AUTOMATED DRIVING AT TOYOTA: VISION, STRATEGY AND DEVELOPMENT
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MESSAGE FROM TOYOTA CHIEF SAFETY TECHNOLOGY OFFICER KIYOTAKA ISE

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Since the 1990s, Toyota has engaged in automated driving technology research and development aimed at contributing to the complete elimination of traffic casualties.

Recently, with the creation of the Toyota Research Institute (TRI) and Toyota Connected (TC), our automated driving research work is progressing much faster than before.

We are releasing this white paper that summarizes our overall approach to automated driving, in the hope it will help explain our way of thinking.

Vehicles with automated driving technology will bring many benefits to society, but one of the top priorities at Toyota is to help make the traffic environment safer.

While it’s a given that one day, cars will be smart enough to drive you, we think building a partnership between you and the car will bring the greatest safety advantage.

We call this the “Mobility Teammate Concept.”

By having our vehicle technologies seamlessly anticipate and interact with human beings and the traffic environment, we will get closer to realizing a future without traffic injuries or fatalities.

As early as 2020, some of our cars will be equipped with automated driving technology to enable driver-supervised automated driving on highways. The system will evaluate traffic conditions, make decisions and take action during highway driving, based on this concept.

We also care about bringing automated safety technologies to the greatest number of people as possible.

That’s why we will equip nearly all our new Toyota and Lexus vehicles in the United States, Europe and Japan with Toyota Safety Sense or Lexus Safety System+ by the end of this year.

As we endeavor to research and develop automated driving technology, we will continue to transfer some of what we’ve learned to future versions of these safety systems. We are dedicated to a future of ever better, and ever safer, cars, for the benefit of all.

伊勢清貴

Kiyotaka Ise,
Chief Safety Technology Officer
Toyota Motor Corporation
1. INTRODUCTION

More than 80 years ago, Toyota Motor Corporation began when Toyoda Automatic Loom Works created an internal department to investigate a new technology: automobile engines. Kiichiro Toyoda saw automobiles would change society, and he understood what mattered was not a machine that could move, but rather what that machine could do for human mobility.

Today, steep declines in the cost of sensors, exponential growth in computing power, and a revolution in the development of artificial intelligence systems once again means technology is poised to revolutionize mobility. At Toyota, we see the potential for automated driving technologies to expand the options available to help people get where they want and need to be – safely and conveniently. Just as we did so many decades ago, we are remaking our company to meet this new challenge.

Importantly, just as Kiichiro Toyoda recognized in 1930, today we understand the true value offered by this groundbreaking technology is not in the machines themselves, but in what they offer to society. Our ultimate goal is not to create autonomy for cars, but rather to expand autonomy for people – to create a society where mobility is safe, convenient, enjoyable, and available to everyone.

As we pursue this vision, we are guided by a commitment to the safety of everyone who uses our vehicles – both in how we research, develop, and validate the performance of vehicle technology and in how we aim to benefit society. In addition to the tremendous positive benefits they offer, cars and trucks are involved in crashes that result in more than a million fatalities annually on the world’s roads. Our research into automated driving is in the direct lineage of Toyota’s long-standing focus on improving automobile safety and advances our ultimate aim of realizing a future without traffic injuries or fatalities.

Thus, we are working to ensure consumers enjoy the benefits of this research sooner rather than later, including by making active safety technology and advanced driver assistance systems available across Toyota and Lexus vehicles. For example, the Toyota Safety Sense and Lexus Safety System + packages include Automatic Emergency Braking, Lane Keep Assist and Automatic High Beams. By the end of 2017, these packages will be available as standard or optional equipment on new Toyota and Lexus vehicles in Japan, Europe, and the United States.

This document provides a comprehensive overview of Toyota’s approach to automated driving, including the dual concepts of Guardian and Chauffeur that guide our research and the Mobility Teammate Concept that guides our product development. We intended it to serve as a central resource to enhance awareness of our accomplishments to date and the work still to be done.

As with any technology revolution, the impact of automated driving will go well beyond cars and trucks to include new business models and product categories, ranging from mobility service platforms to personal robotics solutions. Major challenges remain, but we are inspired to help lead the way toward the future of mobility as we continue to focus on enriching lives around the world with safe and responsible ways of moving people.
TOYOTA’S SAFETY PHILOSOPHY

Toyota approaches automotive safety through three distinct pillars: people, vehicles, and the traffic environment. Under this framework, the company is focused not just on developing new safety technologies, but also on expanding safety education programs and partnerships with governments and other stakeholders to improve the construction of roads and other traffic infrastructure.

Toyota analyzes causes of vehicle-related accidents and occupant injuries by using various accident investigation data. Accidents are recreated in various simulations to help us develop safety technologies. In addition, experiments on actual vehicles are conducted before launch. Post-launch, the effectiveness of the technologies is evaluated by assessing any accidents that might occur. We strive to learn from actual accidents to continue to help meet the industry's ever higher safety standards.

This work is united under the company’s Integrated Safety Management Concept, which focuses on mitigating the risk of collision at each stage of driving. This includes Parking, Active Safety, Pre-Collision Safety, Passive Safety, and Rescue. Since the 1990s, Toyota has used this approach to support the development of automated driving technologies, with new developments offering consumers increases in safety by expanding the range of potential causes of collisions that can be mitigated by the vehicle.
2. THE FUTURE OF THE DRIVER – VEHICLE RELATIONSHIP

For some, a car is nothing more than a means of transportation, moving people or goods from one place to another and not much different than a train or aircraft. At Toyota, we see a car as something more – a feeling we know people share around the world. Indeed, the Japanese language has a word to describe this emotion – “Aisha,” or “My car, I love it.”

