

TOYOTA VOLUNTARY SAFETY SELF-ASSESSMENT FOR SAE LEVEL 4 AND LEVEL 5 AUTOMATED VEHICLE TECHNOLOGY TESTING ON PUBLIC ROADS

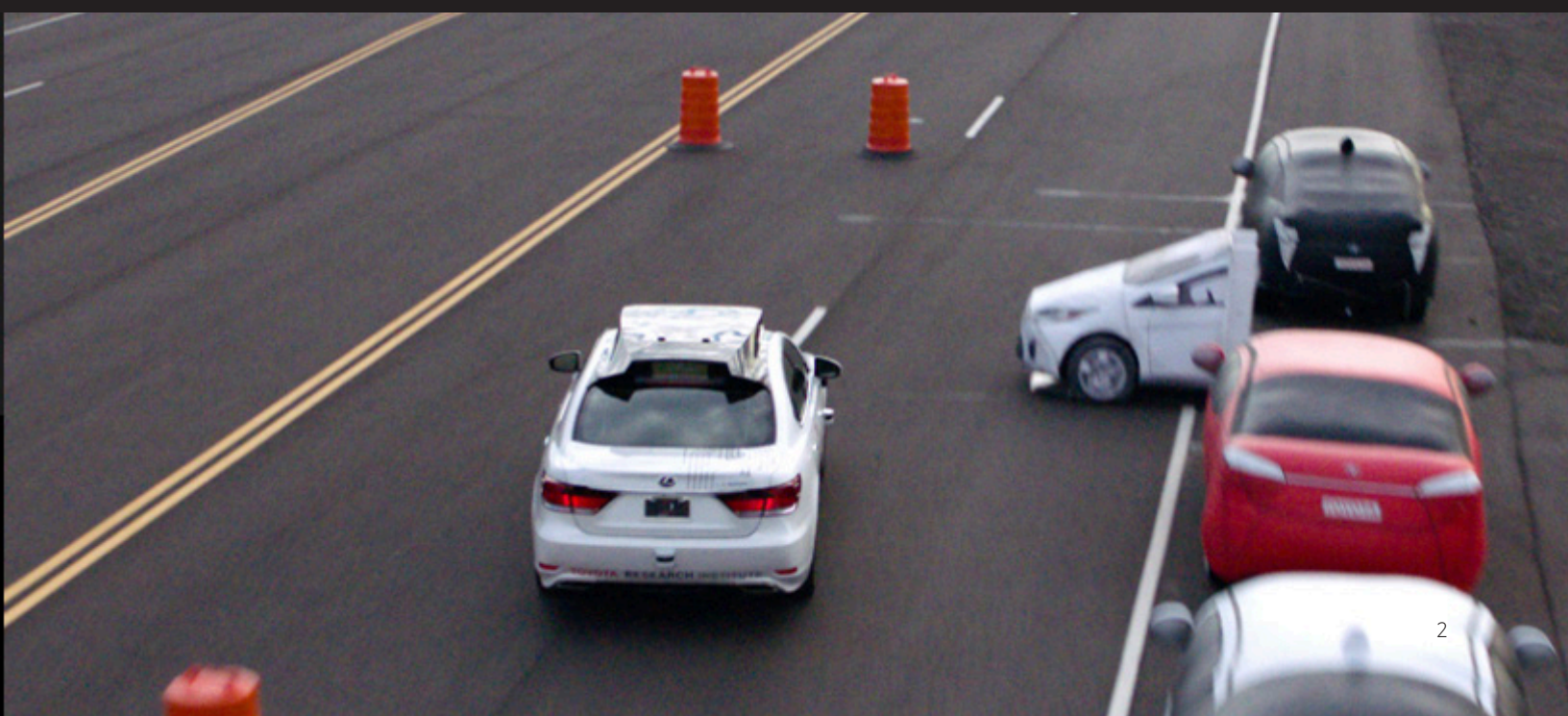
Based on information as of March, 2020



TOYOTA

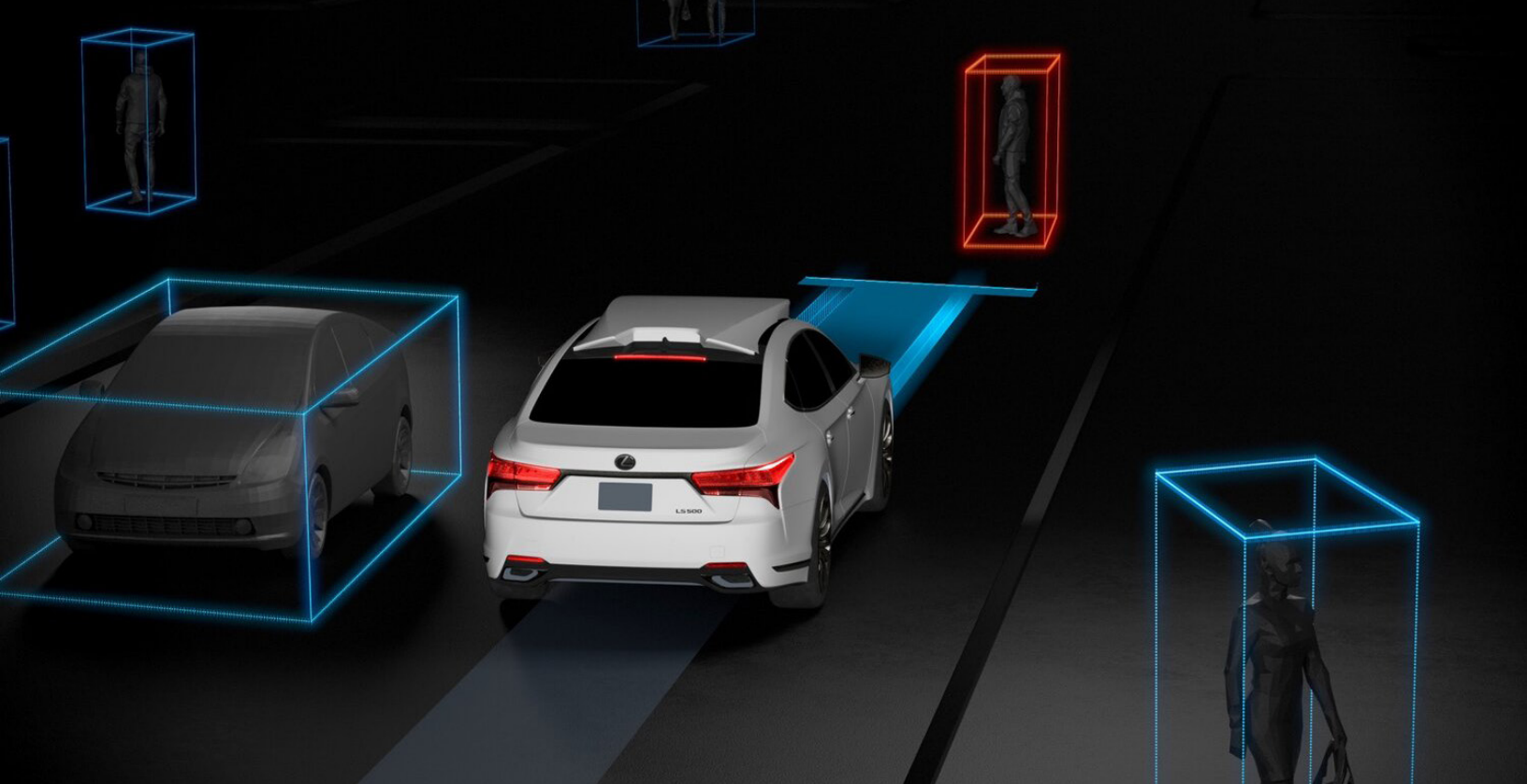
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01 Introduction



Automated driving and active safety hold the promise of fundamentally improving the safety, accessibility, and efficiency of automotive mobility. Their development is also one of the most difficult research challenges in the industry's history, requiring advancements in artificial intelligence, computing hardware, sensors, and human factors design, to name just a few.

This document, developed in accordance with "A Vision for Safety," the Automated Driving Systems 2.0 framework released by the U.S. Department of Transportation (DOT) and National Highway Traffic Safety Administration (NHTSA), details the programs, policies and protocols Toyota has in place to promote safety and support the development of automated driving technology through testing on public roads.

