3 Ensuring the Safety of Automated Driving

(1) Field Operational Tests in Tokyo Waterfront Area

Field Operational Tests in Tokyo Waterfront Area (Overview)

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Overview: As part of the Japanese government's "Investments for the Future Strategy" and ahead of the 2020 Tokyo Olympic and Paralympic Games, field operational tests (FOTs) in the Tokyo waterfront area were conceived and carried out as a domestic and international showcase for the latest automated driving technologies, to create a legacy by demonstrating the feasibility of these state-of-the-art technologies in the Haneda Airport and Tokyo waterfront areas, and to facilitate the establishment of systems, frameworks, and the like. Roadside-to-vehicle communication infrastructure was set up for different purposes in three districts in the Tokyo waterfront area with the objectives of demonstrating the effectiveness of and identifying issues with automated driving technologies. In the Haneda district, tests of automated buses were carried out that included precise arrival (docking) control and the utilization of magnetic markers. In the waterfront district, the provision of traffic signal information via intensive infrastructure installation was tested. Finally, on the Metropolitan Expressway that links these two districts, support for merging and passing through electronic toll collection (ETC) gates was studied.

1 Aims and System for Promoting the Field Operational Tests in Tokyo Waterfront Area

With the Olympic and Paralympic Games due to be held in Tokyo in 2020, plans to carry out a series of field operational tests (FOTs) in the Tokyo waterfront area began to be drawn up in 2018 with the objectives of using the opportunity of the Games to build a valuable social legacy and to communicate state-of-the-art initiatives in the field of automated driving to audiences both inside and outside Japan.

This idea to promote automated driving initiatives using the Tokyo Olympic and Paralympic Games as a showcase was codified as official policy in the Japanese government's "Investments for the Future Strategy," announced in June, 2017. Ahead of the 2020 Tokyo Olympic and Paralympic Games, this policy conceived FOTs in the Tokyo waterfront area as a domestic and international showcase for the latest automated driving technologies, to create a legacy by demonstrating the feasibility of these state-of-the-art technologies in the Haneda Airport and Tokyo waterfront areas, and to facilitate the establishment of systems, frameworks, and the like.

Based on this policy, in 2018, a Tokyo waterfront area FOT taskforce was established for phase 2 of the SIP-adus program. Consisting of members from government, industry, and academia, this group was tasked with advancing plans for the project and laying the groundwork for the tests.

In addition to identifying the effectiveness of automated driving as a step toward its safe implementation on actual roads, the FOTs in the Tokyo waterfront area also aimed to present a tangible expression of the concept of "mobility for all" for a wide range of traffic users, thereby contributing to the realization of a more inclusive society as symbolized by the Paralympics. Specifically, the test areas and transportation modes were selected envisioning a scenario of Paralympians arriving in Japan and traveling from Haneda Airport to the Olympic Village in the waterfront area without assistance.

In the Haneda district, it was decided to carry out automated driving demonstration tests with buses. These tests would involve precise arrival (docking) control with the aim of enabling wheelchair users to get on and off buses without assistance, as well as the adoption of magnetic markers, taking advantage of the fixed route characteristic of public transportation. Due to the proven track record of test environment establishment in the waterfront area (such the preparation of high precision 3D maps in the first phase of the SIP-adus program), this area was selected for the intensive installation of infrastructure to provide traffic signal information, thereby creating a showcase for state-of-the-art level 4-equivalent automated driving technologies. In addition, on the Metropolitan Expressway that links these two areas, tests were carried out related to the provision of information to support vehicles passing through electronic toll collection (ETC) gates.

The various test environments were prepared with assistance and cooperation from various directions. Then, with the participation of a wide range of institutions and companies from inside and outside Japan (Fig. 1), the tests began in October 2019, and were completed without incident in the 2020 fiscal year.

Fig. 1: FOT Participants

2 Overview of Infrastructure Preparation in the Three Areas and FOTs Using this Infrastructure

(a) Tokyo Waterfront City Area

The focus of SIP phase 2 was vehicle-to-infrastructure cooperation technology. As well as on-board vehicle technology, the approach of phase 2 was to enhance the performance of automated driving through the entire traffic infrastructure, with the aim of realizing an even safer and smoother traffic environment.

In SIP phase 2, a framework was constructed to apply traffic signal information as dynamic data to the high precision maps prepared in phase 1.

In addition, taking advantage of the fact that this would be a test of unprecedented scale, a traffic flow impact assessment was carried out in mixed traffic conditions consisting of both automated and manual driving vehicles, with the aim of identifying issues for raising social acceptance of automated driving in the future.

Although primarily a framework for science and technology policies, SIP is also a key initiative to help nurture acceptance for the automated driving-based society of the future that is the logical outcome of the program. Therefore, public relations activities and events involving community participation were also held. The FOTs in the Tokyo waterfront area focused on the provision and use of the minimum level of information necessary to realize advanced automated driving under various traffic environments. FOTs of critical technical themes for practical adoption and standardization, and the provision of traffic signal information on general roads were carried out through the cooperation of the government, industry, and academia, with a particular emphasis on information that is difficult to detect using on-board sensors and effective information for both driving support systems and drivers.

When driving on general roads under a mixed traffic environment, advanced recognition, judgment, and operation technologies are required to enable the safe and smooth passage of automated vehicles through intersections. In particular, since this requires the color of traffic signals to be recognized with high precision and reliability, these tests validated the effectiveness of supplementing recognition by on-board sensing cameras in automated vehicles with communication from infrastructure (V2I) to enhance recognition performance under any traffic environment. This information creates redundancy in traffic signal recognition, thereby helping to enhance safety and reliability.

These tests used the wireless ITS communication technology (760 MHz) adopted by driving safety support systems (DSSS), which have already been implemented by the National Police Agency and prefectural police departments. After enhancing the message sets and systems in accordance with the automated driving systems, information provision systems were installed on traffic signals at 33 intersections in the waterfront FOT area (Fig. 2).

In addition, the whole waterfront area was precisely mapped to create a digital database of the road structures and various structural roadside objects required for automated driving. This static data was used to update the high precision 3D maps of the area, which were then distributed to all the FOT participants.

As well as the current traffic signal color, the use of wireless ITS communication technology also enables the provision of information related to the time that the next traffic signal will change. The tests also examined the effectiveness of this information for realizing automatic advance deceleration and stop controls capable of preventing disturbance to traffic flows and avoiding the so-called dilemma zone (i.e., the zone that is too close for drivers to stop before the stop line by braking normally but is also too far for drivers to safely cross the stop line by maintaining the same speed). Furthermore, by utilizing information about the spatial location of traffic signals though high precision 3D maps and linking this information with dynamic traffic signal data received from wireless ITS communication (i.e., the dynamic map concept), plans were drawn up to identify received traffic signal information as information for upcoming intersections and to demonstrate the effectiveness of this information in preventing erroneous recognition of background objects and traffic signals. At the same time, the benefit of providing this information to drivers of non-automated vehicles was also verified. In this way, in addition to verifying the effectiveness of information, the benefit of information provision by wireless ITS communication in a wide range of environmental conditions and situations as a policy for establishing infrastructure was also clearly defined.

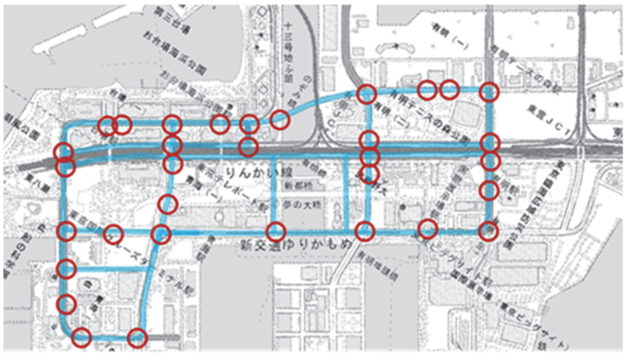

Fig. 2: Traffic Signal Information FOT Area

This information was used in impact assessment analysis by saving data in on-board devices supplied by SIP to the FOT participants.

(b) Haneda Airport Area

To help construct an automated driving system involving public transportation, a next-generation urban advanced rapid transit (ART) system utilizing automated driving technology in the area between Haneda Airport Terminal 3 and Tenkubashi (Fig. 5) was used for FOTs of a vehicle-infrastructure cooperative system and impact assessments of this system on road traffic.

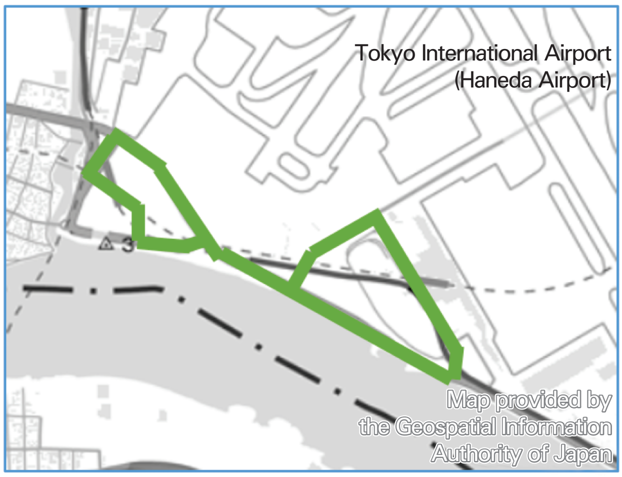

Fig. 3: Test Route

This FOT aimed to realize an automated driving level 4-equivalent ART that would be user-friendly and comfortable for all users by providing the infrastructure to enable (1) automated driving without driver intervention, (2) a regular service, and (3) enhanced comfort through precise arrival at bus stops and careful acceleration and deceleration. This was accomplished by providing the following infrastructure on the test route shown above: a) magnetic markers to enable the location of the buses to be estimated, b) dedicated bus lanes to reduce interaction with other vehicles, c) bus stops structured to allow precise arrival (docking) without level differences or gaps between the bus and roadside, d) public transportation priority systems (PTPS) equipped with green light extension functionality to give buses priority through intersections and the like, and e) equipment to provide traffic signal information via wireless ITS technology. The effectiveness of automated buses utilizing this infrastructure in realizing points (1) to (3) above was then demonstrated. At the same time, the impact of automated buses on the surrounding traffic was also assessed.

(c) Metropolitan Expressway

Automated vehicles utilize information obtained from multiple on-board sensors (cameras, sonar, and the like) to perform integrated vehicle control. However, since current on-board sensor have limited detection ranges, FOTs were carried out with the cooperation of the National Institute for Land and Infrastructure Management to examine the effectiveness of combining this sensor information with support information communicated from roadside infrastructure. These FOTs were carried out at the Airport West ramp of the Yokohama-Haneda route of the Metropolitan Expressway with the aim of realizing a safer, more natural, and smoother automated driving experience on dedicated vehicle-only highways and national expressways.

Specifically, the tests involved the use of the dedicated short-range communication (DSRC, 5.8 GHz) system adopted by the electronic toll collection (ETC) 2.0 services provided by the Ministry of Land, Infrastructure, Transport and Tourism and road management companies. DSRC was used to communicate opening and closing information about ETC gates based on the location of the vehicle with enough time to select the appropriate ETC gate to pass through the gate smoothly (Fig. 6). Another FOT verified the effectiveness of support information in judging whether automated driving can be continued, route planning for automated vehicles, and the like. In this test, information related to merging onto the main lane was detected by infrastructure sensors in the main lane and transmitted to vehicles driving in the merging feeder lane in an environment where on-board sensors have difficulty in guiding automated merging operations (Fig. 7).

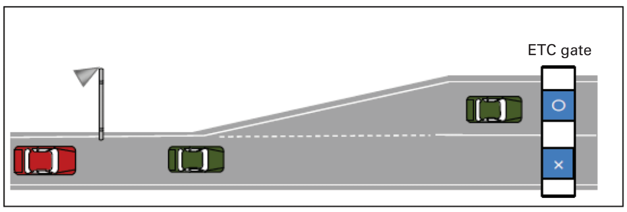

Fig. 4: Transmission of Support Information for Passing through ETC Gates

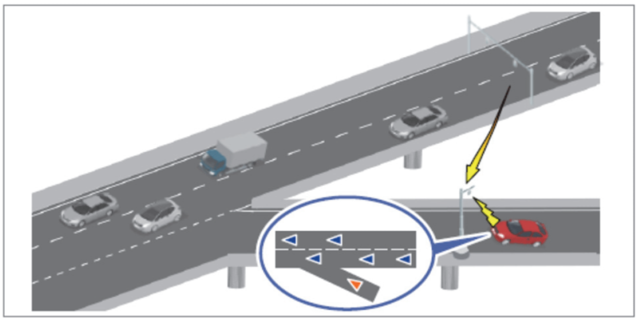

Fig. 5: Transmission of Support Information for Merging onto Main Lane

The results of these tests were as follows. The test that transmitted support information for passing through ETC gates confirmed that, in addition to automated vehicle route planning, this information could also be used to assist drivers in selecting the appropriate ETC gate more smoothly and to help drivers pass through the gate more safely and with more confidence. The test that transmitted support information for merging onto the main lane of the expressway was carried out at the Airport West ramp, which has poor visibility in the merging zone due to the situation of roadside structures. The test confirmed that detecting and transmitting information about the traffic flow in the main lane to vehicles in the feeder lane could be used effectively in judgments about whether to continue automated driving, in automated vehicle route planning, and in acceleration, deceleration, and steering controls. This test also confirmed that this information could be used effectively to alert drivers. In contrast, since this support information is generated by spot detection of main lane traffic flows by infrastructure sensors in the main lane (i.e., the calculated time of arrival assumes driving at a steady velocity), congestion or the like might result in non-uniform traffic flows in the main lane and adversely affect the accuracy of the support information. Therefore, ways of improving this system need to be examined under a wide range of conditions.

In addition, when driving on an expressway, medium- to wide-range road traffic environment data outside the detection range of on-board sensors, particularly various types of lane-based quasi-dynamic data (e.g., data about congestion, accidents, vehicle breakdowns, dropped objects, and the like) that can be linked to high precision static 3D map data is also likely to be useful in achieving even safer and smoother automated driving. However, since current information provision is mainly road-based (such as congestion information provided by the Vehicle Information and Communication System (VICS)), SIP is simultaneously promoting research and development into the generation of road-level traffic environment data using information collected from vehicles on the road (probe data) and the statistical processing of existing traffic information.

In the second half of 2020, plans were made to carry out an FOT of road-level support information on expressways linked with high precision 3D maps utilizing wide-range mobile communication and the like.

3 Results, Issues, and Further Actions

These FOTs can be summarized as an attempt to identify, on actual public roads, issues with the current traffic environment and vehicles before the social implementation of state-of-the-art automated driving systems in a situation where manually driven vehicles are still overwhelmingly dominant.

Although subsequent articles focusing on data analysis will describe the details of the actual assessments, these tests generally validated the original assumptions and hypotheses. Specifically, it was found that cooperation with infrastructure has an extremely large positive impact on safety, and that various issues need to be resolved before this infrastructure can be utilized. Typical issues include the form that smart infrastructure should take to enable the incorporation of future technical advances, and how this infrastructure can coexist with existing manually driven transportation. For example, the format of traffic signal information provision has been raised as a future initiative, and research into this theme is continuing.

Finally, it was originally planned to wrap up these FOTs with a test drive demonstration program organized by the Japan Automobile Manufacturers Association (JAMA) between July 6 and 12, 2020. This program should have been widely publicized both inside and outside Japan as a major event appropriate for an Olympic year. Unfortunately, the program had to be canceled due to the spread of the novel coronavirus COVID-19. The activities of the taskforce have also lasted three years from 2018, including preparations for parallel industry test drive demonstrations. SIP would like to extend its sincere gratitude to everyone involved in this program from industry, government, and the world of academia.

3 Ensuring the Safety of Automated Driving

(1)Field Operational Tests in Tokyo Waterfront Area

Data Analysis of the FOTs in Tokyo Waterfront City Area

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Abstract: In the FOTs in Tokyo Waterfront City area[(1), (2), (3)], we validated data for a total of 29,728 intersection traversals to confirm that traffic signal information provided by ITS Roadside Units installed at 33 intersections within the test area could be used to smoothly and safely traverse intersections with traffic signals on general roads by using vehicle-infrastructure cooperative driving automation (of these intersection traversals, roughly 18% were performed by automated driving using traffic signal information). We confirmed that by acquiring and utilizing current traffic signal color information, we could perform automated driving in road transport environments in which traffic signal colors could not be recognized by on-board cameras due to backlighting, direct lighting, rainfall, concealment or obstruction by preceding vehicles or curves, poor nighttime visibility, traffic signals blending into the background, or other factors. Furthermore, in dilemma zones where there is significant variation in intersection traversal judgement results, we confirmed that traffic signal remaining seconds information could be used to safely stop before reaching intersections without sudden deceleration or to safely traverse intersections without sudden acceleration. We believe that in implementing advanced automated driving on general roads, there is potential for the introduction and expansion of safe, smooth automated driving through the use of vehicle-infrastructure cooperation by defining areas where automated vehicles will be used and preparing ITS Roadside Units that cover entire areas and supply traffic signal information.

1 FOTs in Tokyo Waterfront City area

Realizing vehicle-infrastructure cooperative driving automation in the Waterfront City requires that vehicles be able to reliably recognize traffic signal status and that the problem of dilemma zones be addressed to prevent them from impeding smooth traffic flow. The FOTs in Tokyo Waterfront City area, part of the FOTs in Tokyo Waterfront area, were carried out with the aims of confirming the effectiveness of sending traffic signal color information and traffic signal remaining seconds information from infrastructure to vehicle to infrastructure (V2I) communication and determining the environmental requirements for the practical implementation of traffic signal information distribution.

2 Overview of the FOTs

2.1. Test area

As part of the FOTs in Tokyo Waterfront City area, ITS Roadside Units for providing traffic signal information were installed at 33 intersections in Tokyo Waterfront City area.

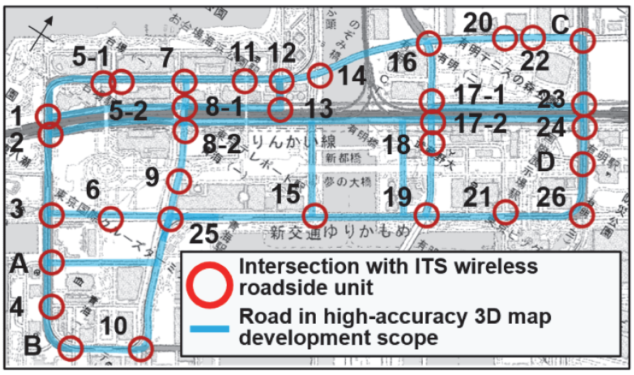

Fig. 1: ITS Roadside Units installation locations(modified version of 1:25,000 scale electronic topographical map (Geospatial Information Authority of Japan))

2.2. Test system

The composition of the on-board systems used in test vehicles is shown in Figure 2 and Table 1. Traffic signal information provided by ITS Roadside Units was received by 760 MHz receivers and own vehicle location information was received by GNSS receivers. These two types of information were then processed by on-board test equipment (BOX-PCs) and output to vehicle control devices via LAN or CAN interfaces. To ensure safety, the FOTs required that movement management systems and video data recording devices used for evaluation purposes be installed. Electronic tally counters were provided for recording when vehicles switched between automated driving and manual driving and when various phenomena occurred.

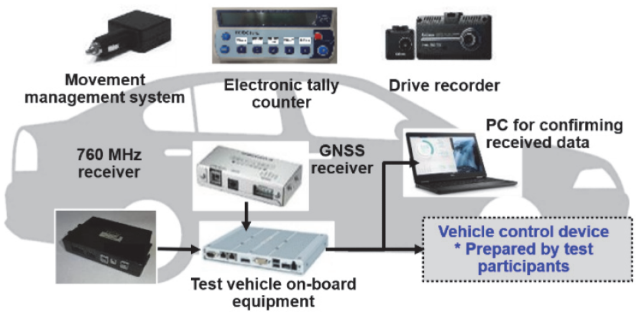

Fig. 2: On-board system configuration

Table 1: Overview of devices

Device name	Overview
PC for confirming received data	Used to collect log data and configure test vehicle on-board equipment
760 MHz receiver	Used to receive and output traffic signal information provided by ITS Roadside Units used to provide traffic signal information
GNSS receiver	Used to receive positioning signals provided by positioning satellites and output the position of the equipment
Test vehicle on-board equipment (BOX-PC)	Used to extract data as necessary from the signals output by ITS wireless receivers for providing traffic signal information, test vehicle on-board equipment for expressway experiments, and GNSS receivers, convert said data, and output it via CAN or LAN interfaces
Movement management system	Used to confirm real-time driving position information for vehicles and past vehicle driving data
Drive recorder	Used to assess the behavior of vehicles in front of and behind the test vehicle, to capture high resolution video, and to record driving logs
Electronic tally counter	Used to record the timing of phenomena and when automated driving is switched on or off by pressing buttons in accordance with defined rules

2.3. Driving results

The FOTs in Tokyo Waterfront City area were conducted over a roughly 16-month period, from October 15, 2019, to February 28, 2021. Within this period, the FOTs were suspended for roughly two months, from April 8 to May 25, 2020 due to the issuing of a state of emergency declaration in the Tokyo area in response to the spread of COVID-19. Test participants drove a total of approximately 64,591 km (figures collected via movement management systems) and traversed intersections a total of 29,728 times. Fig. 3 shows a breakdown of the driving results. Approximately 18% of these intersection traversals were performed through cooperative driving automation using traffic signal information. Furthermore, there was a two-week impact assessment intensive driving period in October/November 2020 and another two-week impact assessment intensive driving period in February 2021. These assisted in providing a relatively large amount of driving data.

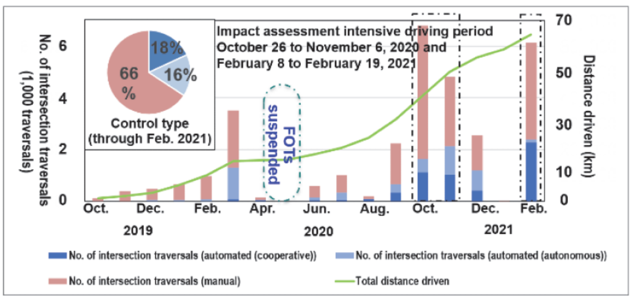

Fig. 3: Results of drives by test participants in Tokyo Waterfront City area

3 Traffic Signal Color Information - Effectiveness and Conditions

In determining the effectiveness of traffic signal color information and the conditions that apply to it, the number of times specific phenomena occurred when traversing all intersections within the test area was determined based on the following hypotheses.

1)Analysis of factors that interfere with traffic signal color recognition

2)Analysis of number of times factors in (1) above occurred when traversing intersections

3.1. Analysis of factors that interfere with traffic signal color recognition

We determined the factors that interfere with traffic signal color recognition by drivers and on-board cameras based on the phenomena in which tally counter buttons were pressed in the driving data submitted by test participants. The main interfering factors determined from this data were direct lighting and backlighting from sunlight, etc., concealment or obstruction of traffic lights by nearby large vehicles, traffic light borders blending into the background of building walls, interference from street lights at night, raindrops, and more. Figure 4 shows the main factors that interfered with traffic signal color recognition.

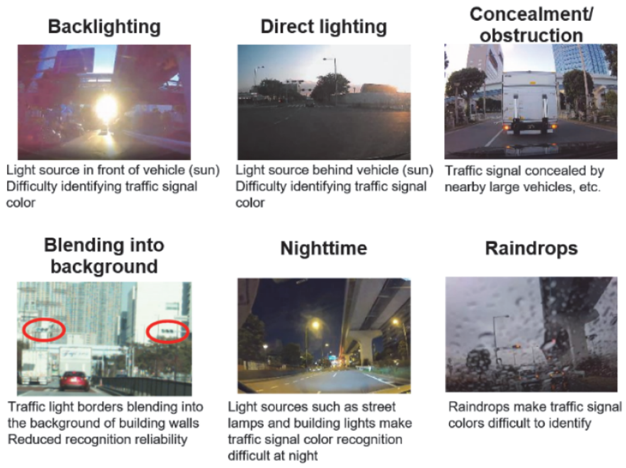

Fig. 4: Factors that interfered with traffic signal color recognition

3.2. Incidences of factors that interfere with traffic signal color recognition

We investigated the number of times the factors that interfere with traffic signal color recognition, shown in Figure 4, occurred in Tokyo Waterfront City area, as well as the locations where they occurred.

3.2.1. Number of incidences of each interference factor for all intersections and on a per-intersection basis

As Figure 5 shows, of the 29,728 total intersection traversals, backlighting occurred 79 times, direct lighting occurred 43 times, concealment/obstruction occurred 602 times, blending into the background occurred 4 times, nighttime interference occurred 6 times, and raindrop interference occurred 9 times.

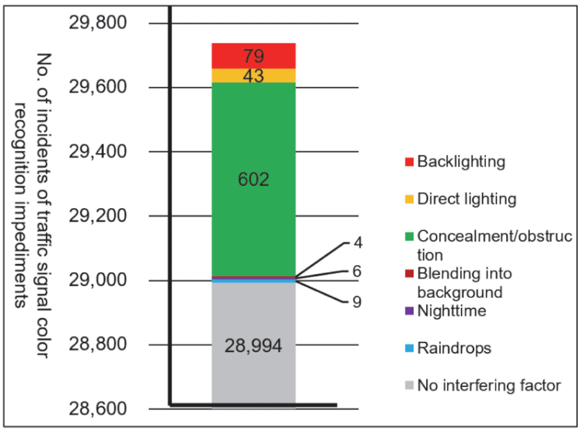

Fig. 5: Number of incidents of each type of traffic signal color recognition interference in all traversals of intersections during the FOTs in Tokyo Waterfront area

Here, the number of concealments/obstructions is greater than other factors due to the fact that the data included driving on roads with curves. Concealment and obstruction by blind spots created by curves, etc., are the result of road structures, so we tabulated the number of traversals of corresponding intersections. Table 2 shows the number of incidences of each interference factor at each intersection. Our tabulation of the number of incidences of each interference factor found that in 9 of the intersection traversals there were multiple interference factors, so the total number of incidents of impediments is greater than the total number of intersection traversals. Table 2 shows that the number of incidences of interference factors at intersections varied by intersection, especially for backlighting, direct lighting, and concealment/obstruction.

Table 2: Number of incidences of each interference factor at each intersection

Name of intersection	No. of intersection traversals	Backlighting	Direct lighting	Concealment/ obstruction	Blending into background	Nighttime	Raindrops
Shiokaze Park North	1,125	0	0	0	0	0	0
Shiokaze Park South	1,230	0	1	0	0	0	0
Museum of Maritime Science Entrance	1,319	3	1	1	0	0	2
Tokyo Port Bay Godo-chosha Bldg-mae	908	0	0	258	0	0	1
Daiba Ekimae No. 1 (West)	801	3	0	0	0	0	0
Daiba Ekimae No. 2 (East)	870	2	0	0	0	0	0
Aomi 1-chome West	705	3	0	0	0	0	0
Daiba	1,265	1	0	0	0	0	0
Central Odaiba No. 1 (North)	723	0	1	2	0	0	0
Central Odaiba No. 2 (South)	998	1	0	1	0	0	0
Teleport Ekimae	1,015	0	0	2	0	0	2
Telecom Center-mae	1,086	0	0	0	0	0	0
Daiba 1-chome	840	5	2	0	0	0	0
Kaihin Park Entrance	935	7	3	0	0	0	0
Ariakebashi West	63	0	0	1	0	0	0
Rainbow Entrance	966	5	3	0	0	0	0
Tokyo Wangan Underpass Exit	1,040	0	3	1	0	3	0
Ariake Tennis-no-mori Park	980	3	2	1	0	0	0
Ariake 2-chome North	329	0	0	3	0	0	0
Ariake 2-chome South	576	2	0	3	0	0	0
Ariake 3-chome	535	0	0	2	0	0	0
Ferry Terminal Entrance	1,363	4	5	6	1	0	0
Ariake Coliseum West	610	2	3	0	1	0	0
Tokyo Big Sight Front Entrance	895	3	3	1	0	0	0
Ariake Coliseum North	609	5	3	0	2	0	0
Ariake Chuobashi North	673	0	1	1	0	0	0
Ariake Chuobashi South	679	0	0	1	0	0	0
Aomi 1-chome	1,877	8	0	4	0	2	1
Tokyo Big Sight-mae	690	0	3	3	0	0	0
Tokyo Wangan Police Station-mae	1,552	17	8	0	0	0	1
Telecom Station-mae	1,045	2	0	310	0	0	1
Ariake Coliseum East	642	2	1	1	0	1	0
Ariake Station-mae	784	1	0	0	0	0	1
Total	29,728	79	43	602	4	6	9

3.2.2. Intersections with high incidences of interference factors

Intersections with high incidences of interference factors are shown in Figure 6 on a map of Tokyo Waterfront City area. Of the interference factors, backlighting and direct lighting were confirmed as occurring on intersections on a major road running from northeast to southwest in Tokyo Waterfront City area. Of the intersections where concealment/obstruction were observed, concealment/obstruction due to curves was confirmed at the Tokyo Port Bay Godo-chosha Bldg-mae and Telecom Station-mae intersections.

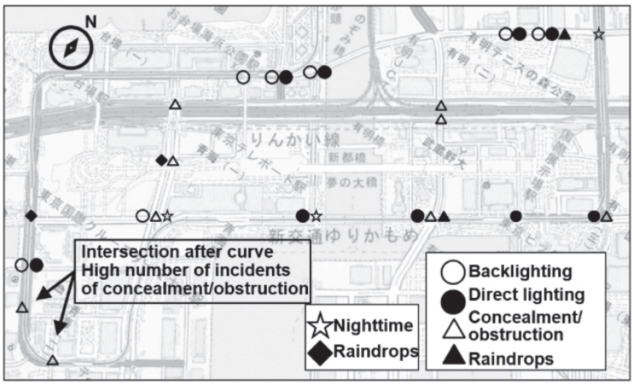

Fig. 6: Intersections with high incidences of interference factors (modified version of 1:25,000 scale electronic topographical map (Geospatial Information Authority of Japan))

3.3. Effectiveness of traffic signal color information when interfering factors are present

We evaluated the effectiveness of traffic signal color information when interfering factors were present.

3.3.1. Backlighting

The main types of backlighting were sunlight, building reflections, and the headlights of oncoming vehicles. Through our exchanges with test participants regarding the impact of backlighting on the recognition of traffic signal colors, we were informed or observed that "backlighting temporarily makes the recognition of traffic signal colors difficult, and traffic signal information is effective in these cases," "until recognition accuracy fell, traffic signal colors were recognized by on-board cameras, so the information made it possible to be continuously aware of traffic signal colors while driving," etc. Based on this, because backlighting produced situations in which traffic signal color recognition was difficult, traffic signal colors could not be detected, or traffic signal colors were incorrectly identified, we believe that in the future providing traffic signal color information will be effective during times of day when sunlight, light reflected from buildings, or the headlights of oncoming vehicles at night would overlap with the light from traffic signals.

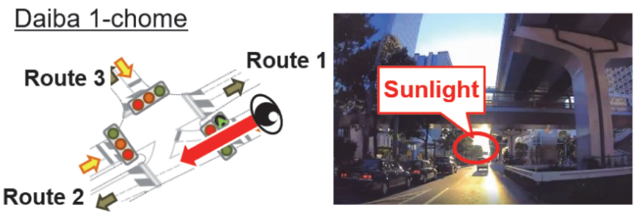

Fig. 7: Situations in which backlighting makes traffic signal color recognition difficult (example)

3.3.2. Direct lighting

Through our exchanges with test participants regarding the impact of direct lighting on the recognition of traffic signal colors, we were informed or observed that "direct lighting temporarily reduced the accuracy with which on-board cameras recognized traffic signal colors," "the traffic signal color recognition accuracy of on-board cameras fell, but because of the information, this had no effect on judgements to traverse intersections," etc. Based on this, because direct lighting produced situations in which traffic signal color recognition was impacted, though not significantly, we believe that in the future providing traffic signal color information will be effective during times of day when sunlight from behind vehicles would overlap with the light from traffic signals.

Fig. 8: Situations in which direct lighting makes traffic signal color recognition difficult (example)

3.3.3. Concealment/obstruction

Through our exchanges with test participants regarding the impact of concealment and obstruction on the recognition of traffic signal colors, we were informed or observed that "While stopped at an intersection that was concealed by a large vehicle, the traffic light changed green, but we were unable to detect this change for roughly four seconds. However, because traffic signal color information was provided, we were able to prepare to pull out before the on-board camera recognized the traffic signal color," etc. Based on this, we believe that in the future providing traffic signal color information will be effective in traffic conditions in which traffic signals are obstructed and on roads whose structures are such that traffic signals are located in blind spots, such as roads where traffic signals are located immediately after curves or crests.

