NISSAN TECHNICAL REVIEW

2024
No. 90

Electrification／
Advanced Driver Assistance Systems (ADAS) & autonomous driving／
Connected service

NISSAN
MOTOR CORPORATION

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Nissan's advanced technology development for constantly staying one step ahead

Senior Vice President **Takao Asami**

1. Introduction

The year 2023 marks Nissan Motor Corporation's 90th anniversary since it was founded in 1933. This is the 90th issue of the Nissan Technical Review. The first issue was published in 1965, before the merger between Nissan Motor Corporation and Prince Motor Company, which was the year automobile imports were liberalized. Since 1965, the Japanese automotive industry has faced global competition. The first commemorative article titled "Research on the Valve Train," introduced the research on engine technologies. Since then, various technologies have been introduced.

Some of the technologies that led to the development of the current electrification and autonomous driving technologies are highlighted in this article. For example, articles related to electrification include those on the MARCH EV concept using an AC Motor published in issue no. 10 (1984), trends in electric vehicles in a special feature highlighting the environment in issue no. 32 (1992), LEAF in issue nos. 69 and 70 (2012), and e-POWER in issue no. 80 (2017). Articles related to autonomous driving include articles on active safety technologies in the special feature highlighting safety in issue no. 33 (1993), ITS in issue no. 40 (1996), telematics development in issue no. 53 (2003), and Safety Shield concept in the special feature highlighting safety in issue no. 63 (2008). These articles confirm that R&D activities accumulated over the years have become the basis for current technologies.

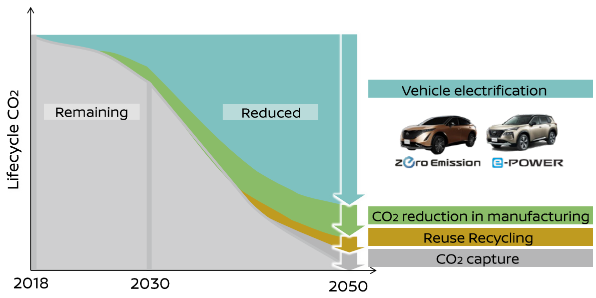
In 2023, when issue no. 90 was planned, the world economy had started to gradually shift to the recovery phase from the economic slowdown caused by the COVID-19 pandemic and semiconductor supply shortages. However, 2023 was a year of continuing international tensions, including policies on economic decoupling between countries, as well as wars and conflicts in several regions. In the automotive industry, the expansion of the electric vehicle (EV) market and significant progress of Chinese automotive manufacturers attracted considerable interest. Europe and China implemented EV promotion policies for improving the environment and stimulating the economy, which led to the ratio of EVs in new-car sales to exceed 20%. In China, automotive manufacturers funded by the local capital that managed to adapt to the new energy vehicle (NEV, corresponds to EVs and PHEVs) promotion policy gained a considerable market share. These manufacturers strived to increase exports to overseas markets, making China the largest vehicle exporter in the world, overtaking Japan. Meanwhile, in Japan, the "Japan Mobility Show," renamed from the "Tokyo Motor Show," was held with the theme of future mobility, comprising automobiles and various other means of transportation. Nissan exhibited five concept vehicles and proposed an attractive product image realized by only EVs as well as a future image of a new mobility system associated with infrastructure for information and energy.

Concept vehicles exhibited in the Japan Mobility Show 2023

In this turbulent era, as Nissan's engineers, we must follow Nissan's DNA ("Do what others don't dare to do"), develop products and services that realize our corporate purpose ("Driving innovation to enrich people's lives"), and establish innovative novel technologies and sophisticated fundamental technological capabilities supporting our purpose. This special feature introduces technologies related to three areas to which Nissan is committed: "electrification," to realize carbon neutrality; "autonomous driving," to realize a safer and more comfortable riding experience; and "connected service," to maximize the value of traveling by automobiles. This article discusses the basic concepts in each area.

2. Electrification

The largest source of CO_2 emission during the life cycle of an automobile, from its production to disposal, is the CO_2 emitted when the automobile is used. To suppress these emissions, CO_2 emissions caused by internal combustion engine vehicles must be minimized by switching to EVs. The CO_2 emissions caused by generating electricity used by EVs must be reduced by utilizing solar power, wind power, nuclear power, etc.



Approach to reduce CO_2 emissions by 2050

After the introduction of a larger number of EVs, several problems have become apparent from the customers' perspectives, including high costs, short driving ranges, and long charging times. Many of these problems are caused by the electrical properties of the battery. For example, the energy densities of lithium-ion and all-solid-state batteries are approximately 200 and approximately 400 Wh/kg, respectively. In contrast, the energy density of gasoline is approximately 12,000 Wh/kg, which is 30–60 times higher than that of the batteries. In the current era of global competition to improve battery performance and cost, Nissan aims to increase energy density, improve charging performance, and reduce costs by utilizing battery technologies accumulated over the years to develop battery technologies of three generations: liquid lithium-ion, all-solid-state, and lithium-free future batteries.

However, developing batteries with an energy density comparable to that of gasoline can take a considerably long time. Therefore, we can work on technologies for improving the electrical energy consumption for efficient energy use. Some specific technologies that we are currently working on include those for reducing vehicle mass, reducing air resistance, comprehensive energy management systems, improving the thermal insulation performance of vehicle compartments, reducing electric power used by the electric equipment, reducing tire rolling resistance, inverters that use SiC, small-sized high-speed motors, and X-in-1 units that integrate the motor, inverter, and reduction gear. We hope to develop EVs that more customers will choose by improving their battery and electrical energy consumption.

The efficiency of electric motors exceeds 90%, which significantly exceeds the accepted efficiency limit for internal combustion engines (50%). In principle, electric motors are highly responsive and controllable, and therefore, electric motors have strong and smooth starting and accelerating performances and can be used as electric power generators when the vehicle is decelerating. An electric motor is ideal for driving power, and therefore, efficiently mounting an energy source and supplying electricity is the challenge that needs to be overcome.

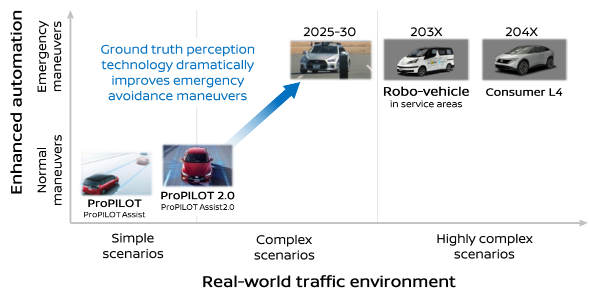
Electrified vehicles with various energy-source configurations such as HVs, BEVs, and FCEVs have emerged worldwide. These variants coexist for some time depending on their usage.

3. Autonomous Driving

Passive and active safety technologies are required to achieve Nissan's goal related to safety, i.e., "zero fatality," which involves eliminating fatalities attributed to traffic accidents involving Nissan vehicles. Nissan has an extensive experience in passive safety technologies. One example is the establishment of the Oppama Crash Laboratory in 1967. As on-board technologies, the three-point seat belt was adopted in 1967; the air bag was adopted in 1989; the "zone body concept," which is the vehicle body structure that absorbs the collision energy, was adopted in 1996; and the "pop-up engine hood" was adopted in 2007. These measures contributed to reducing the severity of injuries inflicted on the vehicle occupants and pedestrians. Meanwhile, analyzing the recent accident statistics data of various regions of the world indicated that there is more potential for contribution by implementing measures to avoid the occurrence of accidents by employing active safety technologies.

Nissan's autonomous driving technology was established based on the accumulation of active safety technologies. Since the introduction of the "safety shield" concept in 2004, Nissan introduced more than ten of the world's first technologies in 20 years. Although active safety technologies contribute to decreasing traffic accidents and the number of victims involved, these technologies contribute to expanding traffic environments and traffic scenes where the driving assistance and autonomous driving systems can perform their function. One such example is the evolution of ProPILOT Assist (2016) into ProPILOT Assist 2.0 (2019).

The emergency avoidance maneuvering technology currently under development is planned to be adopted in next-generation driving-assistance systems. This is expected to improve safety further and manage more complex traffic environments. Another activity, wherein data are collected from a traveling vehicle, uploaded to the cloud, processed in the neural network, and used to develop an AI-powered autonomous driving algorithm, has been initiated to realize fully autonomous driving in future. These technological evolutions will help come one step closer to realizing zero accidents. In future, we intend to provide mobility services to driverless vehicles and implement fully autonomous driving technology for mass-produced vehicles.



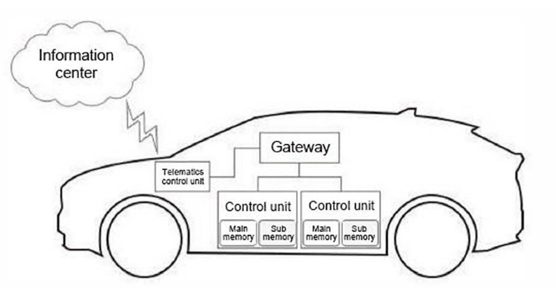
Roadmap for the evolution of ProPILOT Assist

4. Connected Service

Since the IT revolution of 1985, internet revolution of 1995, emergence of smartphones in 2007, start of 4G/5G service in 2012/2020, and generative AI revolution in 2022, the evolution of information and communication technologies appears to be accelerating. For example, the communication speed of smartphones has evolved and become 100,000 times faster in the past 30 years, enabling real-time communication of large-sized data such as videos.

Automobile functions have significantly changed because of these evolutions in information and communication technologies. In Nissan, the company’s first navigation system “MULTI AV SYSTEM” was mounted in CIMA, CEDRIC, and GLORIA in 1989, and the company’s first connected service “Compass Link,” which was a remote-operation assistance service (assisted by a human operator), was started in 1998. Further, “CARWINGS,” which provided an enhanced information service, was started in 2002. Currently, the “NissanConnect” service is provided around the globe using cloud technology. In addition to the map data update service via cloud communication, a system that sends real-time road traffic and traffic light information to vehicles has been introduced in some regions.

In recent years, various manufacturers have introduced the software-defined vehicle (SDV) concept, which is a structure that separates the software and hardware of vehicles. This has led to a significant increase in the speed of development and the deployment of software related to adding and updating various vehicle functions. Further, Nissan benefitted from this in ARIYA, where the software of 32 ECU units could be updated at any time through cloud communication.



Updating the software over the air (OTA)

In future, communication infrastructure is expected to shift from 5G to 6G, enabling us to handle data sizes that are even larger. Various data, including vehicle status and operation status, will be accumulated in the cloud, and IT technologies such as AI and neural networks will help accelerate the development and deployment of software to provide new services and improve existing services. Examples of such services include route guidance that considers road traffic conditions and charging plans, automatic settling of expressway tolls and parking lot fees, version upgrades of the autonomous driving assistance functions, and obtaining driver information from the cloud so that the same HMI can be displayed to the driver, even if the driver drives the vehicle for the first time. As described in this article, automobiles in the future will not only be a means of transportation, but also become a part of the social system, with the vehicle being connected to the information networks inside and outside the vehicle.

5. Summary

The three areas highlighted in this special feature helped Nissan differentiate itself from other companies. Automobiles, which consist of various types of technologies, are expected to adopt novel technologies originating from other industries such as software, AI, cloud, semiconductors, batteries, and electric power control, in addition to conventional automotive technologies to help accelerate their evolution to become society’s mobility infrastructure system. We would like to actively develop revolutionary technologies and create innovations so that by 2050, we can realize carbon neutrality, complete recycling of resources, virtually zero traffic accident fatalities, and improvements in people’s lives through the mobility provided by automobiles.

Special Feature 1:Electrification

1. Nissan’s electrification revolution: History of 75 years from “TAMA” to “ARIYA” and a vision for the future

Atsushi Teraji*

1. Introduction

The electrification history of Nissan Motor started in 1947 with the launch of the electric vehicle (EV) “TAMA” and has spanned 75 years. From the beginning, we recognized the potential of the so-called electrification, wherein vehicles are driven by electricity and motors, to balance environmental and energy issues such as fuel use in the automotive society, while ensuring a fun driving experience. In 1997, the world's first model equipped with a lithium-ion battery, “PRAIRIE JOY EV,” was launched, followed by the world's first mass-produced electric vehicle, “LEAF,” in 2010. More recently, the hybrid “e-POWER,” a 100% motor-driven powertrain, was introduced after “NOTE” and released in 2016. The hybrid system limits the increase in cost by sharing components with EVs as far as possible and successfully enabling more people to share the joy of driving an EV, such as powerful and smooth acceleration and the feeling of one-pedal driving because of the high controllability of the motor as with “LEAF.”

Nissan Motor is now steadily promoting electrification, incorporating many of the latest technologies into the electric-drive vehicles. These achievements have contributed not only to improved environmental performance but also to better driving experience features such as “e-4ORCE,” enhanced mobility values such as “LEAF to Home,” and models ranging from today's EVs, “ARIYA” and “SAKURA,” to vehicles equipped with “e-POWER” such as “NOTE,” “SERENA,” and “X-TRAIL,” through numerous trial-and-error and improvement processes. Therefore, the sales ratio of 100% electric drive vehicles exceeded 50% in the first half of FY2023, especially in Japan, where electrification is currently progressing.

In future, we will promote technological development, such as efficiency improvements based on electrification, eco-cycles that build a large profit structure through the collaboration of products and services across industries, and vehicle grid integration (VGI) that integrates EVs and the power grid to contribute to a sustainable and steady development of not only vehicles but also the entire society.

2. Dawn of electrification

2.1 “TAMA,” the beginning of electrified vehicles

“TAMA” (Fig. 1) was an electric vehicle manufactured by “Tokyo Denki Jidosha” (later Prince Motors) derived from pre-war Tachikawa Aircraft. When TAMA was launched in 1947, Japan suffered from a serious oil shortage under the General Headquarters' control of munitions, although hydroelectric power was available in surplus, drawing attention to EVs. The EVs were accepted in the market because of their equal or superior transportation capacity compared to that of the charcoal-powered vehicles of the time. Employing a replaceable lead-acid battery with a maximum output of 3.3 kW, “TAMA” came first in the first government-sponsored performance tests by achieving a driving range of 96 km and a maximum speed of 35 km/h, earning a high reputation in the taxicab market until around 1951. For example, the engine mounted on “DATSUN 17 SEDAN” of the same class launched around the same time was a type 7 four-cylinder engine with a displacement of 722 cc, compression ratio of 5.4, and an output of 11.9 kW (16 hp). The heat exchange ratio estimated from its specifications was approximately 25%, which was slightly more than 60% of that of a modern Kei car engine, with a ratio approaching 40%.

Fig. 1 “TAMA” (1947)

*EV System Laboratory

Table 1 Distribution status and capacity of charging stations in Japan (1950)[1]

Electric bureau	Less than 50 kW	Less than 100 kW	100 kW or more	Total
Tokyo	37	24	7	68
Nagoya	14	4	4	22
Osaka	25	7	13	45
Hiroshima	3	4	0	7
Shikoku	6	1	2	9
Fukuoka	2	2	3	7
Sendai	0	0	1	1
Sapporo	4	2	1	7
Total	91	44	31	166

Fig. 3 "PRAIRIE JOY EV" (1997)

TAMA's driving range per charge was 65 km, whereas the medium-sized vehicle "TAMA SENIOR" launched in 1949 could travel to 200 km, close to the range provided by the current compact EVs.

The total number of electric passenger vehicles produced on record from 1945 to 1952 exceeded 3,500,[1] with "TAMA" accounting for over 30% with 1,099 units from its first production in 1947 to the end in 1951. As described above, EVs supported the country's recovery in postwar Japan, and charging stations and other infrastructure established in major Japanese cities (Table 1[1]) were now widely known. Unfortunately, this model ended its role because of a sharp rise in the price of lead, one of the main raw materials of batteries, fueled by the Korean War that broke out in 1950 and the rapid turnaround in gasoline supply.

2.2 "PRAIRIE JOY EV," for market launch

Nissan continued to develop EVs, proposing concept cars on a regular basis, including "315X," a concept car equipped with a lead battery and regenerative braking in 1970, "MARCH EV" in 1983 and "FEV" in 1991, followed by a pioneering effort with "CEDRIC EV" in 1993 and "AVENIR EV" in 1994, both of which were marketed mainly to corporate customers. Although lithium-ion batteries are now the standard for many EVs, the world's first lithium-ion battery was not commercialized until 1991.

Fig. 2 Battery module and a cylindrical cell

At this time, lithium-ion batteries were used for small products, such as laptops and cell phones, and it was considered difficult to develop high-capacity batteries for automobile applications. In collaboration with Sony in 1992, we were the first to initiate research and development into lithium-ion batteries for automobiles. Steady research helped us succeed in commercializing lithium-ion batteries in 1996 and selling 30 units of "PRAIRIE JOY EV" (Fig. 3), the world's first EV equipped with cylindrical lithium-ion battery cells (Fig. 2), to various companies and organizations in the following year of 1997.

"PRAIRIE JOY EV" was equipped with an electric motor with a maximum torque and speed of 166 Nm and 120 km/h, respectively, with a charging time per charge and driving range of 5 h and 200 km or more, respectively. It already showed a highly practical performance as an EV. Further, it was utilized as a support vehicle for the Arctic Environment Research Center of the National Institute of Polar Research for six years since 2000 and boasted of a high level of reliability with no failure during six years of operation, even under severe weather conditions. "PRAIRIE JOY EV," produced no noise or exhaust emissions, and could be operated in close proximity to wild animals sensitive to sounds and unusual odors, serving as a symbolic presence at the observation base to a large extent (Fig. 4). Although the resulting sales volume was only 30 units, we gained experience as an EV manufacturer through the sales of "PRAIRIE JOY EV" with subsequent launches of "ALTRA EV" in North America and "R'NESSA EV" in Japan in 1999.

Fig. 4 "PRAIRIE JOY EV" at work in the Arctic circle

These EVs were equipped with many technologies developed that led to "LEAF," including a flat floor, contactless charging system, pre-air conditioning function, digital meter dedicated to EVs, lithium-ion battery, and a neodymium magnet synchronous motor.

2.3 "HYPER MINI," a new form of electric vehicle

"HYPER MINI" (Fig. 5) was unveiled at the 1997 Tokyo Motor Show and launched as a production model in 2000. The HYPER MINI is a very compact EV with an overall length of 2.7 m or less and a minimum turning radius of 3.9 m, developed as a two-seater city commuter suitable for the daily life in the 21st century. Following the "PRAIRIE JOY EV", the world's first EV featuring a lithium-ion battery, the "HYPER MINI" was equipped with a lithium-ion battery and a neodymium magnet synchronous motor for realizing a smaller, lighter battery, higher output, and lower cost. Further, it changed the battery from cobalt-based to manganese-based to further enhance safety considering social experiments such as EV sharing of "HYPER MINI." Although it was a concept EV for a city commuter, it did not compromise on performance, boasting of an electric motor with a maximum torque of 130 Nm, maximum speed of 100 km/h, acceleration from 0 to 30 m in 4.5 s or less, and driving range of 115 km, which was more than sufficient for a city commuter. Further, it also had advanced technologies besides those for EVs, including run-flat tires and lightweight aluminum frames. In addition, HYPER MINI featured a revolutionary keyless entry system using an IC card to realize car sharing, and it played an active role in Japan and the U.S., including the electric car sharing social experiment in Yokohama and Ebina (Fig. 6) and at the University of California, Davis. Further, it was designed considering the environmental performance besides being powered by electricity, adopting the reuse of recycled materials, integrating materials, and an easy-to-disassemble structure for achieving a recyclability ratio of 90% or more by weight.

Fig. 5 "HYPER MINI" (2000)

Fig. 6 Demonstration experiment in Yokohama, Kanagawa Prefecture

Considering the awareness of economic efficiency as a city commuter, the energy cost was one-fifth the price of gasoline at the time, making its sales copy, "You can travel a lot, for just 1 yen per kilometer and only 100 yen for 100 km" well ahead of the times.

Approximately 2,500 patents were applied before launching "HYPER MINI" by accumulating many technologies related to EVs through the release of EVs starting with "PRAIRE JOY EV," of which had more than 300 patents were employed in the next model, "LEAF."

2.4 Birth of "LEAF"

The first-generation "LEAF" (Fig. 7) was launched in 2010 after unveiling its concept in 2009 as the world's first mass-produced EV aimed at realizing a sustainable zero-emission society. We concluded that previous pilot sales and demonstration experiments of EVs identified the need for a longer driving range and higher energy density of the battery. Therefore, a new laminated lithium-ion battery (Fig. 8) was developed in collaboration with the NEC Corporation to replace the conventional cylindrical battery (Fig. 2), allowing twice as much energy to be stored in the battery of the same size. The first-generation "LEAF" was equipped with a high-capacity lithium-ion battery of 24 kWh, providing powerful and smooth acceleration performance, as well as a driving range of 200 km (under JC08 mode) at the time of its launch. The distance was improved to 228 km in 2012 and to 300 km in 2015 by installing a 30 kWh battery.

Fig. 7 First-generation "LEAF" (2010)

Fig. 8 Battery module and laminated cell

This development was conducted while creating safety design and evaluation standards for the battery because it was the first mass-produced EV model to be sold on a global scale. The design process was based on a system that responds to problems such as overcurrent at each stage of production from cells, modules, and packs to vehicles, whereas the evaluation process included extensive driving tests assuming a variety of driving environments worldwide. Tests were conducted for starting and traveling in cold climates, where temperatures drop below freezing, and for driving on flooded roads, as shown in Fig. 9. Further, tests were performed on high-pressure car washing to help ensure reliable safety.

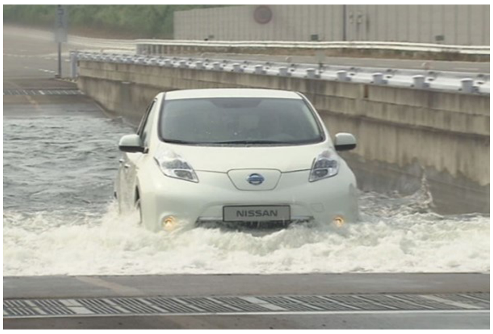


Fig. 9 Flooded road driving test

Nissan did not compromise on the pursuit of fun driving, with a thorough focus on utilizing the capabilities of electric motors. Fig. 10 shows that simply improving the response of the electric motor causes the drive shaft to vibrate significantly because of torsional resonance. The control object was modeled with a combination of feed-forward and feedback controls to achieve both quick and smooth acceleration responses of the electric motor.

This first-generation "LEAF" was created with the intention of exceeding customer expectations in all aspects, such as environmental performance, driving performance, ease of use, and price. Many people around the world are surprised by the unique driving experience of an EV, which is completely different from conventional cars, including the powerful acceleration felt when the driver steps on the accelerator pedal, unparalleled quietness, and handling feel generated by the excellent weight balance and low center of gravity caused by the battery pack being placed under the floor of the vehicle center. A completely new value to connect the owner and the vehicle was provided by the advanced IT system.

