Future Advanced Driving Support System with Automated Driving Technology

ITS & Advanced Driving Support Systems

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Abstract

Recent years have seen active development around the world toward the practical adoption of automated driving technologies. Based on this background and objective, this article describes the development of automated driving technologies by Toyota Motor Corporation. The first section introduces previous efforts toward the practical adoption of these technologies assuming the installation of magnetic nails in the road surface. The next section outlines a type of automated driving technology under development that recognizes the environment outside the vehicle and makes driving judgments using 360-degree three-dimensional (3D) sensors. This section also describes the configuration of a test vehicle system and software that are currently being studied. Finally, this article discusses the details of the latest technological research for the future practical adoption of automated driving technologies.

Background & Objective

According to statistics released by the Traffic Bureau of the National Police Agency in Japan, the number of fatal traffic accidents fell in 2013 compared to 2012. Despite this drop, however, the number of fatalities still totaled 4,411 people. In addition, the Japanese government has announced a target of halving the total number of all traffic accidents, including those that lead to a fatality (*White Paper on Traffic Safety in Japan (Special Feature): Aiming to Reduce Traffic Accident Fatalities by Half,* Part 1, Vol. 1 [in Japanese], Cabinet Office, 2009). Toyota Motor Corporation has a long history of activities to help reduce traffic accidents. Its overall approach can be summarized as follows:

- The development and adoption of passive safety technologies to help mitigate the damage caused by an accident, such as airbags and crashworthy vehicle body design;
- The development and adoption of pre-collision safety technologies to help mitigate damage immediately before the accident occurs;
- The development and adoption of active safety technologies to help the driver avoid an accident altogether.

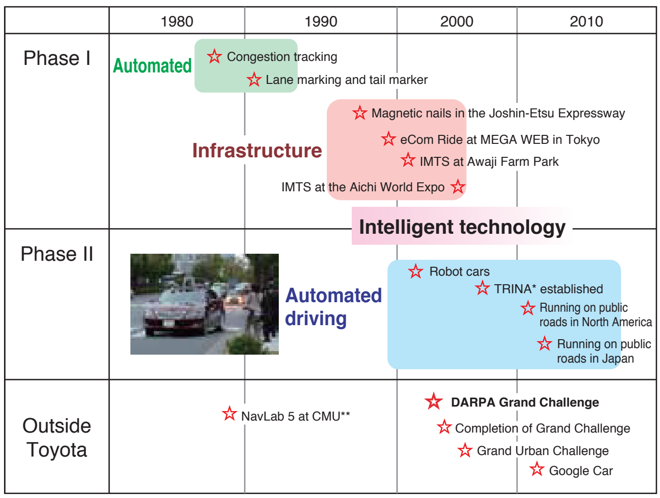
More recently, Toyota has begun to develop automated driving technologies as an effective way of helping to further enhance its active safety technologies. In addition to active safety, Toyota is also working on the development of advanced driving support systems using automated driving technologies to help reduce environmental impacts and to help vitalize mobility in an aging society. This article describes details of previous, current, and future developments related to automated driving technologies.

Previous Automated Driving Technologies

Toyota began the development of automated driving technologies in the 1990s. *Table 1* shows a timeline of this development centering on Toyota. Using the sensing and recognition technology of the time,

TABLE 1

Timeline of automated driving technologies (Year)



*Note: * TRINA: Toyota Research Institute of North America*
*** NavLab 5: name of autonomous vehicle developed by Carnegie Mellon University*
Source: Toyota Technical Review

PHOTO 1
IMTS at Awaji Farm Park

Source: Toyota Technical Review

PHOTO 2
IMTS at Aichi World Expo

Source: Toyota Technical Review

it was difficult to realize highly reliable automated driving in mixed traffic conditions containing non-automated vehicles, as well as under variable weather conditions. As a result, the development of automated driving technologies assumed the establishment of infrastructure devices outside the vehicle, such as the following examples:

- Magnetic nails embedded in the road surface to accurately identify vehicle locations and magnetic guidance controls using on-board magnetic detection sensors;
- Block control coils to help prevent rear-end collisions between vehicle platoons and overall automated vehicle system controls;
- Physically separated dedicated lanes for automated vehicles (manual driving possible in mixed traffic);
- Guard walls provided on both sides of the line to ensure safety in the event of a malfunction and lane departure prevention mechanisms;
- Safety fences to prevent mistaken entry into the lane by pedestrians and the like, and forward monitoring personnel in the leading vehicle of the platoon to confirm the safety of the road ahead.

