TOYOTA
Technical
Review

Special Feature

Application of Vehicle Data-Driven Diagnostics Technologies to Address Mobility-Related Issues

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Preface

Toyota is currently taking on the challenge of achieving a sustainable mobility society focused on electrification, intelligence, and diversification. Recent editions of the *Toyota Technical Review* have featured in-depth articles about the environment from the perspectives of carbon neutrality and the circular economy that showcased the company's technological advances and social contribution.

This edition, Vol. 71, shifts the perspective away from the environment and focuses on the utilization of vehicle data in diagnostics technologies as part of Toyota's measures in the rapidly developing field of intelligent mobility. Consequently, the special feature of this edition of the *Toyota Technical Review* is the application of vehicle data-driven diagnostics technologies to address mobility-related issues. The articles within this edition describe Toyota's current efforts to develop practical intelligent mobility technology as well as some of the initiatives that have already entered the demonstration phase from the three standpoints of people, vehicles, and the traffic environment. The articles are divided into the following sections.

- Driving diagnostics technologies for zero accidents and carbon neutrality: four articles describing how these technologies can be used to analyze driving behavior from vehicle data.
- Vehicle diagnostics technologies for even greater peace of mind and more efficient vehicle inspections: three articles describing how driving data can be used for purposes such as the prediction of oil deterioration and the like.
- Infrastructure diagnostics technologies for more efficient road management: three articles focused on the collection and application of road surface data for road management.

These initiatives are the result of Toyota's development teams finding ways to utilize the characteristics of routine vehicle data and partnering with a wide range of companies and institutions to exchange and hone their know-how with the aim of contributing to society in even better ways. Toyota is delighted to showcase the steady progress made by these initiatives toward addressing a variety of social issues.

By showcasing Toyota's latest technologies through the *Technical Review*, we hope to encourage more people who share our approach to walk hand-in-hand with us into the future so that we can help achieve an ever-better mobility society through the diverse range of vehicle data-driven research and development described in these pages. We are sure that this edition of the *Toyota Technical Review* will hold your attention all the way to the last page.

Planning Team, *Toyota Technical Review*

Cover design:

The cover is designed to visualize the utilization of vehicle data, which is the special feature of this edition of the *Toyota Technical Review*. It uses images representing driving, vehicle, and infrastructure diagnostics technologies to illustrate these technologies in action. In addition, these technologies are also connected by a ring that symbolizes our desire to address the major issues facing a mobility society hand-in-hand with a wide range of partner companies and institutions through initiatives focused on people, vehicles, and the traffic environment.

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Overview of Diagnostics Technologies Utilizing Vehicle Data

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1. Introduction

The automotive industry has a responsibility to address a wide range of issues to help realize a sustainable mobility society. These include working toward achieving carbon neutrality (CN) and creating a society free from traffic accidents, tackling labor shortages in the servicing and maintenance fields, as well as increasing the efficiency of road infrastructure management and upkeep. In response to these issues, Toyota has been working tirelessly to develop autonomous driving and advanced safety technologies, as well as to electrify and enhance the environmental performance of its powertrains.

However, since a mobility society includes a wide range of other stakeholders such as drivers and road infrastructure in addition to vehicles, these issues cannot be easily resolved simply by improving vehicle performance. Therefore, as part of its approach, Toyota is aiming to help address these social issues by developing algorithms capable of estimating the states of vehicles, drivers, and road infrastructure and then providing services that utilize the estimation results. These algorithms use vehicle data collected via the onboard data communication module (DCM) in connected cars as well as vehicle data obtained directly via the controller area network (CAN), Ethernet, and other in-vehicle networks (**Fig. 1**).

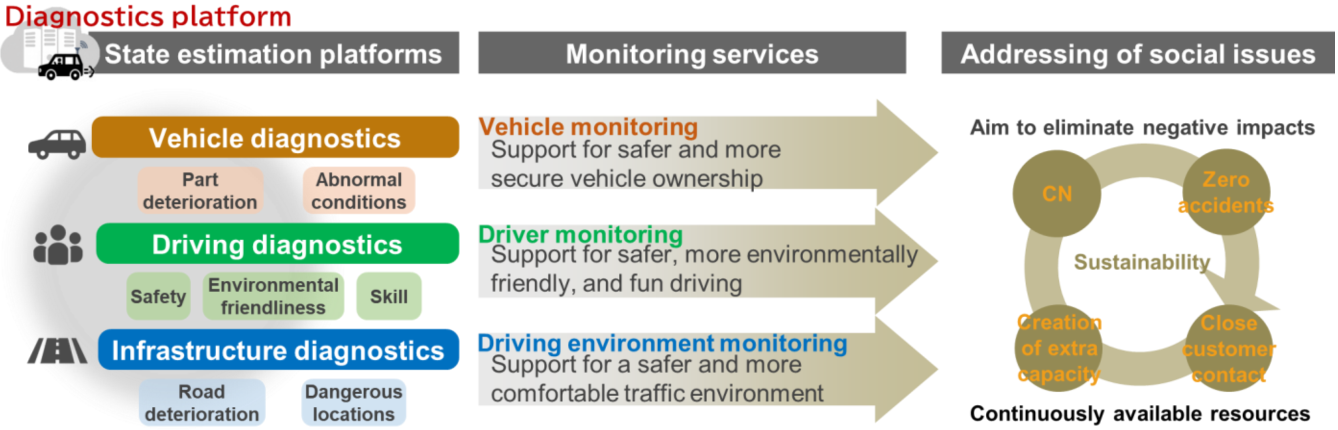

Fig. 1 Addressing Social Issues Utilizing State Estimation Platform

Vehicle data collected from the DCM and in-vehicle networks has the following three characteristics.

First, this data can be obtained from a wide variety of sensors used for vehicle control. In addition to data showing the location of the vehicle and basic vehicle behavior such as speed and acceleration, this data includes items that are difficult to acquire using retrofitted collection devices, such as data from the steering wheel, accelerator pedal, and the like that indicate the extent of driver operation, as well as part state quantities such as engine coolant temperature. Second, this data is highly precise. For example, although retrofitted data collection devices can generally approximate vehicle speed via location information from a global positioning system (GPS), data collected from the DCM and in-vehicle networks includes data that directly indicates parameters such as wheel speed. In addition, since the vehicle accelerometer (G-sensor) is located close to the vehicle center of gravity, the obtained data is more accurate than that provided by retrofitted sensors and is compatible with pre-calibrated data. Third, the DCM and in-vehicle networks can provide big data since the wide variety of highly precise data described above can be collected on a large scale from all connected cars.

Furthermore, data processing and analysis algorithms were developed using Toyota's unique knowledge of vehicles, parts, dynamic performance, and vehicle

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controls, which enables the accurate estimation of vehicle, driver, and road infrastructure states.

2. Examples of Initiatives for Addressing Issues

In addition to companies involved in vehicle manufacturing and sales, Toyota has been working with various stakeholders in public offices such as the central government, local authorities, and police, as well as universities, driving schools, and the like with the aim of contributing to the sustainability of the mobility society by addressing issues through the use of vehicle data and state estimation technologies as described above.

Parts 2 to 4 of this edition of the *Toyota Technical Review* describe some specific examples of these initiatives.

Part 2 (Driving Diagnostics Technologies for Zero Accidents and Carbon Neutrality) describes driving diagnostics technologies capable of analyzing driving behavior from the perspectives of safety and environmental friendliness, and how these technologies are being utilized in initiatives to help eliminate traffic accidents and achieve carbon neutrality by encouraging a transformation in this behavior.

Part 3 (Vehicle Diagnostics Technologies for Even Greater Peace of Mind and More Efficient Vehicle Inspections) describes vehicle diagnostics technologies capable of monitoring part deterioration and signs of abnormal vehicle conditions, and how these technologies are being utilized in initiatives aiming to improve the efficiency of vehicle inspection and maintenance workplaces and to resolve labor shortages.

Part 4 (Infrastructure Diagnostics Technologies for More Efficient Road Management) describes infrastructure diagnostics technologies capable of supplementing location information in vehicle data with vehicle probe data and using the results to estimate the state of road flatness and ruts, as well as intersections and other areas with a high accident risk. This part also describes how these technologies are being utilized in initiatives looking to improve the efficiency of road management.

Although all of the issues mentioned here are affecting society in extremely significant ways, Toyota has only just started to make a partial contribution to finding solutions. Furthermore, Toyota’s efforts are currently focused on separate initiatives covering vehicles, drivers, and the road infrastructure. In the future, the goal is to combine the three separate state estimation platforms into a single diagnostics platform to create a synergistic effect capable of addressing a wider range of larger issues. Toyota intends to continue its efforts to develop technologies and build alliances to help achieve this goal.

Driving Diagnostics Technologies for Zero Accidents and Carbon Neutrality
– Driving Safety Support Using KINTO Connected Driving Trainer –

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Yukinori Ii[*1]

Abstract

The connected driving trainer (CDT) feature was developed with the aim of enhancing drivers' safe and environmentally friendly driving skills as part of Toyota's initiatives to help reduce traffic accidents and achieve carbon neutrality. It consists of two functions: a driving coach function that visualizes driving habits and an upgrade recommendation function that proposes optimum upgrades to the driver. These functions use onboard sensors to provide the type of diagnostics services that only an automaker is capable of offering, such as highly accurate and rapid diagnostics of the driver's turn signal operation and lane sense.

Keywords: *driving diagnostics, behavioral transformation, zero accidents, carbon neutrality, connected, value chain, smartphone app*

1. Reasons for Addressing Driving Diagnostics Using KINTO

Section 1 of this edition of the *Toyota Technical Review* (Overview of Diagnostics Technologies Utilizing Vehicle Data) described the necessary technologies for a diagnostics platform. Building on these technologies, Toyota started full-scale development of driving diagnostics services and technologies in partnership with KINTO Corporation, which shares its vision for a society free from traffic accidents. As a mobility platform developer, KINTO Corporation feels tremendous responsibility toward traffic safety and is working actively to help reduce accidents based on its philosophy that safe driving is a critical service that must be provided to its customers. In addition, since KINTO Corporation provides subscription services through a direct connection with the customer, it is in a position to listen to users and directly understand the situation related to traffic accidents, thereby allowing it to speedily advance the development of effective services and technologies. **Fig. 1** illustrates the subscription services provided by KINTO Corporation. The presence of vehicle insurance in these services indicates that the company directly benefits from reducing accidents.

Fig. 1 Details of KINTO Services(1)

For this reason, it was decided to record driving behavior to help enhance safe driving skills and develop an app capable of diagnosing the positive and negative aspects of this behavior. From the perspective of enhancing driver skills, the aim of this development was to help achieve Toyota's ultimate goal of zero traffic accidents.

In addition, by using the same app to promote environmentally friendly driving skills, another aim of the development is to help achieve carbon neutrality through more fuel-efficient driving.

2. Outline of the KINTO Connected Driving Trainer Feature

The app developed for the reasons described above is called the connected driving trainer (CDT). The CDT is provided as a smartphone app and forms part of the functions available through the KINTO Unlimited services. These services can be categorized as either "upgrade" services that allow customers to update the vehicle after delivery or "connected" services designed to provide smart support for the customer's vehicle-

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based lifestyle. The CDT is one of these connected services. It uses connected technology to visualize the customer's driving data and identify driving habits that might be difficult to discern as a way of supporting safer and more fuel-efficient driving.(2) **Fig. 2** shows some of the app screens. The CDT app consists of two main functions.

Fig. 2　CDT User Interface(2)

The first is called the driving coach function. As shown in **Fig. 3**, this function carries out seven types of diagnostics pertaining to safe driving (as well as six types of diagnostics related to environmentally friendly driving and related behavior), and calculates a score for each trip (i.e., between the start and end of a particular journey) and each month. This enables the visualization of driving habits that might be difficult for the driver to discern both on a per-trip and a per-month basis. A training function is also available that aims to teach the driver safer and more environmentally friendly driving techniques. This function helps to enhance driving skills in an engaging way by setting tasks for the driver to achieve during the course of day-to-day driving (**Fig. 4**).

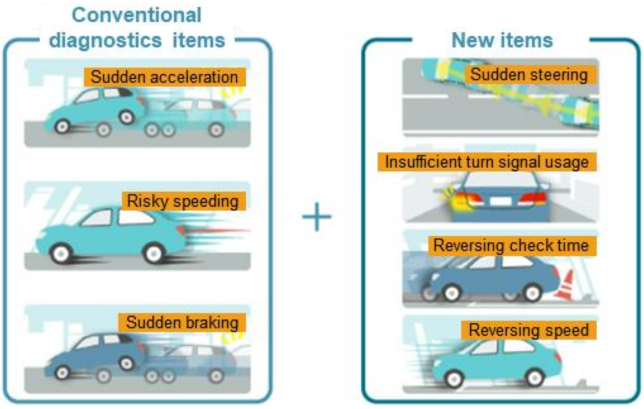


Fig. 3　List of Safety Diagnostics Items(3)

Level 3 ★★★☆

車線中央をブレずに走る

トレーニング内容

車線の中央をブレずに狙って走る運転を身につける

目標

スタート日（mm/dd）から10回のドライブで累計スコア60点以上

累計スコア

あと少し！ 51 / 60点

スタート日 8/9 からのドライブ回数 6 / 10

リセットして再スタートする

今回のドライブ

Level 3 ★★★☆
一般ドライバーの約40%がクリアできる運転レベルです

① 車線中央とのズレ 2 / 5点

あなた	21 cm 右寄り
目標	± 10 cm 以内

② 走行のブレ幅 5 / 5点

あなた	± 12 cm
目標	20 cm 以内

Fig. 4 Trainer Function User Interface

The second is called the upgrade recommendation function. The upgrade recommendation function is part of the "upgrade" category of services offered via KINTO Unlimited. This category of services allows customers to update the hardware and software of the vehicle after delivery. The aim of the upgrade recommendation function is to suggest optimum updates to the driver based on driving data. For example, the system will use driving data to identify drivers requiring a large number of corrective steering maneuvers to park on a routine basis and recommend installation of a panoramic view monitor. Recommending the appropriate safety systems to drivers like this should help to reduce accidents.

Fig. 5 shows a simple overview of the system. Various types of diagnostics are processed via the cloud using data collected from connected cars.

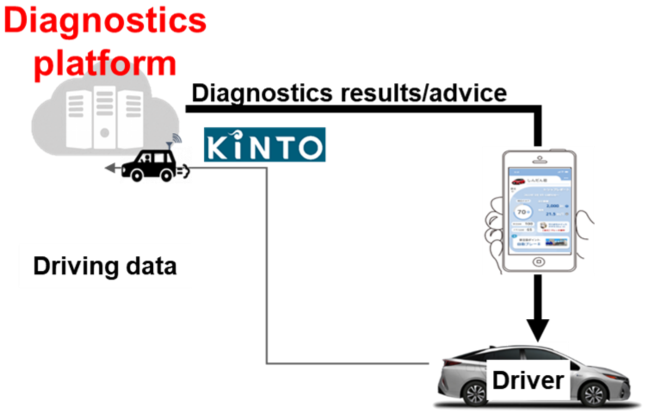


Fig. 5　Overview of System Configuration

3. Toyota's Driving Diagnostics Technologies

Various solutions capable of diagnosing driver behavior have already been developed and adopted. Many of these utilize separate devices such as smartphones or cooperative drive recorders to diagnose driving behavior using built-in accelerometers and angular accelerometers. What differentiates Toyota's technology is the capability to make direct use of vehicle data. Driving data is not limited to acceleration or angular velocity, and also includes information from the accelerator and brake pedal, information about turn signal usage, as well as the shift position. Furthermore, vehicle data also includes information from the pre-crash safety (PCS) system and other safety functions. All this information can be obtained and used. Consequently, vehicle data allows the application of diagnostics technologies to driving behavior rather than vehicle behavior. At the same time, no preparation is required to use vehicle data. For example, whereas smartphone-based diagnostics services require a Bluetooth or similar connection to the vehicle, the developed service requires no connection to obtain data and run diagnostics, and can be activated simply by driving the vehicle.

Fig. 6 shows the architecture of the diagnostics system. The driving diagnostics process consists of the following three modules: (1) driving scenario extraction, (2) key performance indicator (KPI) calculation, and (3) operation label creation (i.e., score creation). The process is intentionally divided into separate modules to facilitate program portability and debugging. This enables other customer-oriented driving diagnostics services to be rolled out more easily, and helps engineers who are unfamiliar with software development to identify the cause of any issues.

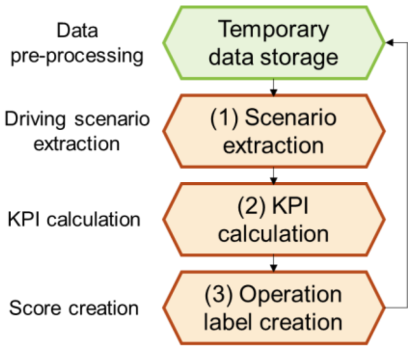


Fig. 6 Architecture of Diagnostics System

The role of each module is as follows.

First, in module (1) Driving scenario extraction, the system identifies and isolates specific driving situations, such as braking and turn signal operation. Scenario extraction allows the large volume of driving data to be narrowed down before processing, helping to reduce the calculation load. In module (2) KPI calculation, parameters that express the positive and negative aspects of the driving behavior in the extracted scenarios are calculated. These parameters are known as KPIs. As an example, the KPI used to diagnose sudden braking is called the deceleration KPI. Finally, in module (3) Operation label creation, the system uses the calculated KPIs as the basis for determining the quality of driving.

Next, **Fig. 7** shows the logic evaluation process. The process consists of two steps: (1) a correlation test and (2) a detection accuracy test. These tests are a necessary part of evaluating driving behavior correctly.

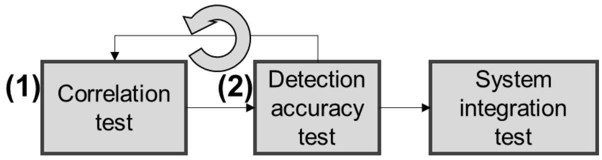


Fig. 7 Diagnostics Evaluation Process

The purpose of the correlation test in step (1) is to confirm the correlation of the driving behavior. Safe driving diagnostics requires a high correlation with the accident occurrence frequency, and environmentally friendly driving diagnostics requires a high correlation with fuel efficiency. Developing these services rested on the assumption that the results of the diagnostics could be enhanced and used to help reduce accidents or encourage more environmentally friendly driving. Driving data from approximately 1,000 vehicles over the course of a year was used to identify the relationship between the diagnostics detection frequency and either the accident occurrence frequency or fuel efficiency. This idea of defining volumes of vehicle data in units consisting of the number of vehicles × the number of years is known as the “earned volume” approach and is used when studying the amount of data to be used in correlation analysis. A more specific example of the correlation results is described below.

The purpose of the detection accuracy test in step (2) is to confirm that the diagnostics results have been detected with sufficiently high accuracy. This accuracy is judged based on the ideas of precision and recall. These ideas are frequently adopted in assessments of machine learning and the like. This driving diagnostics development used the concept shown in **Fig. 8** to define these ideas as expressed by **Equations (1)** and **(2)**.

Number of items	**Applicable operation carried out**	**Applicable operation not carried out**
Detected by diagnostics	TP	FP
Not detected by diagnostics	FN	TN

Fig. 8 Definition of Detection Accuracy

$$\text{Precision} = \frac{TP}{(TP+FP)} \quad \cdots\cdots (1)$$

$$\text{Recall} = \frac{TP}{(TP+FN)} \quad \cdots\cdots (2)$$

Although both are important indicators, precision is regarded as the most important for this purpose. For example, detecting sudden braking when none occurred would adversely affect customer satisfaction with the system. For this reason, an important part of the development phase was to identify operations that are not detection targets. Greater precision would facilitate the appropriate extraction of operations with a high contribution rate to safer or more environmentally friendly driving. Therefore, a precision of 90% or higher and a recall of 80% or higher were set as the performance targets for this service. Since precision and recall tend to have a trade-off relationship in many cases, it is difficult to target a value of 100% for both at the same time. For this reason, the development focused on precision and set targets to enable the service to be delivered to customers as soon as possible.

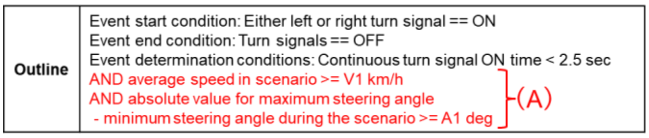
Because the confirmation performance of the correlation test in step (1) is also enhanced by improving the performance of the detection accuracy test in step (2), the performance enhancement process involved carrying out repeated iterations of steps (1) and (2).

As examples, this article describes the details of two types of diagnostics using the kind of vehicle data only available to an original equipment manufacturer (OEM).

(1) Insufficient turn signal usage

Fig. 9 outlines the logic behind the diagnostics for insufficient turn signal usage. This diagnostics extracts left or right turn or lane change operations that the driver carries out without expressing sufficient intention to the surrounding vehicles.

Originally, **item (A) in Fig. 9** was not a condition. Instead, the logic simply assessed the length of time that the turn signal was switched on. However, it was found that this logic detected non-hazardous situations under the following two conditions: (a) driver error when there is no intention to change lanes or to turn left or right, and (b) rapid cancellation of the turn signal. Factoring in these conditions, the precision indicator was increased by adding logic (A). **Fig. 10** shows the results of a correlation test after this improvement was incorporated. The graph confirms that the accident rate increases in accordance with the number of insufficient turn signal scenarios per distance driven.



Outline	Event start condition: Either left or right turn signal == ON Event end condition: Turn signals == OFF Event determination conditions: Continuous turn signal ON time < 2.5 sec AND average speed in scenario >= V1 km/h AND absolute value for maximum steering angle - minimum steering angle during the scenario >= A1 deg (A)

Fig. 9 Logic Behind Diagnostics for Insufficient Turn Signal Usage

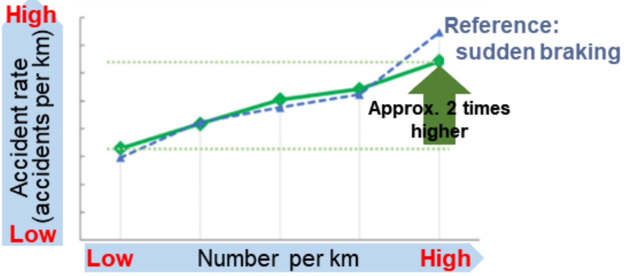


Fig. 10 Relationship between Diagnostics for Insufficient Turn Signal Usage and Accident Rate[3]

(2) Lane sense (stable driving)

Fig. 11 outlines the algorithm behind the lane sense diagnostics. Analysis of accident characteristics involving KINTO vehicles identified many incidents of the driver scraping the left side of the vehicle. This was attributed to inadequate driver perception of the width of the vehicle (i.e., poor lane sense). Accordingly, this diagnostics service aims to encourage drivers to keep the vehicle in the center of the lane by continuously raising awareness of its lateral position. To do this, the service measures the average lane offset and lane stability. The average lane offset and lane stability metrics are measured using information obtained from the front camera installed for functions such as lane tracing assist.

One scenario facing drivers might be moving to the right of the lane to overtake a bus waiting at a bus stop. In this case, the shift to the right of the lane is not caused by poor lane sense, but by a disturbance in the traffic environment. More appropriate scenario extraction was achieved by collecting data about scenarios like these and adding **condition (A) in Fig. 11** to the service conditions. The development also measured the average lane offset and lane stability of drivers under normal driving conditions and when the drivers were particularly aware of these aspects of driving behavior using drivers with various driving skills according to the levels of Toyota’s in-house certification system. **Fig. 12** shows the results. The results identified a proportional relationship with the KPIs, driver awareness, and driving skill. These results were used as criteria for setting the evaluation levels.

Outline	Event start condition: All of the following conditions are satisfied for t1 s or more continuously. – Lateral acceleration due to sudden behavior judgment is less than A1 m/s^2 AND yaw rate is less than Y1 deg/s, – Vehicle speed is V1 km/h or higher. – Turn signals == OFF – There is no continuous steady increase or decrease in the distance from the center of the vehicle lane. – The vehicle is detecting the vehicle lane. – The radar cruise control system is not activated. – The vehicle is not driving around a curve. Event end condition: When one of the conditions described above is not satisfied. Event exclusion condition: When one of the following conditions is satisfied. (1) The time from the start to the end of the scenario is less than t1 s. (2) The distance from the center of the vehicle lane is the upper or lower limit. (3) The vehicle is on a section of road in which the offset value does not change for t1 s. (4) Within t2 s of a lane change ← (A). (5) Period t3 s before and after the sections of road described in (2) and (3).

Fig. 11 Algorithm Behind Lane Sense Diagnostics

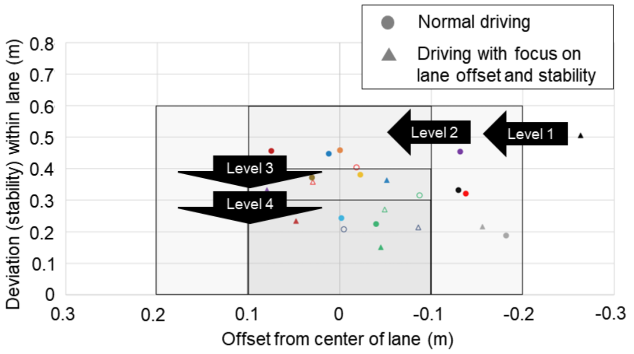


Fig. 12 Relationship between Results of Lane Sense Diagnostics and Driving Level

4. Results

These services were made available as demonstration functions in February 2023, before the formal service launch in February 2024. The services have been upgraded since the formal launch, with several new functions demonstrated and incorporated (including a partial diagnostics service for training). The following results were verified during these demonstrations and upgraded to a formal service.

First, when the detection frequency of the safe driving diagnostics service was compared between people using and not using the app, it was found that app users had, on average, a 42% lower detection frequency across all diagnostics items.

Fig. 13 compares the insurance payments per accident of people using and not using the app. The insurance payments of people using the app was approximately 20% lower. These results suggest that app users are less likely to be involved in accidents resulting in major damage to the vehicle. In addition, **Fig. 14** compares fuel efficiency. Similarly, the fuel efficiency of people using the app was approximately 5% better, which suggests that using the app encourages more fuel-efficient driving.

These results all indicate that these services make a certain contribution to the safe and environmentally friendly driving performance of people using the app. Customer reaction has been positive and a large number of people are frequently accessing the KINTO Unlimited app to make use of these services, which are helping to drive customer engagement with both KINTO and Toyota, and development is ongoing into further expanding the contribution of these services in the future.