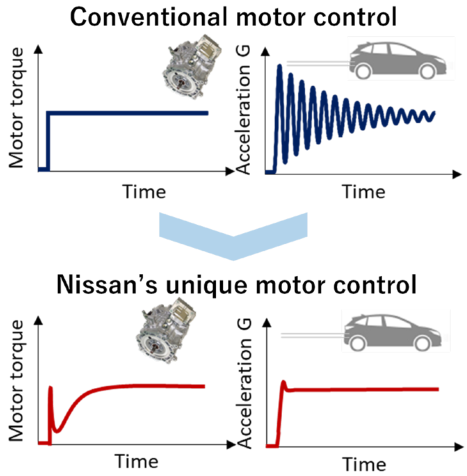


Fig. 10 Smooth acceleration by vibration control

Fig. 11 "LEAF to home"

"LEAF" proposed a pioneering new value for EVs to utilize the battery not only for driving but also as a source of energy. A system that enabled the driving battery embedded in "LEAF" to be used as a storage battery for the home power supply (Fig. 11) was developed and installed. This enabled a stable electricity supply to the home and electricity cost savings using nighttime electricity or electricity generated from renewable energy sources, such as solar power, to charge EVs and use the stored electricity during daytime when the demand for electricity was high. Further, this system was intended for use as a backup power source for power outages during disasters.

3. Toward widespread adoption of electric-drive vehicles

Over a decade has passed since the launch of the first-generation "LEAF" released as a mid-size hatchback comfortably accommodating five adults, and a variety of options of EVs ranging from crossovers to Kei cars, including the second-generation "LEAF" with a greatly improved performance and driving range based on feedback from the first-generation "LEAF," "ARIYA" and "SAKURA" have been offered to customers. A new form of EV, "e-POWER," which combines a unit of an EV and a gasoline engine, was unveiled in 2016 to allow more people to enjoy the powerful and responsive acceleration and excellent quietness only possible with a 100% electric motor drive. All these vehicles have been well received.

3.1 Second-generation "LEAF" to democratize electric vehicles

The second-generation "LEAF" (Fig. 12), released in 2017, was an innovative evolution equipped with state-of-the-art technologies. The output and torque of the new electric motor were increased by 38% to 110 kW and 26% to 320 Nm, respectively, compared to those of the previous-generation model for providing an exhilarating and linear driving experience.

For the newly developed lithium-ion battery, one module consisted of four cells, and a total of 48 modules were installed for the first-generation "LEAF," whereas the second-generation "LEAF" had modules consisting of eight cells to improve power storage density with the increased battery capacity of 40 kWh without changing its size from that of the first-generation "LEAF," thereby achieving a driving range of 400 km (under the JC08 mode).

Fig. 12 Second-generation "LEAF" (2017)

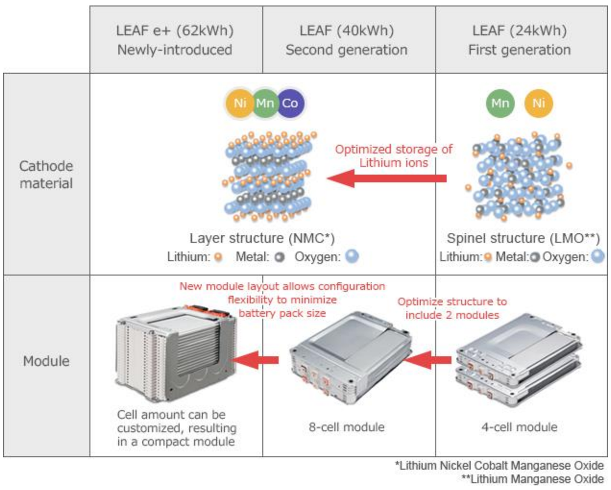


Fig. 13 Evolution of battery in "LEAF"

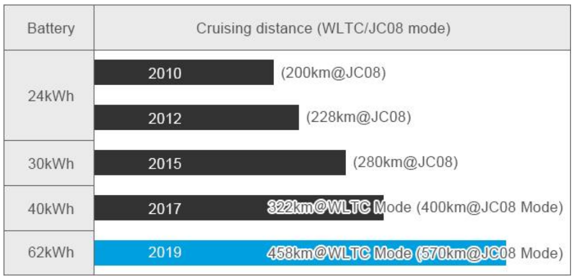


Fig. 14 Evolution of driving range

"LEAF e+" employed a new type of module that can change the number of cells at will by applying a new process called "laser welding" to the joining parts of cells. This shortened the overall length of the module and changed the number of stacked cells for optimizing the module height to match the shape of the vehicle, thereby increasing the driving range to 570 km (under the JC08 mode) by installing a high-capacity battery of 62 kWh (Figs. 13 and 14).

One feature of Nissan's EVs is smooth and quick acceleration response of an electric motor, which makes most of the excellent responsiveness and controllability. This technology has been refined as a core EV technology. Another innovation in the second-generation "LEAF" was the "e-Pedal," shown in Fig. 15. The "e-Pedal" enables the driver to start, accelerate, decelerate, stop, and hold the stop by operating the accelerator pedal, thereby providing extremely smooth deceleration control even under various road surface conditions. This can make driving easy in urban areas, where the driver must repeatedly start and stop, reducing the frequency of stepping on the brake, thereby allowing the driver to enjoy sporty driving by accelerating and decelerating as desired. Further, using the torque of the electric motor and other parameters to estimate the travel resistance can help achieve highly coordinated control of the electric motor with the brake. This coordinated control enabled the vehicle to stop smoothly and hold the stop position for a long period of time, even on a steep slope. The smooth and quick acceleration response of this vehicle not only makes driving fun but also makes every day driving easier, even for an inexperienced driver.

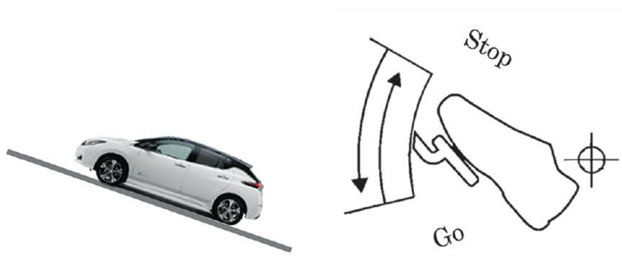


Fig. 15 Conceptual illustration of the e-Pedal operation

3.2 "ARIYA," toward the next-generation flagship

The crossover "ARIYA" (Fig. 16), which started sales in 2021, embodied the new Nissan and "Nissan Intelligent Mobility," aiming to be the "next-generation flagship EV that provides you a feel of the future of vehicles."

We sought to fully utilize the features of EVs while incorporating the latest technologies for satisfying customers in all respects. A new dedicated package that integrates the EV powertrain and vehicle mounting technologies was developed for ensuring roominess that overturns the conventional concept of internal combustion engine SUVs and realizes a completely flat floor, thereby achieving a high-level performance, such as reduced front overhangs, larger wheelbase, reduced minimum turning radius, improved handling stability and comfort, increased driving range, and quieter cabin (Fig. 17).

Fig. 16 "ARIYA" (2021)

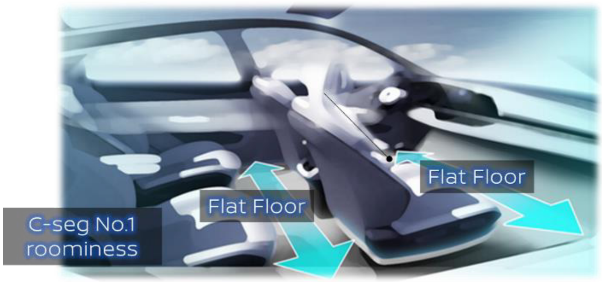


Fig. 17 Aim for great roominess and a completely flat floor

The battery layout must be housed in a limited space to realize a flat floor. Meanwhile, ensuring a higher charge capacity in a short time is required to meet the high demand for quick charging performances from the viewpoint of convenience improvement. The newly developed battery pack is shown in Fig. 18. High volumetric efficiency and a temperature control system were both realized by integrating the bottom plate of the battery housing and cooling plate, thereby improving the energy density per battery pack thickness by approximately 2.3 times compared to "LEAF e+." This contributed to improved cabin comfort while providing top-level volumetric energy density and quick-charging performance for EVs. These efforts resulted in a maximum driving range of 610 km (for the 2WD model with a 90 kWh battery, in-house measured value under 2WD WLTC mode) for "ARIYA."

The evolutionary process of electrification has been described thus far, focusing on the evolution of batteries, although electric motors and other driving technologies are evolving as electrification technologies accelerate. "ARIYA" had been developed and commercialized by focusing on electrically excited synchronous motors (EESMs) in addition to interior permanent magnet synchronous motors (IPMSMs), which have been widely used in the past. An EESM has a winding structure for its rotor because a DC current is applied to the rotor to make it an electromagnet. "ARIYA" secured the necessary electromagnetic force and torque response by increasing the rotor volume, and meanwhile, by adopting an eight-pole structure, as shown in Fig. 19, to accommodate the higher output. The efficiency of an IPMSM deteriorates when operated at high rotational speeds, whereas the motor developed in this study controls the rotor and stator currents to generate the required torque while suppressing the induced voltage by exploiting the magnetic force of the rotor, which varies with an electric current. This prevented an efficiency decline, even at high-RPM operations, and contributed to a longer driving range. The newly developed motor makes the EESM a viable option for meeting customer requirements for vehicle performance and addressing issues of rare-earth cost and supply risk in the future.

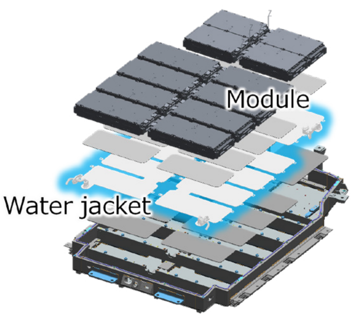


Fig. 18 Battery pack with integrated bottom and cooling plates

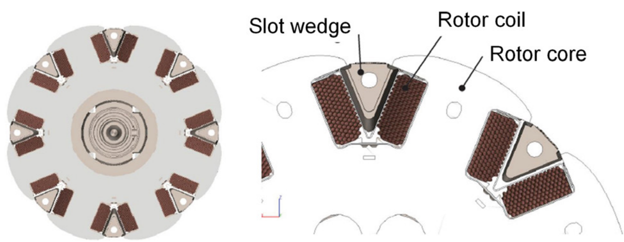


Fig. 19 Eight-pole rotor structure

The most important themes we focus on improving the responsiveness and controllability of the motor drive to pursue the fun of driving. The motor-drive control technology based on "e-Pedal" installed in the second-generation "LEAF," was further refined in "ARIYA." Two electric motors are employed in "ARIYA AWD," one in the front and the other in the rear, to independently control the front and rear driving forces with excellent response and high precision. It was "e-4ORCE" that realized the full performance potential of the EV.

The values provided by e-4ORCE can be broadly classified into three categories:

1) Driving at the driver's will.
2) Reliability regardless of road surface.
3) Comfortable ride for everyone on board (Fig. 20).

Our goal was to ensure its value, not only in terms of driving performance on rough roads, which is expected for conventional four-wheel-drive vehicles, but also under normal driving conditions with an ordinary driver driving on a normal road. In other words, "e-4ORCE" focuses on performance improvements for allowing people to experience the values not "for someday" but "for always."

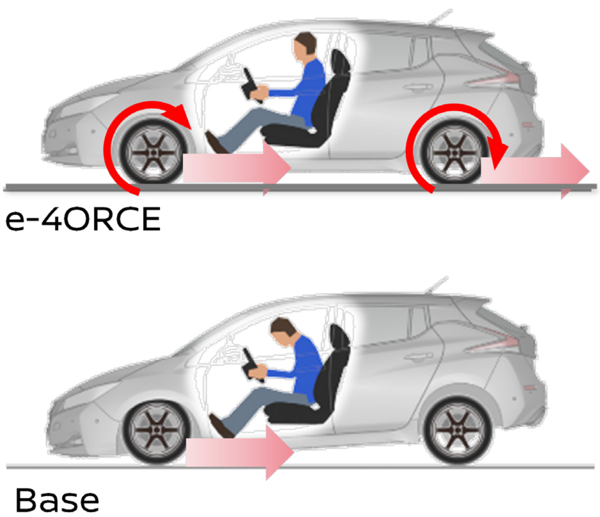


Fig. 20 Posture control during deceleration

3.3 "SAKURA," to add color to the era of the electric vehicles in Japan

"SAKURA" (Fig. 21) plays the role of a flagship car in the unique category of Kei cars in the Japanese market, with a chic and advanced design, high quality and spacious interior space too good to be a Kei car, and the powerful acceleration and smooth driving distinctive of an EV.

Fig. 21 "SAKURA" (2022)

The electric motor with a maximum torque of 195 Nm as well as quick and smooth acceleration with advanced control technologies made merging onto highways effortless and easy, unlike conventional Kei cars. The optimization of the motor structure has led to the highest level of quietness worthy of its flagship name for Kei cars.

Lithium-ion battery technologies developed and refined since "LEAF" are incorporated in "SAKURA." One such feature is the use of laminated cell structures. In addition, the compact stacked structure that has been employed since the second-generation "LEAF" allows the number of stacked cells to be changed at will, providing extremely high flexibility in installation. The battery pack adopted for "SAKURA" is shown in Fig. 22.

Two rows of packs of 96 cells connected in series were arrayed in the second-generation "LEAF" with 40 kWh, whereas a 20 kWh pack of one row is employed in "SAKURA" and arranged to make maximum use of the limited space under the floor of the Kei car.

"SAKURA" has a driving range of 180 km under the WLTC mode, which is sufficient for the typical usage of a Kei car, such as daily shopping, pickup and drop-off, and commuting. It is sometimes difficult to go to a gas station, especially in rural areas, while "SAKURA," which allows charging at home, is expected to make a big difference in the life of Kei car customers as it will be fully charged in the morning after being plugged in when they come home at night.

The comparison of specifications and performance between "SAKURA" described in this section and "TAMA" described in Section 2.1, which is relatively similar in class to "SAKURA," is shown in Table 2. Significant performance improvements have been achieved in every aspect, demonstrating the significant evolution of EVs over the past 75 years.

Fig. 22 Battery pack of "SAKURA"

Table 2 Comparison of specifications and performance between “SAKURA” and “TAMA”

Specifications	Electric vehicle TAMA, 1947	SAKURA, 2022
Overall length x overall width x overall height (mm)	3,035 × 1,230 × 1,618	3,395 × 1,475 × 1,655
Wheelbase (mm)	2,000	2,495
Vehicle weight (kg)	1,100	1,080
Motor	Direct current shunt wound motor	Alternating current synchronous motor
Driving battery	Lead storage battery, 40 V, 6.5 kWh	Lithium-ion battery, 350 V
Battery capacity	6.5 kWh	20 kWh
Rated output	3.3 kW (4.5 ps)	20 kW
Maximum output	-	47 kW
Maximum torque	-	195 Nm
Driving range per charge	65 km (measuring method unknown)	180 km (WLTC)
Maximum speed	35 km/h	130 km/h

3.4 “e-POWER,” the electrification technology born from BEV

EVs were very well received for their smooth and desirable “acceleration,” gentle “deceleration control” and outstanding “quietness,” exploiting the electric drive provided by a high-output electric motor. It was “e-POWER” that combined the fun of driving an EV with the convenience of a gasoline engine at a high level, which was installed in “NOTE” (Fig. 23), when it was launched in 2016.

Fig. 23 “NOTE e-POWER” (2016)

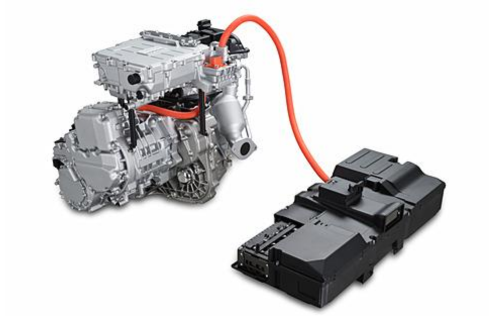


Fig. 24 First-generation “e-POWER” system

“e-POWER” system is illustrated in Fig. 24. “e-POWER” is composed of an integrated powertrain with a high-output electric motor, an inverter, a gasoline engine and a generator, as well as a high-voltage battery. Unlike the typical parallel hybrid system using both an engine and a small electric motor for driving, “e-POWER” is an electric powertrain that integrates a gasoline engine and an electric motor to drive tires with a high-output electric motor as with an EV. The engine runs exclusively for electricity generation, and only an electric motor drives the vehicle, providing the fun of driving as an EV.

“e-POWER” was made possible by combining the integration technology of motor control and electric powertrain, which had been accumulated through the development of EVs, with energy management technology. The operation of the “e-POWER” system is shown in Fig. 25. The engine and tires are not directly connected, thereby enabling flexible control of the engine start timing. The vehicle travels only on the motor from the start to low to medium speeds, and the engine starts generating electricity at high speeds when the road noise increases, thereby reducing the operating time of the engine and ensuring quietness. In addition, it achieves low fuel consumption by generating electricity within the most efficient engine speed range.

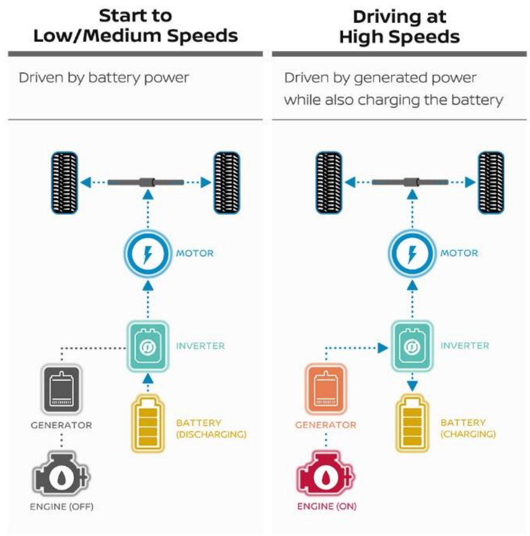


Fig. 25 Conceptual illustration of the “e-POWER” system operation

“e-POWER,” which was available exclusively in Japan, is now in its second generation to be rolled out globally. The second-generation “e-POWER” (Fig. 26) represented a normal evolution from the first-generation “e-POWER” in the right direction, with the entire system improved to be more powerful, smoother, and quieter, thereby providing a more EV-like feeling. The engine was made to be dedicated to “e-POWER,” which focused on electricity generation by making the electric powertrain smaller and more powerful, thereby realizing higher thermal efficiency than before. Further, energy management technologies were thoroughly overhauled, with system control technologies including engine start timing and refined power distribution, and engine start control coordinated with newly developed road noise estimation technology (Fig. 27) and navigation system, to improve quietness and fuel economy.

Equipped with “e-4ORCE,” which is the electric motor control technology developed for EVs, and “e-POWER drive,” which has functions similar to those of “e-Pedal,” it provides customers with ease of use, comfort, and a sense of security that conventional gasoline and hybrid vehicles cannot offer.

Fig. 26 "X-TRAIL with the second-generation e-POWER"

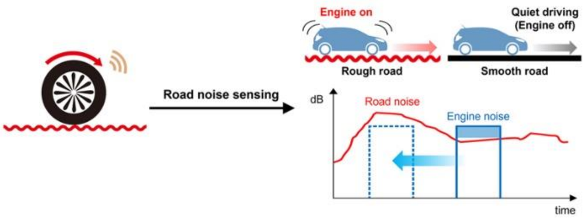


Fig. 27 The system controls engine operation with the addition of road surface information.

4. Toward a sustainable society with the social development

The history of Nissan's electrification spanning 75 years has been described. Nissan will continue its efforts to harmonize environmental and energy issues while ensuring the fun of driving at a high level. In 2021, Nissan announced its long-term vision, "Nissan Ambition 2030," shown in Fig. 28, with the goal of achieving carbon neutrality throughout the entire lifecycle of its products. This section describes the future direction of electrification technologies for a society that simultaneously realizes carbon neutrality and sustainability.

Fig. 28 Nissan's efforts toward carbon neutrality

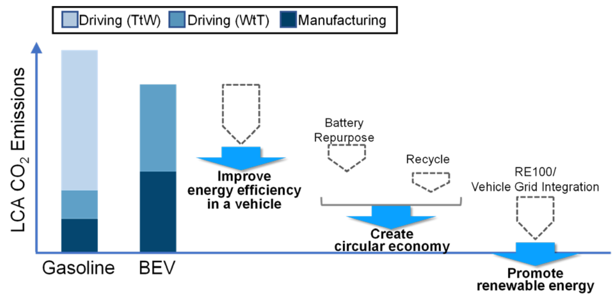


Fig. 29 Toward carbon neutrality and a sustainable society

Carbon neutrality cannot be realized by simply replacing all vehicles worldwide with modern EVs. Further improvement in the efficiency of EVs, establishment of a resource-recycling society, and the promotion of renewable energy will be required for the entire society (Fig. 29). Nissan's future work is discussed in the following section.

4.1 Efficiency improvements and further battery evolution for electric vehicles

Nissan has been making sustained efforts to simultaneously evolve both the hardware and software of its EVs, improving the fun of driving, electricity consumption, and driving range. For example, the evolution of the driving range of Nissan is shown in Fig. 30.

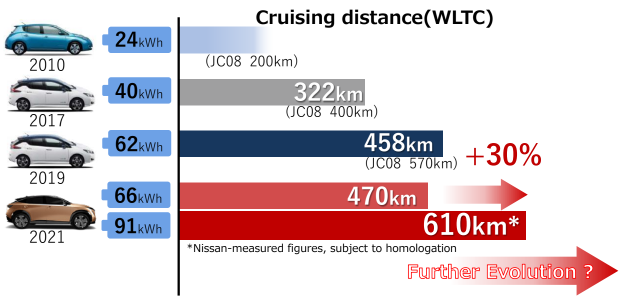


Fig. 30 Evolution of driving range for mass-produced electric vehicles

Owing to the efforts of engineers, EVs are currently being accepted in the market because of their equivalence or superiority over conventional gasoline-engine vehicles.

However, we believe that further reducing electricity consumption and meeting various market requirements are important to promote the widespread adoption of EVs and achieve carbon neutrality. A comparison between gasoline engines and EVs in areas where energy loss is generated when a vehicle travels is shown in Fig. 31. The majority of the energy loss in gasoline, diesel, and other engine vehicles is conventionally accounted for by the powertrain, and therefore, improving the powertrain efficiency, including the thermal efficiency of the engine, has been considered the focus for improving vehicle efficiency. In contrast, EVs produce losses at relatively equal ratios in the powertrain, driving resistance, and air resistance. Therefore, viewing the entire vehicle as a single system, rather than simply focusing on the powertrain, is essential for improving efficiency. The contribution of a smaller and more powerful electric powertrain to aerodynamic improvement through better vehicle design and the reduction of total weight through improved battery power density will help improve the efficiency of the entire vehicle system, which is the desired direction.

Further, it is essential to improve the energy density of lithium-ion batteries to satisfy the market requirements for EVs and expand the range of models, as shown in Fig. 32. However, in practice, there are physical limitations. Increasing the battery capacity to achieve a sufficiently long driving range can satisfy market expectations but increase the weight of the battery, thereby leading to a vicious cycle of deteriorating vehicle efficiency. The all-solid-state battery (hereafter, ASSB) is shown in Fig. 33. The ASSBs are expected to promote the widespread adoption of EVs because of their high energy density, which is approximately twice that of conventional batteries, significantly shorter charging time, and lower battery cost. Conventional lithium-ion batteries use a liquid (organic solvent) as the electrolyte, whereas the solid electrolyte in ASSBs is more resistant to heat and less prone to side reactions, allowing for more combinations of materials. This permits the selection of a less expensive cathode material or anode material with a higher energy density.