At Toyota, we believe in the potential of this emerging technology to help society take a meaningful step towards dramatically reducing traffic injuries and fatalities. It is why we are pursuing this technology at Toyota companies like the Toyota Research Institute (TRI) and why we are collaborating with others in the field to enhance public understanding and support the development of regulations and common standards.

We believe that unrestricted (SAE Level 5) automated driving—anywhere, any time and in any weather—is attainable; but many years away.

Until such time, we believe we can significantly reduce traffic fatalities and injuries by developing and deploying ever more capable active safety systems.

While we believe our current approach is appropriate, we continue to evolve and grow to help lead the development of best practices in the industry. We share a common goal of helping the public quickly and safely benefit from automated technology.



02 About This Report

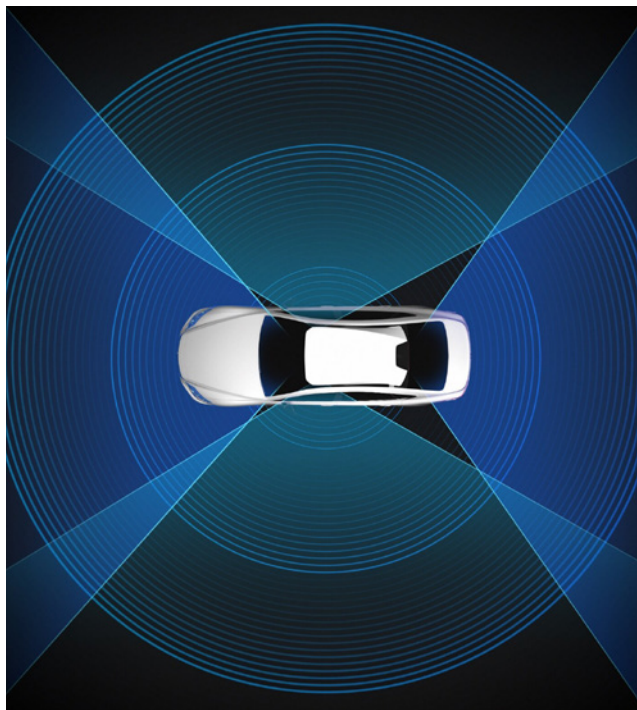
Toyota's research into automated driving and active safety is divided into two distinct approaches:

1. For those who cannot currently drive because of age, infirmity, or any other reason, we are working to develop an automated driving approach that ultimately removes the human from the driving equation, allowing a vehicle to drive on its own without human oversight or fallback responsibility. We call this approach Toyota Chauffeur.
2. To help improve safety in vehicles with a human driver, we are utilizing Toyota's underlying automated technologies to develop an active safety system designed to amplify and enhance the driver's capabilities through blended control, in which the system provides seamless assistance to the driver when the driving task is beyond his or her capability. We call this approach Toyota Guardian™.

Toyota tests Chauffeur and Guardian (and the subcomponents of these approaches) in a manner that safely advances their development, including virtual simulation, scenarios on closed-course test tracks, and driving on public roads. Across this testing program, we follow appropriate industry standards and best practices for safety. This includes the best practice published by the Automated Vehicle Safety Consortium (AVSC), a pre-competitive consortium formed under the SAE (SAE-ITC, Industry Technologies Consortia), entitled "AVSC Best Practice for in-vehicle fallback test driver (safety operator) selection, training, and oversight procedures for automated vehicles under test" and SAE J3018, "Safety-Relevant Guidance for On-Road Testing of SAE Level 3, 4, and 5 Prototype Automated Driving System (ADS)-Operated Vehicles." For example, prior to any public road testing, test vehicles undergo thorough physical and software checks. This includes testing the overrides, the emergency shutoffs, and the system's capability for operating in the specific, documented operational design domain (ODD),

which establishes the specific conditions under which an automated technology is designed—and allowed—to function. The ODD to be tested is set to match the system capabilities being developed and is determined following an analysis of the system through simulations using U.S. public road data, as well as closed-course evaluations of the vehicle and safety driver performance.

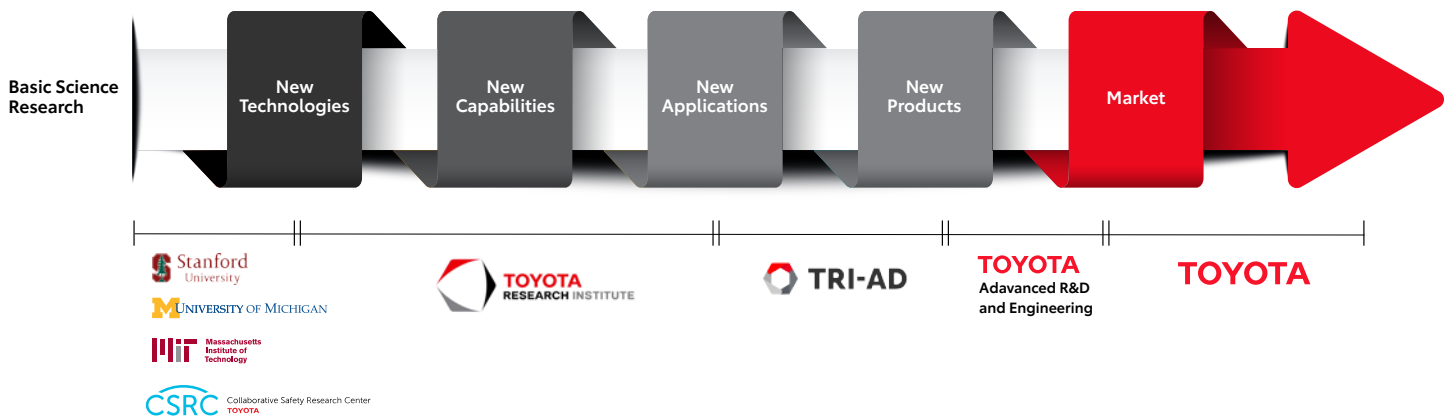
This report discusses Toyota's policies and practices with respect to public road testing of SAE Level 4 and Level 5¹ automated technology in the United States, which is currently being exclusively conducted at TRI. This includes ongoing testing of Chauffeur systems in limited geographies, under a strong technical and procedural framework designed to help ensure the safety of the general public. This report does not address testing of Toyota Guardian™, which is currently only tested on closed-course tracks and through simulation, nor SAE Level 3 which is being pursued through a different research path.



¹ SAE J3016 "Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles" defines the levels of automation. The document is available for free download at https://www.sae.org/standards/content/j3016_201806/. A corresponding summary graphic is available at <https://www.sae.org/news/2019/01/sae-updates-j3016-automated-driving-graphic>.