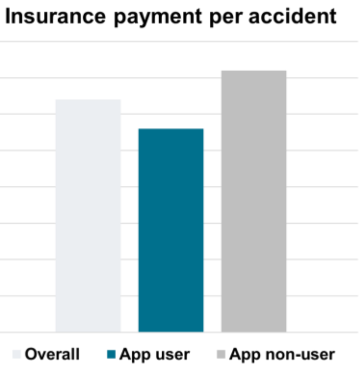


Fig. 13 Difference in Insurance Payments between People Using and Not Using the App

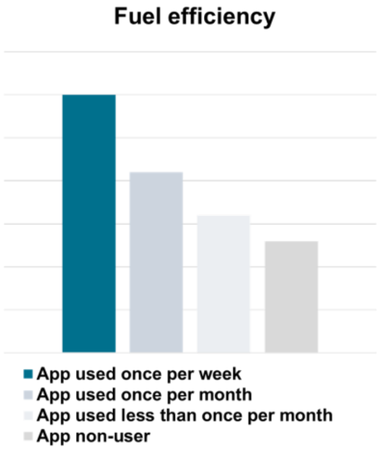


Fig. 14 Difference in Fuel Efficiency between People Using and Not Using the App

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Driving Diagnostics Technologies for Zero Accidents and Carbon Neutrality
– Driving Safety Support Using Rental Vehicle Driving Monitoring –

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Abstract

Starting in 2022, Toyota has been participating in the Okinawa Yuimaru Project, a data-driven initiative to help reduce the number of accidents in Okinawa Prefecture. As part of this project, a driving monitoring app was developed for the in-vehicle multimedia units of rental vehicles to help raise the safety awareness of rental vehicle users. This article introduces the main functions of this app, namely the safe driving status notification function and the dangerous location warning function, the results of a demonstration test carried out with Toyota Rent a Car Okinawa starting in June 2024, detailed observations of these results, prospects for further development, and issues for enhancing app functionality.

Keywords: *driving diagnostics, accident reduction, rental vehicle, Yuimaru Project, passenger effect, multimedia, dangerous location, TOVA, zero accidents, CAN*

1. The Okinawa Yuimaru Project

Although the number of accidents across Japan as a whole is decreasing as advanced driver assistance system (ADAS) technology becomes more sophisticated. the frequency of accidents involving rental vehicles remains an issue in areas such as Okinawa that attract a high number of tourists.(1) To help address this issue, the Toyota Mobility Foundation has been leading an initiative to help reduce accidents in partnership with the vehicle, tourism, airline, and other industries involved in the rental vehicle business. Starting in 2020, this initiative was later renamed the Okinawa Yuimaru Project.(2) **Fig. 1** shows the members of the project as of April 2025. In this project, representatives of industry, government, and academia are utilizing data with the aim of helping to reduce accidents and alleviate congestion through measures such as the development of in-vehicle apps, infrastructure improvements, and the like. Toyota joined this initiative in 2022 and is analyzing the characteristics of rental vehicles using data obtained via the T-Connect connected service to, for example, identify locations with a high estimated accident risk.

Partner organization: Okinawa General Bureau of the Cabinet Office, Government Of Japan
As of April 2025

Fig. 1 Members of the Okinawa Yuimaru Project as of April 2025

2. Driving Monitoring App for In-Vehicle Multimedia Unit

2.1 History of development

Since driving is one of the most effective ways of traveling around Okinawa, rental vehicles are one of the main means of transportation for visitors from both inside and outside Japan. However, it goes without saying that tourists may not be overly knowledgeable about the traffic environment in Okinawa. Furthermore, a certain proportion of visitors to the prefecture tend to be people from urban areas in Japan who are visiting as a graduation celebration and are unaccustomed to driving altogether. Based on these premises, it was proposed that it might be possible to help reduce accidents by providing useful information to drivers in the vehicle. Consequently, the Yuimaru Project decided to conduct a

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demonstration test of services designed to help raise the safety awareness of drivers. These services are provided via an app developed for dedicated in-vehicle tablets produced by Yazaki Corporation, one of the original members of the initiative. This app carries out driving diagnostics based on speed, sudden braking, and other user driving data. The results of these diagnostics are then immediately fed back to the driver, used to provide warnings of dangerous locations, and so on. Toyota contributed to this initiative by working with the Okinawa Prefectural Police Department to identify dangerous locations. However, since these services can be provided to a wider range of people via existing in-vehicle multimedia units and carrying out a software update, Toyota decided to develop another driving monitoring app for multimedia units.

2.2 System outline

Since a speedy development schedule is necessary to realize agile improvements based on user comments obtained through demonstrations, the development utilized the Toyota Open Vehicle Architecture (TOVA, **Fig. 2**). Under the TOVA development environment, software development kits are distributed that are designed to facilitate the development of services based on vehicle data. Since this eliminates the need to develop an app from scratch, it was possible to start the demonstration test in Okinawa within half a year of starting development. Furthermore, these kits also enable subsequent updates to be developed in an even shorter timeframe.

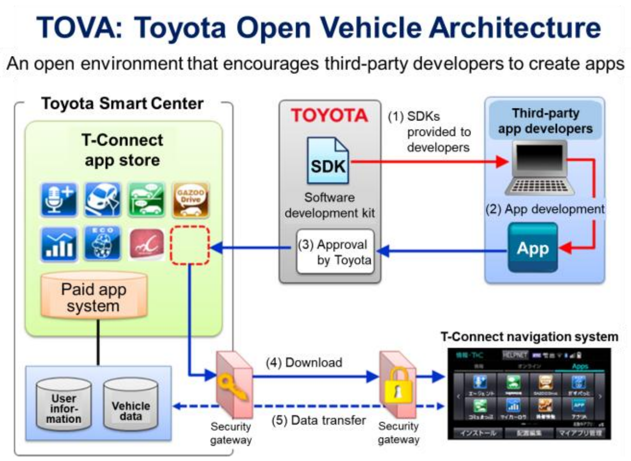


Fig. 2 Outline of TOVA

3. Safe Driving Status Notification Function

The two main functions provided by the developed app are the safe driving status notification and dangerous location warning functions. This section describes the safe driving status notification function.

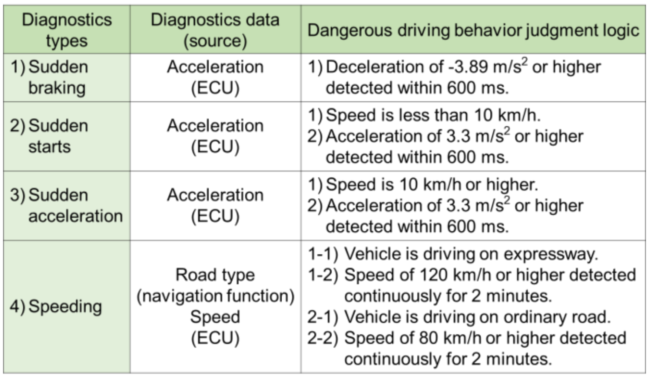
3.1 Function outline

The safe driving status notification function uses information from the onboard controller area network (CAN) and carries out four types of safe driving diagnostics in real time via the in-vehicle multimedia unit (sudden braking, sudden acceleration, sudden starts, and speeding). The function then alters the facial expression of the Yuimaru character displayed in the navigation system window on the in-vehicle multimedia screen to match the results of the diagnostics. As a specific example, **Fig. 3** shows that Yuimaru has a happy expression and turns blue to reflect a continuous period of safe driving. However, to reflect the detection of dangerous driving in the diagnostics results, the expression of Yuimaru becomes less happy and its color changes like a traffic signal to yellow and then to red. This system enables drivers to become intuitively self-aware of their driving level and encourages the adoption of safer driving behavior. At the same time, the presence of a character like Yuimaru induces a feeling of being watched over. This may help to generate the so-called “passenger effect” by which driving behavior tends to change when a passenger is in the vehicle, helping to reduce the accident risk. In addition, since rental vehicles in Okinawa are often used by families or groups of friends, another aim of adopting a friendly character like Yuimaru is to help create a sense of teamwork among the vehicle occupants to realize safer driving.

Fig. 3 Example Images of Safe Driving Status Notification Function Display (Actual Screens Currently Under Development)

3.2 Dangerous driving behavior judgment logic

As described above, this app adopts four types of dangerous driving behavior judgment logic for sudden braking, sudden starts, sudden acceleration, and speeding. The logic utilizes the diagnostics platform logic introduced elsewhere in this edition of the *Toyota Technical Review*. **Fig. 4** outlines the four types of logic. Following this logic, accident correlation analysis is conducted using big data on the diagnostics platform. Threshold values are provided that are capable of classifying drivers into people with a high or low accident rate to a statistically significant degree.



Diagnostics types	Diagnostics data (source)	Dangerous driving behavior judgment logic
1) Sudden braking	Acceleration (ECU)	1) Deceleration of -3.89 m/s^2 or higher detected within 600 ms.
2) Sudden starts	Acceleration (ECU)	1) Speed is less than 10 km/h. 2) Acceleration of 3.3 m/s^2 or higher detected within 600 ms.
3) Sudden acceleration	Acceleration (ECU)	1) Speed is 10 km/h or higher. 2) Acceleration of 3.3 m/s^2 or higher detected within 600 ms.
4) Speeding	Road type (navigation function) Speed (ECU)	1-1) Vehicle is driving on expressway. 1-2) Speed of 120 km/h or higher detected continuously for 2 minutes. 2-1) Vehicle is driving on ordinary road. 2-2) Speed of 80 km/h or higher detected continuously for 2 minutes.

Fig, 4 Diagnostics Types, Diagnostics Data, and Dangerous Driving Behavior Judgment Logic

Fig. 5 shows the diagnostics process flowchart. The process consists of the following four main steps.

1) The CAN signals required to carry out the diagnostics are received from the vehicle electronic control unit (ECU) via TOVA.
2) The road type information required to carry out the diagnostics is received from the navigation function via TOVA.
3) The processing for each diagnostics item is carried out inside the app.
   The judgment logic is used to determine whether dangerous driving behavior has occurred based on the data received in each diagnostics process.
4) Dangerous driving behavior is reflected by changing the color of the Yuimaru character in the navigation system window in the multimedia unit display to red or yellow. (If no dangerous driving occurs for a specific period of time, the color of Yuimaru changes back to blue.)

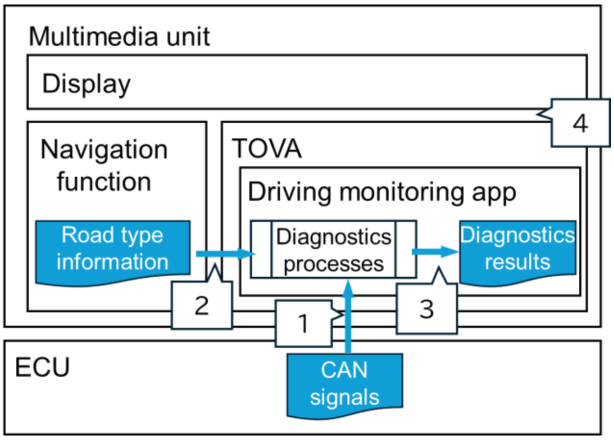


Fig. 5 Diagnostics Process Flowchart of Driving Monitoring App for In-Vehicle Multimedia Unit

3.3 In-vehicle multimedia user interface (UI) issues and innovations

Since the app for the in-vehicle tablet can be used as a dedicated screen installed separately from the in-vehicle multimedia unit, the Yuimaru character can be displayed at all times to notify the driver of the driving diagnostics results. In addition, the full screen can be used to clearly show dangerous locations. In contrast, in-vehicle multimedia units have the merits of being installed as standard equipment, making it possible to quickly increase the number of app users, as well as being installed in locations requiring minimum eye movement. However, a major issue is providing the driving monitoring service without sacrificing the basic functions of the navigation system. Therefore, various innovations were applied with the aim of satisfying the requirements of both the navigation system and driving monitoring functions. First, the passenger effect of the driving monitoring functions was upheld by periodically displaying the navigation system window containing the Yuimaru character. The display frequency was set to once every two minutes to make it easy to notice by the driver, facilitate awareness that the service system is activated, and maintain a proper balance with displays of navigation system information. In addition, since some test drivers reported not noticing the window display while driving, it was decided to show the Yuimaru character even while the vehicle is stopped.

One issue for the dangerous location warning function was the clarity of displays within the small navigation system window area. This issue was addressed by improving the window illustration and using text to warn drivers of dangerous intersections to make the smaller display clearly visible to the driver. In addition, the design of the Yuimaru character was modified with the aim of taking advantage of the *bouba-kiki* effect (a phenomenon in which people create a mental association between certain speech sounds and certain visual shapes). As a result, Yuimaru was redesigned to become gradually more spiky as its color changes from blue to yellow to red.

Furthermore, the display of the driving monitoring window on the navigation system was given a lower priority than the navigation function display so that the navigation system and other functions can be used as normal. These innovations helped to satisfy the requirements of both the navigation system and driving monitoring functions.

3.4 Addition of dangerous driving operation notifications

In the initial demonstration test for the app used with the tablet, some users communicated a need to know the specific reason for changes in the color of the Yuimaru character. For this reason, a function that notifies the driver of the action (i.e., the dangerous driving operation) that caused the color change was added (**Fig. 6**). Since this function raises awareness of a driver's weaknesses, it encourages the adoption of safer driving behavior more effectively. Dangerous driving operations are notified on the in-vehicle multimedia screen as illustrated messages in the navigation system window if the function or the four types of driving diagnostics described above detect a dangerous driving operation.

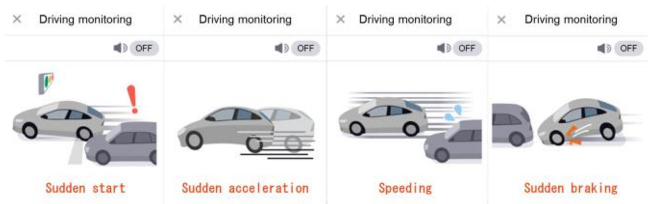


Fig. 6 Dangerous Driving Operation Notification Navigation System Window

4. Dangerous Location Warning Function

This section describes the dangerous location warning function, which is the other main part of the driving monitoring service.

Dangerous location notifications are provided in thirty-five locations around thirteen intersections on the main island of Okinawa shown in **Fig. 7**. All of these intersections and locations were identified by data analysis during the Yuimaru Project. The reason for the warning is displayed on the in-vehicle multimedia screen as an illustrated navigation system window. By informing the driver of accident blackspots at unfamiliar intersections, this function should help to lower the accident rate at those intersections by warning the user to drive with caution. Five types of navigation window displays were designed: frequent rear-end collisions (17 locations), vehicles crossing center line (1 location), frequent merging accidents (2 locations), frequent right-turn accidents (6 locations), and frequent (other) accidents (9 locations). The classification for each location was determined by identifying the target accident warning type using accident data provided by the Okinawa Prefectural Police Department and probe vehicle data provided by Toyota. Although intersections generally have four dangerous locations (one for each road leading to the intersection), three-way intersections, *Michi-no-Eki* rest area entrances, and the like may only have three or less. The effect of the function was enhanced by providing two warnings, 400 and 200 meters from the intersection. Similarly, one issue with this function was the small display area compared to the dedicated tablet. The effectiveness of the warnings was upheld by using pictograms to clarify the content of the warning and text to specify the warning details.

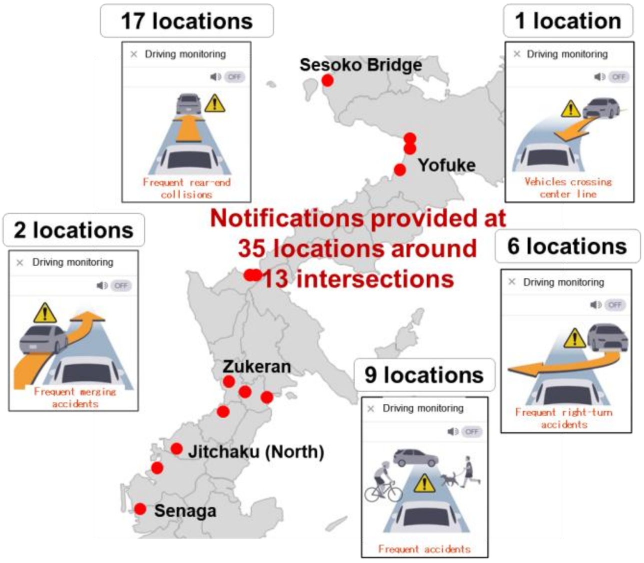


Fig. 7 Notification Locations and Navigation System Window of Dangerous Location Warning Function

5. Results of Demonstration Test in Okinawa and Future Applications

5.1 Demonstration results and observations

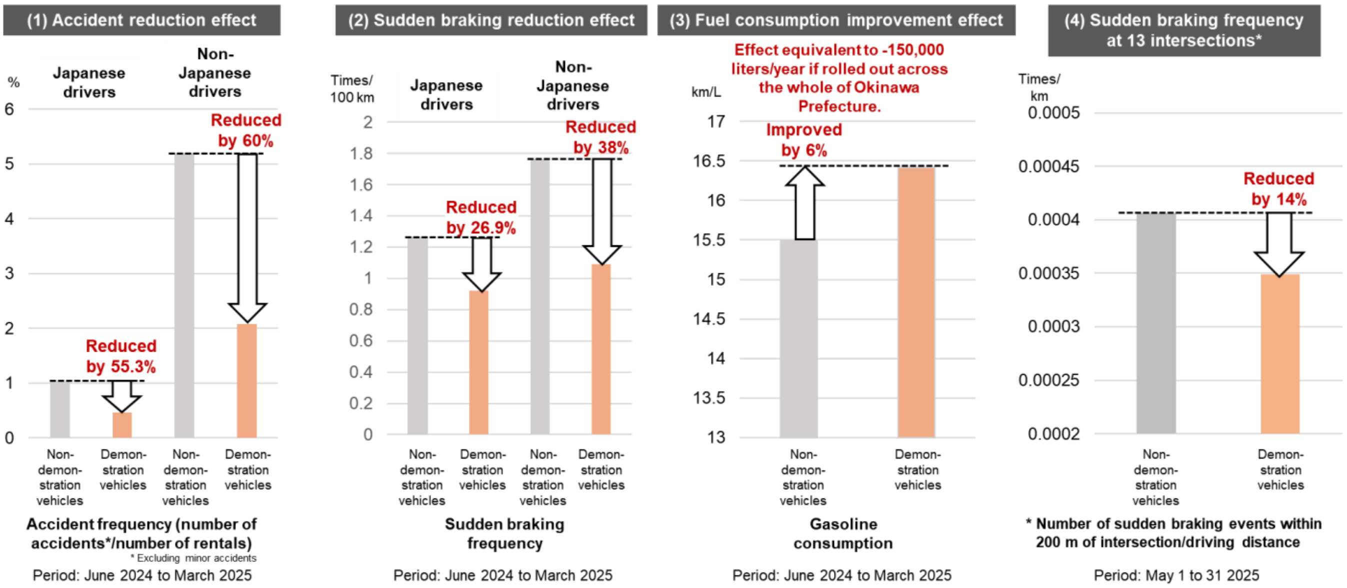
- Demonstration results of safe driving status notification function

  To verify the accident reduction effect of the app with in-vehicle multimedia units, a demonstration test was started in June 2024 involving 63 vehicles provided by Toyota Rent a Car Okinawa. This test is currently ongoing. **Graph (1) in Fig. 8** compares the accident frequency of demonstration and non-demonstration vehicles between June 2024 and March 2025. These accident frequency values indicate the accident frequency for the total number of rentals. Since this app targets accidents while driving, accidents that can be repaired at the rental shop were excluded to eliminate minor collisions in parking lots and the like. The results showed that accidents involving Japanese drivers in demonstration vehicles fell by 55.3% compared to Japanese drivers in non-demonstration vehicles. For non-Japanese drivers, the accident rate fell by 60%. This confirms that adopting this in-vehicle app is likely to have a certain accident reduction effect. In addition, **graph (2)** shows the frequency of sudden braking, which has a high correlation with the accident frequency. The sudden braking frequency of Japanese and non-Japanese drivers in demonstration vehicles fell by 26.9% and 38%, respectively. Both these graphs indicate a difference between Japanese and non-Japanese drivers. However, since the sudden braking frequency for ordinary non-rental vehicles in Okinawa is approximately 0.8 times per 100 km, the higher rate of sudden braking for non-Japanese drivers (1.7 times per 100 km) suggest that the potential reduction effect of this function is higher for non-Japanese drivers. Incidentally, the sudden braking frequency for Japanese drivers was reduced to 0.9 times per 100 km, which is close to the figure for ordinary non-rental vehicles.

In addition, safer driving is also likely to correlate to an improvement in fuel economy. **Graph (3)** shows that the average fuel economy of demonstration vehicles with a lower accident rate in this demonstration improved by 6%. Congestion is common in Okinawa and the average speed of vehicles in Naha on weekday mornings and evenings is reported to be lower than in the 23 wards of Tokyo. Since congestion increases the number of starts and braking operations, smoother driving encouraged by this application may have led to lower fuel consumption.

- Dangerous location warning function

  For the dangerous location notification warning function, the frequency of sudden braking was verified at the thirteen intersections between May 1 and 31, 2025. **Graph (4)** shows these results. The frequency of sudden braking was calculated based on the number of sudden braking events within 200 m of the intersection as a proportion of the total driving distance. The results showed that the sudden braking frequency of demonstration vehicles was 14% lower than non-demonstration vehicles, confirming that the dangerous location notification function has a certain effect.



Accident frequency (number of accidents*/number of rentals)
* Excluding minor accidents
Period: June 2024 to March 2025

Sudden braking frequency
Period: June 2024 to March 2025

Gasoline consumption
Period: June 2024 to March 2025

* Number of sudden braking events within 200 m of intersection/driving distance
Period: May 1 to 31 2025

Fig. 8 Results of Driving Monitoring App Demonstration

5.2 Future applications

The previous section illustrated the potential effects of adopting this app on in-vehicle multimedia units. The aim is to adopt the app across the whole of Okinawa before finally expanding the adoption nationwide. At the same time, some users commented on the demonstration test questionnaire that the Yuimaru character was annoying because it was displayed too frequently. Therefore, from the perspective of technical development, Toyota intends to continue improving and demonstrating the UI with the aim of minimizing user annoyance while maintaining the accident reduction effect of the app. It also intends to continue updating the app to enhance its UI and add functions targeting specific regional issues. For example, there are frequent accidents on roads in the northern region of Okinawa involving rare animal species such as the Okinawa rail and Ryukyu long-tailed giant rat. For this reason, to underline its empathy with nature-positive initiatives, Toyota plans to add warnings to the app for in-vehicle multimedia units, and continue data analysis using the diagnostics platform to verify the effectiveness of such measures. Furthermore, as part of its efforts to help reduce accidents of all users in the future as well as drivers of rental vehicles, Toyota intends to enable the personalization of feedback and to address issues such as the development of a UI and user experience (UX) capable of encouraging the adoption of safer driving behavior while retaining user interest.

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Driving Diagnostics Technologies for Zero Accidents and Carbon Neutrality
– Estimation of Cognitive Function Decline –

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Tatsuya Obuchi*1

Abstract

This article describes the development of a system capable of estimating cognitive function decline in drivers from vehicle data obtained while driving. First, Toyota partnered with research institutes to construct a labelled mild cognitive impairment (MCI) driving data set that includes both cognitive function assessment results and vehicle data. Next, a four-step cognitive function decline estimation method was proposed based on vehicle data obtained from driving scenarios: driving scenario extraction, feature quantity extraction, estimation of cognitive function decline in each driving scenario, and the calculation of representative values for the estimated values in multiple scenarios. Finally, the accuracy of the proposed method was verified by cross-validation. It was confirmed that this method is capable of estimating the cognitive function decline of drivers to a statistically significant degree. By increasing the chance of early MCI discovery, this system has the potential to help maintain the quality of life (QOL) of elderly drivers and contribute to traffic safety.

Keywords: *mild cognitive impairment (MCI), cognitive function, cognitive function decline, cognitive function decline estimation, MCI screening, vehicle data, machine learning model, elderly drivers, driver state estimation*

1. Introduction

The development of measures to help enhance the safety of elderly drivers with mild cognitive impairment (MCI) has become a topic of concern in recent years. The term MCI is used to refer to an intermediate stage between a normal healthy state and dementia. Although it presents as cognitive function decline, this decline is not significant enough to interfere with daily life.(1) In Japan, people diagnosed with dementia are not legally permitted to drive, but this restriction does not apply to elderly drivers with MCI. If the proportion of elderly drivers with MCI(2) is calculated based on the number of elderly Japanese people in 2021 and with the rate of people with symptoms of MCI symptoms set to 18.8%,(3) then approximately 3.93 million elderly drivers in Japan may be suffering from MCI. However, according to a survey conducted in 2018, a higher proportion of elderly drivers who caused a fatal accident were found to have cognitive function decline, which suggests a correlation between cognitive function decline and fatal accidents.(4)

2. Safety Measures for Drivers with MCI

Due to the impact of MCI on safe driving, measures must be developed to enhance the safety of drivers with this condition. The simplest approach is to apply some form of conditional restrictions on driving. However, it has been reported that elderly people who are prevented from driving require nursing care at a rate approximately eight times higher than elderly people who continue driving.(5) This increase in the need for nursing care may be attributed to how restricting driving causes a subsequent reduction in both the size of the person's living space and amount of activity. Therefore, although continuing driving might be regarded as dangerous, applying restrictions could result in a lower quality of life (QOL) for elderly people.

At the same time, if symptoms of MCI are detected early enough, the appropriate interventions may lead to recovery.(6) For this reason, one possible measure might be to carry out regular screenings of drivers for cognitive function decline while healthy or after the onset of MCI (i.e., while the person is still capable of driving safely), which would then lead to treatment or intervention at a medical institution if symptoms of further cognitive function decline were discovered. However, to enable the screening to be carried out on a regular basis, this approach would require the development of less onerous methods of diagnosing the symptoms of MCI.

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2.1 Existing MCI screening methods

Since MCI screening is an important issue, various methods of screening have been proposed. Akasaka et al. found that inconsistencies in assessments carried out by elderly people and their family members for particular items in a gerontology index of competence, i.e., correct self-awareness of competence, could be used as an effective means of determining MCI.(7) Kato et al. and Kiyoshige et al. have proposed MCI screening methods using aspects of acoustic and speech prosody (i.e., the rhythm, stress, and intonation of speech). These include the intonation used in audio response tasks, spontaneous speech, and spoken responses to interview questions.(8)(9) Shibata et al. developed a screening method using language feature quantities in picture and episode description tasks, particularly the amount and complexity of responses.(10) However, although all these methods are capable of highly accurate screening, each requires the subject to intentionally carry out a set task.

In contrast, Bayat et al, and Di et al. have proposed using the amount of driving activity in methods that do not require an intentional task.(11)(12)(13) These methods estimate cognitive function decline by extracting the driving frequency and trends from driving logs created over an extended period of time. However, since the feature quantities used by these methods include factors such as the number of trips per year, the variety of destinations, the ratio of right and left turns, and so on, the results may be affected by the lifestyle choices and local traffic environment of the subject.

Despite this disadvantage, these methods are not self-limiting and can be supplemented by combination with methods that use different feature quantities. This approach may help to realize even more accurate screening.

3. Method of Estimating Cognitive Function Decline Using Vehicle Data

This article proposes a method of estimating cognitive function decline using vehicle data obtained from micro driving scenarios such as moving off, stopping, turning right, and turning left. The use of vehicle data from micro driving scenarios as inputs should help to eliminate the impact of lifestyle choices and locality from the estimation. **Fig. 1** shows a flowchart of the proposed method. The proposed method consists of the following four steps: driving scenario extraction, feature quantity extraction, estimation of cognitive function decline using a machine learning model, and the calculation of representative values for the estimated values in multiple scenarios. Before discussing these steps in more detail, this section first describes the attributes of the vehicle data that forms the foundation of the proposed method.