Model and regional deployment will be accelerated through these improvements in efficiency as a vehicle system and significant innovations in battery technologies, with the widespread adoption of EVs promoted to more people for achieving carbon neutrality.

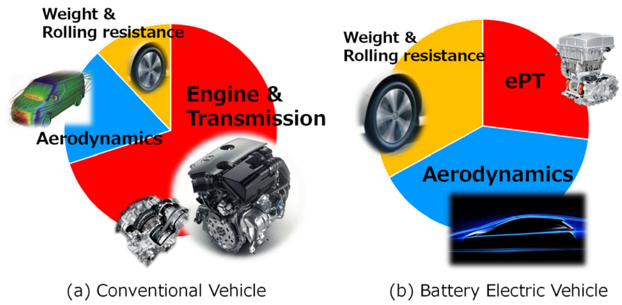


Fig. 31 Ratio of energy loss in vehicles

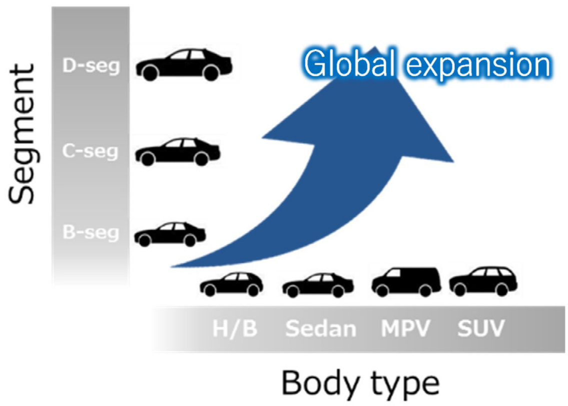


Fig. 32 BEV model deployment in the future

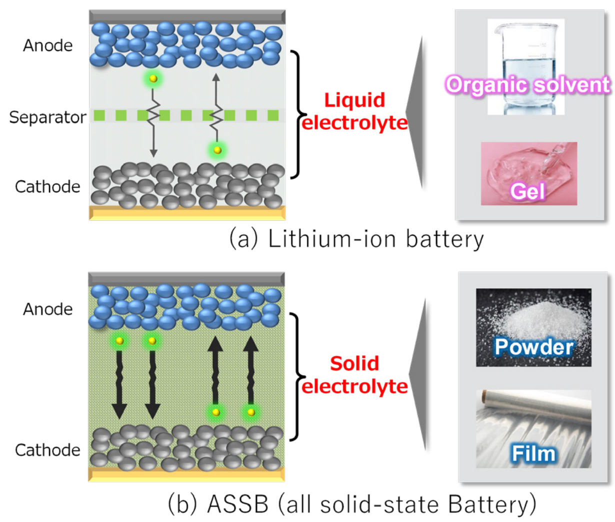


Fig. 33 Comparison of a lithium-ion battery and an ASSB

4.2 Eco-cycle toward a sustainable society

Vehicles are made from a variety of raw materials and parts that collectively create new value. Nissan has been improving its efficiency of resource use and diversifying its use of resources by adopting renewable resources and recycled materials. The focus is on a battery-recycling society and its future outlook. As EVs gain popularity, a large number of batteries are in circulation. Many valuable materials are used in batteries, and therefore, recycling them as resources is important. Nissan established 4R Energy Corporation in collaboration with Sumitomo Corporation when the first-generation "LEAF" was first launched, with a view to make effective use of reusable lithium-ion batteries along with the widespread adoption of EVs in the market.

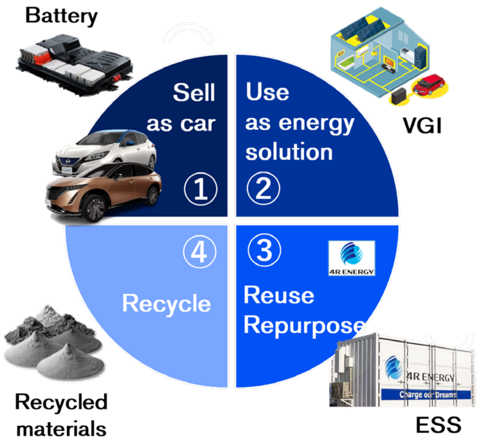


Fig. 34 Conceptual illustration of battery circulation

(a) Emergency power supply (b) Portable battery

Fig. 35 Advanced application example of second life battery

A conceptual illustration of the battery circulation is shown in Fig. 34. Once sold, EVs are not merely a means of transportation, but can be used as a moving storage battery, i.e., as an energy solution (Fig. 34 ②).This aspect of our efforts is discussed in more detail in the next section. After their use as components of a vehicle, batteries can be reused for EVs or repurposed for different uses (Fig. 34 ③). Nissan, through the above-mentioned 4R Energy Corporation, started an initiative to reuse retired vehicle batteries as emergency power supplies at railroad crossings in collaboration with the East Japan Railway Company and started selling portable batteries in collaboration with JVC KENWOOD Corporation (Fig. 35). Batteries, after their use as a component of a vehicle and their reuse and repurposing, are not disposed. Instead, they are recycled by extracting materials (Fig. 34 ④). The recycled materials are returned to the manufacturing process shown in Fig. 34 ① to produce less expensive batteries with lower manufacturing CO_2 emissions for new EVs.

The number of batteries returning to the distribution chain after their respective roles is expected to increase, and therefore, the establishment of the eco-cycle shown in Fig. 34 and the acceleration of the development of contributing technologies will become important. Since the initial launch of "LEAF," Nissan have been making efforts to understand the state of health (SOH) of battery through telematics data obtained from vehicles. The proper method to reuse a battery corresponding to each assessment result of the SOH is shown in Fig. 36.

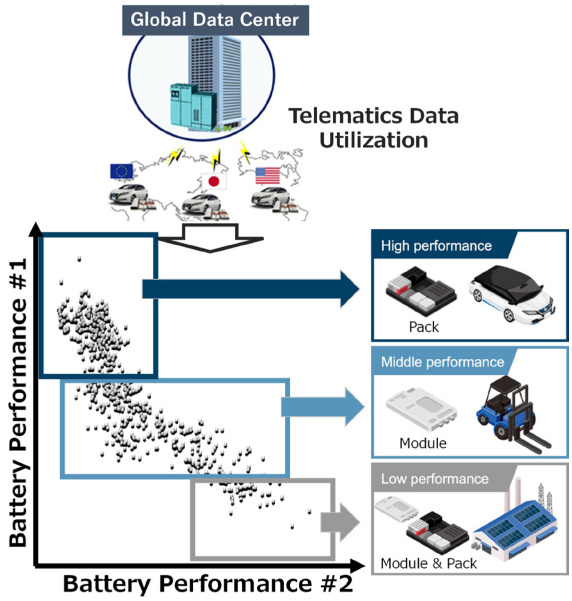


Fig. 36 Concept of the state of health of battery and applications

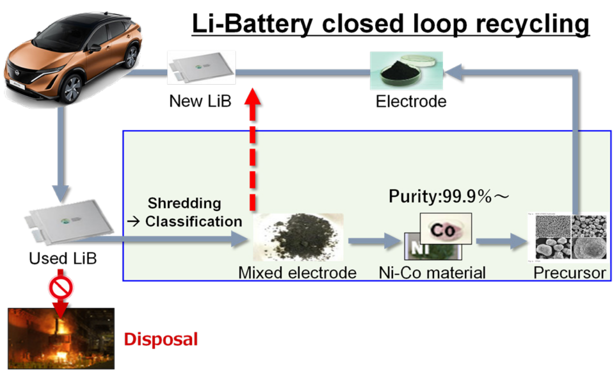


Fig. 37 Battery closed-loop recycling

Nissan, with a view to reuse and recycle, has established a system to monitor how batteries in the market are now used by utilizing telematics data. A battery recycling business in which the SOH of batteries is monitored through data utilization, and the batteries are reused as recycled batteries for vehicles or stationary batteries depending on the state will be promoted. The lithium-ion battery closed-loop recycling is illustrated in

Fig. 37. Some batteries are currently disposed of as waste, which makes it impossible to extract metallic materials in a form that can be used again. The development not only of technology to recycle expensive metals, such as nickel and cobalt, to the level of high-purity raw materials but also direct cathode recycling (DCR) technology to recycle them back into batteries at the electrode level, as shown by the red dotted arrow in Fig. 37 is progressing. Thus, there is an urgent need to establish recycling technologies and build business models. This aims to avoid the depletion of the Earth’s resources and to create a virtuous cycle in which recycling reduces the cost of producing new batteries.

4.3 Vehicle grid integration aimed at power smoothing

EVs can provide society with a new way of utilizing energy and high-capacity batteries installed in EVs can be integrated into the electric energy of an entire city. Nissan's V2X initiative is shown in Fig. 38. The above-mentioned connectivity to home, “vehicle to home,” is now commercially available and is already connected to many homes. The practical use of “vehicle to building” and demonstration experiments at the community and grid levels has begun, suggesting that EVs will be smartly connected to society and city energy wherever they go in the future and contribute to stabilizing the balance of electricity supply and demand in the world. In addition, EVs can be combined with stationary recycled batteries to increase the use of renewable energy. Nissan started a field trial of an energy management system by utilizing the charge/discharge system of EVs in Namie-machi, Fukushima Prefecture, Japan. We utilized renewable energy power generation equipment and power conditioning systems (PCSs) owned by commercial facilities in Namie-machi, and “LEAF,” the official vehicle of Namie-machi, and install Nissan's charge/discharge control system into the PCSs to assess the energy use efficiency and promote local production for the local consumption of clean energy, thereby aiming to establish an energy management system.

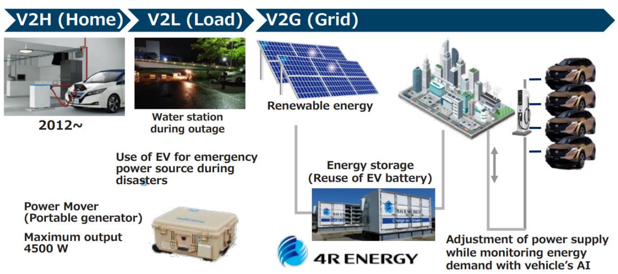


Fig. 38 Nissan's V2X initiative

Fig. 39 Demonstration experiment in Namie-machi, Fukushima Prefecture

The AI-based energy management system that Nissan is aiming for is shown in Fig. 40, and its features will be described below.

1. Autonomous charging/discharging of EVs
   Based on the information on electricity generated from solar, wind, and hydrogen fuel cells, as well as the electricity demand of commercial facilities, Nissan's charge/discharge control system installed in the PCSs autonomously charge and discharge EVs.
2. Priority and timing adjustment for charging/discharging EVs
   This charge/discharge control system determines priority vehicles for charging/discharging based on the power usage of commercial facilities, considering the remaining battery capacity of the EVs and their usage patterns (travel distance, departure time, etc.) to perform charging/discharging at the necessary time.
3. Effective utilization of renewable energy and stabilization of the power grid
   Power costs are expected to be lowered using this system to decrease the peak power usage of commercial facilities. In addition, achieving 100% renewable energy for charging EVs can contribute to the effective use of energy and stabilization of the power grid.

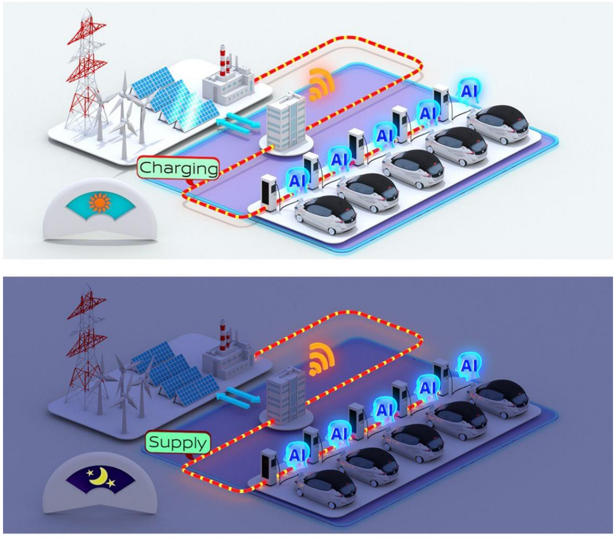


Fig. 40 Concept of Nissan energy management system

Nissan will increase the use of renewable energy at various facilities and local stores by building an energy management system utilizing EVs and stationary recycled batteries for accelerating its low-carbon initiatives.

5. Summary

Nissan will redefine the raison d'etre of vehicles as not only a means of transportation but also mobility that moves society forward, in other words, Beyond Mobility. We believe that this is a great once-in-a-century transformation based on electrification. Therefore, in addition to the evolution of electrification, intelligence, and connectedness as featured in this edition, new ideas and initiatives outside the bounds of conventional practices in the automotive industry will become increasingly important. EVs have the potential to change society.

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Authors

Atsushi Teraji

Special Feature 1:Electrification

2. High package efficiency in platform dedicated to next-generation EVs

Masahiro Oonishi* Kitaru Sone*

1. Introduction

The Nissan LEAF was launched in 2010 as a mass-produced electric vehicle (EV) for the global market. The platform for the LEAF was developed based on the electrification technologies established through the development of the PRAIRIE JOY EV, the world's first EV equipped with a lithium-ion battery, and other EVs such as the ALTRA and HYPERMINI. The aim was to provide reliability and safety comparable to those of gasoline vehicles as well as an EV-like "impressive driving experience." The high reliability and safety of the LEAF, along with its excellent driving performance, have been well received by customers and have contributed to the widespread use of EVs.

To maximize the cruising distance and driving pleasure of the LEAF, technological improvements such as an integrated powertrain with an increased output, air-conditioning system with heat pumps, and high-voltage batteries with increased capacity have been continuously incorporated.

The Common Module Family for EVs (CMF-EV), which is a platform dedicated to next-generation EVs that was employed in the ARIYA (shown in Fig. 1), was developed with a focus on exceeding customer expectations. This was accomplished through a distinctive EV vehicle package and further improvements in the cruising distance and driving performance. These advances were achieved by evolving the advanced reliability and safety features developed for the LEAF.

This article highlights the key points that need to be addressed to achieve a roomy interior, high-capacity batteries, and superior driving performance.

Fig. 1 Nissan ARIYA

2. Current status of EV vehicle packages

Customers expect two primary features for EVs in terms of the vehicle package.

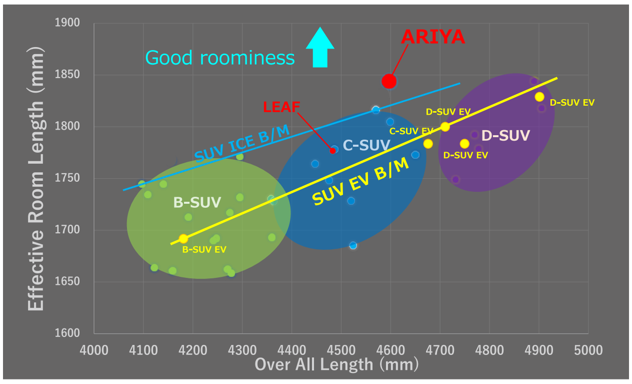
(1) Roomy interior space in the front-to-rear direction (which can be achieved using a compact powertrain).
(2) Completely flat interior floor (without using an exhaust system or propeller shaft).

However, developing an EV that satisfies both of these criteria is more challenging than customers realize.

Figure 2 shows a comparison between the overall length and effective room length (i.e., the distance between the gas pedal and the rear passenger's hip point, which is a representative index of the length of the cabin space in the front-to-rear direction) for a group of commercial sport utility vehicles (SUVs). The figure shows that the benchmark line of SUV EVs is inferior to that of SUV internal combustion engine (ICE) vehicles in terms of package efficiency (i.e., the effective room length relative to the overall length of the vehicle) in the front-to-rear direction. Although the vehicle types differ, the LEAF had a front-to-rear package efficiency similar to that of the C-segment ICE group. EVs equipped with high-capacity, high-voltage batteries for maximizing the cruising distance have significantly higher weights compared with ICE vehicles. This necessitates an increase in the crush stroke required to minimize the

*Product Development Department No.2

damage in low-speed collisions and to help ensure passenger safety and high-voltage safety in high-speed collisions. However this requirement negates the space advantage of a compact drivetrain.



In addition, the LEAF did not fully meet customer expectations for a completely flat floor, as brake pipes, cooling water pipes, and high-voltage harnesses, etc. were placed inside a central tunnel that protruded above the floor.

3. Evolution of the platform dedicated to next-generation EVs: CMF-EV

The CMF-EV employed in the ARIYA achieved a breakthrough; by mounting the air-conditioning unit in the engine compartment and integrating functions in a high-density package, the space efficiency in the front-to-rear direction was maximized. This exceeded the highest benchmark of SUV ICE vehicles and resulted in a completely flat floor, which generated high praise from customers who purchased an ARIYA (Fig. 3).

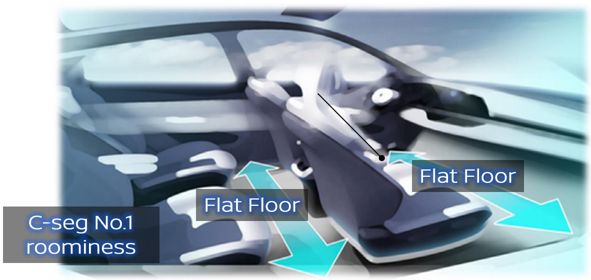


Fig. 3 High space efficiency achieved by the completely flat floor in the ARIYA

By deploying the abovementioned functionally integrated components, the maneuverability and ride comfort expected by EV customers as well as a reduction in weight were achieved in a manner consistent with the body frame rigidity requirement established in the initial planning stage.

4. Arrangement of the air-conditioning unit in the engine compartment

From this section on, the specific measures employed to achieve the goal of a flat cabin floor are described. First, the air-conditioning unit in the ARIYA, which was previously placed in the interior instrument panel, was installed in the engine compartment instead. This allowed for a thin instrument panel, which was introduced at the ARIYA world premiere and other events.

However, simply changing the position of the unit did not improve the package efficiency in the front-to-rear direction because if the interior space was to be extended, the engine compartment would need to be extended to house the air-conditioning unit.

The breakthrough in the ARIYA was the adoption of a structure that actively crushes the air-conditioning unit in the event of a collision in addition to shifting the unit. As shown in Fig. 4, the conventional air-conditioning unit was installed at the rear of the dashboard panel (i.e., in the zone unable to be crushed). Simply moving the air-conditioning unit into the engine compartment while maintaining the crush stroke would require extending the engine compartment by the length of the air-conditioning unit in the front-to-rear direction (as shown in Fig. 5).

By allowing the air-conditioning unit to be crushed in case of a collision, the CMF-EV employed in the ARIYA ensured the necessary crush stroke while reducing the length of the engine compartment in the front-to-rear direction (as shown in Fig. 6).

The air-conditioning unit is primarily composed of a heat exchanger, refrigerant pipes, blower fan, and ducts, along with resin or a hollow space except for the heat exchanger and the blower fan motor, giving room for crushing. Accordingly, the development was carried out by allocating the force-stroke characteristics at the time of collision with the air-conditioning unit and by assuming that the main body of the air-conditioning unit would be crushed by approximately 200 mm in a full-wrap frontal collision.

Another component of the air-conditioning unit, the high-voltage positive temperature coefficient (PTC) air heater, was installed in the cabin (a non-crushable zone) to help ensure high-voltage safety in the event of a collision.

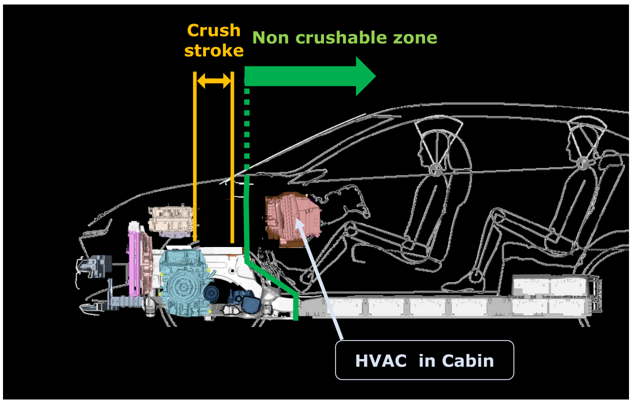


Fig. 4 Conventional arrangement of the air-conditioning unit and crush stroke

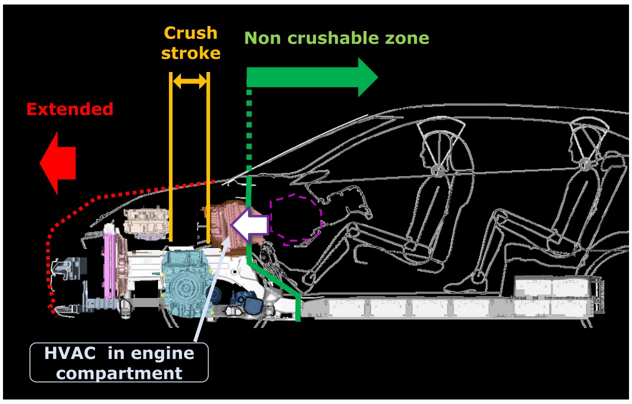


Fig. 5 Shifting the air-conditioning unit and extending the engine compartment

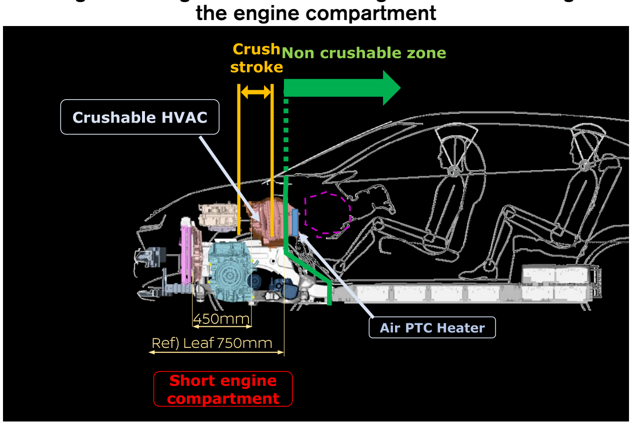


Fig. 6 Crush stroke based on the assumption that the air-conditioning unit will be crushed

The measures required to ensure the stable crushing of the air-conditioning unit are now described. Figure 7 shows the layout of the interior of the engine compartment designed for the CMF-EV. The air-conditioning unit is installed at the extreme rear of the engine compartment, in front of which the upper powertrain unit is mounted with the charger, junction box, and DC-to-DC converter.

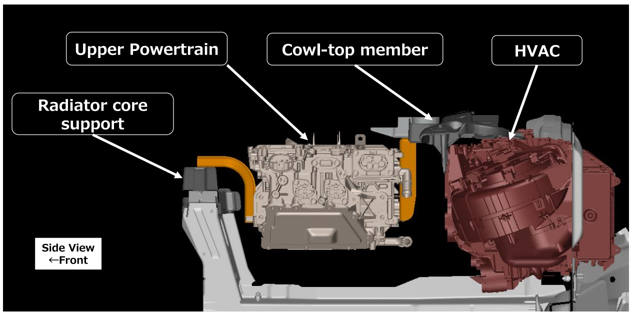


Fig. 7 Layout of the engine compartment designed for the CMF-EV

In the event of a frontal collision, the upper powertrain unit starts retracting halfway through the collision and reaches the maximum extent of its retraction almost simultaneously with the crushing of the entire air-conditioning unit. To ensure the stable crushing of the air-conditioning unit in various collision modes, the upper powertrain unit moves backward while maintaining its initial mounting angle (from the lateral view). The following concepts were employed to achieve motion control.