Example facilities that were developed include the eCom Ride at MEGA WEB in Tokyo (the eCom was a compact EV released by Toyota in 1997), the Intelligent Multimode Transit System (IMTS) at Awaji Farm Park *(Photo 1)* and the IMTS used at the Aichi World Expo in 2005 *(Photo 2)* (A. Tachibana, K. Taguchi, “Practical Application of IMTS”, *Journal of Society of Automotive Engineers of Japan* Vol. 60, No. 10, 2006). These facilities combined the vehicle control technologies described above, electronically guided platoon driving control technologies using vehicle-to-vehicle communication, and multiplex redundant system technologies (such as automated driving computers, safety-critical brakes, control ECUs, and sensors) to ensure safety and maintain system operation in the event of equipment malfunction.

These developments allowed Toyota to gain a wide range of technical expertise related to platoon driving technology, X-by-wire control technologies, traffic system controls, and multiplex redundant system technologies to help prevent collisions in the event of multiple equipment malfunctions.

A number of companies and research institutes have also greatly accelerated the development of automated driving technologies by participating in the Defense Advanced Research Projects Agency (DARPA) Grand Challenge in the United States between 2004 and 2007. This challenge demonstrated the potential of automated driving technologies that recognize the environment outside the vehicle using 360-degree three-dimensional (3D) sensors mounted on the roof. Automated driving processes are then carried out using information from these sensors and map data. Research and development is continuing from various standpoints to achieve practical adoption of these technologies, even after the end of the challenge.

Current Automated Driving System

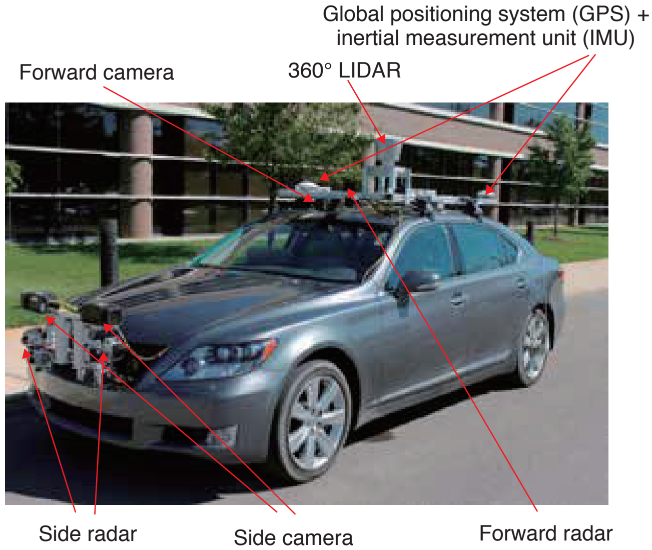
1. System configuration

Toyota is currently developing automated driving technologies for general mixed traffic environments (i.e., normal roads as well as roads dedicated to vehicle usage) containing non-automated vehicles, as well as an advanced driving support system using these technologies.

Photo 3 shows the appearance of the sensors installed on the test vehicle being used in this development. *Chart 1* shows the hardware configuration and *Table 2* describes the roles of each piece of hardware. This vehicle is primarily being used to research and develop aspects of automated driving performance. Before these technologies can be converted into actual products, it will be necessary to optimize the specifications of the sensors and other devices in accordance with the application necessity, as well as to achieve reductions in size, weight, and cost.