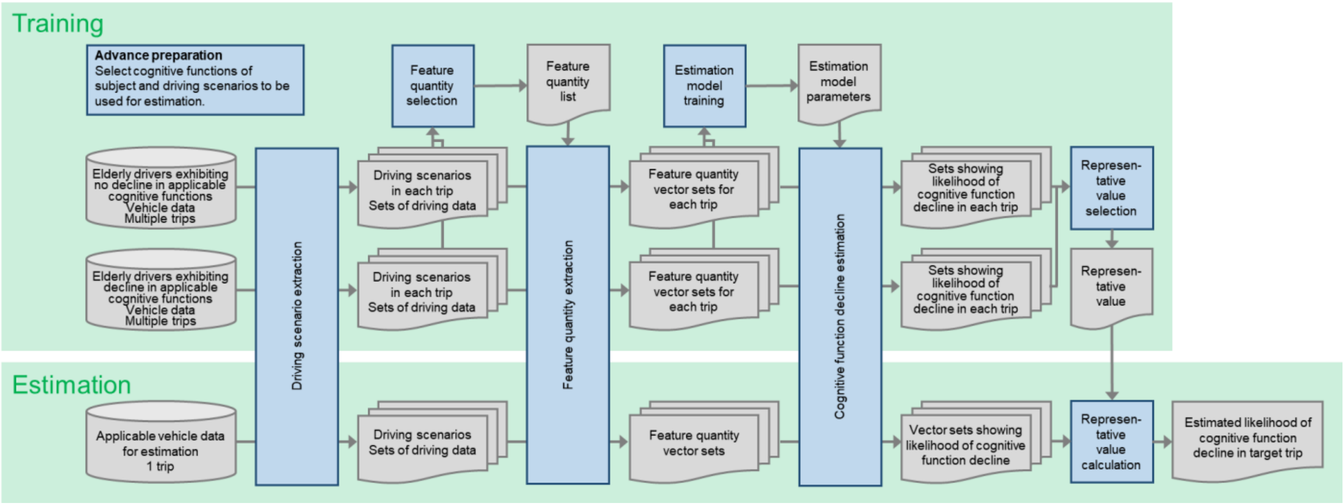


Fig. 1 Flowchart of Cognitive Function Decline Estimation Method

3.1 Labelled MCI driving data set

Before the cognitive function decline estimation method was developed, a driving data set linked to cognitive function assessment results of drivers was constructed. This is referred to below as the “labelled MCI driving data set.” **Fig. 2** shows the information included in the labelled MCI driving data set. It consists of vehicle data obtained from driving on a fixed course on public roads for approximately 30 minutes, videos obtained from both inside and outside the occupant compartment, a driving skill assessment, as well as the results of a separately conducted cognitive function assessment. The vehicle data consists of speed, steering angle, and other aspects of vehicle behavior, as well as signals related to driving operations sampled via the controller area network (CAN) at a frequency of 10 Hz. The driving skill assessment was carried out by driving school instructors riding along with the subject according to the content of elderly driver courses. The cognitive function assessment used the Functional Assessment

Tool developed by the National Center for Geriatrics and Gerontology (NCGG-FAT) to measure four cognitive functions: the memory function, attention function, executive function, and processing speed. The presence of MCI was judged and labelled based on the assessment results for each cognitive function and the age of the subject. **Fig. 3** outlines each cognitive function and the details of the applicable cognitive function assessments. Sample data was obtained from 165 subjects consisting of young and middle-aged people, healthy elderly people, and elderly people with MCI over 277 driving runs. This development only used the vehicle data and labels. It should be noted that the labelled MCI driving data set was constructed as a joint research project with the NCGG. The information obtained in this development was used based on approval from both the Ethics and Conflict of Interest Committee of the NCGG and Toyota's research ethics committee.

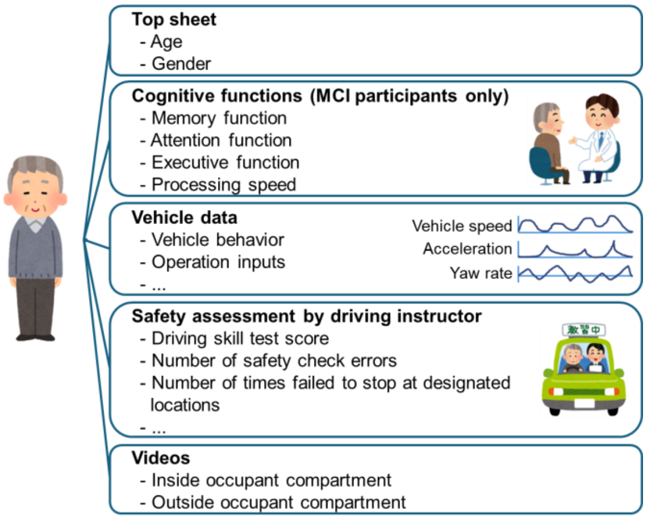


Fig. 2 Information Included in Labelled MCI Driving Data Set

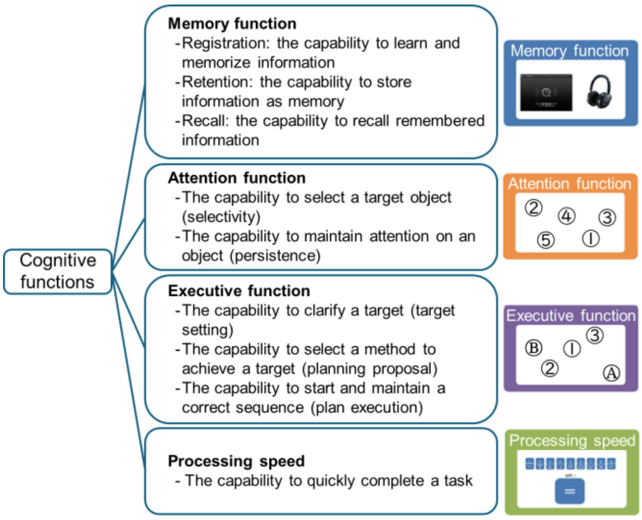


Fig. 3 Cognitive Functions Measured Using NCGG-FAT and Appliable Cognitive Function Assessments

3.2 Driving scenario extraction

In the driving scenario extraction step, the driving scenarios to be used for estimating cognitive function decline are extracted from continuous time series data. During the model training process, the driving scenarios are extracted from time series data sets of drivers exhibiting and not exhibiting cognitive function decline to create sets of driving scenarios for both categories of drivers. During the estimation process, driving scenarios are extracted from the applicable time series data for estimation to construct the sets of driving scenarios for estimation.

This development focused on the use of four driving scenarios for cognitive function decline estimation: moving off in a straight line, stopping in a straight line, turning left, and turning right. Since these are transient scenarios that place a high demand on the cognitive functions of the driver, the effects of cognitive function decline are likely to be more clearly visible in these scenarios. Each scenario is divided into defined units and the feature quantities are calculated for each unit. These divided scenario units are referred to below as "frames." **Table 1** describes the definition of each scenario and how the scenarios were divided into frames.

Table 1 Applicable Driving Scenarios

Driving scenario	Unit	Frame unit
Moving off in a straight line	The first 40.0 m section: after moving off, the ability to drive straight on for 40.0 m or more with an accumulative absolute lateral acceleration value of less than 0.400 m/s^2 AND an accumulative absolute yaw rate value of less than 6.00°.	2.00 m straight section
Stopping in a straight line	The final 40.0 m section: the ability to drive straight on and then stop for 40.0 m or more with an accumulative absolute lateral acceleration value of less than 0.400 m/s^2 AND an accumulative absolute yaw rate value of less than 4.00°.	2.00 m straight section
Turning left	Left turn section located between the two straight sections in which the turning angle is greater than 84.0° and that ends when the turning angle reaches 84.0°.	Turning angle of 2.10°
Turning right	Right turn section located between the two straight sections in which the turning angle is greater than 84.0° and that ends when the turning angle reaches 84.0°.	Turning angle of 2.10°

3.3 Feature quantity extraction

In the feature quantity extraction step, the feature quantities to be used in cognitive function decline estimation are extracted from the driving scenario vehicle data and converted into feature quantity vectors. During the model training process, first, all the feature quantities are extracted as preparation before feature quantity selection, factoring in significant trends between the drivers exhibiting and not exhibiting cognitive function decline, as well as multicollinearity. This development used the eight types of physical vehicle data quantities listed in **Table 2**. The feature quantities were calculated as follows. For each driving scenario frame, the number of samples in the frame and the following six representative values were calculated from the eight physical vehicle data quantities: average value, standard deviation, minimum value. maximum value, difference between minimum and maximum values, and value furthest from zero. These were defined as the feature quantities. In other words, 49 feature quantities were extracted for each frame. These feature quantities can be used to visualize significant trends in the training data between healthy drivers and drivers exhibiting cognitive function decline. The process then selects feature quantities without multicollinearity with other feature quantities and defines these as the feature quantities to be used for cognitive function decline estimation. In contrast, during the estimation process, the feature quantities selected during training are extracted without performing feature quantity selection.

Table 2 Physical Vehicle Data Quantities and Acquisition Methods

Physical quantity	Acquisition method
Vehicle speed	Vehicle sensor
Longitudinal acceleration	Vehicle sensor
Longitudinal jerk	Differential value of longitudinal acceleration
Lateral acceleration	Vehicle sensor
Lateral jerk	Differential value of lateral acceleration
Yaw rate	Calculated from vehicle speed and lateral acceleration
1st derivative of yaw rate	Differential value of yaw rate
2nd derivative of yaw rate	Differential value of 1st derivative of yaw rate

3.4 Estimation using machine learning model

The cognitive function decline estimation step estimates the extent of driver cognitive function decline in each driving scenario (described below as the “likelihood of cognitive function decline”). During the model training process, the estimation models learned from the feature quantity vector sets of the drivers exhibiting and not exhibiting cognitive function decline. During the estimation process, the likelihood of cognitive function decline is estimated for the applicable driving scenarios using the trained estimation models. This development used multilayer perceptron (MLP) neural networks as the estimation models. The hyperparameters, such as the number of layers and number of units, were determined based on Bayesian optimization.

3.5 Calculation of representative values for estimated values in multiple scenarios

In the representative value calculation step, the representative values are calculated from the sets showing the likelihood of cognitive function decline in the driving scenarios extracted from a single trip. It is known that cognitive function decline estimation is affected by the road structure and other traffic users in the driving scenario, which acts as noise in the estimation process. Therefore, representative values are calculated from the likelihood of cognitive function decline in multiple driving scenarios to enhance the accuracy of the estimation using the collective likelihood of cognitive function decline across multiple scenarios. However, since the representative values that should be used depend on the estimation model training results, these values cannot be set in advance. Therefore, during the model training process, the likelihood of cognitive function decline is estimated from the training data after estimation model training is completed, which enables the selection of the representative values capable of most accurately classifying drivers exhibiting and not exhibiting cognitive function decline in each trip. The estimated likelihood of cognitive function decline is calculated for the target trip using the representative values selected in the estimation process. The candidate representative values in this development were as follows: average value, standard deviation, median value, difference between average value and median value, 10% percentile value from 0% to 100%, and the proportion of estimated values below threshold values from 0 to 1 in 0.1 units.

4. Accuracy Verification

This development carried out cross-validation to verify the accuracy of cognitive function decline estimation using the proposed method. This section describes the method, results, and observations obtained from the verification process.

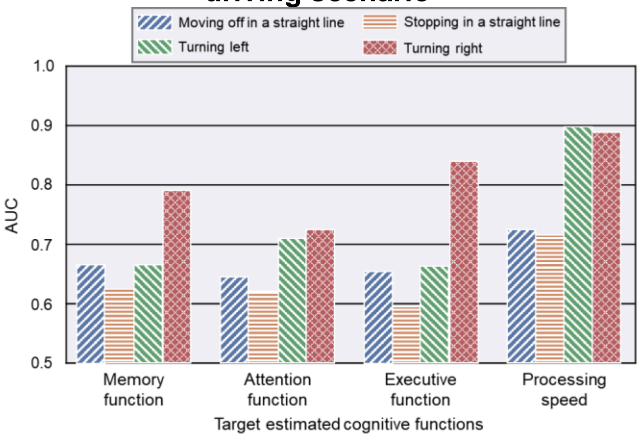
4.1 Verification method

Cross-validation is a method that involves partitioning the training dataset into multiple subsets, designating one subset as the estimation target, determining when the training for that subset is completed, and then using the other subsets for training. Since this development partitioned the training dataset into five subsets, four estimation models were trained (i.e., four combinations of training subsets consisting of one estimation target subset and the subsets for which training is determined to be completed). The average estimated value obtained from these estimation models was used as the final estimation result. Since a single representative value is used, representative value selection uses the whole dataset. Consequently, the verification procedure is as follows. First, the estimation result for the whole dataset is calculated by cross-validation. Then, representative value selection is carried out using the whole dataset, and the selected representative values are used to calculate the classification accuracy for drivers exhibiting and not exhibiting cognitive function decline in each trip. The area under the curve (AUC) was used as the classification accuracy index.

4.2 Results

This development carried out cross-validation for four cognitive functions in four driving scenarios to calculate the classification accuracy of the system. **Fig. 4 (a)** shows the classification accuracy calculated based on estimated values for each driving scenario without using representative values. **Fig. 4 (b)** shows the classification accuracy for each trip using the optimum representative value.

(a) Classification by estimated values for each driving scenario



(b) Classification by representative values for each trip

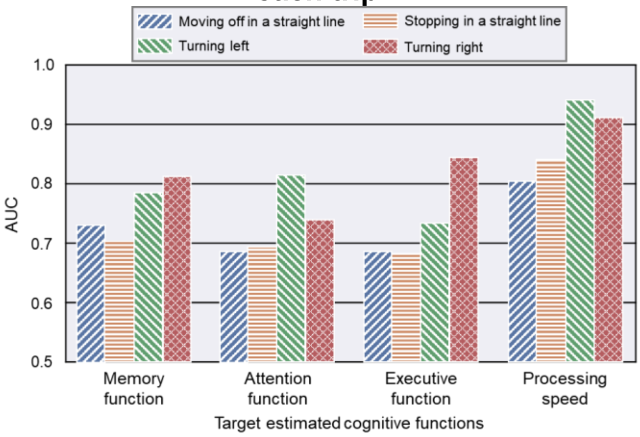


Fig. 4 Classification Accuracy for Drivers Exhibiting and Not Exhibiting Cognitive Function Decline

The results show that, even in the case of classification using individual estimated values, all combinations of driving scenarios and target estimated cognitive functions (except for executive function decline estimation based on the stopping in a straight line scenario) demonstrated a classification accuracy with an AUC value of higher than 0.6, which is the benchmark for a statistically significant classification result. These results suggest that the vehicle data includes information capable of showing whether a driver is exhibiting or not exhibiting cognitive function decline, potentially validating this vehicle data-based approach to cognitive function decline estimation. In particular, cognitive function decline estimation based on the executive function and processing speed in left- and right-turn scenarios achieved AUC values above 0.8, indicating that these combinations achieve highly accurate estimation even with estimated values for individual driving scenarios.

In addition, classification based on representative values achieved a higher classification accuracy then the method using individual estimated values for all combinations of target estimated cognitive functions and driving scenarios. This result demonstrates the value of using representative values. Furthermore, the left- and right-turn scenarios for all four target estimated cognitive functions achieved a classification accuracy with an AUC value above 0.8 both as individual scenarios and when measured together, indicating that these two driving scenarios alone may be capable of estimating a decline in all four of the target estimated cognitive functions.

4.3 Observations

In this test, highly accurate classification was achieved using left-and right-turn driving scenarios regardless of whether the classification was carried out using individual estimated values or representative values. In addition, the classification accuracy of processing speed was particularly high for each target estimated cognitive function. These results probably indicate that the driving scenarios reflect the required cognitive functions in terms of quality and quantity. Left- and right-turn scenarios require high cognitive functionality due to the comparatively high number of required actions, such as checking for pedestrians and oncoming vehicles. As a result, cognitive function decline can be identified more easily in vehicle data. The high classification accuracy achieved using processing speed reflects the fact that driving is a task that continuously changes in accordance with the situation. Therefore, declines in processing speed can also be identified more easily in vehicle data, thereby simplifying estimation.

5. Conclusion

With the objective of constructing a method of detecting cognitive function decline from vehicle data, this article proposed a method of cognitive function decline estimation using vehicle data obtained from micro driving scenarios as a method that would not be affected by the lifestyle choices and locality of the subject. In addition, cross-validation was also carried out using labelled MCI driving datasets to verify the accuracy of cognitive function decline estimation based on the proposed method. The following results were obtained. The proposed method achieved classification with an AUC accuracy value above 0.6 for almost all combinations of the four target estimated cognitive functions and four driving scenarios without representative value calculation, and for all combinations with representative value calculation. These results indicate the feasibility of cognitive function decline estimation using the proposed method.

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Driving Diagnostics Technologies for Zero Accidents and Carbon Neutrality

– Support for Elderly Driver Training Courses –

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Masahiro Misaki[*2]

Abstract

This article describes the development of a system that allows elderly drivers to gain self-awareness of their own driving capabilities and confirm the results of diagnostics for those capabilities. This system is implemented as a part of actual vehicle driving training for elderly drivers carried out at driving schools for the purpose of extending people's active driving age. This development was carried in partnership with driving schools, which helped to select the diagnostics items and carried out demonstration tests of the system. The system analyzes driving operations and vehicle behavior using vehicle data, and carries out driving diagnostics based on vehicle trajectories obtained using high-precision vehicle position measurement and training course maps. After the training course, the participant is given a driving diagnostics report and the results are also made available on a website for the participant's family. In this way, the participant and participant's family can understand for themselves the mental and physical condition of the participant, which can then be used as the basis for decisions about the necessity for further driving training or the like.

Keywords: *elderly driver training course, extension of active driving age, driving skill diagnostics, driving school*

1. Introduction

Alongside the issues of a seriously declining birthrate and an aging population, Japan is looking for ways to enhance the mobility of elderly people in a vehicle-driven society as more people live to be a hundred years old. Although the number of road accidents is decreasing year-by-year as advanced vehicle safety technology evolves, accidents caused by elderly drivers remain fairly steady and are not showing the same decline, setting aside a temporary reduction that occurred during the COVID-19 pandemic (**Fig. 1**).(1) Driving schools are closely involved in efforts to support the lifestyle choices of elderly drivers by providing training courses and cognitive function tests that enable participants to understand their own mental and physical condition and to judge the necessity for further driving training. The Japan Federation of Authorized Driver's School Association established a study group to examine the long-term vision of the association. This group carried out investigations and research into methods of providing further driver training from the perspective of extending people's active driving age, which is an important part of raising the quality of life (QOL) of elderly drivers. Although various training programs have been developed for this purpose, it is vital for elderly drivers to be self-aware of their own driving capabilities. For this reason, there is a growing need for systems capable of quantitatively diagnosing driving capabilities. In response to this situation, Toyota partnered with Shinmei Industry Co., Ltd. (an independent developer of training cars and user-friendly equipment for driving instructors) and the Japan Federation of Authorized Driver's School Association to develop a diagnostics system capable of quantitatively assessing the driving capabilities of elderly people participating in driving courses.(2)

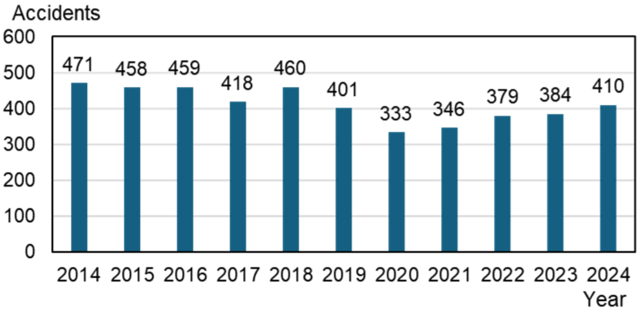

Fig. 1 Trend of Fatal Accidents Involving Drivers Aged 75 or Older (Drivers of Motorized Scooters and Larger Vehicles)

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[*2] Value Chain Development Div., Vehicle Development Center

2. Determination of Driving Diagnostics Items

The driving diagnostics items were studied by observing and riding along with courses for elderly drivers, and discussing assessment methods with driving instructors, in partnership with Kariya Driving School Co., Ltd. in Aichi Prefecture, Takaragaike Driving School Co., Ltd. in Kyoto Prefecture, and Hanshin Driving School Co., Ltd. in Hyogo Prefecture. Through these studies, the issues experienced by elderly drivers were identified and used to determine the diagnostics items.

The diagnostics items were categorized into two main types pertaining to safe or smooth driving. The safe driving category consists of the following items.

- Stopping at intersections without a traffic signal (whether the driver stops in an appropriate location)
- Going off the road (whether the driver runs over a curbstone or turns without touching a lane marker at intersections or around curves)
- Crossing over the boundary line (whether the driver can drive without crossing boundary lines)
- Turn signal start location (whether the driver starts signaling from an appropriate location when turning right or left or when changing lanes)
- Sudden start/acceleration, sudden stop/deceleration (whether the driver avoids sudden starts or acceleration and sudden stops or deceleration)

The smooth driving category was assessed based on whether the driver avoids frequent changes in acceleration, is capable of accelerating and decelerating on straight sections of roads, and is able to drive properly around curves.

3. Development of Driving Diagnostics System

Of the safe driving diagnostics items described above, a new system was developed to analyze the capability of the driver to stop at intersections without a traffic signal, avoid going off the road and cross boundary lines, and operate turn signals appropriately using accurate training course measurements and vehicle position data. As an example, this article describes how this system analyzes the capability of the driver to stop at intersections without a traffic signal.

This capability is determined based on whether the vehicle is stopped in the appropriate position based on the distance between the front end of the vehicle and the stop line as viewed from above. To measure the position of the vehicle, a global positioning system (GPS) antenna was attached to the center of the roof. Distance C from the front of the vehicle to the stop line was then calculated as follows (**Fig. 2**).

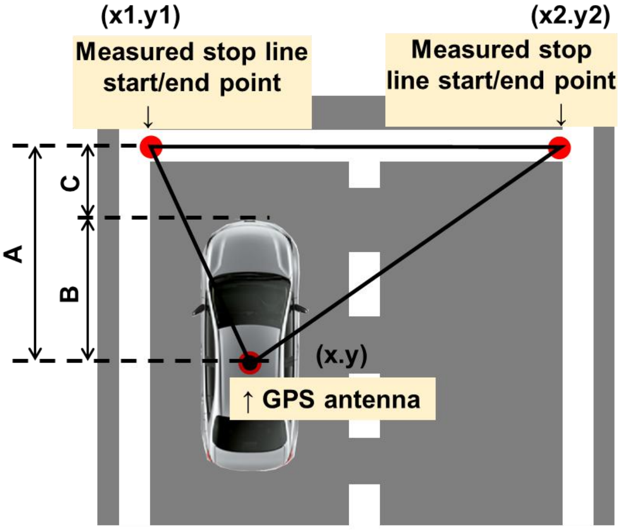


Fig. 2 Vehicle Stop Position Diagnostics

The distance from the stop line to the antenna A can be expressed as shown in **Equation (1)**. Since the distance from the GPS antenna to the front end of the vehicle B is measured in advance, the distance from the front end of the vehicle to the stop line can be expressed as shown in **Equation (2)**.

$$\mathbf{A} = \frac{(x-x2)(y1-y2)-(x1-x2)(y-y2)}{\sqrt{(x2-x1)^2+(y2-y1)^2}} \quad \cdots\cdots (1)$$

where,

(x, y): GPS antenna position

(xn, yn): measured stop line start and end points

$$\mathbf{C = A - B} \quad \cdots\cdots (2)$$

The width of the stop line is 40 cm and the measured start and end points are in the center of the stop line. Since it is recommended to stop the vehicle within 200 cm of a stop line, the diagnostics criteria listed in **Table 1** were set.

Table 1 Criteria for Capability To Stop at Intersection without Traffic Signal

Distance from front end of vehicle to stop line (cm)	Criteria
220 < C	Inappropriate stopping position too far before the line
20 ≤ C ≤ 220	Appropriate stopping position before the line
-20 ≤ C ≤ 20	Stopped on the line
C < 20	Stopped over the line

An algorithm was developed to analyze the capability of the driver to stop at intersections without a traffic signal. This algorithm recognizes a vehicle stop (vehicle speed = 0 km/h) based on speed data obtained from the vehicle and judges whether the vehicle has stopped correctly at the line (**Fig. 3**). This information is combined with the measured stop time and used to analyze the capability of the driver.

A normal GPS system is not sufficiently accurate to measure the distance between a vehicle and a stop line since it generates a measurement error of between several meters and several tens of meters. Therefore, it was decided to adopt relative position measurement using a real-time kinematic (RTK) system. An RTK system simultaneously observes the position of a base station (in a location known accurately in advance) and a mobile unit (i.e., the training car) at the target measurement location. GPS measurement error can then be corrected by calculating the difference between the data for the base station and mobile unit, thereby enabling the acquisition of highly accurate position information with an error of only ±2 cm.

Training course measurement can be carried out by a number of methods, including triangulation. However, it was decided to use a drone equipped with a global navigation satellite system (GNSS). This method has the merit of allowing safe measurement of a wide area over a short period of time at lower cost through the use of onboard drone cameras, which are capable of obtaining accurate position data using RTK-GNSS, capturing topographical images from the air, and obtaining three-dimensional measurement data. This method creates course maps with the same degree of error (±2 cm) as the vehicle position measurement system described above.

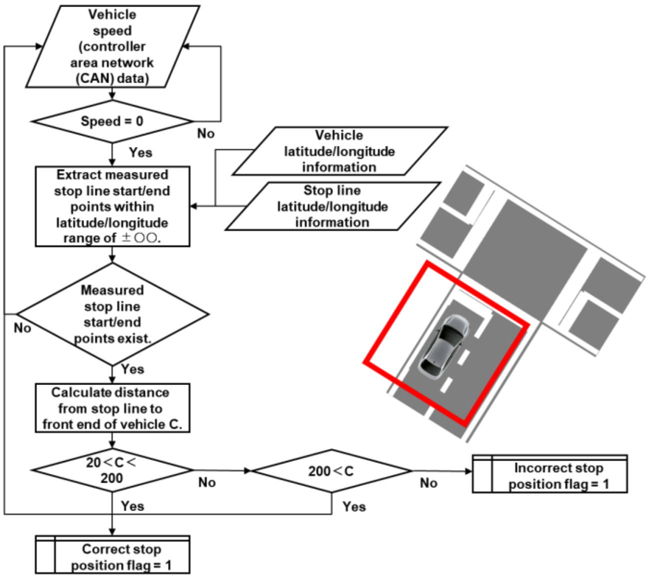


Fig. 3　Logic for Vehicle Stop Position Diagnostics

A diagnostics system that determines the capability of the driver to stop at intersections without a traffic signal was realized by combining the developed diagnostics algorithm with these two existing technologies. The diagnostics system identifies the stopping positions and times of the vehicle, and determines an assessment score based on the number of correct stops. Going off the road, crossing over the boundary line, and turn signal operation are scored in the same way based on the vehicle trajectory and the distance to the center and outer lines on the road, as well as the location of turn signal operation.

For the smooth driving items, a portion of the algorithm devised for Toyota's in-house driver training diagnostics was adopted. The smooth driving weighting of this algorithm was set to a low level factoring in the lower average speed of elderly drivers and the higher weighting given to safe driving as described above.

