our perception system uses multiple independent perception pipelines (sensors and their coupled algorithms) because any single algorithmic approach may have a failure mode.

By using independent sensing-algorithm pipelines, we gain diversity and redundancy. When driving in low lighting conditions, cameras are not as effective as lidar, and therefore lidar pipelines are able to compensate. At longer distances, the laser beams received back from reflection off an object are not as dense as at shorter distances, yet the additional data from radar and cameras adds to that of the lidar for an effective result. Very small objects, which are harder for lidar to detect, and may be unrecognized in a monocular camera system, can be detected by high resolution stereo—a perception process that uses two or more cameras to build 3D models. Together, these diverse perception pipelines are fused intelligently to provide a coherent, accurate model of the world around the autonomous vehicle.

PREDICTION

The job of the prediction system is to forecast what other actors on the road may do. Additionally, the system makes predictions based on the anticipated interaction of actors with the self-driving vehicle. For example, if the vehicle demonstrates a yielding intent by slowing down, then the prediction system will use this information to anticipate that another actor will soon take the right-of-way, either moving when it was stationary or accelerating again if it had begun to slow down.

The SDS must always be aware of its environment, from the vehicle, pedestrian, and cyclist traffic sharing the road, to those nearby who might enter the road.

The SDS is designed to respond to all relevant road users, from the very well behaved to those who are distracted, drowsy, or, for whatever reason, are no longer adhering to legal and social etiquette of safely sharing the road.

In the course of everyday driving, human drivers learn to adapt to a variety of road users, from those that follow the rules—so-called compliant actors— to others who deviate from the rules of the road—so-called non-compliant actors. For example, some drivers do not come to a complete and full stop at stop signs, but only slow down and "roll" through the intersection when they believe it is their turn to go; and some pedestrians cross outside designated crosswalks or even when the "Don't Walk" sign is showing. The prediction system must account for this range of behaviors, and recalculate over time as it gathers more information about which behavior is most likely to occur. In any case of non-compliance, the SDS must find a way to go with the flow, avoid harsh and erratic behavior, and ultimately achieve naturalistic driving. The Argo SDS achieves its naturalistic driving skill in large part because of the power of its prediction system.

While many road users are mildly non-compliant, some go much further, demonstrating aggressive non-compliant driving behavior, including speeding, tailgating, running red lights, making illegal U-turns, failing to slow through a stop sign, and failing to yield when turning across traffic. The Argo prediction system predicts all manner of non-compliant behavior and is trained on large datasets collected from across multiple cities to capture the likelihoods and indicators for when this behavior is likely to happen. By anticipating aggressive maneuvers through diligent and thorough analysis, data collection, and training, the SDS has the ability to avoid extreme situations.

Finally, as with perception, prediction is an open-world problem. Actors may behave in highly unexpected ways that the SDS has never before experienced. The SDS identifies actors displaying surprising or unpredictable behavior, enabling the motion planning system to add further "margin" for these actors. Margin can mean a number of things, including slowing down or moving over to maintain additional distance.

MOTION PLANNING AND CONTROL

Making safe yet confident and assertive decisions is the key to naturalistic driving. The SDS achieves this type of driving through the actions of the motion planning and control (MPC) system, which leverages predictions coupled with mapping information to make decisions in the context of the local situation. This requires the MPC system to consider the possibilities for how other actors might react, as well as complex assessments such as whether the vehicle will block the intersection and create gridlock, or proceed like a local driver would do to prevent being forever stuck.

The MPC system starts by reasoning about other actors and the relationships between the self-driving vehicle and those actors. If the MPC system wants to change lanes, or enter an intersection, it assesses the position, speed, and likely path of other vehicles on the road, identifies its options, and assesses different actions to be sure it understands how "aggressive" each might be toward other road users—not to mention how this might affect the ride quality for any occupants in the vehicle. Each time the MPC system goes through the planning cycle, it needs to arrive at one final decision.

Each of these decisions is carefully validated to ensure consistency with local driving rules and social norms, such as the differing rules from one state to another on interactions with pedestrians in a crosswalk, or how a vehicle should behave at a red light if it intends to turn right, particularly if there is a bike lane. Whether in California, where a car may occupy the bike lane when turning right on red, or in Pennsylvania, where the same right-turning car must remain in the vehicle lane, the SDS ensures that it follows the rules in the jurisdiction in which it operates.

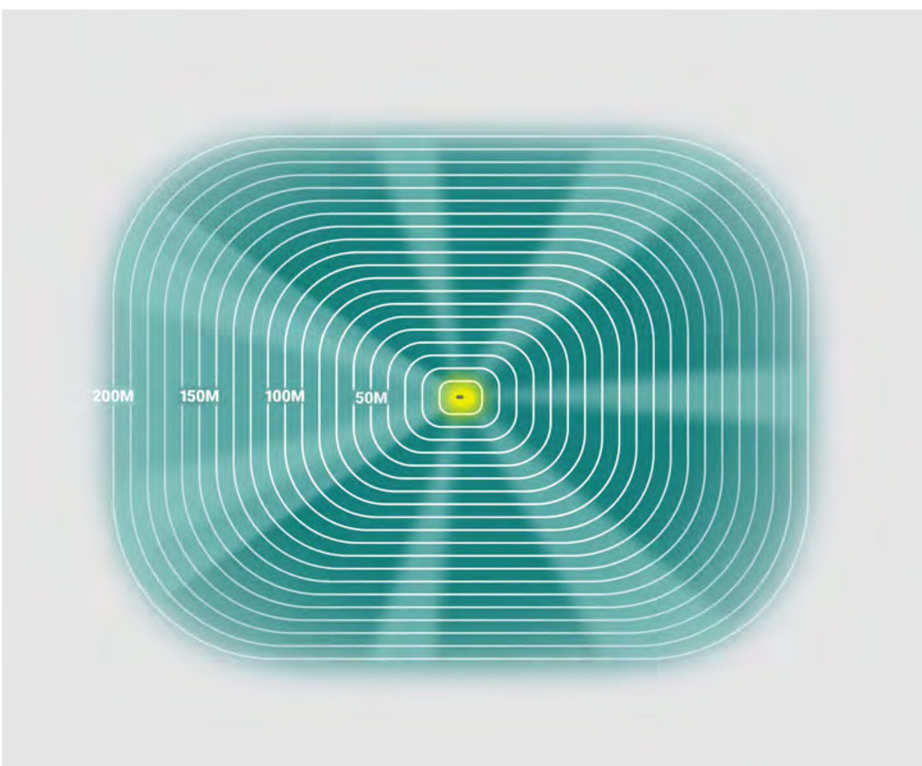
Fundamentally, our SDS makes decisions by selecting driving actions that are verifiably safe given the predictions of other road actors and the rules defined by the traffic control measures in effect.

Multimodal and Redundant Sensor Coverage

The Argo self-driving system (SDS) incorporates multimodal sensing—including lidar, camera and radar—that deliver 360-degrees of overlapping perception capability. This level of redundancy ensures that at least two sensor types are monitoring all the way around the vehicle at a minimum of 200m of range - with some sensors achieving more than 300m.

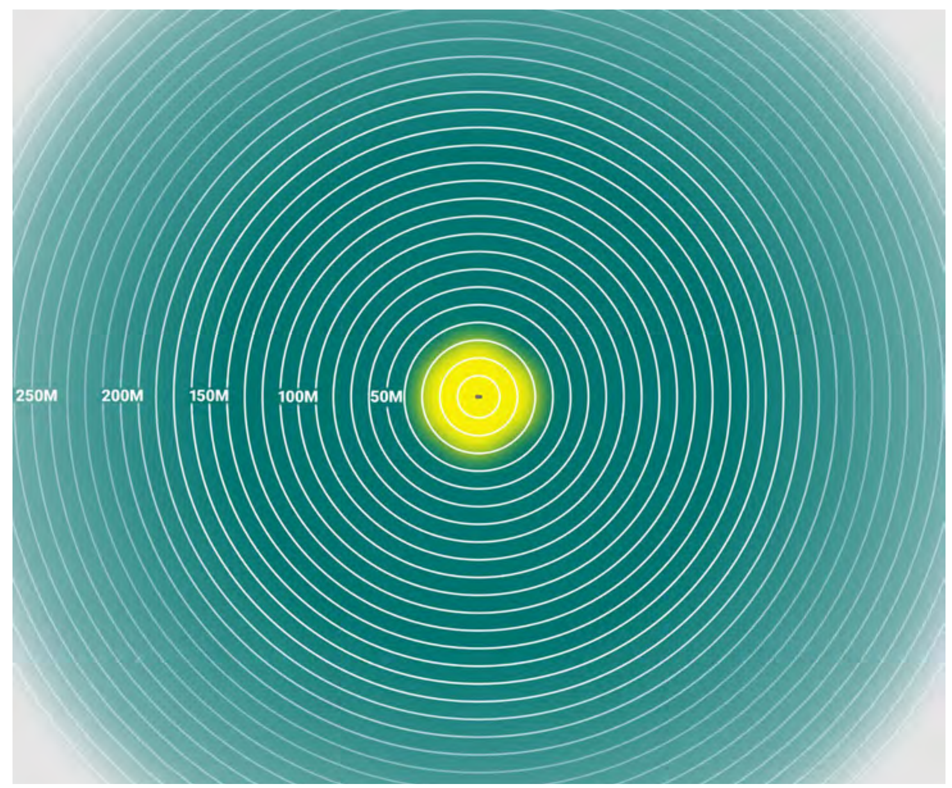
This arrangement anticipates and mitigates the potential of sensor failure, due to the independence and diversity of the perception system - i.e. more than one type of sensor observes the same area, and each detecting in a different way.