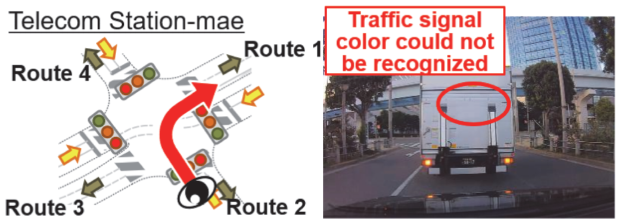

Fig. 9: Situations in which concealment/obstruction makes traffic signal color recognition difficult (example)

3.3.4. Blending into the background

Through our exchanges with test participants regarding the impact of blending into the background on the recognition of traffic signal colors, we were informed or observed that "While traffic signal colors themselves could be detected, the outlines of traffic signal blended into the buildings or other objects behind them, reducing the reliability of traffic signal detection," etc. Based on this, because blending into the background produced situations in which traffic signals themselves were difficult to recognize, we believe that in the future providing traffic signal color information will be effective for road structures and during times of day when traffic signals blend into buildings or other background objects.

Fig. 10: Situations in which blending into the background makes traffic signal color recognition difficult (example)

3.3.5. Nighttime driving

Through our exchanges with test participants regarding the impact of nighttime driving on the recognition of traffic signal colors, we were informed or discovered that "traffic signal colors can be difficult to recognize when there is also light from street lights, buildings, etc.," etc. Based on this, because traffic signal colors (arrow signal colors, etc.) can be difficult to recognize while driving at night, we believe that in the future providing traffic signal color information will be effective at night, when traffic signal color recognition accuracy falls due to the presence of multiple light sources.

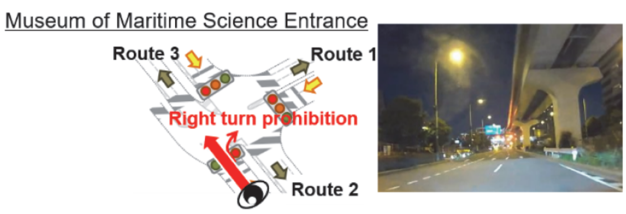

Fig. 11: Situations in which nighttime driving makes traffic signal color recognition difficult (example)

3.3.6. Raindrops

Through our exchanges with test participants regarding the impact of raindrops on the recognition of traffic signal colors, we were informed or discovered that "raindrops on front-facing on-board cameras made traffic signal color recognition difficult," etc. Based on this, because there were situations in which raindrops made traffic signal color recognition difficult, we believe that in the future providing traffic signal color information will be effective in weather situations in which raindrops get on front-facing on-board cameras and reduce the accuracy of traffic signal color recognition.

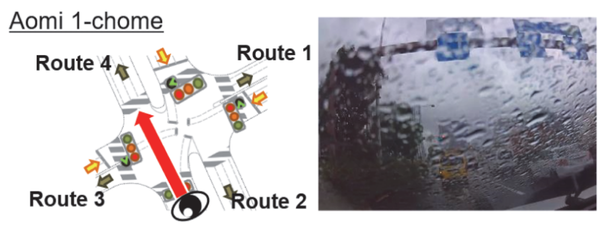

Fig. 12: Situations in which raindrops make traffic signal color recognition difficult (example)

3.4. Effectiveness of traffic signal color information when stopped at an intersection

Based on the driving data from test participants we analyzed the cooperative driving automation situations in which traffic signal color information was used. Figure 13 shows the change in test vehicle speed and acceleration when entering an intersection. We confirmed that traffic signal color information was effective in situations in which traffic signal recognition accuracy was reduced, as it enabled vehicles to traverse intersections without suddenly decelerating.

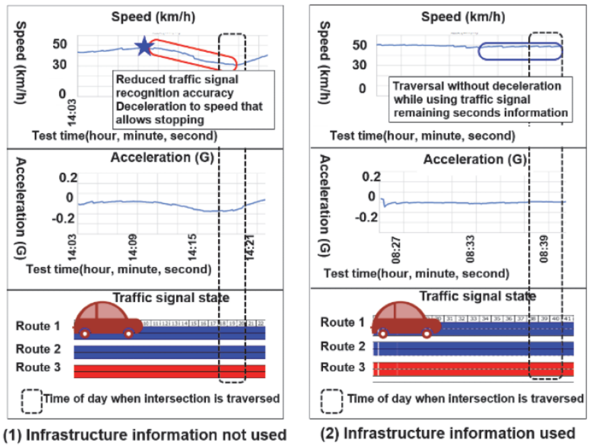

Fig. 13: Results of automated driving with and without using traffic signal color information

3.5. Summary of effectiveness of traffic signal color information

We divided the factors that interfered with traffic signal color detection in Tokyo Waterfront City area into six categories: backlighting, direct lighting, concealment/obstruction, blending into the background, nighttime driving, and raindrops. We then analyzed these factors. We confirmed that the interference factors were contributing factors to erroneous detection or failure to detect traffic signal colors or the presence of traffic signals. Reductions in traffic signal color recognition accuracy can occur in all intersections, due not only to road structures but also to time-dependent conditions, traffic conditions, and weather conditions. In sections in which automated driving is performed, it would be best for traffic signal color information to be provided for all intersections with traffic signals. However, among the intersections with traffic signals in the section where automated driving was performed, due in particular to road structure, traffic condition, and time-dependent factors, there were intersections in which there were frequent drops in traffic signal color recognition accuracy and intersections in which drops in traffic signal color recognition accuracy were rare. It would therefore be best when preparing infrastructure which provides traffic signal color information to prioritize the former intersections.

4 Traffic Signal Remaining Seconds Information - Effectiveness and Conditions

In determining the effectiveness of traffic signal remaining seconds information and the conditions that apply to it, the number of times specific phenomena occurred when traversing all intersections within the test area was determined based on the following hypotheses.

1)Analysis of factors causing differences in intersection traversal judgement

2)Conditions in which there were differences in intersection traversal judgement

4.1. Factors causing differences in intersection traversal judgement

Based on the phenomena in which tally counter buttons were pressed in the driving data submitted by test participants, we divided the factors that led to differences in intersection traversal judgement into the following three categories, as shown in Figure 14: "stopping in traversal areas," "encountering dilemma zones," and "traversal in stopping areas." In our analysis of the relationships between distances to stop lines and speeds, we used the definition of dilemma zones shown in Figure 15 for reference. As parameters, we used the stopping distance when decelerating at normal speeds and the distance covered while traveling at the current speed while the light is yellow, as shown in Table 3.

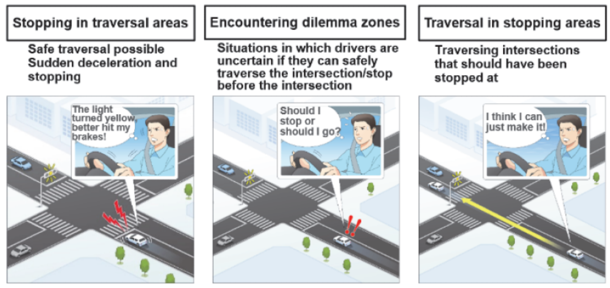

Fig. 14: Factors causing differences in intersection traversal judgement

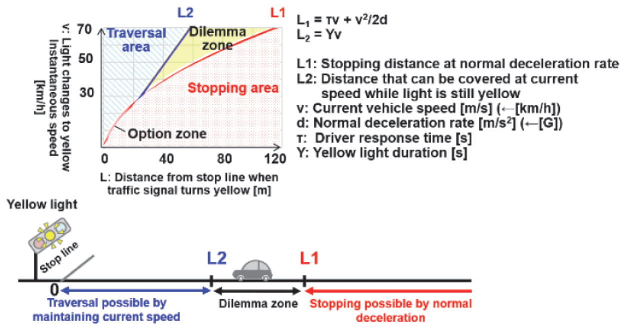

Fig. 15: Definition of "dilemma zone"(4)

Table 3: Dilemma zone parameters

3 seconds of yellow remaining		4 seconds of yellow remaining	
Allowable deceleration	0.2 [G]	Allowable deceleration	0.2 [G]
Response time	1.0 [s]	Response time	1.0 [s]
Yellow light length	3.0 [s]	Yellow light length	4.0 [s]

4.2. Incidence of differences in intersection traversal judgement

We identified the main three categories of factors that contributed to dilemmas.

4.2.1. No. of times per intersection

The number of differences in intersection traversal judgement was tabulated for each intersection. Intersection traversal judgement differences occurred an average of 0.51% of the time, with a maximum of 2.70% and a minimum of 0.00%. The difference rate exceeded 1.00% at seven intersections (Shiokaze Park North, Shiokaze Park South, Central Odaiba No. 1 (North), Central Odaiba No. 2 (South), Kaihin Park Entrance, Telecom Station-mae, and Ariake Station). These are shown in Figure 16 and Table 4.

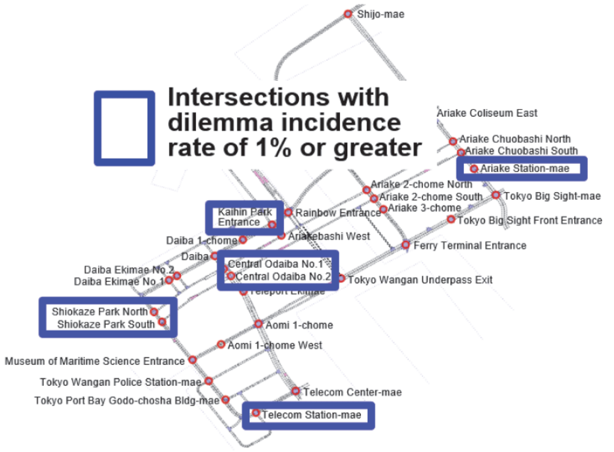

Fig. 16: Intersections with an intersection traversal judgement difference rate of 1% or greater

Table 4: Incidence of differences in intersection traversal judgement at each intersection

Name of intersection	Manual	Manual	Traversal decision differences	Traversal decision difference rate (intersection encounters) (%)	
Shiokaze Park North	673	287	11	11/960	1.15%
Shiokaze Park South	797	289	24	24/1086	2.21%
Museum of Maritime Science Entrance	873	302	4	4/1175	0.34%
Tokyo Port Bay Godo-chosha Bldg-mae	540	281	0	0/821	0%
Daiba Ekimae No. 1 (West)	474	254	2	2/728	0.27%
Daiba Ekimae No. 2 (East)	511	249	5	5/760	0.66%
Aomi 1-chome West	547	76	5	5/623	0.8%
Daiba	737	394	4	4/1131	0.35%
Central Odaiba No. 1 (North)	365	322	12	12/687	1.75%
Central Odaiba No. 2 (South)	570	355	25	25/925	2.7%
Teleport Ekimae	575	347	1	1/922	0.11%
Telecom Center-mae	622	279	0	0/901	0%
Daiba 1-chome	570	180	2	2/750	0.27%
Kaihin Park Entrance	626	193	13	13/819	1.59%
Ariakebashi West	55	8	0	0/63	0%
Rainbow Entrance	630	186	1	1/816	0.12%
Tokyo Wangan Underpass Exit	740	117	0	0/857	0%
Ariake Tennis-no-mori Park	652	174	2	2/826	0.24%
Ariake 2-chome North	226	2	0	0/228	0%
Ariake 2-chome South	417	4	1	1/421	0.24%
Ariake 3-chome	406	1	0	0/407	0%
Ferry Terminal Entrance	965	191	5	5/1156	0.43%
Ariake Coliseum West	441	165	0	0/606	0%
Tokyo Big Sight Front Entrance	644	178	2	2/822	0.24%
Ariake Coliseum North	436	169	0	0/605	0%
Ariake Chuobashi North	505	164	2	2/669	0.3%
Ariake Chuobashi South	512	163	3	3/675	0.44%
Aomi 1-chome	1,231	426	1	1/1657	0.06%
Tokyo Big Sight-mae	493	193	0	0/686	0%
Tokyo Wangan Police Station-mae	1,004	401	0	0/1405	0%
Telecom Station-mae	672	279	15	15/951	1.58%
Ariake Coliseum East	476	163	0	0/639	0%
Ariake Station-mae	559	218	9	9/777	1.16%
Total	19,544	7,010	149	149/26554	0.56%

4.2.2. Intersections with a high frequency of differences in intersection traversal judgement

We analyzed the rates at which differences in intersection traversal judgement occurred at individual intersections from four perspectives: distance from the adjacent intersection with a traffic signal, speed limit, number of seconds of yellow light time, and if the traffic signal remaining seconds information was confirmed or had a margin.

(1)Comparison of distances from adjacent intersections with traffic signal

Figure 17 shows a comparison of the ratios of differences in intersection traversal judgement for intersections less than 100 meters from the adjacent intersection with a traffic signal (basic road section) and intersections 100 meters or more from the adjacent intersection with a traffic signal. The ratio of differences in intersection traversal judgement was 1.00% for intersections less than 100 meters away (0.93% for stopping in traversal areas),but was 0.30% for intersections 100 meters or more away (0.23% for stopping in traversal areas). When there were several intersections in a row with little distances between them, there is the possibility that a vehicle could traverse the first intersection only to be unable to deal with the situation in time in the next intersection, causing it to encounter a dilemma zone. Traffic signal information from ITS Roadside Units can be delivered to vehicles over 100 meters away, so traffic signal remaining seconds information could be used to prevent encountering dilemma zones.

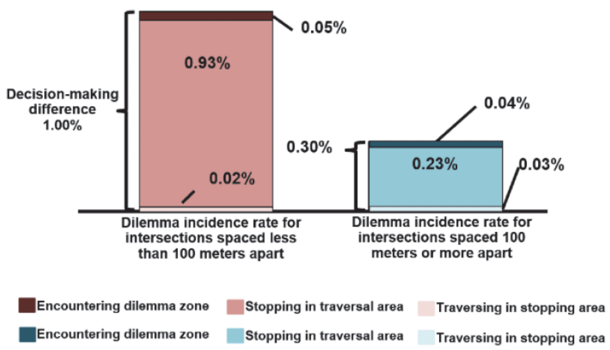

Fig. 17: Incidence of differences in intersection traversal judgement by distance to adjacent intersection with traffic signal

(2)Comparison of speed limits

Figure 18 shows a comparison of the ratios of differences in intersection traversal judgement for intersections whose entry routes had speed limits of 60 km/h and intersections whose entry routes had speed limits of 50 km/h. The ratio of differences in intersection traversal judgement was 0.54% for intersections whose entry routes had speed limits of 60 km/h (0.46% for stopping in traversal areas) and 0.37% for intersections whose entry routes had speed limits of 50 km/h (0.29% for stopping in traversal areas). This shows that differences in intersection traversal judgement occurred more often for intersections whose entry routes had speed limits of 60 km/h.

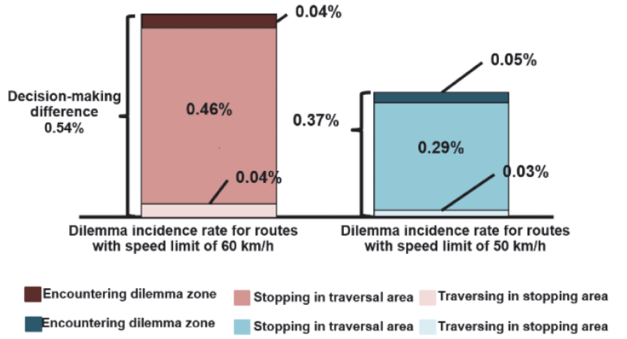

Fig. 18: Incidence of differences in intersection traversal judgement by speed limit

(3)Comparison of number of seconds of remaining yellow traffic signal time

Figure 19 shows a comparison of the ratios of differences in intersection traversal judgement for intersections with 3 seconds and 4 seconds of remaining yellow traffic light time. The ratio of differences in intersection traversal judgement was 0.42% for intersections with 3 seconds of remaining yellow traffic light time (0.26% for dilemma zone encounters) and 0.57% for intersections with 4 seconds of remaining yellow traffic light time (0.53% for stopping in traversal areas). This showed that the rate of incidence of dilemma zone encounters was higher for traffic signals with 3 seconds of remaining yellow light time than for traffic signals with 4 seconds of remaining yellow light time, and that the incidence of stopping in traversal areas was higher for traffic signals with 4 seconds of remaining yellow light time.

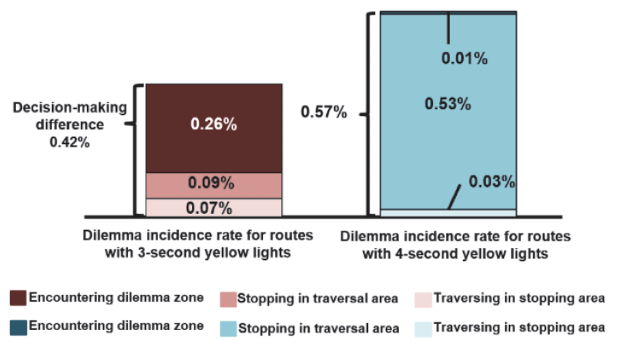

Fig. 19: Incidence of differences in intersection traversal judgement by number of seconds of remaining yellow light time

(4)Comparison of confirmed traffic signal remaining seconds information and traffic signal remaining seconds information with margins

Figure 20 shows a comparison of the ratios of differences in intersection traversal judgement for intersections with confirmed traffic signal remaining seconds information and traffic signal remaining seconds information with margins. The ratio of differences in intersection traversal judgement was 0.03% for intersections with confirmed information (0.03% for stopping in traversal areas) and 0.09% for intersections with information with margins (0.065% for stopping in traversal areas). This showed that the incidence of differences in intersection traversal judgement was high for intersections with information with margins.

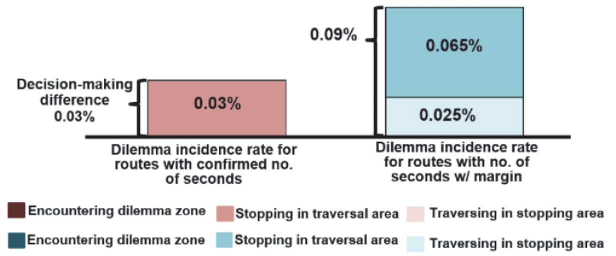

Fig. 20: Incidence of differences in intersection traversal judgement for confirmed information and information with margins

4.3. Effectiveness of traffic signal remaining seconds information in reducing differences in intersection traversal judgement

We tabulated the distribution of vehicle speeds and distances to stop lines when lights turned yellow with yellow light times of 3 and 4 seconds. We then analyzed the effectiveness of traffic signal remaining seconds information when making intersection traversal decisions.

4.3.1. Routes with 3 seconds of remaining yellow light time

As Figure 21 shows, we confirmed multiple cases in which vehicles that were on routes with 3 seconds of remaining yellow light time and that were not using traffic signal remaining seconds information either encountered dilemma zones or stopped in traversal areas/traversed stopping areas near dilemma zones.

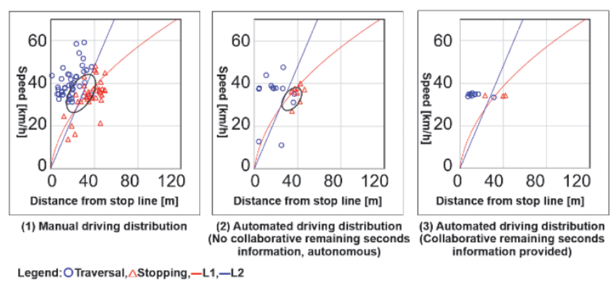

Fig. 21: Results of intersection traversal judgement on routes with 3 seconds of remaining yellow light time

Sudden deceleration was observed for vehicles stopping in traversal areas, but we believe that if vehicles were provided with traffic signal remaining seconds information, they would be able to decelerate to a stop more gradually. Figure 22 shows these driving characteristics. Furthermore, we also observed cases of traversal in stopping areas in which vehicles confirmed that traffic lights were yellow and then accelerated to traverse the intersection. We believe that if vehicles were provided with traffic signal remaining seconds information, they would be able to stop safely. Figure 23 shows these driving characteristics.

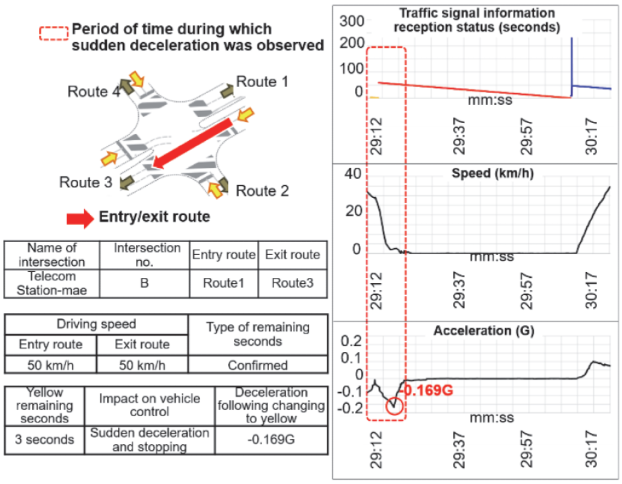

Fig. 22: Stopping in traversal areas (routes with 3 remaining seconds of yellow light)

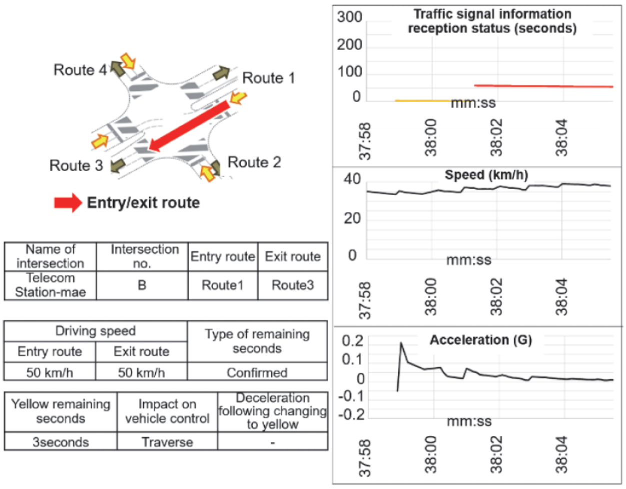

Fig. 23: Traversal in stopping areas (routes with 3 remaining seconds of yellow light)

4.3.2. Routes with 4 seconds of remaining yellow light time

As shown in Fig. 24, routes with 4 remaining seconds of yellow light time for which traffic signal remaining seconds information was not used were observed to have a broad mix of traversal and stopping in traversal areas.

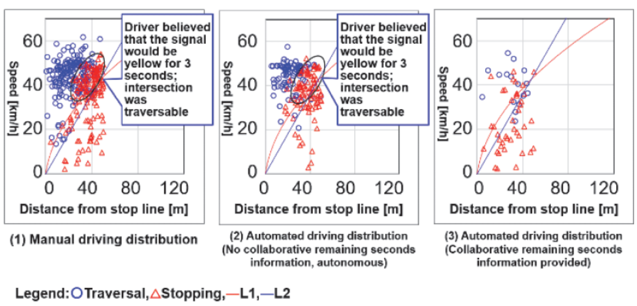

Fig. 24: Results of intersection traversal judgement on routes with 4 seconds of remaining yellow light time

We believe this is because in areas with similar distances to stop lines, where vehicles are travelling at similar speeds, there was a mix of stop and traversal decisions made by drivers. However, in the cooperative infrastructure driving using traffic signal remaining seconds information, there was less of a mix of decisions regarding stopping and traversal, so we believe that providing traffic signal remaining seconds information would be effective in reducing differences in intersection traversal judgement. When providing traffic signal remaining seconds information with margins, the maximum remaining time was 20 seconds and the minimum remaining time was 0 seconds when traffic lights turned yellow, so we believe that it would be difficult to use this information in vehicle-side control to safely stop by performing preliminary deceleration. Figure 25 shows these driving characteristics.

Furthermore, we confirmed that when performing driving using traffic signal remaining seconds information, vehicles performed preliminary deceleration, slowing to roughly 30 km/h before receiving the remaining seconds information, enabling them to gradually decelerate and stop without encountering a dilemma zone. Figure 26 shows these driving characteristics.

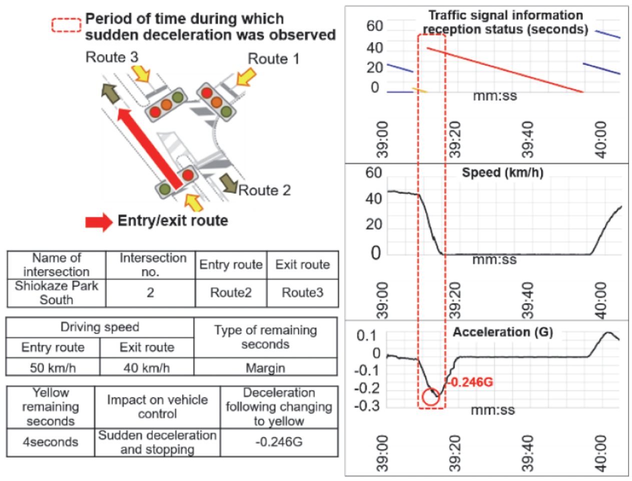

Fig. 25: Stopping in traversal areas (routes with 4 remaining seconds of yellow light)

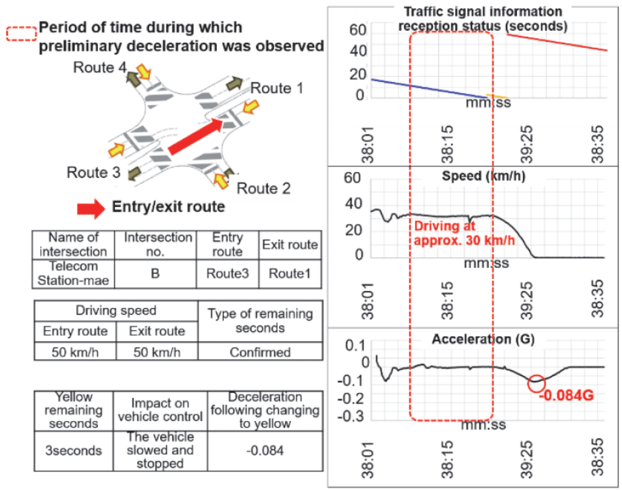

Fig. 26: Preliminary deceleration and stopping (routes with 4 remaining seconds of yellow light)

4.4. Summary of effectiveness of traffic signal remaining seconds information

Providing traffic signal remaining seconds information makes it possible to avoid dilemma zones and make decisions regarding appropriate traversal of traversal areas and smooth stopping in stopping areas, so in sections in which automated driving is performed, it would be best for traffic signal remaining seconds information to be provided for all intersections. In particular, it would be best for traffic signal remaining seconds information to be provided to automated vehicles at intersections located near adjacent intersections with traffic signals, intersections with routes with high-speed limits, and intersections with routes with short yellow traffic lights, where differences in intersection traversal judgement are more likely to occur.

5 Effectiveness of Traffic Signal Information and Infrastructure Recommendations

The FOTs in Tokyo Waterfront City area confirmed that providing traffic signal color information and traffic signal remaining seconds information to vehicles through vehicle-infrastructure cooperation (using Dedicated Short-Range Communications (DSRC) infrastructure) enables automated vehicles to safely and smoothly traverse intersections with traffic lights on general roads. In sections where automated driving is performed, it would be best to provide traffic signal color information and traffic signal remaining seconds information at all intersections with traffic lights. However, with regard to the environmental requirements for providing traffic signal information distribution, based on the Traffic Signal Installation Policy(5) enacted by the National Police Agency on December 27, 2015, and the FOTs, we have confirmed that it would be best to prioritize the provision of traffic signal information for "roads with curves, etc., that result in traffic signals coming into view at short distances from the traffic signals," "roads with high speed limits," "intersections with traffic signals located near other intersections with traffic signals," and when there are "non-permanent conditions (such as backlighting/direct lighting, rain, obstruction by preceding vehicles, nighttime driving, and blending into the background) that make it difficult for on-board cameras to determine traffic signal colors."

Figure 27 shows a summary of our conclusions regarding intersections where the distribution of traffic signal information should be prioritized.

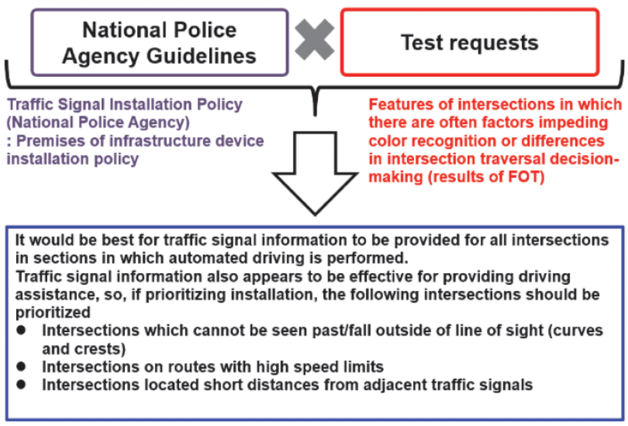

Fig. 27: Intersections where the distribution of traffic signal information should be prioritized

6 Conclusion

In realizing vehicle-infrastructure cooperative driving automation in the Waterfront City, we confirmed that vehicle-infrastructure cooperation can be used to introduce and expand safe, smooth automated vehicle usage by preparing infrastructure covering entire areas after defining areas where automated vehicles, including those providing mobility services, will be used. Although a consensus was reached with test participants in this FOTs

regarding information distributed by ITS Roadside Units for existing services (ISO/TS19091 specification compliant), there were requests that remaining seconds information for actuated traffic signal be confirmed earlier. The impact will be even greater for V2N, so we believe future consideration will need to be given to the delivery of this information using V2N information transmission technologies.

Lastly, we would like to express our gratitude to the test participants in this FOTs for performing test drives and submitting data in the midst of the ongoing COVID-19 pandemic.

【 Reference 】

(1)FOTs in Tokyo Waterfront Area Consortium ["Cross-ministerial Strategic Innovation Promotion Program The second phase of SIP- Automated Driving for Universal Services /Implementation of FOTs in Tokyo Waterfront Area" 2020 Results Report]
(2)Dynamic Map Study Consortium [Automated Driving System Map Data Specification Proposal, Ver. 1.1]
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(4)Hironori Suzuki, Takaya Ishikura, Norikazu Ikoma: Factors Affecting Drivers' Stop / Go Decision and their Intent Inference at Dilemma Zone, Transactions of the Society of Automotive Engineers of Japan, Inc., Vol.47, No.4 (2016)
(5)National Police Agency [The guidelines of traffic signals installation] Shingoki secchi no shishin (in Japanese).2015-12-28

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Analysis of Field Operational Test Data Obtained in Haneda Airport Area

Kosuke Yamada, Naohiro Uchiyama and Shinichi Nedu (Pacific Consultants Co., Ltd.)

The field operational tests (FOTs) carried out in the Haneda Airport area used automated driving support infrastructure such as magnetic markers, bus lanes, traffic signal information, public transportation priority systems (PTPS), and the like to verify whether buses equipped with automated driving technology could achieve a stable and regular service on a circular bus route on public roads in the vicinity of Haneda Airport and realize precise arrival (docking) control at bus stops. Automated driving tests consisting of a total of 322 laps of the circular bus route were carried out, and it was confirmed that a stable and regular service by automated driving could be achieved under a mixed traffic environment. In addition, approximately 80% of manual interventions in the tests were to avoid parked vehicles or because the test vehicle came too close to the stop line of the oncoming lane when turning left. It was also confirmed that the use of PTPS helped to realize a more punctual service with stable travel times. The FOTs also confirmed that bus lanes helped to improve the continuity of automated driving. However, it was found that the resulting conflicts with ordinary vehicles would necessitate publicity and educational activities, as well as campaigns to encourage people to follow the rules of bus lanes. At bus stops, a total of 416 automated driving docking control tests were carried out, confirming the feasibility of highly reproducible docking controls to a standard deviation of less than 10 mm through the use of magnetic markers.

1 Purpose of Field Operational tests in the Haneda Airport Area

Field operational tests (FOTs) of unmanned mobility services and the like incorporating cooperative vehicle-infrastructure automated driving controls were carried out in the Haneda Airport area from June 5, 2020 using public buses, low-capacity transportation, and the like.