03 Toyota's Approach to Automated Driving R&D



Across its global operations, leveraging a range of external research partnerships and internal affiliate capabilities, Toyota pursues basic scientific research into advanced technologies in order to support the development of new technical capabilities that can, in turn, be deployed in new automated driving applications like Chauffeur. These applications are then developed into a range of automated driving consumer products.

This overall progression is implemented through four principal phases. Each supports and informs the others, but follows its own strategies to achieve distinct goals:

- **Research:** Centered in the U.S. at TRI and the Toyota Collaborative Safety Research Center (CSRC). TRI applies basic science research and new technologies to discover, develop, test, and iterate new capabilities for the realization of automated driving applications to create cutting-edge solutions that can demonstrate what is possible. CSRC promotes advanced research and technology to realize the safe integration of future mobility solutions for all.
- **Advanced Development:** Principally managed in Japan at Toyota Research Institute—Advanced Development (TRI-AD), which takes the concepts and feasibility prototypes pioneered by TRI researchers and develops them into automotive-grade hardware and software that is designed to perform reliably. TRI-AD produces vehicle and technology prototypes, still subject to further validation prior to release to the public.

- **Production Engineering and Validation:**

Performed by Toyota's technical operations in Japan and/or at Toyota Motor North America, Inc. (TMNA) in the U.S. As part of Toyota's overall iterative vehicle development process, validation strives to ensure that new vehicles and technology perform as expected, safely and in compliance with applicable standards.

- **Release:** After validation, automated technology will be released for sale in production vehicles.

This organizational strategy allows TRI to explore the most advanced technical solutions and utilizes the deep culture of safety and production efficiencies of Toyota's global operations to help bring technologies to market in a safe and responsible manner. Our research and development programs also allow us to support the discovery of future technologies in parallel to the deployment of current generation systems that may improve the safety of passenger vehicles in the near term.



04 Safety Elements

I. System Safety

Toyota designs its core automated technology, and the protocols used in its testing, to reinforce safety. Collectively, this approach is built on a strong safety culture that incorporates best practices for functional safety into our research activities, which are in turn overseen by multiple layers of institutional controls as research is transformed, refined and prepared for production.

Beyond our research program, Toyota is also working to improve the safety of automated technology testing, development, and deployment industry wide through AVSC and the SAE standards development process. The AVSC is working to create a principles-based safety framework to guide the development of common standards for fleet-managed vehicles equipped with SAE Level 4 and 5 autonomy, and to harmonize the range of programs underway at organizations and standards bodies around the world. In addition, the well-established SAE standards development process has already resulted in publication of multiple documents.

In addition, Toyota is working to improve safety in areas beyond research and testing. This includes joining as a founding member of Partners for Automated Vehicle Education (PAVE), an industry coalition focused on consumer education surrounding automated vehicle technology.

Design Approach

Toyota designs automated technology through a process that is based on best practices regarding functional safety – which means we aim to design the system not only to be safe when it is working properly, but also to take into account reasonably foreseeable malfunctions. This process incorporates a multi-step, end-to-end examination of the entire system, its components and subsystems, including:

- Identifying possible safety risks and the functions needed to mitigate them;
- Assessing the level of performance from each of those functions that would reduce the risk to a safe level; and,
- Designing these functions and verifying them to determine whether they meet the performance needs.

Where applicable, Toyota's functional safety program for automated technology is based upon, and closely emulates, existing functional safety standards. For example, ISO 26262 is a well-known standard for functional safety of electrical or electronic systems in production automobiles. Toyota has adapted these standards to address the realities of automated technology development, as well as incorporating best practices from other industries.

This process is not limited to a technical analysis of the foundational electronic systems. Additionally, it includes a review of a range of real-world dynamic driving situations. Engineers begin by considering what types of behaviors by the vehicle could create unsafe conditions – for example, this includes the boundaries of safe accelerating, braking, and turning – and set those as the limits within which the vehicle can operate in a range of real-world scenarios. Within these guidelines, engineers can analyze elements of the system design, either individually or in combination, to establish potential situations where unsafe behavior might occur and to take steps to prevent them.

Finally, Toyota uses a multi-step process as part of its research efforts to test whether an automated technology is likely to perform as intended. This includes utilizing simulation as a key component of its testing and validation procedures, in conjunction with closed course testing and, ultimately, public road testing.

Safety Case: The Importance of a Safety Driver

Currently, Toyota's safety case utilizes a trained Safety Driver to oversee and control the operations of the automated technology during closed course and public road testing.

The nature of automated technology research is to push beyond those tasks a vehicle can already execute without fault into areas where capabilities are still being developed. Though test vehicles operate in tightly controlled design domains, the traffic environment is complex and unpredictable. As a result, Safety Drivers are not merely a backstop in case of an unexpected disengagement or a

stopgap on the road to full automation. Rather, they are a key component of the development vehicle's overall safety case that can perceive and prevent unsafe driving behavior in situations that push the boundaries of the technology.