← Vehicle Direction



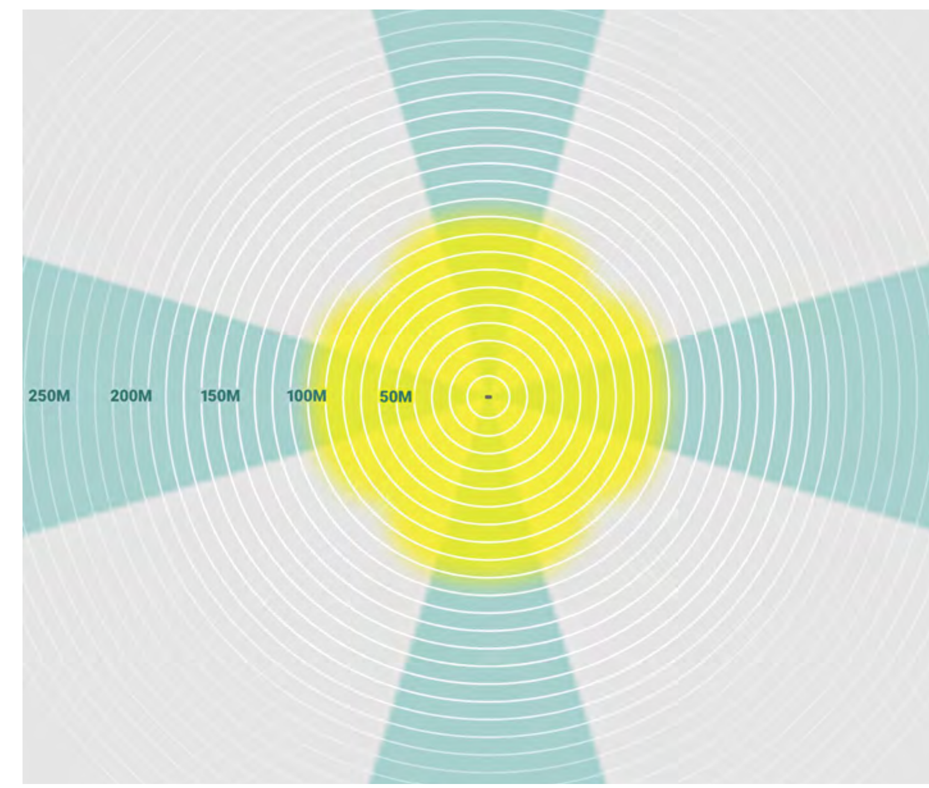
CAMERA COVERAGE - GROUND PLANE

- Near Field Cameras
- Far Field Cameras
- Vehicle



LIDAR COVERAGE - GROUND PLANE

- Short Range
- Mid Range & Long Range
- Vehicle



RADAR COVERAGE

- Mid Range
- Long Range
- Vehicle

ARGO'S COLLABORATIVE MOBILITY PRINCIPLES

Protecting vulnerable road users (VRUs)

According to NHTSA, pedestrians and cyclists accounted for nearly 20 percent of road fatalities in the United States in 2019. Knowing that our vehicles share the road with a wide variety of vulnerable road users (VRUs) including pedestrians and cyclists, as well as people using motorcycles, scooters, strollers, or wheelchairs, we are compelled to do everything we can to share the road safely.

Cyclists are particularly vulnerable. They share the road with cars, often at speed, but they lack not only the weight and presence of automobiles, but also vehicle safety equipment such as seat belts and airbags. Our SDS will behave consistently and predictably around cyclists in any situation, but it also accounts for unpredictable situations, such as a cyclist swerving suddenly to avoid danger.

To prioritize safe interactions between our technology and cyclists and other VRUs, we have defined a set of clear principles to guide our development and operations. These guidelines have evolved through ongoing dialogue with cyclists within our company and external cycling advocacy organizations. This collaborative approach has helped to inform how we behave around bicycles, such as setting and maintaining a conservative following distance from cyclists at all times and establishing a rule that we won't pass a cyclist in the same lane.

Self-driving vehicles **SHOULD ENABLE SAFER STREETS FOR EVERYONE,** including cyclists and pedestrians, not just those utilizing a vehicle.

Self-driving vehicles **SHOULD AUGMENT EXISTING PERSONAL, PRIVATE, AND PUBLIC TRANSPORTATION OPTIONS,** including cycling and bike sharing, to empower mobility choice and equity.

Self-driving technology and service providers **SHOULD ENCOURAGE THE CREATION OF CYCLING INFRASTRUCTURE** and dedicated bicycle lanes where feasible throughout cities.

In addition to following all applicable local traffic laws, self-driving technology and service providers **SHOULD AID MUTUAL SAFETY** by maintaining safe lateral and following distances.

Self-driving technology **SHOULD ANTICIPATE COMMON CYCLIST BEHAVIORS,** such as yielding at stop signs or treating red lights as stop signs, as well as recognize and respect rights-of-way for bicycle lanes and related cycling infrastructure.

Self-driving technology and service providers **SHOULD CONTRIBUTE TO AN ENVIRONMENT OF COLLABORATION, ENGAGEMENT, AND EDUCATION** within the communities in which they operate, including, but not limited to, providing education about how self-driving vehicle systems work and related safety procedures, as well as soliciting feedback from community members.

CLARIFYING AMBIGUOUS BEHAVIORS

The more time it spends on the road, the greater the inevitability that a vehicle will encounter "ambiguous" situations. Consider, for example, approaching a stalled vehicle obstructing the lane ahead. In such a situation, a human driver may slow down or even stop as they take a few moments to assess whether the car has stalled, or just stopped briefly. If a human driver deems it to be safe, they will temporarily cross over a centerline when traffic conditions and space in front of the vehicle allow, and then safely return to their lane. Oncoming vehicles will often alter their behavior, too. Exactly how long to wait, though, and how to recognize when oncoming traffic is attempting to allow a vehicle to pass, has significant ambiguity: in some cases laws or regulations do not define precisely how to navigate such situations. This ambiguity requires legal due diligence to ensure abidance with local laws and regulations and engineering care to ensure that the SDS is able to achieve safe, naturalistic behavior even in confusing situations.

We develop and test for numerous ambiguous scenarios in order to ensure that when it encounters one, the vehicle displays safe, consistent, naturalistic behavior. We generate ideas both through brainstorming and engineering analysis away from the roads, and by discovery of new situations on the road. Once situations are identified, engineers create a proposed behavior that describes in detail the key conditions that necessitate the behavior—where it's likely to occur, how long it's likely to be necessary, and whether future software or hardware improvements would eliminate the need for the behavior.

Once the new behavior has been described, the proposal is reviewed first by leadership, then by the Argo Safety and Security Committee. Upon approval, implementation and testing follows our standard engineering release process.

REMOTE GUIDANCE

Safety of the vehicle is always maintained by the SDS. However, in a select group of particularly challenging conditions, when the SDS is unable to make a requisite decision, or requires additional guidance to do so—such as an unexpected road closure, or a vehicle blocking its exit from a customer pick-up point—our Remote Guidance capability provides human support to the SDS. A Remote Guidance Operator will assess the event and issue guidance to the SDS.

We use cellular connectivity to deliver information to the test fleet and for Remote Guidance, but it is not required for safe on-road behavior of the SDS. Rather, the SDS is always responsible for the vehicle's safety, even at times when cellular connectivity is interrupted. Crucially, although the operator can provide authorization to the SDS to perform specific driving tasks it has recommended, Remote Guidance does not provide teleoperation to remotely drive the vehicle. The SDS remains responsible for planning and driving controls, including ensuring that the path ahead is safe.

> **A dynamic, layered, and sophisticated Minimal Risk Condition handling system is essential for safe autonomous vehicle behavior.**

A Remote Guidance session may be requested automatically by the SDS, and during the testing and development phase, the onboard Test Specialists can also request a Remote Guidance session.

The session ends once the SDS has confirmed with Remote Guidance that the reason for the session has been cleared and has received confirmation that all tasks requiring Remote Guidance have been completed. The Remote Guidance Operator is responsible for authorizing the end of the session, and must disconnect, document relevant notes, and if necessary, forward the event to our data analysts.

LAW ENFORCEMENT AND FIRST RESPONDERS

It is essential that self-driving vehicles perform safely and correctly in the presence of emergency vehicles and law enforcement officers. To this end, we are developing the capability for our SDS to automatically identify police and other emergency vehicles and yield the right of way to them. Until we reach that capability, our Test Specialists will intervene during operation to ensure emergency responders and law enforcement officers get the priority access they need.