In these tests, automated driving support infrastructure such as magnetic markers, bus lanes, and the like were provided in the Haneda Airport area. The different types of data obtained in the FOTs were analyzed to confirm the effectiveness of cooperative infrastructure systems and to identify issues.

Figure. 1 shows the locations where infrastructure was installed in the Haneda Airport area.

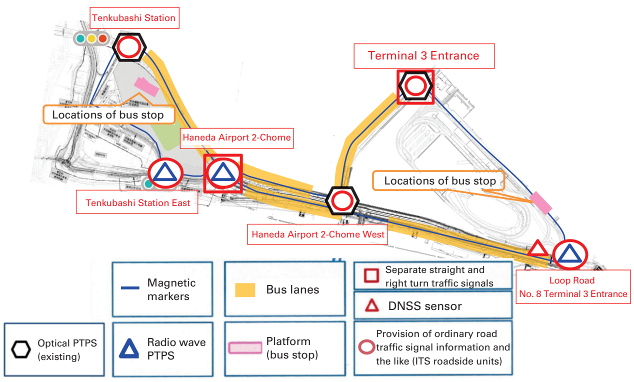

Fig. 1: Locations of Infrastructure for Tests in Haneda Airport Area

2 Methods of Investigation and Summarizing Evaluation Results

Data from on-board equipment (OBE) and observations of the traffic conditions were used to evaluate the effects of infrastructure cooperation on the feasibility of automated driving, the capability of automated buses to run a regular service with stable travel times, comfort, and ordinary traffic. The effectiveness of infrastructure cooperation was then considered based on data analysis. In addition, the test participants were asked to complete a questionnaire to identify comments about particularly effective aspects of infrastructure cooperation. Finally, the proposals for conditions to be satisfied by automated driving support infrastructure were collected with the data analysis results.

3 Test Result Summary and Report

3.1. Analysis of Driver Intervention Causes under Mixed Traffic Conditions

3.1.1. Confirmation of State of Automated Driving under Mixed Traffic Conditions

To confirm that a vehicle-infrastructure cooperative automated advanced rapid transit (ART) system is capable of automated driving under mixed traffic conditions on public roads, a target number of laps of the test route was set and the actual number of laps achieved by automated driving was analyzed.

(1) Analysis procedure

The target number of laps of the test route was set as follows. To evaluate the feasibility, punctuality, travel time stability, and comfort of automated driving, the number of samples capable of realizing a statistically significant evaluation was calculated. It should be noted that, when the actual number of automated driving laps was calculated, the occurrence of brief manual intervention was not counted as intervention if continuous or successive manual driving actions were not required.

(2) Analysis results

The realization of automated driving was confirmed from the driving data obtained by the three companies participated in the test.These results demonstrated that automated driving was accomplished for more than the target number of laps. These results confirmed that infrastructure cooperation is an effective means of realizing automated driving under a mixed traffic environment.

Figure. 2 shows the number of target laps of the test route and the actual number of laps completed.

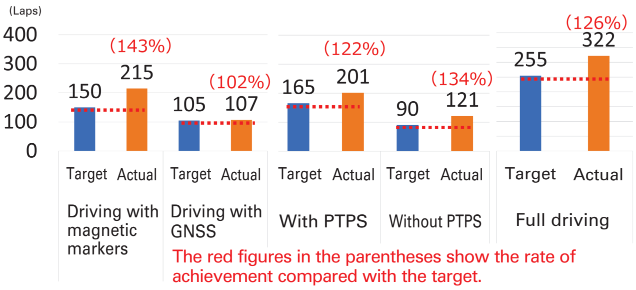

Fig. 2: Target and Actual Numbers of Laps (Three-Company Total, Counted between June and November)

3.1.2. Identification of Causes of Manual Intervention during Driving Using Magnetic Markers

Although most of these FOTs were accomplished by automated driving, manual intervention was required in a number of scenarios. Since manual intervention is an issue for ensuring and enhancing the continuity of automated driving, the causes of this intervention were evaluated to identify topics related to infrastructure provision for the future realization of automated driving.

(1) Analysis procedure

When manual intervention occurred during automated driving, the occupants of the automated buses were asked to press the button of a tally counter to record the time at which the manual intervention occurred. When the timings of manual intervention were paired with drive recorder images, the eight types of intervention causes shown in Fig. 3 were identified.

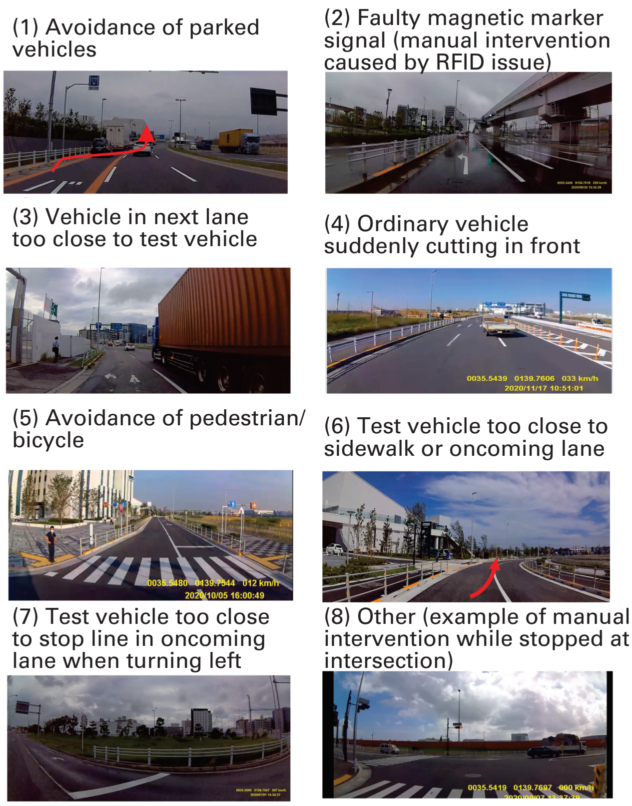

Fig. 3: Details of Manual Intervention Causes

(2) Analysis results

Approximately 80% of manual interventions were carried out to avoid parked vehicles (1) or because the test vehicle came too close to the stop line in the oncoming lane when turning left (7). The next most frequent cause was a vehicle in the next lane coming too close to the test vehicle (3).

Figure. 4 shows the breakdown of manual intervention causes. The continuity of automated driving could be enhanced by improving the driving environment to facilitate the avoidance of parked vehicles and improving road structures and operation (such as adjusting the position of stop lines) to address the issue of proximity to the stop line in the oncoming lane when turning left.

3.2. Effectiveness of Infrastructure Cooperation for Realizing Regular Service with Stable Travel Times

3.2.1. Confirmation of Effectiveness of PTPS on Improving Punctuality and Travel Time Stability

The effect of PTPS in shortening travel times and improving travel time stability was identified the travel time per route with and without PTPS, and from the resulting standard deviation and the like.

(1) Analysis procedure

(a)History point data (acquisition times, latitude, and longitude) during driving obtained from on-board Global Navigation Satellite System (GNSS) units was used to calculate the travel time per lap of the circular test route in the Haneda Airport area. This data was also used to obtain various statistical values such as average travel times, the standard deviation, and so on.

(b)Of this history point data, only the data for confirmed laps of the circular test laps was extracted and used to calculate the travel time. The measurement scope of the circular route travel time was from the point the test vehicle left the Terminal 3 bus stop zone to the point that the test vehicle left the Terminal 3 Entrance intersection zone. It should be noted that, to ensure the homogeneity of evaluation-eligible runs, laps in which the speed on the southern roads of zone 1 was low (an average of 10 km/h or less) were excluded. In addition, during driving with PTPS, analysis was limited to runs in which at least seven of eight intersection uplinks were successful.

(2) Analysis results

The average travel time of laps with PTPS was 21 seconds (approximately 4%) shorter than without PTPS. The standard deviation for the travel time was 12 seconds shorter, and it was identified that the shortening of the median travel time value was 38 seconds and it was the large reduction.

Figure. 5 shows the statistical values for travel time and Fig. 6 shows the travel time distribution.

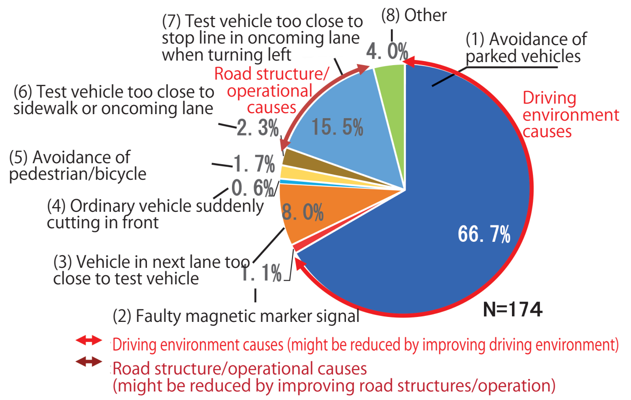

Fig. 4: Breakdown of Manual Intervention Causes (Driving Using Magnetic Markers)

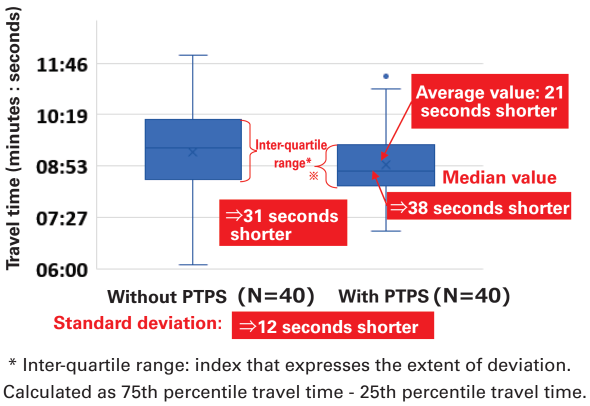

Fig. 5: Statistical Values Pertaining to Use/Non-Use of PTPS

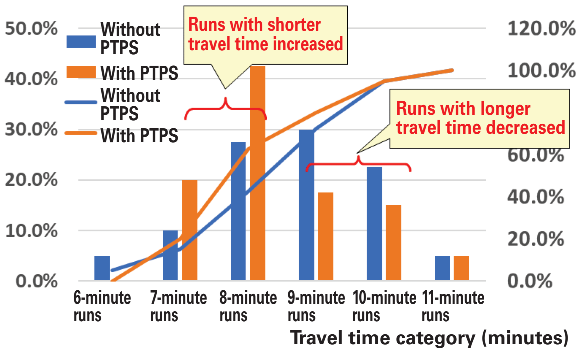

Fig. 6: Comparison of Travel Time Distributions
(Runs Carried out by Company C)

3.3. Comfort of Embarking and Disembarking

3.3.1. Identification of Stopping and Starting Acceleration

When the vehicles stopped and started at intersections and bus stops, the occurrence frequency of maximum longitudinal acceleration intensities was identified and used to evaluate the safety and comfort of the bus considering the existence of standing passengers.

(1) Analysis procedure

(a)On each lap, drive recorders were used to confirm the stopping and starting times at the Terminal 3 bus stop, as well as the stopping and starting times at each intersection due to a red traffic signal.

(b)The acceleration data obtained from the drive recorders was then used to analyze the maximum acceleration and deceleration generated in the twenty seconds before and after the bus stopped and started due to the traffic signals.

(2) Analysis results

Approximately 90% of all acceleration and deceleration was in a range that causes no discomfort to passengers (0.2 G or lower) when both stopping and starting. This is gradual acceleration and deceleration that does not discomfort standing passengers.

It should also be noted that deceleration exceeding 0.3 G occurred several times, but that this occurred when the traffic signal changed to yellow just before the bus entered the intersection. In the future, it should be possible to eliminate this sudden deceleration by adopting stop and start controls that incorporate information on the number of seconds remaining before traffic signals change color.

Figure. 7 shows the frequency of acceleration and deceleration intensities.

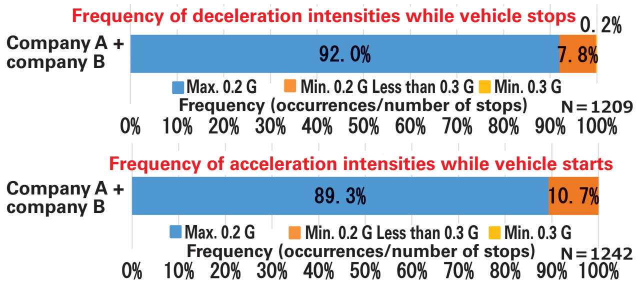

Fig. 7: Frequency of Acceleration and Deceleration Intensities
(Company A + Company B, Driving Using Magnetic Markers)

3.3.2. Evaluation of Extent of Docking Control Reproducibility

When the automated buses stopped at a bus stop, the distance from the edge of the bus stop to the bus door was measured to confirm the extent of docking control reproducibility using magnetic markers.

(1) Analysis procedure

The distance between the edge of the bus stop and the bus door under docking control was measured. The extent of docking control reproducibility was confirmed, by calculating the standard deviation based on at least fifty measurement values by each company. It should be noted that, in these FOTs, the middle door was used for the verification since the system was developed to enhance the ease that wheelchair users can embark and disembark buses via the middle door.

(2) Analysis results

Magnetic marker-based docking control realized highly reproducible and precise arrival at bus stops with a standard deviation of less than 10 mm in both zone 1 and at Terminal 3.

Figure. 8 shows the standard deviation of measured values at the zone 1 and Terminal 3 bus stops. Despite the different shapes of the bus stops in zone 1 and at Terminal 3, highly reproducible and precise docking control was realized, thereby demonstrating the effectiveness of magnetic markers in achieving a reproducible and stable bus stop docking control.

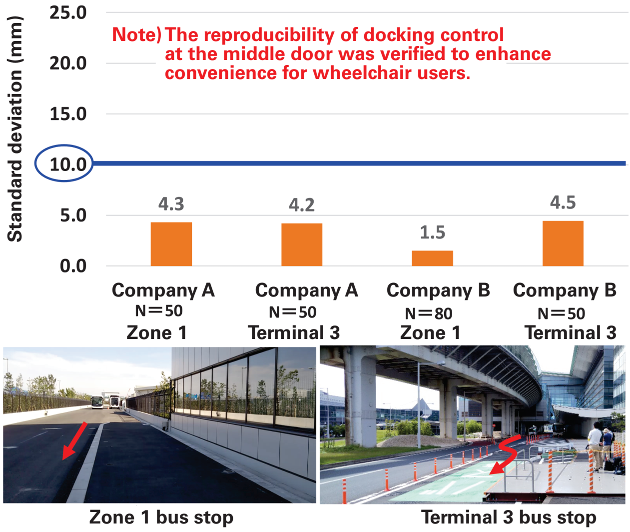

Fig. 8: Standard Deviation at Zone 1 and Terminal 3 Bus Stops
(Localization Method: Magnetic Markers)

3.4. Effects of Automated Vehicles on Traffic Flows and Causes of these Effects

3.4.1. Changes in Congestion States by Establishing Bus Lanes

The provision and operation of bus lanes reduces the capacity of a road since the number of lanes usable by ordinary vehicles on normal stretches of road decreases. However, it should be possible to eliminate the impact of a bus lane on road capacity at intersections by ending the bus lane approximately 90 to 160 meters before the intersection. In general terms, the capacity of a road network often depends on its capacity at intersections. However, depending on the conditions, the provision and operation of bus lanes may still have a negative impact on the capacity of normal stretches of road. Therefore, the length of congestion was monitored to confirm the impact of the infrastructure (bus lanes) provided for the FOTs and the automated buses on traffic.

(1) Analysis procedure

The results of congestion lengths investigated on October 28 (Wednesday) and November 11 (Wednesday) were used to confirm the differences in maximum congestion lengths during the bus lane operation time (10:00 to 17:00) and outside the bus lane operation time (07:00 to 10:00 and 17:00 to 19:00).

(2) Analysis results

Although the volume of traffic on these dates was approximately 60% of the volume before the COVID-19 pandemic, the length of congestion during the bus lane operation time did not increase. Therefore, the provision of bus lanes under the traffic conditions during the FOTs had no impact on congestion. Figure. 9 shows the maximum congestion lengths at each intersection and section of road.

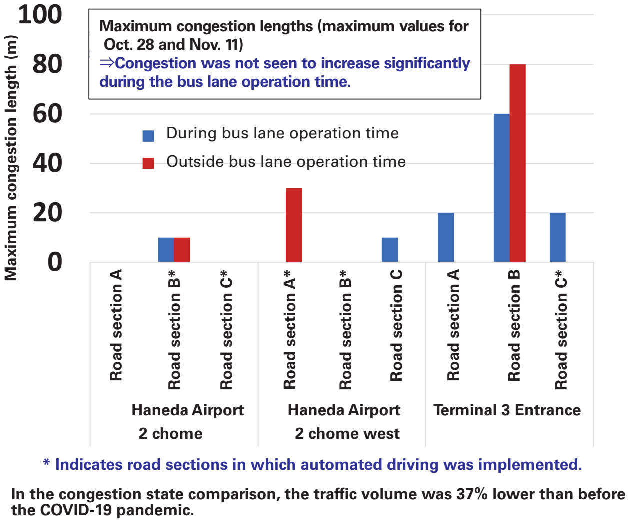

Fig. 9: Maximum Congestion Lengths at each Intersection and Road Section

3.4.2. Conflicts Created by Automated Buses

Since automated buses will strictly follow posted speed limits, drivers of ordinary vehicles may regard these buses as moving too slowly. In particular, one possible conflict may occur in the zone immediately before an intersection when the bus lane ends if an ordinary vehicle overtakes a bus and suddenly changes lanes into the space in front of the relatively slow moving bus to turn left or right. Therefore, the conflicts between automated buses driving in the bus lanes and ordinary vehicles was examined to confirm the impact of bus lanes on traffic.

(1) Analysis procedure

Images from three bird's eye cameras at the three intersections shown in Fig. 10 were used to identify conflicts between automated buses and ordinary vehicles when passing through the intersection. Here, "conflict" was defined as a narrowing of the distance between the vehicle and automated bus accompanying a lane change or other maneuver by the vehicle, leading to a change in the behavior (such as speed or acceleration) of either vehicle.

(a)The locations of these conflicts was categorized into conflicts in a bus lane and conflicts at a stop line between the end of a bus lane and the beginning of an intersection.

(2) Analysis results

Conflicts were identified in 19 of the 300 times a bus passed through an intersection in the test. These conflicts occurred in both the area after the bus lane ended and within the actual bus lane.

Figure. 10 shows the breakdown of conflicts at each intersection. Since conflicts also occurred within bus lanes, improvements must be made to ensure a safer driving environment for automated buses. Therefore, campaigns explaining the importance of following the rules of bus lanes, such as publicity and education related to the behavior of automated vehicles, improving signage of dedicated driving lanes*, and other measures will be important.

* In the FOTs, signs were provided at the start and end points of the bus lanes

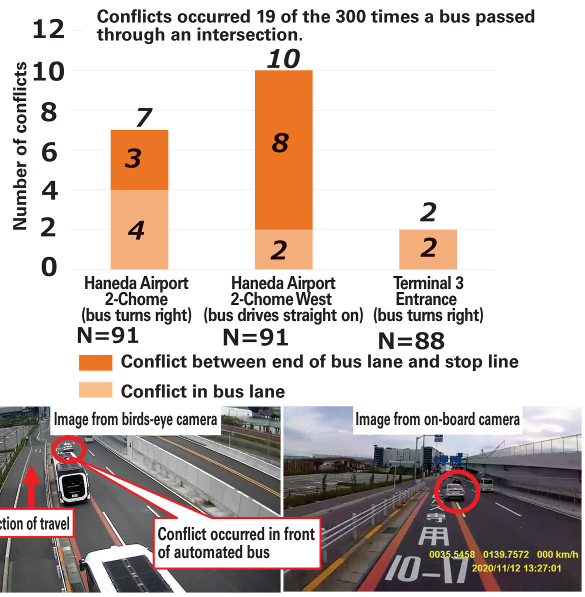

Fig. 10: Ratio of Conflict Occurrence at each Intersection

4 Conclusions

The results of the FOTs in the Haneda Airport area and questionnaires given to test participants were examined to identify the effectiveness of cooperative infrastructure and the issues created by installing this infrastructure. An outline of these results is detailed below.

(1) Magnetic markers

Magnetic markers are an effective means of carrying out precise arrival (docking) control in locations where the localization accuracy of GNSS is degraded. Such locations may be regarded as priority locations for providing magnetic markers. In addition, it would also be preferable to improve factors related to the traffic environment, road structures, and operations that are possible causes of manual intervention in automated driving (e.g., adjusting stop line positions and so on).

(2) Traffic signal information and PTPS

The reduction in the average travel time per lap of the test route confirmed the effectiveness of PTPS on improving punctuality and travel time stability. In addition, it would be preferable to provide traffic signal information to realize smoother automated driving when traffic signals are blocked by large vehicles in front, and other scenarios in which the color of traffic signals is difficult to gauge.

(3) Bus lanes

With the current level of automated driving technology, it is difficult to continue automated driving when other vehicles are parked on the road. Under these conditions, the provision of bus lanes should help to improve the continuity of automated driving. However, to ensure that bus lanes function effectively, education regarding the behavioral characteristics of automated vehicles, and campaigns explaining the importance of following the rules of bus lanes will be important.

(4) Effects of automated ART system on traffic flows

It may be assumed that adding automated buses to ordinary traffic will have a slight negative effect on traffic volumes at intersections and the like. Therefore, for future social implementation, it will be necessary to confirm in advance the effects on traffic in the field of introduction.

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Data Analysis of the FOTs on the Metropolitan Expressway

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Abstract: In the FOTs on the Metropolitan Expressway[(1), (2), (3)], data was validated from a total of 365 traversals of the Airport West Entrance (12 of which (approx. 3%) were performed by automated driving using information provided by infrastructure) in order to verify if ETC gate passing support information and merging lane assistance information provided by ETC2.0 wireless roadside units was effective as support information for vehicle-infrastructure cooperative driving automation and as support information for drivers. The FOTs confirmed that ETC gate passing support information can be used to rapidly and accurately determine the open/close states of ETC gates. In particular, this information appears likely to be particularly effective for toll booths whose operating status cannot be visually confirmed until late and toll booth areas with numerous toll booths. Merging lane assistance information is generated based on information detected by roadside sensors installed in upstream areas of expressway cruising lines. It is effective in enabling automated vehicles and drivers to determine the state of the cruising line in advance. However, it was confirmed that because the information that is provided is based on spot detection of vehicles on cruising lines, the information could not reflect changes in the speeds of vehicles on cruising lines that occurred after the sensor was passed, which presented problems with smoothly merging in critical traffic flow and when there is traffic congestion.

1 FOTs on the Metropolitan Expressway

Passing ETC gates and merging while matching cruising line vehicle speeds are challenges that must be met in order to realize vehicle-infrastructure cooperative driving automation on expressways. The goals of the FOTs in Tokyo Waterfront area performed on the Metropolitan Expressway were to provide vehicles with ETC gate passing support information and merging lane assistance information using DSRC vehicle to infrastructure (V2I) communication, to confirm the effectiveness of different information, and to identify the issues involved in social implementation. Here, ETC gate passing support information refers to information regarding toll booth gate operation states (ETC/mixed/general/closed) provided to approaching vehicles. Merging lane assistance information refers to information regarding the lengths and speeds of vehicles driving on cruising lines and calculated merging area arrival times, determined from the detection results of sensors installed in upstream areas of expressway cruising lines.

2 Overview of the FOTs

2.1. Test area

The FOTs on the Metropolitan Expressway were performed at the Airport West Entrance of the inbound Metropolitan Expressway that connects Haneda Airport and the Waterfront City area. The location of Airport West entrance is shown in Figure 1.

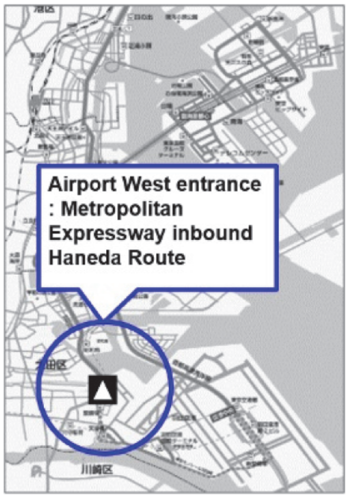

Fig. 1: Test area (1:2500 electronic topographical map (Geospatial Information Authority of Japan))

2.2. Test system

(1)Infrastructure system configuration

The infrastructure system configuration is shown in Figure 2. DSRC vehicle to infrastructure (V2I) communication was used between a roadside unit used to provide ETC gate passing support information (an antenna in front of the toll booth) and test vehicles. The presence or absence of test vehicles was detected, and when test vehicles were present, ETC gate passing support information was supplied to the test vehicles. When the gate information distribution server received information that a test vehicle had approached, it informed the roadside unit used to provide merging lane assistance information (an antenna after the toll booth) that the test vehicle had approached. The antenna after the toll booth then used DSRC vehicle to infrastructure (V2I) communication to provide the test vehicle with the latest merging lane assistance information from the vehicle sensor processing device.

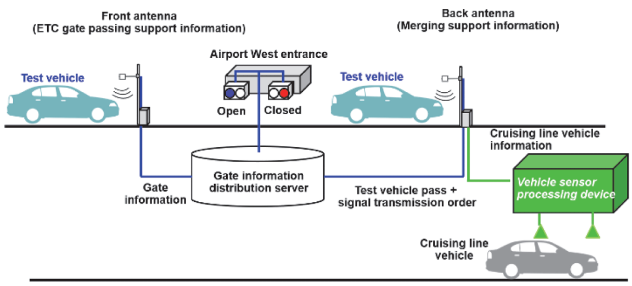

Fig. 2: Infrastructure system configuration

(2)On-board system configuration

The composition of the on-board systems used in test vehicles is shown in Figure 3 and Table 1. The test vehicle on-board equipment (BOX-PC) processes the ETC gate passing support information and the merging lane assistance information received by the test vehicle on-board equipment for expressway experiments and the own vehicle location information received by the GNSS receiver. It then provides output to vehicle control devices via LAN or CAN interfaces. To ensure safety, the FOTs required that movement management systems and video data recording devices used for evaluation purposes be installed. Electronic tally counters were provided for recording when vehicles switched between automated driving and manual driving and when various phenomena occurred.

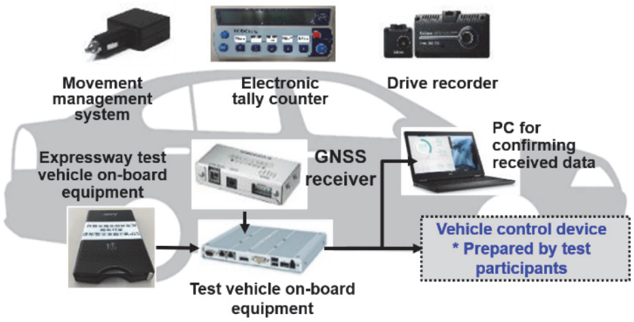

Fig. 3: On-board system configuration

Table 1: Overview of devices

Device name	Overview
PC for confirming received data	Used to collect log data and configure test vehicle on-board equipment
Expressway test vehicle on-board equipment	Used to receive and output ETC gate passing support information and merging lane assistance information provided by roadside units for gates and merging
GNSS receiver	Used to receive positioning signals provided by positioning satellites and output the position of the equipment
Test vehicle on-board equipment (BOX-PC)	Used to extract data as necessary from the signals output by expressway test vehicle on-board equipment and GNSS receivers, convert said data, and output it via CAN or LAN interfaces
Movement management system	Used to confirm real-time driving position information for vehicles and past vehicle driving data
Drive recorder	Used to assess the behavior of vehicles in front of and behind the test vehicle, to capture high resolution video, and to record driving logs
Electronic tally counter	Used to record the timing of phenomena and when automated driving is switched on or off by pressing buttons in accordance with defined rules

2.3. Driving results

The FOTs on the Metropolitan Expressway were conducted over a roughly 11-month period, from March 16, 2020, to February 28, 2021. Within this period, the FOTs were suspended for roughly two months, from April 8 to May 25, 2020, due to the issuing of a state of emergency declaration in the Tokyo area in response to the spread of COVID-19. There were a total of 365 test drives by test participants at the Airport West Entrance. Fig. 4 shows a breakdown of the driving results. Of these test drives, 12 test drives (approx. 3%) were performed through cooperative automated driving using infrastructure information for vehicle control, 5 test drives (approx. 1%) were performed through autonomous automated driving that did not use infrastructure information for vehicle control, and the remaining 348 test drives (approx. 95%) were performed through manual driving.

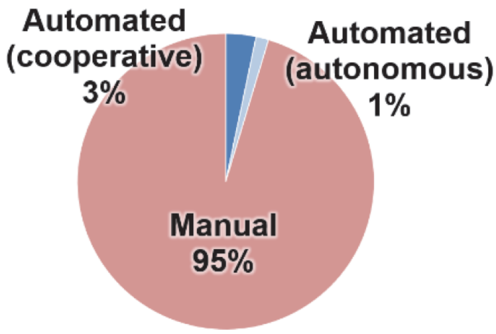

Fig. 4: Test driving results (Airport West Entrance)

3 ETC Gate Passing Support Information

3.1. Appropriateness of system operation

The test system shown in Figures 2 and 3 was used to confirm that ETC gate passing support information was provided appropriately. Airport West Entrance is composed of two booths, each of which can be in one of four operating states: "ETC," "Mixed," "General," or "Closed." There are therefore a total of 16 possible combinations for the two booths, and the FOTs confirmed that ETC gate passing support information indicating the states of the booths was received correctly, transmitted through BOX-PCs, and output for use in vehicle control. Figure 5 shows received ETC gate passing support information displayed on the dynamic map viewer and corresponding video from the drive recorder.

The FOTs confirmed that during the test period, for all drives while the test system was in operation, ETC gate passing support information was correctly received and output.

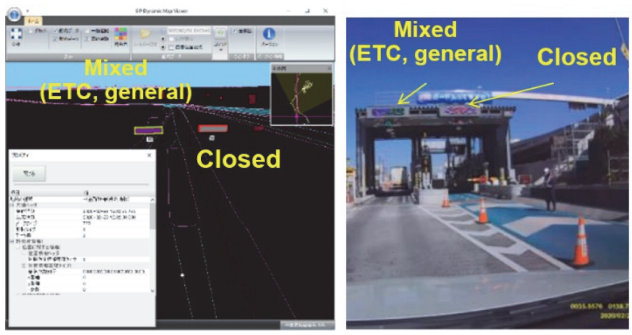

Fig. 5: ETC gate operating status (drive recorder image) and dynamic map viewer display

3.2. Effectiveness of support information

(1)Driving data analysis

Figure 6 shows an example of vehicle behavior when passing the ETC gate.

There is a gradual curve in front of the ETC gate at the Airport West Entrance, and the ETC gate's state can be visually confirmed from the vehicle roughly 110 meters in front of the gate. In these FOTs, a roadside unit for providing ETC gate passing support information was installed roughly 185 meters in front of the gate, and test participants confirmed that the ETC gate operating status could be determined sufficiently far ahead of the point at which the ETC gate's status could be visually confirmed.

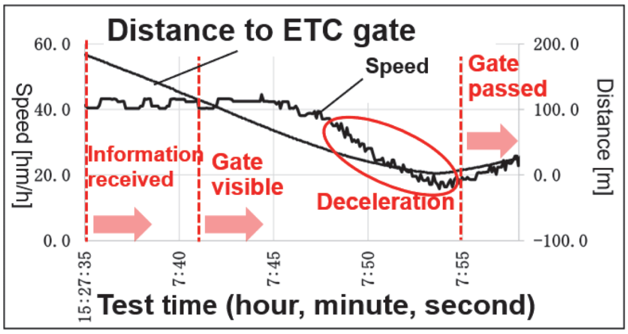

Fig. 6: Vehicle behavior when passing the ETC gate

(2)Evaluation questionnaire

No test participants pointed out any issues in the provision of ETC gate passing support information, and many indicted that they wanted the system to be put into practical operation quickly. Below are some of the main results from the evaluation questionnaire.

- Participants stated that they wanted this system to be deployed for all toll booths. In particular, they indicated that it would be particularly effective for toll booths whose operating status cannot be visually confirmed until late and toll booth areas with numerous toll booths.
- In addition to automated vehicles, they also indicted that the system would be highly effective for drive assistance systems.
- They wanted consideration to be given to how to handle sudden gate closures.