Shinmei Industry Co., Ltd. developed a system and practical services based on this algorithm. The system is called Satry and is a registered trademark.(3) **Fig. 4** shows an outline of the Satry system.

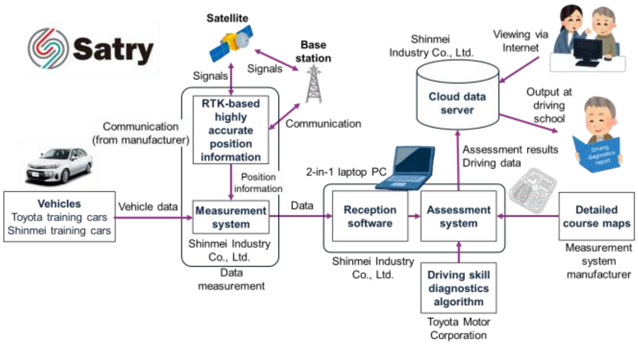
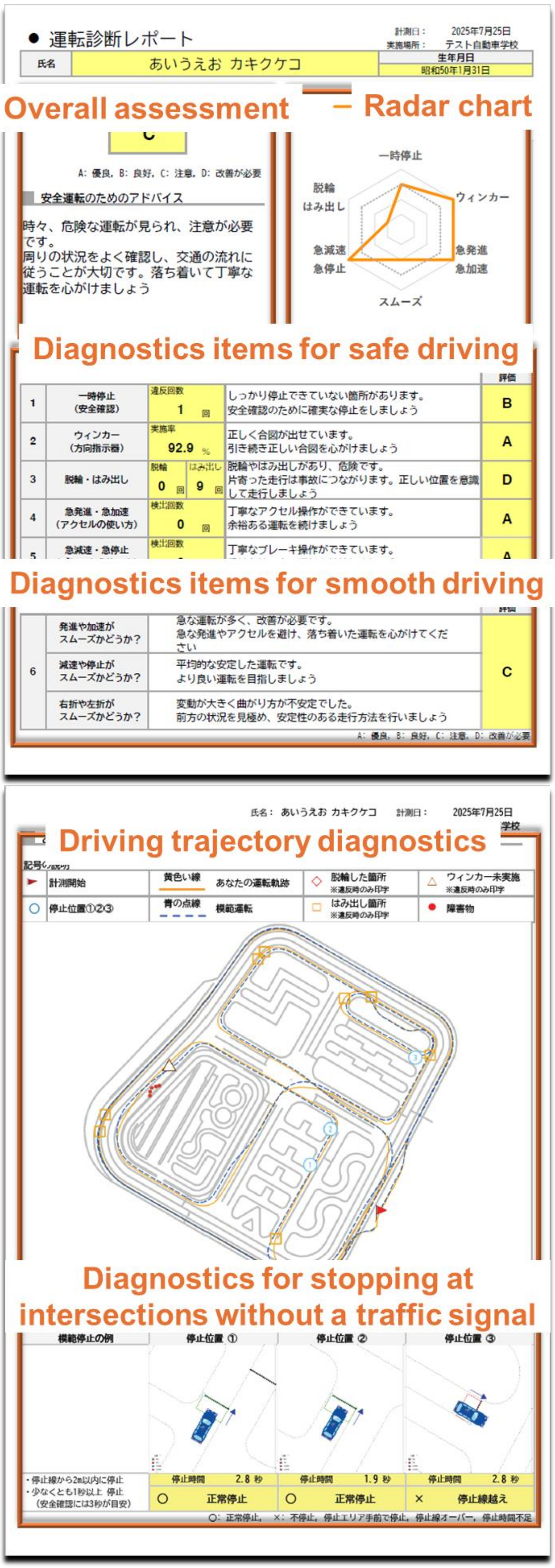


Fig. 4　Outline of Satry System

4. Demonstration Tests

To identify any issues with the developed system and its operation, Toyota partnered with the driving schools mentioned above to carry out demonstration tests. The purpose of these demonstration tests was to detect operational issues from participant registration to the handing over of the driving diagnostics report, as well as any issues related to PC use. In more detail, the system was verified by detecting practical issues, such as whether the presence of objects on the course caused instability in acquiring GPS position information, whether the driving instructors felt that the assessment scores were appropriate, whether the explanation given for the assessment was sufficient, and so on.

Scores for each diagnostics item and an overall score were calculated based on vehicle data using a tablet PC after activating the system and completing the training course. The results are downloaded into a report (**Fig. 5**) via the data server.



● 運転診断レポート

計測日： 2025年7月25日
実施場所： テスト自動車学校

氏名	あいうえお カキクケコ	生年月日 昭和50年1月31日

C

A: 優良，B: 良好，C: 注意，D: 改善が必要

安全運転のためのアドバイス

時々、危険な運転が見られ、注意が必要です。
周りの状況をよく確認し、交通の流れに従うことが大切です。落ち着いて丁寧な運転を心がけましょう

					評価
1	一時停止 （安全確認）	違反回数 1 回		しっかり停止できていない箇所があります。 安全確認のために確実な停止をしましょう	B
2	ウィンカー （方向指示器）	実施率 92.9 %		正しく合図が出せています。 引き続き正しい合図を心がけましょう	A
3	脱輪・はみ出し	脱輪 0 回	はみ出し 9 回	脱輪やはみ出しがあり、危険です。 片寄った走行は事故につながります。正しい位置を意識して走行しましょう	D
4	急発進・急加速 （アクセルの使い方）	検出回数 0 回		丁寧なアクセル操作ができています。 余裕ある運転を続けましょう	A
5	急減速・急停止	検出回数		丁寧なブレーキ操作ができています。	A

			評価
6	発進や加速がスムーズかどうか？	急な運転が多く、改善が必要です。 急な発進やアクセルを避け、落ち着いた運転を心がけてください	C
	減速や停止がスムーズかどうか？	平均的な安定した運転です。 より良い運転を目指しましょう	
	右折や左折がスムーズかどうか？	変動が大きく曲がり方が不安定でした。 前方の状況を見極め、安定性のある走行方法を行いましょう	

A: 優良，B: 良好，C: 注意，D: 改善が必要

氏名： あいうえお カキクケコ 計測日： 2025年7月25日

▶	計測開始	黄色い線	あなたの運転軌跡	◇	脱輪した箇所 ※違反時のみ印字	△	ウィンカー未実施 ※違反時のみ印字
○	停止位置①②③	青の点線	模範運転	□	はみ出し箇所 ※違反時のみ印字	●	障害物

模範停止の例	停止位置 ①	停止位置 ②	停止位置 ③
・停止線から2m以内に停止 ・少なくとも1秒以上 停止 （安全確認には3秒が目安）	停止時間 2.8 秒 ○ 正常停止	停止時間 1.9 秒 ○ 正常停止	停止時間 2.8 秒 × 停止線越え

○: 正常停止，×: 不停止，停止エリア手前で停止，停止線オーバー，停止時間不足

Fig. 5 Driving Diagnostics Report

Some of the safety-related diagnostics items cannot be judged based on vehicle data, and require manual assessment and entry by the driving instructor, such as whether the driver ignored traffic signals, successfully drove over a step, or failed to follow an instruction given by the driving instructor. These items are currently entered manually onto a paper driving assessment sheet, which must be stored for a predetermined period of time at the driving school.

Driving instructors were also asked for comments about the demonstration tests. Various issues were identified with the explanations provided to the participants. Although many recognized poor driving based on a viewing of the vehicle trajectory, it was felt that the length of the explanation time for individual participants was too short. Furthermore, many participants only looked at the overall assessment score. It was concluded that a report or Internet-based explanation capable of providing a more thorough commentary would be required. From the perspective of system operation by the driving instructors, the demonstration test confirmed that the system could be operated smoothly, despite the need to adopt countermeasures for a number of operation errors.

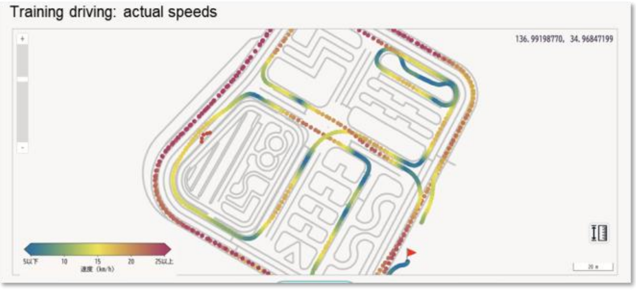
5. System Issues and Countermeasures

One example of a system issue identified in the test was unstable GPS accuracy due to the signal being blocked by structures on the course. In many cases, the areas at the driving schools where people get in and out the training cars is roofed and used as the start/end point for elderly driver courses. This structure might prevent accurate vehicle position detection, potentially destabilizing the detection accuracy of the starting, ending, and stopping positions on the training course, as well as the accuracy of the starting and stopping diagnostics. This issue was resolved by, for example, changing the start/end position of the course to a location without a roof. Another issue was the limited available training period, which meant that the driving instructors had insufficient time to communicate important comments to the driver after the end of the course. This was resolved by providing a diagnostics report that is easier to understand, and posting the diagnostics results on the Internet in a format that provides more detailed feedback (**Fig. 6**).

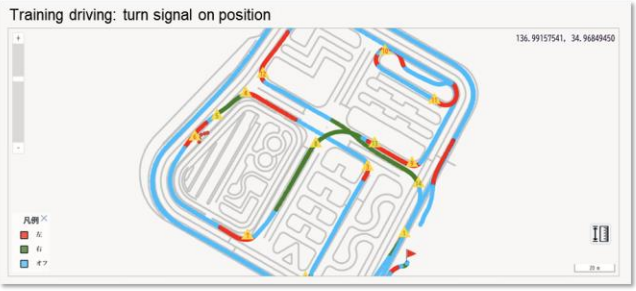
The demonstration test also discovered that the assessment conditions for in-course diagnostics items differ depending on the driving school due to the conditions of the stop lines, location of the step assessment, and so on. Since the step assessment affects the smooth driving part of the driving data, efforts are ongoing to confirm whether this area can be excluded at some driving schools to prevent major variations in assessment scores.

Training driving: overall

Training driving: driving line comparison



Training driving: actual speeds



Training driving: turn signal on position

Fig. 6 Driving Status during Training Course (Example of Website Screen)

An issue in course map creation was also identified. Although a precise course map that includes both latitude and longitude measured by a drone is required for this system, it is difficult for some driving schools that have requested the adoption of this system to allow drone flights over the training course. The development of a system for creating precise course maps without using drones and with a reasonable cost balance is under way.

In addition, the driving instructors are required to both add entries to the system using a PC and complete the driving assessment sheet described above. Driving instructors have requested a system-based replacement for the driving assessment sheet. Public safety commissions in some prefectures have agreed to allow this system to be used as a replacement for the driving assessment sheet as long as it covers the assessment items described on the sheet and the driving instructors can enter comments into the system. Although some prefectures have yet to confirm this request, this change should help to alleviate some of the workload of driving instructors.

6. Future Applications

With the aim of adopting this system at driving schools throughout Japan, an introduction plan has been drawn up for interested driving schools that satisfy the conditions. Currently, only training cars manufactured by Toyota or modified by Shinmei Industry Co., Ltd are capable of acquiring the necessary vehicle data. This limits application to driving schools that use these types of vehicles. However, this system can be applied to even more vehicles providing the necessary vehicle data can be obtained. Other key conditions include the capability to create detailed course maps simply and at low cost, as well as the capability to accurately measure the latitude and longitude of the training car by precision measurement. Toyota intends to continue both technical development to enable the adoption of the system by even more driving schools and research into ways of extending people's active driving age using driving data from elderly drivers obtained via this system.

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Vehicle Diagnostics Technologies for Even Greater Peace of Mind and More Efficient Vehicle Inspections
– Prediction of Deterioration of Vehicle Components Requiring Maintenance –

Ryosuke Fukaya[*1]
Yosuke Kimura[*1]
Atsuhisa Tamano[*2]

Abstract

Vehicle components and consumable items that require maintenance are replaced based on guidelines such as distance driven and elapsed time. This article uses the example of engine oil to describe the outline of a system that utilizes vehicle operation and driving data to predict the state of deterioration in accordance with usage conditions. This approach can be used to optimize part replacement, thereby helping to promote carbon neutrality and reduce dealer workload. The developed system has already been adopted as part of the Connected Car Care feature on vehicles available through the KINTO subscription service in Japan, and Toyota has plans to both roll out the system globally and expand the number of applicable components and consumable items.

Keywords: *big data, deterioration prediction, carbon neutrality, components requiring periodic replacement, use-up, connected car, maintenance, component lifetime*

1. Introduction

In Japan, the replacement cycles of engine oil and other vehicle components and consumable items are described in the inspection and maintenance method for the vehicle in accordance with the Type Designation Regulations for Motor Vehicles (**Table 1**). Depending on the component, two types of replacement cycles (normal and severe conditions) can be set for different vehicle usage scenarios. Whether vehicle usage falls under the definition of "severe conditions" is determined on a case-by-case basis by each dealer under a predetermined set of conditions in accordance with how the customer uses the vehicle (**Table 2**). Components such as the auxiliary battery that have a shorter lifetime than the lifetime of the vehicle but do not require periodic replacement are normally replaced (after confirmation using a tester or the like) as a preventive measure before an issue with the vehicle occurs. In contrast, although it is not impossible to determine the deterioration status of engine oil from the appearance of the oil on the end of the dipstick, appearance is difficult to use as an accurate gauge of deterioration, as shown in **Fig. 1**.

Using data that depicts the operational and driving status of the vehicle to predict the residual life of components and consumable items that require replacement should help to eliminate variations caused by human judgment and allow the proposal of optimum maintenance schedules. Adopting this approach to optimize component and consumable item replacement should also help to achieve carbon neutrality and enhance the environmental friendliness of vehicles, while at the same time helping to alleviate the workload of dealers facing a labor shortage. This article describes an outline of this approach applied to the prediction of engine oil deterioration.

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[*2] Powertrain Function Development Div., Powertrain Company

Table 1 Inspection and Maintenance Method (Replacement Timings for Toyota Harrier (Private Passenger Vehicle))

Components and consumable items requiring periodic replacement	Replacement timing		Remarks
	Time-based replacement Unit: years	Driving distance-based replacement Unit: 1,000 km	
Brake hose replacement	15	200	
Brake fluid replacement	2 (3)		
Brake vacuum pump blade replacement		200	Models equipped with the M20A engine
Transmission fluid replacement (models equipped with continuously variable transmission)		[100]	
Transfer case oil replacement		[100]	
Differential oil replacement		[100]	Since the front differential is integrated with the transmission, implement in accordance with the transmission item.
Spark plug replacement (iridium tipped spark plug)		200	
Air cleaner element replacement		20 [25]	
Engine oil replacement	1 [0.5]	15 [7.5]	
Oil filter replacement		15 [7.5]	
Coolant replacement (models using long life coolant (LLC))	4 (7) *4 (15)	80 (160) *80 (200)	*: inverter

Note 1: Figures in square parentheses ([ ]) indicate the replacement timings under severe conditions.
Note 2: Figures in curved parentheses (( )) indicate the initial replacement timing.

Table 2 Definition of Severe Conditions

Components and consumable items requiring periodic replacement	Severe conditions
Transmission fluid replacement (models equipped with automatic transmission)	[ ] conditions A and C
Transmission fluid replacement (models equipped with continuously variable transmission)	[ ] conditions A and C
Transfer case oil replacement	[ ] conditions A and C
EV transaxle fluid replacement	[ ] conditions A and C
Propeller shaft grease replacement	[ ] conditions A and C
Differential oil replacement	[ ] conditions A and C
Air cleaner element replacement	[ ] conditions A and C
Engine oil replacement	[ ] conditions A, C, D, E, and F
Oil filter replacement	[ ] conditions A, C, D, E, and F
Electric fan motor replacement	[ ] condition F

Severe conditions	
A	Rough roads (uneven roads, gravel roads, snowy roads, unpaved roads)
B	Long driving distances
C	Driving involving frequent use of mountainous roads, hill climbing and descents.
D	Repeated short-distance driving
E	Frequent high-altitude driving (2,000 m above sea level or higher) (diesel vehicles only)
F	Extended periods of idling or frequent low-speed driving (excluding diesel vehicles)

Fig. 1 Appearance of Engine Oil when New and after Driving 5,000 to 15,000 km

2. Prediction of Gasoline Engine Oil Deterioration

To understand the phenomenon of deterioration, it is first necessary to understand the functions of engine oil. The following sections describe the reasoning behind deterioration prediction focusing on the functions of engine oil.

2.1 Functions of engine oil

Engine oil has a wide range of functions for supporting the smooth operation of internal combustion engines. The most basic function of engine oil is lubrication. Engine oil is used to form films between metal parts that are moving at high speeds in the engine, such as the pistons, crankshaft, valves, and the like. These films block direct contact between the metal parts, preventing abnormal wear, seizures, and so on. Engine oil also has a cooling function by which it absorbs and removes heat generated by combustion and friction. This prevents localized overheating, and helps keep pistons, bearings, and other components at an appropriate temperature. Another important aspect of engine oil is its detergency effect inside the engine, whereby it neutralizes acidic compounds generated by the engine operating process and disperses combustion residue. Coating engine oil on metal surfaces also helps to suppress the generation of corrosion and rust. Since the inside of an engine is highly susceptible to the effects of moisture and combustion products, the corrosion resistance provided by engine oil is indispensable for protecting metal components. Finally, engine oil is used to seal the gaps between the piston rings and cylinders, which prevents compression leakage and provides a sealing action that supports efficient combustion. These functions are mutually supporting and help to maintain engine performance and extend engine lifetime.

Engine oil mainly consists of a blend between a base oil refined from petroleum and multiple additives as listed in **Table 3**. Additives are used both to enhance the functions of the base oil and to provide additional functions. Specific examples include anti-wear additives that help to create stronger lubrication films and prevent wear, friction modifiers that lower the friction coefficient, anti-oxidants that delay oil oxidation and extend the oil lifetime, detergents and dispersants that disperse combustion products and prevent the accumulation of deposits on engine components, as well as rust inhibitors that protect metal surfaces and prevent rust. Viscosity index improvers suppress changes in oil viscosity in response to temperature fluctuations, and are added to help maintain a more appropriate viscosity over a wide temperature range. Modern engine oils feature sophisticated combinations of base oils and additives for the purpose of protecting the engine and maintaining the appropriate functions for a longer period of time even under harsh internal engine environments.

Table 3 Main Types of Engine Oil Additives

Name of additive	Main functions
Ashless dispersants	Dispersion of soot and insoluble content, detergency (especially at low temperatures)
Metallic detergents	Acid neutralization, detergency (especially at high temperatures)
Zinc dialkyldithiophosphates (ZnDTP)	Oxidation, wear, and corrosion prevention
Antioxidants	Oxidation and deposition prevention
Friction modifiers	Friction reduction and wear prevention
Rust inhibitors	Rust prevention
Antifoaming agents	Foaming prevention

2.2 Mechanism of engine oil deterioration

As shown in **Fig. 2**, the following three engine oil deterioration phenomena occur due to the usage conditions and driving environment: (1) changes in viscosity and other physical properties, (2) degradation of functionality due to depletion of additives such as dispersants, antioxidants, and the like, and (3) accumulation of foreign matter such as insoluble content, fuel, water, particulate matter (PM), abraded metal, dust particles, and the like.

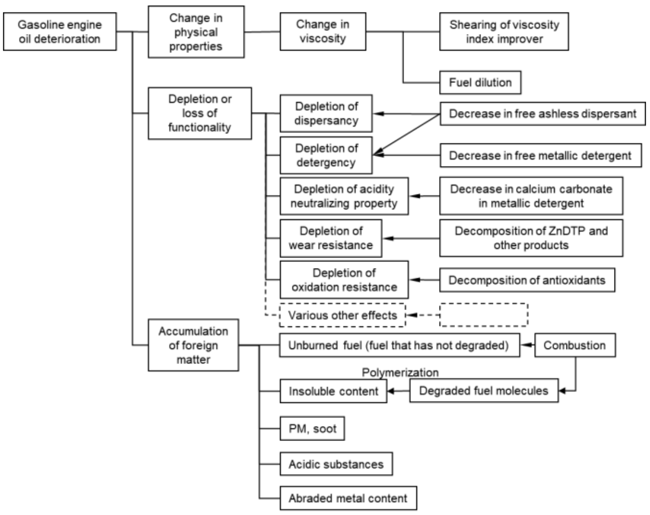


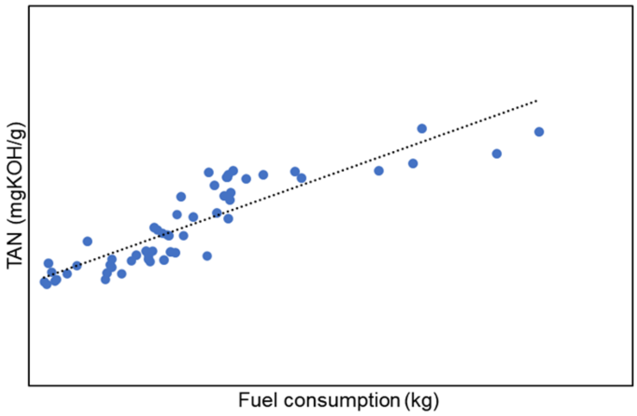
Fig. 2 Engine Oil Deterioration

Although kinematic viscosity decreases due to shearing of the viscosity index improver and fuel dilution, it also increases due to the generation and accumulation of insoluble content. Since the physical properties of oil can change in either direction due to these various causes, it is difficult to predict the extent of oil deterioration using the kinematic viscosity.

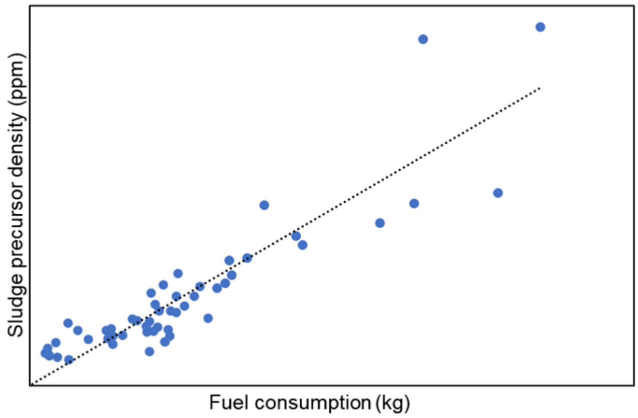
One additive depletion mechanism is oxidative degradation under high-temperature environments. This type of oxidation reaction causes the generation of acidic substances such as carboxylic acid, sulfonic acid, and phosphoric acid. The total acid number (TAN), which denotes the amount of acidic substance accumulation and expresses the extent that deterioration has progressed, increases uniformly and is relatively simple to predict. Because the largest promoting factor for oxidative degradation is high heat caused by combustion, a correlation with fuel consumption can be hypothesized.

In addition, excess accumulation of insoluble content can cause piston deposits and sludge. This insoluble content is produced when degraded fuel molecules generated by incomplete combustion accumulate and polymerize. For this reason, the degraded fuel molecule content in the oil can be used as a proxy indicator for insoluble content accumulation. Tests confirmed that the degraded fuel molecule content in oil is proportional to the fuel consumption amount. This relationship can also be used a simple predictive deterioration indicator. Degraded fuel molecules and polymers are referred to as sludge precursors, which is a technical term referring to materials that eventually produce sludge. Since sludge precursors are thought to generate micro-particles in the oil and are brown in color, a unique measurement device was developed using the optical properties of these sludge precursors. The density estimated by this device is referred to as the sludge precursor density.

To verify the accuracy of these approaches to predict engine oil deterioration, engine oil samples reflecting a wide range of usage conditions were recovered from the market and analyzed. **Fig. 3** shows the results. As expected, a correlation was identified between the deterioration indicators and fuel consumption.



Relationship between fuel consumption and TAN



Relationship between fuel consumption and sludge precursor density

Fig. 3 Analysis Results of Engine Oil Samples Recovered from Market

These relationships were used as the basis for calculating a deterioration prediction formula that incorporates a certain safety factor. This prediction formula can be utilized to estimate the residual life of engine oil in accordance with how the vehicle is being used, helping users and dealers determine the optimum replacement timings of components and consumable items.

3. Conclusion

The residual life of engine oil can be predicted by combining the developed deterioration prediction model with vehicle driving data. Toyota has launched these systems on vehicles in Japan available through the KINTO subscription service by incorporating the systems into the Connected Car Care feature of the KINTO Unlimited program. Under this feature, vehicle data is used to predict the deterioration of both the engine oil and auxiliary battery (**Fig. 4**).(1)

Toyota intends to expand the availability of these systems to both privately owned vehicles in Japan and markets outside Japan, as well as to further expand the number of applicable components and consumable items.

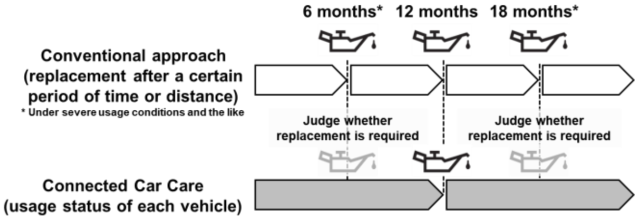


Fig. 4 Maintenance under the Connected Car Care Feature

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Vehicle Diagnostics Technologies for Even Greater Peace of Mind and More Efficient Vehicle Inspections
– Support for Rental Vehicle Inspections by Minor Collision Detection –

Kentaro Nagaya*1
Yosuke Kimura*1

Abstract

Toyota has developed a minor collision detection system using driving data from connected cars to help alleviate the workload of businesses when vehicles are damaged in a collision. In the development of this system, a method was proposed that estimates acceleration caused by driving operations using a long short-term memory (LSTM) model and then detects minor collisions by subtracting that acceleration from actually measured acceleration values. This method was verified from data obtained over half a year from around 1,000 taxis operating on the outskirts of Tokyo. The results found that this system is capable of detecting approximately 90% of accidents that cost 200,000 yen (around 1,300 USD) or more to repair, while also estimating the location of the damage from the acceleration direction. Another demonstration test using 850 rental vehicles in Okinawa showed that the number of false positives caused by local characteristics could be reduced by post-processing. Work is currently under way to enhance this system to enable even more detailed collision detection while minimizing false positives.

Keywords: *minor collision detection, accident detection, machine learning, LSTM, vehicle driving data, acceleration sensor, driving operation*

1. Background and Objective

Vehicle damage caused by accidents has serious negative consequences for the car-based lifestyles of customers and businesses alike. In addition to proactive measures to prevent accidents from happening at all (*mizen boshi*), efforts are also needed to minimize the workload involved in repairing vehicle accident damage. This article describes the development of a system that detects minor collisions from the driving data of connected cars, which can then be used to help realize new services. These include a service for used car appraisals that provides alerts so that the repair history of a vehicle is not overlooked, and a service that allows dealers to confirm the safety of customers after an accident and to encourage those customers to bring the vehicle in for inspection. In addition, by detecting even more minor collisions, the developed system can also be used to help shared or rental vehicle business operators to inspect and identify damage to vehicle exteriors.