Self-driving vehicles must also be prepared for the possibility of being pulled over by law enforcement officers. If this happens during our development phase, the Test Specialists disengage the vehicle from autonomous mode and manually pull the test vehicle over. They stop in a safe location, and communicate directly with the law enforcement officers.

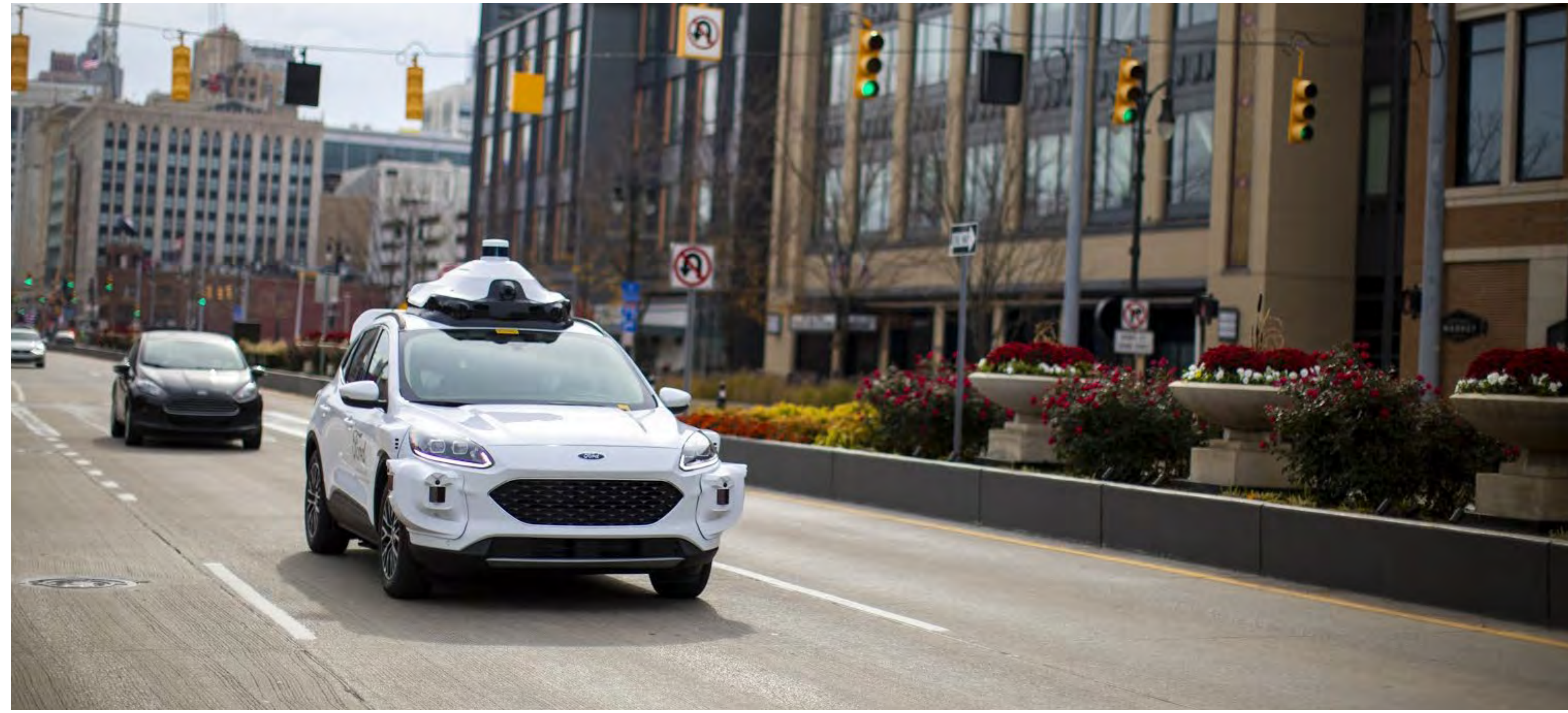
Additionally, Argo has a phone line for emergency responders and law enforcement officers, which is available during the hours of the day when we operate our test fleet.

When we move into commercial operation, if the SDS detects and confirms an active and relevant emergency vehicle, the vehicle will attempt to pull over as soon as possible. After stopping, law enforcement officers will be able to communicate with remote Customer Care teams. Once the traffic stop has ended, the Customer Care team will hand the session over to Remote Guidance and, if it is safe to do so, they will authorize the vehicle to resume its original operations.

FALLBACK MANEUVERS AND MINIMAL RISK CONDITION

In the unlikely event that any part of the system may experience a problem that, if not addressed, could compromise the safety of the vehicle, the SDS must be prepared to take appropriate action. If necessary, the SDS will carry out a fallback maneuver to put the vehicle into a safe state that reduces the risk of a crash, known as a minimal risk condition.

The relevant architectural mechanisms can be categorized into three parts: detecting safety-critical failures; performing fallback maneuvers; and ensuring that the minimal risk condition is achieved. To identify potential faults, we monitor the system to detect safety-critical failures that could result in a hazardous condition. We also define appropriate fallback maneuvers to take when a given failure is detected, and we define the actions required to put the vehicle into a minimal risk condition.



DEVELOPMENT PHASE

Our SDS is still in the development phase, and Test Specialists act as safety operators in our test vehicles, prepared to intervene in the event that they determine the SDS is about to enter a situation beyond its developmental capabilities. Test Specialists count on the intervention mechanisms available to them to be working at all times. If those systems are not working correctly, the Test Specialists need the vehicle to alert them while also transitioning to a minimal risk condition.

Our vehicles provide many different ways for the Test Specialists to take over driving control. The most commonly used ones include turning the steering wheel, pressing the accelerator, or pressing the brake.

Using the techniques previously described, and in close collaboration with our automaker partners, we have developed monitoring to detect failures of this takeover system. If faults are detected at startup, the vehicle will not allow the operator to enter autonomous driving mode. If faults occur while driving, the SDS will attempt to slow the vehicle down at a moderate deceleration rate until it reaches a stop, and will not allow further operations in autonomous mode.

COMMERCIAL PHASE

When our system is ready for driverless operation, the entire SDS will have completed thorough engineering analysis, design, implementation, and verification testing. Our initial verification processes have already led to the addition of numerous safety monitors located strategically throughout the SDS to detect underlying software and hardware errors within a specific timeframe.

Our safety-critical software and hardware are constantly monitored to detect failures, including sensor, hardware, software, and autonomous vehicle platform failures. We include preemptive responses when applicable to attempt to mitigate or avoid a minimal risk condition or MRC.

Upon detecting a critical fault or other triggering condition, our system maps the condition to a specific fallback response. The defined response varies based on the fault criticality and the vehicle operating mode. In addition, every MRC-triggering condition is mapped to a corresponding recovery state. This means that we actively control whether the vehicle can return to normal operations following a fallback maneuver.

Each fault response has a strict set of rules and policies to which the SDS must adhere. These include allowable and prohibited locations, time- and distance-based thresholds, strict timing requirements, and, if applicable, recovery sequences. These policies are strictly enforced by the SDS and a violation of a rule or policy would result in a fallback maneuver of increased severity.

MRC LEVELS

We have grouped fallback maneuvers into four main MRC categories, and each fallback maneuver must be performed safely within a specified time limit, according to the level of urgency:

- Service: the vehicle requires service or maintenance soon or immediately
- Pull over: the vehicle should pull over immediately, or as soon as possible
- Stop: the vehicle should stop as quickly as possible without attempting to pull over
- Emergency braking: the vehicle will perform an emergency braking maneuver within its collision-mitigation capabilities

The AVS computer is responsible for the driving task and most fallback maneuvers, including the ability to pull the vehicle over within different time windows based on severity. The AVS and the CAVS both have the ability to stop the vehicle along a given path. Additionally, while the AVS has the ability to perform emergency braking, the CAVS can also intervene to perform collision-mitigation braking maneuvers, providing an additional diversity in the SDS design.

Service-related faults that do not affect safety-critical operation of the vehicle, such as an interior display screen failure, result in the vehicle completing its current trip and then re-routing back to a facility for appropriate service and troubleshooting.

In the event of a fallback maneuver being triggered, the SDS will notify Remote Guidance, Fleet Operations, and the partner's customer service operation. These teams work together both to determine whether the fault is recoverable or non-recoverable, and to keep any passengers in the car informed of the progress in diagnosing the problem. If it is recoverable, a specific recovery process and sequence is initiated. If it is non-recoverable, a support team is dispatched to the vehicle to assist any customers and to retrieve the vehicle.

Of course, not all conditions require an immediate MRC. Fallback maneuvers are primarily triggered by hardware or software failures, but they can also be triggered by events that negatively impact the vehicle's ability to operate. These might include sensor obstructions, emergency trip pullovers requested by a passenger, a vehicle door being opened while driving at speed, and more. Temporary conditions, such as a camera obstruction that cannot be cleaned while driving and requires a pullover for sensor cleaning, may not require the dispatch and recovery of the vehicle or our partner's customer service department. In such situations, the SDS will execute a fallback maneuver, then go through a recovery sequence to resolve the obstructed camera and determine whether it is able to recover to normal operations; it will also keep any passengers informed of the issue and the automated recovery sequence progress.