(1) The front of the upper powertrain unit is connected to the vehicle body frame to stabilize the unit's backward movement in the event of a collision.

(2) When the upper powertrain unit retracts, the rear fixing point bracket is detached to allow the upper powertrain unit to retract.

In accordance with concept (1), the front of the upper powertrain unit is fixed to the radiator core support member, which is connected to the front member. The allowable bracket deformation and deformation modes are then specified.

For concept (2), a slit is inserted into the bolt-fastening component of the rear fixing point to allow the bracket to slide out only when it endures a backward input force during a collision (as shown in Fig. 8).

The rigidity, surface treatment, dimensional accuracy, and fastening torque control of the bracket are precisely controlled to ensure it is securely fixed during normal driving conditions and in collisions.

The abovementioned efforts have enabled the space occupied by the air-conditioning unit to be utilized as a crushable zone, which simultaneously provides a sufficient crush stroke and satisfies the customer's expectation of a roomy interior space in the front-to-rear direction via a compact powertrain.

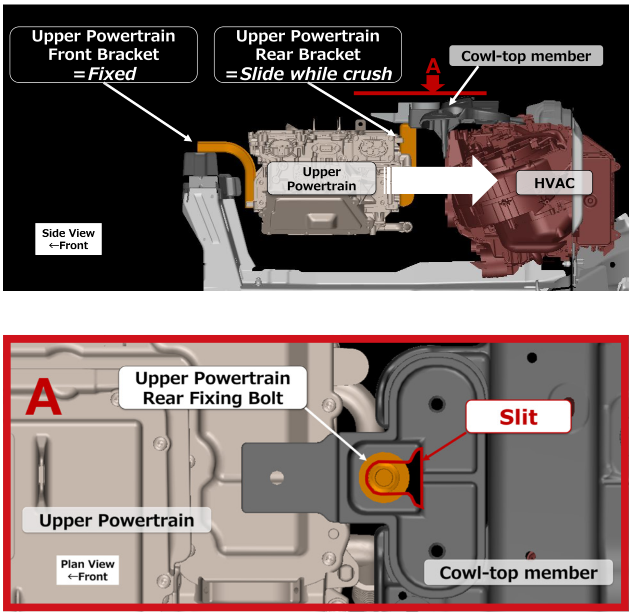


Fig. 8 Intended unit motion during a frontal collision (top) and the slit structure of the fastening point (bottom)

5. Preservation of space and the enhancement of the body rigidity via function integration

The vehicle package was also densified by integrating functions to enable the installation of a high-capacity battery, increased cabin space, a flat floor and high driving performance. Two major examples will be presented here.

The first is a cowl-top member that integrates the fixing structures for the upper powertrain unit and the air-conditioning unit, and the strut tower bar. As shown in Fig. 8, the upper powertrain unit and the air-conditioning unit are mounted on the member connecting the side members and on the steering member in the cabin, respectively, in the conventional structure. For vehicles that require even higher maneuverability, a strut tower bar is individually added.

To reduce the space required for the fixation structure and decrease the weight while improving the frame rigidity around the strut tower, the CMF-EV incorporated the fixation of the upper powertrain and air-conditioning units and the integration of the function of the strut tower bar into the newly developed aluminum cowl-top member (as shown in Fig. 9).

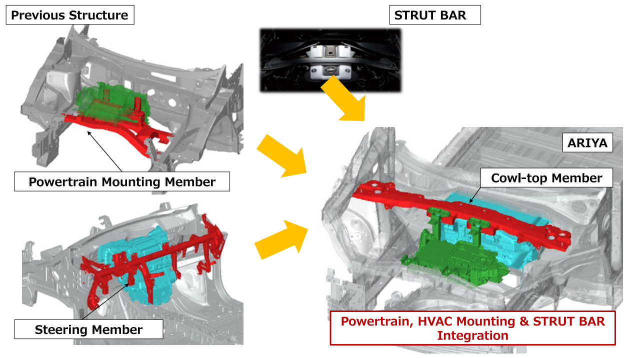


Fig. 9 Integration of functions into the cowl-top member

The second factor is the multifunctionality of the high-voltage battery frame. In a conventional structure, the primary function of the high-voltage battery frame is to secure the body of the battery and protect it from various disturbances, such as collisions and road surface interference. The details are given in the article on the development of a high-voltage battery.

In addition to the abovementioned functions, the CMF-EV utilized the advantages of extruded aluminum for the battery frame to integrate the water jacket (for battery temperature control) and the cooling water pipes leading to the rear motor inverter (for 4WD) into the cross section of the frame (as shown in Fig. 10).

The high-voltage harness leading to the rear motor inverter was also made into a bus bar to be installed inside the high-voltage battery pack, while the brake pipes were placed in the gap between the high-voltage battery pack and the side sills to eliminate the need for a tunnel. This satisfied EV customer expectations for a completely flat interior floor without using an exhaust system or propeller shaft.

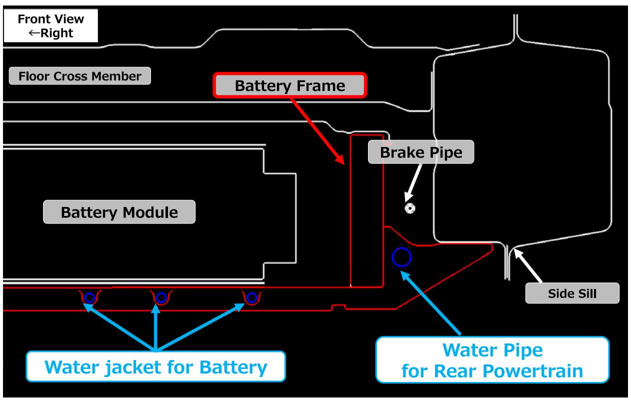


Fig. 10 Integration of the cooling water pipes into the high-voltage battery frame

Because the high-voltage battery frame is a major framework component, the coupling of the battery frame with the body frame and suspension members was also strengthened.

As shown in Fig. 11, the floor cross members of the hot-stamped material on the vehicle floor and the cross members in the high-voltage battery were arranged such that their positions in the front-to-rear direction alternated. The cross members in the high-voltage battery were coupled to the side sills of the vehicle body via side frames and side rails, which contribute not only to the protection of the high-voltage battery in the event of a side collision, but also to the improvement in rigidity of the vehicle body frame.

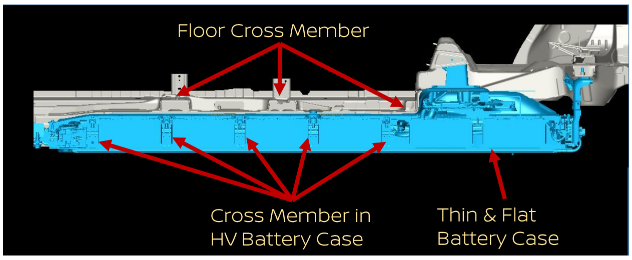


Fig. 11 Relative positions of the vehicle floor and high-voltage battery frame

To improve the steering responsiveness, the lateral rigidity of the fastening point of the suspension member was improved. This was accomplished by connecting the rear side fastening point of the front suspension member, the front side fastening point of the rear suspension member, and the high-voltage battery frame via the suspension pin stay (as shown in Fig. 12).

In this way, utilizing the high-voltage battery frame as the primary frame component achieved a flat floor by reducing the cross section of the cross member on the body side while increasing the rigidity by a factor of approximately 1.9 times that of a conventional C-segment SUV. This resulted in a low and flat floor, dynamic performance, and ride comfort.

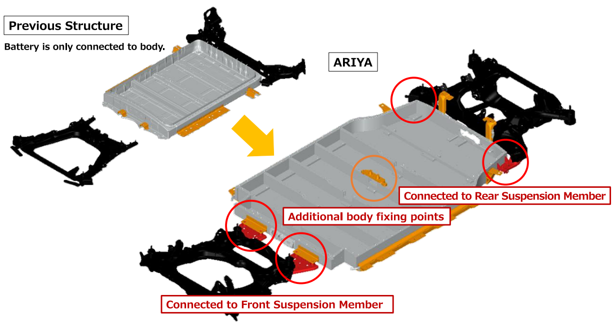


Fig. 12 Strengthening the coupling between the suspension and high-voltage battery

6. Conclusion

During the development phase of EVs, their economic environment changed constantly and significantly. However, the initial goal of exceeding customer expectations in terms of the vehicle package, cruising distance, and driving performance remained unchanged. The advanced reliability and safety features developed for the Nissan LEAF was a sound foundation on which to develop additional innovations.

Although not mentioned in this article, the cruising distance, charging performance, and capacity reduction performance of high-voltage batteries in EVs in real-world scenarios (e.g., while using the air conditioning and encountering various temperatures) have also been improved relative to those of the LEAF. Additional efforts have focused on further improving the driving performance of EVs (e.g., e-4ORCE) and their ease of use offered by connectivity.

Consequently, Nissan can proudly state that the ARIYA has been classified in the EV category and has become a product that can be purchased solely as a car.

The CMF-EV platform was developed for vehicles more compact than the ARIYA. Accordingly, it also has a variable range of wheelbases and treads.

Nissan will continue to significantly contribute to sustainable mobility by encouraging customers who are hesitant to purchase EVs to choose models featuring the CMF-EV platform.

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Special Feature 1:Electrification

3. Evolution of batteries for electric vehicles: Nissan's future vision

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Yuichiro Tabuchi** Masahiro Morooka** Norihiko Hirata***

1. Introduction

In an effort to progress toward a more sustainable society, Nissan Motor Corporation announced a new goal to achieve carbon neutrality throughout the lifecycle of its vehicles by 2050. To achieve this goal, more competitive and efficient electric vehicles (EVs) and innovative battery technologies are being developed, with the aim of making all new vehicles launched in major markets EVs starting in the early 2030s.

Nissan has undertaken continuous efforts to minimize the carbon footprint of its vehicles and business activities while developing the "Nissan Green Program." As a pioneer of zero-emission vehicles, it has sold a total of over one million EVs globally. In addition, it has collaborated with industry organizations, the government, and local municipalities to build EV infrastructure and educate the public about the value of EVs. In particular, the Nissan LEAF, which was launched in 2010 and was the world's first mass-produced EV, has accumulated over 650,000 units of global sales as of July 2023(1). Between 2010 and 2023, the performance of the batteries, as measured by their capacity and input/output capabilities, has been improved without sacrificing their quality and reliability.

This article describes the history of the development of EVs, the evolution of batteries (including all-solid-state batteries, or ASSBs), and a vision for the future, with a focus on the LEAF.

2. History of EVs and the evolution of batteries at Nissan

2.1 History of the development of EVs

The history of EV development at Nissan is depicted in Fig. 1. The first EV, TAMA, which was prototyped in 1947, achieved a driving range of 96.3 km and a maximum speed of 35.2 km/h. In the 1990s, the PRAIRIE JOY EV, the world's first EV equipped with a lithium-ion battery, was developed, and Nissan began leasing it to various companies and organizations in 1997.

Subsequently, EVs were further developed, including the minivan-type R'NESSA (in 1998) and the ultra-compact two-seater HYPERMINI (in 2000), which have led to the current developmental trajectory of EVs. The world's first mass-produced EV, the LEAF, was launched in December 2010 in major markets in Japan, the US, and Europe. The LEAF represents a strong determination to address various challenges that must be overcome to achieve a zero-emission society. The second-generation LEAF and LEAF e+ were launched in 2017 and 2019, respectively, with significant improvements in the driving range and output.

In 2021, a new crossover sport utility vehicle (SUV), the ARIYA, was launched. The ARIYA is a globally competitive SUV featuring all the latest Nissan technologies, including not only a stylish design and a dedicated EV platform, but also a motor, a high-capacity battery (66 kWh or 91 kWh), built-in connected technology, improved version of ProPILOT Assist 2.0, high-quality ride comfort, and quietness enabled by the e-4ORCE all-wheel control technology. Because of the attractive design of the ARIYA, it has received a number of domestic and international design awards, including the 2022 German Red Dot Design Award. In 2022, a completely new kei EV, the SAKURA, was released in the Japanese market. The SAKURA fully incorporates the technologies developed for the LEAF and provides customers with pleasant driving experiences in their daily lives. The SAKURA won the 2022-23 "Japan Car of the Year" award.

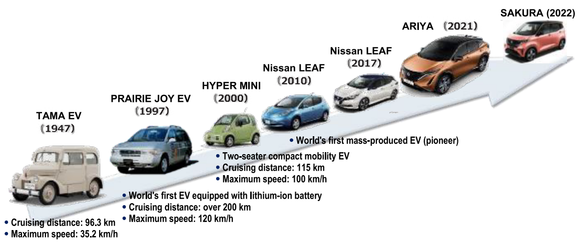

Fig. 1 History of Nissan EV development

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The evolution of the driving ranges of the LEAF and ARIYA is shown in Fig. 2(a). The initial LEAF (which had a battery capacity of 24 kWh) could reach a driving range of 200 km in the JC08 mode (the standard for measuring fuel economy at the time), and the second-generation LEAF (which had a battery capacity of 40 kWh) was able to reach a driving range of 400 km. In October 2018, the standard for measuring fuel economy was revised to the worldwide harmonized light vehicle test cycle (WLTC) mode. The second-generation LEAF (40-kWh version) had a driving range of 322 km in the WLTC mode, while the 62-kWh version had a driving range of 458 km, representing twice as much or more improvement as the initial model. In contrast, the ARIYA was rolled out in two grades: the B6 grade (which had a battery capacity of 66 kWh) had a driving range of 470 km in the WLTC mode, and the B9 grade (which had a battery capacity of 91 kWh) had a driving range of 610 km (the in-house measured value).

The evolution of the charging performances of the LEAF and ARIYA is shown in Fig. 2(b). The values shown in the figure were normalized by dividing the energy (kWh) added to the battery from the moment the battery's low-charge warning was activated until the charge reached 80% by the predetermined charging time (30 min). The second-generation LEAF and LEAF e+ exhibited charge acceptances higher than that of the initial LEAF by a factor 1.3, enabling a shorter charging time. Furthermore, the ARIYA achieved a charging performance that was a factor of 2.1 better than that of the initial LEAF.

This progress in the driving range and charging performance was accomplished through the evolution of various technologies throughout the vehicle, including batteries and powertrains. This article describes the evolution of these technologies, primarily those pertaining to batteries.

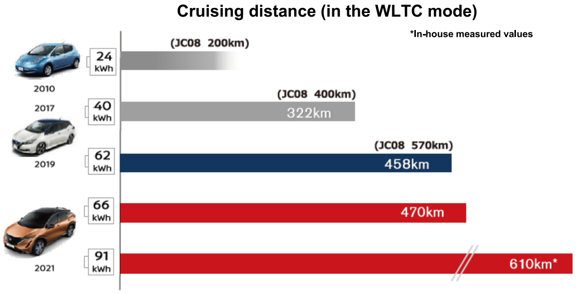

Fig. 2(a) Driving ranges of the LEAF and ARIYA

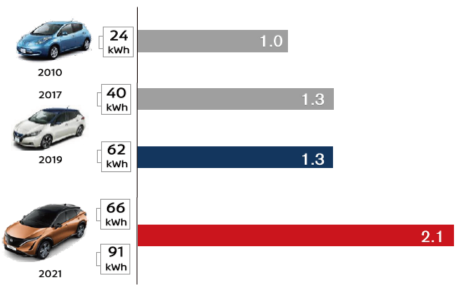

Fig. 2(b) Charging performances of the LEAF and ARIYA

2.2 History of the development of EV batteries

To enhance the appeal of EVs, the driving range and charging performance have been improved via the development of battery technologies. The typical technical challenges faced in the evolution of the driving range and charging performance of batteries are shown in Fig. 3. The technologies that have contributed to solving these challenges (the major battery cell and material technologies, as well as the pack and module technologies incorporated in the LEAF and ARIYA) are now introduced.

2.2.1 Evolution of cell and material technologies toward higher capacities

Increasing the energy density of a battery cell is an effective method for improving the driving range. One of the key methods for achieving this is to increase the capacity of the active cathode material. The evolution of the active cathode material is shown in Fig. 4. In the initial LEAF, a manganese-based material ($LiMn2O4$) with a spinel crystal structure was used as the cathode material. In contrast, in the second-generation LEAF, a nickel–manganese–cobalt (NMC)-based material with a layered structure (ternary: a mixture of nickel, manganese and cobalt) was applied. The cathode in the ARIYA contained a higher nickel content to further increase its capacity specifications. This NMC-based material can store lithium ions at a high density in its crystal structure, which enabled the second-generation LEAF and ARIYA to achieve battery capacities that were factors of 1.6 and 1.8, respectively, higher than the battery with the conventional manganese-based material.

However, the high-capacity NMC-based material has a layered structure, which causes its crystalline structure to be weaker in overcharged conditions than that of the conventional manganese-based material, reducing its reliability. To improve its robustness and reliability, the composition ratio of the NMC material, as well as other materials and components such as the separator layer structure, were optimized to produce a cell with well-balanced performance and reliability. This effort resulted in a high energy density cell that did not compromise its reliability. The cell resistance was decreased to further improve the charging performance. The NMC-based material contributes to decreasing the resistance because the lithium ions inside it are easier to move compared to those inside conventional manganese-based materials. Additionally, because of improvements in the composition ratio of the NMC material, anode material, and electrode properties, as well as decreases in the electrolyte resistance and the optimization of the stacked-layer structure of a cell, the cell resistance was reduced by over 50% compared to that of the cell for the initial LEAF.

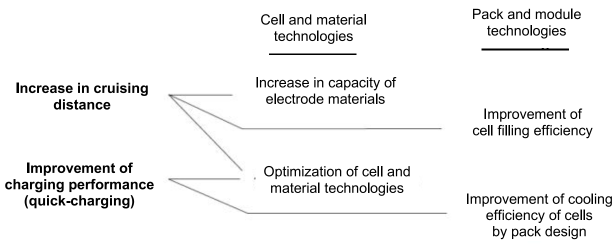

Fig. 3 Key technological challenges faced when evolving the driving range and charging performance of EV batteries

	Initial "Nissan LEAF" (24 kWh)	Second-generation "Nissan LEAF" (40 kWh, 62 kWh)	"ARIYA" (66 kWh, 91 kWh)
Cathode material composition	Mn Ni	N M C	N M C
Main material structure Lithium: ● Metal: ● Oxygen: ●	Spinel structure (LMO)	Layered structure (NMC)	Layered structure (NMC)
Capacity ratio	1	≧ 1.6	≧ 1.8

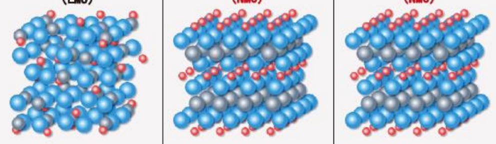

Fig. 4 Evolution of the active material of the cathode

2.2.2 Evolution of the pack and module technologies aimed at improving the mounting and cooling efficiencies

Increasing the driving range, increasing the energy density of the cell, and placing the cells to fill a pack as efficiently as possible are effective techniques for improving EV performance. To improve the quick-charging performance, suppressing the temperature rise of the cells during charging is also important, and one effective measure for accomplishing this is to increase the cooling efficiency of the cells. This requires increasing the heat transfer coefficient by switching from air cooling to liquid-loop cooling (LLC) and optimizing the layout inside the pack to effectively cool the modules that house the cells.

To increase the cell-mounting efficiency, the module structure for the second-generation LEAF was improved on the basis of the module structure for the initial LEAF. The initial model had a pack composed of modules containing four laminated cells stacked on top of each other, whereas the second-generation 40-kWh model had modules containing eight stacked cells. This reduced the number of components required to form a module and improved the space efficiency with which the cells were mounted. In addition, the space efficiency was further improved for the 62-kWh LEAF e+ by applying laser welding to the module, which eliminated the need to connect the tabs of the cells to the module via connectors. This resulted in a 10% increase in the cell-mounting efficiency compared to the 40-kWh model.

In contrast, the pack for the ARIYA, which employs a platform dedicated to EVs, required a thin and flat structure to allow a flat and roomy interior space. By designing a layout with a thin and wide arrangement of modules (Fig. 5(a)), the cell-filling efficiency was improved while maintaining the interior space. Although the narrower space between the outer framework of the pack and the battery module posed an impact resistance issue, a high impact resistance was achieved by arranging multiple cross members inside the pack. In contrast to the B6 grade, the B9 grade has a two-story structure, with modules arranged in the space under the rear seat to provide high energy capacity, which also contributes to a reduction in the number of parts because the same basic structure for the first story is used (Fig. 5(b)).

The ARIYA also employs a cooling (temperature control) system that uses LLC. In this system, a plate is placed across the bottom of the pack, and the battery is cooled by the coolant, which the LLC system cools with a chiller and then flows through the plate. To uniformly cool the modules (cells) placed inside the pack, the coolant of the LLC must flow evenly over the entire bottom plate, whereas the space inside the pack must be a watertight space that is separated from the flow channels of the LLC. A thinner design was achieved by integrating the three structures of the bottom plate, the LLC flow channel mechanism, and its protective plate (Fig. 5(c)). Even though the ARIYA's pack is also equipped with a temperature control system, this efficient arrangement produced an energy density per unit battery pack thickness that was 2.3 times higher than that for the LEAF e+, resulting in a superior volumetric energy density and an excellent quick-charging performance.

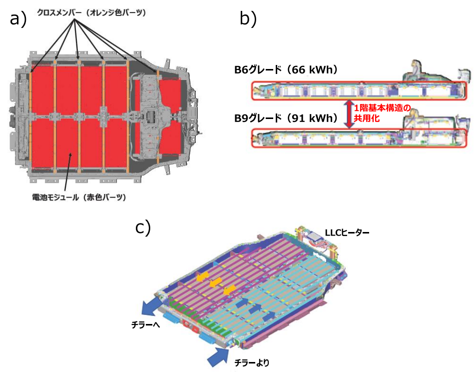

Fig. 5 (a) Battery pack layout for the ARIYA (B6 grade)
(b) Side views of the battery packs for the ARIYA (B6 and B9 grades)
(c) Bottom plate of the battery with LLC flow channels for the ARIYA (B6 grade)

3. Vision for the future: expectations for all-solid-state batteries

Nissan's battery roadmap is illustrated in Fig. 6. To improve the driving range, the energy density of the cells and the cell/pack volumetric efficiency (i.e., cell-filling efficiency) were further increased from the second-generation LEAF and to the ARIYA. The energy density of a cell can be increased by changing the cathode and anode materials. Specifically, silicon with a high capacity can be added to conventional graphite to produce the anode material, and the cathode material can be fabricated using a higher nickel content and less cobalt, but this is expensive. For the cell/pack volumetric efficiency, the components of the modules and pack were simplified and integrated while helping ensure collision resistance and reliability. Simultaneously, the performance and structural design of cells, modules, and packs can be promoted to achieve a precise balance between battery input and output capabilities, such as quick-charge performance, durability, and reliability. Efforts related to ASSBs, which are planned to be installed in vehicles from 2028 onward, are highlighted below.