Toyota has built its Safety Driver program with these factors in mind. This includes deploying an extensive training program to help maximize the capabilities of its field operations teams, as well as engineering the automated technology itself to keep vehicle dynamics within certain predetermined limits designed to allow for safe intervention by the Safety Driver during testing.

When testing on public roads, Toyota requires at least two field operations team members in the vehicle. This includes a Safety Driver, who drives the vehicle when it is in manual mode. While the automated technology is engaged, he or she is trained to continuously monitor the immediate environment for anticipated safety hazards and override the automation as necessary. The second operator in the vehicle is a Software Technician, who is trained to monitor the proper operation of the automation, including the sensors, perception, prediction, planning, and control systems, and to inform the Safety Driver of any irregularities. In addition, the Software Technician is responsible for communicating with the Safety Driver to enhance the Safety Driver's situational awareness.

The field operations team works in accordance with defined policies, and its performance is tracked through automated and manual logging. Driver best practices set out appropriate body positioning; mirror positioning; approaches to maintain awareness on the road and make conservative judgments; rules of the road for manual driving; and communication requirements for the driving team during automated operation. In addition, Toyota's policy is to activate the sensors to log information about the test drive even when driving manually or in transit to a test location. Operational checklists are completed every time the car is started; this includes updates and checks for both insurance and registration.

System Architecture

As part of our functional safety approach, the software and systems that control Toyota's

automated technology are designed to reinforce safety. Vehicles are controlled by the driving system, which makes decisions about vehicle behavior on the road. The driving system, in turn, is governed by a separate safety system that is run via a separate code base on separate hardware. This safety system imposes limits on the driving system, such as steering, braking, and acceleration boundaries. This keeps vehicle behavior within safe limits such that the driving conditions would likely remain within the Safety Driver's capability of safely taking control of the vehicle if needed.

Safety is also built into the creation of these systems through Toyota's development and testing cycle. As part of our code release process, we employ a code review process as well as regression testing. After code review, the software is then tested using simulation to validate the performance of the components of the code, and then to validate each piece of code when it is integrated with all the other parts of the overall system—a process called unit and regression testing.

After simulation, vehicles and the underlying technology are tested on closed test courses that simulate real world environments. After this testing, additional software modifications are made as necessary, followed by additional simulation to verify their performance. This process is repeated as necessary to verify the proper functionality of the system and the vehicle before testing is conducted on public roads.

Driver Training and Evaluation

The foundation of Toyota's Safety Driver program is a comprehensive training and evaluation program. We apply screening criteria for potential candidates that requires an interview, set number of years of experience, driving test, drug testing, and driving record and criminal background checks.

New Safety Drivers must complete an extensive training program, which includes one hundred sixty-eight hours of total training and multiple levels of qualification to allow for the various types of vehicles in the Toyota research fleet and for both manual and automated operation. In total, trainees spend one month in Toyota's test facilities in California or Michigan to go through



initial training, including observation time shadowing instructors, fault injection training on closed courses, in-class lectures, in-car training on closed courses and public roads, and closed-course emergency drills. Trainees also complete two-days of advanced defensive driver training at Toyota's Arizona Proving Grounds. As stated above, TRI follows, as appropriate, the AVSC's best practice document entitled: AVSC Best Practice for in-vehicle fallback test driver (safety operator) selection, training, and oversight procedures for automated vehicles under test.

II. Operational Design Domain

The ODD limitations can range from geography to traffic conditions, speed, weather, and more. Toyota's automated test vehicles operate on public roads within a defined and tested ODD that is limited by factors including road type, speed, time of day, and environmental conditions. Among other restrictions, public roads testing is currently limited to daytime operations, and automated operation of test vehicles does not currently occur in adverse weather conditions such as rain or snow above set limits.

In addition to setting limitations on vehicle testing, the ODD is also closely linked to the development of performance criteria for the vehicle's object and event detection system. Toyota uses naturalistic driving data and video, simulation, real world driving and other elements to train the automated technology to help it to properly recognize and respond to road conditions and the traffic environment within the defined ODD.

Toyota also sets limits on the operations of its test vehicles that go beyond the criteria established by the ODD. This includes applying vehicle dynamics and operational limits to help assure that the vehicle remains within a safety envelope that allows Safety Drivers to take over operational control within a set period of time in the public road testing environment. These limits are established in close coordination with Toyota's Safety Driver training and evaluation program, which measures Driver response times under various operating conditions, and are set based upon the Driver response times observed during testing.