Why is this? What is it about cars that makes people love them?

We believe the relationship with our car is fundamentally different from so much else in our lives. It’s a safe, personal space that provides a comfortable and relaxing environment. It grows and changes to reflect who we are. The interior space, with features such as audio or entertainment systems, and the external appearance of the vehicle itself can be customized to express our unique identity. At a more social level, cars belong to families and are sometimes passed on to the next generation. They grow with us; we don’t drive the same car at age 16, 20, 30, 40 or 60.

Each of these changes helps to build a deep and meaningful relationship between a car and its owner. Our car becomes the only one like it in the world: a unique reflection of our own life. We pamper our cars, abuse them, and use them extensively. They carry our things and bear the marks of our relationships: a sticker here, a coffee stain there, and that time where we made a tear in the back seat and never bothered to get it fixed. Over time, a car stops being just a mode of transportation and becomes something we love.

For Toyota, the relationship between cars and people is fundamental to everything we do, including our research into automated vehicles. We use the word “teammate” to describe our concept for automated driving. It reflects our belief car and driver must help each other to make driving safe, comfortable, and fun. Even in a future where driving has been automated, we believe this relationship means cars will continue to be loved and that automated driving technologies can bring cars and people even closer together.

What does this relationship mean in practice? When it comes to safety, driving skills don’t just differ between people; they vary over time for everyone as well. Experience, age, medical conditions, or simple fatigue can all change our capability on the road from moment to moment. That’s why Toyota designs automated driving technologies to meet these shifting needs, helping to support safe driving regardless of the condition of the driver.

Of course, there are also people who want a specific driving experience and expect the vehicle to perform the way they want, when they want. That may mean a sporty driving mode in some situations and a smooth ride in others. We believe advanced vehicle technologies should respect these unique and changing needs and respond with the capability that a driver desires while maintaining the appropriate level of safety support.

In short, Toyota believes cars should learn from their owners, becoming more loved as they meet their needs, and grow to reflect their unique tastes over the course of their lives together.
3. WHY TOYOTA IS DEVELOPING AUTOMATED DRIVING TECHNOLOGY

Toyota is guided by its Global Vision, which calls on the company to “lead the way to the future of mobility, enriching lives around the world with the safest and most responsible ways of moving people.” This mission influences everything we do, including making high-quality cars and trucks, constantly innovating, and working to safeguard the environment.

Automated driving is the natural next step in our work as a mobility company. It expands upon traditional automotive capabilities to help people get to where they want and need to be. Toyota believes automated driving technologies have the potential to benefit all of society, helping to eliminate traffic fatalities and injuries, reshape cities, reduce emissions, and achieve our ultimate goal: safe and smooth mobility for everyone.

IMPROVING SAFETY

First and foremost, Toyota is committed to automated driving because the technology offers the promise of a world with almost no casualties from crashes. At present, there are about 1.3 million worldwide traffic fatalities annually and far more traffic injuries. Automated driving technology could drastically reduce this number. Our work on this technology follows from our commitment to safe driving, with a goal of developing a car incapable of causing a crash and that can avoid many crashes caused by other vehicles or external factors on the road.

This focus on safety carries through all of Toyota’s research and development of automated driving systems. This means extensive testing and validation to help ensure the proper performance of new technologies before their market introduction and a focus on expanding the adoption of potentially life-saving features to non-fully autonomous vehicles.

MORE EFFICIENT TRANSPORTATION

Beyond their core safety benefits, automated driving systems may help make the traffic environment smoother and more efficient. This could provide meaningful improvements to air quality, through reduced emissions, and to the quality of life of drivers. This would also allow everyone to continue to enjoy the fun of driving while significantly improving the quality of time spent in a vehicle during routine commuting or long drives.

Vehicle automation also holds the promise of increasing access to vehicle travel to a larger portion of the world’s population through affordable, on-demand mobility models. “Mobility-as-a-Service” (MaaS) will increase personal mobility, especially for people with physical limitations, supporting more economically vibrant and efficient communities. This type of on-demand transportation can transform cities. For example, parking areas in urban centers could be repurposed for people rather than vehicles, with autonomous MaaS vehicles helping cities evolve into more environmentally friendly spaces with greatly reduced emissions, traffic, and noise.

A REVOLUTION BEYOND CARS

Toyota believes the technology behind automated vehicles will bring sweeping benefits that extend far beyond cars and trucks. Artificial intelligence offers the potential to revolutionize and improve the daily lives of millions by creating new categories of technologies and services.
Toyota leverages its research into automated driving to create new solutions, such as robots with enhanced perception, movement and reasoning that can expand the freedom of movement for all, including people with limited mobility associated with age, illness, or disability.

Assistive robots, for example, can empower and enable people who might otherwise be restricted in their ability to move around their homes or in their communities. These systems show promise in helping seniors “age in place” rather than moving into assisted living facilities – an important potential benefit given current demographic trends in many societies.

4. HOW TOYOTA APPROACHES AUTOMATED DRIVING DEVELOPMENT

DEFINITIONS: AUTOMATED OR AUTONOMOUS?

Over decades, vehicles have become more automated. Direct control over key functions, such as acceleration and braking, is increasingly handled by computers. More recently, new technologies have emerged to perform additional tasks, such as helping keep a vehicle in its lane or taking some control if a collision is imminent.

With the rise of systems that can perform some or all driving tasks, a host of terms have entered the market to describe them. These include “automated,” “highly automated,” “semi-” and “partially autonomous,” “self-driving,” and “driverless,” to name a few.