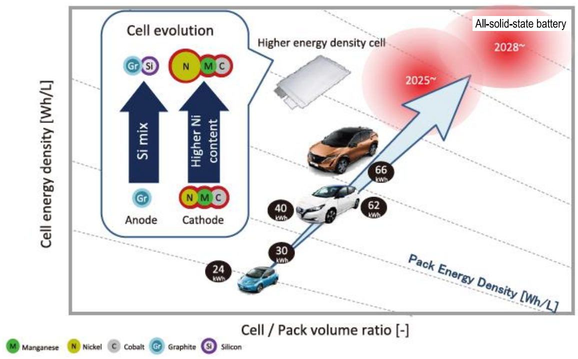

Fig. 6 Nissan's battery roadmap

In Nissan's long-term vision, called "Nissan Ambition 2030," the company announced that it aims to launch EVs equipped with ASSBs developed in-house by FY2028. ASSBs have high energy densities that are approximately twice that of conventional batteries, they have shorter charging times because of their excellent charge/discharge performance, and their costs are lower owing to the inexpensive materials they incorporate. Thus, ASSBs are regarded as game-changing technology that will facilitate the widespread use of EVs. Accordingly, ASSBs are expected to be installed in a wide range of vehicles, including pickup trucks.

In conventional lithium-ion batteries, the electrolyte is a liquid organic solvent, which is flammable and therefore can cause fire accidents. In contrast, the electrolyte used in ASSBs is solid, with no volatile or flammable properties. As a result, ASSBs are generally more reliable and less susceptible to temperature changes (Fig. 7(a)). In addition, although liquid electrolytes must be chosen from a limited selection of materials because of possible side reactions with the cathode and anode materials, solid electrolytes can be a combination of more diverse materials owing to the fewer side reactions that result from their solidity. This permits the selection of a less expensive cathode or anode material with a higher energy density.

Although ASSBs have outstanding technological advantages, various challenges must be addressed prior to their practical application. For example, because the solid electrolyte in an ASSB serves as a substitute for a liquid electrolyte, it is necessary to uniformly distribute the cathode and anode materials and the solid electrolyte, and to maintain a stable interface between each solid material, which requires a design that meets these criteria. For the cell, it is also necessary to deliver a surface pressure that maintains this interface, and for the manufacturing process, it is important to find the appropriate conditions that will allow uniform mixing (Fig. 7(b)).

Through joint research and development with global experts in various fields, a principled approach was employed to solve these problems. It involved identifying materials using cutting-edge computational science, establishing a basis for converting theoretically derived ideal materials into production-ready materials, and identifying and improving the factors underlying the phenomena occurring in prototype batteries. In the future, the development of practical applications will continue to accelerate by applying the knowledge accumulated from past experiences to the continual development of lithium-ion batteries and EVs. This endeavor includes research on battery materials at the atomic or molecular level, as well as cells, modules, packs, and EV vehicle bodies.

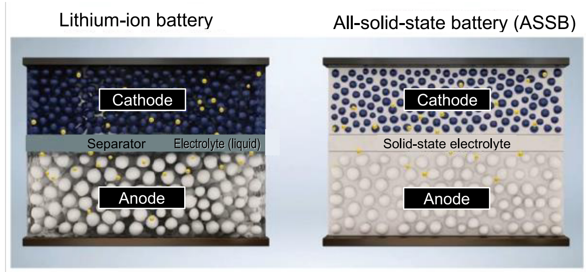

Fig. 7(a) Cell structures of a lithium-ion battery (left) and an ASSB (right)

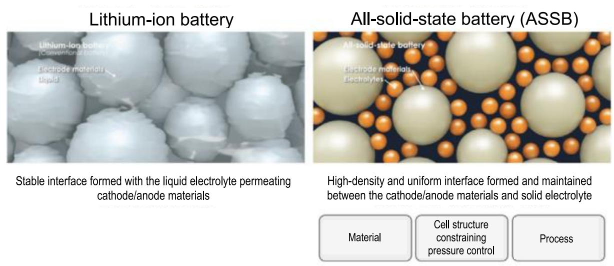

Fig. 7(b) Challenges of ASSBs (right) as compared to lithium-ion batteries (left)

4. Conclusion

According to a study by the Ministry of Economy, Trade, and Industry, in 2022 1.5 million of the 5 million automobiles sold domestically were exported overseas as used cars, while the remaining 3.5 million were scrapped. Out of those 3.5 million, 1.09 million were reused domestically for parts, and the rest were distributed to unknown domestic or international destinations. Only 420,000 of the 3.5 million were returned to their original dealers for scrapping(2).

As mentioned at the beginning of this article, Nissan will continue its efforts to achieve carbon neutrality throughout the lifecycle of its vehicles by 2050. However, as described above, the circulation of major vehicle components is not well tracked. Various components and vehicle bodies, including batteries, are currently being diligently designed for the manufacture and sale of EVs. If the majority of batteries, which are a key component of EVs and account for a large proportion of their overall cost, are lost after being designed, manufactured, and sold, with no clear destination in the distribution chain, the company would bear a major loss in terms of resources, costs, CO_2 emissions, and business opportunities.

Therefore, it is essential to build a sustainable eco-cycle for batteries, such as that depicted in Fig. 8. Batteries and EVs can be sold and used for conventional purposes, such as accessing a zero-emission means of transportation (including the used car market), and can also be used in new ways, such as grid stabilization, backup power sources, and an effective use of renewable energy (in coordination with an energy system called vehicle-to-everything, or V2X). Batteries that are decommissioned as EV components will be reused in a number of different ways. For example, batteries with relatively low degradation will be recycled for subsequent installation in used cars, sorted for forklifts, or energy storage systems (ESSs), or will be deployed for reuse and repurposing applications. After a battery has completely exhausted its service life, its raw materials will be recycled as new materials, which will then be used again for manufacturing additional batteries.

To establish such an eco-cycle of batteries, Nissan founded 4R Energy in September 2010 (prior to the launch of the initial LEAF), and started investigating the business of selling battery packs returned from the market for reuse purposes(3). Then in 2018, it established the Namie Factory and initiated a full-fledged business of remanufacturing returned battery packs from LEAF cars to resell for installation in used cars, forklifts, and ESSs.

As EV sales grow globally, such eco-cycles must function sustainably. To this end, it is important to develop schemes, technologies, and services for circulating EVs and batteries and returning them to Nissan. For example, technologies that correctly assess battery health and maximize their service life once they are manufactured and sold are necessary. Battery design and recycling methods that enable batteries to be simply and quickly removed from vehicles for disassembling and recycling are also required. Furthermore, a recycling network that enables batteries to be efficiently recycled with minimal environmental impact at the lowest possible cost must be established. It is also important to develop a scheme that allows this eco-cycle chain to work as a business, create new value to attract customers, build an information platform that centrally manages component IDs and carbon footprints, and build a network of business partners.

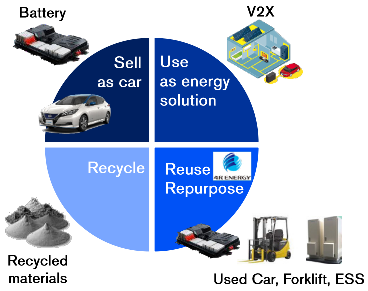

Fig. 8 Sustainable eco-cycle for recycling EV batterie

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Authors

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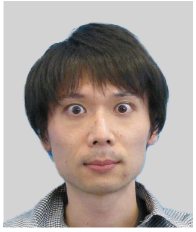

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Special Feature 1:Electrification

4. Evolution of the electric all-wheel drive e-4ORCE

Ryozo Hiraku*

1. Vision of electrification and electric all-wheel drive

Nissan believes that the electrification of power sources can extend beyond the mere replacement of internal combustion engines with electric motors. Electric motors can control power with high responsiveness and precision, and therefore, Nissan aims to realize the benefits of electric motor driving in vehicle performance by maximizing the abilities of electric motors. This vision has been consistently followed from LEAF, which was a battery electric vehicle (BEV) sold in 2010, to all latest 100% electrified vehicles equipped with e-POWER. In addition, an electric all-wheel drive (AWD) equipped with an electric motor on the trailing wheel does not indicate that only the mechanical system of the AWD is electrified. This implies that a drastic evolution occurs when two independent power sources are placed at the front and rear of the vehicle. In conventional mechanical AWD systems, the power generated by an internal combustion engine is distributed between the front and rear axles via transfer, and the power is mechanically transmitted to the trailing wheels through the connected propeller shaft (Fig. 1).

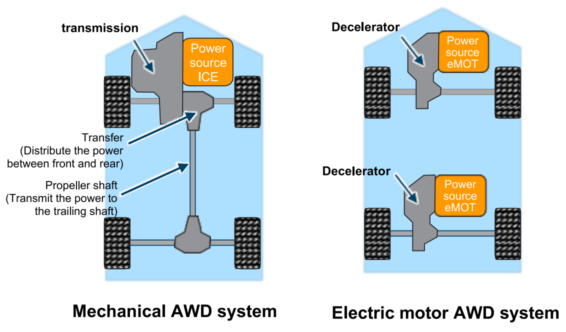


Fig. 1 Comparison of AWD systems

Controlling the output power with responsiveness as high as that of electric motors is difficult when the power source is an internal combustion engine, and there exists mechanical limitations, such as delayed power transmission and poor distribution resolution. It is challenging to control the total driving force and power distribution by the order of 0.1 s.

In contrast, for electric AWD systems with two electric motors installed at the front and rear, it is possible to control the driving force at the front and rear independently, with high responsiveness and precision.

The e-4ORCE aims to realize its benefits in terms of vehicle performance.

The vehicle performance referred to here is not limited to scenarios, such as the ability to travel on rough roads and stability on slippery roads, which is expected for conventional four-wheel drive vehicles. The aim of e-4ORCE is for the driver to appreciate its benefits even when an ordinary driver is driving normally on an ordinary road. In other words, e-4ORCE is committed to improving vehicle performance, thereby allowing people to experience its benefits not “for someday” but “daily.”

2. New drive control by two independent front and rear power sources

The basic control system of conventional cars is that the power generated by the power source, an internal combustion engine, is controlled by the steering, brake system, etc., each having a separate role in the control that can achieve good driving performance in “running,” “stopping,” and “turning” (Fig. 2).

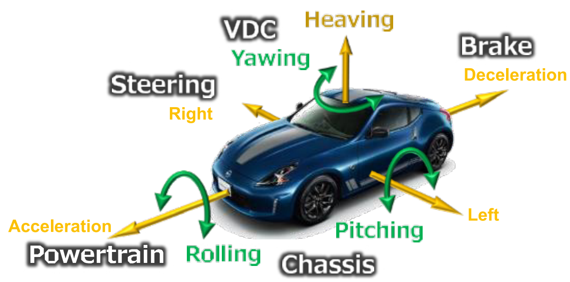


Fig. 2 Vehicle movement and system roles

*Powertrain and EV Engineering Division

When electric motors are used as power sources, they can perform functions that have not been handled previously by power sources. For example, some of the functions traditionally performed by the brake can be performed by carefully controlling the regenerative ability of the motor. In addition, unprecedented, smooth, and easy-to-handle driving characteristics can be achieved by skillfully using the high controllability of the motor. One such examples is "e-Pedal," which was adopted on LEAF.

In electric AWD systems equipped with two independent power sources at the front and rear, many movements can be controlled using an electric motor power source. For example, movements previously not controlled by a power source, such as the pitching and yawing of a vehicle, can now be controlled, albeit under limited conditions (Fig. 3).

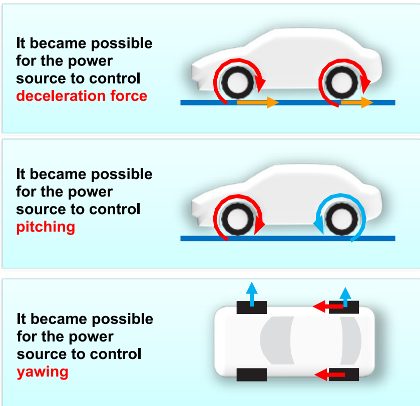


Fig. 3 Movement of electrified AWD

The technical framework of e-4ORCE is as follows: The role of each system within the vehicle is increased and the high potential of the electric motor is maximized using 100% electrified AWD as a premise to increase the vehicle performance to a level unreachable by conventional internal combustion engine vehicles and mechanical four-wheel drives. Nissan possesses expertise in maximizing the effects of driving-force control, brake control, and chassis control, obtained from developing ATTESA E-TS (electronically controlled torque split four-wheel drive system) of "GT-R" and the intelligent 4×4 system of X-TRAIL. Nissan's decades of experience in developing electric motor drives and advanced four-wheel drive systems have enabled the successful development of an innovative e-4ORCE AWD system with twin electric motors (Fig. 4).

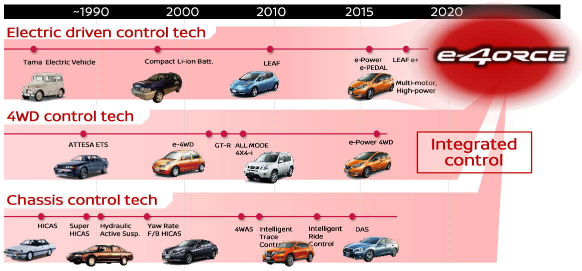


Fig. 4 Technical flow of e-4ORCE development

3. Benefits of e-4ORCE

The e-4ORCE delivers the following three benefits (Fig. 5).

1) Superior control and intuitive handling
2) Confidence in all surface conditions
3) Comfortable ride for all passengers

These benefits are discussed below.

Fig. 5 Benefits of e-4ORCE

3.1 Superior control and intuitive handling

A vehicle is supported by four wheels, and the load on each wheel (wheel load) changes constantly depending on the road surface and vehicle conditions. The ability of each tire to transmit a force to the road surface (tire traction force) (Fig. 6) changed with the wheel load. Stable driving can be achieved by controlling the balance of the tire traction force such that the wheel load of all tires are well within their limits. The e-4ORCE distributes the driving force to the front and rear wheels, considering changes in the traction force that responds to the changing wheel load depending on the road surface and driving conditions (Fig. 7). Further, it controls the driving force distribution between the right and left wheels according to the driving situation using integrated brake control, thereby coupling the brake force even outside the deceleration process and achieving better driving performance.

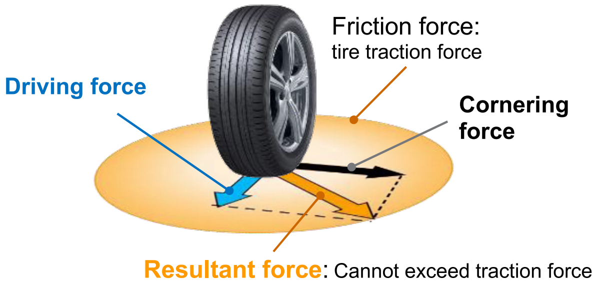


Fig. 6 Tire traction and driving forces

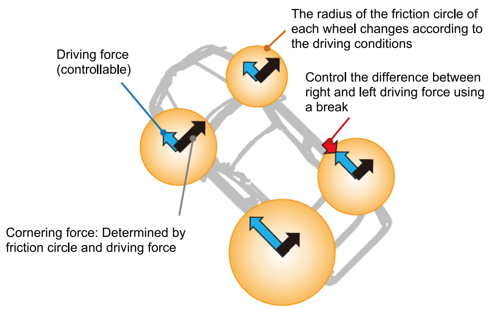


Fig. 7 Control of the force to turn each wheel using driving force

The driving line of the vehicle shifts outward (understeer) when a front-wheel drive vehicle accelerates while turning. Therefore, the driver must respond by either turning the steering wheel further (corrective steering) or slowing down (Fig. 8-a). This can be attributed to the limit value of the friction circle determined by the wheel load being used to accelerate the driving force, which weakens the force on the front wheel in the turning direction. However, in such situations, the rear wheels often have sufficient traction to withstand forces in the turning direction.

Under such conditions, e-4ORCE reduces the front driving force and redistributes the driving force to the rear wheels, whereas the front wheels do not exceed the limit value of the friction circle. In addition, e-4ORCE optimizes the right-left distribution of the driving force to stabilize the vehicle movement by integrating brake control, whereby the distribution of the driving force among all wheels is constantly optimized automatically without the driver noticing (Fig. 8-b).

At the end of the turn, e-4ORCE increases the side force on the rear wheels by transferring the driving force from the rear wheels to the front wheels to correct the yaw that occurs during turning. This prevents the vehicle from turning excessively inward (oversteering) because of the inertia while turning, thereby allowing a stable exit from the corner (Fig. 8-c).

During operation, the steering correction is minimized, and the driver feels smooth and stable vehicle movements that precisely follow the steering operation.

This control may appear beneficial only in special driving environments that test the limits of performance. However, even in normal driving environments, drivers tend to make unconscious steering corrections. If the vehicle reduces these steering corrections automatically without the driver noticing, it would benefit the driver by making the driving “less tiring” and “easy.”

3.2 Confidence in all surface conditions

e-4ORCE aims to provide benefits in normal driving situations, but it also provides a stable driving experience regardless of the surface conditions that vary depending on the terrain, season, and weather by improving the performance in difficult driving conditions such as wet surfaces, iced surfaces, and snowy roads, where AWD is expected to be handled. The following sections discuss the representative driving conditions.

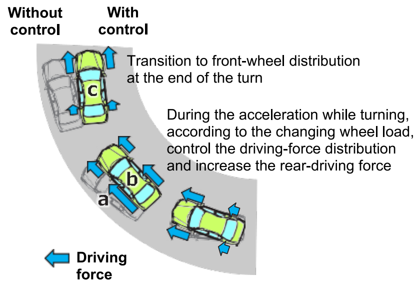


Fig. 8 Control of driving force distribution during turning acceleration

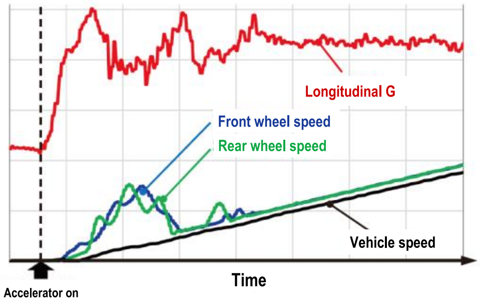
Starting on a slippery road

Sudden starting acceleration on a slippery road causes slippage of the driving wheels. However, AWD vehicles normally have no issues starting on a compacted snowy road by optimizing the distribution of the driving force among all four wheels. After detecting slippage, the conventional mechanical AWD stabilizes the vehicle movement by optimizing the driving force distribution, torque-down of the powertrain, and, if necessary, control of the wheel speed by brakes. However, it takes a certain amount of time for these actions to be reflected in the vehicle movement. Consequently, the driver is likely to feel uneasy by sensing wheel slipping.

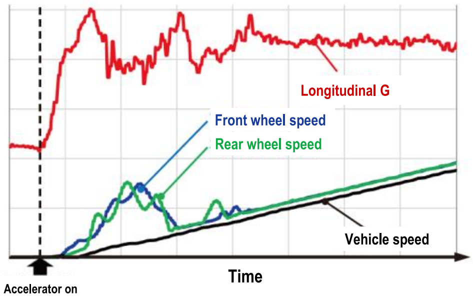
Fig. 9 Slippery road (image)

Figure 10 shows the driving performance between the e-4ORCE and mechanical AWD when the vehicle is started with an acceleration of 0.3G on a compacted snow road. For the mechanical AWD, the speed calculated from the number of rotations of the wheels (wheel speed) deviate from the vehicle speed immediately after starting, indicating the slippage of the wheels. Slippage destabilizes the longitudinal G (acceleration) and vehicle behavior, which is likely to cause an uneasy feeling for the driver. In contrast, for the e-4ORCE, wheel slippage is suppressed to an almost unnoticeable level, and G is stable because of the precise control of the motor.

Thus, e-4ORCE delivers a sense of security by reducing wheel slippage when starting on slippery roads.



e-4ORCE (new X-TRAIL)



Mechanical AWD (former X-TRAIL)
Figure 10 Starting on compacted snow road

Driving through deep snow road

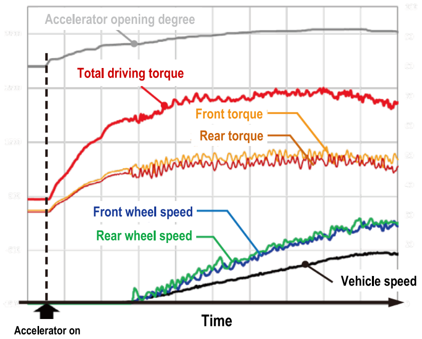
A sufficient driving force is required to overcome the running resistance caused by the tires being buried in the snow when the road is covered with deep snow in which the tires sink. However, the frictional force between the tires and road surface is small, and an excessive driving force can cause the vehicle to spin.

Fig. 11 Driving through deep snow road (image)

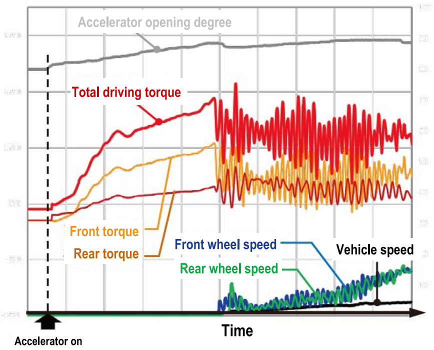
It is necessary to provide sufficient driving force to overcome the running resistance, and simultaneously, a precise control of the motor torque is necessary to prevent excessive tire slippage in such circumstances. The e-4ORCE controls the optimal front and rear motor torques according to the ground load of the tire in coordination with brake control, thereby achieving stable starting and running performances.

Figure 12 compares the vehicle behavior between e-4ORCE and mechanical AWD when the vehicle starts on a deep-snow road.

On such road surfaces, a sufficient driving force to overcome the increasing running resistance cannot be generated by the frictional force between the road surface and tires alone. An insufficient driving force can be recovered by kicking the snow backward. In other words, the vehicle ran while maintaining a certain slip rate (slippage) to kick the snow backward. For mechanical AWD systems, it is difficult to stably maintain the necessary slip rate, thereby causing excess slippage. To suppress this, the accelerator is released by the driver upon detecting excess slippage. However, Figure 12 shows that torque punching occurs with slippage, impeding the generation of a stable driving force. In contrast, e-4ORCE realized smooth starting and acceleration by allowing a certain slippage through precise control and a high torque response of the motor.



Mechanical AWD (former X-TRAIL)



Mechanical AWD (former X-TRAIL)
Figure 12 Driving through deep snow road

3.3 Comfortable ride for all occupants

Unrivaled smooth and easy driving characteristics can be obtained during deceleration by utilizing the excellent controllability of electric motors. The electric AWD can contribute to delivering an even higher level of comfortable riding experience.

For an electric vehicle (EV), applying regenerative brakes to front-wheel drive vehicles can cause a sharp “dive” even though deceleration is smooth because the front motor is used for the braking. The e-4ORCE suppresses the “dive” and vibration of the vehicle body during deceleration by optimizing the regenerative brakes of the twin electric motors installed at the front and rear (Fig. 13). This reduces the rocking motion even when the vehicle starts and stops repeatedly, thereby reducing the chance of motion sickness and providing a comfortable and enjoyable driving experience. The e-4ORCE delivers a smooth and comfortable ride not only to the drivers but also to all passengers in the passenger and back seats.