2. Method

2.1 Issues of minor collision detection

Driving data previously collected from connected cars already on the market was utilized to enable the rapid commercialization of new services using the developed system. Data pertaining to collisions includes airbag deployment signals and acceleration measured by floor acceleration sensors. However, one issue of used car appraisals is that airbags only deploy in 10% of all accidents recorded in the repair history.(1) Although the use of acceleration values may help to detect minor collisions in which the airbags did not deploy and allow the location of damage to be estimated, false positives may be triggered by noise generated by normal driving operations such as acceleration, braking, and steering, unevenness of the road surface, and the like.

2.2 Minor collision detection logic

Although huge amounts of data can be collected from connected cars, most of this data is normal accident-free driving data. Therefore, the characteristics of this data were used to build a model that estimates the acceleration generated by a vehicle in normal driving. The causes of this acceleration at any given time may be regarded as either driving operations or impacts from outside the

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vehicle, such as collisions or unevenness in the road surface. The following two categories of measured data are collected from connected cars: (1) data showing the history of vehicle behavior (vehicle speed, acceleration, and the like) up to a certain point in time, and (2) driving operations such as acceleration, braking, steering, and the like. It should be possible to estimate the acceleration mainly generated by driving operations by learning the interrelationship between the acceleration generated by these two categories. Since acceleration generated by an impact from outside the vehicle cannot be estimated from data categories (1) and (2), minor collisions can be detected by treating this acceleration as an abnormality (**Fig. 1**).

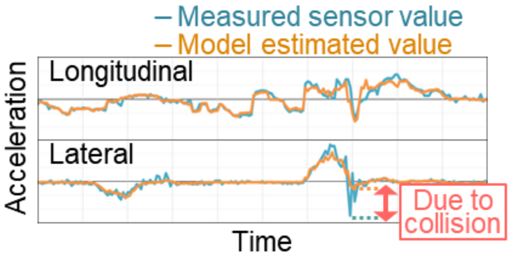

Fig. 1 Collision Detection Using Acceleration Estimation Model

To create this acceleration estimation model, it was decided to adopt a long short-term memory (LSTM) neural network, which is known to be an effective way of analyzing time series data.(2) Model learning was carried out as follows. Time series data inputs (16 channels × 5 seconds (100 ms intervals)) were created from elements such as vehicle behavior and driving operations. The internal LSTM weighting parameters were then adjusted to minimize the mean squared error between the estimated acceleration output values and the measured acceleration used as training data. The LSTM consisted of one layer and 512 dimensions. To prevent over-learning, repetitive learning was carried out over 30 steps. The values obtained by the trained acceleration estimation model and the measured acceleration values were used to calculate resultant acceleration a_t due to impacts from outside the vehicle (a value that excludes acceleration generated by driving operations) and acceleration direction d_t, as shown in **Equations (1 to (3)**.

$$\Delta a_{s,t} = a_{s,t} - f_s(\boldsymbol{x}_t) \quad (s \in \{fb, lr\}) \tag{1}$$

$$a_t = \sqrt{(\Delta a_{fb,t})^2 + (\Delta a_{lr,t})^2} \tag{2}$$

$$d_t = \tan^{-1}(\Delta a_{fb,t}/\Delta a_{lr,t}) \tag{3}$$

X_t is the input data used to estimate the acceleration caused by driving operations in time t, $a_{s,t}$ is the measured acceleration in time t, f_s is the acceleration estimation model, and f_b and l_r indicate the longitudinal and lateral directions, respectively. In this development, a collision was determined to have occurred when acceleration a_t generated by an impact from outside the vehicle exceeded a threshold value of 5 m/s^2. Although lowering the a_t threshold would allow the detection of more minor collisions, this would have the trade-off effect of creating more false positives. From the perspective of actually adopting this system in a service (Section 4), this threshold was determined based on the results of the accuracy verification tests described below to create the optimum balance between correct collision detection and the number of false positives. The machine learning library TensorFlow(3) was used in the creation of the LSTM neural network model.

2.3 Accuracy verification

The detection accuracy of this system was verified by testing the developed logic using driving data provided by taxi operators in which the existence of accidents is already flagged. Driving data obtained over half a year from around 1,000 taxis operating on the outskirts of Tokyo was used for this verification. The following accident information from the applicable period was utilized: the vehicles that were involved in an accident, the accident date and time, the location of damage, and the repair cost. Images from onboard cameras were also used to identify the time of the accident more accurately. It should be noted that the test plan was approved after an examination by Toyota's research ethics committee.

3. Results

3.1 Acceleration estimation model learning

The taxi acceleration estimation model was created by learning using driving data equivalent to 20,000 km (100 taxis × 1 day). The estimation accuracy of this model was then verified using 20,000 km of driving data including acceleration, deceleration, and steering scenarios from 100 other taxis not included in the learning dataset. The results identified a standard deviation between the estimated and measured values of 0.14 m/s^2 (longitudinal direction) and 0.15 m/s^2 (lateral direction). Therefore, for example, since normal braking generates deceleration of approximately 3 m/s^2, the developed model was judged to be capable of accurately estimating acceleration generated by driving operations.

3.2 Frequency of false positives

The frequency of false positive generation was verified by testing the developed logic using driving data equivalent to 200,000 km (900 taxis × 1 day) known to contain zero accidents. **Fig. 2** shows the frequency distribution of acceleration a_t generated by impacts from outside the vehicle. The frequency of false positives (non-accidents determined to be collisions when a_t exceeds 5 ms/^{2}) was 21 cases per 200,000 km (around 1 case per 10,000 km). When the occurrence of a collision was detected using only the measured acceleration with the same threshold value, the frequency of false positives was 4,200 cases per 200,000 km (around 200 cases per 10,000 km), which indicates that the developed logic reduced the frequency of false positives to 1/200 of the previous level.

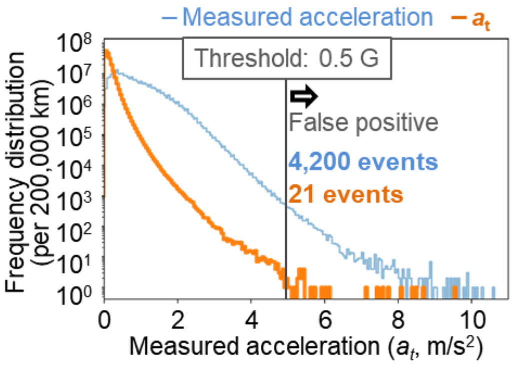

Fig. 2 Frequency Distribution of Measured Acceleration (Blue) and Acceleration Caused by Impacts Outside Vehicle a_t (Orange) (per 200,000 km)

Next, information such as images from onboard cameras was used to verify the causes of these false positives. For example, as shown in **Fig. 3**, it was confirmed that a false positive was created by the impact generated by a vehicle driving over the end of a ramp at an underground terminal. When the causes of all 21 false positives were verified in the same way, it was found that more than half were caused by sensor inputs from the road surface via the tires (**Fig. 4**). Inputs from the road surface include the change in level at the end of ramps heading underground, rough road surfaces, joints between road sections, level differences at the boundary between roads and sidewalks, and speed bumps. Causes other than inputs from road surfaces include shock from emergency braking (the model failed to identify when the deceleration suddenly returned to around 0 when the vehicle stops) and braking when the vehicle slides backward down a steep uphill gradient (the system mistakenly identified the sign (positive/negative) of braking deceleration because it cannot identify the direction of movement when the vehicle moves backward despite the gear position being either D or N).

Fig. 3 Example of Camera Image Immediately before False Positive

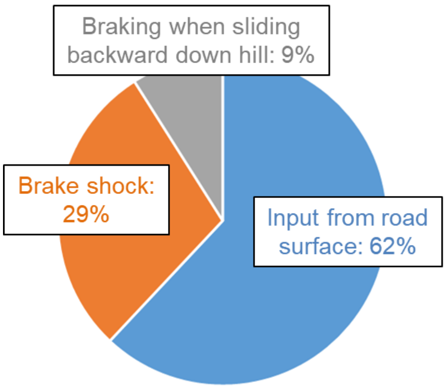

Fig. 4 Breakdown of Causes of False Positives

3.3 Detection rate

It was verified that the developed logic detected all accidents in a test using driving data known to contain accidents. The detection rate for each classification of repair cost was calculated by randomly extracting a specific number of accidents in each repair cost classification from all the accidents in the target accuracy verification period and applying the following formula: number of detected accidents ÷ (number of detected accidents + number of overlooked accidents). **Fig. 5** shows the results. Each point in the figure represents a single accident. The x axis shows the acceleration a_t generated by a collision impact and the y axis shows the repair cost. The points are arranged generally from the bottom left to the top right of the graph, showing that the size of the collision impact is roughly proportional to the vehicle damage. If the collision judgment threshold is set at an a_t value of higher than 5 m/s^2, the system detected approximately 90% of all accidents costing 200,000 yen (around 1,300 USD) or more to repair. In contrast, the system only detected approximately 20% of accidents costing less than 200,000 yen to repair. In addition, when the occurrence of a collision was detected using only the measured acceleration and a threshold value of 8.5 m/s^2, which achieves the same false positive frequency (1 case per 10,000 km) as the developed logic, the detection rate of accidents costing between 200,000 and 400,000 yen to repair fell substantially to 50%. This result demonstrates that the developed logic improves the detection rate of accidents costing between 200,000 and 400,000 yen to repair from 50% to 90%.

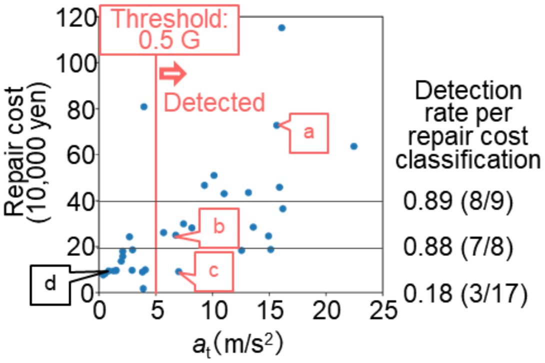

Fig. 5 Detection Rate per Repair Cost Classification

Fig. 6 shows onboard camera images immediately before four typical vehicle collisions (points a to d in **Fig. 5**). **Fig. 6a** shows a side impact collision between a vehicle driving straight on at a collision and a vehicle that drove straight into the intersection from the left. **Fig. 6b** shows a collision between a vehicle turning right with a vehicle that drove straight into the intersection from the left. The system detected both cases due to the relatively high acceleration generated by two vehicles in motion colliding with each other. In addition, **Fig. 6c** shows a vehicle hitting a concrete block in a blind spot on a narrow road at night as an oncoming vehicle drives past. Despite a low collision speed of 3 km/h, the system detected the accident due to the relatively high acceleration generated because the driver did not try to avoid the collision by steering or braking. In contrast, **Fig. 6d** shows an accident in which the driver scraped the left side of the vehicle against a pole when slowly turning left at a narrow intersection at night. In this case, the system failed to detect the accident because the low collision speed of 2 km/h and a low collision angle minimized the degree of acceleration. Consequently, accidents that occur at low collision speeds and angles and that only result in shallow scratches may be regarded as a type of accident that is difficult to detect and easy to overlook.

* The brightness of these images was adjusted for greater visibility in this article.

Fig. 6 Example of Camera Images Immediately before Vehicle Collisions

3.4 Estimation of collision direction

The capability of the system to estimate the direction of vehicle damage was verified by comparing damage location information with the acceleration direction d_t calculated using the developed logic for 18 accidents successfully identified in the detection rate verification. **Fig. 7** shows the results. The location of vehicle damage is shown as the red shaded locations in a maximum of four directions (longitudinal × lateral) based on the damage location labels used by taxi operators. Since the arrows show the direction of acceleration generated by the collision, the direction 180 degrees in the opposite direction to the arrow may be estimated as the damage location. This comparison confirmed that this direction was roughly consistent with the actual damage location.

In two cases, the estimated damage location differed from the actual location of damage (the cases at the far right and second from the right in the middle row). In the first case, the actual damage occurred at the front-right of the vehicle. However, the force was probably detected in the front-left direction (slightly forward of the precisely leftward direction) because the accident was caused by the other vehicle scraping against the side of the driver's vehicle during an overtaking maneuver. The second case shows damage to the rear bumper. However, the force was probably detected in the rear-right direction (slightly rearward of the precisely rightward direction) because the other vehicle collided with the left side of the bumper at an acute angle measured from the front to the rear of the driver's vehicle.

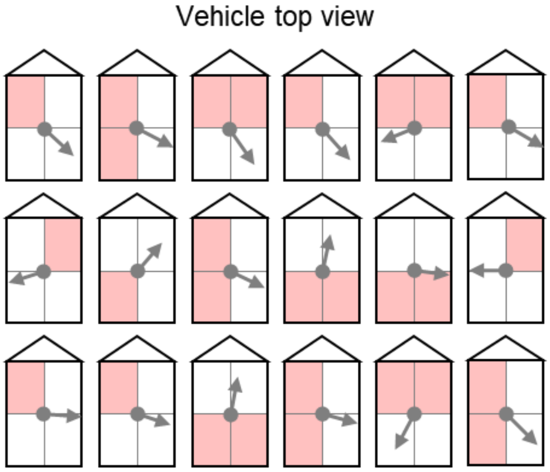

Fig. 7 Comparison of Vehicle Locations Damaged by Collision (Red) and Acceleration Directions Calculated by Developed Logic d_t (Arrows)

4. Service Applications

4.1 Support for rental vehicle inspections

When customers return a vehicle to a rental shop, the staff inspect the vehicle for damage. In busy periods like peak tourism season, these inspections must be carried out rapidly to prevent a backlog of vehicles building up. This system helps staff carry out accurate inspections in a short period of time by alerting the shop in advance of vehicles that may have been involved in a collision during the rental period, as well as the locations of the vehicle that should be checked more closely.

4.2 System demonstration

The accuracy of collision detection was verified in partnership with rental vehicle operators in Okinawa. A verification system was constructed consisting of 850 rental vehicles equipped with connected technology, a cloud-based calculation function for detecting collisions, and a database for saving and confirming the detection results. The detection results were then verified by comparison with accurate accident report data held by the taxi operators. It should be noted that the test plan was approved after an examination by Toyota's research ethics committee.

First, the false positive frequency was verified using detection results from driving data collected over one month (700,000 km). The frequency of false positives was 145 cases per 700,000 km (1 case per 5,000 km), roughly twice as high as the verification results from the outskirts of Tokyo described in Section 3.2. Surveys carried out of the local road environment found that most of false positives were caused by impacts generated by driving over speed bumps (**Fig. 8**) located within the grounds of tourist hotels. For this reason, the high false positive frequency may be regarded as a local characteristic of Okinawa, which attracts a high number of tourists. Scenarios of vehicles driving over speed bumps and other similar road structures were isolated from the data by applying the following three conditions. (1) When a disturbance in the wheel speed waveforms at each of the four wheels due to contact between the wheels and a structure is generated in sequence from the front to the rear wheels matching the wheelbase of the vehicle. (2) When the acceleration of the detected collision is smaller than the upper limit of acceleration generated by driving over a structure (empirical value obtained by demonstration). (3) When a collision is detected at an uneven part of the road as determined by the roughness index.(4) After adding post-processing filtering logic to exclude detected collisions that satisfy any of conditions (1) to (3), the false positive frequency fell to 4 cases per 700,000 km (1 case per 200,000 km). Consequently, the addition of post-processing filtering logic is a potentially feasible means of minimizing any increase in false positives caused by the local road environment.

Fig. 8 Speed Bump within Grounds of Tourist Hotel

In contrast, the system only managed to detect 3 out of 43 accidents that occurred in the two-month period. However, one of the detected accidents identified damage that had been overlooked in the inspection by the rental shop staff, which demonstrates that the system provided effective support for rental vehicle inspections. However, this accident detection rate of less than 10% (3 cases out of 43) is lower than that achieved in the taxi operator verification test described in Section 3.3 (detection rate of 20% for relatively minor accident (repair cost of less than 200,000 yen). Possible causes for this gap include people driving unfamiliar rental vehicles and the number of accidents in busy parking lots in tourist areas, which may have increased the rate of extremely minor accidents resulting in shallow scratches. These types of accidents can only be detected by lowering the acceleration threshold a_t used to determine whether an accident has occurred (**Fig. 5**). However, this will have the trade-off effect of exponentially increasing the frequency of false positives (**Fig. 2**). Therefore, to help realize a service that supports rental vehicle inspections, Toyota intends to continue development of this system to enable the detection of extremely minor collisions while minimizing false positives generated by inputs from the road surface.

5. Conclusion

This article described the development of fundamental logic enabling the remote detection of minor collisions involving connected cars. In addition, a system for verifying the rental vehicle inspection support service was constructed to confirm the accuracy of the developed logic.

To help realize a service that supports rental vehicle inspections, Toyota intends to continue development of this system to enable the detection of extremely minor collisions resulting in shallow scratches while minimizing the number of false positives.

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Vehicle Diagnostics Technologies for Even Greater Peace of Mind and More Efficient Vehicle Inspections
– Detection of Signs of Wheel Detachment –

Takahiro Tsuji[*1]
Yosuke Kimura[*1]

Abstract

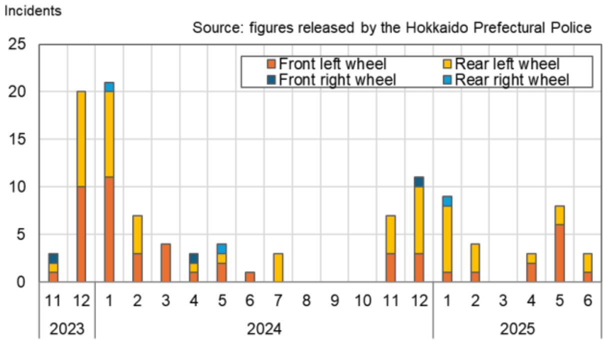
With accidents involving tire and wheel detachment attracting increasing attention, Toyota has developed and verified the effectiveness of an algorithm that detects signs of wheel detachment using wheel speed sensor information from connected cars. In partnership with dealers, data from approximately 550,000 vehicles over around five months was analyzed to verify the situation on actual vehicles. The effectiveness of the algorithm in detecting signs of detachment such as lug nut looseness was confirmed. However, since the developed algorithm also detected a wide range of abnormal conditions as well as lug nut looseness, further work is needed to enhance its accuracy. In the future, Toyota is aiming to help realize an even safer vehicle-based society by enhancing and implementing this detection algorithm in the real world.

Keywords: *tire and wheel detachment, wheel detachment, lug nut looseness, lug bolt, tire replacement, retightening*

1. Introduction

Accidents involving tire and wheel detachment have become a major focus in the media. Although this focus used to be limited to incidents involving heavy-duty trucks, an increasing number of cases involving passenger vehicles are now being reported. Causes of tire and wheel detachment accidents include do-it-yourself tire replacement by users and issues with tools. The fastening of wheels to a vehicle generally involves the use of a torque wrench to control the tightening torque. This tightening torque is an indirect value used to express the friction of the hub bolt axial force, which is the actual value that needs to be controlled. Since this friction is affected by foreign matter and contamination on the thread and tightening surface, the components must be cleaned before the wheels are attached. In addition, even if tightening is carried out in accordance with the correct procedure, it is recommended to retighten the wheels after a certain driving distance. Despite warnings about tire and wheel replacement work issued by the Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT)(1) as well as by police in cities and prefectures across the country,(2) tire and wheel detachment incidents are still occurring. Since this type of public awareness raising is not sufficient, a more tangible and effective measure to address the situation is required.

Fig. 1 shows the number of tire and wheel detachment incidents per month in Hokkaido. The number tends to increase between the beginning of winter and the following spring. One cause may be attributed to the sudden change in weather that occurs at the beginning of winter, which prompts many people to switch from summer to winter tires at this time. Although this number trended downward in the period from 2024 to 2025 in response to media reports of incidents and public awareness campaigns, the number still remains high at around ten per month.



Source: figures released by the Hokkaido Prefectural Police

Fig. 1 Number of Wheel Detachment Incidents

2. Market Trends

The articulated nut rotation indicator for heavy-duty vehicles(3) is one example of a detachment prevention measure that is currently in use. This is seen as an effective approach for heavy-duty vehicles that are

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generally subject to daily inspection since it enables a simple visual check. In addition, the Loose Wheel Indicator manufactured by NIRA Dynamics AB(4) is an example of a system developed for passenger vehicles. Generally, the root cause of tire and wheel detachment is loose lug nuts, which are the parts used to fasten the wheel to the vehicle (vehicles in Europe use lug bolts). This looseness is highly likely to generate some kind of vibration or noise during driving, something that is backed by comments from drivers involved in such accidents. Although drivers tend to be aware of this abnormal vibration or sound, the vehicle is often driven until the wheel detaches because the driver fails to identify the cause of the abnormality. This is a typical case of normality bias, a cognitive bias that leads people to disbelieve or minimize threat warnings. Therefore, providing an alert that encourages drivers to check or maintain the vehicle may be an extremely effective means of preventing detachment in advance.

This article describes the analysis of data from connected passenger cars driving in Japan, as well as the results of a technical demonstration test examining the feasibility of detecting this phenomenon even in vehicles not equipped with a means of predicting tire and wheel detachment. It should be noted that the connected car data obtained in this study was handled in accordance with Toyota's privacy regulations and that requests for cooperation were only made to customers who had agreed to the terms of data usage.

3. Outline of Technical Demonstration Test and Information Collection Process

This section outlines how the detection algorithm was verified (**Table 1**).

Table 1 Outline of Technical Demonstration Test

Period	November 2023 to March 2024 (5 months)		
Applicable region	Japan nationwide (Vehicle inspection-based surveys were carried out in some areas only: Hokkaido and the Tohoku and Hokuriku regions.)		
Models (not all vehicles of each model)	Starting in November	Alphard Vellfire	Approx. 150,000 vehicles
	Starting in February the following year	RAV4 Harrier Noah Voxy	Approx. 400,000 vehicles

Total: 550,000 vehicles

It was decided to start the demonstration test in November since the information on the number of monthly incidents described above and previous surveys identified that a high number of detachment incidents occur in this period, which is around the time that users install winter tires. The applicable regions were determined as follows. Actual vehicle surveys during dealer visits were limited to snowy regions with a high winter tire installation rate. However, an interview-based survey was carried out nationwide to collect the widest possible number of cases. The vehicle models were selected in the same way. The applicable models were selected from sport utility vehicles (SUVs) and minivans equipped with connected features since previous survey results indicated the high frequency of incidents with these models. However, the survey covered gasoline, hybrid, front-wheel-drive, and four-wheel-drive vehicles without distinction. When converted into a driving distance, the total target data processing amount was set to the equivalent of 1 billion kilometers. This value itself is equivalent to the distance driven by 100,000 vehicles over a year. The number of vehicles surveyed increased during the demonstration test period, and was the equivalent to approximately 300,000 vehicles per month when averaged over the five-month period.

Fig. 2 shows the information collection process. However, it should be noted that this survey required one to two days to analyze past data. Therefore, for the customers, the survey amounted to confirmation after the result.

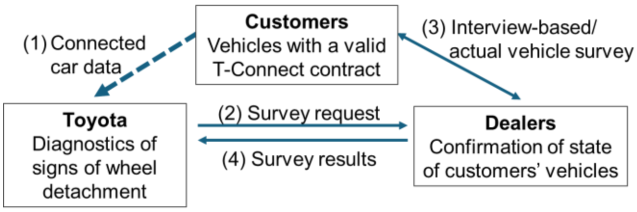


Fig. 2 Information Collection Process

(1) Processing of all the driving data collected over a single day, automatic first-stage sorting of vehicles with high detection scores, review of time-series data and second-stage sorting by visual inspection, and exclusion of known similar phenomena.
(2) Notification to dealer of vehicles open to survey request from the candidate vehicles.
(3) Dealer interview customer about vehicle state, request to bring vehicle to dealer if necessary, and confirmation of vehicle.
(4) Response of confirmation results from dealer to Toyota.

Regularly activated batch processing was carried out based on a distributed processing program utilizing the Apache Spark open source cluster computing framework to accelerate daily processing of large datasets from several hundred thousand vehicles. This approach allowed analysis to be conducted under a typical analysis environment at Toyota without having to install new servers or build dedicated systems.

4. Identification Process for Signs of Detachment

This section describes the process adopted to identify the signs on the vehicle of tire and wheel detachment. The data used to predict detachment primarily consisted of values obtained from wheel speed sensors installed for the anti-lock brake system (ABS) at each of the four wheels, as well as various state sensor values used to observe vehicle operation and driving states. The following detection process was carried out using these sensor values to calculate the detection rate. This was the process used for the first-stage sorting described in (1) above.

(1) Detection permission: this step decides whether the data state satisfies the requirements to allow detection (e.g., the wheel slip state and other values are excluded if the vehicle has been driven on unpaved surfaces or on rough roads).

(2) Feature calculation: this step calculates the features that express the vibration state of each wheel from the four wheel speed sensors.

(3) Provisional detection: provisional detection is determined to have occurred if the features exceed the threshold values and the state described in (1) has continued for a predetermined period of time.

(4) Detection determined: detection is determined to have occurred if the provisional detection state exceeds a predetermined threshold value for a certain proportion of the trip time.

(5) First-stage sorting: vehicles that satisfy the detection conditions and have a confirmed increasing trend over past trips are identified as candidate vehicles.

To apply this process to a variety of road surfaces (rough roads, snowy roads, and the like), a function that compares the values from all four wheels was provided. In addition, a measure to help prevent false positives was adopted that varies the threshold values used to determine the vibration state in accordance with conditions such as vehicle speed. In addition, when confirming the time series data during the second-stage sorting process, attention was focused on the trend of the ratio of detections within a specific time period of a particular trip as the basis for the decision to enable rapid alert activation in the future. **Fig. 3** shows an outline of the looseness detection mechanism.

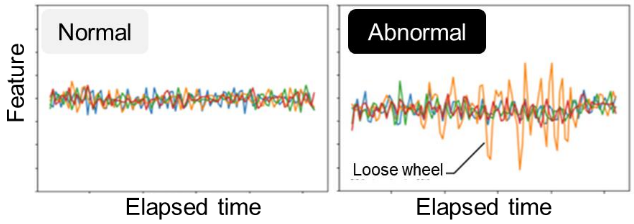


Fig. 3 Conceptual Diagram of Looseness Detection

5. Technical Demonstration Test Results

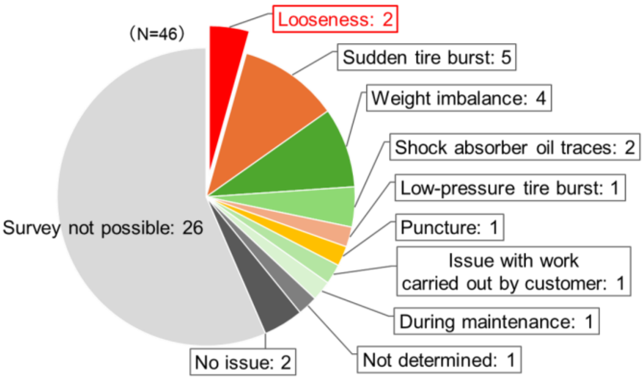
Table 2 lists the results of the technical demonstration test that was carried out over five months.

First, this section discusses the dealer survey results. This survey obtained results from 20 vehicles, as shown by the breakdown in **Fig. 4**. Two cases of actual lug nut looseness were detected. At the same time, many other phenomena were detected in addition to lug nut looseness.