In general, Toyota uses the word “automated” to describe vehicle functions performed with little or no direct human control. We use the term “autonomous” to describe only those vehicles where an automated system can perform the full-time dynamic driving task.

By contrast, much of what is commonly described as an “autonomous vehicle” is not truly “autonomous” from human oversight or driving responsibility. Care using these terms is important, as their application to vehicles in the market may impact consumer expectations and understanding about how those vehicles perform. As we implement these technologies in passenger vehicles, we believe it is more appropriate to describe accurately, or to use terminology that suggests, the actual function the vehicle can perform.

Regardless of whether one prefers “automated” or “autonomous,” just one word fails to describe the range of research into the capabilities of these emerging vehicles. For that, international standards have been developed to establish a baseline.

STANDARDS FOR VEHICLE AUTONOMY

The SAE International standard J3016 categorizes vehicle autonomy based on whether a system can operate in some or all driving modes, and whether the driver or the vehicle is responsible for three categories of driving tasks: steering and acceleration/deceleration; monitoring the driving environment; and fallback responsibility if the system cannot manage dynamic driving tasks.
SAE has defined levels of vehicle automation that range from no automation at Level Zero to full automation at Level Five.

<table>
<thead>
<tr>
<th>SAE level</th>
<th>Name</th>
<th>Narrative Definition</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>No Automation</td>
<td>the full-time performance by the human driver of all aspects of the dynamic driving task, even when enhanced by warning or intervention systems</td>
</tr>
<tr>
<td>1</td>
<td>Driver Assistance</td>
<td>the driver assistance system of either steering or acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task</td>
</tr>
<tr>
<td>2</td>
<td>Partial Automation</td>
<td>the driving mode-specific execution by one or more driver assistance systems of both steering and acceleration/deceleration using information about the driving environment and with the expectation that the human driver perform all remaining aspects of the dynamic driving task</td>
</tr>
<tr>
<td>3</td>
<td>Conditional Automation</td>
<td>the driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, with the expectation that the human driver will respond appropriately to a request to intervene</td>
</tr>
<tr>
<td>4</td>
<td>High Automation</td>
<td>the driving mode-specific performance by an automated driving system of all aspects of the dynamic driving task, even if the human driver does not respond appropriately to a request to intervene</td>
</tr>
<tr>
<td>5</td>
<td>Full Automation</td>
<td>the full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver</td>
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These levels provide valuable and useful guidance, and they serve an important role to bring consistency to global discussions and regulation around vehicle automation. However, when using this scale, we also consider the following three points:

1. The taxonomy collapses several dimensions of varying capability and responsibility onto a single axis, and therefore implies a progression in vehicle automation from Level Zero to Level Five. In fact, automakers and technology companies are exploring the automated driving aspects of several SAE levels simultaneously.

2. SAE Level Three automation, where the vehicle is 100 percent responsible for monitoring the driving environment and must give sufficient time for drivers to act as fallbacks, is potentially as challenging to implement as Level Four automation, where the human driver has no responsibility at all.

3. The difficulty of the driving environment – whether from traffic, weather conditions, construction, or other factors – is only used to differentiate SAE Levels Four and Five. In fact, this is a complex metric that applies to all levels.
HOW TOYOTA THINKS ABOUT VEHICLE AUTOMATION IN ITS RESEARCH

Toyota’s work is divided into three basic areas of study: the capabilities of the automated driving system, the capabilities of the driver, and the difficulty of the driving environment.

Autonomy Capability

In our research into automated driving, we focus on two types of capability – one we call “Chauffeur” and another we call “Guardian”:

1. **Chauffeur Capability** is a measure of the degree to which the vehicle takes primary responsibility for driving, relieving the human driver of some or all driving tasks. If the Chauffeur capability is low, the human may be responsible for monitoring the environment and acting as a fallback (similar to SAE Level Two). If the capability is a bit higher, the human driver may be responsible only for acting as a fallback (similar to SAE Level Three). If the Chauffeur capability is high, the human driver may have no responsibility at all (like SAE Levels Four and Five).

2. **Guardian Capability** is a measure of how much the automated driving system helps to protect vehicle occupants while the human is driving – both from mistakes or other errors by the driver and from external factors on the road such as vehicles, obstructions, or traffic conflicts. The higher the Guardian capability, the greater the number and types of crashes it can help protect against. For example, at a modest level of Guardian capability, systems like Lane Departure Alert (LDA) and Automatic Emergency Braking (AEB) can help prevent some crashes. At the highest level, Guardian capability would help ensure a vehicle driven by a human being would never cause a crash, regardless of any error made by the human driver, and steer a vehicle to avoid many crashes that would otherwise be caused by other vehicles or external factors.

Although Chauffeur and Guardian capabilities reflect distinct concepts for automated driving, their development builds on similar perception, prediction, and planning technology. Indeed, the hardware and software required for Guardian capability serves as the backbone for Chauffeur capability.

Human Driver Capability and Environmental Difficulty

Toyota’s work to develop automated driving technology is broader than just the capabilities of the vehicle itself. It also considers the capability of human drivers and the difficulty of the driving environment.

Importantly, driver capability and driving difficulty are not static. They instead rise and fall over time – driver capability adjusts based on factors like skill, level of fatigue, and level of distraction; driving difficulty shifts based on a range of issues including weather, traffic, or construction. Most of the time, driver capability may be sufficient to prevent a crash. It is the times when driving difficulty rises above the driver’s skill that a crash is likely.
Automated driving offers the potential to help offset those periods when driving difficulty is higher than the driver’s capability to navigate safely and provides Guardian capability when necessary to help prevent a crash. What’s more, at times of low driving difficulty, automated driving might be able to provide Chauffeur capability to relieve the driver in certain conditions.