4 Merging Lane Assistance Information

4.1. Appropriateness of system operation

The test system shown in Figures 2 and 3 was used to confirm that merging lane assistance information was received appropriately, regardless of what kind of driving was being performed when the vehicle passed the antenna after the toll booth (normal driving, driving off-center to the left or right, or driving in a successive two-vehicle configuration), and that the information was transmitted through BOX-PCs and output for use in vehicle control. Figure 7 shows received merging lane assistance information displayed on the dynamic map viewer and corresponding video from the drive recorder.

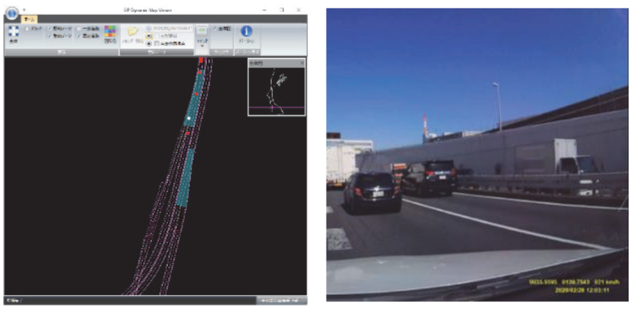

Fig. 7: State of cruising line when merging (drive recorder image) and dynamic map viewer display

4.2. Effectiveness of support information

(1)Driving data analysis

When automated vehicles merge into a cruising line, it is preferable that they match their speeds to those of vehicles in the cruising line, take no sudden actions, and smoothly merge with the vehicles in the cruising line.

Figure 8 shows the relationships between cruising line vehicle speeds and test vehicle speeds when merging into the cruising line, as well as whether or not there was any sudden action when merging (involving an acceleration force of ±0.15G or more), when no infrastructure cooperation was used. Figure 9 shows this information when infrastructure cooperation was used.

Here, driving is considered to use infrastructure cooperation if merging lane assistance information provided by the infrastructure is used in vehicle control or if it is provided to the test driver via on-screen display or another method to assist with driving. If none of these apply, the driving is considered to have been performed without using infrastructure cooperation.

Figures 8 and 9 show that, regardless of whether or not infrastructure cooperation was used, test vehicle speeds when merging were between roughly 20 km/h and 60 km/h. When traffic on the cruising line was steady, test vehicle speeds were mostly between approximately 40 km/h and 60 km/h. When there was heavy traffic or congestion on the cruising line, test vehicle speeds varied during merging. When infrastructure cooperation was not used, even when there was traffic congestion on cruising lines and vehicle speeds were 20 km/h or below, there were scattered cases of merging vehicles accelerating to speeds of 40 km/h or more and then sudden decelerating to merge into the cruising line. However, when infrastructure cooperation was used, no cases of excessive acceleration were observed when there was traffic congestion on cruising lines. Based on this, it was confirmed that using merging lane assistance information to identify conditions on the cruising line made it possible to perform merging with speeds matched to those of vehicles on the cruising lines.

Furthermore, looking at the incidence of sudden actions, when infrastructure cooperation was not used, we observed occasional cases of sudden action due to differences in the speeds of cruising line vehicles and test vehicles. However, when infrastructure cooperation was used, although sudden actions did occur in some drives, none were due to differences between the speeds of cruising line vehicles and test vehicles. Instead, they occurred because cruising line vehicles were directly next to test vehicles when test vehicles wished to merge into cruising lines with heavy traffic or congestion. Based on this, it was confirmed that using merging lane assistance information to identify conditions on the cruising line reduced the incidence of sudden actions.

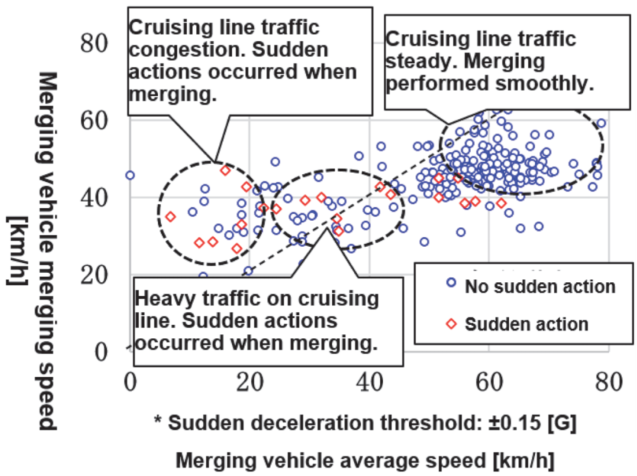

Fig. 8: Relationship between average cruising line vehicle speed and merging vehicle speed
(When not using infrastructure cooperation)

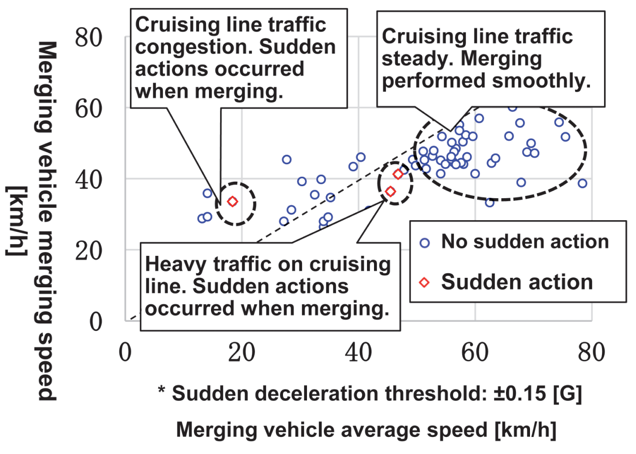

Fig. 9: Relationship between average cruising line vehicle speed and merging vehicle speed
(When using infrastructure cooperation)

Figure 10 shows an example of test vehicle behavior when merging into a cruising line with steady traffic while using infrastructure cooperation. In this drive, the vehicle's speed was adjusted based on merging lane assistance information received from the infrastructure, which we believe enabled the vehicle to smoothly merge into a gap. However, the test system provides calculated arrival times that it determines based on the assumption that the vehicles on cruising lines will continue driving at the same speed as when they passed the sensor upstream on the cruising lines. It cannot reflect changes in cruising line vehicle speeds that occur after the sensor is passed. Because of this, in critical traffic flow situations or traffic congestion in which cruising line vehicle speeds change by a large degree, it appears difficult for vehicles to smoothly merge into gaps between vehicles on the cruising lines by using the merging lane assistance information provided in the FOTs.

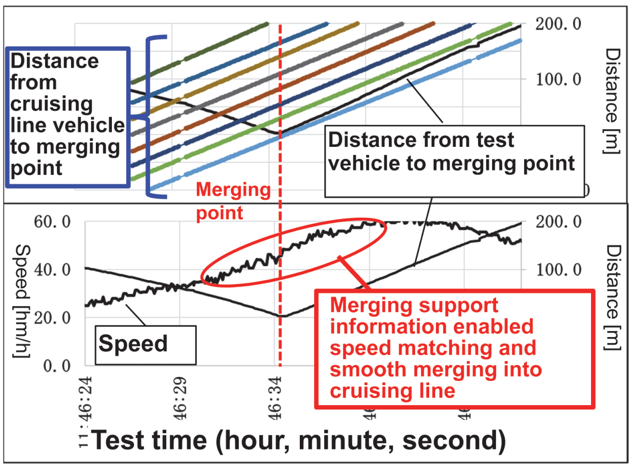

Fig. 10: Test vehicle behavior when merging into a cruising line with steady traffic while using infrastructure cooperation

(2)Analysis using cruising line merging simulations

The road structure and cruising line traffic conditions at the Airport West Entrance were reproduced in a traffic flow simulator and the merging success rates were verified for different distances between the antenna after the toll booth and the upstream cruising line sensor. In the simulation, actual cruising line traffic data from when the traffic state was "steady," "heavy traffic/critical traffic," and "traffic congestion" was combined with simulation data from simulations in which the antenna after the toll booth and the sensor were located in the same place as in the actual FOTs, simulations in which they were positioned closer to the merging area, and simulations in which they were positioned further away from the merging area. The merging success rates are shown in Figure 11.

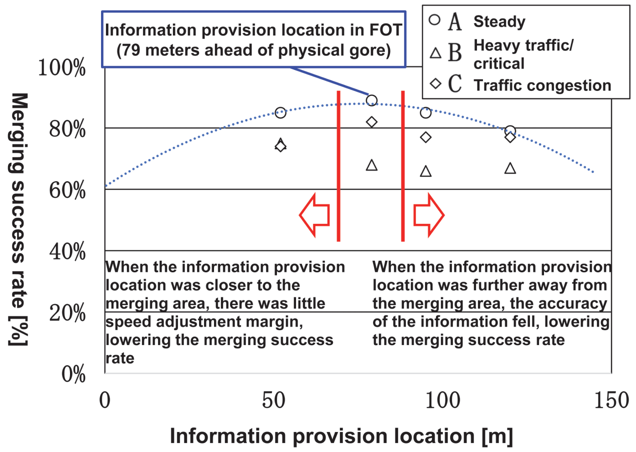

Fig. 11: Merging success rates from cruising line merging simulations with different positions for the antenna after the toll booth and the sensor and different cruising line conditions

As Figure 11 shows, when the traffic on the cruising line was steady, providing merging lane assistance information has the potential to improve merging success rates, but when there is heavy traffic or congestion, the accuracy of the predicted merging arrival time falls, lowering the merging success rate. We confirmed that the locations of the infrastructure in the FOTs had the highest merging success rates. Placing the infrastructure closer to the merging area would reduce the amount of space in which vehicles could adjust their speeds, thereby reducing their merging success rates. Placing the infrastructure further away from the merging area would reduce the accuracy of the calculated arrival time, thereby reducing merging success rates.

(3)Evaluation questionnaire

Many test participants indicated that providing merging lane assistance information would make it possible to determine cruising line conditions in advance in areas where conditions were not visually apparent, which would be effective for automated vehicle control and drive assistance systems. However, several test participants also pointed out that because the information that is provided is based on spot detection of vehicles on cruising lines, the information could not reflect changes in the speeds of vehicles on cruising lines that occurred after the sensor was passed, which presented problems with smoothly merging into spaces between vehicles on cruising lines. Many participants favored addressing this issue through planar sensing of vehicles on cruising lines and using continuous communication to provide merging vehicles with information on changing cruising lines conditions. Below are some of the main results from the evaluation questionnaire.

- The information was effective for merging locations where cruising line conditions cannot be observed in a timely fashion.
- Test participants requested that planar sensing of vehicles on cruising lines and continuous communication be used to provide information to merging vehicles so that they could keep informed of changing cruising line conditions.
- Test participants requested that ETC gate passing support information be accompanied by cruising line condition infor-

mation (overall speed of traffic flow, degree of congestion, average time between vehicles).

5 Conclusion

Through the FOTs on the Metropolitan Expressway, we confirmed that providing ETC gate passing support information early using dedicated short-range communications was effective in formulating automated vehicle route plans and was also effective for drive assistance systems for drivers. Furthermore, we also confirmed that providing information regarding vehicles driving on cruising lines with poor visibility via DSRC to merging vehicles was effective for merging support provided by automated driving functions and as caution information for drivers.

However, the merging lane assistance information provided by the test system was spot information regarding cruising line vehicles and calculated arrival times were calculated with the assumption that vehicles would maintain the same speed as when they passed the system's sensor. We therefore determined that the accuracy of the information was reduced when cruising line vehicle speeds changed between the cruising line sensor and the merging area, and that this presented issues with smoothly merging with vehicles on the cruising lines. We believe that in order to realize cruising line merging through vehicle-infrastructure cooperative driving automation on expressways, consideration must be given to improving information accuracy, such as through the use of continuous distribution of cruising line vehicle location information.

Lastly, we would like to express our gratitude to the test participants in this FOTs for performing test drives and submitting data in the midst of the ongoing COVID-19 pandemic.

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(1)FOTs in Tokyo Waterfront Area Consortium [“Cross-ministerial Strategic Innovation Promotion Program The second phase of SIP- Automated Driving for Universal Services /Implementation of FOTs in Tokyo Waterfront Area” 2020 Results Report]
(2)Dynamic Map Study Consortium [Automated Driving System Map Data Specification Proposal, Ver. 1.1]
(3)Dynamic Map Study Consortium [Automated Driving System Map Data Encoding Specification Proposal (test data encoding specifications), Ver. 1.0]

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Analysis of Impact Assessment Field Operational Test (FOT) Data

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In the impact assessment field operational tests (FOTs), various automated vehicles were driven in mixed traffic environments on general roads, and the impact of these vehicles on ordinary vehicles and pedestrians was evaluated. For these tests, a visualization system was constructed and adopted that combines image data from fixed point cameras installed at multiple intersections, image data from on-board cameras, and vehicle behavior data. The tests confirmed that the addition of automated vehicles did not have a significant negative effect on action times when turning left or right, and that the variance in these action times was smaller for mixed traffic than traffic containing only ordinary vehicles. In contrast, sudden deceleration by automated vehicles on normal stretches of roads, immediately before intersections, and the like, caused various near-miss incidents involving surrounding vehicles. Additionally, the tests did not find a lack of eye contact been drivers and pedestrians on crossings and the like as a result of automated driving. As a result, it was confirmed that the automated vehicles in the tests drove safely in the presence of pedestrians. To help realize advanced automated driving in harmony with ordinary vehicles and pedestrians, similar assessments to those carried out in these FOTs should be continued as automated driving technology becomes more sophisticated and automated vehicles become more widespread.

1 Overview of Impact Assessment Field Operational Tests (FOTs)

1.1. Definition of Impact Assessments

It is hoped that the introduction and popularization of automated vehicles will have a range of positive effects, such as enhanced safety and comfort, lower traffic accidents, smoother traffic flows, and so on. FOTs on public roads have started to demonstrate both these positive effects and the impacts of automated vehicles, and it is hoped that these results will help to increase understanding and the social acceptance of automated driving technologies among the general public.

An "impact assessment" is the name given to the process of evaluating the differences between actual traffic environments containing a mix of automated vehicles and traffic environments containing no automated vehicles, and then analyzing the effects of automated vehicles on the surrounding traffic environment. More specifically, impact assessments evaluate the effects of automated vehicles in defined scenarios that are likely to be affected by the addition of automated vehicles to actual traffic environments and collecting data about those scenarios.

1.2. Studying and Setting Assessment Items

The following hypotheses were considered pertaining to the effects on other vehicles and pedestrians of adding automated vehicles.

- Automated vehicles are likely to lower the traffic capacity, increase congestion, and have other effects because automated vehicles are designed to ensure a sufficient safety margin and tend to drive more slowly than other vehicles.
- Automated vehicles are likely to create hesitation in pedestrians crossing the road and lower driver attention toward other vehicles because automated driving may result in insufficient communication, such as eye contact with pedestrians.
- The impact of automated vehicles on traffic flows is likely to change the behavior of other vehicles (such as increasing the number of vehicles that cut in front of or overtake automated vehicles).

Based on these hypotheses, possible scenarios with the potential to create different traffic flows with or without the presence of automated vehicles were identified. These were then listed as evaluation items for the impact assessment, and the final evaluation items were then set (Table 1 and Fig. 1).

Table 1: Effects of Automated Vehicles and Evaluation Items

Focus of evaluation	Envisioned effects	Evaluation items
Impact on traffic flow	- Reduction/increase in traffic flow - Changes to length of traffic accumulation/congestion - Higher traffic volumes in overtaking lanes - Lower travel speeds - Fewer vehicles turning left or right	- Effects of number of vehicles turning left or right on smoothness of traffic flow - Effects of encounters with oncoming vehicles when turning right
Impact on other vehicles	- Vehicles cutting in front of or tailgating automated vehicles - More vehicles overtaking	- Effects of stopping behavior and the like at red traffic signals when driving straight on - Behavior of other vehicles when driving straight on and the like - Effects of vehicles parked at the side of the road - Divergence in speeds when driving straight on (overtaking)
Impact on pedestrians	- Crossing hesitation - Increased checks for safety - Lower level of attention to other vehicles	- Effects of crossing pedestrians when turning left or right - Effects of crossing pedestrians when driving straight on - Risk of contact with bicycles

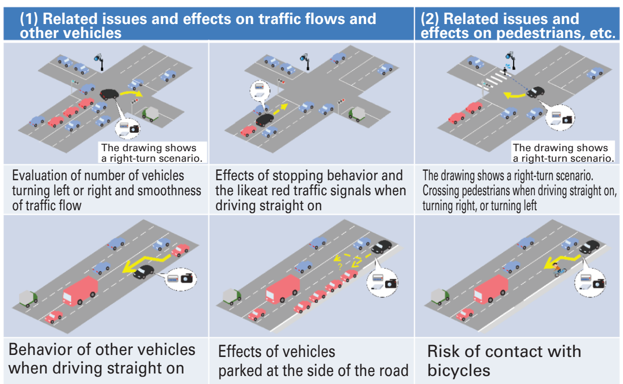

Fig. 1: Set Evaluation Items

1.3. Evaluation Plan

The period of the driving tests in the FOTs was set for between October 2019 and the end of February 2021. Based on the test plan and questionnaire results from the test participants, the 2019 fiscal year was defined as a preparatory period for automated vehicle development, and the 2020 fiscal year was set as the evaluation period for actual automated driving functions. During the 2019 fiscal year, pre-evaluations were carried out to collect data from traffic flows containing only ordinary vehicles. Then, the 2020 fiscal year was set as the actual evaluation period to collect data from mixed traffic flows of automated and ordinary vehicles.

To ensure the efficient collection of test data from the participants, two periods were set in which the participants were requested to emphasize automated driving. After asking the participants in advance for the most convenient timings for these concentrated automated driving periods, the two weeks from October 26 to November 6, 2020, and the two weeks from February 8 to February 19, 2021, were set.

2 Preparations for Tests and Evaluations

2.1. Preparation of Test Equipment and the like

2.1.1. Evaluation Image Data Recorders

To evaluate the effects on other vehicles and the surrounding environment in the impact assessment, the test vehicles were equipped with dashcam drive recorders to obtain evaluation image data. High-resolution images and high-frequency data logs (including speed, acceleration, and position (Global Navigation Satellite System (GNSS)) data) were collected.

2.1.2. Tally Counters

To enable effective and efficient evaluation and analysis during the impact assessment, tally counters were distributed to the test participants. The participants were asked to press specific buttons when the automated driving system turned ON or OFF, and when certain envisioned events occurred. The times that these events occurred were recorded by the tally counters. In addition, the characteristics of the event were analyzed and evaluated using images and logs (including notes recorded by the participants) from before and after the time that the participants pressed the tally counter buttons.

2.1.3. Fixed Point Cameras

To evaluate the events described in Table 1, such as decreases in traffic flows, changes in the length of traffic accumulation and congestion, crossing hesitation, and so on, it was necessary to obtain image data capable of showing an overview of the vehicles involved and the surrounding traffic environment. Therefore, fixed point cameras capable of video recording were set at a maximum height of 10 meters on existing light poles, and so on.

2.2. Intersections for Setting Fixed Point Cameras

These fixed point cameras were installed during the concentrated automated driving periods (Section 1.3) to obtain data that provides an overview of the vehicles and traffic environments at certain intersections. These intersections (Fig. 2) were selected after identifying the driving routes and the like of the test participants.

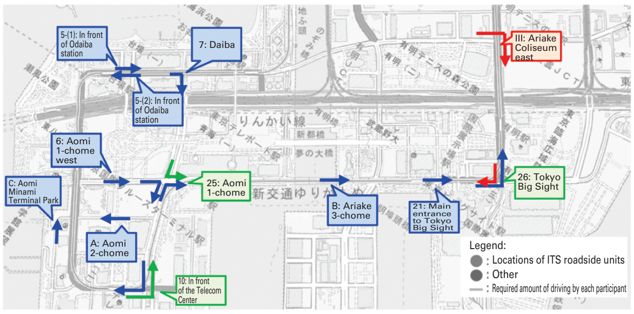

Fig. 2: Installation Locations of Fixed Point Cameras (Red: Evaluated in October and November, Blue: Evaluated in February, Green: Evaluated in Both Periods)

2.3. Construction of Visualization System

In FOTs, data was obtained from various items of infrastructure and test devices. Different types of data was collected and plotted on graphs and maps. At the same time, a visualization system was constructed to help display and reproduce the events as time sequences. Figure 3 shows an example of a visualization system screen.

Fig. 3: Example of Visualization System Screen

3 Evaluation Implementation

3.1. Evaluation of Number of Vehicles Turning Left or Right and Smoothness of Traffic Flow

The method and focus points of this evaluation were as follows.

- Focus points
  (1) Did changes occur in the turning times of automated vehicles?
  (2) Did changes occur in the turning times of other vehicles?
- Evaluation method: The times that vehicles pass spotting lines were measured using fixed point camera images and the turning times were calculated from the differences in these times (target: ordinary passenger vehicles)
- Applicable intersection: (III) Ariake Coliseum east

A box plot of the right-turn times (seconds) of individual vehicles is shown below. Compared with the average value, the turning time of automated vehicles was 1.4 seconds longer than ordinary vehicles and the turning time of ordinary vehicles following automated vehicles was 0.8 seconds longer. Additionally, no change was found in the quartile range (an index that expresses the degree of variation, calculated as the 75%tile value - the 25%tile value). However, the minimum values showed that the turning time of manually driven vehicles was around 2 seconds shorter than automated vehicles. Vehicles following automated vehicles also showed similar trends.

Since these results confirmed that automated vehicles result in increased average turning times compared to manually driven vehicles, overall traffic flows may be regarded as less smooth. In contrast, the small quartile range also indicates that the variation between individual vehicles was low and that stable driving was realized. As a result, automated vehicles were confirmed to have a stabilizing effect on traffic flows.

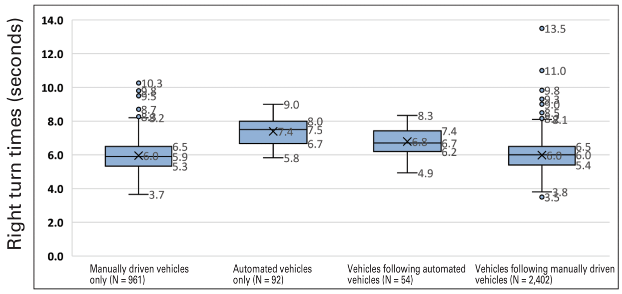

Fig. 4: Box Plot of Right Turn Times

3.2. Evaluation of Effects of Encounters with Oncoming Vehicles when Turning Right

The method and focus point of this evaluation were as follows.

- Focus point: were there differences in gap acceptance behavior between automated and ordinary vehicles?
- Evaluation method: the time headway and vehicle right-turn behavior were confirmed and analyzed.
- Applicable intersection: (26) In front of Tokyo Big Sight, right turn
- Data used: fixed point camera image data

Gap acceptance behavior refers to the decision to turn right in the gap between oncoming vehicles driving straight on (i.e., the time headway). Of the observed gaps, gaps in which vehicles turned right are referred to as accepted gaps, and gaps in which vehicles did not turn right are referred to as rejected gaps. The gap value at the intersection of the resulting cumulative frequency curves is referred to as the critical gap, which is used as one factor to express the characteristics of gap acceptance behavior.

With ordinary vehicles, 233 accepted gap samples were obtained. In contrast, with automated vehicles, only 1 accepted gap sample was obtained. This reflected the low number of driving samples at the evaluation intersections and the fact that automated vehicles mostly turned right after all the oncoming vehicles had passed through the intersection. Insufficient data samples were obtained to analyze differences in gap acceptance behavior between automated and ordinary vehicles.

3.3. Effects of Stopping Behavior and the Like at Red Traffic Signals when Driving Straight On

The method and focus point of this evaluation were as follows.

- Focus points
  - (a) Were there differences in speed distribution and maximum deceleration?
  - (b) Did differences occur depending on the provided infrastructure information (traffic signal color information only, current color + remaining seconds information (ranges), current color + remaining seconds information (specific values))?
  - (c) Did vehicles bunch up to the preceding or following vehicles?
- Evaluation method: the changes in speeds and maximum deceleration when stopping were identified and analyzed.

The differences in vehicle behavior caused by the provided infrastructure information were analyzed. Figure 5 shows the evaluation results for intersection (6) Aomi 1-chome west. Vehicles at this intersection were provided with the specific number of seconds remaining before the traffic signal changes color. With such infrastructure-cooperative driving, the maximum deceleration when both the current color and remaining seconds information were provided was smaller than when only the current color was provided. It was assumed that the specific number of seconds information was used to enable smooth deceleration from an earlier timing.

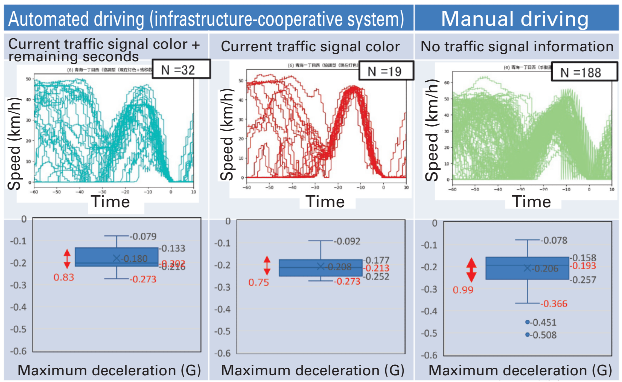

Fig. 5: Evaluation Results for Intersection (6) Aomi 1-Chome West

When evaluating whether vehicles bunched up to the preceding vehicle, the assessments in Aomi 1-chome found that the maximum deceleration during infrastructure-cooperative driving (current traffic signal color and remaining seconds information provided) was lower than when either only the current traffic signal color or no infrastructure information (i.e., autonomous driving) was provided. It was assumed that the specific number of seconds information was used to enable smooth deceleration from an earlier timing.

Figure 6 shows an example of an infrastructure-cooperative driving (current traffic signal color and remaining seconds information) scenario. With the infrastructure-cooperative system (current traffic signal color and remaining seconds information), the vehicle started cautionary deceleration 98 meters before the stop line, during which time the preceding vehicle was detected. The vehicle then decelerated again (two-stage braking) and came gradually to a stop.

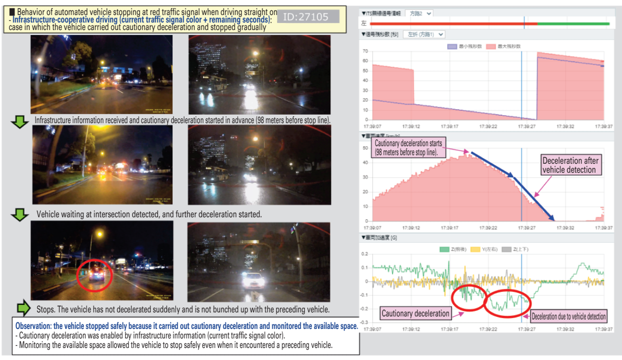

Fig. 6: Example Scenario (Effects of Stopping Behavior and the Like at Red Traffic Signal when Driving Straight On) (1)

Next, Fig. 7 shows the assessment results at intersection (14) Rainbow Bridge entrance, which were used to evaluate whether following vehicles bunched up to the test vehicles. Vehicles at this intersection were provided with a range for the number of seconds remaining before the traffic signal changes color. The maximum deceleration was smaller than when only the current traffic signal color was provided (infrastructure-cooperative system) and for manually driven vehicles, showing that the remaining seconds information was used to realize smoother deceleration.

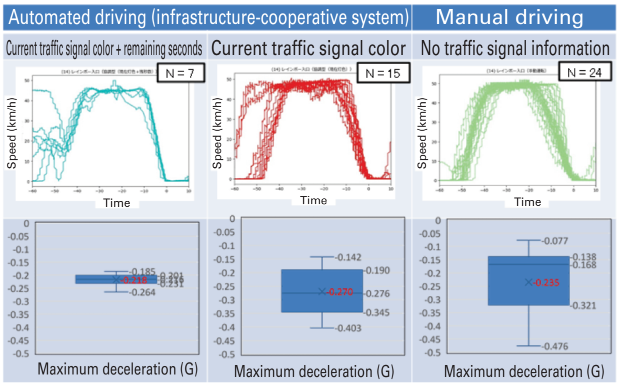

Fig. 7: Evaluation Results for Intersection (14) Rainbow Bridge entrance

With the infrastructure-cooperative system (current traffic signal color and remaining seconds information), the vehicle started cautionary deceleration 98 gradually came to a stop. As a result, the following vehicle did not bunch up to the test vehicle. When only traffic signal color information was provided, the vehicle started to decelerate 48 meters from the stop line when it detected the change in color. This required a slightly high degree of deceleration (approximately -024 G), which caused the following vehicle to bunch up behind the test vehicle (Fig. 8). In this way, the effectiveness of infrastructure information (particularly the number of seconds remaining for a traffic signal color) was confirmed.

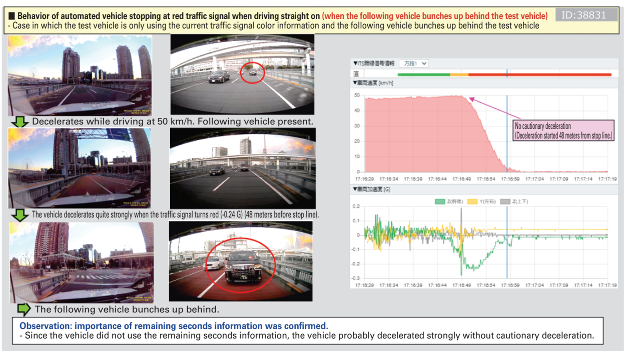

Fig. 8: Example Scenario (Effects of Stopping Behavior and the Like at Red Traffic Signal when Driving Straight On) (2)

3.4. Effects on Other Vehicle Behavior when Driving Straight On

The method and focus point of this evaluation were as follows.

- Focus points:
  (1) Changes in frequency of sudden braking and cutting in
  (2) What were the causes of sudden braking and cutting in?
- Evaluation method: the causes of events were analyzed with a focus on sudden deceleration of the test vehicles (longitudinal acceleration: max. -0.35 G)
- Applicable intersections: all
- Data used: visualization system data (dashcam drive recorders (acceleration sensors (longitudinal), forward and rearward images)

The charts below show the number times the vehicles passed through or stopped at the intersections, and the number of sudden deceleration events for manually driven and automated vehicles during the concentrated automated driving periods. The proportion of sudden deceleration events with respect to the number of times the vehicles stopped at the intersections was 3.1% for manually driven vehicles and 15.2% for automated vehicles. This showed that automated vehicles were responsible for a higher number of sudden deceleration events that might lead to a near-miss incident.

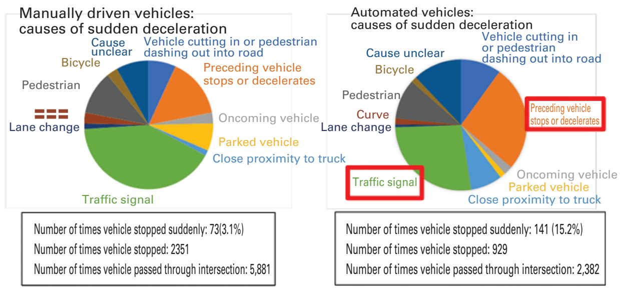

Fig. 9: Factors Involved in Sudden Deceleration Scenarios

When the factors involved in the sudden deceleration scenarios were analyzed, traffic signals were the most frequent cause for manually driven vehicles. In contrast, automated vehicles were equally affected by traffic signals and the behavior of the preceding vehicle. Knock-on risks were also confirmed due to sudden deceleration affecting the following vehicle.

An example traffic signal scenario is described below. In this scenario, the vehicle joins a line of traffic waiting to turn right. Usually, the stopping behavior of automated vehicles when turning right causes the following vehicle to bunch up behind.

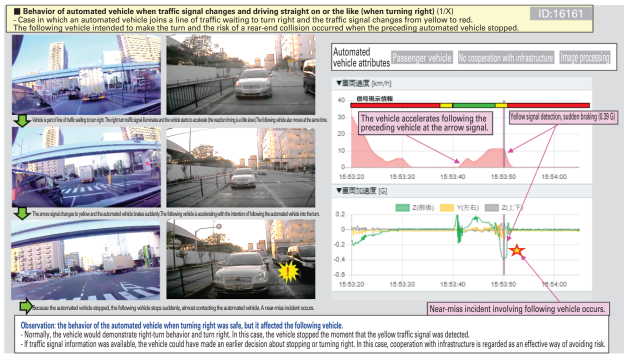

Fig. 10: Example Scenario (Effects on Other Vehicle Behavior when Driving Straight On)

As shown in the figure, vehicles without an infrastructure-cooperation function (i.e., vehicles that detect traffic signal information using cameras or the like) braked suddenly immediately after a traffic signal turned red or yellow, leading to a spate of near-miss incidents involving the following vehicles. This demonstrates the necessity for support from infrastructure-cooperation systems, such as the provision of the number of seconds remaining for traffic signals.