Table 2 Technical Demonstration Test Results

Total driving distance	1.34 billion km (target achieved)
Total number of trips	Approx. 140 million trips (equivalent to an average of 300,000 vehicles over five months)
Number of trips sorted in first stage	Approx. 13,000 trips (94 ppm*)
Number of trips sorted in second stage	Approx. 3,000 trips (21 ppm*, equivalent to approx. 2,200 vehicles)
Number of vehicles in dealer survey	20
Number of vehicles with loose lug nuts	3 (including one with estimated data)

*Parts per million: equivalent to the number of vehicles per million units.



Other: wheel speed sensor error, tire degradation, wheel distortion, etc.

Fig. 4 Dealer Survey Results

Next, this section discusses the results estimated by combining various items of data based on the dealer survey results. These results detected one vehicle at risk of tire and wheel detachment. Simple data-only inference without the results of the dealer surveys also identified a number of other phenomena including cases possibly caused by the user attaching snow chains to the tires based on the weather forecast, intermittent abnormalities prior to wheel speed sensor errors being diagnosed (based on the vehicle maintenance history), tire degradation, wheel distortion, and the like (**Fig. 5**). Although these can be categorized as false positives from the perspective of lug nut looseness detection, all these phenomena indicate items that should be repaired or addressed from the standpoint of vehicle safety and user peace of mind. Therefore, these results can be used as the basis for future studies into function development. Furthermore, these results confirmed the existence of many phenomena in which the vibration level increases in accordance with the vehicle speed. In addition to the issue of weight imbalance, which can be adjusted by balance weights, this increase in vibration may also be caused by tire non-uniformity. Therefore, it was decided to continue the market survey after the end of the technical demonstration test in cooperation with the customers and dealers. This non-uniformity is affected by degradation due to wear, usage, and storage conditions, and may lead to noise and vibration when driving at high speeds.

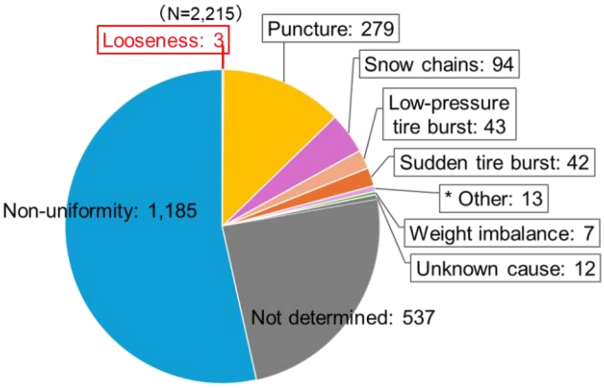


Fig. 5 Data-Only Inference Results (Including Dealer Survey Results)

6. Conclusion

This article described an algorithm that was developed to detect lug nut looseness as part of measures to identify signs of tire and wheel detachment using data from connected cars. It was confirmed that the performance of the algorithm achieved a certain level of effectiveness. However, there is room for improvement since the algorithm also detected many other phenomena in addition to lug nut looseness. Toyota intends to continue working to build a deeper level of technical know-how with the aim of helping to achieve an even safer and more supportive vehicle-based society through the practical implementation of this detection algorithm.

Acknowledgments

The actual vehicle confirmations carried out after the data analysis in the demonstration test were accomplished thanks to the invaluable cooperation of our customers who choose to use our products on a daily basis as well as everyone at Toyota's dealers across Japan. The authors would like to take this opportunity to express their sincere gratitude to everyone involved.

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Infrastructure Diagnostics Technologies for More Efficient Road Management
– Support for Paved Road Surface Inspections –

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Abstract

This research developed a system that estimates the state of flatness and ruts on paved road surfaces using vehicle probe data obtained from connected cars. First, flatness estimation was carried out by analyzing input data based on fluctuations in vehicle wheel speed and generating an indicator that quantifies the state of paved road surfaces. After confirming the validity of the indicator values by comparison with road repair data, verification tests were carried out in partnership with actual road management authorities. These tests determined that the developed indicator achieved a correlation coefficient of R = 0.65 compared to the maintenance control index (MCI) commonly used by road administrators. Next, the state of ruts was estimated by evaluating changes in the road surface reaction force using vehicle lateral acceleration. The resulting indicator is highly accurate and recorded a correlation coefficient of R = 0.75. These indicators have the potential to enhance the efficiency and reliability of road inspections and advance the feasibility of real-world adoption of this system.

Keywords: *connected car, vehicle probe data, road surface roughness, rut, paved road surface state estimation, inspection support, vehicle sensor, repair priority, administrative service*

1. Introduction

The automotive industry is continuously working to diversify the added value of vehicles in the face of rapid technological innovation and changes to the market. Toyota is able to obtain customer vehicle probe data from connected cars equipped with a data communication module. The company is also researching how to identify traffic and road conditions by combining different elements of this big data, and is working on ways of using this data to address various social issues. One of these social issues relates to the aging of roads and other elements of social infrastructure. Facing the need to further minimize the costs of upkeep, the potential of advanced technologies to help deliver more efficient inspection and diagnostics systems has been recognized.(1) In Japan, the upkeep of paved road surfaces requires road surface inspections to be carried out by local authorities and other road management bodies following the inspection procedure laid down by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT).(2) Paved road surfaces are generally inspected visually, which is a laborious and time consuming process. For this reason, there is a need to develop more efficient methods of paved road upkeep that can reduce the effort required for inspections within a limited budget.

2. Development of more Efficient Road Inspection Method by Paved Road Surface State Visualization

It might be possible to make the upkeep process more efficient by visualizing the state of paved road surfaces using vehicle probe data. Although vehicle probe data is obtained from connected cars using pre-installed sensors, these sensors are not designed to directly identify the state of paved road surfaces. Therefore, the development of analytical technology capable of using this existing data to estimate paved road surface states may help to raise inspection efficiency without the need for dedicated sensors, thereby helping to address a major social issue. For this reason, it was decided to develop a system that estimates the state of paved road surfaces using vehicle probe data (**Fig. 1**).

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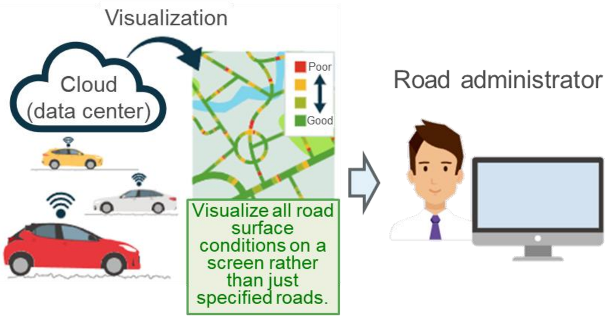


Fig. 1 Paved Road Surface Inspection Support

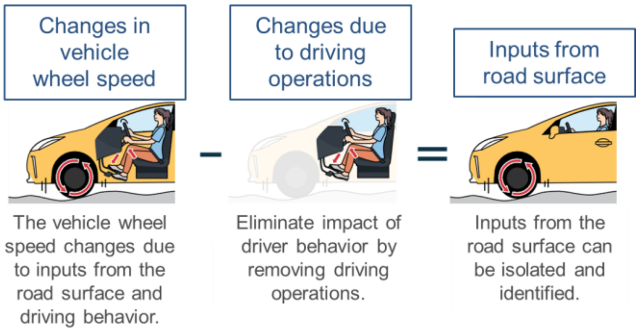


Fig. 2 System that Identifies Effects of Road Surface from Changes in Vehicle Wheel Speed

3. Roughness Index

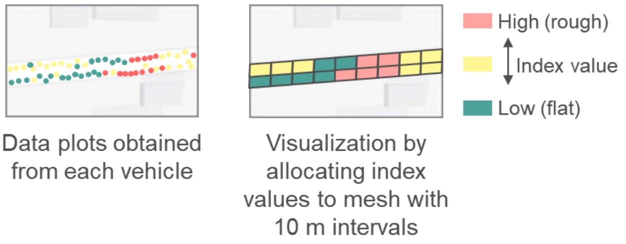
3.1 Study into flatness estimation system using vehicle probe data

Uneven areas on a paved road surface caused by cracks and the like are transmitted to the vehicle via the tire contact patches as vertical displacement inputs. The size of this displacement depends on the extent of the cracks and unevenness. Therefore, it may be possible to accurately evaluate the flatness of a paved road surface by identifying and quantifying signals from the road surface that include vertical inputs to the tire contact patches.

At the same time, wheel speed sensors can be used to estimate the necessary vehicle attitude for sprung mass damping and other controls. This method focuses on fluctuations in vehicle wheel speed caused by inputs to the vehicle (such as steering torque, brake and drive torque, and road inputs) as well as the changes in vehicle attitude (such as pitch and bounce) triggered by these inputs (**Fig. 2**). The actual vehicle attitude can be estimated based on the contribution of the latter items. This study aimed to develop a method of estimating the flatness of paved road surfaces by isolating and identifying fluctuations caused by road surface inputs. To help realize this goal, the study focused on eliminating inputs caused by changes in driving operations. Fluctuations in vehicle attitude due to the vehicle specifications were also eliminated to isolate and identify the changes in inputs specifically caused by the road surface.(3)

Before adopting this method, processing was carried out to remove the unnecessary data. In actual driving situations, and especially when driving on non-public roads, it is common to drive up and over sidewalks when entering a shop or a parking lot. Inputs generated in such situations are unrelated to paved road surface unevenness, and must be removed before analysis starts. Although this can be accomplished using operational information obtained from the brakes, steering system, and the like, it was decided to eliminate low-speed data to simplify the logic and reduce the number of applicable data types as a way of generating good quality data at a reasonable cost (*ryohin-renka*). Since these driving situations usually involve a distinct degree of deceleration, it was hypothesized that this data could be almost entirely removed by setting a vehicle speed threshold value. Data involving less deceleration occurs rarely and the impact of this data can be disregarded by averaging (described below).

Subsequently, the data obtained after these steps was processed as follows (**Fig. 3**). Since a paved road surface can be damaged in a wide range of ways and in various locations, the maximum values from the data of all four wheels were defined as the road surface input values estimated for the applicable driving zone on that particular trip. Latitude and longitude values from a global positioning system (GPS) were used to identify the location of the vehicle, The same processing was carried out using massive quantities of trip data, which enabled road surface input values to be densely applied to roads used by connected cars. Next, these road surface input values were processed into index values that would be useful for road management authorities. Even small-scale road upkeep work carried out based on the results of paved road surface inspections covers a section of road about 10 meters long. Therefore, an index value that expresses flatness over a similar road section length (referred to below as the “roughness index”) should be useful for evaluations of the priority of upkeep work. Consequently, the target roads were divided into meshes at 10 m intervals and the average value of the many data points in each section were used as the roughness index of that section.



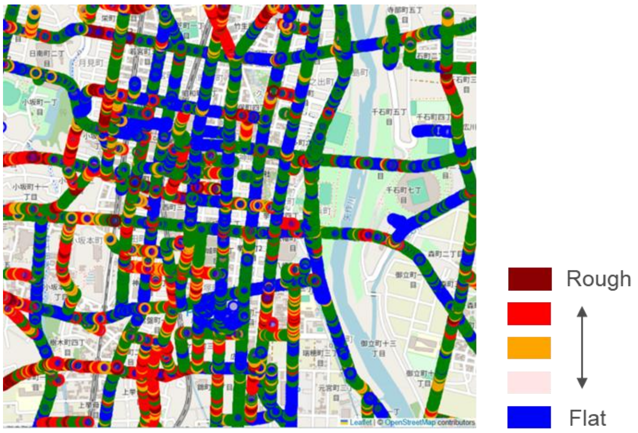
Data plots obtained from each vehicle

Visualization by allocating index values to mesh with 10 m intervals

Fig. 3 Illustration of Roughness Index Generation

3.2 Verification of roughness index and applicability for administrative services

To confirm the usability of a roughness index-based service in the real world, the development team partnered with the municipal authorities in Toyota city, Aichi Prefecture, who are responsible for administering the roads in that area, to carry out a verification test. **Fig. 4** shows the results of visualization using the roughness index over a wide area. The Japanese Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and local government bodies commonly carry out road upkeep using an indicator called the maintenance control index (MCI) to quantitatively evaluate the state of paved road surface deterioration. However, MCI measurements cannot be used on every kind of road. However, after applying it over a wide area, it was found that the roughness index was capable of identifying the state of any paved road surface, including roads in residential areas that previously depended on visual inspections and could not be measured using the MCI. In addition, a section of road in Toyota city with a length of approximately 1 km was selected for a comparative evaluation between the MCI and the roughness index. This evaluation found a correlation coefficient of R = 0.65 However, the contribution of rut depth, which was not reflected in the roughness index used in this comparison, was also removed from the MCI (**Fig. 5**). Based on these results, it was determined that the roughness index can be used in road repair planning proposals. In addition, since the roughness index proved capable of identifying paved road surface deterioration over time as intended through the provision of high-frequency information statement, the practical application of the roughness index was given the go-ahead.(4)



* Map data from OpenStreetMap

Fig. 4 Example of Visualization of Paved Road Surface State Using Roughness Index (Urban Roads in Toyota City)

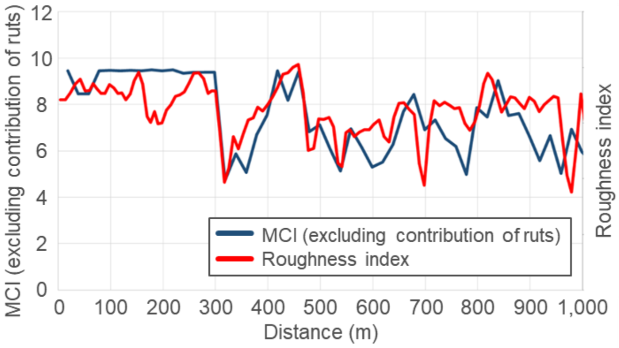


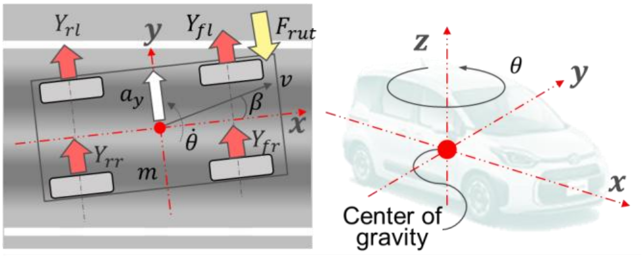
Fig. 5 Relationship between MCI and Roughness Index

The roughness index has been included in both the New Technology Information System (NETIS) and in MLIT's Inspection Support Technology Performance Catalog as Japan's first big data-driven technology. It was listed in this catalog in April 2025 as a system for evaluating road surfaces using big data from private passenger vehicles based on the international roughness index (IRI) and rut depth.(5)(6) When the developed roughness index was examined for inclusion in the catalog, a close correlation was found between the index values and the IRI (an index used to measure road flatness that is a component of the MCI described above). In the roughness categories defined by the IRI for paved road surfaces, the developed roughness index achieved the following excellent results: a detection rate and accuracy of between 90% and 100% on category II roads (medium roughness), as well as a detection rate of between 90% and 100% and an accuracy of between 80% and 90% on category III roads (severe roughness). Thanks to these results, the roughness index passed the technical examination and was subsequently included in the catalog.

4. Rutting Index

4.1 Study into rut estimation system using vehicle probe data

It is understood that ruts on paved road surfaces are caused by the plastic deformation of asphalt mixtures and follow the track width of heavy-duty vehicles that generate large tire loads. Ordinary vehicles with a narrower track width than heavy-duty vehicles are forced to drive up and down these ruts,(7) which is believed to cause changes in lateral acceleration. This study into a rutting index focused on this phenomenon (**Fig. 6**).



F_{rut}: external force caused by rut, Y: turning force of vehicle applied to each wheel
$I, \dot{\theta}$: moment of inertia and yaw rate around the z axis
β: vehicle slip angle
v: vehicle speed, m: mass, a_y: lateral acceleration,
θ: rotational angle of vehicle body

Fig. 6 Vehicle Behavior when Driving Over a Rut

Lateral acceleration a_y can be expressed using **Equation (1)** providing vehicle speed v, vehicle slip angular velocity $\dot{\beta}$, and yaw rate $\dot{\theta}$ are known.

$$a_y = v(\dot{\beta} + \dot{\theta}) \quad \text{.......} \quad (1)$$

Lateral acceleration a_y changes when the reaction force of the road surface is applied to the vehicle as the vehicle is driven over the top of a rut. Vehicle slip angle due to steering β is smaller than the rotational angle of the vehicle body $\dot{\theta}$. In addition, a large proportion of the differential component of vehicle slip angle $\dot{\beta}$ can be attributed to angular variations caused by ruts. For this reason, the vehicle slip angle $\dot{\beta}$ was regarded as an effective evaluation index. Since vehicle probe data can be used to obtain the following items: lateral acceleration a_y, vehicle speed v, and yaw rate $\dot{\theta}$, $v\dot{\beta}$ can be estimated from **Equation (2)** and the amount of change in $v\dot{\beta}$ can be defined as an index relating to ruts (referred to below as the "rutting index").

$$v\dot{\beta} = a_y - v\dot{\theta} \quad \text{.......} \quad (2)$$

However, it is still necessary to remove changes in $v\dot{\beta}$ caused by factors other than ruts. Specifically, this refers to (1) changes due to steering when turning right, left, or around a curve, (2) changes caused by crosswinds, and (3) changes caused by driving over curbstones. Since the road surface reaction force caused by a rut creates a shorter input than factors (1) and (2), the vehicle yawing motion contains relatively higher frequency components. Factor (2) is a higher value than that generated by a rut. Therefore, (1) and (2) were removed by filtering components close to the direct current (DC) generated during normal driving. For factor (3), statistically singular values were removed to minimize inputs caused by features other than ruts.

4.2 Verification of rutting index and applicability for administrative services

A study was carried out to compare rut depth with the rutting index obtained using vehicle probe data. The measurement results described above were used to calculate rut depth in 100-meter intervals in line with the interval lengths used by local government bodies. The results of this comparison are as follows.

Fig. 7 compares the rutting index with values obtained using a measurement vehicle. A correlation coefficient of R = 0.75 was obtained, indicating a close correlation between the two.

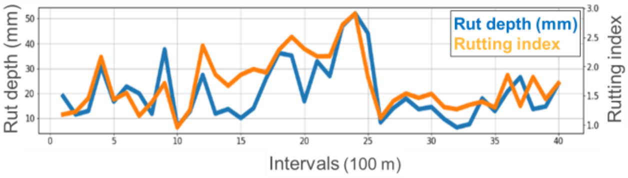


Fig. 7 Comparison of Rutting Index and Rut Depth

The paved road surface inspection procedure expresses the health of a road surface in three diagnostic levels. After calculating a regression line from the results described above, the rutting index was similarly divided into three diagnostics levels. The diagnostic levels obtained using the rutting index were compared with the diagnostic levels obtained from actual rut depths and found to be a general match.

5. Conclusion

A system was developed that efficiently estimates the state of flatness and ruts on paved road surfaces using vehicle probe data obtained from connected cars. An objective roughness index was developed after analyzing vehicle wheel speeds, enabling the comprehensive identification of road surface roughness. In addition, a highly accurate rutting index was established based on lateral acceleration, resulting in a similarly comprehensive method of identifying ruts. Together, these two systems should help to realize safer and more efficient paved road surface upkeep.

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Infrastructure Diagnostics Technologies for More Efficient Road Management
– Support for Traffic Safety Measures –

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Abstract

This article discusses the utilization of vehicle probe data obtained from Toyota's connected cars in road safety measures that are designed to help reduce traffic accidents. Vehicle probe data can be statistically processed to create quantitative frequency indicators for events such as sudden braking, stopping at intersections without a traffic signal (unsignalized intersections) , speeding, and so on. These indicators can then be used to identify hazardous locations that are difficult to detect by conventional subjective surveys, as well as to help propose and determine the priority order of safety measures. In addition, data from before and after the adoption of a safety measure can be compared to enable objective verification of its effectiveness. This technology has also been utilized in field demonstrations and other aspects of real-world traffic safety measure development, helping to enhance the efficiency of these measures.

Keywords: *connected car, vehicle probe data, traffic safety measure, sudden braking frequency, frequency that vehicles stop at unsignalized intersections, frequency of driving over 30 km/h, objective effectiveness verification, objective risk assessment*

1. Introduction

The automotive industry is continuously working to diversify the added value of vehicles in the face of rapid technological innovation and changes to the market. Toyota is able to obtain customer vehicle probe data from connected cars equipped with a data communication module. The company is also researching how to identify traffic and road conditions by combining different elements of this big data, and is working on ways of utilizing this data to address various social issues.

One critical social issue is traffic safety. In 2024, the number of traffic accident fatalities in Japan was 2,663 people. This is less than one-sixth of the 16,765 fatalities that occurred in 1970, the worst year on record.(1) Despite this substantial reduction, tragic accidents such as those involving elementary school children on school routes, continue to occur, underscoring the need for further efforts to reduce accidents. Toyota's ultimate goal is to help realize an ideal mobility society in which zero traffic accidents occur. This goal requires an integrated three-pillar approach to safety measures that involves people, vehicles, and the traffic environment. This article presents Toyota's initiatives for using the latest technologies to help accelerate road safety measures in that traffic environment.

2. Issues of Road Safety Measures

Road safety measures carried out by administrative bodies generally involve four steps: (1) location selection, (2) measure proposal, (3) measure implementation, and (4) effectiveness verification (**Fig. 1**). Locations are often selected based on past accident data. These locations tend to be places particularly susceptible to accidents or where fatal accidents have occurred in the past. However, there is a lack of objective data to support requests from local residents or schools for preventative measures in locations where accidents have yet to occur, which makes it difficult to determine the priority order of measures. In addition, in the study phase of examining which measures to implement, it can be a time-consuming and expensive process to obtain the necessary expert opinions and carry out local surveys. Furthermore, when verifying the effectiveness of a measure, since it takes several years to collect sufficient accident data, assessments tend to be carried out based on subjective information from local residents, and it is difficult to quickly obtain objective evidence.

For these reasons and to help resolve these issues, Toyota is studying ways of utilizing vehicle probe data obtained from connected cars. Vehicle probe data can be used to obtain a wide range of comprehensive information such as the speed, acceleration, and the like of vehicles in motion. This objective data can be combined with conventional methods to help determine the priority order of safety measures for all locations,

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even those where an accident has yet to occur. This data can also help to raise the efficiency continuous improvements (*kaizen*) applied to measures through the plan-do-check-action (PDCA) cycle (**Fig. 1**).

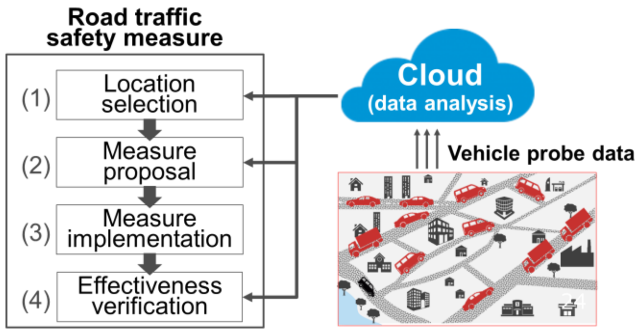


Fig. 1 Support for Traffic Safety Measures Using Vehicle Probe Data

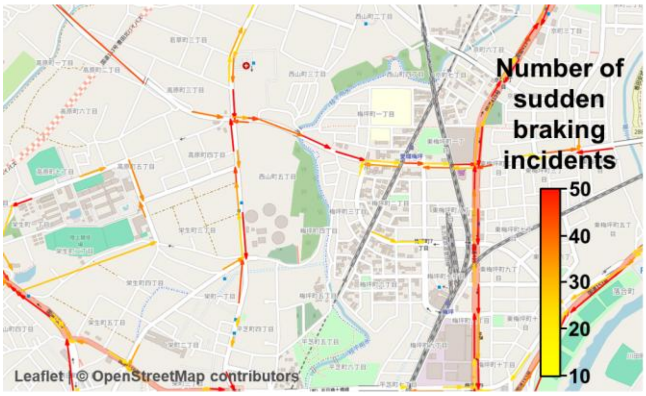
3. Use of Vehicle Probe Data to Support Safety Measures

3.1 Determining the priority order of safety measures

When determining the priority order of safety measures, locations of sudden braking by connected cars can be used as near-miss incident information. This study defined sudden braking as deceleration of at least 0.4 G. Although this degree of deceleration is not extreme enough to activate the anti-lock braking system (ABS), it is strong enough to cause a bag to fly off the front passenger seat. Since past verification tests have confirmed that locations at which this type of sudden braking occurs more frequency often coincide with actual accident black spots, sudden braking can be seen as a highly reliability warning sign for potential accidents. However, some drivers habitually brake the vehicle at this level of sudden braking. This vehicle data can be filtered out to enable an even more objective risk assessment.(2)

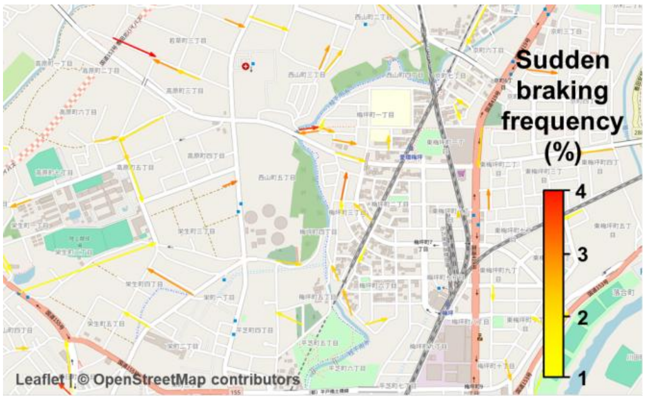
Fig. 2 visualizes road sections with a high frequency of sudden braking. These sections tend to be on major roads and intersections with a high volume of traffic. Rear-end collisions occur particularly frequently in these areas and this data can be used as supplemental information when studying the location for a safety measure.

At the same time, it is also important to identify hazardous locations on quieter residential roads. Therefore, instead of looking simply at the number of sudden braking incidents, assessments can use the sudden braking frequency of connected cars, which factors in the number of trips made on the target road sections. As shown by the indicator in **Fig. 3**, this approach can identify locations with a relatively high frequency of sudden braking incidents even outside major roads. This capability to support objective risk assessments factoring in traffic volume on all types of roads is a major merit of vehicle probe data.