At present, Guardian capability’s technical abilities might be higher than the driver’s skill only in some circumstances. Over time, though, Guardian capability will grow steadily as technology improves, with a goal of creating a vehicle never responsible for a crash regardless of errors made by a human driver. At the same time, Chauffeur capability will advance toward a goal of being able to drive safely in all conditions without any human responsibility for supervision or fallback.

Importantly, driving environments can be extremely complex and difficult, and no automated driving system – regardless of how capable it may be – is likely to prevent crashes entirely. A fundamental question yet to be addressed is “how safe is safe enough?” The answer will depend on government regulation, liability risks, societal acceptance, and what is technically possible. In general, we believe systems providing Chauffeur capability will need to be significantly safer than average human drivers to be accepted by society. Guardian capability, by contrast, may be judged against a lower standard, which is, on average and as often as possible, to “do no harm.”
5. AUTOMATED DRIVING TECHNOLOGY DEPLOYMENT STRATEGY

OUR GUIDING DEVELOPMENT PHILOSOPHY: THE MOBILITY TEAMMATE CONCEPT

Toyota’s overall development philosophy for automated driving technology is the Mobility Teammate Concept (MTC), an approach built on the belief people and vehicles can work together in the service of safe, convenient and efficient mobility.

The MTC combines all of Toyota’s research into automated driving capability – the ability of the human driver, and driving environment difficulty – and merges them into a vision in which people and vehicle “team up” to monitor and help each other whenever necessary. In the near term, this approach capitalizes on the different skills that humans and machines bring to the challenge of safe driving. Indeed, thanks to the power of connected systems and cloud-based technology, this sharing of responsibilities means intelligent vehicles will improve continually, with every car and truck benefiting from the experience of each driver. As technology advances, MTC will allow for vehicles to adapt and expand their support based on the capabilities of individual drivers, including those who might otherwise be unable to drive safely.

Importantly, MTC is a philosophy built on the belief people should have choices. Rather than removing humans from any engagement with their own mobility, this allows people to enjoy the fun and freedom of driving when and if they choose, while also benefiting from the capabilities of automated driving when they wish. Indeed, under MTC, individuals can choose Chauffeur capability in some situations, such as highway and long-distance travel, or the support of Guardian capability in others, such as at lower speeds or on shorter trips.

Finally, MTC expands its focus on human vehicle interaction to go well beyond the relationship between automobile and driver. This includes the interactions among vehicles and others sharing the road, including pedestrians, bicyclists, and other drivers.

PRIVATELY-OWNED VEHICLES

In 2003, Toyota introduced its first millimeter wave radar based Pre-Collision System (PCS). Later Toyota rolled out the system to more-affordable vehicles such as Prius. Developing advanced technologies first, then finding ways to bring them to a more popular and affordable range of vehicles, continues to be Toyota’s strategy. This two-axis approach also applies to automated driving technologies, which in many ways are an extension of our previous work on advanced safety systems and which share the same ultimate goal of zero casualties from traffic accidents.
The results can be seen most clearly in Toyota Safety Sense and Lexus Safety System+, which make advanced safety technologies available as standard or optional equipment on new Toyota and Lexus vehicles in Japan, Europe, and the United States. Indeed, future generations of both systems will expand to include a broader range of automated safety systems and technology as research and development progresses.

This approach of beginning with personally owned vehicles is a proven and valuable method for technology development, as it speeds the introduction of advanced systems that can help improve safety, reduce accidents, and ease traffic. Today, thanks to rapid component and IT technology developments, we can often reach mass-vehicle deployment much faster.

Toyota is committed in the near term to bringing vehicles with automated driving capabilities to market. This includes two planned vehicle systems:

- **Highway Teammate**, targeted for commercial availability in 2020, is expected to enable driver-supervised automated driving on highways. The system will evaluate traffic conditions, make decisions, and take action during highway driving. Potential capabilities include merging onto or exiting highways, maintaining or changing lanes, and maintaining distances between vehicles.

- **Urban Teammate**, targeted for commercial availability in the 2020s, will build on the capabilities of Highway Teammate. In addition to detecting pedestrians, bicycles and other vulnerable road users in and around the vehicle, the system is being developed to operate in accordance with local traffic regulations for surface streets, including navigating intersections and obeying traffic lights.

**MOBILITY AS A SERVICE (MAAS)**

Through its own programs and in partnership with various companies in the mobility services space, Toyota actively explores MaaS markets and opportunities. We believe these platforms will accelerate automated driving technology development and help bring its benefits to people who can’t drive.
MaaS addresses one of the key challenges in developing automated vehicle systems – the need for significant driving data to improve core technologies. Initial component costs mean vehicles with automated driving systems are likely to be expensive and sell in small numbers. What’s more, the low usage rates of private vehicles mean each will likely generate relatively little data. With MaaS, those costs can be amortized across a fleet, where higher utilization rates increase the data gathered.

Toyota believes MaaS provided by vehicles with automated driving systems can help lower costs per passenger mile, creating new waves of consumer demand and a virtuous cycle of affordable mobility, safety and convenience. It can also help improve automated driving technology and support greater societal acceptance and consumer adoption. Taken together, the system will bring forward key benefits of automated driving much faster than through private ownership alone.

Beyond automated driving, Mobility Services also offer promising opportunities for Toyota to expand the services it can offer customers. To this end, Toyota has established a Mobility Service Platform to enable collaboration with a variety of services providers.