If, after the vehicle has entered MRC, the SDS is able to resume its original driving task, the recovery process may involve a Remote Guidance Operator and our partner's customer service operation; if so, the operator will assess the state of the vehicle and decide whether to authorize the SDS diagnostic system to revert to an operational state.

In the unlikely event that any part of the system may experience a problem that, if not addressed, could compromise the safety of the vehicle, the SDS must be prepared to take appropriate action.

Test and Validation

- Hardware Testing
- Software Testing
- Virtual testing
- Closed Course Testing
- Fleet Testing on Public Roads
- Test Specialist Training and Certification
- Human-Machine Interface (HMI)

At Argo, we believe that because the self-driving system (SDS) consistently learns and expands in capability based on experience, our development can never be "finished."

This philosophy lies at the heart of our process of continuous testing. This section details the numerous stages that make up our development cycle. Each stage is significant in its own right, but when combined as a coherent feedback loop, they create a powerful and highly effective testing regimen.

Long before our SDS reaches public roads, our software goes through a testing and release process that begins in the virtual world with the simulation of millions of scenarios, and is followed by physical testing on our test track. If, after passing each of these stages, the team determines that the system is ready, we subject it to rigorous and highly specific testing in a limited number of vehicles on public roads before issuing a software release to the entire fleet of road-test vehicles.

Our software is tested at every stage of the cycle, and if faults or errors are identified, testing of that particular software is halted, the appropriate developers are alerted, and the code is repaired or rewritten, before being readmitted to the development cycle.

Importantly, even after commercialization, when our SDS has been fully integrated into our automaker partners' products, we will continue to improve and refine our software, enabling us to expand our features and self-driving capabilities. We will also constantly enhance our fleet operations processes, including refinements to driving style, pick-ups, and drop-offs, to ensure optimum performance of our SDS, and to accommodate customer feedback.

The efficacy of our SDS is rooted in our commitment to meeting stringent development, design, and testing standards for each hardware and software component. We test and validate at all levels of the system, from the computer hardware and sensors we use, to the software that powers them. Everything is tested at the component level, prior to being tested as part of an integrated system.

All Argo SDS hardware is designed to comply with rigorous environmental and functional safety standards. In addition, we continuously collaborate with our automaker partners to ensure our supply base is equipped to produce custom hardware in a cost-effective and scalable way.

We utilize a wide range of testing methods and techniques—from simulation to closed course to public roads—to constantly improve our technology, and to provide appropriate scale and diversity to our testing.

In addition, we employ a variety of test approaches and techniques to ensure adequate coverage and robust verification. Our culture of safety means the testing process never ends; Argo employees in all roles constantly evaluate and improve the way things are done, from corporate processes, to simulation, to public road testing.

HARDWARE TESTING

Hardware modules, including sensors and computers, are rigorously tested in collaboration with our automaker and supplier partners to ensure the modules are automotive grade--that is, that they meet high standards for performance and reliability in a diversity of environmental conditions, from extreme heat and cold to harsh vibrations and impacts.

Prior to proceeding to full vehicle testing, we use test benches to facilitate the development and integration of all SDS and AVP components. As an example, Hardware-in-the-Loop (HiL) testing involves verification of the full hardware architecture on a testbench. This allows rapid and highly repeatable testing of vehicle response to fault injection in a safe environment.

Lastly, we work with our automaker partners to verify that the full vehicle meets expected environmental performance targets. This includes ensuring mechanical, electrical, and thermal targets are achieved across the broad range of expected operating conditions.

SOFTWARE TESTING

Software development is governed by coding standards to ensure a consistent approach to software generation. Once written, our software goes through a verification process that involves multiple stages of code review, simulation, and testing. Just like the hardware testing process, we test individual software units, and then continue testing as we integrate and create software subsystems. Finally, we test the software on target hardware.

VIRTUAL TESTING

Virtual testing enables us to create a virtual world in which we can safely test a wide variety of scenarios. Our virtual testing program is made up of three main test methodologies: simulation, resimulation, and "playforward."

SIMULATION

The first part of our virtual testing process involves the simulation of a vast range of scenarios and environments. Each simulation is the result of a detailed analysis of road geometry, road actors, and other factors that affect behavior. The results can be built into a single street or multi-block base scenario constructed on top of the 3D models of our operational cities.

We deploy many techniques to add randomness to the base scenarios, such as adding weight, changing initial speed, or adjusting initial lane positioning of the self-driving vehicle at the start of the simulation. We also change related things, such as a simulated actor's starting position, speed, and motion. Argo also includes a process to add random actors to a scene, or to modify certain characteristics of an actor, like the state of brake lights for a parked vehicle. All of these alterations create a testing environment that is rich with real-world randomness.

Each scenario is evaluated through dozens of measurable metrics ranging from vehicle passing margins to steering jerk. Noted events are analyzed daily and cycled back to development teams for action, and road-testing scenarios are analyzed in a similar way. We match events from our road data to the simulation set and evaluate the effectiveness of the simulation to predict the outcomes seen in the real world. This enables us to build confidence in our virtual testing environment.

RESIMULATION

We have developed tools that enable us to resimulate the recorded sensor data from our public road testing, and execute the autonomy software, from perception through to motion planning and control. This allows us to assess the virtual performance of updated or new software releases against previous challenging situations.

Resimulation is the process of taking logs, or data records, generated by the test fleet and running new software over the sensor data, typically from lidar, camera, and radar sensors. By creating a new log out of that simulated SDS behavior, we can see whether the performance of any individual sensor could be improved.

This enables us to manipulate inputs, and test thousands of logged and "ground-truthed data sets"—that is, data which has been assessed and verified by our software engineers.

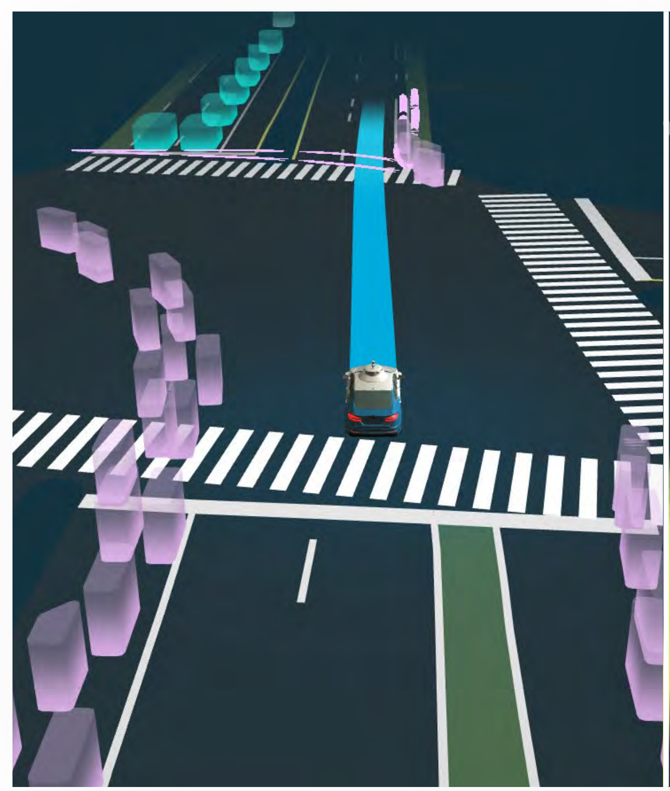
PLAYFORWARD

The third aspect of our virtual testing is known as "playforward." This is a variant of resimulation that allows us to investigate what might have happened in scenarios where a Test Specialist took back control of the vehicle. For example, the Test Specialist may have disengaged autonomous mode at an intersection; during data analysis of this event, we can use playforward simulation to analyze the likely scenarios that would have occurred in the seconds after the disengagement. Using playforward, we can test software updates against the most challenging scenarios that our vehicles have encountered with real sensor playback.