PHOTO 3

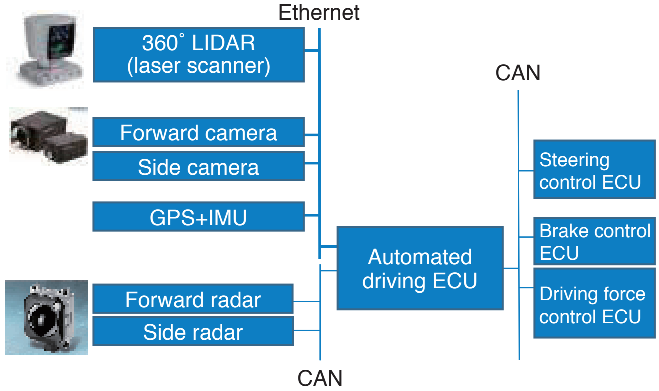
Appearance of automated driving test vehicle



Source: Toyota Technical Review

CHART 1

Hardware configuration



Source: Toyota Technical Review

2. Overall software configuration

Chart 2 shows the overall software configuration. The overall flow of the software processing is as follows. Inputs come from the sensor devices on the left of the figure. Object detection/judgment and route generation is performed on the right. Automated driving is then sustained by outputting control commands to the vehicle (i.e., to each control ECU).

The location of the driver's vehicle is carried out by cross-checking against map data built into the 360° 3D sensors. This location information, the output values of the 360° 3D sensors, static object data, and the like is then used for object detection. Based on these results, the system performs judgment and generates a route. Camera data is used to recognize the state of traffic signals.

3. Recognition of surrounding environment

The largest difference between the current advanced driving support system and previous systems such as IMTS is the technology used to recognize the environment surrounding the vehicle. IMTS resolved the issue of environment recognition by limiting the driving environment through infrastructure. In contrast, the current advanced driving support system uses an object detection module comprised of multiple sensors to obtain the necessary data for automated driving. The performance requirements of this object detection module are as follows: first, the capability to detect every object even in complex environments containing large numbers of random objects and, second, the capability to classify the detected objects as much as possible *(Chart 3)*.

TABLE 2

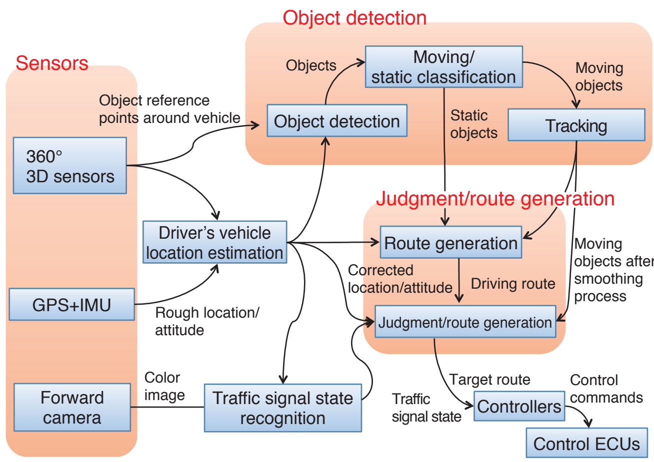
List of hardware

Name	Description/role
360˚ LIDAR laser scanner	Measures objects all around vehicle in 3D. Also used to estimate the location of the driver's vehicle by cross-checking against highly accurate maps.
GPS+IMU	Used to determine the search range for map cross-checks (not to determine the location of the driver's vehicle).
Radars	Detects vehicles approaching at intersections from the front or sides.
Cameras	Recognizes observable light (traffic signals).
Automated driving ECU	Carries out individual sensor recognition operations, integration of recognition results, estimation of the location of the driver's vehicle, and vehicle controls. Actually constructed from multiple PCs.
Control ECUs	ECUs with specifications that expand the permitted control ranges of ECUs used in mass-production vehicles.