6. ELEMENTS OF AUTOMATED DRIVING

FUNDAMENTALS OF AUTOMATED DRIVING

Driving automation operates thanks to the interaction of several systems that enable the vehicle to understand the driving environment, make intelligent decisions, and safely navigate to a destination:

● **Localization and Mapping** determines where the vehicle is located within its environment. This requires building a specialized map of the surrounding environment, either from scratch or by drawing from a baseline of prior knowledge that is well-understood and trusted to be mostly correct, and then localizing the vehicle within that map. This system helps a vehicle correctly interpret the data its sensors gather.

● **Perception** combines information from the Mapping and Positioning system with data from vehicle sensors – including cameras, LIDAR, RADAR, global positioning systems (GPS), and inertial navigation units (INU), among other inputs – to collect and interpret information about the vehicle’s current situation and its relationship to its environment. This includes the location and movement of the full range of obstacles, both static and dynamic, including infrastructure, vehicles, pedestrians, bicycles, and more. The amount and complexity of data for analysis makes this one of the most challenging steps in automated driving.

● **Prediction** helps the vehicle imagine where other vehicles, pedestrians, bicycles, etc. are likely to be in the future. Often there are multiple possible predictions (known as hypotheses).

● **Planning** determines one or more safe courses of travel for the vehicle, including decisions such as which lane to travel, where to position the vehicle relative to other dynamic objects, and how much space to afford obstacles. Critically, the Planning system must make decisions about how to safely guide the vehicle under conditions of uncertainty, such as when other vehicles on the road may be blocked from view, or if they behave in unexpected ways. Multiple hypotheses may lead to multiple
possible plans, with the ultimate choice depending on the actions of other vehicles, pedestrians, and more.

- **Control** executes the planned driving trajectories set by the planning system, which are updated constantly based on new information. This is accomplished using actuators that direct vehicle drive functions.

- **Coordination** communicates with other vehicles, the road infrastructure, and cloud databases.

- **External Human Machine Interaction (e-HMI)** manages the communication of information between the vehicle and humans in the traffic environment. Importantly, while communication between driver and vehicle is obviously important, particularly in managing the handoff of control, so too is communication between the vehicle and humans outside the vehicle, such as drivers and pedestrians.

**KEY TOOLS FOR AUTOMATED DRIVING**

An overlapping set of core technologies and tools make the fundamentals of automated driving possible. These include:

- **Artificial Intelligence (AI)** is a broad term for technology that processes information and makes decisions to achieve a certain goal. This may be accomplished via a rule-based system, such as if a vehicle perceives a stop sign and follows a programmed command to stop, or via machine learning, in which a system might process large volumes of information to differentiate a car from a bicycle.

- **Computer Vision** is the process of gathering information from sensors and using it to perceive the surrounding environment. This process leverages artificial intelligence to draw knowledge from the data, identifying and differentiating individual elements, such as cars, pedestrians, trees, and roads.

- **Predictive Algorithms** are used to anticipate the likely behavior of other objects in the road environment, such as the expected future position of another vehicle on the road based on its current trajectory and proximity to other vehicles.

- **Decision Algorithms** choose the vehicle’s proper path based on the predicted behavior of others on the road. Importantly, decision algorithms must operate despite uncertainty, which varies based on conditions including visibility and traffic congestion.

- **Maps** are baseline representations of the core elements of the physical world the vehicle occupies. These include both high-definition maps, which can be generated ahead of time and used by a vehicle when it enters an environment, or generated in real time using algorithms such as Simultaneous Localization and Mapping (SLAM).

- **Sensors** gather data from the driving environment or from the vehicle itself. These include systems that gather data about the world, such as video cameras, LIDAR, and RADAR; those that track location, such as GPS; and those that monitor the movement of the vehicle itself, such as inertial measurement units, or wheel speed and angle monitors.
- **Actuators** are used to control the physical operation of the vehicle, opening or closing the throttle, turning the wheels, or engaging the brakes. Importantly, while much of automated driving is performed by computers at very high speed, actuators are limited by physical constraints, including vehicle dynamics and the speed of the actuator itself. Thus, automated drive systems must account for the lag between issuing commands and the vehicle’s physical response.

- **Simulation** is used to test the performance of automated driving software in a virtual environment. Data gathered from real world testing is used to recreate a variety of traffic scenarios in simulation to test and measure system response and ensure proper operation.

- **V2X Communication** consists of a direct information exchange between vehicles, with roadside traffic management systems, and with pedestrians via digital short-range communication and via cellular networks. These vehicle-to-vehicle (V2V), and vehicle-to-infrastructure (V2I), and vehicle-to-pedestrian (V2P) communications share information about road signals, signs, road conditions, and other vehicles or pedestrians that may be difficult to see. They can also alert drivers of approaching vehicles, pedestrians, red lights, and slow or stationary vehicles. Vehicle-to-network (V2N) supports map data generation and map data updates, as well as various kinds of information delivery and remote control. Together, V2X communications provide an additional means for automated vehicles to gain knowledge about surrounding traffic. The information obtained is combined with data from on-board sensors to enable the vehicle to make better decisions for vehicle control, traffic safety, efficiency, and driver interaction.

7. **CHALLENGES FACING AUTOMATED DRIVING DEVELOPMENT**

We face various challenges to realize and popularize automated driving. These include legal/regulatory updates, social-system reform, and the time needed for societal acceptance, with the detailed situation varying between countries and regions. Automated driving technology also depends on other industries that provide key technologies that together make up the automated driving eco-system. Key subjects, listed below, typically reflect geographical or cultural differences, globally, and regionally. Therefore, one key and unique success factor for automated driving is how we collaborate and cooperate with various stakeholders who are not always actors in the traditional auto industry. To realize and popularize automated driving, we need to appreciate their expectations. Industry collaboration in non-competitive areas that act as a foundation of automated driving systems and vehicles, such as infrastructure or social systems, is an effective way forward.