3.5. Effects of Vehicles Parked at Side of Road

The evaluation method was as follows.

- Focus point: behavior of following vehicle or the like after behavior to avoid vehicles parked at the side of the road changes (e.g., does bunching, conflict, or the like occur, or are there any other changes, such as near-miss incidents?)
- Evaluation method:
  (1) The vehicle behavior was confirmed when vehicles parked

at the side of the road were encountered.
(2) The effects on other vehicle behavior were analyzed.
(3) Analysis focused on cases of avoidance.
- Applicable intersection: (A) Aomi 2-chome
- Data used: visualization system data

Figure 11 shows a box plot for the maximum lateral acceleration (lateral G) in the rightward direction (direction of avoidance) when vehicles parked at the side of the road were encountered and a box plot for the maximum deceleration in the rearward direction (braking G). These figures confirm that the maximum deceleration (lateral G) of automated vehicles in the rightward direction (direction of avoidance) when encountering vehicles parked at the side of the road was smaller than that of manually driven vehicles. In addition, automated vehicles decelerated smoothly to avoid oncoming vehicles driving straight on. The maximum deceleration (braking G) of automated vehicles when encountering vehicles parked at the side of the road was roughly the same as manually driven vehicles. In two cases, the vehicle behind followed the automated vehicle in avoiding the parked vehicles. Of these two cases, the following vehicle bunched up behind the automated vehicle.

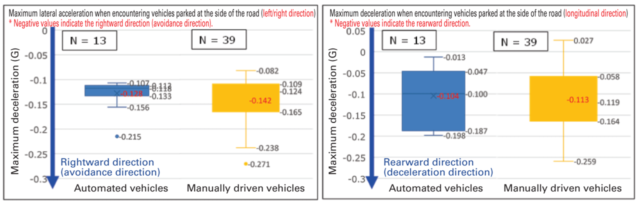

Fig. 11: Evaluation of Deceleration when Encountering Vehicles Parked at the Side of the Road

3.6. Divergence in Speeds when Driving Straight On (Overtaking)

The method and focus point of this evaluation were as follows.
- Focus points:
(1) Did speeds change when automated vehicles were added to traffic?
(2) Did other vehicles overtake or cut in front of automated vehicles?
- Evaluation method: The times that vehicles pass spotting lines were measured using fixed point camera images and the speeds were calculated and dashcam driver recorder images confirmed.
- Applicable intersection: (B) Ariake 3-chome, driving straight on
- Data used: fixed point camera image data

Figure 12 shows a box plot for speeds measured at Ariake 3-chome (normal stretch of road). The average speed of automated vehicles (orange) was 50.4 km/h, confirming that these vehicles followed the speed limit. The quartile range for ordinary vehicles was 13.5 km/h compared to 6.4 km/h for automated vehicles, which shows that automated vehicles drive stably with less variation in speed.

Since the automated vehicles drove more slowly than the ordinary vehicles, an automated vehicle was overtaken in 2 of the 12 cases in which an automated vehicle was followed by an ordinary vehicle. However, neither of these cases affected other vehicles by causing deceleration or bunching up to the automated vehicle.

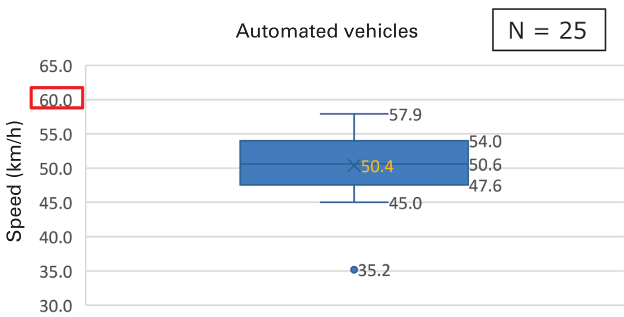

Fig. 12: Box Plot of Speeds Passing Through Intersection B) Ariake 3-Chome

3.7. Effects of Crossing Pedestrians when Turning Left or Right

The method and focus point of this evaluation were as follows.
- Focus point: what type of stopping behavior occurred in response to crossing pedestrians (examples: differences in stopping position and whether the crossing pedestrian or vehicles crossed first)?
- Evaluation method: the behavior when encountering a crossing pedestrian was analyzed.
- Applicable intersection: (25) Aomi 1-chome
- Data used: fixed point camera image data

Figure 13 shows the positions of crossing pedestrians when vehicles were encountered for each direction of pedestrian movement between October 26 and November 6. In this figure, circles indicate cases when the vehicle stopped, triangles indicate cases when the vehicle drove slowly and allowed pedestrians to cross first, and crosses indicate cases when the vehicle drove slowly but passed through the crossing before the pedestrians. The results found that manually driven vehicles passed through the crossing before the pedestrians in 14 cases. In contrast, the automated vehicles did not pass through the crossing first in any cases. Although it is necessary to take the differences in the overall number of data samples into consideration, the behavior of the automated vehicles appears to be less likely to result in contact with crossing pedestrians than the manually driven vehicles.

In addition, using images from the on-board dashcam drive recorders confirmed that the pedestrians checked with the vehicles before crossing, indicating that use of an automated driving system did not result in insufficient eye contact.

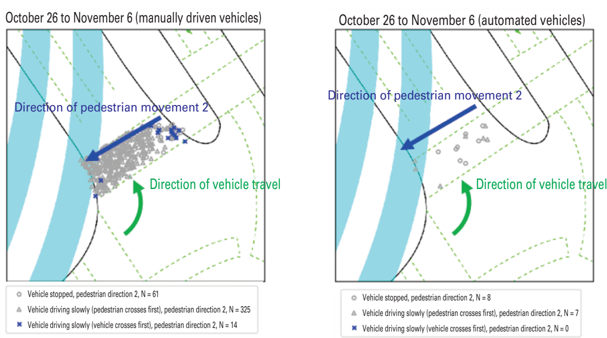

Fig. 13: Positions of Crossing Pedestrians when Vehicles Encountered

3.8. Effects of Crossing Pedestrians when Driving Straight On

The method and focus point of this evaluation were as follows.
- Focus point: did the vehicle wait for crossing pedestrians to cross the road first?
- Evaluation method: the behavior when encountering a crossing pedestrian was analyzed.

- Applicable intersection: (A) Aomi 2-chome
- Data used: fixed point camera image data, on-board data

The differences between the behavior of manually driven and automated vehicles when encountering pedestrians were as follows. In approximately 30% of cases, the manually driven vehicles passed through the crossing without waiting for the pedestrians. In contrast, automated vehicles waited for the pedestrians to cross the road in every case. This shows that automated vehicles make decisions erring on the side of safety when crossing pedestrian are detected.

However, when the stopping deceleration was confirmed, although the automated vehicles stopped in every case that a crossing pedestrian was present, Fig. 14 shows that the average deceleration was approximately -0.4 G and sudden deceleration occurred more frequently than with the manually driven vehicles. This is probably due to delays in detecting the presence of pedestrians near the crossing, or for similar reasons.

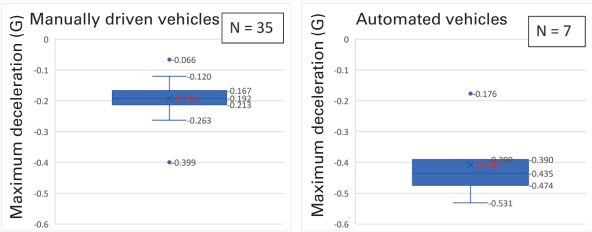

Fig. 14: Comparison of Maximum Deceleration on Normal Stretch of Road at Intersection (A) Aomi 2-Chome

3.9. Risk of Contact with Bicycles

The method and focus point of this evaluation were as follows.

- Focus point: what was the behavior of automated vehicles in response to bicycles (sudden deceleration or the like)?
- Evaluation method: the behavior and relevant factors when encountering a bicycle were analyzed
- Data used: visualization system data

When the acquired scenarios from the concentrated automated driving periods were confirmed, it was found that bicycles did not slow down even after confirming the presence of an automated vehicle.

In addition, although no scenarios in which automated vehicles had a major impact on bicycle behavior were found, there were many cases of sudden deceleration caused by the behavior of bicycles. There is the concern that such sudden deceleration might affect following vehicles.

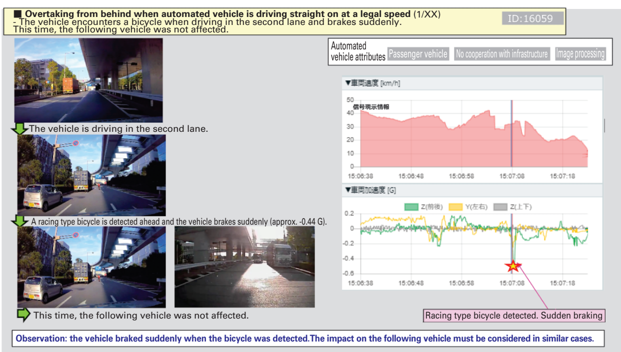

Fig. 15: Example Scenario (Risk of Contact with Bicycle)

4 Observations and Prospects

From the results described above, the following observations were made about the impact of automated vehicles on ordinary traffic environments.

4.1. Traffic Flows (Smoothness and Congestion)

Under the hypotheses described in the introduction, automated vehicles will drive at legal speeds and secure sufficient safety margins. Since these speeds will be lower than other vehicles, this may have effects such as reducing traffic capacities, extending congestion, and the like. However, the measured results for judgment times when turning left or right found that the judgment times of automated vehicles increased by only approximately 1 second. As these results also confirmed that following vehicles drove stably behind automated vehicles, it is possible that adding automated vehicles may lead to safer traffic environments.

4.2. Impacts on Pedestrians

It was also hypothesized that automated vehicles might create hesitation in pedestrians crossing the road and lower driver attention toward other vehicles because of insufficient eye contact between drivers and pedestrians. However, no events occurred in the test periods to justify this hypothesis. However, since such events may occur in the future as the development of automated driving systems advances and level-four driver-less vehicles start driving on ordinary roads, verifications and evaluations will become necessary from the standpoint of human-machine interfaces (HMIs).

4.3. Impacts on Safety (Accidents)

These tests confirmed that cooperation (with infrastructure and with the behavior of other vehicles, pedestrians, bicycles, and so on) will be an important requirement for the popularization of automated vehicles.

For example, safe driving was confirmed mainly in intersections (Sections 3.1 (effects on number of vehicles turning left or right and smoothness of traffic flow), 3.7 (effects of crossing pedestrians when turning left or right), and 3.8 (effects of crossing pedestrians when driving straight on). Examples of safe driving in these sections included the automated vehicles waiting for pedestrians to cross the road before passing through the crossing, turning left or right at a constant speed while following the traffic signals, and the like. These results demonstrated that a certain amount of cooperation could be realized with the surrounding traffic environment. The results also demonstrated that a certain amount of cooperation could be realized with infrastructure by providing the traffic signal color and remaining number of seconds before a traffic signal changes (Section 3.3 (effects of stopping behavior and the like at red traffic signals when driving straight on)).

However, near-miss incidents of sudden deceleration also occurred on normal stretches of road and immediately before intersections (Sections 3.4 (effects on other vehicle behavior when driving straight on) and 3.9 (risk of contact with bicycles), demonstrating that automated vehicles may have an impact on other vehicles. These impacts are probably caused by the need for more flexible responses to various traffic environments (such as when other vehicles conceal traffic signals or when driving in close proximity to other vehicles) when driving on normal stretches of road and immediately before intersections compared to when driving in intersections. The results confirmed that cooperation with various surrounding traffic environments will be an issue for the future popularization of automated vehicles.

4.4. General Comments

Impact assessments are evaluations of the effects of automated vehicles on actual traffic environments. As the development and popularization of automated vehicles advances, it is likely that the proportion of automated vehicles on the road will increase. These assessments were carried out within a transition period in which automated vehicles are driving surrounded by larger numbers of ordinary vehicles. During this period, cooperation with the surrounding traffic environment (mainly with these ordinary vehicles) will be important, and the relevant systems must be prepared to facilitate cooperation (such as legislation pertaining to accident responsibility and the like) and prevent conflict or confusion under mixed traffic environments containing ordinary vehicles.

The period following this transition period is likely to be a period of maturity. When driver-less vehicles equivalent to SAE levels four or five are on the road, it will be necessary to verify whether smooth communication can be achieved with the surrounding traffic environment (pedestrians and the like). It is thought that impact assessments should be continued even in this mature period.

5 Conclusion

The impact of automated vehicles on other vehicles and the surrounding traffic environment was assessed. These tests confirmed that cooperation (with infrastructure and with the behavior of other vehicles, pedestrians, bicycles, and so on) will be an important requirement for the popularization of automated vehicles. The results also confirmed that cooperation with the surrounding traffic environment (mainly with ordinary vehicles) is an issue for the future.

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3 Ensuring the Safety of Automated Driving

(1) Field Operational Tests in Tokyo Waterfront Area

Research on the Recognition Technology Required for Automated Driving Technology (Levels 3 and 4)

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Automated driving equivalent to level four in urban areas requires both advanced and autonomous recognition and decision making functions using on-board artificial intelligence (AI), as well as supporting infrastructure such as roadside and communication equipment. However, since installing such infrastructure throughout Japan would require a massive budget, the feasibility of using the bare minimum of infrastructure and recognition/decision-making technologies must be examined. Therefore, to stimulate discussions into future cooperative areas, this project is researching and investigating the infrastructure and recognition and decision making technologies that are absolutely necessary for automated driving systems through experiments on public roads by academic researchers who have been allowed a certain degree of disclosure of acquired data and the technologies.

1 Introduction

Automated driving equivalent to level four in urban areas requires both advanced and autonomous recognition and decision making functions using on-board artificial intelligence (AI), as well as supporting infrastructure such as roadside and communication equipment. However, since installing such infrastructure throughout Japan would require a massive budget, the feasibility of using the bare minimum of infrastructure in addition to the recognition and decision making technologies based on that infrastructure must be examined. Therefore, this project is cooperating with universities that are already in the process of testing automated driving on public roads as well as universities currently engaged in cutting edge research into relevant basic automated driving technologies to help construct recognition and decision making technologies for fully automated vehicles equivalent to level 4 under complex urban traffic environments featuring a mix of ordinary traffic users and other automated vehicles. In addition, through the automated driving technologies obtained in this way, the project is also aiming to assess the minimum level of infrastructure (such as roadside and communication equipment) required to enable automated driving in urban areas.

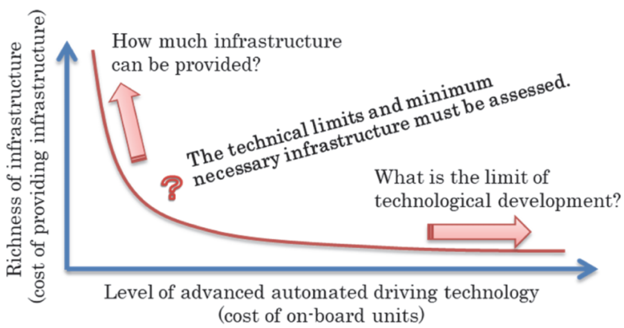

Fig. 1: Relationship between Richness of Infrastructure and Level of Advanced Automated Driving Technology

2 Research Results

2.1. Development of Traffic Signal Recognition Technology and Studies of Conditions that Complicate Recognition

Correct recognition of the status of traffic signals is extremely important to allow automated vehicles to pass smoothly through intersections. This project is aiming to address two issues of traffic signal recognition during automated driving: improving recognition performance, and determining the traffic environment of intersections using communicated information. Consequently, cutting edge algorithms to maximize traffic signal recognition performance are being realized by developing technology from two standpoints: (1) conventional pattern recognition technology using the latest cameras developed for on-board and other applications and (2) the latest artificial intelligence technologies. In addition to the development of advanced traffic signal recognition algorithms, studies are under way into the use of traffic signal information obtained via vehicle-to-infrastructure (V2I) communication from compatible traffic signals to address the fundamental issue of recognizing hidden traffic signals. Other studies are also examining the sensor specifications and infrastructure equipment required for traffic signal recognition.

(1)Using pattern recognition to recognize traffic signals and determine when to enter intersections

In the process of traffic signal recognition using pattern recognition, decisions to enter the intersection are made by recognizing the illuminated state of traffic and arrow signals in camera images while referring to digital maps. This aspect of the project involved the development of an autonomous recognition algorithm using on-board sensors to clarify the required conditions for providing support via infrastructure such as V2I communication. A recognition rate of 99% for traffic and arrow signals within a range of 120 meters was defined as the condition for permitting an automated vehicle to enter an intersection. A recognition algorithm was developed to realize this condition and the circumstances that complicate recognition were analyzed. In addition, to verify the effects of using V2I communication via infrastructure-support traffic signals, an algorithm that decides when to enter an intersection was developed using look-ahead information obtained through communication.

To realize these objectives, the effects of various weather and lighting conditions on traffic signal visibility were investigated in the 2018 fiscal year, and the cameras required to realize the recognition target were selected. Then, in the 2019 fiscal year, studies were carried out into recognition algorithms using advance information from digital maps, which helped to increase the recognition distance of arrow signals[1]. Subsequently, data obtained from the field operational tests (FOTs) in the Tokyo waterfront area showed that the developed algorithm realized a green/red/arrow signal recognition rate of 95% within a range of 120 meters. In addition, an algorithm to avoid sudden deceleration using look-ahead information was developed to enable the vehicle to decide whether to enter the intersection based on traffic signal information obtained from infrastructure-support traffic signals. Finally, in the 2020 fiscal year, the technical issues for traffic signal recognition (primarily environmental factors) were analyzed and the algorithm evaluated in the continuing series of Tokyo waterfront FOTs. The results of these tests confirmed which environmental conditions have a temporary adversely effect on recognition performance, including backlight, direct light, concealment, background assimilation, nighttime, and so on. However, since the effects of these conditions are temporary when nearing an intersection, the impact on the decision to enter the intersection is limited. Furthermore, the evaluation verified that the target green/red/arrow signal recognition rate of at least 99% within a range of 120 meters could be achieved by adopting a strategy of deciding whether to enter the intersection based on the state of multiple traffic signals. However, since the evaluation also confirmed that backlight and direct light have a major impact on recognition, quantitative evaluations of the impact of sunlight were carried out and a recognition algorithm for the backlight impact range was developed. Subsequently, measures to suppress detection errors when the traffic signal cannot be recognized due to the performance limits of the camera under backlight conditions were examined as an auxiliary approach to resolving this issue. In addition, an algorithm that decides when to enter an intersection using infrastructure-support traffic signals was evaluated in an FOT on general roads. The algorithm was evaluated from the standpoint of its capability to avoid sudden deceleration in the dilemma zone when definite look-ahead information can be obtained.

(2)Traffic signal recognition by semantic segmentation

If a traffic signal is completely or partially concealed or assimilated into the background, or the lamps of a traffic signal are old and not bright enough, it may be impossible to recognize the position or color of the traffic signal accurately simply using the conventional approach of recognizing rectangular or circular characteristics. To resolve this kind of issue, a method of extracting the position of the traffic signal in pixel units by semantic segmentation using deep learning was developed. It is hoped that this approach can detect traffic signals even when the traffic signal is small or partially obscured, by considering the configuration of entire images rather than relying on local shape information. Furthermore, as shown in Fig. 2, a two-step method of traffic signal recognition was adopted using a convolutional neural network for traffic signal regions identified by semantic segmentation.

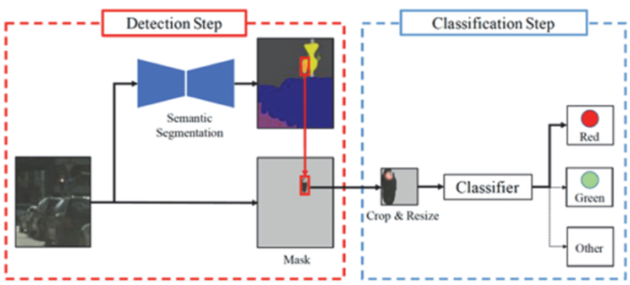

Fig. 2: Outline of Traffic Signal Recognition Algorithm

In the 2018 fiscal year, the effectiveness of semantic segmentation was confirmed. In the 2019 fiscal year, a recognition accuracy of 95% was achieved through the development of a traffic signal recognition function. Then, in the 2020 fiscal year, by adopting images of a wide range of weather conditions as learning data and recognizing traffic signals on a time-series basis, traffic signal recognition in both daytime and nighttime conditions was accomplished (Fig. 3) and a recognition accuracy of 99% was achieved. However, further countermeasures will be required for backlit conditions and flashing traffic signals.

Fig. 3: Traffic Signal Recognition Results

2.2. Development of AI Technology Required for Far Object Detection

The accurate detection of vehicles, motorcycles, pedestrians, and the like around the driver's vehicle is essential to realize safe and smooth automated driving. This project is aiming to improve the detection performance of moving objects far away from the vehicle, which is one of the issues of moving object detection. To achieve advanced detection performance, it is absolutely necessary to create an algorithm that detects small objects at long distances using on-board cameras capable of detecting moving objects far from the vehicle and the latest AI technology. For this purpose, the project is developing object detection technologies and studying the sensor specifications to realize sufficient detection capabilities. (See Section (1) Selection of long-distance on-board camera and development of detection algorithm.) In addition, the project is also developing an algorithm that enhances the recognition performance of far objects using information obtained by lidar and millimeter wave radar. (See Section (2) Far object recognition based on lidar and millimeter wave radar.) Finally, the project is working to realize accurate object recognition using both passive and active sensors.

(1)Selection of long-distance on-board camera and development of detection algorithm

Normal on-board cameras have a view angle of approximately 100 degrees. With an image size of 1,024 × 786 pixels, the height of a pedestrian at a distance of 50 meters will be only 37 pixels, falling to 27 pixels at a distance of 70 meters. At the same time, because on-board cameras have to focus at a certain distance, objects that are not close to that distance will become unfocused and blurred. These issues were addressed as follows. In the 2018 fiscal year, a camera suitable for long-range object detection was selected and data collected. In the 2019 fiscal year, the collected data was used to select the optimum algorithm for long-range object detection. Then, in the 2020 fiscal year, a refined algorithm was created based on the latest YOLOv4 object detection algorithm. This refined algorithm enabled the accurate detection of small objects (vehicles at a distance of 200 meters and pedestrians at a distance of 70 meters) by addressing the focus blurring in the object detection process.

Fig. 4: Example of Far Object Detection

(2)Far object recognition based on lidar and millimeter wave radar

When using lidar to recognize objects, a methodology has been reported that identifies objects using machine learning based on feature quantities related to shape and motion obtained from measured point group information of the object. This methodology is capable of recognizing traffic user categories such as vehicles, motorcycles, pedestrians, and so on. However, one issue with lidar detection is recognizing isolated objects far from the vehicle. Therefore, this project developed a far object recognition algorithm based on sensor fusion, that is, the use of information obtained from multiple sensors, including millimeter wave radar, cameras, and the like. This approach achieved a recognition rate of at least 90% for vehicles within a range of 200 meters and for pedestrians within a range of 70 meters.

In the 2018 fiscal year, three-dimensional on-board lidar was used to investigate the feasible detection distances of far objects. In the 2019 fiscal year, far object recognition accuracy was evaluated, again using three-dimensional on-board lidar. In these evaluations, data from test vehicles equipped with three-dimensional lidar was obtained while driving inside Kanazawa city and in the Tokyo waterfront area. Labelled data sets of vehicles, motorcycles, and pedestrians were created. In addition, to improve the recognition range of lidar, a sensor fusion recognition algorithm was developed that incorporated rectangular recognition frames obtained from cameras. Through this approach, the 2019 fiscal year target of a 90% recognition rate for vehicles at 135 meters and pedestrians at 50 meters was achieved. These tests verified the effectiveness of fusing lidar detection with camera images to supplement point groups long distances from the vehicle. Then, in the 2020 fiscal year, the recognition algorithm developed in the previous fiscal year was enhanced. In this process, a recognition algorithm that operates in combination with digital maps was developed to realize a sensor fusion algorithm particularly suited for long-distance recognition. Increasing the recognition distance of the camera is regarded as an essential part of realizing stable and continued recognition of far objects. Therefore, to improve camera-based recognition distances and enable real-time recognition, a method of generating recognition areas using digital maps was studied. Using digital maps to identify the key areas of the road in real-time while driving should help to increase recognition distances by focusing on those areas. The effectiveness of this approach on long-distance recognition was then evaluated. The evaluation results demonstrated that the detection distance of rectangular image frames was improved for those specific areas. The performance of the developed algorithm was evaluated in combination with the lidar object tracking algorithm. As a result, the 2020 fiscal year target of a 90% detection rate for vehicles within 200 meters and pedestrians within 70 meters was achieved.

2.3. Development of Highly Accurate Localization Technology

Autonomous driving in urban areas using digital maps depends on localization technologies capable of estimating the position of the driver's vehicle to a high degree of accuracy. Localization is carried out by matching the position of the vehicle on a map with measurements from lidar and other sensors, taking the position measured by the Global Navigation Satellite System (GNSS) or the like as an initial position. In this process, the measurement of highly accurate position information enables the acquisition of a highly reliable initial position, while also helping to validate the results of map matching. This project developed GNSS/inertial navigation system (INS) technology suitable for automated driving systems that can estimate the position of the vehicle even with general-purpose GNSS/INS systems. The project also developed a highly accurate localization algorithm that functions in combination with lidar and other map matching technologies to investigate the impact of errors between the actual environment and map caused by map freshness. In addition, the project also investigated the impact of the state of lane markings on automated driving systems since such systems are required to recognize road lane markings in various states. It should be noted that the accuracy of GNSS/INS systems is susceptible to deterioration. At the same time, in locations with no map features, it is likely that vehicles will have to rely on roadside infrastructure for localization, even if the technology described above is successfully developed and adopted. For this reason, the conditions to enable the stable operation of automated driving systems were studied.

(1)Development of GNSS/INS system technology

Two targets were set in the GNSS/INS technology development process: the localization accuracy required for automated driving was set to 1.5 meters, which is necessary to determine whether the vehicle is in the driving lane, and the localization accuracy for allowing the operation of the automated driving system by GNSS/INS technology alone was set to 0.3 m. The project aimed to realize these two targets using the Michibiki Quasi-Zenith Satellite System. To realize the 1.5-meter accuracy target, the effectiveness of the GNSS Doppler method was studied as a stable localization approach to examine the feasibility of maximizing the use of general-purpose GNSS technology. For the 0.3-meter target, judgment technology was developed using vehicle behavior focusing on the height direction, which is a particular focus of attention for accuracy.

First, evaluation tests in Tokyo using multi-GNSS technology that were carried out in the 2018 fiscal year confirmed that the system achieved the following accuracy values: 77% at 30 cm and 90% at 1.5 m in Odaiba, and 57% at 30 cm and 92% at 1.5 m in Shinjuku. In the 2019 fiscal year, focusing on the locations that achieved a localization accuracy of 0.3 meters or less, tests confirmed that the position of the vehicle could be determined to an accuracy of 0.3 meters or less in the same evaluation areas 99% of the time[(2)]. Then, in the 2020 fiscal year, the Centimeter Level Augmentation Service (CLAS) correction information transmitted from the Michibiki Quasi-Zenith Satellite System was used to examine whether the localization accuracy of 0.3 meters necessary for automated driving could be achieved. These results found that, on the Odaiba test route, a 99% rate was achieved for 0.3-meter accuracy target. In contrast, the results also noted lower performance in locations assumed to have exposure to fewer Michibiki satellites, even when CLAS was received. Therefore, to ensure position measurement accuracy, it will probably be necessary to use supplemental technology such as infrastructure-based map matching or the like to maintain localization accuracy.

(2)Development of map matching technology

Map matching technology is an indispensable part of accurately identifying the position of the driver's vehicle. It is important to enable continuous and highly accurate position detection even in locations with poor GPS radio wave reception, such as inside tunnels or on streets surrounded by high rise buildings.

In the 2018 fiscal year, a technical paper-based investigation was carried out to study map matching algorithms using different methods. The following three methodologies for development and study were selected: (1) Normal Distributions Transform (NDT) scan matching using three-dimensional point groups, (2) template matching using two-dimensional road surface pattern images, and (3) linear matching using image lines and the like on digital maps. An evaluation route in Kanazawa city (single-direction distance: 20 km) was selected and data measurement carried out. In the 2019 fiscal year, with the aim of achieving a localization accuracy of 0.1 m using highly accurate GNSS/INS systems when the attitude angle is known, several map matching algorithms were adopted and the localization accuracy estimated. Of the candidate algorithms selected in the 2018 fiscal year, the following two were adopted as representative algorithms with a proven track record in automated driving systems: (1) NDT scan matching and (2) template matching. It was confirmed that these algorithms achieved the target accuracy of 0.1 meters. In addition, to investigate the effects of seasonal changes on localization accuracy, the impact on map matching was examined at locations in which map data identified changes in vegetation. In the 2020 fiscal year, a map matching algorithm assuming the use of on-board grade GNSS/INS technology was developed. This algorithm achieved a localization accuracy of 0.1 meters. Since on-board grade GNSS/INS technology uses low-cost gyroscopic sensors, the orientation angle of the vehicle cannot be obtained with the same degree of precision as highly accurate GNSS/INS systems. Therefore, a methodology to estimate the position and orientation angle of the vehicle was developed and adopted based on a localization algorithm using the template matching method that was applied in the field operation tests (FOTs) in the Tokyo waterfront area up to the 2019 fiscal year. Accurate localization was achieved by incorporating orientation angle estimation based on Hough transformation even when the orientation angle of the GNSS/INS system was less accurate.

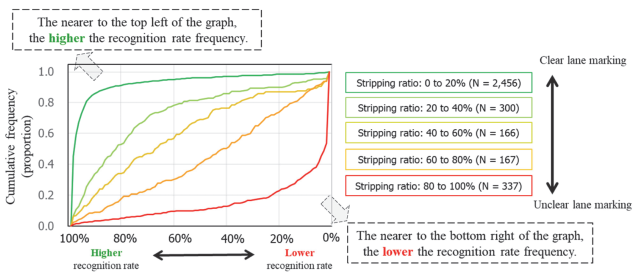

Fig. 5: Cumulative Recognition Rate Frequency at each Stripping Ratio

(3)Investigation of effect of state of lane markings on automated driving systems

The effect of the state of lane markings, as defined by the lane marking stripping ratio, lane marking reflectance, and reflectance contrast between the lane markings and road surface, on lane marking recognition and map matching was investigated.

First, this project investigated the effect of the lane marking stripping ratio on semantic segmentation, which is one methodology for recognizing lane markings. This investigation examined the relationship between the ratio of areas without residual lane markings (i.e., the stripping ratio) extracted by on-board camera image binarization using manually extracted areas regarded as originally lane markings as the reference and the ratio of lane marking areas estimated by semantic segmentation (i.e., the recognition rate). The results showed that the recognition rate increased as the stripping ratio decreased (i.e., as the lane markings become more clear), and that the recognition rate decreased as the stripping ratio increased (i.e., as the lane markings become more unclear).

Next, the project investigated the effect of the lane marking reflectance and reflectance contrast between the lane markings and road surface on map matching. The reflectance was measured using lidar before and after the lane markings were re-painted, and the identification of lane marking regions and map matching accuracy were evaluated. The results showed that the map matching accuracy increased as the reflectance contrast between the lane markings and road surface increased, In addition, when the map used for map matching resembled the observed state of lane marking degradation (i.e., a good map maintenance state), the map matching error in the lateral direction of the vehicle was ±0.375 m or less in roughly all frames, regardless of the state of lane marking degradation ((2) and (3) in Fig. 6). In contrast, when the lane markings used in the map used for map matching differed greatly from the observed stripping state of the lane markings (i.e., insufficient map maintenance), the state of the lane markings tended to have an adverse impact on map matching and the number of frames with an error of ±0.375 m or more increased ((1) and (4) in Fig. 6).