* Map data from OpenStreetMap

Fig. 2 Locations of Frequent Sudden Braking (Occurrences per Month)



* Map data from OpenStreetMap

Fig. 3 Sudden Braking Frequency

3.2 Support for measure proposal

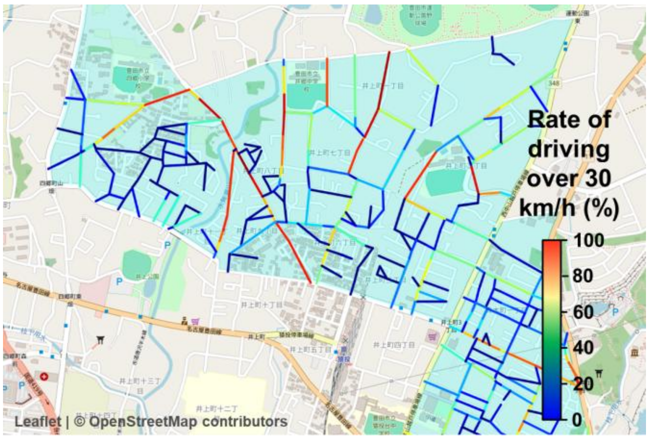
Vehicle probe data can also be used in the measure proposal study phase. More rational and evidence-based safety measure policies can be determined by quantitatively evaluating how vehicles drive on specific roads. Here, information about traffic volume and average speed obtained from connected cars was supplemented by a new evaluation indicator that measures the rate of driver compliance to speed limits and other regulations. Traffic control information published by the police through the Japan Road Traffic Information Center (JARTIC)(3) was used to identify traffic rules involving speed limits and stopping at intersections without a traffic signal (unsignalized intersections) on individual roads, and compared with actual driving data on those regulated sections.

Fig. 4 shows road sections with traffic rules requiring vehicles to stop at the ends of roads without a traffic signal. The rate of vehicles that decelerated to 3 km/h or less when passing through those sections (defined as the "stopping rate") was calculated. At some locations with a high frequency of sudden braking and a low stopping rate, it was found that the stop line had faded, prompting the implementation of measures such as re-drawing the line, or emphasizing the line by coloring.

* Map data from OpenStreetMap

Fig. 4 Rate of Vehicles Stopping at Intersections Without Traffic Signal

Next, the proportion of vehicles driving in excess of 30 km/h in designated 30 km/h zones (shaded in light blue) was calculated (**Fig. 5**). Roads with a high rate of speeding that cut through 30 km/h zones tend to be used as shortcuts. This issue can be addressed effectively by closing roads to traffic at specified times, installing poles that prevent speeding by reducing the width of roads, and the like.



* Map data from OpenStreetMap

Fig. 5 Rate of Speeding in 30 km/h Zone

Since road usage cannot be thoroughly assessed through local visual-based surveys and subjective feedback, vehicle probe data can be used to quantitatively and objectively assess road usage to support the measure proposal process.

3.3 Safety measure effectiveness verification

This section describes a case study in which vehicle probe data was used to verify the effectiveness of a safety measure on a school route in Toyota city, Aichi Prefecture. The target crossing is used by children that walk down a set of steps on the left. The wall close to the crossing blocks the driver's view of the children until the last moment. This crossing was identified in a questionnaire carried out by Toyota city authorities as a location with a high frequency of near-miss incidents. Various measures were implemented, such as using colored paint to make the crossing more visible, signs urging drivers to exercise caution, and zebra markings warning drivers to slow down before the crossing (**Fig. 6**).

Fig. 6 Location of Safety Measures on School Route

To assess the effectiveness of these measures, a quantitative comparison was carried using two months of data before and after the measures were applied. **Fig. 7** shows that the sudden braking frequency fell from a relatively high value of 1.8% before the measures were applied to just 0.4% after application, a reduction of 78%. In addition, **Fig. 8** shows the changes in the average speed of the connected cars driven down this road. The blue line shows the data before the measures were applied and the pink line shows the data after the measures were applied. The data indicates that drivers reduced speed approximately 100 m before the crossing, with an observed decrease of about 2.1 km/h at a point 20 m before the crossing. These results are evidence that drivers are intentionally slowing down. A follow-up questionnaire confirmed that no near-miss incidents had occurred after the measures were applied.

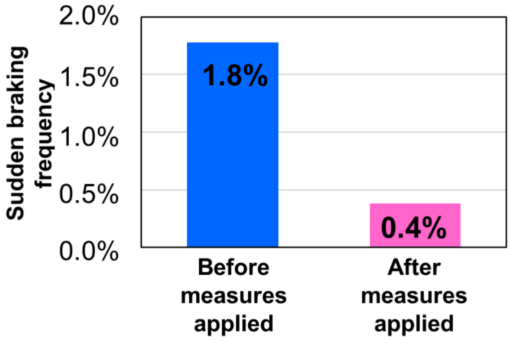


Fig. 7 Changes in Sudden Braking Frequency Before and After Measure Application

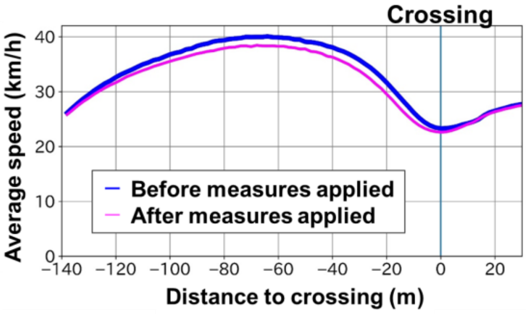


Fig. 8 Changes in Average Speed Before and After Measure Application

In this way, vehicle probe data can be used to objectively verify the effectiveness of a safety measure within a short timeframe rather than having to wait to gather accident data. In addition, since vehicle probe data can also enable the continuous monitoring of a safety measure over a number of years, it can be used to assess the sustainability of a measure's effectiveness and the need for additional measures.

4. Conclusion

Toyota has developed technology that utilizes vehicle probe data to support the implementation of road traffic safety measures. Sudden braking data that indicates the occurrence of near-miss incidents can be used to quantitatively assess hazardous locations on both major and residential roads. In addition, vehicle probe data can also be analyzed and used to quantitatively and objectively assess road usage to support the measure proposal process, freeing this process from its reliance on local surveys and subjective decision making. In addition, data from before and after the adoption of a road safety measure can be compared to enable objective verification of its effectiveness within a short timeframe. This technology is already being utilized in verification testing and other aspects of actual traffic safety measure development.(4)

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Infrastructure Diagnostics Technologies for More Efficient Road Management
– Queue Length Estimation –

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Abstract

As the use of vehicle probe data from connected cars expands, Toyota is working on ways of using this data to address social issues. As part of this approach, this article describes Toyota's measures for mitigating traffic congestion, which is a major vehicle-related issue. Since many roads administered by local government bodies are not equipped with roadside sensors, measures for mitigating traffic congestion generally utilize local visual-based surveys. However, because such local surveys can only be carried out for limited periods due to cost and time constraints, surveys might not be capable of identifying the state of traffic congestion accurately. In response to this concern, Toyota has developed a data acquisition system capable of replacing local surveys by using vehicle probe data to simulate queue length, which is commonly used as an indicator for traffic congestion mitigation by local government bodies. This article outlines this technology and describes an example of its use for traffic congestion mitigation in Toyota city, Aichi Prefecture.

Keywords: *connected car, vehicle probe data, traffic congestion, queue length, traffic flow, traffic signal*

1. Introduction

The automotive industry is continuously working to diversify the added value of vehicles in the face of rapid technological innovation and changes to the market. Toyota is able to obtain customer vehicle probe data from connected cars equipped with a data communication module. The company is also researching how to identify traffic and road conditions by combining different elements of this big data, and is working on ways of using this data to address various social issues. Traffic congestion is one of these issues. Traffic congestion occurs in every region of Japan and approximately 40% of all time spent traveling by car is lost to traffic congestion or a similar issue.(1) The increase in CO_2 emissions caused by traffic congestion only serves to underline its importance as a serious social issue. For this reason, Toyota is studying technology to help resolve the issue of traffic congestion using vehicle probe data. This article describes Toyota's initiative for identifying traffic congestion using vehicle probe data and an example of its application in Toyota city, Aichi Prefecture.

2. The Difficulty of Identifying Traffic Congestion

Traffic congestion mitigation efforts on major roads are carried out based on data from roadside vehicle detectors. However, only about 15% of roads are equipped with vehicle detectors,(2)(3) and most roads administered by local government bodies have no detectors at all. Consequently, data about traffic congestion on roads without vehicle detectors has to be measured manually by visual surveys. Since such surveys are expensive and time consuming, data can only be obtained over limited periods, making it difficult to obtain an accurate picture of traffic congestion on those roads. In contrast, although traffic congestion evaluation technologies using vehicle speed data are being used by map applications and car navigation system services, these technologies tend to use average speeds as the basis for determining whether congestion is occurring, which can lead to false positives caused by vehicles stopping at traffic signals and the like.(4) To help resolve this issue, Toyota has developed a system that uses vehicle probe data obtained from connected cars to replace vehicle detector data and manual surveys.

3. Traffic Congestion Identification System Using Vehicle Probe Data

3.1 Traffic congestion identification indicator

Traffic congestion mitigation measures implemented by local government bodies commonly use the terms "storage length" and "queue length" as indicators to

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[*1] Advanced Mobility System Development Div., Advanced R&D and Engineering Company
[*2] Mobility Material Engineering Div., Advanced R&D and Engineering Company
[*3] Digital & Software Performance Development Div., Software Development Center

define the extent of traffic congestion.

Storage length refers to the maximum length of a queue of vehicles waiting at a traffic signal (**Fig. 1**) This indicator is complemented by queue length, which refers to the length of the queue of vehicles that could not pass through the traffic signal while it was green and were forced to stop for a second time by a red traffic signal. Since a long storage length will not fall under the definition of congestion if all the affected vehicles manage to pass through the traffic signal while it is green, a system that uses vehicle probe data to identify traffic congestion must be capable of estimating the queue length.

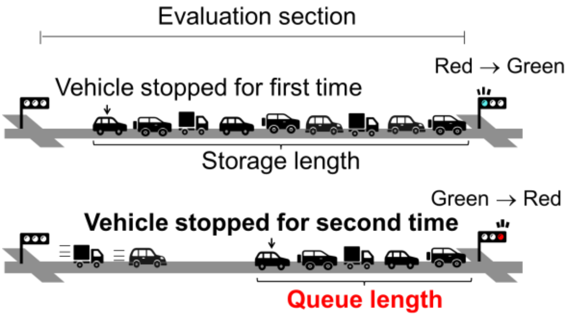


Fig. 1 Illustration of Storage Length and Queue Length

3.2 Queue length estimation method

When a road is congested, vehicles will be unable to pass through a traffic signal during a single cycle and will be forced to stop at the same traffic signal multiple times. Therefore, it should be possible to measure queue length most accurately by extracting the position of the vehicles forced to stop a second time at a traffic signal and identifying the stopping position of the final vehicle in the queue furthest from the traffic signal. However, since not all the vehicles on the road are connected cars, it is difficult to identify the final vehicle in this queue from the probe data of Toyota vehicles alone. For this reason, the following queue length estimation method was adopted. A queue length evaluation is carried out every fifteen minutes, during which the stopping positions of vehicles forced to stop for a second time at the same traffic signal are sampled for every traffic signal cycle during that period. The queue length can then be estimated probabilistically by selecting the stopping position furthest from the traffic signal in those samples (**Fig. 2**). Furthermore, movement that satisfies either of the following two conditions is extracted to specifically identify large amounts of movement in accordance with the traffic signal cycle.

- When vehicle movement exceeds a standard distance.
- When the time interval between the vehicle moving off once and moving off again exceeds a standard time and the moving distance is half the standard distance or longer.

The standard distance is defined as the length of the queue of vehicles created by a single red traffic signal. The standard time is defined as the length of a single traffic signal cycle. The methods used for determining these standard values from the data are described below.

The length of a queue of vehicles created by a single red traffic signal is calculated from the distribution of distances that each vehicle advances during one traffic signal cycle. Vehicles at the back of a queue often move short distances by, for example, adjusting the gap to the vehicle in front. Therefore, as shown in the histogram in **Fig. 3(a)**, no clear peak occurs in the moving distance. In contrast, **Fig. 3(b)** shows a clear peak for vehicles closer to the traffic signal, indicating that a standard moving distance value can be estimated. Consequently, a value around the statistical mode in the distribution of moving distance between stops at the position closest to the traffic signal was selected as the standard distance. The time for a single traffic signal cycle was defined in a similar way by calculating the stop/start time interval at the position closest to the traffic signal.

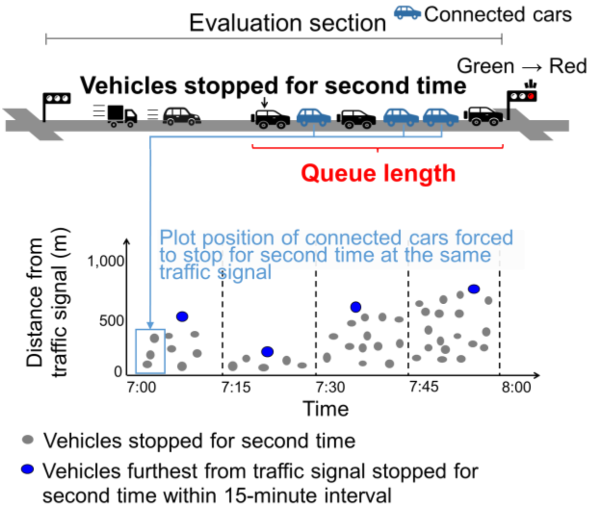
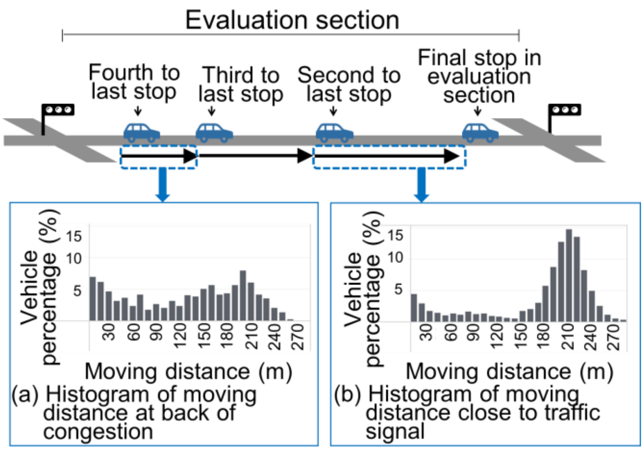


Fig. 2 Queue Length Estimation Using Vehicle Probe Data



(a) Histogram of moving distance at back of congestion

(b) Histogram of moving distance close to traffic signal

Fig. 3 Moving Distance Histograms

3.3 Confirmation of queue length estimation results

To validate the developed system, the queue length estimated using vehicle probe data was compared with actual measurements obtained from local surveys at an evaluation section on the west side of the Seishincho 2-chome S. intersection in Toyota city. The evaluation was carried out at the following times on each weekday: likely period of traffic congestion (07:00 to 09:00) and likely period without traffic congestion (12:00 to 14:00). In addition to the comparison with survey data, the purpose of the evaluation was to identify whether the acquired data is as accurate as that acquired using vehicle detectors. Key intersections in the Tokyo metropolitan area are equipped with vehicle detectors at 150-, 300-, and 500-meter intervals from the stop lines.(5) Since the shortest detector interval is 150 meters, a target accuracy of half that value (75 meters) was set. **Fig. 4** shows the results of the comparison between the estimated and measured queue lengths. The horizontal axis shows the measured values and the vertical axis shows the estimated values. The red dotted line shows the equal position of the values on both axes. The error (mean squared error) was 53.4 m, higher than the target accuracy and equivalent to the accuracy of a roadside vehicle detector.

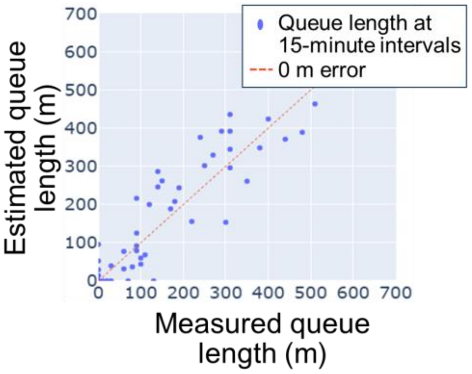
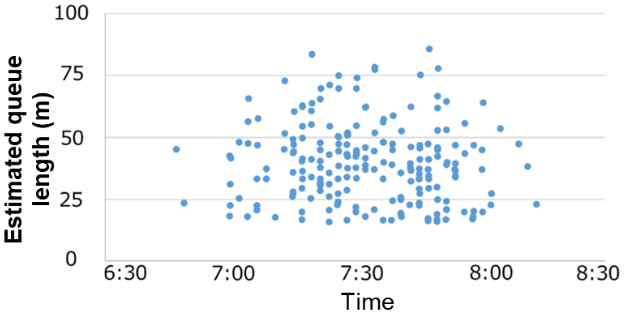


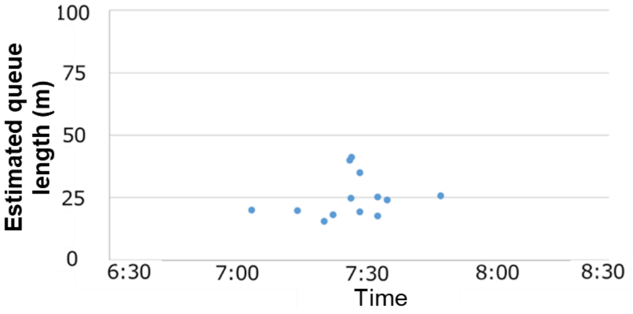
Fig. 4 Results of Comparison between Estimated and Measured Queue Lengths

4. Verification of Effect of Traffic Congestion Mitigation and Future Prospects

To confirm the usability of the developed system, the effectiveness of changing the traffic signal cycle was verified using the highly congested Hiratobashicho-mabase intersection in Toyota city. This intersection had previously been designated as an applicable area for changing traffic signal cycle times as a traffic congestion mitigation measure. It was confirmed that these estimated changes matched the shortened queue lengths achieved by changing the traffic signal cycle time (**Fig. 5**).



(a) Before change



(b) After change

Fig. 5 Queue Length Estimation Results Before and After Changing Traffic Signal Cycle Time

5. Conclusion

This article described the estimation of queue lengths using vehicle probe data and demonstrated its feasible application as part of traffic congestion mitigation measures carried out by local government bodies. It is planned to continue verifying this system by increasing the number of target locations and application cases. In addition, since vehicle probe data contains vehicle location information, it is possible to create data showing the origin and destination (OD data) of each vehicle passing through a target area. Furthermore, the feasibility of time- and day-based analysis should also enable analysis of the factors behind traffic congestion (for example, whether it is caused by commuting or leisure traffic) and the routes arriving at the congested area, in line with the characteristics of the region. Since this type of OD data cannot be obtained by conventional local surveys, the combined use of these two methods may help to develop even more closely focused traffic congestion mitigation measures.

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40th Sokeizai Industry Technology Award (2024), Director-General’s Award of the Manufacturing Industries Bureau, Ministry of Economy, Trade and Industry
2024 JSME Medal for New Technology
The Technological Development Award (75th JSAE Awards)

Development of One-Piece Differential Thickness Curved TWB Structure and Mass Production Facilities Using Hybrid Laser Arc Welding

Takaya Komatsuzaki[*1] Eita Niisato[*2] Tetsuji Egawa[*3]
Hiroshi Uchiyama[*4] Masahiro Onoda[*1] Tokukatsu Suzuki[*1]

1. Introduction

Sports utility vehicles (SUVs) with ladder frame structures have come to play a valuable role in supporting people’s lifestyles on the various types of roads that exist around the world (**Fig. 1**). In addition to excellent reliability, driveability on rough roads, crashworthiness, and rust prevention, ladder frame vehicles must also be lightweight enough to comply with fuel consumption regulations (corporate average fuel economy (CAFE) regulations) and contribute to achieving carbon neutrality. One typical ladder frame structure is a reinforced structure in which reinforcements are layered over the main body (**Fig. 2**). The weight of this structure can be reduced using linear tailor welded blank (TWB) technology to create a structure with different thicknesses (**Fig. 3**). This article describes the development of an industry-leading mass production technology that creates a curved TWB structure using curved weld lines to achieve a further substantial advance in weight reduction (**Fig. 4**). After extensive discussions among relevant departments to ensure welding quality capable of withstanding various road conditions, it took approximately six years to establish this mass production technology.

Fig. 1 Ladder Frame SUV

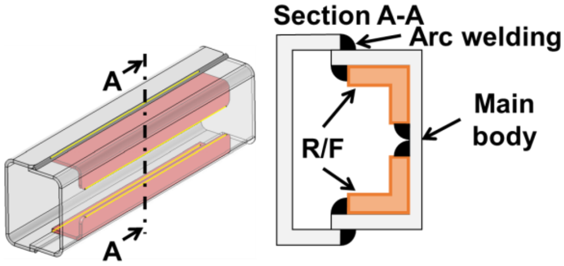


Fig. 2 Conventional Reinforced Structure

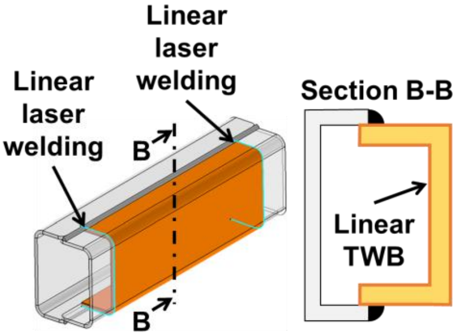


Fig. 3 Conventional Differential Thickness Structure (Linear TWB Structure)

[*1] MS Platform Development Div., Mid-size Vehicle Company
[*2] Vehicle Engineering Development Div., Vehicle Development Center
[*3] Productization Manufacturing Engineering Div., Vehicle Development Center
[*4] Body Manufacturing Engineering Div., Production Group

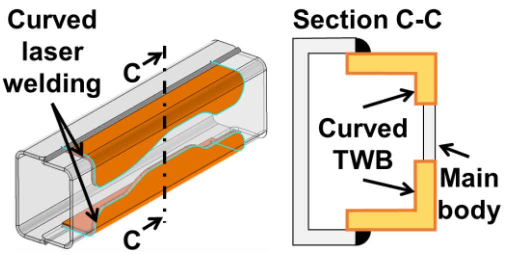


Fig. 4　Curved TWB Structure

2. Outline of Technology

Computer-aided engineering (CAE) analysis was carried out to compare and examine the fatigue strength of one of the cross-sectional structures (**Fig. 5**). The results found that a curved TWB structure with a sheet thickness of 3.8 mm achieved the same fatigue strength as a reinforced structure with a total thickness of 6.5 mm when combined with the main body. Since reinforcements arc welded to the inside of the cross-section can only be partially joined to the main body, the application of load results in mutual movement that probably hinders the effective functioning of the structure. After optimizing the sheet thickness and material strength of the frame components based on a wide range of performance requirements, a linear TWB structure achieved weight reduction of 4.8 kg and a curved TWB structure achieved weight reduction of 11.2 kg compared to a conventional structure (**Fig. 6**). Therefore, adopting curved welds helped to maximize the weight reduction effect of TWB technology.

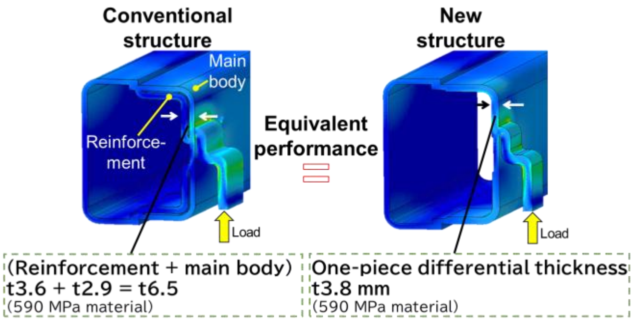
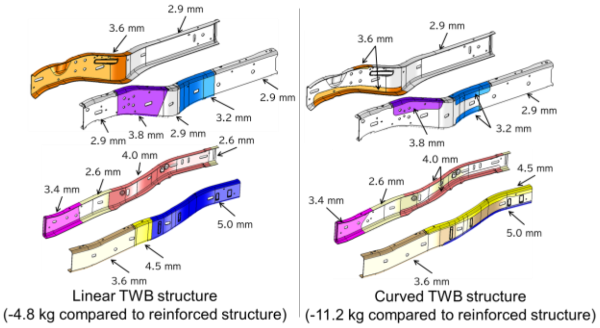


Fig. 5　Strength CAE Analysis Results



Linear TWB structure
(-4.8 kg compared to reinforced structure)

Curved TWB structure
(-11.2 kg compared to reinforced structure)

Fig. 6　Comparison of Weight Reduction Effect

3. Mass Production Technology

The use of curved weld lines raised two major issues: how to expand the range of defect-free (*ryohin joken*) welding conditions (i.e., robustness) and how to address gap changes caused by welding heat distortion. The *ryohin joken* for ensuring strength involved setting an underfill amount of less than A% of the sheet thickness t on the thin plate side (**Fig. 7**). This was calculated using the sheet thickness on the vertical axis and the target position of the welding torch on the horizontal axis. Initially, laser welding alone was judged to be inadequate for mass production. For this reason, a new technology called hybrid laser arc (HLA) welding was developed that combines arc and laser welding. Due to differences in the thermal expansion of steel plates during welding, the gap expanded from d1 (in the first half of the welding process) to d2 (in the second half) (**Fig. 8**). This issue was addressed by applying various innovations, such as melting a wider area in the first arc welding step and adopting a twin-spot laser in the second welding step (**Fig. 9**), resulting in a more stable keyhole during welding. This measure and the accommodation of other variations in mass production helped to broaden the range of defect-free welding conditions.

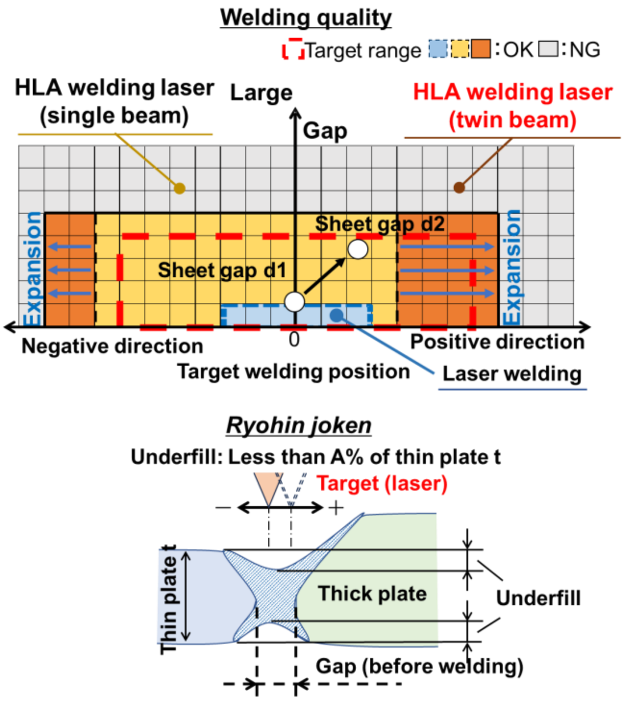


Fig. 7　*Ryohin Joken* for TWB Welding

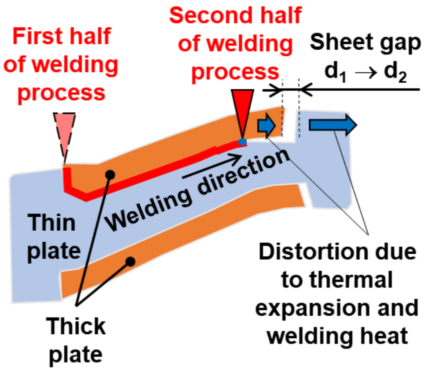


Fig. 8 Change in Sheet Gap during Welding

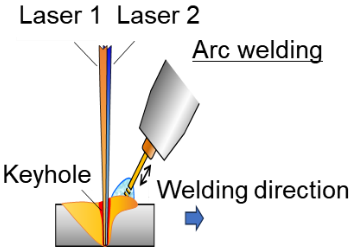


Fig. 9 Adoption of Twin-Spot Laser Welding

4. Conclusion

The developed curved TWB structure and HLA welding technologies described in this article achieve a high level of reliability, safety, weight reduction, and productivity. It should be possible to apply these technologies to a wide number of parts in addition to ladder frames. Toyota intends to continue developing and improving products capable of mass producing happiness for the customer.