For example, in Japan, SIP (Cross ministerial Strategic Innovation Promotion Program), under the Japan Cabinet Office, identifies areas of collaborative work and promotes research and development among relevant stakeholders. SIP collaboration scope includes dynamic mapping and cybersecurity.

For some technologies, regional or global harmonization and collaboration across borders would be required to establish a common shared foundation. With such a foundation, we can accelerate our technology development towards improving our customers’ safety, and toward enhancing freedom and efficiency of mobility.
LEGAL/ REGULATORY FRAMEWORK CHALLENGES

- Infrastructure (Traffic Design and Management, Road Construction)
- Cybersecurity
- Data Privacy
- Safety Assurance (Design, Construction, Performance)
- Social System (Vehicle Registration, Licensing, Driving Education and Training, Traffic Rules, Insurance, Law Enforcement, Crash Investigation, Safety and Emission Inspections etc.)

SOCIAL CHALLENGES

- Regional Differences (Custom & Behavior, Tacit Driving Manner and Rules, Ethical Perceptions).
- Social Acceptance (Safety Concerns)
- Sustainable solutions (Smart Cities, Urban Planning).

TOYOTA’S AUTOMATED DRIVING PROGRAMS, PARTNERSHIPS AND INVESTMENTS

TOYOTA COMPANIES WORKING ON AUTOMATED DRIVING TECHNOLOGY

JAPAN

- Toyota Motor Corporation: TMC’s Advanced R&D and Engineering Company leads the company’s efforts to develop automated driving technologies at the global level, pulling together the resources and work of all the other entities listed here, in addition to organizing the research, development, and testing of these technologies by all relevant functions at Toyota Motor Corporation.

- Toyota Central Research & Development Laboratories: Toyota CRDL contributes to the present and future businesses of the Toyota Group by conducting research in a variety of fields. At the same time, it surveys global technology trends and explores new fields of science to propose a vision of the future that will lead to new businesses while contributing to the advancement of science, technology, and industry.

NORTH AMERICA

- Toyota Research Institute (TRI): Toyota Research Institute is a wholly owned subsidiary of Toyota Motor North America under the direction of Dr. Gill Pratt. The company, established in 2015, aims to strengthen Toyota’s research structure and has four initial mandates: 1) enhance the safety of automobiles, 2) increase access to cars to those who otherwise cannot drive, 3) translate Toyota’s expertise in creating products for outdoor mobility into products for indoor mobility, and 4) accelerate scientific discovery by applying techniques from artificial intelligence and machine learning.
• **Toyota Motor North America Research and Development (TMNA R&D):** TMNA R&D has been the driving force behind Toyota’s North American engineering and research and development activities. Based in York Township, Mich., TMNA R&D engineers, scientists and technicians work primarily in three main areas: product development, advanced research and evaluation, and crashworthiness.

• **Toyota Collaborative Safety Research Center (CSRC):** CSRC partners with leading universities, hospitals, research institutions and federal agencies, with a focus on safety research projects aimed at developing and bringing to market new and advanced safety technologies. Research areas include active/passive integration, human experience, driver state detection, and big data/safety analytics, with the results shared publicly with other companies and academia.

• **Toyota Connected:** Toyota Connected launched in 2016 with two mandates: 1) delivering seamless and contextual services and 2) using cutting-edge data analytics to support product development for customers, dealers, distributors, and partners. Toyota Connected provides a range of data and computer science services across Toyota’s operations, including support for ongoing research into artificial intelligence and robotics and the Toyota Research Institute. Toyota Connected is based in Texas and Japan.

• **Toyota InfoTechnology Center:** Toyota InfoTechnology Center, U.S.A., Inc., is a wholly owned subsidiary of Toyota Motor Corporation and has five research divisions: Next Generation Mobility and Society Research, Cloud/Infra Architecture, Intelligent Computing, Network, and System & Software. Projects include next generation cloud platform research, AI based distributed processing and data analysis platform research, and intelligent vehicle communication network research. The company has headquarters in California and Japan.

**EUROPE**

• **Toyota Research on Automated Cars in Europe (TRACE)** Toyota Motor Europe’s Advanced Research team in Brussels collaborates with experts across Europe in the field of computer vision for automated cars. It is organized loosely around a lab structure named TRACE (Toyota Research on Automated Cars in Europe).

  Current partners include KU Leuven, University of Cambridge, CTU Prague, Max Planck Institute Saarbrücken, and ETH in Zürich. Each partner contributes with unique research algorithms, and all elements are integrated into the experimental vehicles under the responsibility of KU Leuven.

  Current activities include state-of-the-art deep learning algorithms for object detection, robust and precise tracking and full scene segmentation and classification. Monocular and stereo-camera algorithms provide long-range depth measurements. The objective is real time-free space estimation for path planning and vehicle control.
TOYOTA AUTOMATED DRIVING RESEARCH DIVISIONS

TOYOTA PARTNERSHIPS FOR AUTOMATED DRIVING TECHNOLOGY DEVELOPMENT

*Toyota Research Institute*

- **Massachusetts Institute of Technology:** The CSAIL-Toyota Joint Research Center projects range from autonomy to self-awareness. Research is aimed at furthering the development of automated driving technologies.

- **Stanford University:** Stanford’s SAIL laboratory is engaged in research projects that include human-computer and human-robot interactions. The focus is on developing innovative and impactful approaches, algorithms, and data. The approach includes research in perception, learning, reasoning, and interaction.