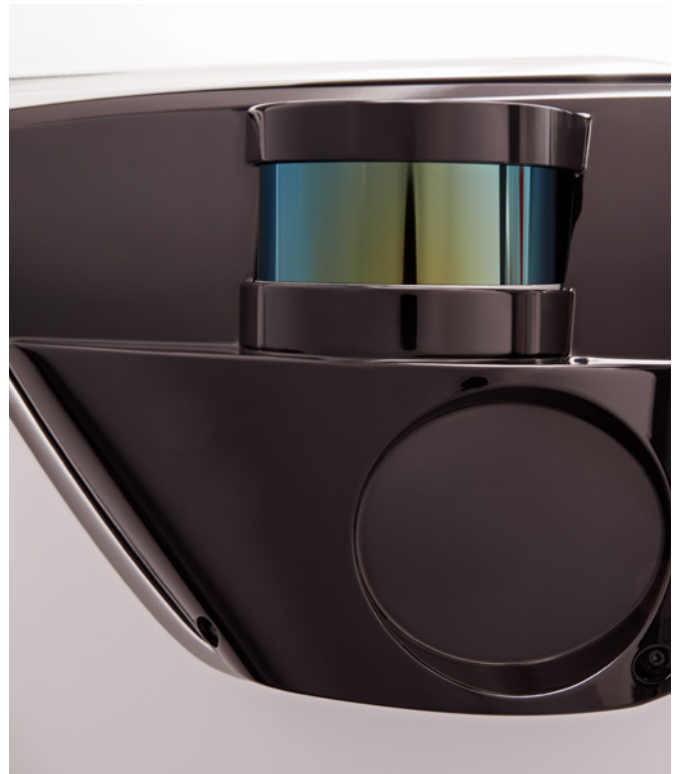
III. Object and Event Detection and Response

Toyota's automated test vehicles make use of a range of sensors and technologies to establish constant, real-time situational awareness of the driving environment inside and outside of the vehicle. This sensor suite, which changes on a regular basis to reflect improvements in technology and specific testing needs, makes Toyota's test vehicles among the most perceptive in the industry. It currently includes:

- **LIDAR (Light Detection and Ranging):** LIDAR uses pulses of near-infrared light to measure the distance between the vehicle and other objects in the surrounding environment, using the results to build a highly detailed, three-dimensional map. Toyota test vehicles use a long-distance LIDAR device that covers the vehicle's complete 360-degree perimeter to perceive objects up to a range of 200 meters. Shorter-range LIDAR sensors positioned low on all four sides of the vehicle are used to detect low-level and smaller objects near the car, such as children and debris in the roadway.
- **Radar:** Radar uses radio waves to measure the distance between the vehicle and objects in the surrounding environment. Though it is similar to LIDAR, the two technologies differ in important ways. For example, while LIDAR can typically build a more detailed map of the environment, radar can more easily measure the velocity of a moving object. Toyota has optimized the radar system on its test vehicles to improve the field of view, especially for close range detection around the vehicle perimeter.
- **Machine Vision Cameras:** High definition digital cameras with a wide field of view help to monitor the environment around the vehicles, especially for close-range detection of people or objects around the vehicle perimeter. We are also currently experimenting with high dynamic range and thermal imaging cameras to incorporate a greater range of perception capabilities.

These sensors feed into a perception system that detects and identifies objects in the road environment, as well as road elements including road signs and lane markings. In addition to vehicle control, this also supports the development of high definition maps.

Collectively, the information provided by vehicle sensors and the perception system support the operations of the vehicle control system, which is designed to evaluate all available data and not rely solely on one input. This means that errors in a single sensor will not necessarily influence the performance of the system. In addition, Toyota's automated vehicle systems possess diagnostic capabilities that assess whether sensors are operational and to detect failures or other interruptions of service.



IV. Fallback (Minimal Risk Condition)

As detailed above under "Safety Case: The Importance of a Safety Driver," public road testing of Chauffeur depends on the Safety Driver to provide fallback support in the event of a system malfunction. Safety Drivers are also trained to proactively take over from the automated technology, even if it is functioning appropriately, in order to avoid potential risks based on the Safety Driver's judgment. As necessary, the Safety Driver is capable not just of taking control from the automated technology, but of completely disengaging it from any interaction with vehicle control.

V. Validation Methods

As discussed, Toyota follows a multi-layered development and testing cycle for any incremental change to its test vehicles with automated technology and their automated driving systems. This includes code testing and review by engineers, system testing and validation in simulation, and then physical testing of the vehicle itself on a closed course prior to operation on public roads.

This process is used for technology research. While Toyota follows many of the same core functional safety principles when developing and validating products intended for consumers, the process is not identical. As automated technologies go beyond the research stage, they will move through later stages of Toyota's R&D program and further evaluated for safety and reliability.

VI. Interaction between Humans and Vehicles with Automated Technology

Toyota believes in the importance of designing automated technology with the human in mind. The industry term for this is human machine interface (HMI), which is one important aspect of automotive safety generally, and to the design of automated vehicles technology specifically.

In particular, user experience (UX) will help determine whether consumers will adopt the automated technology of the future, and in turn whether they will fully benefit from those technologies' life-saving potential. In the case of Chauffeur-style fully automated technology, interactions would need to be designed to encourage user trust that the car will keep them safe en-route to their destination.