Source: Toyota Technical Review

CHART 2

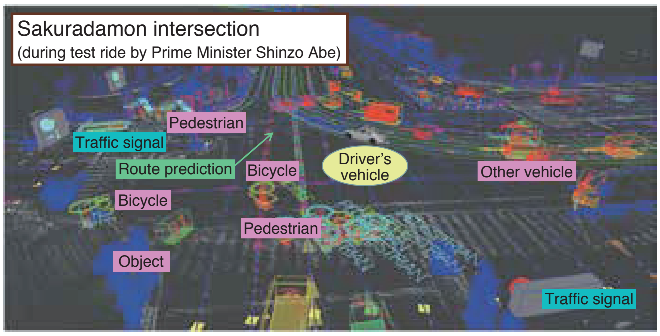
Overall software configuration



Source: Toyota Technical Review

CHART 3

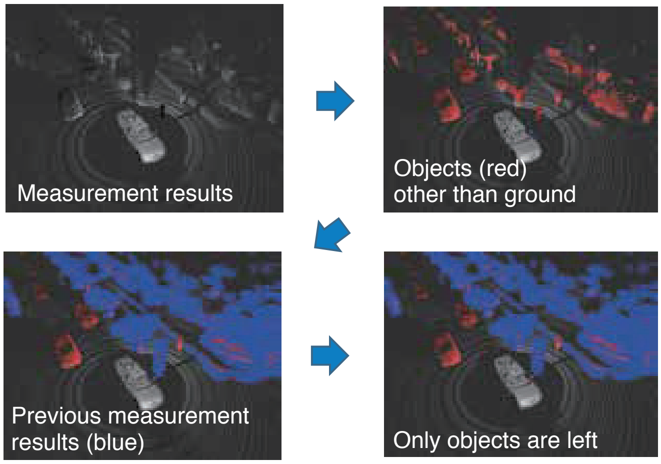
Surrounding environment recognized by vehicle-mounted sensors



Source: Toyota Technical Review

CHART 4

Memory-based object detection



Source: Toyota Technical Review

To detect every object, the object detection module retains the 360° 3D sensor detection results when no object is present as static object data. Measurement data at each time interval is then compared with this static object data and portions that do not match are detected as moving objects. This is called the background subtraction method. In actual operation, the calculation time is shortened by reducing the volume of data through estimating the ground in the measurement results *(Chart 4)*.

Normal object classification is applied to the moving objects detected by background subtraction. These classification results are outputted as additional data for the moving objects. The final surrounding environment recognition results are similar to those shown in *Chart 3*.

4. Actual environment evaluation

In addition to driving on test courses and simulations, evaluations have also been carried out on public roads to help enhance the reliability of the system under various environments *(Photo 4)*. Since road environments differ greatly around the world, the widespread application of this technology is being examined under varying conditions around Ann Arbor in the US and the Tokyo Imperial Palace.

The current override rate (i.e., the frequency of test driver intervention when the vehicle inconveniences another vehicle) is approximately once every several tens of kilometers, depending on the complexity of the road environment. Development is continuing to reduce this frequency and expand the applicability of this technology to more complex road environments.

PHOTO 4

Automated driving in actual road environment (around Tokyo Imperial Palace)

Source: Toyota Technical Review

Latest Technological Development

There are a number of issues that have to be resolved before highly reliable automated driving on normal roads can be achieved. In particular, it is important to develop practically usable sensors and ECUs capable of correctly recognizing and understanding the surrounding environment. It will also be necessary to establish advanced communication technologies between the automated driving system and driver to encourage drivers to trust the vehicle to operate safely.

Toyota is actively working with various leading universities and research institutions around the world to help resolve these issues. Of these efforts, the following sections describe the joint research and development that Toyota is carrying out with universities in Europe into advanced image recognition technology related to traffic environment recognition and the estimation of driver states.

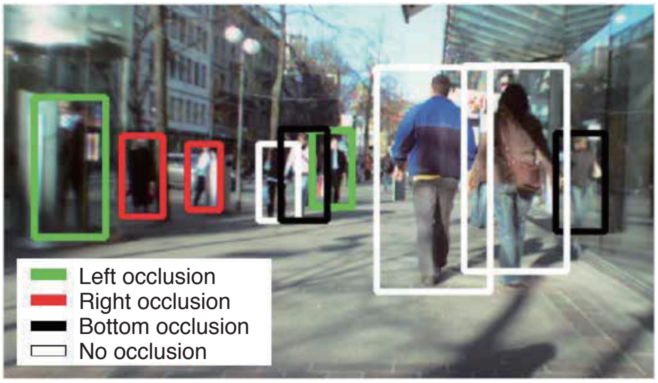
1. Traffic environment recognition technology

A precondition for automated driving on normal roads is the accurate detection, tracking, and future route prediction of various objects in the traffic environment.