CLOSED COURSE TESTING

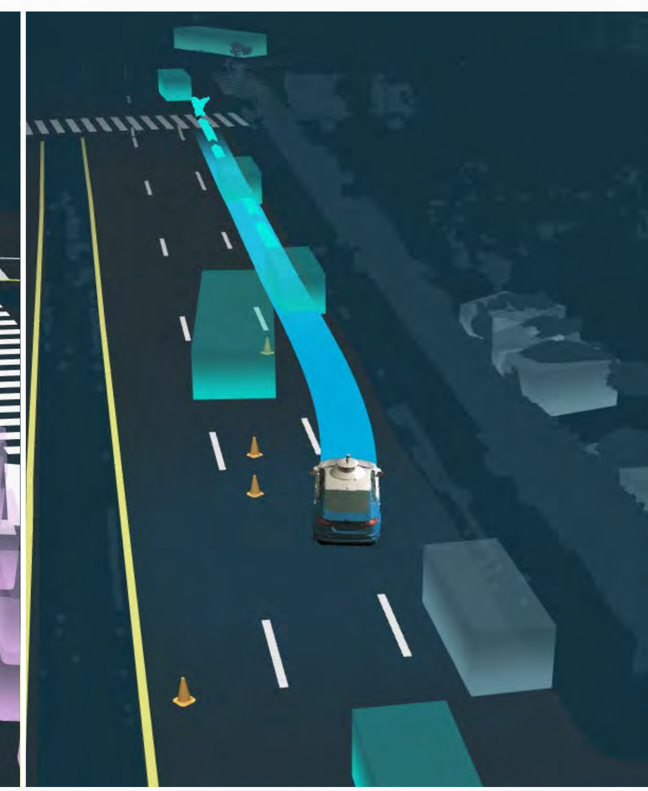
Once a software version has passed virtual testing, we take it to a closed course staffed by test engineers and associates to safely test whether the software behaves on the test track as it did in simulation.

Our 50-acre U.S. test track has 10 miles (16km) of driveable roadway with an extensive list of city-street features. The test track includes traffic circles and complex intersections with traffic light controls, tight bends with reduced visibility, fog and rain generators, an area of roadway that we can flood, traffic-calming measures, and typical road infrastructure such as mail boxes, street signs, and bollards.



Simulation

A rare scenario, such as a bicycle race, can be simulated and tested in a virtual environment.



Resimulation

By running resimulation, we are able to evaluate perception improvements for objects such as construction equipment.

Playforward

In this simulation, we look at what our test vehicle was projected to have done, as noted by the green vehicle, if the Test Specialist had not disengaged the self-driving system.

We use a variety of tools to help replicate situations that we may encounter on the road, including pedestrian and animal mannequins and remote-controlled cyclists and skateboarders.

We rigorously test the capabilities of the SDS in a variety of scenarios, up to and beyond expected operating conditions. We call this structured testing, and we carry this out at multiple levels of the system, from the individual sensor level (e.g., camera performance) to functional level (e.g., traffic light detection) to the full system level, as well as testing environmental factors and combinations of conditions. If we observe unwanted behavior in the SDS, we revert to development and simulation testing before we return to the track.

This enables us to ensure completeness of testing against conditions that have not been experienced during public road tests. The process is tied to robust systems engineering and safety processes, and mapped to national databases of crash statistics to help identify conditions that result in crashes.

RELEASE CANDIDATE PROCESS AND INITIAL PUBLIC ROAD TESTING

Before new software is rolled out to our public road test fleet, it passes through our Release Candidate Process, which ensures that new software configurations perform as expected. This also looks at all operational processes, not only to ensure that end-to-end data can be delivered and evaluated, but also that those changes will not affect earlier improvements.

The code is tested first in simulation and then at the test track, against all of the functional requirements for perception, prediction, motion planning, and controls. We check that the vehicle functions as intended, and is able to make the best decisions, drive correctly, and identify and avoid objects. The next stage of release candidate testing at the test track involves driving routes and scenarios that simulate common and unusual interactions, such as a pedestrian appearing between two parked cars, or a delivery vehicle pulling out suddenly.

We then take that release candidate out for limited public-road testing, still under test-engineering control, and drive predetermined routes to again test all necessary functionality. We analyze all of that data, and once that release candidate has been approved, the software is promoted for use by the test fleet.

FLEET TESTING ON PUBLIC ROADS

Testing on public roads is a privilege we take very seriously, and we abide by all applicable laws, regulations, and guidelines in the cities where we operate. We test on public roads for a number of reasons; ultimately, that is where our product will be deployed, and public road testing provides two elements that are crucial to our upfront development and backend validation phases. First, it enables us to gather sensor data of real-world scenarios that we can recreate in simulation or on our test track; and second, we can validate that the software performs in the real world in the same manner it does in simulation and on the test track.

We are in the process of growing our fleet of test vehicles into a global operation across partners, vehicle platforms, and driving cultures. We have test vehicles on the roads in Washington, D.C.; Miami, FL; Pittsburgh, PA; Detroit, MI; Palo Alto, CA; and Austin, TX, and have recently launched test operations in Munich, Germany.

Each test vehicle is currently operated by two highly trained Test Specialists—one in the driver's seat and one in the front passenger seat—who carry out very different, but complementary, tasks.

The Test Specialist in the driver's seat focuses on the road. Their task depends on the mode in which the car is driving. Aside from driving the vehicle in manual mode, following routes

chosen specifically to gather data to train the system or conduct map quality assurance, the Test Specialist in the driver's seat is responsible for engaging and disengaging the vehicle from autonomous mode, and responding to any potential faults.

The Test Specialist in the front passenger seat monitors their teammate and their surroundings, taking notes on a laptop which also displays what the SDS sees and expects. The laptop is directly connected to the SDS, and runs a visualization tool displaying turn-by-turn directions for the vehicle's route, and a trajectory that shows exactly what the vehicle will be doing up to a certain amount of time ahead of its current action. That trajectory is indicated by color-coded tracks, showing the activities of other road users, such as a door being opened on a parked car, or a truck pulling out of a side road up ahead. The Test Specialist records notes if the SDS makes a poor decision, or even if they just observe any anomalies that did not cause an issue but could have if the situation played out differently.

DATA ANALYSIS

When a test vehicle returns to the terminal, we upload the data from the road test. That data is assessed by our data analysts, who quickly access annotated or other disengagement events selected for examination. For quality control purposes, analysts also assess a number of randomly selected events.

The data analysis team sorts and prioritizes the data, and based on the nature of the disengagement, assigns the logs to the appropriate software team for resolution. Analysts may also choose to run the data for these takeover events through our playforward simulation process.

The team works with all parts of the company, and may assign an issue to the appropriate team. The allocated team plans the appropriate resolution, and, once ready, new software code is published according to our release candidate testing process.

TEST SPECIALIST TRAINING AND CERTIFICATION

Our rigorous recruitment and training process for Test Specialists results in only 4% of those that apply for the role making it through to full certification, making selection of Argo Test Specialists more exclusive than many of the top universities in the United States.

Once they have passed driving history and drug checks, and aptitude and driving tests, our Test Specialist candidates undergo an intensive, multi-week, three-phase training program described below. We support and review the AVSC best practices guidance for test-driver selection, training, and oversight procedures. Tests at the end of each phase ensure that only the leading candidates progress to the next phase.

Throughout the process, Test Specialist candidates are taught a mental model of Search, Evaluate, and Execute (SEE) that allows them to drive safely across every intersection.

Phase 1: Manual Driving Training and Calibration

During the initial phase of our training program, candidates are introduced to high-performance urban-driving concepts with a focus on safety over speed, navigating dense urban streets, and handling frequent pedestrian, cyclist, and motorist interactions. Phase 1 includes:

- Reintroduction to proper driving etiquette
- Proper ergonomic positioning
- Mirror adjustments, spatial awareness, and blind-spot corrections
- Smooth accelerating and braking
- Turning trajectories and profiles
- Comfortable and correct stopping distances
- Acclimation to testing-area streets

Phase 2: Advanced Driver Training and Introduction to Autonomy on Test Track

In the second phase, candidates experience our self-driving technology in a closed course setting, and see how an autonomous vehicle reasons and reacts, and what to expect while operating under controlled conditions. Phase 2 involves:

- Development of autonomous mode operations
- Advanced Driver Training
- Car control drills
- Collision avoidance
- Autonomous Mode engagement/disengagement
- Autonomous Mode fault-injection training
- Steering
- Acceleration / deceleration
- Emergency disengagement

Phase 3: Public Road Autonomous Mode Operations and Certification

During the third and final phase of our training program, candidates experience our self-driving technology in autonomous mode on public roads. Phase 3 includes:

- Trainee ride-alongs with certified operators
- Supervised Application of autonomous mode
- Graduated exposure to road scenarios
- In-vehicle and classroom evaluations

Like any skill, these techniques require a combination of classroom instruction, in-car instruction, practice, and feedback. Repetition and reinforcement throughout the program build strength and comfort with the techniques.

All of this is performed with a three-to-one trainee-to-trainer ratio. If trainees are unable to meet our thresholds for safety and professionalism, they are dismissed from the program.

EMPOWERMENT

Once certified, each Test Specialist is empowered with a responsibility for safety. We entrust all full-time employees with authority and accountability to raise concerns in operations should a critical fault or failure be discovered in the system. Test Specialists are equipped to disengage the autonomous system and to annotate any potential critical issues or concerns experienced on the road, flagging them for the data analysis team and further assessment.

This process promotes active dialogue between the Test Specialists and the engineers, and full transparency throughout the organization. In turn, this builds knowledge of the SDS and promotes our safety-first culture.

OPERATIONAL POLICY AND PROCEDURE

We have produced extensive policy documents and procedures for all aspects of Fleet Operations. The Road Testing and Mapping teams constantly reference these documents and conduct ongoing studies. All employees are required to regularly study and review a master index of all policies, procedures, practices, and protocols, as well as role-specific digital binders organizing all material relevant for each role and responsibility.