The Technological Development Award (75th JSAE Awards)

Development of New 8-Speed Automatic Transmission and Single-Motor Hybrid Transmission

Koichi Miyamoto[*1] Terufumi Miyazaki[*1] Kazunari Nagai[*1]

1. Introduction

Toyota is following a multi-pathway strategy for achieving carbon neutrality that factors in the energy situation and fuel economy regulation trends in countries and regions around the world. As part of this strategy, Toyota must raise the fuel economy of its medium-size pick-up trucks and sports utility vehicles (SUVs), which account for around 500,000 units of its annual global sales. In addition to greater fuel economy, these vehicles must also maintain excellent handling in a wide range of road environments. To help meet this requirement for improved driving performance while satisfying the needs of off-road vehicle customers, Toyota has launched a new 8-speed automatic transmission to replace its previous 6-speed unit.

At the same time, Toyota has developed a parallel type single-motor 8-speed hybrid transmission that combines the new 8-speed automatic transmission with a motor (generator) and features an engine-disconnecting clutch located between the engine and motor. This configuration maximizes the power potential of the engine and motor, while also providing excellent fuel economy alongside torqueful and highly responsive driveability. These transmissions are available on the new Toyota Tacoma, Land Cruiser 250, and 4Runner, as well as the Lexus GX.

2. Transmission Specifications

First, this section address the selection of the transmission for hybrid electric vehicles (HEVs). The development assumed that the target vehicles for this transmission would be used under both loaded (such as towing) and harsh primarily off-road conditions (such as winding mountain roads and deserts). Therefore, it would be necessary to maintain high reliability in the base 8-speed automatic transmission and properly transfer this reliability to the HEV transmission. In addition to disconnecting the engine with the clutch and driving the vehicle using the motor generator (MG), which also involves the regeneration of braking energy, this transmission must also accommodate conventional engine drive. Accordingly, the transmission was configured to maximize the properties of both its mechanical and electrical elements.

Furthermore, Toyota understood that creating the optimum product lineup would be extremely important considering the different speeds of vehicle electrification in countries and regions around the world, which is also reflected in the need to offer combinations that meet market and customer demand for conventional gasoline and diesel engine powertrains.

Under Toyota's policy of building products close to where the demand is located, these units are produced at two locations in Japan and the U.S. This enables good quality and reasonably priced (*ryohin-renka*) vehicles and transmissions to be provided to the customer more easily.

Fig. 1 shows the configuration of the single-motor hybrid transmission based on the conventional 8-speed automatic transmission.

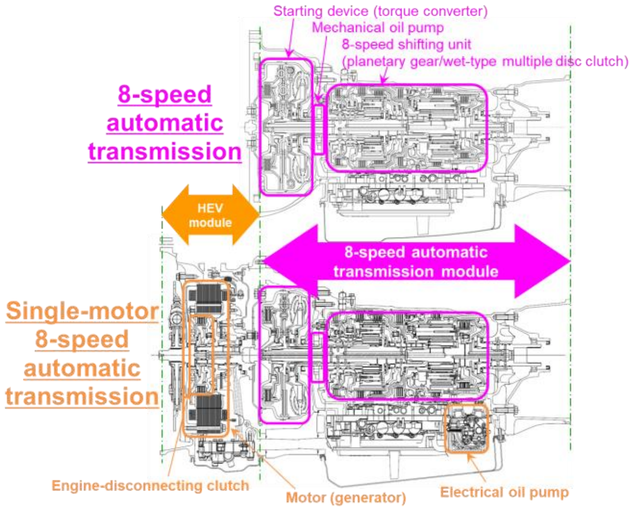


Fig. 1 Configuration of Conventional 8-Speed Automatic Transmission and Single-Motor Hybrid Transmission

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[*1] Transmission Development Div., Powertrain Company

Fig. 2 shows a skeleton diagram of the 8-speed automatic transmission.

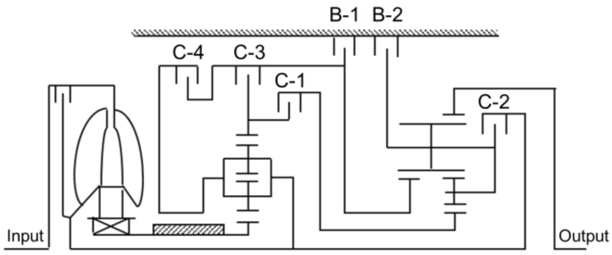

Fig. 2 Skeleton Diagram of 8-Speed Automatic Transmission

To realize this configuration, the base 8-speed automatic transmission module was developed to satisfy the mountability requirements of the target medium-size pick-up trucks and SUVs, while delivering sufficient torque capacity to cover the engine and motor performance range of these vehicles. This was achieved by reducing the diameter and substantially lowering the aspect ratio of the flow paths in the torque converter and by adopting a Ravigneaux planetary gear structure in the gear train (**Fig. 3**). In addition, the previous 6-speed automatic transmission was converted into an 8-speed unit within the same size constraints by adopting a multi-layered element structure and eliminating the one-way clutch. This enables the transmission to be paired with a variety of power sources and installed in wide range of models.

A multi-disc clutch was adopted instead of the previous single plate lock-up clutch and the optimum vibration damping devices were selected to match the target engine characteristics, enabling a wider applicable lock-up area. These measures help the transmission to convey a more direct driving sensation while reducing loss and vibration.

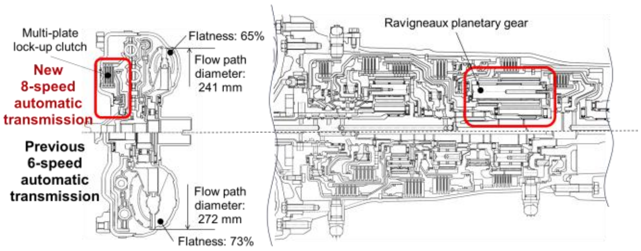

Fig. 3 Torque Converter (Conventional) and 8-Speed Gear Train Configuration

Next, **Fig. 4** compares the gearing of the new 8-speed automatic transmission with that of the previous 6-speed unit.

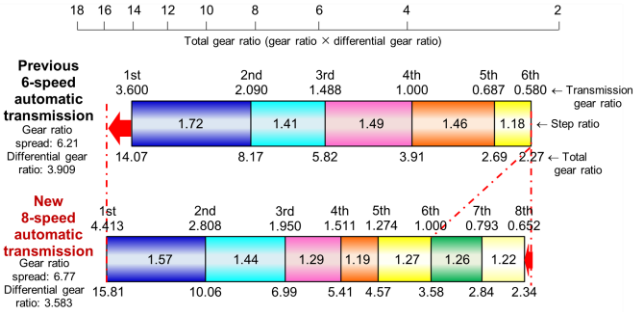

Fig. 4 Gearing Comparison

Vehicle driving force targets were set after carrying out big data analysis based on the results of a market usage environment survey to accurately identify customer expectations and requirements with respect to driving performance. Model-based development tools were then used to maximize the potential of each power source (i.e., the engine and hybrid system), and gearing capable of comprehensively realizing the driving force targets at every vehicle speed and shift position was selected.

The gear ratio of the low speeds was further reduced to deliver powerful and highly responsive standing start performance under on-road conditions, while ensuring controllability at low vehicle speeds and driveability under off-road conditions. The close-ratios set for the medium and higher speeds were set to achieve acceleration and deceleration performance in line with the driver's intention on both urban roads and highways. Together, these measures help to realize the ideal product appeal for pick-up trucks and SUVs.

3. Contribution to Improved Vehicle Performance

3.1 Improved fuel economy

Fuel economy was improved by measures covering the whole powertrain. The flexibility of gear selection was increased to encourage the engine to operate in regions with high thermal efficiency. The torque converter lock-up area including slip control was substantially widened by adopting a multi-plate lock-up clutch structure and setting vibration damping devices with the optimum damping performance. At the same time, the loss of the automatic transmission module was reduced by the adoption of a highly efficient oil pump and low-drag wet friction materials. In addition, the installation of a stop and start system with the conventional transmission was enabled by the adoption of an electromagnetic pump. In combination, these measures increased fuel economy by 8% for the conventional transmission and 22% for the single-motor hybrid transmission after factoring in driving in EV mode and the provision of motor assist (**Fig. 5**). Applying these comprehensive measures to each of the target vehicles also helps Toyota to meet its corporate average fuel economy (CAFE) targets.

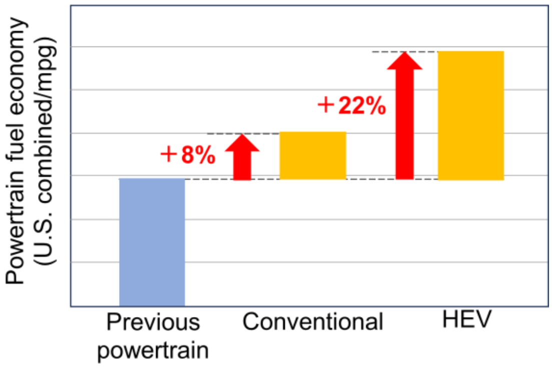

Fig. 5 Powertrain Fuel Economy Improvement Rate[1]

3.2 Improved driveability

Various driving performance improvements were achieved. The optimum torque converter fluid performance was selected in accordance with the power characteristics of each power source, and the gearing was designed in consideration of specific vehicle driving scenarios. These measures allow the transmissions to deliver driving force that matches the driver's intention both on-road and off-road. In addition, close-ratio gearing and adjustment of the high-response gear-change clutch hydraulic pressure using high flow rate linear solenoid actuators help to realize a rhythmical and satisfying shifting quality. In addition, the single-motor hybrid transmission achieves high levels of both fuel economy and driveability by combining smooth K0 clutch (the engine-disconnecting clutch) operation and motor assist in accordance with the driving scenario. The result is unprecedented acceleration and cruising performance in all vehicle speed ranges (**Fig. 6**).

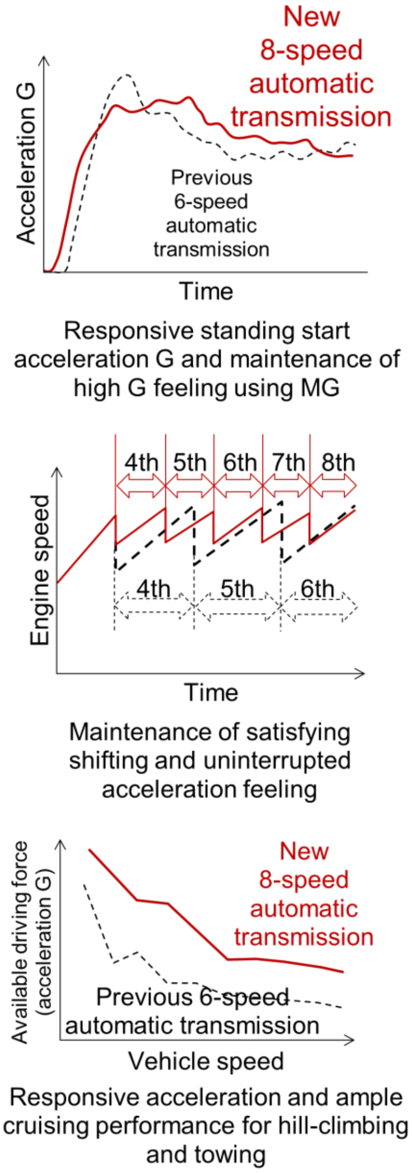

Fig. 6 Improvement of Acceleration Feeling. Shifting Rhythm, and Driving Force

4. Conclusion

These transmissions were developed with the invaluable cooperation of Aisin Cooperation. Following its multi-pathway strategy, Toyota is aiming to expand the electrification of powertrains for off-road vehicles while further evolving the base transmission units. The transmissions described in this article play a significant role in increasing vehicle product appeal as a component part of powertrains designed to achieve groundbreaking fuel economy and driving performance. Going forward, Toyota regards these 8-speed automatic and single-motor hybrid transmissions as key powertrain units. By creating a foundation for further improvements and advances in response to changes in the market environment and user needs, these transmissions should help to deliver ever-more appealing vehicles in the future.

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The Technological Development Award (75th JSAE Awards)

Development of Affordable and Compact Stabilizer Disconnection System for Off-Road Vehicles

Asaki Imai[*1] Masaki Kanatani[*1] Kazuyoshi Sakazaki[*1] Kazuaki Shirayama[*2] Toshio Kuwayama[*2]

1. Introduction

With many roads around the world remaining unpaved and the existence of a wide range of opportunities for off-road driving (including camping and off-road driving in Japan), systems that help ensure driveability and comfort when driving off-road are an effective way of providing added value to a vehicle. However, due to the high price and space requirements of many of these off-road systems, application has been limited to luxury models such as some grades of the Toyota Land Cruiser 300 series. With this understanding, development of the Toyota Land Cruiser 250 series was started under the concept of creating a simple and sturdy vehicle that can be trusted by customers to fulfill their lifestyle choices and practical needs. Consequently, it was decided to develop an affordable and compact stabilizer (anti-roll bar) with a disconnection mechanism (SDM) to make an off-road system available to a larger number of users.

2. System Characteristics

The stabilizer connects the left and right wheels with a torsion bar to enhance on-road handling. However, if the left and right wheels are connected off-road, this will inhibit the ability of the suspension to expand and contract, and have a negative impact on the road-holding performance of the tires (**Fig. 1**). The SDM allows the front stabilizer to be unlocked at the touch of a button, helping to realize excellent tire road-holding performance. This focus on enabling the front stabilizer to be unlocked via a button means that the state of the stabilizer can be controlled entirely based on the intent and preference of the user. However, if the stabilizer is unlocked and the vehicle speed exceeds a set value, the system will judge that the vehicle is now on the road and automatically activate the stabilizer to ensure excellent handling on the road as well.

Fig. 1 Stabilizer Lock State on Different Road Surfaces

3. System Details

3.1 System configuration

A compact system and installation flexibility are achieved by mounting the stabilizer locking and unlocking mechanism on the same axis as the stabilizer bar. In addition, the stabilizer can be locked or unlocked by pressing a button on the console (**Fig. 2**).

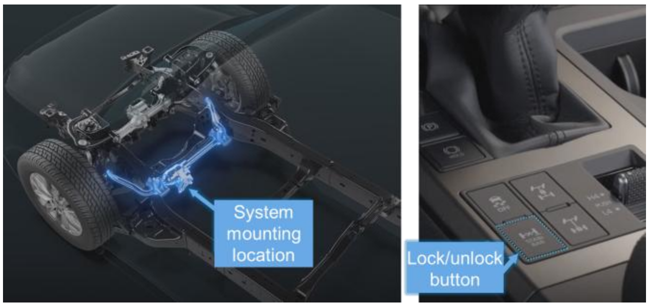

Fig. 2 System Mounting Location and Lock/Unlock Button

3.2 Stabilizer lock/unlock mechanism

The stabilizer bar is divided into two sides (left and right), and grooves (shown in dark pink in **Fig. 3**) are provided on one side. Hooks (blue) engage or disengage with those grooves to lock or unlock the system. The system uses a motor to change the balance created by two springs, causing the cam ring (yellow) to rotate and changing the engagement of the hooks. However, if the stabilizer bar is twisted (such as while the vehicle is turning or the like), the frictional force between the cam ring and hooks may stop the cam ring rotating and prevent stabilizer lock or unlock (**Fig. 4**). If the motor is driven in this state, spring force accumulates and the

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[*1] MS Platform Development Div., Mid-size Vehicle Company
[*2] Chuo Spring Co., Ltd.

stabilizer will automatically lock or unlock as soon as the stabilizer bar is no longer twisted. This helps to prevent dramatic changes in vehicle posture during cornering or the like. It also helps to streamline the control since the motor can be driven regardless of the degree of stabilizer bar twisting. The system also saves energy by adopting a motor structure consisting of a spring and worm gear, which can maintain the state of the stabilizer without the application of power.

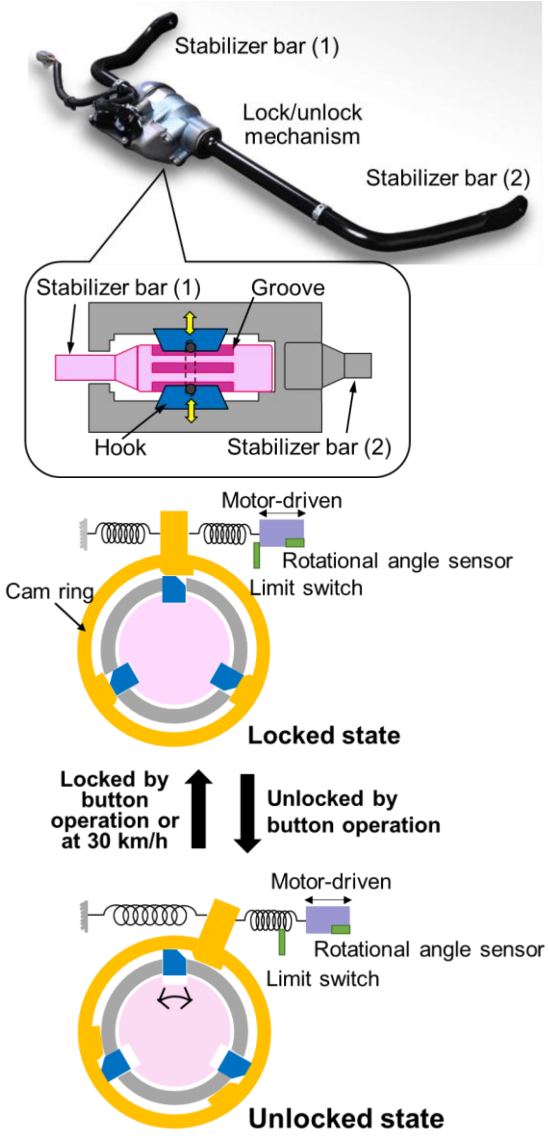

Fig. 3　System Lock/Unlock Mechanism

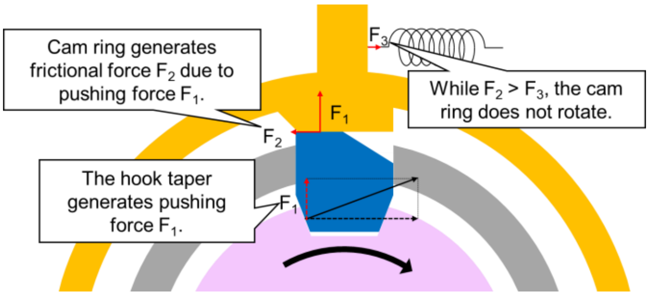

Fig. 4　Relationship between Forces Generated during System Lock/Unlock

3.3　Characteristics of lock/unlock mechanism

The stabilizer lock/unlock mechanism functions by inserting wedge-shaped hooks into the stabilizer bar at right angles to the stabilizer bar shaft (**Fig. 4**). This structure results in half the amount of looseness than a mechanism that drives the hooks in the axial direction (i.e., the thrust direction) of the stabilizer bar. Furthermore, by adjusting it to match the spring constant of the stabilizer, a similar design with the same lock/unlock structure can also be installed on compact vehicles.

3.4　System effectiveness

Adopting this system increases the wheel articulation (an indicator of off-road performance that describes the ability of a tire to stay on the ground) by approximately 10%, thereby enhancing off-road performance under harsh conditions (**Fig. 5**). This system also helps to realize gentler vehicle movement during off-road driving, thereby reducing the amount of head and body sway and achieving ride comfort that diminishes fatigue (**Fig. 6**). Reducing the looseness of hook engagement structure on the stabilizer bar allows the stabilizer to generate a reaction force in response to even small steering motions. This ensures the same level of handling as a conventional stabilizer during on-road driving.

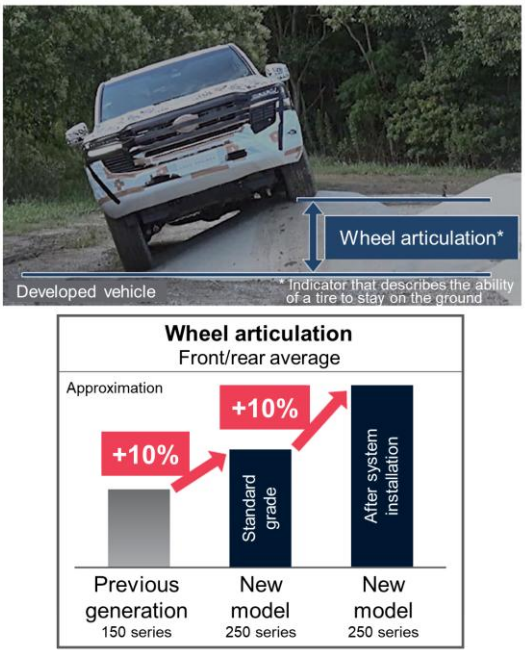

Fig. 5　Amount of Increase in Wheel Articulation

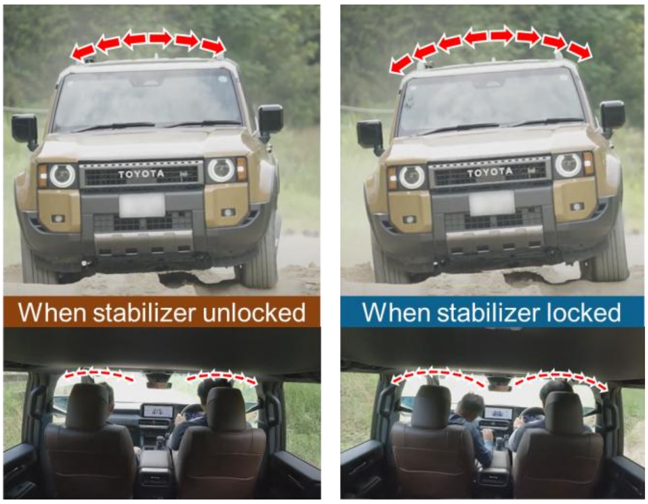

Fig. 6 Illustration of Sway when Stabilizer Locked and Unlocked

4. Conclusion

This project successfully developed and commercialized an affordable and compact off-road SDM system, which has subsequently been adopted on the Toyota Tacoma and 4Runner as well as the Land Cruiser 250 series. The adoption of a scalable structure means that this technology can be applied to a wide range of models from large to compact vehicles. Moving forward, the aim is to continue providing good quality and reasonably priced (*ryohin-renka*) products to even more customers in all regions around the world, and to further enhance off-road performance by reflecting feedback from the market into improved controls and the like.

References

(1) K. Moritsu et al. “The Toyota Land Cruiser 250 Series.” *Toyota Technical Review* Vol. 70 No. 1 (2024) pp. 34-48.

List of Externally Published Papers from the second half of FY2024 to the first half of FY2025

Publication Name	Title	Presenter	Affiliation
Transactions of the Society of Automotive Engineers of Japan	Development of Analyzing Method of Condensation Water Splashing on Electric Parts in a Vehicle by Using MPS Method	Yasuhiro Ohshima	Toyota Motor Corporation
		Hisao Nishimori	(same as above)
		Yusuke Imai	(same as above)
		Hiroshi Kamatani	(same as above)
	Front/Rear Driving Force Distribution Control Based on Tire Workload Considering Vehicle Behavior in the Turning Limit	Kohei Sakaguchi	Toyota Motor Corporation
		Takuma Takeuchi	(same as above)
		Etsuo Katsuyama	(same as above)
	Matrix Based Automotive Structure Design Method for Circular Economy	Daichi Kunishi	Toyota Motor Corporation
		Ryohei Tsuruta	Toyota Central R&D Labs., Inc.
	A Proposal of Suspension characteristics model for Vehicle dynamics design	Motoshi Ohki	Toyota Motor Corporation
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		Keisuke Suzuki	(same as above)
		Kazuhiro Kato	Toyota Motor Corporation
	Development of Aerodynamic Noise Prediction System Using Generative AI by Flow of Vehicle Shape.	Yuta Ito	Toyota Motor Corporation
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		Junya Suzuki	Tokio Marine & Nichido Fire Insurance Co. , Ltd.
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	Experimental Study about Avoidance Behavior of the Driver Who Meets with the Dangerous Scenes during City Driving (Second Report)	Toru Kojima	Automobile and Land Transport Technology
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		Takamichi Ueda	Toyota Motor Corporation
		Yoshiro Masuda	(same as above)
		Kiyotaka Tahara	National Institute of Advanced Industrial Science and Technorogy
		Mitsutaka Matsumoto	(same as above)
		Masashi Hara	Toyota Central R&D Labs., Inc.
		Tetsuro Kobayashi	(same as above)
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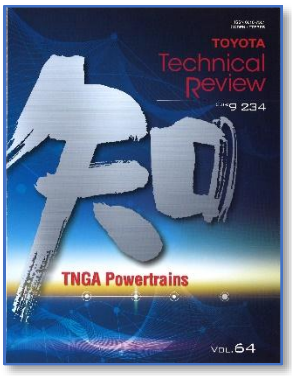

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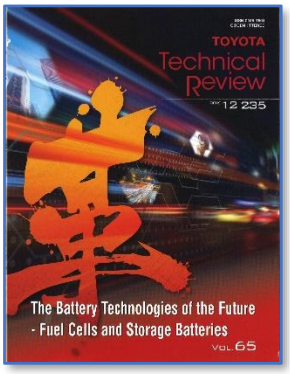

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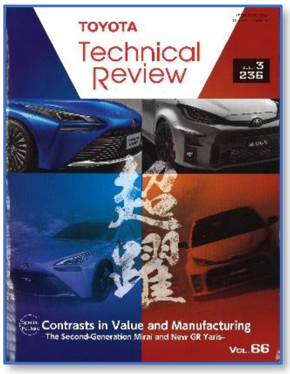

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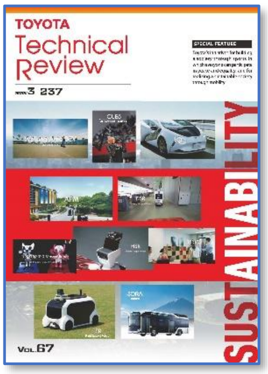

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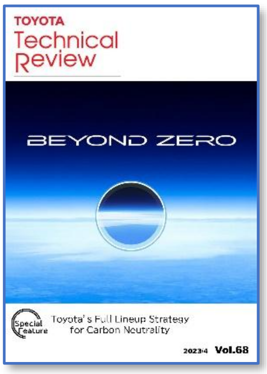

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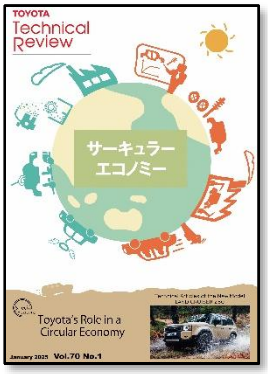

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