Together with the Swiss Federal Institute of Technology Zurich

PHOTO 5

Pedestrian detection technology



Source: Toyota Technical Review

PHOTO 6

Pedestrian motion prediction technology

Source: Toyota Technical Review

(ETH Zurich) and the Catholic University of Leuven (KU Leuven) in Belgium, Toyota is researching methods of recognizing objects as common frameworks, including basic objects such as pedestrians, vehicles, motorcycles, and bicycles, as well as objects with a range of different shapes and motions. The latest research results have accomplished ultra-high speed pedestrian recognition technology with world-leading performance that is particularly robust against occlusions *(Photo 5)* (R. Benenson, Timofte, Van Gool, "Stixels Estimation without Depth Map Computation", *CVVT Workshop at International Conference on Computer Vision (ICCV)*, 2011; R. Benenson, Mathias, Timofte, Van Gool, "Pedestrian Detection at 100 Frames Per Second", *Conference on Computer Vision and Pattern Recognition (CVPR)*, 2012; M. Mathias, Benenson, Timofte, Van Gool, "Handling Occlusions with Franken-Classifiers", *International Conference on Computer Vision (ICCV)*, 2013), while other results include technology that can accurately predict pedestrian motions *(Photo 6)* (S. Pellegrini, Ess, Van Gool, "Predicting Pedestrian Trajectories", in *Visual Analysis of Humans* [Springer, London, 2011]; S. Pellegrini, Van Gool, "Tracking with a Mixed Continuous-Discrete Conditional Random Field", *Computer Vision and Image Understanding (CVIU)* Vol. 117, No. 10, 2013). Toyota is also carrying out joint research with the Max Planck Institute for Informatics in Saarbrücken, Germany, on the same theme (C. Wojek, Walk, Roth, Schindler, Schiele, "Monocular Visual Scene Understanding: Understanding Multi-Object Traffic Scenes", *IEEE Transactions on Pattern Analysis and Machine Intelligence (PAMI)* Vol. 35, No. 4, 2013).

PHOTO 7

Object tracking technology

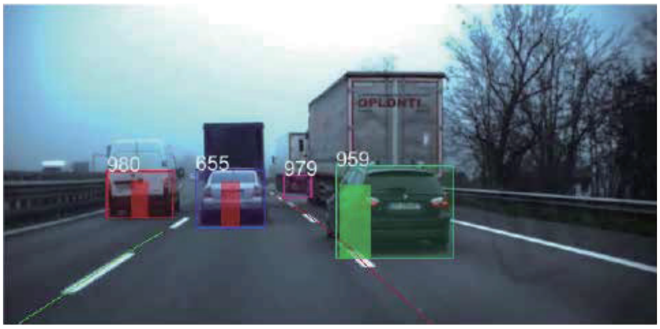
Source: Toyota Technical Review

Additionally, Toyota is carrying out joint research into object tracking technologies with the Czech Technical University in Prague *(Photo 7)* (T. Vojir, Matas, "The Enhanced Flock of Trackers" in *Registration and Recognition in Images and Videos – Studies in Computational Intelligence* [Springer, London, 2014]; (C. Caraffi, Vojir, Trefny, Sochman, Matas, "A System for Real-Time Detection and Tracking of Vehicles from a Single Car-Mounted Camera", *Intelligent Transportation Systems Conference (ITSC)*, 2012). The orientation and shapes of vehicles and pedestrians constantly change as these objects move through a scene, becoming hidden in the shadows of other objects. The capability to determine that an object is the same through a series of scenes (i.e., accurate tracking technology) is indispensable for the prediction of continuing motions and route generation. This joint research has achieved an object tracking algorithm that is robust against changes in shape and occlusions while dynamically updating an object tracking model.