These materials are frequently accessed and referenced in conversations, safety meetings, and manager meetings. We receive feedback throughout our organization on how we can improve or update these materials, and these documents are updated in line with the fast pace of the industry.

OPERATIONAL PERFORMANCE MANAGEMENT AND EVALUATION

Many of our Test Managers are former Test Specialists, giving them valuable operational experience and knowledge on how to coach, mentor, and train our Test Specialists. Bi-weekly one-on-one meetings between Test Specialists and Test Managers keep management and employees connected. In this way, each specialist knows where they stand and how they can improve performance. A 360 Performance Evaluation cycle also provides a clear and concise checkpoint during the year. Each individual is evaluated on six performance dimensions for their level: safety, knowledge and technical skill, teamwork, communication, organizational impact, and leadership. Managers are also evaluated on their people-management skills.

COMMENTARY DRIVING

During all test drives, Test Specialists use a concept called Commentary Driving. With its roots in rally driving—where the navigator provides a constant stream of vital information to the driver—the two Test Specialists provide ongoing commentary about what is happening in their view during any advanced vulnerability situation, such as intersections, merge areas, or locations with a known high concentration of pedestrians or other vulnerable road users.

Commentary Driving provides confirmation that what the left-seat Test Specialist is seeing in the real world matches what the right-seat Test Specialist is seeing and interpreting through the sensors, and that the SDS is making the same predictions and executing motion controls that a human driver would make. Commentary Driving acts as an additional safety net, and maintains the Test Specialists' levels of alertness.

CONTINUOUS IMPROVEMENT OF CONFIDENCE AND KNOWLEDGE THROUGH SAFETY

Learning and development never stops at Argo. Release notes are distributed and reviewed as new software becomes available for road testing, often several times throughout the week. Test Managers create individualized coaching and learning strategies for each Test Specialist on their team. Frequent and random spot checks of dashboard-camera footage from our Driver Monitoring System also ensure that managers can keep a pulse on performance.

Once the areas of improvement are identified, Test Managers review video logs generated when a Test Specialist annotated a scenario of interest during testing. In the event of a disengagement, we can even confirm what the AVS was planning to do using playforward. By combining specific disengagements with dashcam video, Test Managers are able to give a detailed play-by-play of a Test Specialist's performance to highlight areas of improvement and confirm areas of strength. Test Managers also ride in vehicles with Test Specialists to observe their driving technique, completing the circle of experience, learning, and real-world application with feedback.

CONTINUOUS DIALOG WITH ENGINEERS

Our Test Specialists and Managers are in the test vehicle every day, and our release candidate software process brings iterative improvements on a daily basis. In this way, the Fleet Operations team are subject-matter experts on our SDS performance. Software developers routinely engage with our Road Test team. They also make weekly deep-dive presentations on systems, and new and forthcoming features.

Software developers are in constant communication with our Test Specialists and Test Managers, and they, too, often ride in the vehicle to see the progress firsthand, observing, asking questions, and taking notes from the back seat. Other key components of this dialog are recurring start-of-shift briefings and end-of-shift debriefs, in which changes in the software are discussed, expectations are set, and feedback is analyzed.

Similarly, our Test Specialists touch the vehicles every day, and conduct physical inspections of those vehicles, giving them vital information for the hardware engineers. And hardware engineers with roles in reliability and durability seek out the Test Specialists for their knowledge and insights for any indications of unusual wear patterns, both to intervene before something breaks, and to inform and improve future designs.

HUMAN-MACHINE INTERFACE (HMI)

A user-friendly human-machine interface (HMI) with simple manual controls and clear display of information is essential for our Test Specialists to engage or disengage autonomous mode, and to be aware of potential faults or other aspects of vehicle performance.

The HMI in our test vehicles is the result of meticulous work in collaboration with our automaker partners to engineer an interface that maximizes safety during the development process.

The three main features of the HMI are the Driver Monitoring and Driver Alert systems, the Heads Up Display with accompanying audio signals, and the controls for engagement and disengagement.

DRIVER MONITORING AND DRIVER ALERT SYSTEMS

To ensure maximum safety across our test fleet, we use a Driver Monitoring System which automatically captures specific in-vehicle behaviors, such as seatbelt usage, food and drink consumption, handheld device usage, and smoking. A range of other driving behaviors—such as speeding, rolling stops, and lane departures—can also trigger email alerts for dispatchers.

We have also developed a second notification system, called Driver Alert, that is integrated into our SDS. It predicts potential traffic light and stop sign violations before they happen, alerting Test Specialists with an audible sound from the operator laptop. The system does this if the vehicle approaches a stop sign or traffic light at a speed that would require hard braking, and it will trigger for yellow lights if the vehicle is predicted to pass through them. Driver Alert will also notify our test drivers if they are making a move that is counter to the map, such as a wrong turn into a one-way road.

Testing on public roads is a privilege we take very seriously, and we abide by all applicable laws, regulations, and guidelines in the cities where we operate.

HEADS UP DISPLAY (HUD)

Each test vehicle is equipped with a Heads Up Display (HUD), which provides clear visual and audible communication of the vehicle's driving mode with LED lights and audible chimes. LED lights also alert the Test Specialist in the driver's seat to any faults in the SDS or the vehicle platform. The display's LED and audible chimes each serve as a fallback to the other in case of a fault, as they are controlled by independent systems.

ENGAGING AUTONOMOUS MODE

Engaging the test vehicle in autonomous mode involves a two-step process controlled by buttons on the steering wheel, which the Test Specialist uses to first enter ready mode, and then engaged mode. Solid or flashing lights on the LED light bar in the HUD, and auditory chimes, provide status alerts to the Test Specialists.

In autonomous mode, the SDS operates the driving task while the Test Specialist stands by—hands hovering at 8 and 4 o'clock—ready to take manual control at any time by gripping the wheel. In this mode, the steering wheel turns with the motion of the vehicle, but the pedals stay still. By behaving as if driving the car, the Test Specialist can quickly disengage from autonomous mode, and continue the action that they feel the vehicle should be doing at that given time.

Argo has calibrated intervention methods for the vehicle's brakes, throttle, and steering in order to be sure the vehicle will consistently respond and return control back to the driver within 10 milliseconds.

DISENGAGEMENTS

The transition from autonomous mode to manual modeis called a disengagement or a takeover. There are two types of disengagements: voluntary, in which a Test Specialist chooses to take control, and mandatory, in which a Test Specialist is required to take control.

Disengaging from autonomous mode is a single-step process. The primary methods are for the Test Specialist to turn the steering wheel or to press the brake or throttle; secondary disengagement methods include unbuckling the seat belt or opening a car door. In case of emergency, test vehicles have buttons installed in the center console; a yellow one that disengages autonomous mode and a red one that cuts engine power to the vehicle.

Our Test Specialists are trained to exercise maximum caution, and will likely have voluntary disengagements, but mandatory takeovers are based on policies we set during the development phase. For example, our Test Specialists are currently required to take manual control when encountering an active school bus, or when they encounter a first responder vehicle with emergency lights flashing.

Our Test Specialists are empowered to take over whenever they feel it is necessary, with the confidence that their takeovers will never be met with a punitive action. We believe there is no such thing as an unnecessary takeover.

The Fleet Operations team holds daily meetings to educate and debrief the Test Specialists, in order to maintain the highest levels of system awareness and feedback. At the beginning of each shift, the manager explains in detail the implications of new software releases and mandatory takeover procedures in specific situations under testing, such as at pick-up/drop-off locations. At the end, the Test Specialists review their testing experience and provide anecdotal feedback to better understand the functionality of the software and any changes necessary.

Ensuring Safety and Security

The security of physical and data-related aspects of our product development and corporate operations underpins our safety strategy.

This section of the report looks at our approach to cyber security and how we handle data, as well as our engagement with consumers, and our adherence to laws, regulations, and guidelines.

CYBER SECURITY

Our cyber security strategy is an essential element of our safety program and is designed to ensure the operational resilience of the company and our products and services. Safety and security are interconnected, and our cross-functional cyber security working group reports to the Argo Safety and Security Committee.

We take steps to ensure the safety of our operations even (perhaps especially) in the face of disruptive events. At Argo, we combine proactive behavior with resilience, and we strive to identify potential risks and protect against them before they can become a realized threat.

Our approach to cyber security is guided by the five-tier cyber security framework developed by the U.S. National Institute of Standards and Technology—namely identify, protect, detect, respond, and recover—and we apply this to all aspects of corporate cyber security and product cyber security.

CORPORATE AND PRODUCT

Our corporate cyber security efforts focus on our operational infrastructure. We secure the code that we write, the environment in which our staff operate, and our employee and corporate data.

Ensuring the confidentiality, integrity, and availability of our corporate resources is essential for all Argo team members. We also know how important it is to maintain the trust of our partners, vendors, and suppliers, and for that reason, our headquarter operations, up to and including software development, are ISO/IEC 27001-certified, the international standard for best practices in digital data management.