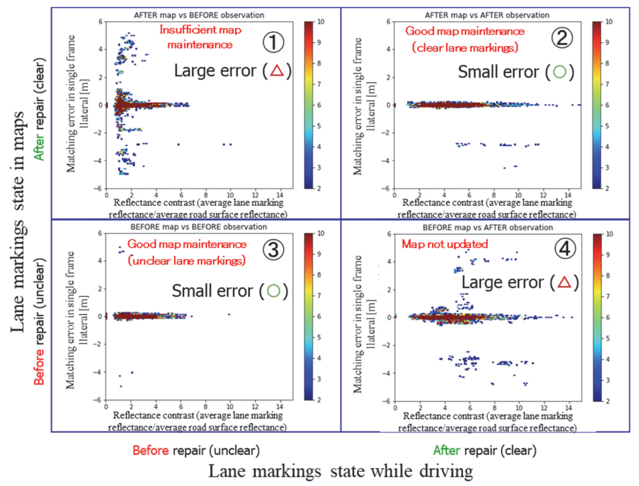

Fig. 6: Reflectance Contrast and Map Matching Error

2.4. Estimation of Traffic User Behavior and Consequent Development of Path Planning Technology

Urban areas contain a wide range of moving objects, including vehicles, motorcycles, bicycles, and pedestrians. To enable safe driving while avoiding collisions with these moving objects, the future behavior of the moving objects must be predicted and the path (i.e., the route and speed that the driver's vehicle must take in the future) of the vehicle planned considering those predictions. This project addressed these issues by calculating the attributes (physical direction, age, and the like) of slow-moving pedestrians based on AI technology and researching technology to predict pedestrian behavior (Section (1) AI-based pedestrian behavior prediction), and predicting the behavior of fast-moving vehicles based on time series tracking and researching path planning technology considering the predicted future paths of these vehicles (Section (2) Vehicle behavior prediction based on time series tracking and path planning). Then, by combining these technologies, the project constructed a technique to enable vehicles to drive smoothly and safely in complex urban area environments. This project also aimed to examine the necessity for infrastructure support in urban area driving and to determine the requirements for such infrastructure.

(1)AI-based pedestrian behavior prediction

Path prediction technology estimates the paths that pedestrians will take in the future. The factors that determine the path of a moving object can be categorized into external factors such as the environment around the object and the internal factors of the object itself. If, for example, the vehicle is driving in an area in which pedestrians and vehicles are not separated by guard rails or the like, external factors include pedestrians walking in the road to avoid parked cars. In contrast, internal factors include attributes such as gender and age. One example may be the possibility of a child running out into the road suddenly without paying attention to the surrounding environment. To carry out path planning under these conditions, it is important to predict the behavior of moving objects. Therefore, in the 2018 fiscal year, data was collected to help estimate pedestrian attributes as internal factors. In the 2019 fiscal year, this data was used to develop a pedestrian attribute estimation method. Then, in the 2020 fiscal year, a path prediction algorithm considering pedestrian attributes was developed. When estimating the future paths of pedestrians, two types of inputs can be envisioned: inputs from the perspective of the vehicle, and inputs from an overhead perspective. After evaluating which perspective is better for path prediction, it was understood that path prediction from an overhead perspective is more accurate. At the same time, the effectiveness of maps with and without map information (scenario labels) in path prediction from an overhead perspective was also evaluated. The results found that, without map information, the paths that collide with buildings and other objects could be predicted, and that, with map information, paths to avoid the objects could be predicted. These results demonstrate that map information is an important part of path prediction. In addition, the paths of moving objects were analyzed based on the moving object attributes. Specifically, this project analyzed how far in advance a pedestrian dashing out into the road from a sidewalk can be predicted. The results found that the path of adults and elderly people dashing out into the road could be predicted from a position up to between approximately 3 to 5 meters from the road. However, the path prediction method adopted in these studies could not easily predict the path of a child dashing out into the road unless the child was at least 9 meters away. Since the prediction accuracy differs depending on the path prediction method, it will be necessary to evaluate the latest methods and examine more effective ways of using map information.

(2)Vehicle behavior prediction based on time series tracking and path planning

For automated driving in urban areas, it is important to predict the paths of moving objects and plan the trajectory of the driver's vehicle in real time to prevent collisions with these paths. However, various issues have to be resolved to realize this objective particularly in urban areas that contain large numbers of moving vehicles. One major issue is realizing smooth and safe driving considering the predicted future paths of moving objects through stable moving object recognition even when the existence of large number of moving vehicles temporarily conceal other objects and create blind spots and relatively narrow spaces. Therefore, this project developed technology to accurately estimate the motion and shape of moving objects, and to predict the future paths of these objects. Then, a path planning technique that enables vehicles to drive smoothly and safely in urban areas was constructed considering the predicted paths of these moving objects. The developed recognition and path planning technologies were used to realize an algorithm capable of maintaining an automated driving state in an urban area for at least 5.0 km.

In the 2018 fiscal year, the applicable test areas for the evaluations were selected and the specifications for sensor positions and the like to support blind spots were studied. The Tokyo waterfront area and Kanazawa city in Ishikawa Prefecture were selected as the urban environment evaluation areas. In the 2019 fiscal year, to improve peripheral prediction using automated driving, a moving object tracking algorithm using extended object tracking (EOT), which is capable of simultaneous estimation of the shape and motion of moving objects around the vehicle, as well as a map-based moving object behavior prediction algorithm entered development. When the override trends of automated driving in the FOTs carried out in the Tokyo waterfront area from September 2019 were evaluated, it was found that the targeted average continuous automated driving distance of 2.5 km was achieved.

Then, in the 2020 fiscal year, the algorithms developed up to the end of the previous year were adopted for real-time applications and sequentially incorporated into the FOTs. These algorithms achieved the targeted average continuous automated driving distance for the 2020 fiscal year of 5 km Additionally, the override frequency factors were analyzed based on the evaluation results to identify which factors related to the road environment had an impact on automated driving. Based on this analysis, the primary factors affecting overrides under specific traffic environments and scenarios were analyzed. These included right turns at intersections where roadside structures and other vehicles create blind spots, and right turns at intersections with short arrow signal times.

2.5. Studies of Issues when Multiple Automated Vehicles Are Present

Future road traffic environments are likely to contain multiple automated vehicles, and it is highly possible that automated vehicles will encounter each other under various traffic conditions.

Since automated vehicles drive while following the applicable regulations, the behavior of these vehicles should fundamentally be in line with traffic laws. Consequently, when automated vehicles encounter each other in a complex environment, the result may be a deadlock in which neither can predict the behavior of the other. For this reason, measures must be studied to avoid deadlocks in future traffic environments containing interactions between automated vehicles. This research project addressed this issue by studying deadlock avoidance using robotics (Section (1) below) and AI (Section (2)) technologies. The project also aimed to identify situations in which deadlocks involving only automated vehicles occurred even when these advanced avoidance measures were adopted. Another objective was to propose what type of infrastructure support would be necessary for deadlock avoidance.

(1)Deadlock avoidance using robotics technologies

A simulation environment was constructed to reproduce the fundamental decision making involved in automated driving in urban areas using simulation software and verify deadlock events. Situations susceptible to deadlock under traffic environments containing multiple automated vehicles were identified using the developed simulator. At least five scenarios susceptible to deadlock in normal traffic environments were identified and the effectiveness of a deadlock avoidance algorithm developed using simulations and actual vehicle tests was verified.

In the 2018 fiscal year, the deadlock avoidance algorithm methodology was investigated in a constructed environment containing multiple automated vehicles. In the 2019 fiscal year, potential deadlock conditions were studied through automated driving tests in the Tokyo waterfront area and verified by simulations. Since automated vehicles are generally programmed to closely follow traffic rules, the presence of other vehicles and the like that fail to obey these rules is also considered likely to cause deadlock. To investigate and analyze these situations and deadlock events, a simulator that incorporates multiple automated vehicles was developed. This simulator identified five types of environments in which deadlock may occur, factoring in traffic rule violations, vehicles yielding to each other, and physical restrictions. In the 2020 fiscal year, these five types of deadlock scenarios were analyzed and measures were studied from the standpoints of resolving the situation after a deadlock occurs and preventing the deadlock from occurring in advance. Deadlock avoidance was then studied mainly using robotics technology for the former approach and AI technologies (Section (2) below) for the latter approach. The algorithm to address deadlocks that have already occurred was created by giving the automated driving system the flexibility to temporarily and intentionally cross road markings. It should be noted that whether regulations actually permit the temporary breaking of traffic rules to help avoid a deadlock must be discussed even in situations regarded as unavoidable. This research simply studied the feasibility of incorporating this approach into the deadlock avoidance algorithm. The effectiveness of this deadlock avoidance algorithm was examined using a simulator and in actual vehicle tests on non-public roads. It was confirmed that deadlocks could be avoided under certain conditions with sufficient driving space.

(2)Deadlock avoidance using AI technologies

Path planning technologies for automated vehicles plot the vehicle trajectory based on rules or formulations in accordance with measured information. Such path planning technologies have limits, and deadlock scenarios occur in real-world scenarios that cannot be addressed with one-off rules or the like. Therefore, this study envisioned deadlock scenarios and verified whether deadlock avoidance measures could be identified through deep reinforcement learning.

In the 2019 fiscal year, deadlock scenarios were investigated in the Tokyo waterfront area FOTs. The following five deadlock scenarios were identified: 1) scenarios in which the vehicle provides driving space for other vehicles while waiting at a traffic signal with a vehicle parked in the opposing lane and a vehicle arrives to turn right, 2) scenarios in which vehicles are parked at the roadside on roads with poor visibility in either lane, 3) scenarios involving avoiding oncoming vehicles when vehicles are parked in the driving lane, 4) scenarios involving merging onto main roads, and 5) scenarios at entrances and exits to parking lots of commercial facilities or the like. In the 2020 fiscal year, a simulation environment was constructed for these scenarios and the feasibility of deadlock avoidance using deep reinforcement learning was verified. Appropriate rewards were designed for each scenario. In scenarios 3 and 5, deadlocks were prevented by identifying actions that consider the other vehicles. In contrast, actions were not identified that could avoid the deadlocks in scenarios 1, 2, and 4. This is because the scenarios in which the deadlocks were avoided involved unique or limited avoidance behavior, which simplified the measures to avoid deadlock. However, the other scenarios are more complex since these scenarios involve a large number of avoidance behavior choices or require coordinated avoidance behavior from multiple vehicles. In response, it will be necessary to reconsider the simulation environments to avoid these scenarios and revise the reward rules to identify avoidance behavior.

3 FOTs

To verify the research and development items described in Section 2, test vehicles equipped with surrounding environment recognition sensors such as multiple lidar units, millimeter wave radars, cameras, localization sensors such as GNSS and INS systems, onboard V2X terminals, and so on were constructed and tested on public roads.

In advance of these public road tests, regulatory compliance and the like was confirmed by inspecting and registering structural changes and so on with the transportation bureau branch offices of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). In addition, the preliminary test service for public road FOTs involving automated vehicles run by the Japan Automobile Research Institute (JARI) was used to carry out safety assurance using a third-party institution. This approach was adopted to ensure the mutual safety of the test vehicles and drivers, and to allow the vehicles to be tested on public roads. Subsequently, the FOTs started in the center of Kanazawa, Ishikawa Prefecture, in July 2019, followed by the FOTs in the Tokyo waterfront area in September 2019.

As of the end of the 2020 fiscal year, the FOTs in the Tokyo waterfront area had achieved approximately 2,137.8 km of automated driving over 121 days. Figure 7 shows an automated vehicle driving on a public road in the Tokyo waterfront area.

Fig. 7: Automated Vehicle in the Tokyo Waterfront Area

4 Conclusions

To help realize automated driving equivalent to level four in complex urban traffic environments, this project carried out academic investigations and research involving universities as a neutral research organization. The project investigated the situations in which autonomous recognition and decision making technologies using on-board sensors find it difficult to operate, and studied what infrastructure would be needed in these cases. It is planned to continue this project until the end of the 2022 fiscal year. In addition to further studies into infrastructure and the difficult conditions for recognition and decision making technologies, this project intends to disclose the data obtained through FOTs to encourage discussions of future cooperative areas, and to pursue studies into verifying the safety of autonomous recognition and judgment technologies using on-board sensors in coordination with other SIP projects.

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3 Ensuring the Safety of Automated Driving

(2) Realizing a Safe Automated Driving Society

Technological Development and Education for Enhanced Safety (Overview)

Osamu Hosaka and Yasuyuki Koga (Cabinet Office)

Overview: Ensuring safety and reliability are two issues of the highest importance for the practical adoption and popularization of automated vehicles. For this reason, the establishment of safety assurance methods for automated vehicles is an urgent task. At the same time error-free communication must be realized between automated vehicles and other traffic users. SIP-adus is working to construct a safety assurance environment in a virtual space, and to establish sustainable and effective countermeasures against cyberattacks targeting connected vehicles, appropriate methods for communicating the intentions behind automated vehicles to people, and effective educational and awareness-building methods for people using automated vehicles and automated driving services.

1 Background and Significance

Currently, initiatives to construct safety assurance methods for automated driving are attracting a great deal of attention around the world and various projects are in progress. As an example, SIP-adus has been carrying out safety assurance exercises on public roads, such as through field operational tests (FOTs) in the Tokyo waterfront area. However, although such real-world road tests and actual vehicle tests on proving grounds are important, simulated assessments that are reproducible and capable of recreating critical conditions are an indispensable part of assessments. Therefore, placing a particular focus on the assessment of sensor performance, SIP-adus has started to develop a safety assurance simulation platform with the aim of constructing a sensor model that is highly consistent with actual environmental conditions.

In addition, with respect to cybersecurity, SIP phase 1 worked to establish an evaluation method for the level of cybersecurity protection provided against cyberattacks from outside the vehicle. As a result of these efforts, an evaluation method applicable at the development stage was developed. However, as the technology behind cyberattacks becomes more and more advanced, it is necessary to develop a system of detecting and monitoring cyberattacks while vehicles are being driven after market launch.

In this situation, intrusion detection systems (IDS) are currently attracting attention as a possible countermeasure against cyberattacks of vehicles from malicious third parties. Consequently, SIP phase 2 has moved onto the development of methods of assessing the performance of IDS.

Additionally, to address an issue with human machine interfaces (HMIs), research and development is being carried out into appropriate methods of information provision, education, and the like, to help prevent communication errors when automated vehicles encounter other vehicles or pedestrians in a mixed traffic environment.

Collaborative research and development into these three topics is currently being carried out under a joint Japanese-German framework of cooperation.

2 Construction of Safety Assurance Environment in Virtual Space

With current assessment methods, which are centered on FOTs using actual vehicles on public roads, it is impossible to intentionally set the required driving environment conditions, which makes it difficult to judge whether automated vehicles have achieved the necessary level of safety. It is also difficult to use actual vehicles to assess all possible scenarios that might occur on public roads. For these reasons, the development of a method capable of assessing the safety of automated vehicles under specific driving environment conditions is regarded as an urgent task. In addition, the development of simulation tools focusing on sensor performance assessments and the standardization of interfaces are also necessary for increasing the efficiency of safety assurance methods using actual vehicles, which currently take up large amounts of time during automated vehicle development.

Consequently, with the aim of realizing highly reproducible safety assurance methods under various traffic environments, SIP-adus has started to develop a simulation model that is highly consistent with actual phenomena and that is capable of replacing real vehicle test under real-world conditions. Then, based on this model, SIP-adus is also working to construct a driving intelligence validation platform (DIVP), in other words, a safety assurance environment in a virtual space.

A DIVP consortium was formed consisting of Professor Hideo Inoue of the Kanagawa Institute of Technology as the head of research and development, two universities (Kanagawa Institute of Technology and Ritsumeikan University), and eight companies (Denso Corporation, Pioneer Smart Sensing Innovations Corporation, Mitsubishi Precision Co., Ltd., Nihon Unisys, Ltd., Soken, Inc., and Solize Corporation). This consortium is working on the development of an environment model that simulates the outside world, a sensor model that simulates the detection performance of actual sensors, an automated driving model that simulates automated vehicle driving controls, as well as tools and the like that generate test data based on assessment scenarios.

Automated vehicles use combinations of sensors, including

Fig. 1: Validation of Consistency of DIVP Sensor Model

cameras, radar, and lidar. Since assessments of this type of sensor fusion are indispensable, the standardization of interfaces to realize these assessments via simulations is important. Process toward this standard is being advanced in collaboration with the standardization body Association for Standardization of Automation and Measuring Systems (ASAM).

At the same time, another important aspect of establishing safety assurance methods for automated vehicles is verifying the validity of scenario definitions, assessment criteria, and the like. Based on a proposal from the Safety Assurance Subcommittee of the Japan Automobile Manufacturers Association (JAMA), to accelerate the practical adoption of safety assurance technology, the DIVP consortium is coordinating with the Safety Assurance Kudos for Reliable Autonomous Vehicles (SAKURA) project being run by the Ministry of Economy, Trade and Industry and the Ministry of Land, Infrastructure Transport and Tourism. A joint working level taskforce and steering committee were established in the 2021 fiscal year and are currently in action. Additionally, SIP-adus started the Virtual Validation Methodology for Intelligent Driving Systems (VIVID) project in October 2020 as a collaborative effort with the German VIVALDI research project. Through these initiatives, it is planned to advance safety assurance systems for automated driving and the standardization of simulation interfaces at the International Organization for Standardization (ISO), ASAM, and elsewhere, while strengthening international cooperation.

In addition, in the future, to enable the continuous construction and operation of the DIVP data platform, a database capable of reproducing the FOT environments in the Tokyo Waterfront City area is being built with the aim of advancing and commercializing initiatives to verify consistency with real environments, confirm connectivity, and so on through FOTs in the Tokyo waterfront area and monitoring assessments by automakers and sensor manufacturers.

It should also be noted that an intellectual property strategy is being formulated factoring in the idea of open/closed research results and the likelihood of future shifts in competitive and cooperative areas. The objective of this initiative is to ensure that intellectual property is secured through a strategic approach.

3 Cybersecurity

The social implementation of automated driving depends on the acquisition of road traffic environment data such as high precision 3D maps and traffic signal information via communication. A particularly important aspect of utilizing connected technology for automated driving is the application of security measures assuming cyberattacks against vehicles via external communication systems. A series of reports about methods of carrying out cyberattacks on various vehicles have already been presented at international conferences and the like. In response, IDS are attracting attention as a means of countering cyberattacks on vehicles.

For this reason, investigative research has been opened into new methods of cyberattacks and countermeasure technologies based on the idea that IDS may be an effective means of countering new cyberattacks on connected vehicles. In addition to investigating IDS, this initiative is also assessing the performance of IDS using test beds and actual vehicles, establishing IDS assessment methods, and formulating assessment guidelines.

In addition, it is also looking into methods of monitoring, collating, analyzing, and accumulating information about threats due to cyberattacks on connected vehicles, as well as information sharing systems for supporting initial responses. Progress is being made in studies of overall system performance targets as well as toward the formulation of basic overall system specifications.

As part of this initiative, based on a collaborative framework between SIP-adus in Japan and the Federal Ministry of Education and Research (BMBF) in Germany, a joint project called Securing Automated Vehicles (SAVE) was started in October 2020 in collaboration with a German research project called SecForCars. The objective of these efforts is to strengthen international cooperation and, particularly, to advance studies into information sharing systems.

In the future, it is hoped to transfer the formulated IDS assessment guidelines to the Japan Automotive Software Platform and Architecture (JASPAR) industry organization to advance the creation of guidelines across the whole industry. Another aim is to transfer the formulated basic specifications related to the monitoring, collation, analysis, and accumulation of information about threats to connected vehicles as well as related to information sharing systems for supporting initial responses to an industry organization such as J-Auto-ISAC or the like.

4 Safety Education

One topic in the social implementation of SAE level 3 or higher automated driving systems is communication between people and vehicles, such as between driver-less automated vehicles and other traffic users (such as pedestrians, cyclists, drivers of other vehicles, and the like) and between automated vehicles and drivers. From this standpoint, SIP-adus is investigating how to best to realize

HMIs, including methods of appropriate information provision, education, and the like while also factoring in international trends. Progress is also being made into developing the necessary technology, and studies are being carried out into the creation of guidelines and so on. Initiatives in cooperative areas related to HMIs are focusing on the following three subjects.

1) Assuming mobility/logistics services using automated vehicles with functionality equivalent to SAE level 4, identification of seamless communication methods capable of ensuring safety between automated vehicles and other traffic users (such as pedestrians, cyclists, drivers of other vehicles, and the like) and enabling the clear and confident mutual communication of intentions.

2) The development of HMIs capable of appropriately handing control over to the driver when the driving environment conditions change or the functionality of the automated driving system deteriorates, and the identification of educational methods for drivers.

3) As automated vehicles with functionality equivalent to SAE level 3 or 4 become more widespread, the identification of what items of knowledge should be acquired by drivers, pedestrians, and the like with respect to SAE level 2 driver support systems and the effective educational methods for such knowledge.

In this initiative, based on the collaborative framework between SIP-adus in Japan and BMBF in Germany, a joint project was started in July 2019 in collaboration with a German research project. This collaborative approach is working to strengthen international cooperation with regard to these three subjects.

Development of Driving Intelligence Validation Platform (DIVP®) for Automated Driving Safety Assurance

Hideo Inoue (Kanagawa Institute of Technology)

As automated driving systems become more complex, it is necessary to ensure a high level of safety in the countless driving environments that occur. However, currently automated vehicle safety can only be validated through costly (in terms of labor, equipment, financial, and time) and comprehensive practical assessments in actual driving environments. In addition, it is also difficult to validate the limits of external sensors such as cameras, radar, LiDAR, and the like that form the interface between the vehicle and the real world, which complicates decisions about the level required upon establishing system safety. Against this background, this research project is developing an assessment platform using simulators to create a virtual models by adopting a series of models consisting of driving environments, spatial propagation, and sensors that are highly consistent with the actual phenomena required to assess the safety of automated driving.The goal of the project is to precisely and efficiently assure the safety of automated driving under as many environmental conditions (scenarios) as possible.

1 Project Background and Overview

A survey carried out by the U.S. National Highway Traffic Safety Administration (NHTSA) reported that accidents involving automated vehicle systems have been caused by the failure of sensors to detect objects. The erroneous recognition of detected objects has also been raised in reports [(1)(2)].

At the same time, countries around the world have trialed various approaches to safety assurance. Typical examples include the PEGASUS Project, which was implemented by using funds provided by the German Federal Ministry for Economic Affairs and Energy (BMWi) and concluded in the year 2019, and its successor, the SET Level Project. These projects proposed a driving scenario-based assessment method for safety assurance [(3)(4)]. Essentially, these initiatives are looking at whether sensors are capable of perceiving and recognizing objects to assure the safety of automated vehicle. However, no full-scale research and development had addressed the issue of building a simulator provided with highly consistent sensor models with actual phenomena to support these processes. Therefore, at the end of 2018, "The second phase of SIP- Automated Driving for Universal Services (Expansion of Systems and Services) " inaugurated the Driving Intelligence Validation Platform (DIVP®) research and development project as a collaborative consortium between sensor manufacturers, software companies, universities, and other parties, with the aim of building a virtual automated driving safety assurance simulation platform focusing on sensor models as highly consistent sensor modeling (Fig.1).

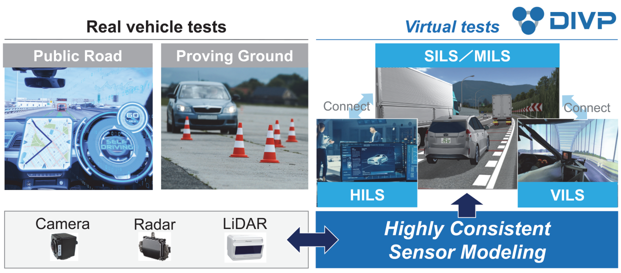


Fig. 1: Necessity for Sensor Model that Is Highly Consistent with Actual Phenomena

In addition, by connecting and taking advantage of the expertise of the twelve institutions from industry and academia mentioned above(as of April 2021, Fig. 2), this project is also working to define the specifications for the interfaces of a safety assurance platform that combines an automated driving control model with a series of models consisting of driving environments, spatial propagation, and sensors, while also aiming to contribute toward global standardization.

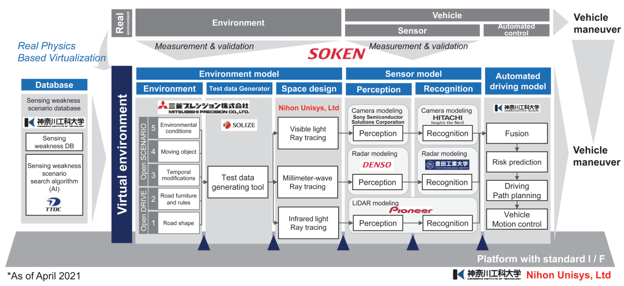


Fig. 2: Configuration of DIVP® Project

2 Highly Consistent Sensor Modeling based on Physical Property Measurements

Unlike normal vehicle component models, external environment recognition sensors have a functional role that connects the driving environment and automated driving control models. Conventional simulators focus on assessing whether system controls are functioning correctly. For these simulators, so-called grand truth(normal function)-based sensing models are frequently adopted. As mentioned previously, for automated vehicle safety assurance, it is necessary to identify the respective pros and cons (i.e., the limits) of each peripheral monitoring sensor, and to advance system design, sensors, and the perception/recognition algorithms considering these limits. However, it is difficult to reflect the validation results of the spatial propagation of electromagnetic waves into a grand truth-based sensor model, which complicates the process of integrating sensing weakness conditions as environmental conditions into a model. In response, this project is building physical models of the reflection characteristics (including the reflexive characteristics, diffusion, and specular reflection) and transmission characteristics of millimeter wave radar waves, visible light for cameras, and near-infrared light from LiDAR, and constructing them as spatial propagation models of ray tracing and the like. At the same time, the project is also working on creating physical models of physical phenomena affected by the surrounding environment, such as rain, fog, sunlight, and so on through sophisticated experiments and measurement technologies. Through these initiatives, the integration of spatial propagation characteristics as perceived by sensors into a series of models based on the electromagnetic wave principles involved in driving environments, spatial propagation, and sensors is another unique aspect of this project (Fig. 3). Specific examples of each of these models are described below.

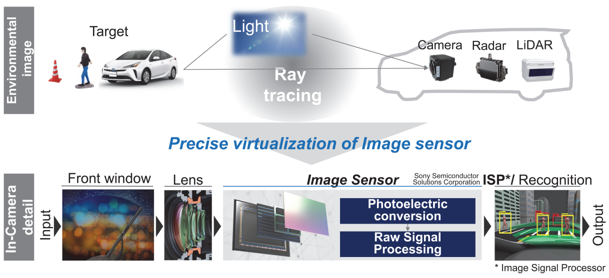


Fig. 3: Sensor Model to Simulate Spatial Propagation (for Camera)

2.1. Camera Model

The DIVP® camera model simulates the spectroscopic characteristics inputted into a CMOS or other semiconductor, rather than the RGB output visible to humans as images. In addition, sunlight is formularized as a sky model, which allows the precise simulation of solar light sources based on time, latitude, and longitude inputs.

As described below, realistic sensor simulation view have been realized by defining the reflection characteristics of objects as property (Fig. 4).

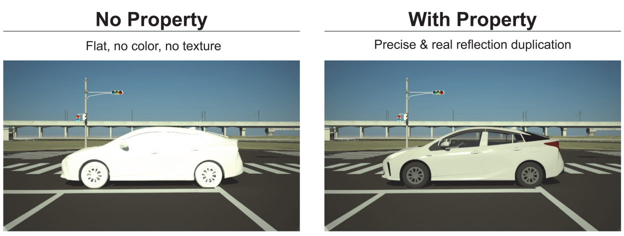


Fig. 4: Effects of Incorporating Reflection Characteristics of Objects

In addition, in difficult visible light scenarios, such as in dark tunnels and the intense backlighting that occurs at tunnel exits, the precise environmental & space models realize validation High Dynamic Range (HDR) camera model is capable of securing sufficient visibility for recognition in simulations (Fig. 5).

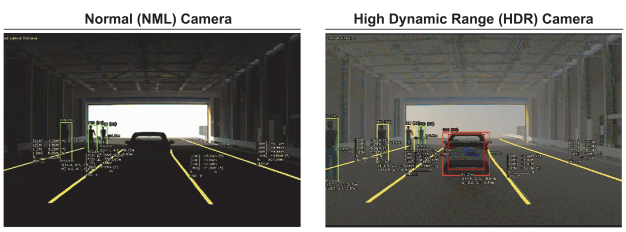


Fig. 5: Example of HDR Camera Effectiveness Validation

2.2. Millimeter-Wave Radar Model

Millimeter wave radars are the most difficult sensors to model. Three reflective models were defined based on the behavior of radio waves reflecting from objects. These models were then applied depending on the object. Vehicles, people, and other small objects are regarded as scattering bodies. Physical Optics (PO) approximation was adopted for the scattered model. In contrast, Geometric Optics (GO) approximation was used for the reflector model and applied to large objects such as buildings and road surfaces. These models were combined with a Radar Cross Section (RCS) model containing objects defined in advance to shorten analysis times and applied to scenarios and objects (Fig. 6).

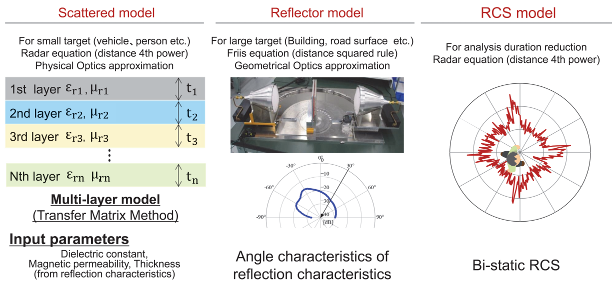


Fig. 6: Three Models to Simulate Precise Reflection Characteristics (Millimeter Wave Radar)

As shown below, one disadvantage of a millimeter wave radar occurs when passing between two other vehicles on similar distance with similar speed (Fig. 7). The inability of a radar with lower resolution to obtain perception outputs at the correct position can be simulated, as well as the improvement realized by a radar with higher resolution.

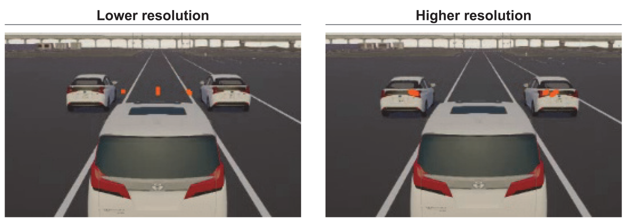


Fig. 7: Effect of the Angular Resolution of Millimeter Wave Radar

2.3. LiDAR Model

LiDAR is a comparatively easy sensor to model based on the directivity of near-infrared light. As shown below, the LiDAR model can assess environmental disturbances such as background light through a 360-degree scan. In this project, it was possible to realize simulations that are highly consistent with the real world using LiDAR by combining a near-infrared light scanning model for LiDAR radiation with precise representations of the footprint created by the expansion of near-infrared light and the effects of sunlight and other background light sources (Fig. 8).

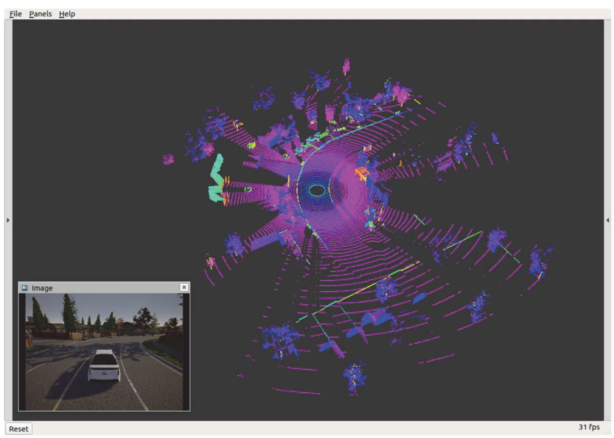


Fig. 8: LiDAR Model

2.4. Validation of Sensor Output Consistency

Quantitative validations with the results of experiments in the real world are being carried out for the inputs and outputs of each sensor model to validate the consistency of the simulations (Fig. 9).

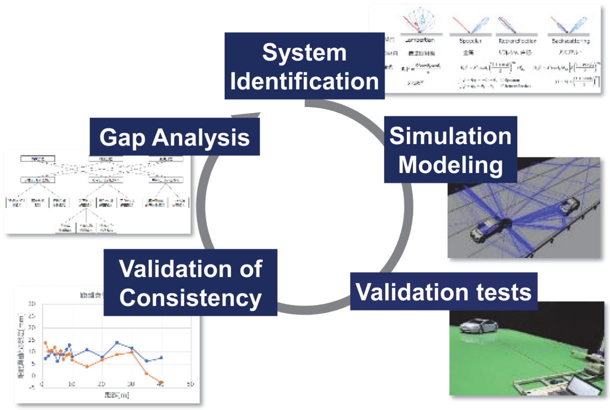


Fig. 9: Incorporation of Actual Physical Phenomena

Based on these results, highly consistent simulations were realized for cameras and LiDAR, and progress was made in validating the consistency of millimeter wave radar simulations with particular objects. However, validations of consistency under difficult compound scenarios and conditions, such as reflections from tunnel walls, multi-path factors, and so on must be improved further. The prospects of improving performance by combining conventional ray tracing with PO approximation, GO approximation, RCS, and the like were established and work is continuing into the implementation of these techniques into simulations.