- **University of Michigan:** TRI’s Ann Arbor research facility with University of Michigan (U-M) is focused on research into enhanced driving safety, partner robotics and indoor mobility, automated driving, and student learning and diversity.

*Collaborative Safety Research Center*

- **Children’s Hospital of Philadelphia, University of Virginia, Ohio State University:** A project attempting to quantify key occupant responses (kinematics, kinetics, and muscle activity) to evasive swerving and emergency braking using both adult and child subjects on a test track.

- **Virginia Tech:** A research study attempting to estimate the Residual Safety Problem after Integrated Safety Systems (ISS) is deployed in 2025. ISS consists of all active (auto braking for vehicle, pedestrian, bicyclist, lane keeping, etc.) and passive safety systems (advanced airbag, curtain shield airbag, roof strength, pedestrian protection active hood, etc.)
University of Michigan Transportation Research Institute: An investigation into kinematics of minimally aware adult occupants exposed to Automatic Emergency Braking (AEB) and evasive maneuvers on a test track.

University of Iowa: Research attempting to measure the response characteristics and estimated benefit with respect to reduction in injury/fatalities of adaptive headlamp system that highlights detected pedestrians and bicyclists using both driver and pedestrian/bicycle simulator study.

TASI – Indiana University, Purdue University at Indianapolis: A project attempting to develop test scenarios and methods for the evaluation of vehicle road departure warning and assist and control systems on a test track.

Massachusetts Institute of Technology Age Lab: A project attempting to develop a deep-learning-based, full-scene recognition of vehicle environment from a vision sensor. Examples are vehicles, pedestrians, bicyclists, traffic signs, buildings, curbs, etc.

University of Wisconsin: A project attempting to provide a theoretical and mathematical framework of how drivers communicate with each other in an intersection.

University of California at San Diego: A project attempting to provide a computational prediction model for a transfer of control between the automation and the human driver. The model has factors originated from human motor and perceptual behaviors as well as from scenarios and environments.

University of Iowa – National Advanced Driving Simulator: A project attempting to provide a meaningful and useful dataset of driver behaviors when encountering situations where transfer of control between automation and the human is required.

**TOYOTA INVESTMENTS IN AUTOMATED DRIVING TECHNOLOGY COMPANIES**

Toyota invests in a broad range of companies, either directly through capital investment, through investment funds established in partnership with financial institutions, or through the corporate venture capital arm of the Toyota Research Institute, called Toyota AI Ventures. Portfolio companies include:

*Toyota AI Ventures*

- **Nauto** provides a technology system, designed for professional drivers and fleet managers, that monitors drivers and the road environment to prevent collisions, improve driver behavior, and learn from the diverse data shared across its smart cloud network. The Nauto device is packed with AI-powered sensors and mounted inside a vehicle’s windshield, where it provides powerful visual context inside and outside the vehicle and collects data that can provide meaningful insights.

- **Intuition Robotics** is a leader in the development of social companion technology, including its ElliQ active-aging robotic companion. The company’s technology is designed to positively impact the lives of millions of older adults by connecting them seamlessly with family and friends, making technology accessible and intuitive, and promoting an active lifestyle.
SLAMcore develops advanced algorithms designed to help technology platforms like autonomous cars, drones, and AR/VR systems to simultaneously build a map of their surroundings and position themselves within it. Critically, SLAMcore approaches this challenge with a core focus on power efficiency, a crucial factor for autonomous mobility applications given the need to maximize the power available for locomotion.

8. AUTOMATED SAFETY TECHNOLOGY ON TOYOTA VEHICLES

Some of the following features are only available in specific markets, or may be limited in their capabilities on a market-by-market basis.

I. Toyota Safety Sense and Lexus Safety System+ Features

- **PRE-COLLISION SYSTEM – VEHICLE DETECTION**: Available on TSS-C, Pre-Collision System – Vehicle Detection uses a forward-facing radar and camera designed to scan the road ahead to help you avoid a potential frontal collision in certain situations. When a potential collision is detected, you are alerted with audible and visual warnings on the dash, and brake assistance is automatically activated. If you do not apply the brakes, and the system determines the collision is unavoidable, the brakes are automatically engaged in some conditions.

- **PRE-COLLISION SYSTEM - VEHICLE AND PEDESTRIAN DETECTION**: Available on Toyota Safety Sense P and Lexus Safety System+, Pre-Collision System - Vehicle and Pedestrian Detection uses an in-vehicle camera and radar to help detect a vehicle or a pedestrian in front of you and can help to mitigate or avoid a potential collision. If the system determines that a frontal collision is likely, it prompts the driver to take action using audio and visual alerts. If the driver notices the potential collision and applies the brakes, the system may apply additional force using Brake Assist. If the driver doesn’t brake in time, the system may automatically apply the brakes to reduce speed, helping to minimize the likelihood of a frontal collision or reduce its severity.

- **LANE DEPARTURE ALERT**: Lane Departure Alert helps you stay in your lane. Using a forward-looking camera, the system is designed to detect visible painted lane markings on the road and alert you if you are inadvertently moving out of your lane. The system will alert you with an audible beeping sound, and an indicator light on the instrument panel will flash so that you can then take corrective action.

- **LANE DEPARTURE ALERT WITH STEERING ASSIST FUNCTION**: The Lane Departure Alert helps you stay in your lane. Using a specialized camera, the system is designed to detect visible painted lane markings on the road and alert you if you are inadvertently moving out of your lane. The system will alert you with an audible beeping sound and indicator light on the instrument panel will flash so that you can then take corrective action. The Lane Departure Alert with Steering Assist system brings added functionality. Should the system determine that the driver is not taking corrective steering action, the Steering Assist function will initiate and provide gentle corrective steering when necessary to help keep the vehicle in the lane.