Once accurate vehicle detection and tracking technology is possible, it will also be possible to predict how vehicles will move in the future. In joint research with Inria in Grenoble, France, Toyota has proposed a method to predict vehicle behavior several seconds in advance as a probability that a vehicle will go straight on or change lanes to the right or left, based on the relative locations and speeds of surrounding vehicles with respect to the driver's vehicle (M. Perrollaz, Yodery, Negre, Spalanzani, Laugier, "A Visibility-Based Approach for Occupancy Grid Computation in Disparity Space", *IEEE Transactions on Intelligent Transportation Systems* Vol. 13, No. 3, 2012; C. Laugier et al, "Probabilistic Analysis of Dynamic Scenes and Collision Risk Assessment to Improve Driving Safety", *Intelligent Transportation Systems Journal* Vol. 3, No. 4, 2011). The validity of the acquired data is being confirmed on actual highways *(Photo 8)*.

PHOTO 8

Vehicle behavior prediction technology



Source: Toyota Technical Review

An example of joint research for the future is being carried out with the University of Cambridge in the United Kingdom. The aim of this research is to develop technology capable of universal recognition of traffic scenes (V. Badrinarayanan, Budvytis, Cipolla, “Mixture of Trees Probabilistic Graphical Model for Video Segmentation”, *International Journal of Computer Vision (IJCV)*, 2013; V. Badrinarayanan, Budvytis, Cipolla, “Semi-Supervised Video Segmentation Using Tree Structured Graphical Models”, *IEEE Transactions on Pattern Analysis and Machine Intelligence (PAMI)* Vol. 35, No. 11, 2013). This technology uses deep learning methodology to appropriately consider spatial contrasts and split a scene into meaningful units. Statistical models that express various relationships, such as the relative positional relationship between vehicles and the road and the location of buildings at the top of the screen are being used to derive machine learning frameworks. As shown in *Photo 9*, a certain level of recognition performance has been confirmed in actual traffic environment scenes.

2. Driver state estimation technology

In the application of advanced driving support using automated driving technologies, Toyota believes that properly communicating the state of the system to the driver will help to encourage greater peace of mind and trust in the system. Toyota is working with the University of Manchester in the UK to research a way of accomplishing this goal (A. Caunce, Taylor, Cootes, “Using Detailed Independent 3D Sub-Models to Improve Facial Feature Localisation and Pose Estimation”, *International Journal on Artificial Intelligence Tools* Vol. 22, No. 6, 2013). An important factor in effectively communicating warnings and the state of the system is the capability of the system to accurately identify the alertness of the driver. Driving relies heavily on visual sensations. Fatigue, drowsiness, and other factors that affect alertness are also clearly expressed in the face. Therefore, it is possible to estimate the general drive state from the face, gaze orientation, blinking, and changes in expression. This research is studying basic technology to perform this estimation by tracking feature points on the driver’s face. Real-time processing with a high recognition performance has already been achieved in actual driving environments *(Photo 10)*.

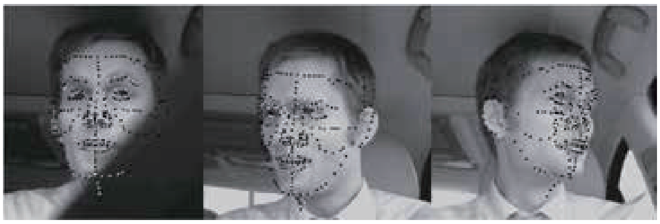
PHOTO 9

Universal recognition technology for traffic scenes

Source: Toyota Technical Review

PHOTO 10

Driver facial tracking technology



Source: Toyota Technical Review

Conclusion

This article has introduced examples of Toyota’s automated driving technology, as well as an advanced driving support system using this technology. Vehicles have made a major contribution to supporting and developing the lifestyles of people around the world. Mobility will remain a critical part of societies in the future.

However, the establishment of a sustainable mobile society requires the implementation of measures to help reduce traffic accidents to zero by further enhancing safety, the mitigation of environmental impacts, and the vitalization of mobility in an aging society. Automated driving technology is a possible means of helping to achieve these aims, and Toyota intends to step up the development of technologies and products in the future.

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