At a product level, vehicle cyber security is addressed from concept through operation and maintenance as part of a secure development lifecycle. This includes:

- Security in design through identification of threats and analyzed attack surfaces
- Security in implementation and verification to ensure that code has not been altered or corrupted, by identifying and remediating vulnerabilities, and ensuring that security mechanisms identify and react to attacks
- Security in deployment and maintenance to ensure the authenticity and integrity of updates and changes.

The cyber security of our corporate operations is as important for safety as the cyber security of the self-driving system (SDS) itself. We constantly perform Threat and Risk Assessments across all of our corporate activities as well as on everything related to our product. We use a centralized Root of Trust with public key infrastructure, a best-practice approach to cyber security that ensures safety and security in all of our policies and across our operations, and in our hardware and software.

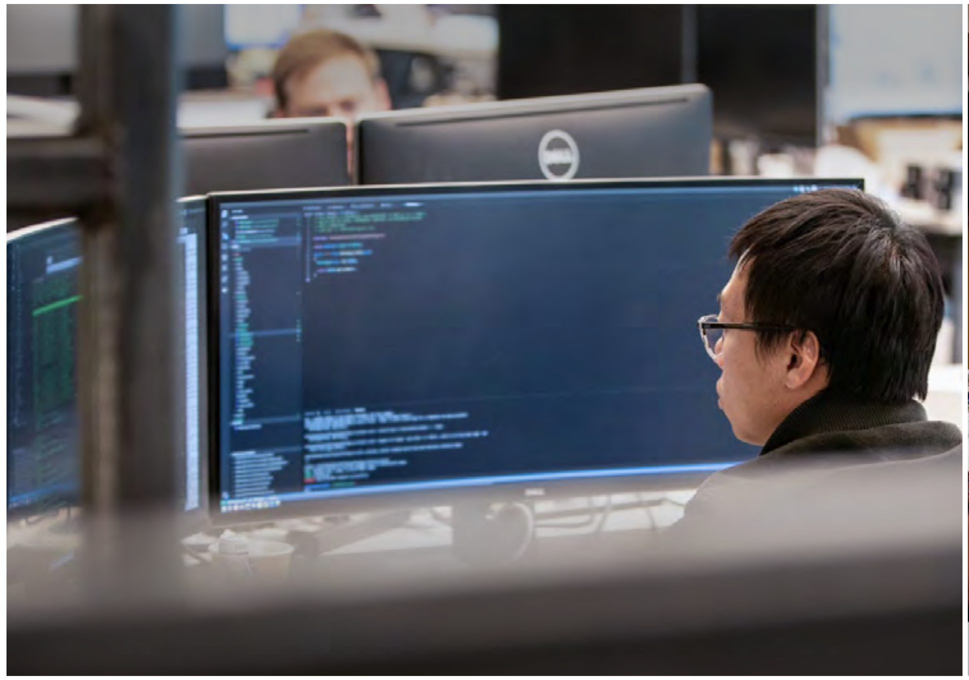
We leverage the public key infrastructure and onboard cryptographic devices to protect the vehicle from any unauthorized deployment of code or data (such as firmware, map data, machine learning models, and calibration data). And crucially, because everything we do is designed for privacy, we encrypt all ingested data in flight to ensure the confidentiality of all sensitive data that we gather, and leverage our cloud providers to store the data encrypted at rest.

TRAINING

All Argo team members, right up through senior executive level, undergo an ongoing program of cyber security training. We carry out training throughout the year, from basic education and phishing exercises to specific courses on internal cyber risks, such as malicious and unintentional threats, identification of data exfiltration and sabotage, and separation of duties. We provide role-specific training for code-writing and -reading, and for the use of open-source software. All of this ensures that cyber security remains front of mind, all the time, throughout the company.

INTERNATIONAL STANDARDS AND INFORMATION SHARING

As part of our global growth, we also adhere to the national and international standards and certification that enable us to operate in global markets and collaborate fully with our global partners. Our U.S. headquarters is certified for ISO 27001, an international standard on how to manage information security, for enterprise operations and we're in the process of getting this certification extended to our Munich office. We are also pursuing TISAX certification, with an audit pending. TISAX is an assessment and exchange mechanism. TISAX was developed for automotive industry information security by the German Association of the Automotive Industry (VDA).



On the product side, we meet the current draft version of ISO 21434, an automotive standard that forms the basis for our product security lifecycle activities. We will continue to analyze and meet this standard as it evolves and is finalized.

Argo serves as a member of the Advisory Board for the Auto-ISAC (Information Sharing and Analysis Center), an industry-driven community that shares and analyzes emerging cyber security risks to the global automotive industry. This position enables Argo to coordinate with automakers, suppliers, commercial vehicle companies, academia, and other ISACs on cyber security vulnerabilities, threats, research, best practices, and solutions.

DATA RECORDING

Learning from our continuous testing process is critical to developing our SDS. Test vehicles are capable of continuously monitoring and logging data pertaining to the dynamic driving environment, as well as Test Specialists' notes about the SDS performance.

Using this data, we can analyze vehicle sensor input, including the system's detection of external objects; the system's tracking of the motion of these objects; its prediction of their next moves; and its response to all of these inputs. In addition, we use this data to develop scenario simulations related to driving interactions we encountered on the road.

Above and beyond these data-recording requirements, onboard SDS storage systems are capable of storing continuous, data-rich driving information that can be made available during vehicle maintenance or service.

The SDS data we log is consistent with emerging industry guidelines such as those published by the Automated Vehicle Safety Consortium. Additionally, Argo complies with state and local data-collection requirements.

As we move from development to commercial deployment with our automaker partners, our SDS recording practices and onboard recording system will begin to progress from continuous to event-based recording, consistent with emerging industry standards and National Highway Traffic Safety Administration guidance.

Production vehicles equipped with our SDS will comply with federal requirements for recording crash-event data. On these vehicles, our SDS onboard recording system will also be capable of storing triggered event information, including additional event details, system and SDS information, or Minimal Risk Condition fallback maneuvers, as outlined elsewhere in this report.

PRIVACY

The privacy of the data we log is also very important, and we treat it securely and with great care. This testing data is collected exclusively for research purposes and to advance the development of our autonomy software in compliance with existing requirements. The data is not used to identify any individual or household. We will protect the data and any personal information and comply with data-privacy regulations. In particular, it is important to note that we do not apply any facial recognition or other personally identifying technology to the images and other data collected by our test vehicles. For more information, go to our privacy policy.

CONSUMER EDUCATION AND TRAINING

An essential part of the successful development and deployment of self-driving vehicles is consumer education and training. Only through a concerted effort to inform the public about the societal benefits of self-driving vehicles—and only by demonstrating both how they work and how safe these vehicles are—can we ensure societal acceptance of our technology and realize a self-driving future.

We believe and support our automaker partners' efforts to introduce advanced driver assistance systems into mainstream vehicles, preparing consumers for the idea of a self-driving future and broadening public acceptance of the growing role for automated technology in the future of mobility. We're also members of Partners for Automated Vehicle Education (PAVE), a coalition informing the public about the future of transportation.

We emphasize clear and frequent sharing of information through a wide range of communication channels in our education and training efforts. This includes traditional media outreach, our website, and social media platforms. Our blog, Ground Truth contains stories about our company and insight from our executive leadership team, and our CEO also co-hosts the No Parking Podcast, which focuses on self-driving technology and artificial intelligence.

We also conduct outreach in the communities where we test, whether meeting with government, business, or advocacy leaders, or engaging in educational initiatives to share information about our efforts and answer questions.

FEDERAL, STATE, AND LOCAL LAWS

As the regulatory landscape continues to evolve, we ensure that our testing program and test vehicles meet all applicable federal, state, and local laws, regulations, and guidelines. We are in continual contact with policymakers at all levels of government to keep them informed about developments in our technology, testing practices, and progress, as well as to provide technical expertise and assistance as they consider and implement policies with respect to self-driving vehicles. Most importantly, as we refine our SDS and continue to expand our testing program, we do so with safety and compliance as our top planning priorities.

FEDERAL LAWS

Our test vehicles comply with federal law and existing autonomous vehicle testing policies. The vehicles we test on public roads meet all applicable Federal Motor Vehicle Safety Standards or have appropriate exemptions from various requirements, if necessary. At the federal level, we work closely with the National Highway Traffic Safety Administration to keep it apprised of our development and testing activities and to engage in important policy discussions to advance the development and implementation of self-driving technology.

Furthermore, Argo is a participant in the U.S. Department of Transportation's Automated Vehicle Transparency and Engagement for Safe Testing (AV TEST) initiative, launched in 2020, to increase public education and testing transparency. Through this voluntary reporting program, information submitted by manufacturers, developers, and state and local governments is provided to the public through an interactive website.

STATE AND LOCAL LAWS

At the state and city levels, our testing program and test vehicles meet or exceed all applicable permitting and reporting requirements, and comply with all data protection, inspection, insurance, registration and titling, among other requirements. We analyze state and local rules of the road on an ongoing basis to ensure that our test vehicles are capable of operating in accordance with them in the applicable Operational Design Domain (ODD). Above all, we ensure that safety remains our top priority as we evaluate any changes to road rules that impact our ODD. As we are notified of these changes, we adjust our systems accordingly so that our vehicles comply in a safe manner.