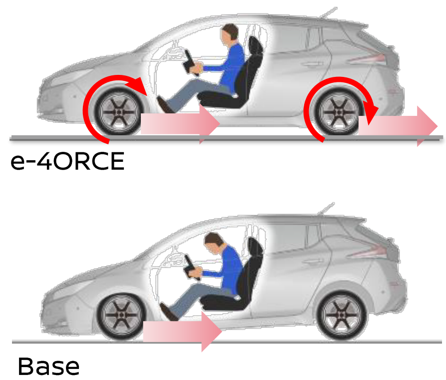
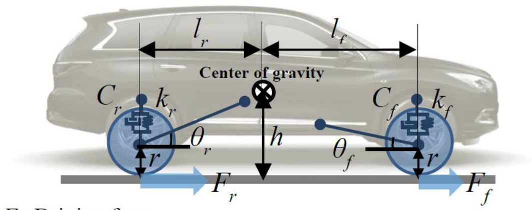


Fig. 13 Posture control during deceleration

This control utilizes the generation of a moment around the center of gravity of the vehicle, which is a function of the driving forces Ff and Fr of the front and rear tires and the anti-scud angles θf and θr of the front and rear suspensions as depicted in Equation (1) (Fig. 14).



F_f, F_r: Driving force
l_f, l_r: Distance, Fr/Rr wheel to center of gravity
θ_f, θ_r: Anti squat angle
h: Height of center of gravity
r: Tire radius
T_{df}, T_{dr}: Front and rear wheel drive torque
M_y: Moment generated in the vehicle body

Fig. 14 Pitch control by front and rear driving forces

Theoretically, it is possible to control the pitch angle θ of the vehicle body arbitrarily by optimizing the driving force and its distribution between the front and rear wheels, thereby enabling the vehicle movement that was impossible using conventional mechanical AWD systems.

$$My = lfFf\tan\theta f + lrFr\tan\theta r - (Ff+Fr)(h-r) - Tdf - Tdr \quad \text{------ (1)}$$

Conventional technologies control vehicle body posture using devices such as air suspensions, which can directly control the suspension. The proposed control in the e-4ORCE can suppress pitching without the use of variable suspension mechanisms.

Moreover, it is confirmed that the absolute pitch angle and changes in the vertical movement of the occupant caused by the changing rate of the pitch, i.e., pitch rate, and the changes in the longitudinal position of the center of pitch rotation, are important parameters for improving physical comfort. The e-4ORCE controls both the pitch angle and the two aforementioned parameters to improve riding comfort.

This control was adopted in the e-POWER 4WD, which was released before the official market launch of the e-4ORCE.

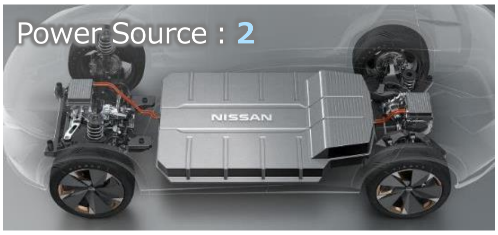
4. Summary and future prospects

e-4ORCE aims to improve driving performance not only in the challenging driving situations expected for conventional 4WD vehicles, but also in everyday driving experience. In other words, e-4ORCE is considered as a technology that revolutionizes cars in general, instead of only 4WD vehicles. Among the lineup of Nissan cars, these superior performances can be realized only by 100% electrified AWD vehicles equipped with a combination of BEV and e-POWER.

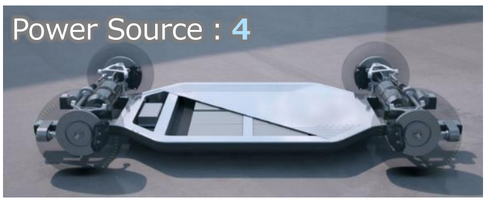
The aim of e-4ORCE is to bring out the full potential of the two onboard electric motors. However, it is believed that its full potential has not yet been realized. There is still room for improvement in the e-4ORCE, and Nissan aims to further develop this technology to enhance the benefits of vehicles.

The era of EVs is still in its infancy, and the possibilities for technological evolution, not only in control technology but also in hardware, continue to expand. There has been a drastic revolution in hardware to increase the number of power sources from only one to two. In future, the installation of three or four onboard power sources should be considered. In response to these future developments, we wish to continue promoting the evolution of vehicle mobility by utilizing the full potential of EVs to realize their benefits in driving performance.

機械式AWD：NISSAN GT-R



e-4ORCE：NISSAN ARIYA



NISSN EV Platform Concept

Fig. 15 Number of power sources

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Authors

Ryozo Hiraku

Special Feature 1:Electrification

5. System technology that provides EV-ness to e-POWER

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Hidekatsu Akiyama*** Azusa Ito*

1. Introduction: system control concept of e-POWER

Recently, Nissan has been developing e-POWER, which provides customers with a comfortable driving experience by utilizing the high-power motors of electric vehicles (EVs)*1. This article discusses the system control technologies for controlling the engine start timing and power distribution in an e-POWER system equipped with a power-generating engine.

The aim of e-POWER is to generate a driving experience unique to EVs that other systems cannot offer. Nissan's EVs have three key elements.

- Quietness: exceptional quietness that vehicles with conventional engines cannot offer.
- Smoothness: shock-absorption and smooth acceleration and deceleration.
- High response: torque that quickly responds to the driver's handling and is accurately linked to its extent.

To achieve these performance elements in e-POWER, Nissan developed the following two system control methods: energy management for controlling the power supply from the battery and engine, and power management for achieving torque characteristics unique to the motor drive.

An important component of system control for achieving quietness is energy management, which reduces the discomfort caused by the timing of the engine's start-stop operations and by the accompanying engine noise, which are responses to the request for power generation. The power management system controls the smoothness of the response; it calculates the motor torque command strictly according to the driver's request and optimally supplies power from the engine and battery according to the torque command. Energy management, which recharges the battery when energy has been consumed, also plays an important role in ensuring smooth operations.

This article discusses the performance improvements in the e-POWER system achieved through the evolution of the system's two basic control functions: energy management and power management.

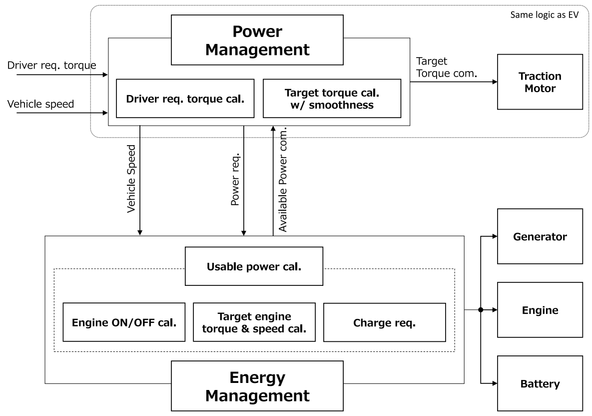

Fig. 1 Conceptual diagram of the e-POWER system

2. Outline of the e-POWER system's control method

Figure 1 outlines the control method of the e-POWER system. This system was designed based on battery electric vehicles (BEVs)*2, which are also motor-driven vehicles. In addition, the power management system used for calculating the traction is controlled using the same control logic as that used for BEVs. For energy management, the BEV control method has been adopted for battery-related systems, and e-POWER's own control block has been added to systems related to the combined operation of the engine and generator. In the case of a BEV, a charging system is provided instead of a combination of the engine and generator.

Because the power management system is used in the traction calculation, the smooth and highly responsive traction characteristics achieved via the development of the Nissan LEAF were also achieved in the e-POWER system.

In addition, because the engine revolutions can be controlled flexibly in the e-POWER system, the engine sound is utilized to produce an impression of acceleration by changing the rate of increase of the engine revolutions

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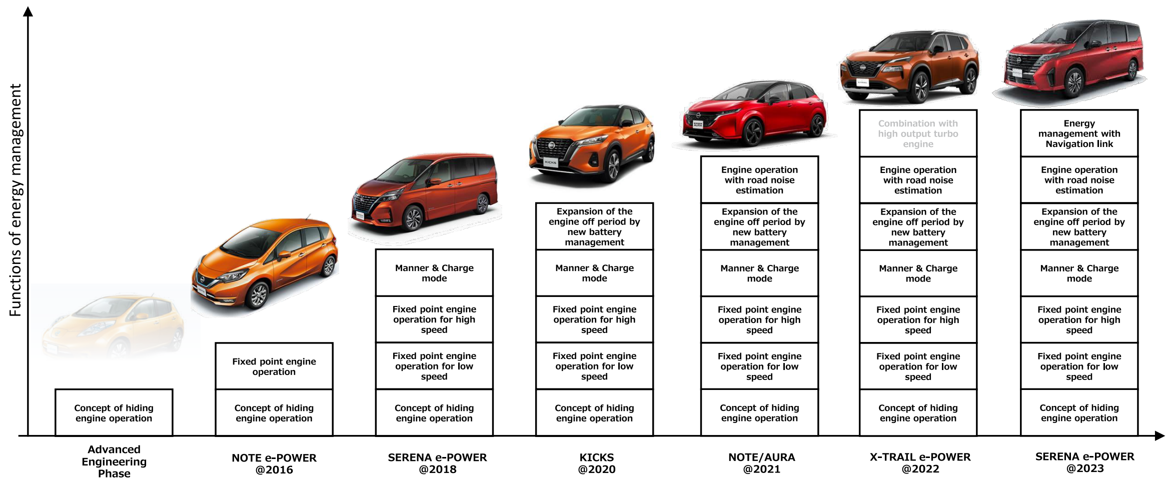

Fig. 2 Evolution of Nissan's energy management systems.

according to the driver's interaction with the acceleration pedal. Hence, the impression of acceleration is realized by the increase in engine sound, as well as the quick response and power unique to electrified vehicles.

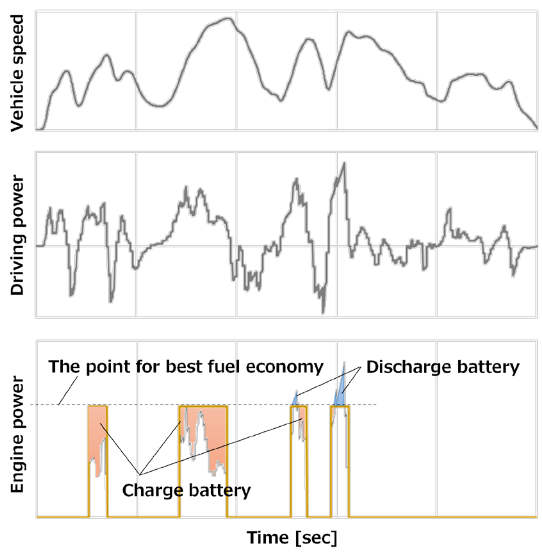

Fig. 4 Determination of engine operating points

3. Pursuing quietness: measures that make the engine less noticeable

In the e-POWER system, the control methods of the engine and battery affect various functions and outputs, such as quietness, fuel economy, acceleration performance, and heating and cooling. These engine operation control and battery charging/discharging functions are collectively called energy management. The evolution of e-POWER technology is strongly linked to improvements in energy management. Figure 2 illustrates this evolution.

The quietness of the e-POWER system was achieved as a result of conformity to the following directive (which was developed for advanced vehicles): generate the engine's power when the engine's noise is below the vehicle's ambient noise so that the engine will be less noticeable. To the best of the authors' knowledge, the engine does operate at high speeds . However, because requests for starting the engine originate from various components, power generation is not limited to the high-speed range, in which the ambient noise is high.

The following describes how the system is operated to enable the engine to be less noticeable.

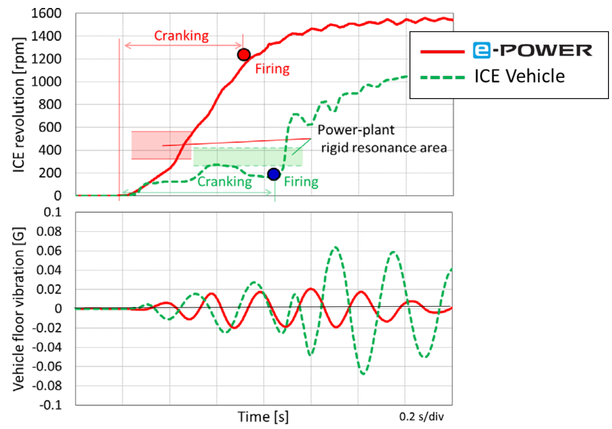

Fig. 5 Relationship between the timing of the engine ignition and the vibration of the floor

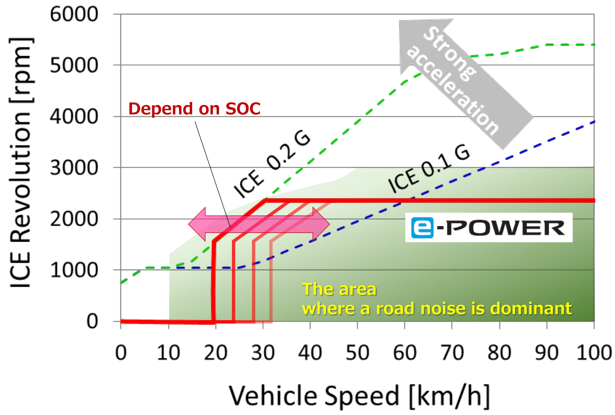

Fig. 6 Conceptual diagram of road noise in NOTE e-POWER with respect to engine revolution

3.1 Initial energy management

When Nissan started the NOTE e-POWER project, which was scheduled to be launched in 2016, it aimed to develop a system with significantly reduced battery power and capacity relative to advanced vehicles to satisfy the assembly and cost requirements of a compact car. Nissan also aimed to achieve a high fuel economy by masking the engine operation noise using the ambient vehicle noise, which is a technique that was employed in advanced vehicles.

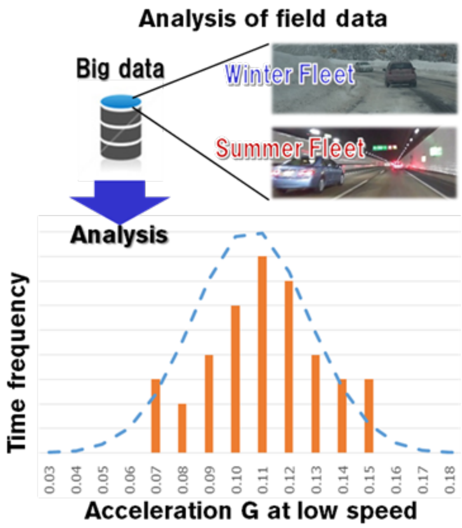

Fig. 7 Distribution of vehicle accelerations in the Japanese market

The basic purpose of energy management is to ensure that the power required for driving is generated at the optimal efficiency. Figure 4 outlines this operation. In the case of e-POWER, the engine operating points can be flexibly selected regardless of the vehicle speed, and power can be generated at the operating points using the optimal fuel economy pathway according to the required vehicle power. In addition, by compensating for the difference between the required vehicle power and the power generated at the optimal fuel economy via charging or discharging the power difference in the battery, the frequency at which the optimal fuel economy is exploited increases, leading to an improved fuel economy.

At low speeds, the engine ceases to generate power, and EV driving[*3] is performed using only battery power. Thus, when a battery's state of charge (SOC) is high, EV driving can also be performed at a higher speed. Because engine operation conditions are not constrained by vehicle speed, e-POWER enables EV driving at higher speeds.

Another important factor affecting quietness is the behavior of the engine when it starts. Engines have resonance bands at low-revolution levels. Therefore, if the engine revolves slowly for a long period of time, floor vibrations will occur and significantly affect the quietness. In the e-POWER system, a high-power generator is used as the engine starter. Therefore, as shown in Fig. 5, a shorter time is required for the engine to pass through the revolutions at which the powertrain resonance occurs, which suppresses the vibration when the engine is started.

3.2 New system control identified through market results

For the energy management systems of the NOTE and SERENA, the focus was on the coordination between the accelerator operation and the start of the engine. To further improve the quietness, Nissan modified this concept for the KICKS and developed a control method that expanded the engine's stopping range while performing conventional SOC management.

An analysis of the actual driving data on the Japanese market revealed that only small amounts of energy were required for scenarios in which acceleration did not continue for a long time, such as a right turn at an intersection or a standing start after a traffic light changes. Therefore, for such scenarios, Nissan assumed that the amount of power the engine needed to generate to recover the SOC would be small.

Accordingly, Nissan has decided to maintain the EV mode at the lowest possible SOC to offer the quietness of EV driving, and has established this control policy as the foundational concept of its energy management systems.

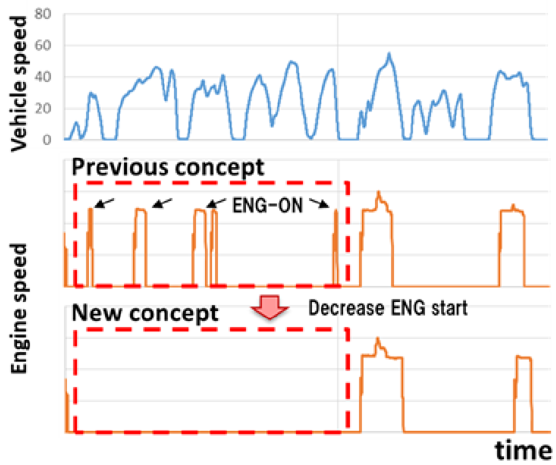

Fig. 8 Comparison between new and previous engine operating points

The key factors required to fulfill the abovementioned control policy are the appropriate values for the upper limit of the acceleration and the permissible SOC at which EV driving can be maintained. Unless these factors are optimally balanced, adverse effects can occur, such as the depletion of battery-assisted power during acceleration and the continual generation of power when the engine needs to be stopped.

To optimize the permissible range at which EV driving is maintained, Nissan collected actual driving data for the NOTE and SERENA over hundreds of thousands of kilometers. The data were analyzed to ascertain the distribution of driver acceleration patterns in the Japanese market. Figure 7 shows the distribution of accelerations in the Japanese market for low speeds (below approximately 30 km/h). The figure indicates that, in general, engine starts can be avoided in normal driving scenarios by maintaining the EV driving mode with an acceleration of approximately 0.15G. Nissan also obtained data such as the energy consumed per acceleration/deceleration for various speed ranges, which enabled the engine start time to be optimized.

By adopting a new energy management concept based on these market data analyses, the timing of the supply of engine-generated energy could be shifted to higher speeds.

Shifting the timing of the energy supply to higher speeds produces the following two effects. The first is a reduction in the frequency of starts at low speeds (specifically, a reduction in the frequency of engine starts and stops within a short time period), at which the ambient noise is low. The second is a reduction in the frequency of engine starts and stops by generating power in bulk at high speed to effectively use the power generation system.

Figure 8 shows the engine operation modes of the new and old energy management concepts. The frequency of low-speed engine starts was reduced. In particular, the frequency of engine starts and stops within a short period was decreased. At speeds 30 km/h or less, the number of engine starts was reduced by approximately 70% compared to conventional energy management systems. This superior level of control significantly contributed to the improvement in quietness, which is a major feature of e-POWER.

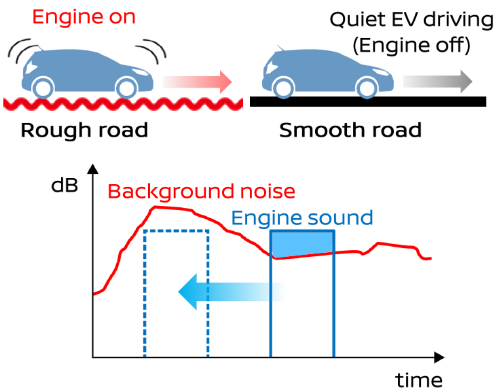

Fig. 9 Energy management concept based on the estimated road noise

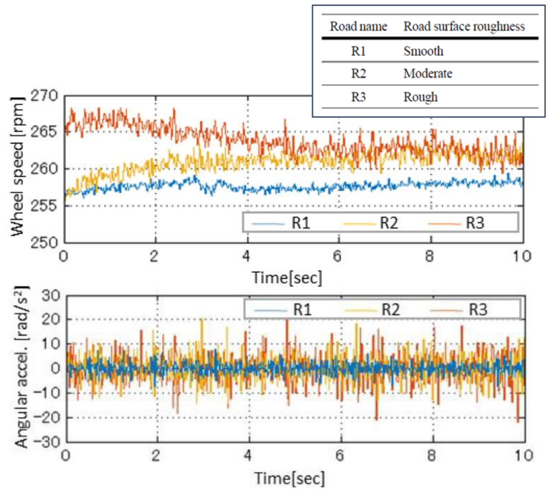

Fig. 10 Relationship between the road surface roughness and the angular acceleration of the wheel

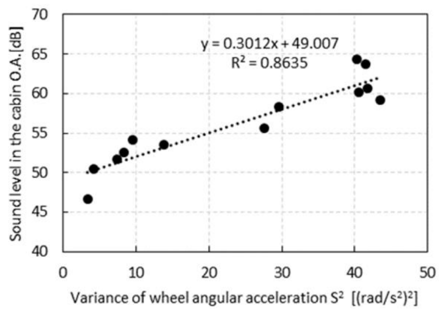

Fig. 11 Relationship between the angular acceleration of the wheel and the road noise

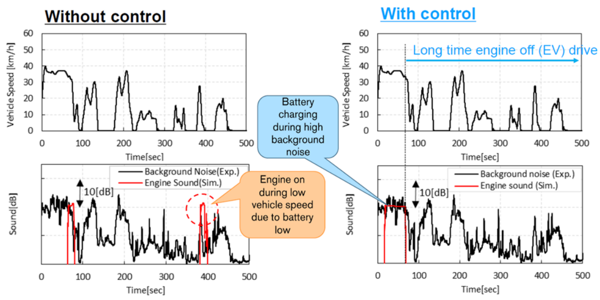

Fig. 12 Comparison between engine starts with and without road surface detection control

3.3 System control with active estimation of road noise

In conventional energy management systems, the engine start timing is determined by the driver's operations, SOC, and other factors based on conditions established offline, such as the results of market data analyses. To further improve the quietness, Nissan focused on the tire noise caused by the roughness of the actual road surface. A new system control method was devised to generate power when the road noise exceeded the engine noise and to maintain EV driving when the road surface is smooth. Figure 9 illustrates this energy management concept.

According to driver experience, the road noise generated by tires is greater when the road surface is rough. Therefore, to estimate the roughness of the road surface, Nissan focused on the angular acceleration of the wheel and measured its relationship with the road surface conditions.

Figure 10 shows the relationship between the road surface roughness and the angular acceleration of the wheel. The latter fluctuated more severely when the road surface was rougher. Figure 11 shows the relationship between the angular acceleration of the wheel and the road noise. As shown in the figure, the angular acceleration of the wheel and the road noise were strongly correlated.

Accordingly, Nissan used real-time measurements of the angular acceleration of the wheel to develop a logic that determines the roughness of the road surface and, by extension, the magnitude of the road noise. This logic detects loud road noise when the magnitude of the angular acceleration is high for a certain period of time. This logic was adopted in the new NOTE launched in 2020. Figure 12 shows a comparison between the engine start timings for vehicles with and without road surface detection control. Using this control method, the engine can generate power in areas where the road noise is high, further improving the quietness.

This control method decreases the likelihood that the engine start timing will be noticed, giving the driver the impression that the SOC has recovered imperceptibly.