The HMI team is comprised of designers from multiple modalities (interaction, visual, auditory, haptics, industrial), researchers (qualitative and quantitative), and engineers (front end, back end, and systems). Using a user-centered design (UCD) process, the team repeatedly iterates designs, implementation prototyping, and research evaluation cycles with potential customers. This process helps to ensure that designs meet the needs of the ultimate users and the goals of the technology. The team deploys multimodal

interactions both in simulation and in-car. Using human-in-the-loop simulators allows the rapid iteration of prototypes as well as allowing study participants to test interactions in safety critical situations while still safely seated in the laboratory.

In addition to proprietary HMI research at TRI, Toyota is also working on public-facing research designed to benefit the industry as a whole. Through the Toyota Collaborative Safety Research Center (CSRC), and in partnership with George Mason University and the Rockville Institute, we are working to develop a taxonomy for how people build mental models of advanced vehicle technologies, and for how those models influence how people learn about, understand, and work with them on the road. We expect the findings will be an important input to assist the development of next generation user interfaces that intuitively help to support the safe operation of automated technology. The CSRC has also partnered with the Massachusetts Institute of Technology, the University of Iowa, and the University of Wisconsin on projects to study approaches to communications between the automated technology and other road users, particularly during the handoff of control between human and vehicle and understanding both driver and road users behavior/acceptance for specific system features.

Finally, as part of our public road test program, Toyota uses a custom HMI system to notify the Safety Driver in the event that the automated technology is about to disengage control of the vehicle. This system leverages a range of communications modes, including lights, sounds, and haptic feedback through the steering wheel. It is also supplemented by the ongoing monitoring of the automated technology performed by the Software Operator in the rear seat of the test vehicle.

VII. Vehicle Cybersecurity

With vehicles becoming more connected, Toyota strives to address ever-changing cybersecurity risks, and as a result, continues its efforts to strengthen and further improve the security of its vehicles. This includes collaborating with other industry members to further strengthen automotive cybersecurity with respect to vehicle technologies. Among other steps,

Toyota was a founding member of the Auto-ISAC focused on sharing cybersecurity threat information within the auto industry and the development of automotive cybersecurity best practices.

With respect to the development and testing of automated technology, Toyota protects the vehicles, and the servers they talk to, from general network access via a multilayer security architecture. Vehicle software and servers are manually updated on a routine basis, helping ensure the use of the latest software releases including functional improvements, bug-fixes, and underlying software security updates. Testing data is logged locally, then transferred, stored and protected by a multi-layer security architecture.

In addition, redundancy is built into the automated technology itself. Test vehicles use several different methods to establish constant, real-time situational awareness of the driving environment inside and outside of the vehicle. The control system is designed to evaluate all of the available data and not rely solely on one input. Acceleration, braking and steering controls are segmented from the rest of the automated system through a separate software compute box to lower the risk of crucial functions being compromised. This means that errors in the driving PC are redundantly checked for soundness by the control unit so there is less likelihood of unduly influencing the performance of the system. In addition, the systems possess diagnostic capabilities to assess whether both external and built-in sensors are operational and to detect failures or other interruptions of service.