We also appreciate the roles that first responders and law enforcement agencies play in maintaining public safety. We have provided briefings for these important partners in the states and cities in which we test in order to ensure they know how our test vehicles work and how to interact safely with them, both under ordinary circumstances and in the event of a crash. Our first responder guide also includes contact information for a dedicated Argo staff member, who is available during the hours of the day when we operate our test fleet. Moreover, we continue to research and work with the first-responder community to understand how to better design our SDS to follow their commands and respond appropriately to their presence.

As mentioned, we provide technical assistance to federal, state, and local policymakers as they consider new self-driving laws, regulations, and requirements. We are members of the Texas Connected and Automated Vehicle Task Force, the Pennsylvania Autonomous Vehicles Task Force, the Florida Automated, Connected, Electric, and Shared (ACES) Transportation Roadmap Initiative, and the Washington, D.C. Autonomous Vehicles Working Group. Likewise, we are frequently in contact with the California State Transportation Agency, the Michigan Department of Transportation, and the Michigan Council on Future Mobility and Electrification.

COLLABORATION AND ENGAGEMENT

We engage with the National Highway Traffic Safety Administration and relevant state and local regulators by organizing update meetings and submitting comments and other feedback in formal and informal agency proceedings. In all cases, we stress the need for uniform and reasonable policies with clearly defined roles and responsibilities, not only to facilitate compliance, but to bolster safety and to increase the public's understanding and acceptance of this potentially transformative technology. We also work closely with our trade associations, including the Self-Driving Coalition for Safer Streets, the Alliance for Automotive Innovation, the Consumer Technology Association, and TechNet, to inform industry consensus on these issues and engage with policymakers where appropriate and necessary.

Crashworthiness and Occupant Safety

While we take every precaution to ensure safe operations, we must prepare with the mindset that collisions are inevitable.

We do this in collaboration with our strategic global automaker partners, Ford and Volkswagen, leveraging their combined 200 years of experience in vehicle safety design, development, testing, and manufacturing.

Our partners have the same passion for safety as we do, and they design and build it into their vehicles every day. We will fully integrate our self-driving software and technology into their vehicles through collaborative engineering and systems design. Our partners will take responsibility for vehicle certification, ensuring that the vehicle meets all applicable safety requirements, including crashworthiness and occupant protection.

Although our automaker partners will ultimately operate the vehicles powered by the Argo SDS, our primary product principle is for our SDS to be safe and trustworthy. To ensure this, we focus on the safety of our passengers and every road actor that our vehicles encounter.

As an example, this means that our SDS will not depart from a ride-hailing scenario until all passengers are safely on board, and all closures such as doors, liftgate, and tailgate are closed. During the journey, we provide situational awareness to the passenger, and upon safe arrival at a drop-off location, the vehicle will provide the passenger with a notification that it is safe to exit the vehicle. Our SDS will safely stop the car if someone opens the door while driving, or if someone hits the passenger-emergency stop button.

POST-CRASH BEHAVIOR

If a collision is detected, our SDS will immediately bring the vehicle safely to a stop and log the event on the onboard event-data recorder and the autonomous vehicle data-recording system for analysis purposes (see Data Recording section). This also includes taking other measures, such as requesting hazard-light activation.

In the event of a collision during the development phase, our Test Specialists are trained to follow a specific sequence of procedures. They will immediately evaluate whether the occupants of the test vehicle or any other parties involved in the collision are injured, and call first responders as appropriate. Our Test Specialists will assess any property damage, if applicable, and communicate the event to the respective local Argo Fleet Operations team, which may dispatch representatives to the scene to meet first responders on-site and provide additional support.

During the development phase, any interaction with emergency responders or law enforcement, and any collision, is annotated by our Test Specialists to ensure that all relevant data is logged on the onboard event-data recorder.

We believe in working closely and having open dialogue with first responders in our test cities. In addition to the outreach and training material we share, important vehicle documents are located in the glovebox of every test vehicle for easy reference and availability. This information includes an Emergency Responder In-Car One-Pager, vehicle owner information, vehicle registration, and proof of insurance.

We focus on the safety of our passengers and every road actor that our vehicles encounter.

Conclusion

It's thanks to a relentless pursuit of safety that we have made such significant progress in the four years since Argo was established.

We now have test vehicles on the roads in six U.S. cities, and we're preparing to begin testing in Europe. We have come a long way, but we know there is still much to be done.

Success in self-driving hinges on a number of key factors, and as we prepare for commercialization, our goal is to ensure that the technology we have developed helps our automaker partners offer a valuable experience. We are working closely with them to integrate our self-driving system in their vehicle platforms, and innovative pilot programs will help us and our partners build sustainable businesses that enhance the communities where we operate.

All of this will be guided by our Safety Case. As previously outlined, the Safety Case is a comprehensive assessment of safety risks associated with our self-driving system, and how we plant to mitigate them. The Safety Case will form the basis of any independent safety assessments so its execution remains the top priority in our product development and commercialization efforts.

However, developing and delivering the technology is not enough. Even when we reach the point of commercialization, our mission to build self-driving technology that consumers can trust is not complete. We need to be actively involved in preparing the public for a self-driving world, to be sure that the people we want to use our technology know about self-driving vehicles, understand them, and eagerly anticipate their arrival. The work that we carry out now on consumer outreach and education will have a major impact on public acceptance and understanding of self-driving vehicle technology and its societal benefits.

GLOSSARY

Autonomous mode: The state of the vehicle when no human operation is required to drive the vehicle. The self-driving system is responsible for planning a route and driving safely, but during the development phase, Test Specialists operate and monitor our autonomous vehicles on public roads.

Autonomous Vehicle Platform (AVP): The base vehicle, such as the Ford Escape Hybrid, into which the self-driving system (SDS) is integrated.

Autonomous Vehicle System (AVS): The main computing system that makes up the self-driving system that is responsible for performing the driving functions. The AVS, like the CAVS, is also responsible for safely and correctly communicating with the AVP.

Complementary Autonomous Vehicle System (CAVS): The backup computing system that runs in parallel with the AVS; designed to take over control of the vehicle in the event that the AVS enters a degraded state or stops communicating, and to ensure that the vehicle brakes with maximum force if a collision is imminent or guides the vehicle to a minimal risk condition.

Disengagement: The transition of a test vehicle operating in autonomous mode to being driven in manual mode by a Test Specialist. There are two types of disengagements: voluntary, in which a Test Specialist chooses to take control, and mandatory, in which a Test Specialist is required to take control.

Fleet Operations: The team responsible for maintenance and support of the test vehicles, training and coordination of the Test Specialists, and oversight of track and road testing operations

Geonet: A subset of our Operational Design Domain that specifies the exact streets and locations, such as parking lots, that define commercial service areas where the SDS is authorized to operate in driverless mode. Over time, each city's geonet will expand with the addition of new roads and areas where driverless operations will be deployed.

Manual mode: The state of the vehicle when a Test Specialist has the responsibility for driving.

Operations Advisory: A notification issued across the company to report a safety concern, direct appropriate changes to fleet operations and start a review process designed to continuously improve the self-driving system.

Operations Manager: The person responsible for road testing operations in any one of the cities where we operate.

Playforward: A type of simulation which shows how the SDS would have handled a specific scenario in the seconds after a Test Specialist took manual control of a test vehicle.

Release Candidate Process: The carefully managed testing and review process for all new versions of software prior to any approval for distribution to the entire vehicle fleet.

Remote Guidance: A cellular-based connectivity capability that provides human support in the form of authorization to the SDS to perform specific driving tasks, but does not provide teleoperation to remotely drive the vehicle.

Resimulation: A virtual testing technique in which data logged during a closed course or public road vehicle operation is played back through the SDS to measure how it would respond to the same situation with updated hardware or software.

Safety Case: An evidence-based document supporting the commercialization of driverless operations enabled by the Argo self-driving system.

Safety Management System: A formal, top-down, organization-wide approach to managing safety risk and assuring the effectiveness of safety risk controls, as described by the U.S. Federal Aviation Administration, that Argo uses as a model to define its systematic procedures, practices, and policies for the management of safety risk.

Self-driving system (SDS): The integrated hardware and software system composed of a suite of sensors, including high-resolution cameras, lidar, radar, microphones, and inertial sensors, as well as custom, power-efficient, high-density ruggedized computing hardware, that together enable SAE Level 4 self-driving capability.

Terminal: The location in our operational cities where the test vehicles are based, maintained and supported by the Fleet Operations team.

Test Specialist: An individual trained to be responsible for operating and monitoring our autonomous test vehicles during the development phase.

Test Managers: The employees responsible for the test mission assignments, dispatch and all policy and procedures of fleet operations, including management of the Test Specialists; plus serving as a liaison between the Fleet Operations and engineering teams.

ARGO AI

www.argo.ai
info@argo.ai
+1 412-525-3483
Pittsburgh, Pennsylvania