- **AUTOMATIC HIGH BEAM** Automatic High Beams is designed to help drivers see more of what’s ahead at nighttime without dazzling other drivers. When enabled, this feature uses a forward-
looking camera to help detect the headlights of oncoming vehicles and taillights of vehicles in front of you, then automatically switches between high and low beams to provide the most light possible and enhance forward visibility. By using high beams more frequently, AHB may help driver's earlier detection of vehicles and obstacles.

- **DYNAMIC RADAR CRUISE CONTROL (DRCC)**: While staying within a preset speed range, the system maintains an appropriate distance between vehicles, helping make long highway drives less tiring. The system operates at all speeds, enabling the vehicle to follow the vehicle ahead in low speed. This, in turn, helps reduce driver fatigue even in traffic congestion.

II. Additional Features on many Toyota and Lexus Vehicles

- **REAR VIEW MONITOR**: The Rear-View Monitor displays view of the area to the rear of the vehicle when driving in reverse. In some models, a guidance line appears based on the position of the steering wheel. By letting the driver confirm where they are driving, this equipment helps the driver park smoothly.

- **PANORAMIC VIEW MONITOR**: High-resolution cameras mounted on the front, sides and rear of the vehicle are designed to give drivers a “bird's-eye view” of the near environment. Moving View and See-Through View options create a composite image of the vehicle's surroundings as on-screen guides help assist with parking and tight maneuvering.

- **PARKING ASSIST SONAR**: Parking Assist Sonar utilizes ultrasonic sensors integrated into the bumpers that are designed to detect surrounding objects. Using audible tones and an indicator on the multimedia display, the system can notify you of a detected object's location and proximity, helping with routine tasks like parallel parking.

- **INTELLIGENT CLEARANCE SONAR (ICS)**: Intelligent Clearance Sonar scans for stationary objects, like walls or parked cars. Should the system anticipate a collision, it will emit an audible alert, reduce engine or motor output, and may automatically apply the brakes.

- **INTELLIGENT PARKING ASSIST (IPA)**: Intelligent Parking Assist uses ultrasonic sensors to detect surrounding objects and identify parking spaces. The driver stops the car before the open parking space and by pushing a single button, the system guides drivers to the right position for reverse parking and assists drivers in backing into the space.

- **LANE KEEPING ASSIST (LKA)**: When the Radar Cruise Control is activated and the system senses the vehicle deviating from its lane, LKA helps the car stay on course near the center of the lane by continuously applying a small amount of counter-steering force to keep the vehicle in the center of the lane.

- **BLIND SPOT MONITOR (BSM)**: BSM is a system which aims to reduce accidents by alerting the driver to other vehicles in the vehicle’s blind spot diagonally behind the driver’s seat with and visual display in the side mirrors while changing lanes, by using rear side radars.
• **REAR CROSS TRAFFIC ALERT (RCTA)**: RCTA is designed to provide audible and visual indicators, alerting the driver when a vehicle if a vehicle approaches while backing out of a driveway or parking space.

• **REAR CROSS TRAFFIC AUTO BRAKE (RCTAB)**: RCTAB is designed to detect a vehicle using a rear camera, and in the case of a possible collision, helps to minimize damages by using alerts and brake control.

• **INTELLIGENT ADAPTIVE FRONT-LIGHTING SYSTEM (AFS)**: Intelligent AFS is designed to redirect low-beam headlamp units in accordance with the steering angle and vehicle speed at night to improve visibility during cornering.

• **ADAPTIVE HIGH-BEAM SYSTEM (AHS)**: AHS helps provide optimized forward visibility during nighttime driving and automatically turns off the high beam headlamps when another vehicle is detected. When no other vehicle is present, the system turns on the high beams. The system also automatically optimizes the headlamp light distribution so that the high beams do not directly illuminate preceding or oncoming vehicles.

• **APPROACHING VEHICLE AUDIBLE SYSTEM (AVAS)**: EV-operated (Electric Vehicle) hybrid cars run very quietly. When the vehicle is driven at 25km/h or reversing, the system emits an alert sound to help notify pedestrians.

• **ITS CONNECT**: ITS Connect uses the dedicated ITS frequency for road-to-vehicle and vehicle-to-vehicle communication to obtain information that cannot be easily captured with onboard sensors. At intersections with poor visibility, information about oncoming vehicles and pedestrians detected by sensors above the road will be conveyed via road-to-vehicle communication, and information about approaching vehicles will be conveyed via vehicle-to-vehicle communication, with audio and visual alerts warning drivers when necessary. In addition, ITS Connect includes Communicating Radar Cruise Control feature, enabling the vehicle to follow the preceding vehicle more smoothly, obtaining its acceleration and deceleration information via vehicle-to-vehicle communication.

• **AUTOMATIC CRASH NOTIFICATION (ACN)**: ACN helps drivers receive a response from emergency teams. In the event of either an airbag deployment or a severe rear-end collision in an area with coverage, the response center will be automatically notified via embedded cellular technology and GPS. Once the response center agent receives the vehicle ID and the vehicle’s location, the agent can speak with the driver to ascertain the level of emergency. If the driver is unable to communicate, the agent automatically treats the call as an emergency. The response center agent then uses the vehicle’s GPS location to determine the nearest Public Safety Answering Point (PSAP) available to provide emergency support and will offer to stay on the line until emergency assistance arrives.