3 Environmental Models

The six categories of driving environment scenarios under the European PEGASUS Project and the high precision 3D maps used in automated driving have defined effective driving environment information for automated driving controls (i.e., localization, traffic flows, routes, and the like). However, there are virtually no environmental models incorporating physical characteristics defined from the standpoint of external environment sensors, such as reflection, transmission, and the like.

Another distinguishing characteristic of this project is the creation of environmental models that define and incorporate the reflection, transmission, attenuation, and the like of electromagnetic waves from the standpoint of sensors, with respect to (1) Static objects, (2) Moving objects such as vehicles, pedestrians, and the like, and (3) Environmental conditions (Fig. 10).

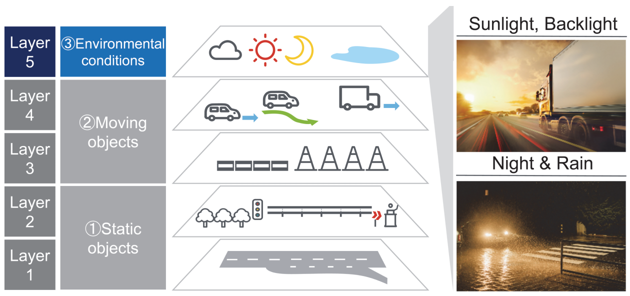


Fig. 10: Construction of Environmental Models

To apply reflection characteristics to object surfaces, this project focused on physical experiments and measurements of objects, which were then incorporated into the simulation models. To realize this, considerable ingenuity was applied to the instruments used to measure the electromagnetic waves of visible light, near-infrared light, and radio waves (Fig. 11).

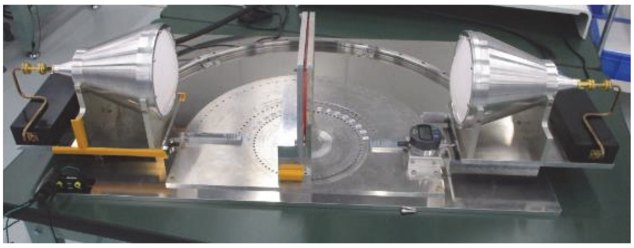


Fig. 11: Millimeter Wave Measurement Instrument

These instruments were used to sequentially validate the reflection characteristics of necessary objects on each assessment environment. These characteristics are being continuously updated as a property library for environmental model assets. Currently, the project is continuing to measure and validate the properties of high-priority asset models for NCAP assessment scenarios and the like, as well as to help model sensing weakness conditions under real-world environmental conditions in the Odaiba district and C1 metropolitan expressway in Tokyo, which are the locations of automated vehicle Field Operational Tests (FOTs) (Fig. 12).

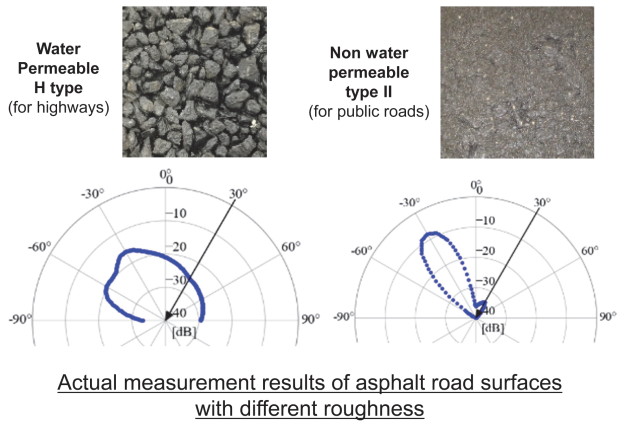


Fig. 12: Example of Measured Reflectivity

4 Space Designed Model for Each Sensor

The precise simulation of sensor detection requires the precise duplication of the physical phenomena for each sensor. For example, in the case of a camera, the visible light radiated by the light source propagates through space and is reflected by or permeates into the surface of objects. This light then propagates again through space before reaching the camera lens. The light that passes through the lens is photoelectrically converted into electrical signals and provided to each control. In this process, optical phenomena such as diffusion and attenuation that occur during spatial propagation have a major impact on light inputs to the camera and must be precisely simulated. This phenomenon must be simulated for millimeter waves in the case of millimeter wave radar and for near-infrared light in the case of LiDAR.

The sky light model that is used to simulate sunlight is capable of duplication sunlight conditions through time as well as object longitude and latitude inputs (Fig. 13).

Fig. 13: Sky Light Simulations

5 Contribution to Safety Assurance

Although the necessary coverage of the safety assurance scenario remains an issue, the efficiency of assessments can be dramatically improved by setting highly consistent conditions in the virtual environment. Therefore, this project established two milestones for the construction of an assessment scenario: (1) assessments such as those adopted by NCAP or similar programs as virtual-PG (Proving Ground), and (2) assessments using community models of FOTs in Odaiba and on the C1 Expressway as actual traffic environments (aiming to simulate environments that are difficult for sensors) as virtual-CG (Community Ground). Then, under these milestones, a series of models consisting of driving environments, spatial propagation, and sensors is being created. For this purpose, it is necessary to determine virtual environment units (package scenarios) in line with the targets and to continuously raise the level of reliable safety assurance for these scenario package units (Fig. 14).

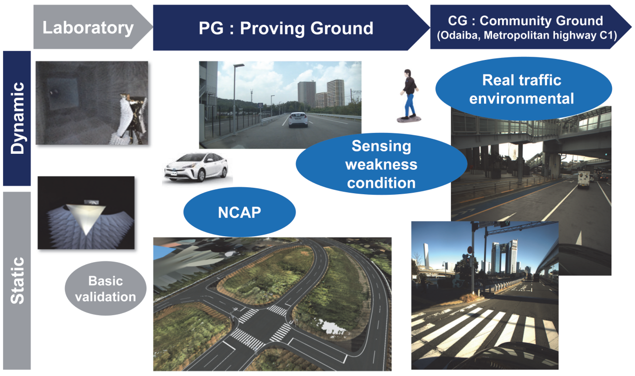


Fig. 14: Roadmap for DIVP® Scenario Packages

5.1. Application to NCAP Assessments as Virtual-PG

Detailed assessment protocols have been defined in Euro-NCAP, J-NCAP, and the like for advanced safety systems with automated driving functions such as Automated Emergency Braking (AEB), Lane Keeping Systems (LKS), Adaptive Cruise Control (ACC), Automated Lane Keeping Systems (ALKS), and the like. Although the traffic accident situation differs slightly from country to country, protocols incorporating accident conditions (such as the involvement of pedestrians, bicycles, left and right turns at intersections, and the like) and scenarios pertaining to ALKS (such as cutting in and out) are important. Although these scenarios do not involve many environmental conditions that are affected by sensing weakness points, this may be regarded as an effective simulation under conditions affected by surrounding light sources, such as conditions involving pedestrians stepping out into the road at night. This project is sequentially modeling each NCAP scenario (Fig. 15).

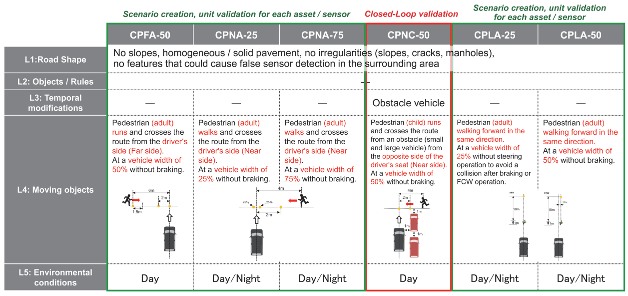


Fig. 15: Modeling of NCAP Assessment Environment

The following figure shows an example of a simulation incorporating the sensor model for a scenario in which a pedestrian suddenly emerges from behind a parked vehicle (Fig. 16).

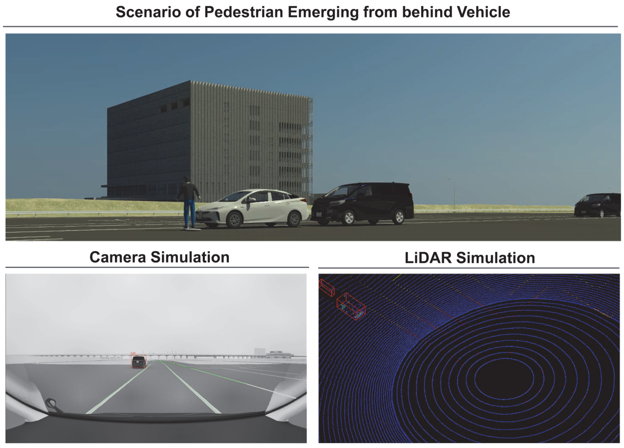


Fig. 16: Simulation of NCAP Scenario of Pedestrian Emerging from behind Vehicle

This type of virtual proving ground type scenario can be further expanded to system assessments factoring in the effects of rain, fog, the afternoon sun, and the like within a virtual environment (Fig. 17).

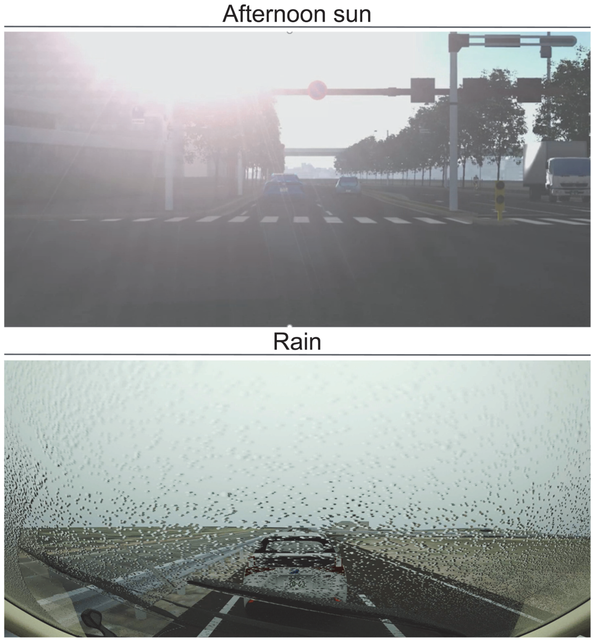


Fig. 17: Modeling of Afternoon Sun, Rain, and other Conditions

5.2. Application to Real-World Environments (Odaiba, C1 Expressway) as Virtual-CG

As the next scenario package, the project is constructing environmental models of Odaiba and the C1 Expressway, the two locations where the automated vehicle FOTs are carried out (Fig.18).

Fig. 18: Odaiba Driving Environment Model

This package is regarded as an effective means of assessing difficult sensor scenarios within a virtual environment combining real environmental factors (such as the driving environment, roads, geographical features, dynamic objects, weather, and so on). By liaising with other SIP-adus automated driving FOTs, conditional data for sensing weakness points that have occurred in real-world environments (locations, images, recognition outputs, and the like) are being fed back into the DIVP® simulator to facilitate the creation of a virtual environment capable of allowing assessments by more users as a virtual community ground.

For example, because the road surface in front of the Odaiba Telecom Center has a thermal shielding paint, the reflection characteristics of the asphalt and lane markers are similar, which makes lane marker detection by LiDAR difficult. This has been incorporated into the simulation model (Fig. 19).

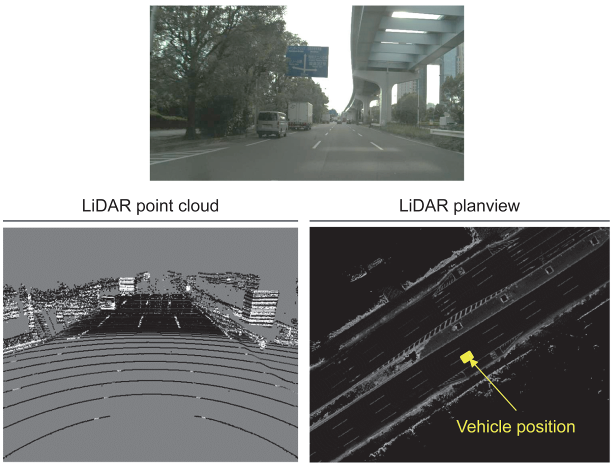
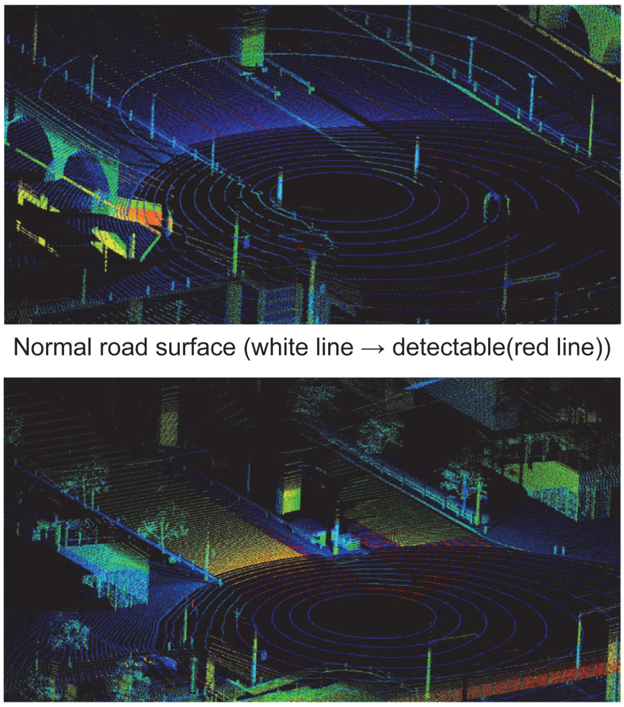


Fig. 19: Thermal Shielding Paint in Front of Odaiba Telecom Center (Source: measured data obtained in "The second phase of SIP- Automated Driving for Universal Services (Expansion of Systems and Services) ": "Research Related to Recognition Technologies and the like Necessary for Automated Driving Technology (Levels 3 and 4)", Kanazawa University [5])

Figure 20 shows the appearance of the simulation results. Although LiDAR is capable of detecting lane markers (white or red lines) with different characteristics on normal roads, when a thermal shielding paint on the road, the reflective characteristics become similar and white lines are not detectable.

Such collaboration with other automated driving projects demonstrates the effectiveness of the SIP-adus framework.



Thermal shielding paint (white line un-detectable)

Fig. 20: LiDAR Simulations (Near Front of Daiba Station)

6 Liaison Initiatives within Japan

6.1. OEM and Sensor Manufacturer Monitoring

To enable the research results to make a positive contribution to industry, DIVP® & Japan Automobile Manufacturers Association (JAMA) organized workshops involving OEMs in Japan. These workshops carried out two interim reviews of the research results and helped deepen understanding of the virtual environment simulations (Fig. 21).

Fig. 21: Workshop Involving Japanese OEMs

In addition, to obtain specific feedback from industry users, monitoring activities are being carried out with Japanese OEMs and sensor manufacturers. These liaison initiatives have helped to form a consensus on the value of using highly consistent simulations, improve connectivity with existing user simulations, identify requirements for expanding the scope of the simulations assuming industrial use (i.e., expanded assets, scenario models), and so on, and raise expectations for interface standardization. As a result, requirements pertaining to simulations have become clearer. It should also lead to the expansion of the DIVP® plan for the 2021 fiscal year into coordination with other simulations (such as Co-sim. and the like).

6.2. Collaboration with SAKURA Project for Safety Assurance

At the same time, the systemization of driving scenarios is advancing under the SAKURA Project adopted by the Japan Automobile Research Institute (JARI) under the auspices of the Ministry of Economy, Trade and Industry. With the cooperation of the SIP-adus DIVP® project, there are growing expectations for the development of a Japanese safety assurance system. This item started under a stronger organization in April 2021 as the Safety Assurance Foundation Joint Steering Committee.

7 Standardization and International Collaboration

7.1. Japan-Germany Collaborative VIVID Project

The German VIVALDI project shares the objectives of this project from the standpoint of contributing to automated driving safety assurance based on sensor modeling. Based on this background, a collaborative framework between SIP-adus in Japan and the Federal Ministry of Education and Research (BMBF) in Germany was created between VIVALDI and DIVP®. The collaboration between these projects began in October 2020 under the name VIVID. Through VIVID, the standardization of automated driving safety assurance systems and interfaces is currently in progress (Fig. 22).

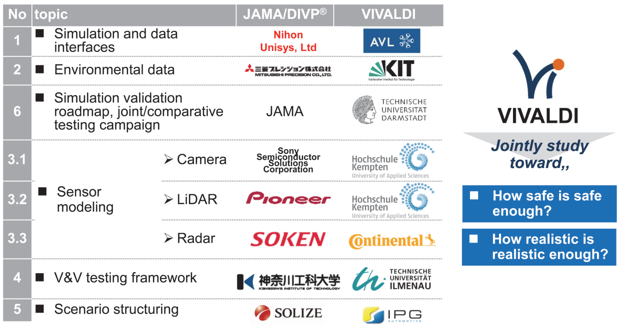


Fig. 22: VIVID Implementation Structure

7.2. Contribution for ASAM

The Association for Standardization of Automation and Measuring Systems (ASAM) is engaged in a wide range of standardization activities related to automated driving. DIVP® members are participating in Working Groups (WGs) such as OpenDRIVE/OpenSCENARIO, Open Simulation Interface (OSI), and the like, and is working to propose perception interfaces and other standards (Fig. 23).

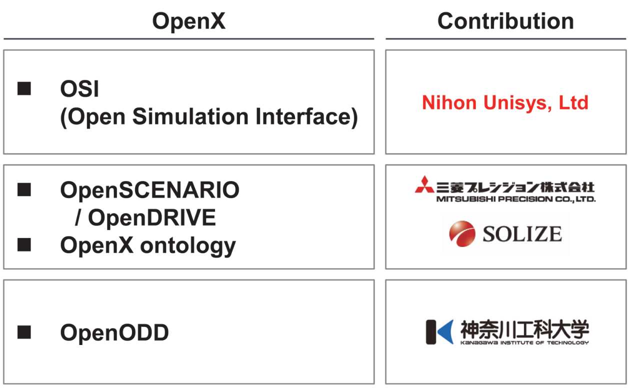


Fig. 23: Participation of DIVP® Members in ASAM WGs

8 Conclusion

This project has promoted industry-academic-government collaborative research and development as a part of the SIP-adus program. Utilizing the outcome of a series of models consisting of driving environments, spatial propagation, and sensors, this project would also like to enable connectivity with other simulators and provide a fundamental technological base to enable the efficient and widespread implementation of increasingly complex automated driving safety validations. The members of DIVP® hope that simulation based validation technology, which can create a precise digital twin of real-world environments, can help to raise consumer acceptance of the safety of automated driving while also helping to accelerate the social implementation of automated driving.

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Survey of New Cyberattack Techniques and Countermeasure Technologies

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The information on vehicles, people, infrastructures, and other elements projected onto maps and advanced map data that constitute automated driving system platforms is mostly obtained from external networks and sent to control units and information systems in order to controlling the vehicle. However, this situation is also a factor liable to trigger cybersecurity problems not found in traditional vehicles. The agreement on UN R155/R156 reached at the UNECE WP.29 also makes addressing cyberattacks necessary from a regulatory perspective. To solve such issues, this investigative research project focused on intrusion detection systems (IDS) as a technology to combat new cyberattacks after shipment. We formulated IDS evaluation guidelines to serve as a baseline for testing and evaluation when installing an IDS. At the same time, we assessed ways of collecting and storing information on connected car threats and carried out collection experiments using honeypots and other mechanisms in the context of building a system to provide initial response support in the event of an actual incident. The plan for this project extends to fiscal 2022, and the present fiscal year centered around fundamental research and studies. This report summarizes the outcomes of those activities.

1 Purpose and Overview of this Survey & Research Project

As part of the research and development plan for the second phase of the Strategic Innovation Promotion Program (SIP)–Automated Driving for Universal Services/surveys and research on new cyberattack techniques and countermeasure technologies, and in accordance with its purpose and objectives, the formulation of guidelines for IDS evaluation techniques and surveys and research on connected car threat information and initial response support will be carried out from August 2020 to March 2022.

2 Formulation of IDS Evaluation Guidelines

As shown in Fig. 1, this theme aims to contribute to security measures after shipment. We formulated IDS evaluation guidelines intended to serve as a baseline for individual OEMs in selecting, validating, and operating an IDS, with the objective of finally handing them over to an industry organization. The formulated guidelines also aim to raise security quality after vehicles are shipped, and notably envisions OEMs that have just begun considering introducing an on-board IDS as the primary target audience.

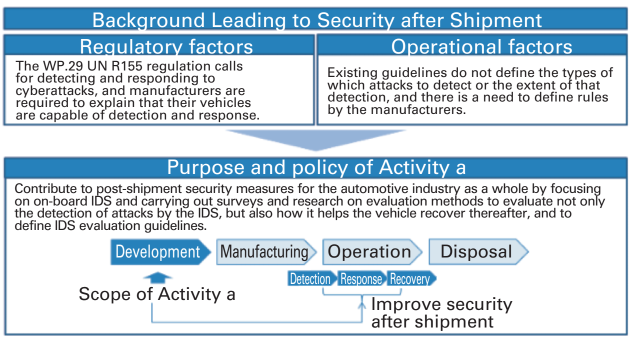

Fig. 1: Purpose and Policy for the Formulation of IDS Evaluation Guidelines

2.1. Approach to the Formulation of IDS Evaluation Guidelines

An overview of activities planned for the formulation of IDS Evaluation Guidelines is presented in Fig. 2. Of those, this section describes the survey of IDS basic functional elements and the assessment of evaluation points based on specifications.

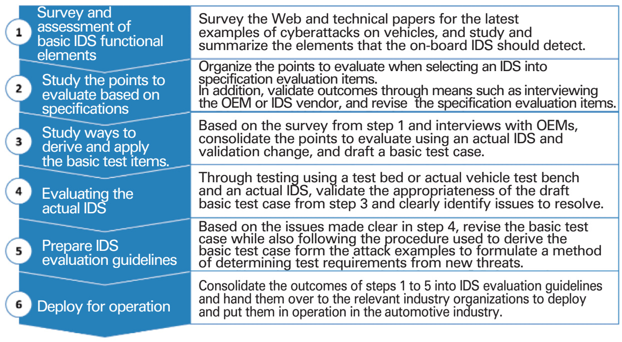

Fig. 2: Overview of the Approach to the Formulation of IDS Evaluation Guidelines

2.2. Survey and Assessment of Basic IDS Functional Elements

As part of our activities, we used actual attack examples as a basis for surveying conferences held in 2020, Web information, and vulnerability information to identify security events that an IDS should detect. We further narrowed down the results to twelve cases that directly affect the vehicle by reaching a control system and analyzed them in detail (Table 1). This analysis was used to identify phenomena that can occur and be observed in the network or the host as security events for each case (Table 2).

Table 1: Number of Cases Surveyed and Analyzed

	Cases surveyed	Cases analyzed
Web or vulnerability information	1,329	6
Technical papers	1,062	6
Total	2,391	12

Table 2: Security Events Identified from the Surveyed Cases

Event location	Event	Security event example
Network	Actions that contradict the context in the vehicle network	Sending a control message that does not affect basic actions, or a valid diagnostics message, at a timing that conflicts with the driving situation.
	Attack against the UDS protocol	Attack against the UDS protocol
	Physically connecting an unauthorized device to the vehicle network	Connecting an external device to the OBD I/F
	Fuzzing attack against the vehicle network	Fuzzing attack from the OBD I/F
Host	Unauthorized behavior	System or library calls from an unregistered process
	Unauthorized external communication	Communication with an unauthorized source or destination outside the vehicle
	Unauthorized file system manipulation	Changing critical file attributes (e.g., permissions)
	Unauthorized application installation	Installation of an unregistered application
	Unauthorized logs	Unauthorized system or application logs
	Unexpectedly frequent errors	Errors in processing requests to an external public service that exceeds the value set (in a unit time).
	High load	High CPU or memory load
	Modification to firmware	Modification to firmware

2.3. Study of Points to Evaluate Based on Specifications

As part of our activities, we used the answers to a 2019 questionnaire as a basis to prepare a questionnaire covering 24 items such as basic specifications for detection and other algorithms, types of detection functions and logged items. The questionnaire targeted six products from three IDS vendors, and we examined the information obtained about the evaluation (questionnaire) items. We designed the questionnaire to use multiple choice questions and followed up with inquiries to make the responses as easy to compare as possible.

2.3.1. Discussion

Each vendor had a similar set of security events subject to detection, indicate that they all support basic detection functions. There were no major differences in nominal specifications, making it impossible to compare vendors based on this item. However, distinctions in vendor approach started to appear in some functional specifications such as the types of protocols supported and functions to detect external devices. Each vendor supported logging and communication protocols or allows customization, which is normally carried out only at the request of the OEM. This means that for OEMs, knowing how the functions required of the IDS differ from the customized functions makes some degree of comparison between IDS products possible. Another distinction is the security operation center (SOC) operational level service to analyze detected contents offered by some vendors but not others. This is a useful item in making comparisons that also assess the availability of analysis following monitoring or detection by the IDS and support for response and recovery when needed.

2.4. Future Activities

The plan for this theme continues until March 2022. Our next step will be to work with OEMs and IDS vendors to test the feasibility and validity of the test items based on the ideas provided by already conducted surveys to perform actual tests, which will then be incorporated into the guidelines. In addition, we will continue to hold regular review meetings with stakeholders to ensure the guidelines prove useful to our target audience.

3 Surveys & Research on Connected Car Thread Information and First Response Support

This theme involves establishing methods to collect and store connected car threat information and formulating basic designs for first response support that leverages threat intelligence. The goal is to transfer their operation to industry organizations in 2023. Threat intelligence refers to information on collecting, analyzing, and storing information to provide support for responding to cyberattacks and other threats. Some industries are carrying out activities to share that intelligence between corporations[1]. Sharing threat intelligence is expected to prove effective at preventing a chain on damages from similar cyberattacks. Most of the information that is being shared at this point is threat information in the IT field.

3.1. Approach to Research

We drafted a plan based on the approach below to formulate basic designs for first response support that leverages threat intelligence. An overview of the approach to our overall activities is presented in Fig. 3 below. In addition to presenting our fundamental research and study of information collection and storage methods, this section also describes the early start for some honeypot-based information collection tests.

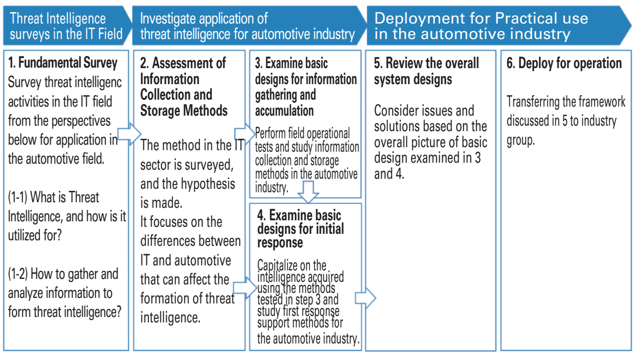

Fig. 3: Overview of Survey & Research Approach

3.2. Fundamental Survey

To define the basis of threat intelligence for vehicles, we looked at examples of threat intelligence activities in the pioneering field of IT to survey what type of threat intelligence is provided and how threat information is collected and analyzed. In the context of our activities, threat intelligence refers to the information collected and analyzed to provide support for responding to threats.

3.2.1. Threat Intelligence in the IT Field

Threat intelligence activities in the IT field are carried out by countries, industry groups, private businesses, and other organizations for a variety of purposes. Our research focused on threat activities intended to provide first response support.

There are five main types of information that constitute threat intelligence (Table 3). Next, we looked at how the threat intelligence was utilized. The results of consolidating the activity examples according to the Identify, Protect, Detect, Respond, and Recovery functions defined in Section 2 of the NIST Cybersecurity Framework (CSF)[2] is presented in Fig. 4.

Table 3: Examples of Information that Constitutes Threat Intelligence

No.	Information	Definition/overview
1	Indicators	Specific traces left by a cyberattack (e.g., malware hashes, IP addresses, URLs, or domain information).
2	TTPs (techniques, tactics, procedures)	Resources that make use of the attacker's intentions, behavior, and techniques. Approach based on the perspective of the target of the attack.
3	Security alerts	Information on system vulnerabilities or exploits.
4	Intelligence reports	Document detailing threat information to raise the situational awareness of the organization
5	Tool configuration	Establish tools to assist in making use of the information obtained from Nos. 1 to 4.

	Identify	Protect	Detection	Respond/Recover
(a) Indicators Specific events observed due to a cyberattack		Blacklist and block IP addresses, URLs, and domains used in cyberattacks.	Define and detect the security events among events observed in a cyberattack.	Verify traces of attacks and judge whether they are cyber-attacks, and formulate responses and restorations
(b) TTPs (techniques, tactics, procedures) An attacker's intention are explained from the viewpoint of resources to be used.	Identify information assets or systems representing potential targets and evaluate the impact a cyberattack would have.	Prepare attack scenarios and perform response training.	Define special behaviors in the TTPs and detect suspicious actions.	
(c) Security alerts Vulnerability information and exploit information for the system	Assess vulnerability systems and their impact when they are exploited.	Upgrade the programs of systems with vulnerabilities.		
(d) Intelligence reports Document describing threat-related information	Identify threats to the organization and evaluate their impact on business.			
(e) Tool configuration Setting of tools to support the use of information obtained from (a) to (d).		Using the information obtained in (a) to (d), define security tool settings and distribute them as a matter of policy to prevent attacks, detect them, and recover from them.		

Fig. 4: Example of Information Use Based on CSF

3.2.2. Threat Information Collection Methods in the IT Field

In the IT field, threat information is mainly obtained from publicly released surveys, incident reports, and the monitoring and testing of target networks and systems. Table 4 lists typical examples of information collection. Similarly, Fig. 5 presents the extent to which each of these collection methods can capture attacker techniques in terms of the cyber kill chain[3]. The weaponization phase of the cyber kill chain refers to the development stage of malware or exploit kits and cannot be captured by the methods shown in Table 4.

Table 4: Examples of Threat Information Collection Methods

Method	Overview	Example
Internet fixed-point monitoring	A method of finding out the global trend of cyber-attacks by observing communications on the Internet at fixed points.	• NICTER(NICT) • TSUBAME(JP-CERT/CC)
Honeypot	A method of publishing a system intended to be attacked on the Internet and gathering attacker access information. It is sometimes used as a decoy that is subject to attack instead of protecting a real system.	• MITF (IIJ) • IoT: A Malware Story (Kaspersky) • Connected home laboratory (Yokohama National University)
CTF	This method involves collecting information by asking white hackers to deliberately attack an environment simulating a system. Offering a playground for simulated attacks is also used as an alternative to the approach of setting anattack objective (flag) is set and competing for points (CTF).	• DEFCON CTF • SECCON
Bug bounty programs	A way to collect vulnerability information for actual systems in the filed by providing rewards to those who discover bugs.	• LINE Corporation Bug Bounty Program • Services such as HackerOne or Sprout
OSINT collection	This method collects information from the Internet both manually and through web crawlers, products, services, or other mechanical means. In addition to reporting examples, it can sometimes lead to discovering threats that are already active, such as a fake site or fake application for the organization.	• (Many products and services have been deployed.)

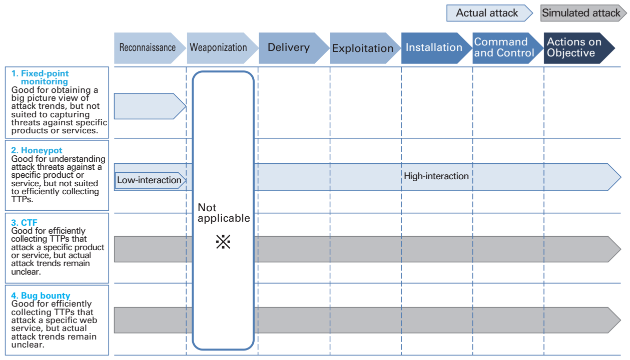

Fig. 5: Relationship between Information Collection Methods and the Cyber Kill Chain

3.3. Assessment of Information Collection and Storage Methods

In OS systems, the OS and other platform components are largely the same for the organization using them and between users, but in vehicles, the architecture differs in each model. Consequently, it might not be possible to make use of the format for sharing threat intelligence in the IT field to prepare countermeasures. This major difference from the IT field stems from the dependence of automotive hardware, software, and communication protocols involved in vehicle control on the OEMs. Conversely, analyzing the attack sequences leading taking control of the vehicle has shown that the methods used until the final objective is reached are not OEM-dependent. This constitutes promising potentially valuable information to share on common threats.