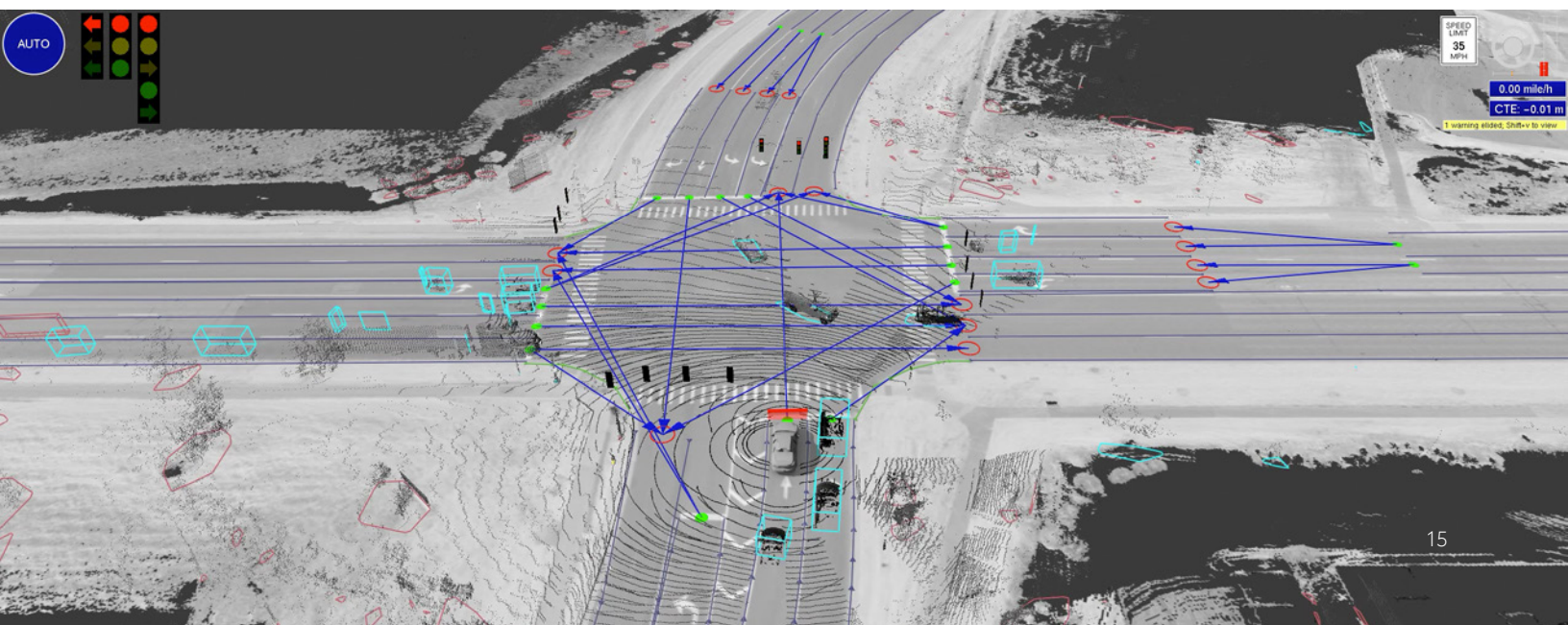
VIII. Crashworthiness

Toyota's fleet of test vehicles with automated technology are adapted from production Lexus vehicles, which were originally designed and manufactured to fully comply with all Federal Motor Vehicle Safety Standards. TRI's principal test model vehicles in the U.S. with automated technology, announced in January 2018, are built on 2016 Lexus LS 600hL vehicles. The next generation test vehicles, announced in January 2019, are built on 2018 Lexus LS 500h vehicles. In addition, when the automated technology is operating, Toyota conducts all public roads testing with the vehicle's underlying automatic emergency braking system active.

IX. Post-Crash ADS Behavior

While Toyota Safety Drivers are trained to follow operational protocols that call for proactively taking over from the automated technology to avoid undue risk, even if it is operating properly, there is still the possibility that a collision could occur when the automated technology is operating.

In the event of a collision, Toyota has defined mandatory "Incident Response" protocols for the field operations team, fleet manager, and executive team. These include consideration for grounding the broader test fleet if necessary, notification of higher-level personnel, securing on-vehicle hard drives to protect crash data, and conducting an investigation of the incident by an internal Collision Review Board. The company also notifies all applicable regulators as necessary and appropriate.



In accordance with Toyota's standard practice, the company seeks to cooperate and be transparent with its regulators and law enforcement.

In the event of a collision, we anticipate a similar data sharing process in the automated technology testing context as with any involving a vehicle without automated technology.

X. Data Recording

Toyota's test platform records data gathered from on-board sensors and system operation onto local hard drives stored on board the vehicle, which is saved for a period of time for later use in system evaluation or simulation as necessary. The platform itself is also designed to capture in read only format log information in the event of a collision to allow for post-crash reconstruction. In the event of a crash, Toyota has processes in place to immediately replicate the log and store the original in a secure facility to prevent tampering and allow for analysis of the data.

After testing data is gathered by the test vehicle, it is transferred, stored and protected by a multilayer security architecture.

XI. Consumer Education and Training

Toyota believes in the importance of education to driving safety. It is a key component of our Integrated Safety Management Concept, through which we work to promote safety at different stages of driving, including parking, active safety, pre-collision safety, passive safety, and rescue. The emergence of automated technology presents new important consumer education needs because these vehicles would fundamentally alter the vehicle's existing relationship with its driver, with its passengers, and with other road users such as drivers of other vehicles, cyclists, and pedestrians.

To support education programs more directly, Toyota has joined with a coalition of industry, nonprofit and academic institutions to launch Partners for Automated Vehicle Education (PAVE). PAVE represents the spectrum of stakeholders who believe in the potential of automated technology. It includes advocates for the blind, seniors, and other groups seeking new mobility

options. Industry members include traditional automakers, parts makers, and technology companies. PAVE also includes insurers seeking to reduce the human and financial costs of road crashes, and an advisory group of leading academic institutions supporting PAVE's activities.

The group has one goal: to inform and educate the public and policymakers on the facts regarding automated technology. The organization is purely educational and does not advocate for a particular technology or for specific public policies. Its members believe that in order to fully realize the benefits of automated technology, policymakers and the public need factual information about the present and future state of technology and its potential benefits.

Toyota is excited to support the educational activities that PAVE will launch, including a website and social media channels providing facts about the potential and reality of automated technology; hands-on public demonstration events so Americans can see, feel, and experience automated technologies; policymaker workshops to help federal, state, and local officials make informed decisions; and training materials for auto dealers to help their customers understand and make use of the technology in vehicles today.

XII. Federal, State, and Local Laws

Toyota complies with applicable federal, state, and local laws when testing automated technology, including test driving in both manual and automated operation. We are also actively engaged through industry organizations and with other stakeholders to support the development of appropriate regulatory standards that both supports innovation and protects everyone who shares the road.

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