Because this control method generates power in bulk in areas where the road noise is high, it also reduces the frequency of engine starts. Therefore, transient fuel consumption required by frequent engine starts is minimized, thereby contributing to fuel economy. This control method, which optimizes the system in real time, is the first energy management method that utilizes information on the ambient environment. Systems that operate by using information other than conventional information (e.g., the driver's requests and system conditions) are categorized as “intelligent technology.” In the new NOTE and subsequent models, energy management was further improved using intelligent technology, as described in the following subsection.

3.4 System-controlled SOC that utilizes navigation information

Nissan developed an energy management method in which navigation information is utilized to predict the energy required for driving, which enabled the EV driving mode to be activated near the destination.

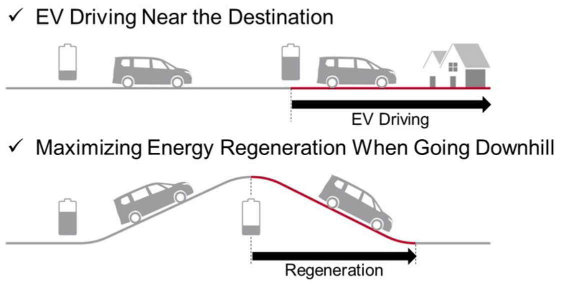

Fig. 13 Concept of predictive charging/discharging control

Figure 13 shows the concept of predictive charging/discharging control. After the destination is defined in the navigation system, the slope angle and average speed information along the route (up to approximately 7 km ahead of the vehicle's current position) are sent from the navigation system to the system controller. Based on the information received, the system controller then calculates the amount of power the vehicle will consume as it travels along the route. These data are updated as required while the vehicle is traveling. The energy consumption is estimated accordingly, and the battery SOC is adjusted based on this estimation.

Based on this information, two primary functions were developed. The first is a control method that lowers the battery's SOC until the vehicle reaches a downhill slope, which allows the energy to be recovered. The other is a control method that raises the SOC upon arriving near the destination, so that the vehicle can actively perform EV driving within 500 m of the destination.

Figure 14 shows the relationship between the navigation information for a downhill slope and the SOC of the battery. Before arriving at the downhill slope, the energy that could be recovered via regeneration is calculated, and the permissible SOC of the battery is lowered by the same amount before the vehicle reaches the downhill slope. As a result, energy can be recovered when the vehicle drives along a downhill slope without needing to fully charge the battery (i.e., without wasting energy).

Fig. 14 Relationship between navigation information and the battery's SOC

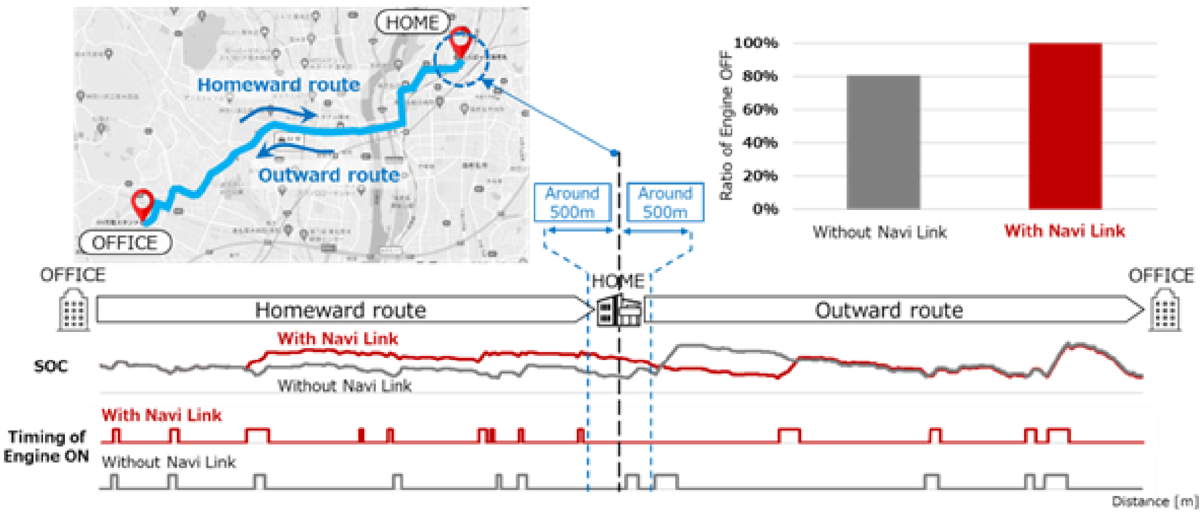

Fig. 15 Effect of predictive charging/discharging control (for enabling EV driving mode near the destination)

Figure 15 shows the effect of enabling EV driving mode when the vehicle is near the destination. In this study, this function was evaluated for a flat urban road approximately 10 km long. As the vehicle approached its destination, the predictive charging/discharging control caused the SOC to be higher on average than that achieved by the conventional control method. Consequently, EV driving mode was active within 500 m of home, which was the destination. One characteristic exhibited by this control method was the absence of continuous power generation immediately after the vehicle embarked on the outbound route from home to the office. Hence, the aim of having a vehicle travel quietly near home was realized.

In addition, the duration over which the engine was stopped increased by approximately 20% compared to the conventional control method. The main difference between the new and conventional control methods was the stoppage of the engine within 500 m of the destination, which contributed to the overall quietness along the route. This control method was adopted for the SERENA.

Because of the success of intelligent technology in obtaining various types of information from the environment to further improve certain driving characteristics (e.g., quietness), intelligent technology will be a major focus of future research.

4. Pursuing comfortable acceleration: generating a sufficient power supply and smooth acceleration

The traction control mechanism derived via the development of the Nissan LEAF is well accepted in the market, and the power management system of e-POWER was derived from that control feature. However, unlike an EV, in which power is supplied only from the battery, e-POWER receives power from both the battery and the engine. Therefore, a delay in the supply of engine-generated power affects the acceleration performance.

In this section, measures taken against such issues, as well as the system control technologies that led to improvements in e-POWER's acceleration smoothness, are discussed.

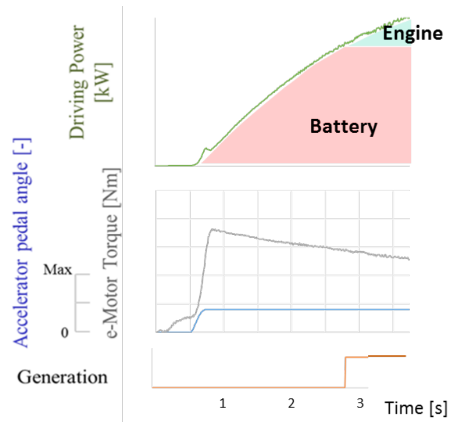

Fig. 16 Power distribution when the battery's SOC is high

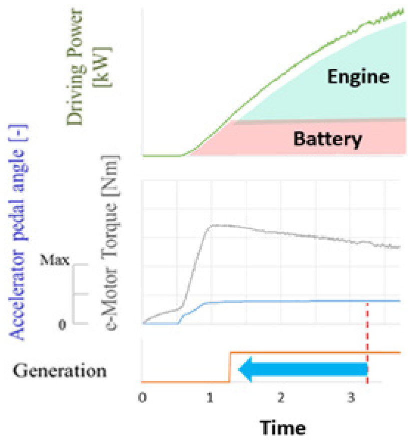

Fig. 17 Power distribution when the battery's SOC is low

4.1 SOC-independent acceleration performance

Compared to BEVs, the improvement offered by the power management of the e-POWER system is control that does not create an acceleration drop, even when the battery power is low.

Figure 16 shows the engine starting conditions when the vehicle accelerates and the battery has sufficient power with a high SOC. The EV driving mode was maintained and the engine power generation was suppressed for as long as possible. In contrast, Fig. 17 shows the conditions when the SOC is low and sufficient power cannot be supplied by the battery. The engine starts generating power early to avoid producing an acceleration drop. Using this control method, the same acceleration is achieved regardless of the system conditions.

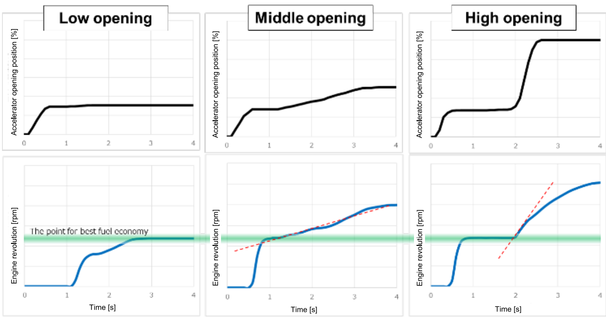

Fig. 18 Engine revolutions according to the intended acceleration

4.2 Acceleration smoothness and fuel economy

As discussed above, the e-POWER system uses power from the engine to generate the power required by the vehicle when the acceleration is high.

An increase in the engine operation noise reduces the quietness of the EV-ness[*4]. Nonetheless, to create a sensation of acceleration commensurate with the driver's intended acceleration, we utilized e-POWER's ability to flexibly control the engine revolutions and designed the system such that the engine revolutions changed according to the driver's intended acceleration, as indicated by the accelerator opening position.

Figure 18 shows the engine revolutions as a function of time for each accelerator opening position. If the opening position is small, it should be controlled to achieve both the required fuel economy and quietness. The increased rate of revolutions and target revolution match the intended acceleration to the corresponding sensation of acceleration, which is produced by the engine sound as the power required for driving is generated.

These controls, which are used in the e-POWER system and are mounted along with a small-displacement naturally aspirated (NA) engine, have been developed so that traction more similar to that of EVs can be provided in any situation.

4.3 Improved acceleration in a high-power system

In the new X-TRAIL system, e-POWER was combined with a turbocharged engine for the first time. Turbocharged engines are characterized by their ability to increase the torque, although a delay occurs as the boost pressure increases. Therefore, in e-POWER, the battery-assist function is actively utilized to achieve smooth and powerful acceleration.

Figure 19 shows the acceleration characteristics of e-POWER when combined with the VC-TURBO engine. With the assistance of the battery, the engine responded well as the acceleration increased. However, when the engine torque was added, stagnant acceleration (i.e., lack of acceleration growth) occurred owing to the turbo lag. Therefore, assistance from the battery was coordinated with the increase in boost pressure, and increases in the rate of change of the engine revolutions were suppressed to generate the appropriate sensation of acceleration, realizing both smooth and powerful acceleration and a rise in the engine revolutions.

Figure 20 shows a comparison between the engine revolutions attained during acceleration by the e-POWER 4WD and that by another manufacturer's conventional hybrid electric vehicle (HEV) 4WD. In the figure, the points at which the person evaluating the vehicle detected a synchronization between the increase in engine revolutions and the vehicle's acceleration are plotted.

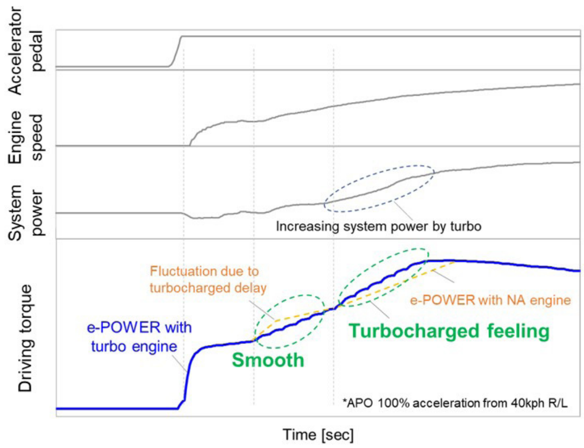

Fig. 19 Acceleration characteristics of e-POWER when combined with the VC-TURBO engine

For the other manufacturer's vehicle, in which the NA engine was mounted, the required power was supplied by quickly increasing the engine revolutions. Therefore, the vehicle's acceleration and the increase in engine revolutions were weakly correlated, and the engine revolutions were maintained at their upper limit while the vehicle was accelerating, resulting in discomfort. Therefore, the engine revolutions were significantly higher than they were in the zone in which no synchronization was detected.

In contrast, the X-TRAIL implemented balanced control between the abovementioned rise in engine revolutions and the vehicle's acceleration (referred to as "linear control"). Specifically, the increase in engine revolutions was suppressed within the zone in which synchronization was detected, contributing to a sensation of an increase in acceleration.

Because of this linear control, the X-TRAIL is favored by European customers who pay close attention to the behavior of engine revolutions.

5. Further evolution of system control

The energy and power management systems described in this article are scheduled to be improved further so that they can be adopted in the next-generation e-POWER system.

When evolving the e-POWER system in the future, the primary focus will be on using intelligent technology to create additional value in practical areas. To comply with the increasingly stringent exhaust emission regulations and optimize fuel economy, the range of data that can be utilized needs to be expanded even further. For example, cloud information can be utilized to execute real-time control that adapts to traffic congestion, and optimizing the air conditioning can also be examined.

Because the engine and wheels are not mechanically constrained, e-POWER is highly flexible, which allows its performance to be improved with relative ease. However, owing to the large number of degrees of freedom, interference problems resulting from multivariable control requirements may occur. Therefore, it will be necessary to address the increasingly complex issue of managing the development of control. By utilizing recent developments, such as artificial intelligence, further improving the performance may be possible. This represents one of the many ways in which Nissan actively engages in new development policies that offer greater value to customers.

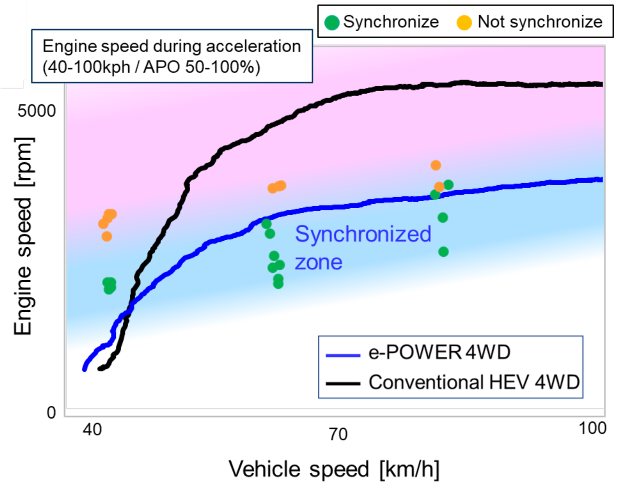

Fig. 20 Comparison between the engine revolutions of the e-POWER 4WD and a conventional HEV 4WD. The green dots indicate when the evaluator detected a synchronization between the increase in engine revolutions and the vehicle's acceleration, and the orange dots indicate when they did not detect such a synchronization

Explanation of terms

*1 EV: vehicle powered only by electric motor
*2 BEV: EV powered only by battery power
*3 EV driving: driving with e-POWER via battery power only with the engine stopped
*4 EV-ness: quiet, powerful, and smooth driving experience unique to electric vehicles

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Authors

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Special Feature 1:Electrification

6. Challenging to reach 50% thermal efficiency for engine dedicated to e-POWER for sustainable mobility

Tadashi Tsurushima*

1. Introduction

The demand for the mitigation of global warming and the reduction in pollutants has been rapidly increasing. Today, the realization of a sustainable society is a pressing and common goal of the world. To contribute to creating a sustainable society, Nissan is pursuing two pillars of mobility solutions. The first pillar is a battery electric vehicle (BEV) that emits no CO_2 in the tank-to-wheel segment. The second is an "e-POWER" series hybrid electric vehicle (HEV) equipped with an engine that operates at a high thermal efficiency. Nissan introduced e-POWER to transition from conventional internal combustion engine vehicles to BEVs, with the aim of reducing the well-to-wheel (WtW) CO_2 emissions to a level similar to that of BEVs.

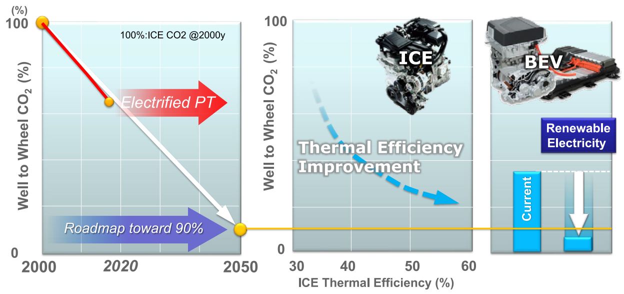

Fig. 1 NISSAN WtW CO_2 reduction strategy

The ultimate goal was to increase the e-POWER engine's brake thermal efficiency (BTE) to over 50%. To this end, a roadmap for the next generation of sustainable mobility was created. In this roadmap, a new engine technology that exploits the excellent characteristics of e-POWER allows the engine operating points to be selected independent of the vehicle's running conditions.

This article first describes the concept of the thermally efficient engine customized for e-POWER as well as its development goals. Next, a new combustion concept called "Strong Tumble and Appropriately stretched Robust ignition Channel" (STARC), which can handle highly diluted combustions, is explained in detail. Subsequently, the technologies developed to achieve 45% thermal efficiency at λ=1 are discussed. Finally, the test results are presented.

Experiments demonstrated that a thermal efficiency of 43% was achievable using a 1.5-L three-cylinder engine equipped with three items: STARC, an air intake system customized for e-POWER, and a friction reduction system. The combination of the new engine concept and the new heat recovery system was expected to achieve a thermal efficiency of 45%. This article also discusses future prospects for increasing the thermal efficiency up to 50%.

2. Increasing the thermal efficiency of the engine dedicated to e-POWER

2.1 Dedicated engine and development goals for e-POWER

The e-POWER system stores the engine's power output in a battery as electric energy instead of transmitting it to the driving system via a series of hybrid operations. This allows the engine's operating points to be selected independent of the vehicle's running conditions, which is one of e-POWER's unique characteristics. Figure 2 shows a schematic of the concepts behind the engine dedicated to e-POWER. The basic concepts are as follows. First, the engine requires no low-end torque because of the high-output motor, which BEVs also have. Second, the engine can maintain the optimal thermal efficiency throughout its operating range for the series hybrid operation and does not operate in the low-load region after the catalyst temperature is increased. Additionally, e-POWER does not require idling and can reduce the engine's rotational speed by controlling the charging operation. Owing to these operating conditions, the engine specifications can be optimized for two operating points: the optimum thermal efficiency and the maximum output power.

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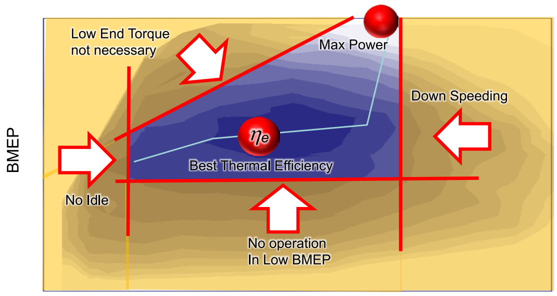


Fig. 2 Schematic of e-POWER engine operation and dedicated engine concept

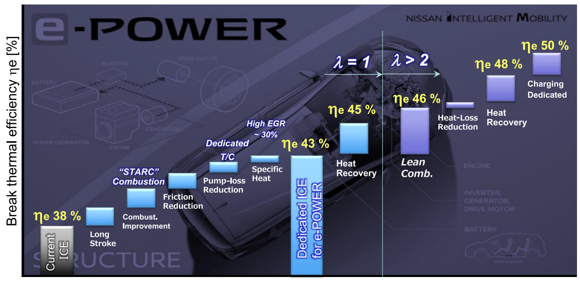


Fig. 4 Thermal efficiency roadmap toward 45% with lambda=1 and 50% with lambda > 2 (RON95)

Based on a preliminary study, the target for the maximum thermal efficiency was 45% (which included the engine improvements and waste heat recovery), and the target for the specific output power at λ=1 was 80 kW/L. These targets represented outstanding performance compared to current engines, especially considering the trade-off between thermal efficiency and output power (λ=1), as shown in Fig. 3.

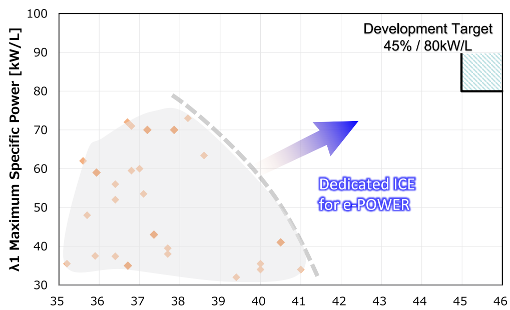


Fig. 3 Positioning of the new concept engine development target in brake thermal efficiency vs maximum specific output power (lambda=1) scatter band

Figure 4 shows the roadmap used for improving the thermal efficiency using the new e-POWER engine concept, and Fig. 5 presents an overview of the engine. Fundamental technologies used for the improvement, such as lengthened strokes, combustion precision, and friction reduction, are also used for improving conventional engine technologies. However, owing to the characteristics of the series hybrid operation, further improvement in the thermal efficiency was possible with e-POWER via highly diluted combustions, a dedicated turbocharger, and friction reduction. As a result, achieving a high thermal efficiency of 43% and a high specific power output of 80 kW/L at λ=1 was expected.

The following sections describe the details of the engine dedicated to e-POWER.

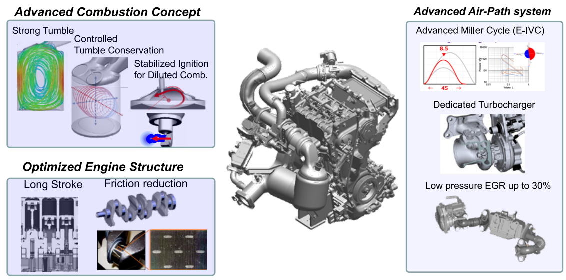


Fig. 5 New engine concept dedicated for e-POWER

3. New combustion concept: STARC

For the new high-efficiency engine concept, a new combustion technology was developed to achieve a cooled exhaust gas recirculation (EGR) rate of up to 30% for highly diluted combustions (λ>2). To increase the stability under highly diluted combustion conditions and to reduce the cycle variation, the STARC combustion concept was formulated to ensure the stable formation of discharge channels via a strong tumble flow with minimal cycle variation. The cycle variation in the ignition delay time was reduced via the stable formation of initial flame kernels.

3.1 Key technology for stable combustions under highly diluted combustion conditions

Figure 6 shows the schematic of the STARC concept. This new combustion concept was developed to produce a high compression ratio, high specific heat ratio, and low cooling loss by enabling rapid combustions under highly diluted conditions to reach a maximum cooled EGR rate of up to 30%.

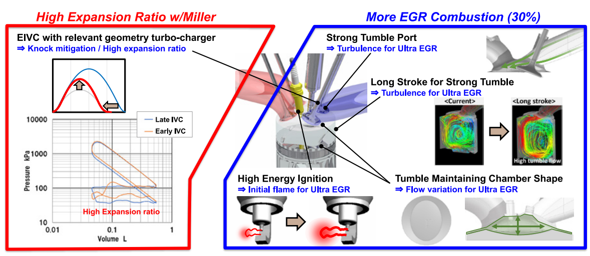


Fig. 6 New combustion concept "STARC" for highly diluted combustion

To generate stable combustions under highly diluted conditions, creating a rapid and stable initial flame propagation is important. To visualize the behavior of the spark discharge channel and initial flame propagation, the cylinder bore was observed with an endoscope, which was connected to a high-speed camera (FASTCAM SA-2X, Photron). Figure 7 shows a schematic of the visualization system. The endoscope was inserted through the sidewall of the combustion chamber to visualize the vicinity of the spark plug. Images of the light produced by the spark discharge and initial flame were captured directly.