3.4. Test on Collecting Information Using a Honeypot

We have begun tests on collecting threat information using honeypots in after-sales products. First, we surveyed after-sales products that can be picked up in a broad area scan, and developed prototype honeypots for the applicable products. We initiated cyberattack monitoring tests in late January 2021.

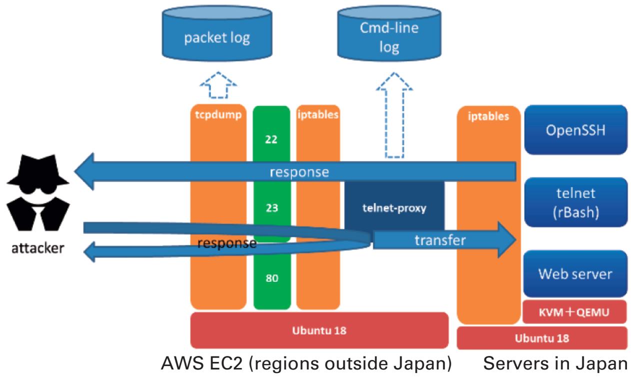

Fig. 6: Configuration of Honeypot Prototype Simulating an After-Sales Product

Current monitoring results have demonstrated many instances of activity consistent with the IoT malware (e.g., Mirai) pattern use against IoT products of sending IDs and weak password to the telnet server. These are viewed as automated attacks from devices infected with the same malware rather than attacks in which the applicable honeypot was targeted specifically as an on-board device.

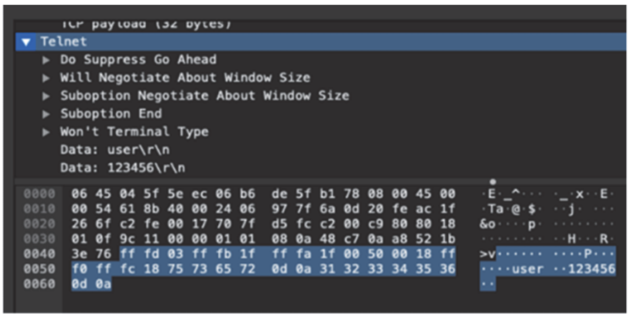

Fig. 7: Examples of Monitored Packets

3.5 Future Activities

The plan for this theme extends to March 2023. We will study sharing methods that allow responses to incidents in the industry to make use of the threat information collection tests and the collected information. To collect information, we are currently considering assessing the parameters to identify an attack targeting the vehicle using approaches such as capture the flag (CTF) and asking white hat hackers or vendors to deliberately attack the honeypots we set and monitoring the activity during those attacks.

4 Japan–Germany Cooperation

In Germany, the Federal Ministry of Education and Research (BMBF) is leading efforts to support research and development on connected car (automated driving) security, and currently has no less than four projects underway. Of those, SIP is cooperating with SecForCARs[4]. We will maintain regular communication and exchange opinions on the progress and outcomes of our respective research.

5 Summary

Ensuring vehicle cybersecurity also has an impact on the safety of the vehicle. This makes it appropriate to define minimum security standards to meet and shared industry threats as a cooperative area for the entire Japanese automotive industry and to proactively share information. Doing so will facilitate the development of connected services and allow greater operational efficiency that will help Japanese businesses retain their international competitiveness. At the same time, the framework for sharing stipulated security measures and information should not be restricted to sharing only within the Japanese industry. It is also necessary to present proposals for international standards and rules involving current vehicle security development, and to strategically approach standardization bodies to enable the use of the framework as a strength of Japanese businesses.

Given the above, information security activities involving automated driving systems have a critical role to play and are expected to contribute to the growth of industry security activities.

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Investigation of HMI and Education Methods for Advanced Automated Driving Systems

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This paper describes the research and development on HMI to carry out proper driving takeover in the event of a deviation from the driving environment conditions or a failure of the system, and research and development on the knowledge drivers and pedestrians should acquire, and effective education methods for that purpose initiatives of the second phase of SIP-Automated Driving for Universal Services. For the former, we studied evaluation parameters for driver situation monitoring before the transition from automated to manual driving, as well as the effectiveness of the HMI in fostering driver understanding of the system. We studied evaluation parameters for driver situation monitoring before the transition from automated to manual driving, as well as the effectiveness of the HMI in fostering driver understanding of the system. For the latter, guided by our main objectives, we defined and researched the three themes of (1) proposing education methods that build upon individual characteristics, (2) proposing motivational approaches, and (3) the development of modular educational material taking topic-specific training into account. Using our draft educational material, we also validated the effectiveness of providing advance general knowledge of automated driving in a driving simulator. The outcomes served as the basis for a workshop on automated driving education we held in the context of Japan–Germany cooperation.

1 Situations Involving a Transition from Automated to Manual Driving

During automated driving, limitations in system functions or other factors may require a transition from automated to manual driving. Consequently, it is essential for the system to monitor the driver's state during automated driving and know whether the driver is ready to take over driving. With respect to driver states, the first phase of SIP focused on distraction (eyes off road)(1), cognitive distraction (mind off road, namely thinking of something else and not paying attention to the information required for driving)(1)(2), and drowsiness (diminished alertness)(1)(3), and assess evaluation parameters for each of those states, as well as their effect on driving performance after a transition(4). Tactics to prevent a drop in alertness(5)(6) were also studied.

In the second phase, we categorized transitions into system-initiated and driver-initiated transition scenarios, and looked into issues involving human factors. In a system-initiated transition, the driver takes over after the system shows a notification to make the transition. In a driver-initiated transition, the driver realizes the limitation of the system functions and intentionally takes over driving.

2 System-Initiated Driving Transitions

2.1. Overview of Issues

In level 3 automated driving, having a driver engaged in something else during automated driving take over appropriately requires suitably redirecting that driver's focus back to the task of driving. Therefore, having the driver monitor the situation shortly before the request to intervene is viewed as an effective way to prepare for the transition. This makes evaluating whether a driver is monitoring the situation a crucial issue. In this theme, the recognition of that issue led us to work on evaluating the effect of pre-transition driver situation monitoring on post-transition driving behavior, methods for evaluating driver situation monitoring, and HMI that redirects attention back to situation monitoring.

2.2. Evaluation of the Effect of Pre-Transition Driver Situation Monitoring on Post-Transition Driving Behavior

(1)Test procedure

We tested 30 participants (15 women and 15 men in the 20 and 70 age range, with an average age of 45.7 years) in a driving simulator. Under automated driving, the vehicle cruised in the middle lane of a three-lane highway at a speed of 60 km/h. While the vehicle drove automatically, the test participants played a game (Tetris) on a tablet PC. A few minutes after the start of automated driving, a transition was initiated and a lane change was made manually. We measured the driving behavior, eye movement, and head movement of the driver at that time. Quitting Tetris and monitoring the situation one minute before the driving transition, and transitioning without such prior monitoring were set as test conditions.

(2)Test results: Driving performance after the driving transition

Calculating the percentage of successful lane changes in the predetermined section without hitting other vehicles after the transition showed a significantly higher score when monitoring was performed than when it was not. Those results suggest that a more appropriate driving transition can be achieved by monitoring the situation and preparing for the transition when a driver engaged in something else during level 3 automated driving has to transition to manual driving.

(3)Test results: Evaluation parameters for driver situation monitoring

Analyzing the rate of attention to the road every 10 seconds after the start of situation monitoring based on the driver's gaze behavior detected by an eye camera showed that the rate of attention to the road after the start of monitoring rose from 50% to 60% in the first 20 seconds, and then to 70% after 30 seconds. It subsequently remained at that level during and after the driving transition. Gaze behavior other than focusing on the road involved looking at the side mirrors, rearview mirror, and instruments. Those results established the rate of attention to the road after the start of monitoring as an evaluation parameter for driver situation monitoring, and suggest that the rate of attention rising to 70% from the low level after the start of monitoring could be used to determine that the driver is aware of road conditions and has reached a stable road monitoring state.

3 Driver-Initiated Driving Transitions

Under level 2 automated driving, the driver must remain aware of the situation and of the status of the system, and be ready to intentionally take over driving in scenarios at the limit of the system's functionality. We therefore studied both methods of evaluating whether the driver has an appropriate understanding of the system status, and HMIs that foster an understanding of the system to fully achieve an intentional driving transition by the driver.

3.1. Method for Evaluating Driver Understanding of the System

A driver state in the manual driving even during automated driving is coexisting with the system, which means that driver understands the status of the system. We analyzed differences in driver behavior during manual and level 2 automated driving and studied methods of evaluating the driver's understanding of the system status.

We conducted driving simulator tests with 10 participants[7], who drove manually and using level 2 automated driving in the second lane of a three-lane road with hidden risks requiring attention to the situation set along the driving route. Measuring gaze behavior during driving using a non-contact eye camera demonstrated a significant difference in attention span in several areas, with level 2 automated driving tending to exhibit a shorter attention span for the road ahead or the instrumentation, but a longer span for the surroundings or the mirrors.

3.2. HMI Fostering Understanding of the System

We proposed candidate HMIs to facilitate the driver's understanding of missed or erroneous detection by the system, and ran trials in a driving simulator. One of those was a test involving 18 participants in which the HMI was used to show the results of traffic condition recognition results in real time[8]. Answers to a questionnaire showed that having the HMI let drivers know about the possibility that the automated driving system had failed to recognize an object other than vehicles, suggesting that the HMI helped increase driver understanding of the system.

4 R & D on Knowledge Drivers and Pedestrians Should Acquire and Effective Education Methods

4.1. Proposing Education Methods That Build Upon Individual Characteristics

The results of the tests in the first phase of SIP[9][10] made it clear that going through various experiences gradually increase driver response ability. In contrast, delays in intervening in driving were observed when a "Sensor failure" or similar difficult situation was encountered suddenly. We also confirmed that acquiring experience with a "function failure (breakdown)" situation, probably the most severe of the conditions requiring a driving transition, proved useful when that situation actually occurred, and also that the experience had the potential to remain useful for a long time.

We then focused on resilience, one of the individual difference variables in personality traits, and looked into the effect of knowledge acquisition when transitioning from level 3 automated driving to manual driving. We analyzed the results of an Internet survey answered by 3,240 people during the first phase of SIP (in February 2019) for the relationship between personality traits and knowledge acquisition. We used flier-, quiz-, and video-based educational materials to compare the effectiveness of knowledge acquisition after studying with each type of material[12].

We set the binary variable for increased and non-increased groups obtained using propensity score matching as a dependent variable, and the group of variables expected to affect it as independent variables, and performed a logistic regression analysis. The results showed that the different types of educational material differed in their effectiveness at balancing resilience variations, and that videos had the highest potential for such balancing. Differences in resilience based on sex, age, and learning style were observed, and we intend to carry out further validation.

In addition to studying methods to build individual traits and provide effective education for many people, we also assessed method to easily distinguish traits. This led to the development of an abbreviated scale for learning style and career resilience.

4.2. Proposing Motivational Approaches

Safety education applies to all transportation users, resulting in a broad and diverse range of ages, backgrounds, and learning styles. Many of the people to educate have no interest in automated vehicles. Driver education can be provided in the driver's license renewal lecture, for example, but ways to make learning effective in a limited time have to be found. Therefore, we went beyond educational materials to also study ways of triggering interest in the contents taught. For this research, we employed the ARCS model of motivation and developed two types of motivational videos for safety education. The results of formative assessments suggest that both types of videos have equivalent motivation potential.

To study motivational methods for automated driving education, we also used the two types of motivational videos we developed in a web survey of 2,790 people, and assessed the validity of those videos while taking the effect of individual traits into account[14]. The propensity score matching results showed that compared to the fact-based motivational video, the narrative-based video balanced out individual resilience factors, and potentially led to commensurately higher score increases after the fact for lower levels of resilience. The use of the narrative-based motivational video also balanced out differences in individual resilience and showed that further taking individual learning styles into account could raise the usefulness of the material. The results also suggested that narrative-based motivation had the potential to balance out differences in individual attributes such as sex, age, marital status, and whether the person has children.

4.3. Developing Modular Educational Material Taking Topic-Specific Training into Account

Due to the diverse backgrounds of transportation users to educate, one of our goals is to develop and accumulate diverse educational modules that can be combined, enabling users to learn from materials adapted to their personal traits and learning style. In 2020, in addition to the two types of motivational videos described in Section 4.2, we developed a total of four modules consisting of quizzes and videos to learn about automated driving in general. Developing a variety of short teaching materials that allow microlearning makes it possible to use the modules on their own or in combination adapted to learning targets or actual purposes. We plan to continue our research aimed at offering individually optimized learning methods that encompass ways of combining the material as well as ways of presenting them that are suited to the individual.

In conjunction with educational materials, we also developed an abbreviated scale for learning style and career resilience to enable people to easily measure their own traits.

5 Validating Education Effectiveness on the Basis of Learning Opportunities

5.1. Learning Opportunities

This research products is also assessing learning opportunities for automated driving with social implementation in mind. Various learning opportunities, notably mass media and websites, can be envisioned as opportunities to present the knowledge required by people who use automated driving or interact with automated vehicles. Every opportunity is limited in terms of time available or resources. We therefore consider it important to select an appropriate degree of concreteness and level of detail matching its characteristics.

For a specific system, opportunities to impart knowledge and information to actual users include explanations at the offices of dealers or car rental agencies, or when the vehicle is delivered. Alternatively, the on-board system itself can convey knowledge.

Repeated surveys conducted until now in this research project[15] have shown that some people have zero knowledge of automated driving. However, some general knowledge is considered necessary before descriptions of a specific system can be understood. Therefore, in the context of this project, we have decided to work on validating the usefulness of conveying general knowledge of automated driving in advance.

5.2. Validation Using a Simulator

First, we decided to validate the effectiveness of providing general knowledge in trials preceding the educational material trials described earlier (Test 1). Building on the instruction material used in research on providing knowledge carried out in the first phase of SIP, we summarized the general knowledge on automated driving, created explanatory videos, and showed them to the test participants. Approximately one month later, we used a driving simulator to test the transition from automated to manual driving. In that test, we used two systems, one providing level 3 functionality only when following at low speeds and the other providing level 3 functionality without speed restrictions (between-subjects factors) to validate whether general knowledge applied usefully to multiple specific systems. Neither system has a lane changing function.

An example from the test results[16] is presented in Fig. 1. This example consists of a scenario where a vehicle has broken down and is stopped in the lane of the subject's vehicle, and a lane change must be made to avoid it. Since the automated driving systems used in this test do not have a lane changing function, the driver must take over to continue driving. The graph in Fig. 1 shows the proportion of people who collided with the broken down vehicle. The figure illustrates that providing general knowledge of automated driving in advance has the potential to enable an appropriate driving transition when the system presents a request to intervene in a situation requiring a transition.

Next, we conducted a validation test using the video material we developed described earlier (Test 2). For this test, a description of the system used in the test was provided in conjunction with general knowledge approximately one month before the simulator test. In the driving situation experienced in the first half of the test, many subjects failed to notice the request for a transition even though a request to intervene was displayed.

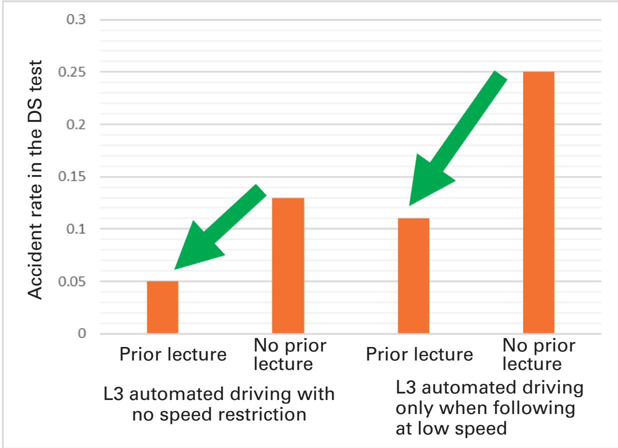

Fig. 1: Example from the Test Results

The difference between the tests is that in Test 1, the description of the actual system used was given on the same day as the test, while in Test 2 it was given one month earlier. Although the usefulness of providing general knowledge was confirmed in Test 1, it is necessary to promote the provision of that knowledge to enable truly safe use. We are currently studying that point.

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Research on Communication between Low-Speed Automated Transportation and Logistics Services Vehicles and Surrounding Traffic Participants

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The development of technology for low-speed automated transportation and logistics services vehicles, as well as field operational tests (FOTs) using the services vehicles in semi-mountainous regions, notably, are being carried out as part of efforts aimed at ensuring mobility for vulnerable road users as well as addressing the shortage of drivers in the field of transportation and logistics, reducing costs, and solving other social issues. Unlike traditional manually driven vehicles, low-speed automated services vehicles will not have a driver maneuvering the vehicle at all times in future. This creates safety, security, and traffic efficiency issues with respect to communication with other traffic participants such as pedestrians or other drivers. We analyzed the characteristics of communication measured in FOTs and other observations, and conducted experimental studies of communication methods (e.g., vehicle behavior and external HMIs) aimed at communicating the intent or state of the low-speed automated services vehicle to surrounding traffic participants, for the purpose of achieving safe, confident, and smooth communication between those vehicles and participants. Our research and development focus on recommending designs for communication methods to install in low-speed automated services vehicles and on extracting the knowledge surrounding traffic participants should have, and making proposals in that respect.

1 Background

The introduction and use of transportation and logistics services using automated vehicles operating at level 3 or 4 of the automated driving levels defined in the Society of Automotive Engineers (SAE) J3016 standard (June 2018) are being considered to solve the problems of ensuring mobility for vulnerable road users in semi-mountainous or depopulated regions, and to mitigate the driver shortage in the field of transportation and logistics services. As the early stages, the use of automated transportation and logistics services vehicles is envisioned based on low-speed cruising operations on public roads where pedestrians, drivers, and other surrounding traffic participants go and come. In regional FOTs, an operational crew in the vehicle is ready to intervene emergently from automated driving to manual driving to ensure safe operation. Upcoming advances in technology are expected to lead to operational patterns adapted to regional circumstances or restrictions, including a pattern where an operational crew may ride in the vehicle but almost never intervene in driving operations, and a pattern with no operational crew riding in the automated vehicle.

Introducing low-speed automated transportation and logistics services vehicles (automated services vehicles) on actual roads will create interactions with pedestrians, drivers, and other surrounding traffic participants. Such interaction differs from those with traditional manually driven vehicles. In manual driving, the driver in the vehicle frequently uses gestures or eye contact to ensure conditions are safe with respect to surrounding vehicles, pedestrians, or other traffic participants, or ensure smooth traffic flow by clearly yielding to the other party. These indications of intent by the driver can be viewed as communication that enhances the safety of other traffic participants and facilitate the smooth flow of surrounding traffic. In the context of automated services vehicles and surrounding traffic participants, such traditional communication by the driver will be difficult under the envisioned conditions of an operational crew who rarely intervenes in driving operations or of no operational crew riding the vehicle. At the same time, surrounding traffic participants attempting to rely on such communication cue will be unable to do so. With low-speed automated services vehicles, vehicle behavior such as deceleration is difficult for traffic participants to perceive as a communication cue, and it is possible that available communication means and media will be more restricted than in traditional manual driving.

From these circumstances, our research and development focus on extracting recommendation of designs for communication methods to be installed in low-speed automated services vehicles and the knowledge that surrounding traffic participants should have. Through these research and development, we aims to realize the safe, secure, and smooth communication between automated services vehicles and surrounding traffic participants.

2 Communication Analysis Based on Video Data

In cooperation with the Field Operational Tests of Automated Driving Services in Semi-Mountainous Regions Using Michi no Eki Roadside Stations as Hubs, we analyzed the video data from dashcams installed in low-speed automated transportation and logistics services vehicles. We extracted unsafe or inefficient cases caused by communication mix-ups or failures between automated services vehicles and the surrounding traffic participants from the traffic situations involving the two approaching or interacting with one another, based on the video data[1]. We then analyzed the characteristics of such cases.

2.1. Analyzed FOT Regions and Automated Services Vehicles

The analyzed FOT regions consisted of the seven regions centering on a michi-no-eki roadside station shown in Table 1. Automated services vehicles operated for a total of 233 days, with 20 or more days of operation per region. Two types of automated services vehicles, the golf cart and bus as shown in Fig. 1. were used in the various FOTs. For automated driving, the golf carts ran a route along electromagnetic induction lines embedded in the road, while the buses employed GPS, electromagnetic induction lines, and gyroscopic sensors, with each type of vehicle only driving along it specified course.

Table 1: Analyzed FOT Regions(2)

FOT region	Prefecture	Vehicle used
Cosmall Taiki Michi-no-Eki	Hokkaido	Bus
Kamikoani Michi-no-Eki	Akita	Golf cart
Hitachioota Michi-no-Eki	Ibaraki	Golf cart
South Alps Village Hase Michi-no-Eki	Nagano	Bus
Ashikita Dekopon Michi-no-Eki	Kumamoto	Golf cart
Yamakawa Branch Office of Miyama City Hall	Fukuoka	Golf cart
Okueigenji Keiryunosato Michi-no-Eki	Shiga	Golf cart

(a) Golf cart

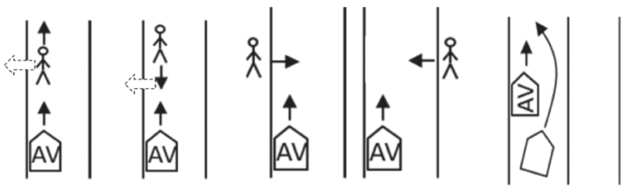
(b) Bus

Fig. 1: Low-Speed Automated Transportation and Logistics Services Vehicles(2)

Vehicle speed during automated driving was 12 km/h or less for the golf carts, and 35 km/h or less for the buses. Nevertheless, the operational crew riding in the vehicle sometimes had to intervene and manually slow down or steer the vehicle to ensure safe operation or avoid parked vehicles. In all FOT regions, the automated services vehicles used the michi-no-eki or branch office as a hub and traveled between government offices, post offices, hospitals and other major community facilities or connected to routes for the transport of goods such as agricultural products. However, the road environment and traffic conditions exhibited different characteristics between regions.

2.2. Communication Scenarios Observed and Their Analysis

In analyzing the video data, we broadly defined communication as "traffic situations in which a traffic participant recognizes the presence of the automated services vehicle, which then appears to affect the subsequent behavior of that participant in some way". Based on that definition, we extracted the three main types of communication patterns between automated services vehicles and surrounding traffic participants as shown in Fig. 2. (In the figure, "AV" identifies the automated services vehicle.) The observed communication patterns are described as below.



(a) Approach and avoidance (b) Crossing (c) Overtaking

Fig. 2: Categories of Communication Patterns with Traffic Participants

(1) The approach and avoidance case

As shown in Fig. 2(a), this case involves either the traffic participant or the automated services vehicle moving away from the course of the other party to let them pass when the automated services vehicle approaches the course of the traffic participant from behind (or from the front). We observed the following type of inefficient communication for this case.

- The traffic participant who notices the approach of the automated services vehicle tries to let it pass by moving away from its course, but does not move aside sufficiently, preventing the automated vehicle from resuming its course and requiring the operational crew to intervene and manually steer the vehicle outside the scheduled course.
- The traffic participant who notices the approach of the automated services vehicle moves to the road shoulder to avoid it, but does not move aside sufficiently, and blocks the automated vehicle's scheduled course. The participant moves further aside little by little until the automated services vehicle is finally capable of proceeding along its scheduled course and resumes driving.

While the cause of these inefficient communication instances is dependent on technical restrictions in the automated services vehicle, there is also a possibility that they are triggered by the traffic participant either failing to understand or not knowing at all that the automated vehicle can only drive along a specified course.

(2) The crossing case

As shown in Fig. 2(b), this case involves the pre-determined courses of the automated services vehicle and the traffic participant intersecting, with one party stopping to yield the way to the other. When the traffic participant is a pedestrian, the automated services vehicle yields the way in almost all situations. We observed the following type of inefficient communication for this case.

- The automated services vehicle stops ahead of the traffic participant's with the intention of yielding the way, but the traffic participant does not cross immediately even after noticing that the automated vehicle has stopped. They only start crossing after the operational crew in the vehicle gives a signal such as a gesture or eye contact, or after a certain amount of time has elapsed.

This inefficient communication is caused by the traffic participant being unable to determine whether the automated vehicle is indicating that it is yielding the way or some other intent. This brings up the possibility that without a gesture, eye contact, or other signal from the operational crew surrounding participants cannot properly recognize or determine automated vehicle intentions such as yielding or starting off.

(3) The overtaking case

As shown in Fig. 2(c), this case involves another driver (the following driver) approaching the low-speed automated services vehicle from behind, and overtaking it after coming close. This case was observed relatively often. We observed the following type of unsafe communication for this case.

- The following driver fails to check the oncoming lane properly before overtaking the low-speed automated services vehicle, or rushes to overtake despite the presence of an oncoming vehicle. The overtaking maneuver sometimes leads to straddling the center line, causing a near miss when passing the oncoming vehicle.
- Several other drivers approach and follow behind the low-speed automated services vehicle. When the first following driver starts to overtake the automated vehicle, the second and subsequent drivers follow suit without checking the oncoming lane properly, or rushing to overtake despite the presence of an oncoming vehicle. The overtaking maneuver sometimes leads to straddling the center line, causing a near miss when passing the oncoming vehicle.

Prolonged following of the low-speed vehicle, rather than the fact that it is an automated services vehicle, is thought to be the cause of these unsafe instances. Nevertheless, such unsafe instances triggered by low-speed operation can also be interpreted as a technical restriction confronting current automated services vehicles. In contrast, use of a combination of the turn signal and vehicle behavior by the low-speed automated services vehicle to communicate that it is yielding the way to the following driver can potentially cause confusion between the intent to turn left or yield for that driver[1].

3 Study of Communication Methods for Low-Speed Automated Transportation and Logistics Services Vehicles

Using the technical restrictions on low-speed automated driving services vehicles and the characteristics of surrounding traffic participant behavior with respect to such vehicles as a basis, while also taking the completeness of communication use cases into account, we analyzed the dashcam video data from the Field Operational Tests of Automated Driving Services in Semi-Mountainous Regions Using Michi no Eki Roadside Stations as Hubs. That analysis revealed the three notable cases of approach and avoidance, crossing, and overtaking, as instances unsafe or inefficient communication that will require making improvements or providing support. Candidate communication for those use cases include not only the vehicle behavior (stopping position, slowing down) and external HMI outcomes of the first phase of SIP[3], but also additional approaches such as the road markings and audio messages already implemented in some FOT regions. We are assessing the anticipated effectiveness of communication based on the introduction of those approaches through both desk study and experiment.

4 Study of Communication with Pedestrians Using a VR Experiment

4.1. Experiment of Communication with Pedestrians for Crossing a Basic Road Section

Targeting the communication use case of inefficient crossing on a basic road section, we conducted experiments using a head-mounted display (HMD) and a virtual reality (VR) environment. We evaluated and analyzed how communication method affects the recognition and decision to cross of pedestrians, and are assessing recommended designs and other aspects of communication methods with surrounding traffic participants for crossing on a basic road section.

Fig. 3: VR Environment for Residential Roads in Regions around a Michi-no-Eki Hub

Fig. 4: Conveying Intent or State Using an External HMI

(1) Procedure

We prepared a road environment representing residential roads in a region around a michi-no-eki hub (see Fig. 3), and had the test participants playing the role of pedestrians experience a situation where an automated services vehicle approaches as they are about to cross a residential road. We then studied how factors such as the automated services vehicle stopping position or deceleration, and the conveying of intent or state through an external HMI (see Fig. 4) affected the perception and psychological aspect of the pedestrians and their decision to cross.

(2) Results

Among the methods of communication used by the automated services vehicle to indicate its intent to yield the way, main factor influencing the pedestrian's decision to cross is the vehicle's behavior. Implementing an external HMI has been shown to enable a faster decision to cross when vehicle behavior alone is not enough to make that decision. While the negative effects of external HMIs also have to be considered to fully determine their operation, promising results were obtained regarding external HMIs decreasing the decision-making uncertainty caused by buses or other large vehicles even if they are still far from the pedestrian.

4.2. Experiment of Communication with Pedestrians for Crossing in a Parking Lot

Targeting the communication use case of inefficient crossing in a parking lot, we conducted experiments using an HMD and a VR environment. We evaluated and analyzed how communication affects the mindset and decision to cross of pedestrians, and are assessing recommended designs and other aspects of communication methods with surrounding traffic participants for crossing in a parking lot.

(1) Procedure

We prepared a road environment representing a michi-no-eki parking lot (see Fig. 5). In this scenario, they got out of their vehicle and walk across the passage of cars at parking lot to the michi-no-eki building. When they were about to cross the passage of cars, they experienced a situation where an automated services vehicle approaches. We then studied how factors such as the automated vehicle stopping position or deceleration, and the conveying of intent or state through an external HMI affected the perception and psychological aspect of the pedestrians and their decision to cross.

Fig. 5: VR Environment for Michi-no-Eki Parking Lot

(2) Results

Unlike basic road section, parking lots are characterized by not very clear through-traffic zones or priority rules. Among the methods of communication used by the automated services vehicle to indicate its intent to yield the way, main factor influencing the pedestrian's decision to cross is the vehicle's stopping position. Implementing an external HMI has been shown to enable a faster decision to cross when vehicle behavior alone is not enough to make that decision, and the results obtained were the same as those for the basic road section. The results also suggested that if the automated services vehicle is still far away from the pedestrian when it communicates its intent to yield through a combination of stopping position and external HMI, it can be difficult for that pedestrian to determine whom that communication is targeting and it also induce uncertainty in making decision to cross.

4.3. Experiment of Communication with Pedestrians for Approach and Avoidance on a Basic Road Section

Targeting the communication use case of inefficient approach and avoidance on a basic road section, we conducted experiments using an HMD and a VR environment. We evaluated and analyzed how communication affects the recognition and decision to cross of pedestrians, and are assessing recommended designs and other aspects of communication methods with surrounding traffic participants for approach or avoidance on a basic road section.

(1) Procedure

We prepared a road environment representing a basic road section around a michi-no-eki hub (see Fig. 3), and had the participants playing the role of pedestrians experience a situation where they walk along the left side of the basic road section and an automated services vehicle approaches from behind and stops, and the subject turns around and sees the state of the automated vehicle. We then studied how factors such as the automated services vehicle and external HMI, and road markings (see Fig. 7), affected the perception and psychological aspect of the pedestrians, as well as their avoidance decision and behavior.

(2) Results

In terms of communication when the automated services vehicle approaches a pedestrian from behind, conveying the behavior of the vehicle through an external HMI such as “I will stop” is unlikely to make that pedestrian aware of the need to move away from the scheduled course of the vehicle or prompt a decision to do so. We are continuing to study combinations that use audio messages and external HMIs to address situations were setting road markings or other roadside approaches is difficult.

Fig. 6: VR Environment for Basic Road Section in Regions around a Michi-no-Eki

Fig. 7: External HMI Equipment and Installation of Road Markings

5 Study of Communication with Following Drivers Using a DS Experiment

Targeting the communication use case of unsafe overtaking on a basic road section, we conducted experiments using a driving simulator. We evaluated and analyzed how communication affects the perception and decision to overtake of following drivers, and are assessing recommended designs and other aspects of communication methods concerning decisions to overtake on a basic road section.

(1) Procedure

We prepared a road environment representing roads in a region around a michi-no-eki hub and had the participants playing the role of driver experience a situation where they follow and then overtake an automated services vehicle from behind. We then studied how factors such as the automated vehicle behavior or lighting devices, and the conveying of intent or state through an external HMI (see Fig. 8) affected the psychological aspect of the following drivers, as well as their perception and decision to overtake.

(2) Results

Fig. 8: Conveying Intent or State Using an External HMI

The experiment confirmed that when following drivers repeatedly experience an automated services vehicle using its left turn signal and slowing down to convey its intent to yield, those actions can potentially create confusion and lead to misunderstanding about whether the automated vehicle is making a left turn or yielding. At the same time, the experiment indicated that such confusion or misunderstanding could be cleared up when an external HMI is used to convey the intent to yield to the following driver. Studies in this area are still underway.

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