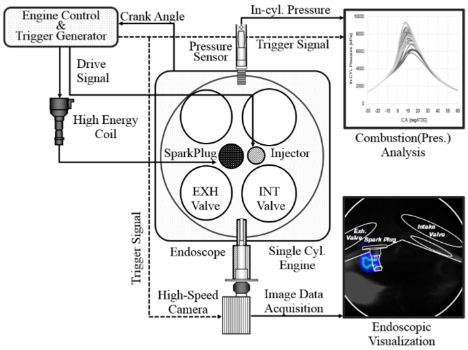
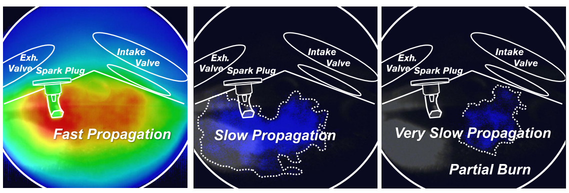


Fig. 7 Visualization system of spark discharge channel and initial flame kernel

Figure 8 compares the images of the initial flame propagation for combustions with λ=1 (Fig. 8(a)) and λ=2 (Fig. 8(b) and (c)). The figure indicates that, for the λ=2 combustions, the flame propagation was slower and the formation of an initial flame kernel was more varied between cycles (relative to the λ=1 combustions without dilution). In addition, for cycles in which the formation of an initial flame kernel was slow (Fig. 8(c)), a partial burn[7] was observed later in the cycle, indicating that the formation of initial flame kernels was an important parameter for cycle variations.



(a) λ=1 (b) λ=2 (c) λ=2 (Partial burn)

Fig. 8 Initial flame propagation with lambda=1 w/o dilution (a), lambda=2 slow propagation (b), lambda=2 very slow propagation (c)

An initial flame kernel formed through the spatial energy supply via a discharge channel stretched by the flow velocity at the spark plug gap[8]. Figure 9 shows the behavior of the spark discharge channel for different flow velocity conditions at the spark plug gap. When the flow speed was low (Fig. 9(a)), the spark discharge channel did not stretch, and the supply of thermal energy to the spark plug gap was insufficient. When the flow speed was high (Fig. 9(c)), the energy supply was insufficient because the discharge channel was blown off. In either case, the formation of the initial flame kernel slowed and caused cycle variation. Therefore, to reduce the cycle variation, stabilizing the flow speed at the spark plug gap in each cycle is important. This study aimed to stabilize the formation of an initial flame kernel by inducing a strong tumble flow with minimal cycle variation for highly diluted combustions.

Figure 10 shows a schematic illustrating the formation of the ignition and in-cylinder flow, which were used to stabilize the highly diluted combustions. The key to stable combustion is minimizing the cycle variation by inducing an appropriate flow direction and flow rate in the vicinity of the spark plug gap, which can be accomplished by controlling the timing of the growth of an initial flame kernel. This strategy was realized by combining an in-cylinder flow design with a high-energy ignition system. In addition, for mitigating knocks, early intake valve closing (E-IVC) was adopted to maintain a low temperature in the lower unburnt zone.

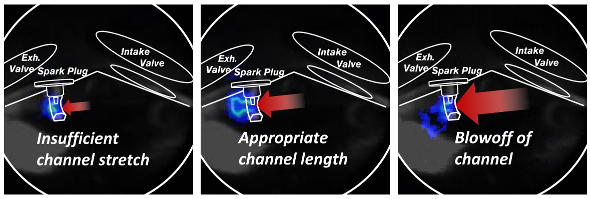


Fig. 9 Spark channel behavior under different flow velocity at the spark gap

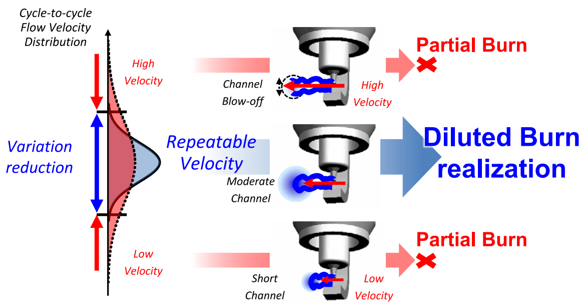


Fig. 10 Desirable flow to realize stabilized ignition for highly diluted combustions

3.2 Design of in-cylinder charge motion

To realize rapid and stable combustion under highly diluted conditions, providing an appropriately high flow velocity around the spark plug with minimal cycle variation is necessary. In addition, compensating for the decrease in the laminar flow flame speed caused by the dilution requires a high turbulent intensity. Considering the formation process of the tumble flow inside the cylinder bore, which is shown in Fig. 11, the following three design requirements were proposed to stabilize the flow speed at the spark plug gap in every cycle.

1.Inducing tumble flow along the upper part of the cylinder bore
2.Conserving tumble flow until ignition
3.Guiding the direction of the flow toward the spark plug

When swirling flows remain during the expansion stroke, the cooling loss increases. Therefore, this study focused on using tumble flows in which the swirling components tended to decay or collapse after reaching the top dead center. The following sections describe the details of each of the three design requirements and the technologies used to fulfill them.

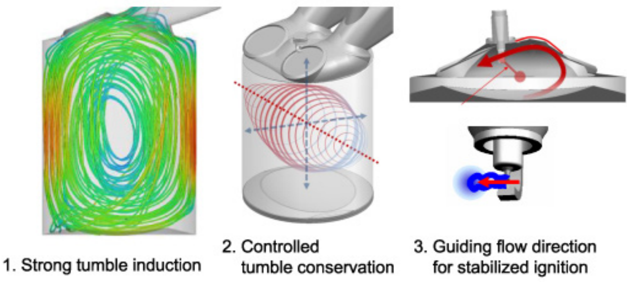


Fig. 11 In-cylinder charge motion design to realize STARC combustion concept

3.2.1 Methods for inducing strong tumble flows

The in-cylinder flow motion is driven by the kinetic energy of the gas sucked into the cylinder from the air intake port. Therefore, maintaining a stable air intake without energy losses at the port location is important. For this reason, the first design requirement, which involved inducing tumble flows from the upper surface of an air intake port along the combustion chamber exhaust pent roof without deviation, was introduced, and a valve-seatless technology[9] was adopted using cold spraying and the enlargement of the valve-induced angle.

Because valve-seatless technology provides design freedom for the shape of the air intake port, structuring the intake port such that it is smoothly connected to the combustion chamber is possible, as shown in Fig. 12. Figure 13 shows the flow velocity and turbulent kinetic energy (TKE) distribution (which were determined using steady-state flow analysis) for the valve-seatless design developed in this study and the conventional design with valve seats. For the valve-seatless configuration, the flow rate was higher and the TKE was lower near the exhaust pent roof compared to the conventional design. This result confirmed that the valve-seatless design induced an efficient air intake with minimal variation.

Figure 14 shows the tumble ratios and flow coefficients (Cv), which were determined using an airflow test, for the new and conventional designs. The figure indicates that the new design achieved greater air flow with high tumble and high flow volume compared to the conventional engine with valve seats. Figure 15 shows the variation ratio of the flow velocity measured using a hot-wire anemometer, which indicated the stability of the tumble flow. The figure shows that the variation ratio was smaller for the new design than for the conventional design at the same tumble ratio, which indicated that a stable flow was successfully induced.

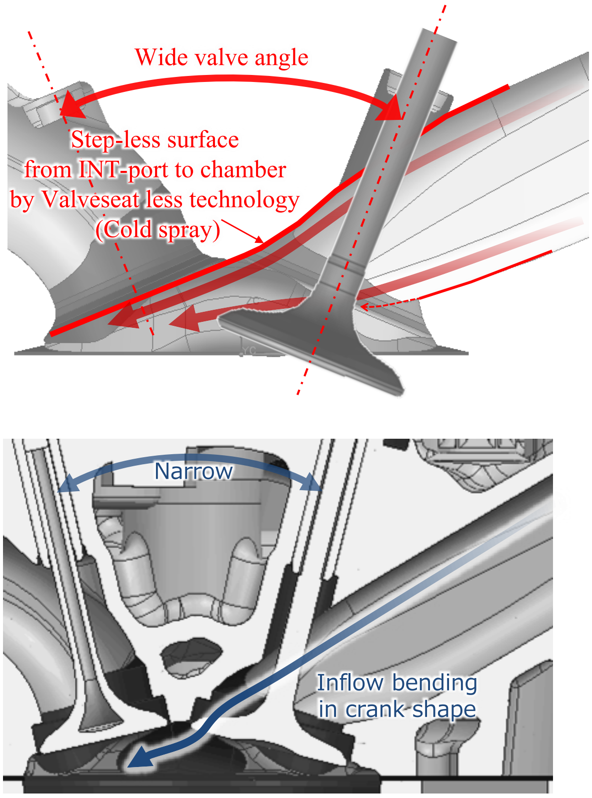


Fig. 12 Comparison of design concept of intake port and combustion chamber (New design with cold spray valve seat (left), current design (right))

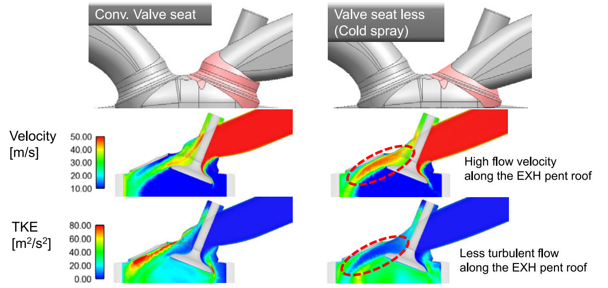


Fig. 13 Flow velocity and TKE distribution (CFD)

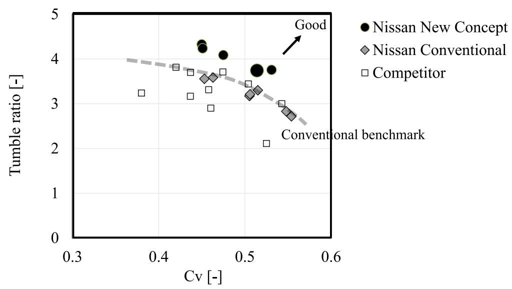


Fig. 14 Improvement of tumble-ratio-to-flow coefficient with new designs of intake port and combustion chamber equipped with a cold-spray valve seat

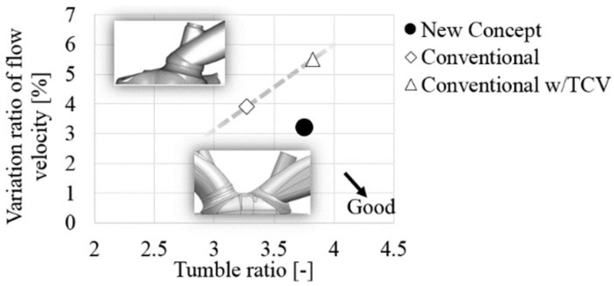


Fig. 15 Tumble ratio vs variation ratio (Air-flow test result)

3.2.2 Methods to conserve strong tumble flows

The tumble flow generated during the intake stroke increases its swirling speed as the piston rises from the bottom dead center through a compression stroke. For the tumble flow to be conserved until ignition, minimizing the change in the speed vector component in the direction of rotation is necessary for reducing the kinetic energy loss and suppressing the speed vector component perpendicular to the tumble. For this purpose, the second design requirement, which involved keeping the tumble center at the middle of the cylinder to ensure that the central axis of the tumble vortex was straight with no distortion, was introduced, as shown in Fig. 16. This requirement was fulfilled using elongated strokes and a combustion chamber with a low aspect ratio.

The valve timing was narrowed by using the engine solely for electricity generation, thereby limiting the engine operating points. Moreover, a smooth shape for the piston crown was adopted by eliminating the valve recess pockets required in the conventional designs. In addition, longer strokes were used, and the valve angles were widened. Furthermore, a piston crown in the shape of a rugby ball was designed, as shown in Fig. 17.

Figure 18 compares the in-cylinder distribution of the tumble vortex centers for the new and conventional designs. In the conventional design, the central axis of the tumble vortex was distorted, whereas in the new design, it was kept straight at the center of the cylinder with no distortion, thus creating a tumble flow that satisfied the design requirements.

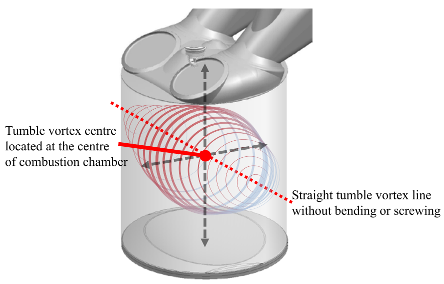


Fig. 16 In-cylinder charge motion design to maximize tumble conservation

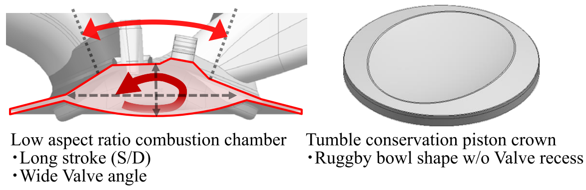


Fig. 17 Combustion chamber and piston crown design for tumble conservation

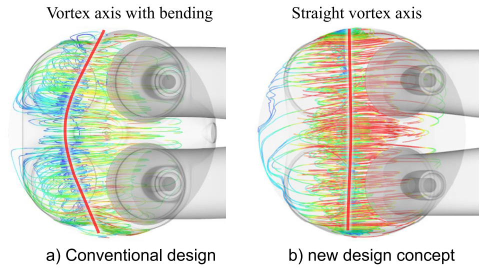


Fig. 18 CFD results of in-cylinder charge motion with conventional design (a) and new design concept (b).(2400 rpm, middle of compression stroke)

3.2.3 Control of in-cylinder flow for stable ignition

For the stable formation of initial flame kernels, ensuring that the discharge channel stretches from the spark plug without touching the wall of the exhaust pent roof is important. For this purpose, the third design requirement, which involved improving the uniformity of the flow speed at the spark plug gap by adjusting the direction of the flow velocity, was introduced. As shown in Fig. 19, a concave shape was designed to guide the tumble flow along the upper surface of the combustion chamber upstream of the tumble flow from the spark plug.

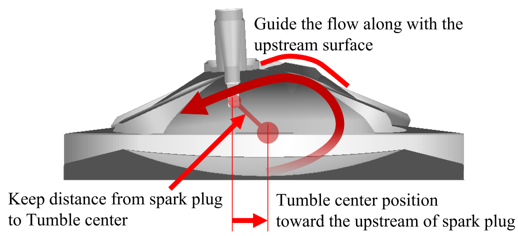


Fig. 19 Combustion chamber design to guide flow direction for appropriately stretched robust ignition channel

To validate the new concave design and its function in guiding the tumble flow along the upper surface of the combustion chamber, the in-chamber flow during the compression stroke was visualized using a particle image velocimetry (PIV) method on an engine unit, as shown in Fig. 20. Figure 21 shows the results of the PIV measurements and in-cylinder flow distribution around the ignition timing at a before top dead center (BTDC) of 40°. The figure shows that the distance between the spark plug and tumble centers widened, and the uniformity of the flow speed distribution in the vicinity of the spark plug improved. This occurred because the concave shape of the upper surface of the combustion chamber guided the tumble flow toward the lower section of the combustion chamber, and the tumble flow toward the spark plug did not approach the surface of the combustion chamber exhaust pent roof, impeding the development of the initial flame. The concave shape also guided the tumble vortex center toward the intake side.

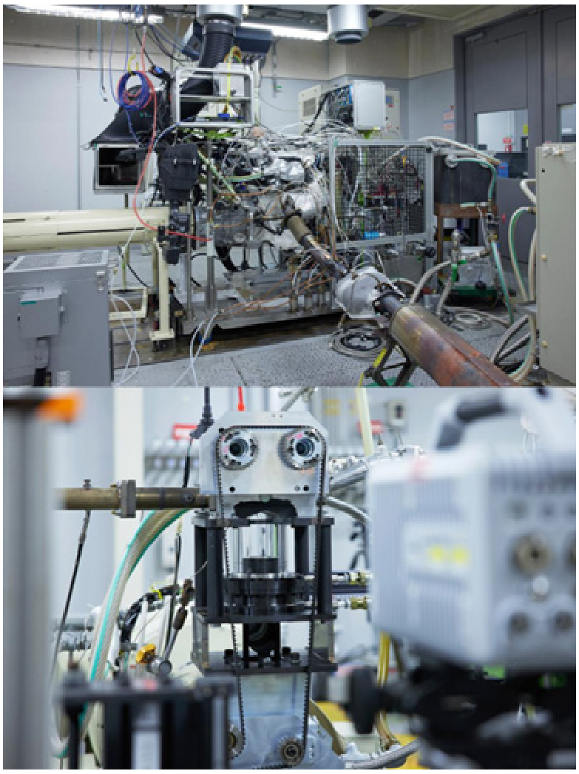


Fig. 20 Experimental equipment for new engine concept

3.3 Ignition system

The ignition system is another key function for stabilizing the formation of initial flame kernels under highly diluted combustion conditions, in addition to the aforementioned in-cylinder flow characteristics, including the gas flow rate around the spark plug. To achieve a stable ark channel elongation at a high gas flow velocity, improving the ignition system is necessary. The high discharge current of the ignition coil suppresses the restrikes of the ark channel and contributes to increasing the ark channel length at a high gas flow velocity. The average ignition current correlated strongly with the EGR combustion limit[8] for a certain period of time. In the new ignition concept, a high-current and high-energy ignition system was adopted for stable combustion under highly diluted conditions. A cooled-EGR combustion limit of over 30% was achieved using the new ignition system (as shown in Fig. 22).

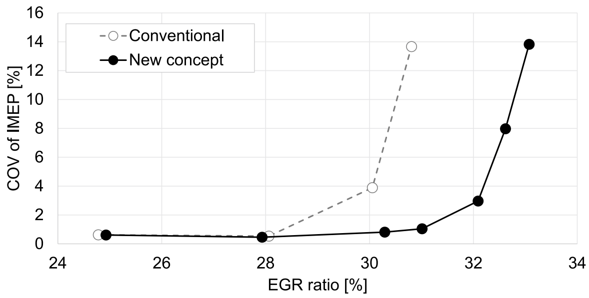


Fig. 22 Comparison of stable combustion limit against EGR between Conventional igni-tion system and new ignition concept with high energy ignition system

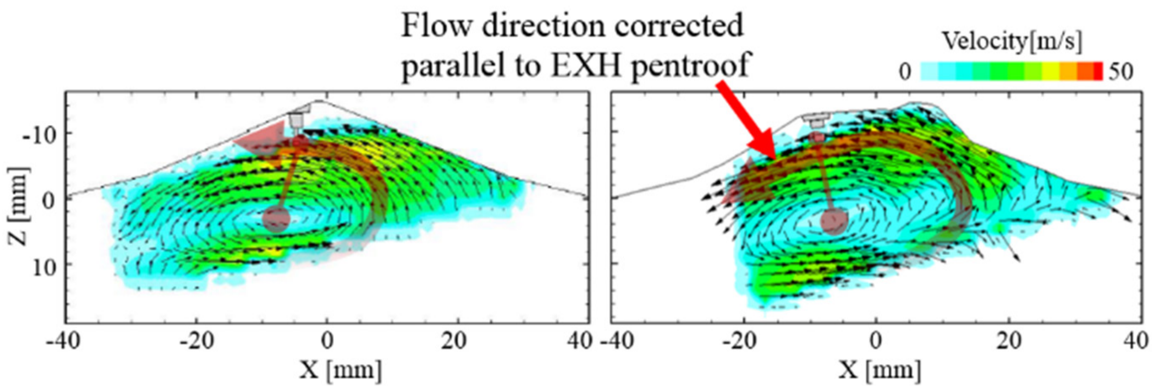


Fig. 21 Effect of the rectification pocket on the flow distribution around spark plug (PIV images, 2400 rpm, 40 deg. BTDC)t

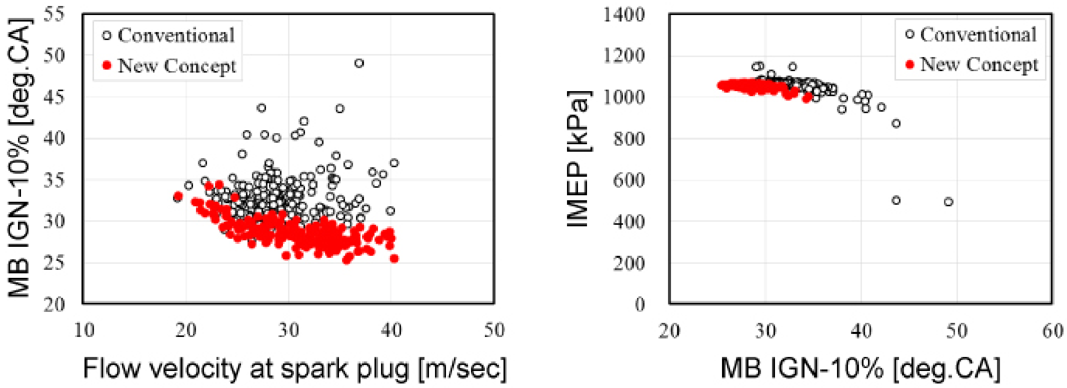


Fig. 23 Cyclic distribution of initial combustion period of CA ign-MB10% in relation to gas flow velocity at spark gap under EGR 30% conditions on same engine configuration except the ignition system

Figure 23 compares the effects of the gas flow velocity near the spark plug with an EGR of 30% on the initial combustion period of CA ign-MB10% for the new and the conventional ignition systems. In the conventional ignition system, a large cycle variation was observed for CA ign-10%. In relatively fast gas flow cycles, longer CA ign-10% was observed. In contrast, in the new ignition concept, rapid and stable initial combustions were detected, and cycles with longer initial combustion periods were suppressed in relatively fast gas flow cycles (Fig. 23, left). The cycle variation of the indicated mean effective pressure (IMEP) for an EGR of 30% was substantially reduced owing to the rapid and stable initial flame propagation (Fig. 23, right).

Owing to the new STARC combustion concept, stable combustions with an EGR of 30% were achieved and an indicated thermal efficiency of 45.6% was reached in a single-cylinder engine operating at 2400 rpm and an IMEP of 10.5 bar.

4. Dedicated e-POWER engine concept for achieving a thermal efficiency of 45% and specific power output of 80 kW/L

In the previous section, a new combustion concept called STARC was described in detail. In addition to STARC, this section describes a new air intake system and a new engine friction reduction technology.

4.1 Engine specifications

Table 1 lists the specifications of the new engine concept developed in this study. A 1.5-L three-cylinder turbocharged engine was selected because of the requirements for compact packaging and the high output power from the e-POWER system. In addition, a stroke/bore ratio of 1.26 was assigned to balance the thermal efficiency and output power. Furthermore, a centrally mounted direct-injection system was adopted to meet the future emission regulations.

Table 1. Specifications of the new concept engine

Engine Type	1.5 L / 3 Cylinder / Turbocharged
Bore x Stroke (S/D)	79.7 mm x 100.2 mm (1.26)
Connecting Rod Length	150.3 mm
Compression Ratio	13.5
Engine Speed @ Max. Power	4800 rpm
Valve train	Roller Rocker
Fuel Injection / Injector location	Direct Injection / Central Injection
Turbocharger Type	Fixed Geometry Turbocharger

4.2 Air intake system

As explained earlier, the air intake system of the engine dedicated to e-POWER was designed with a focus on the maximum thermal efficiency and maximum output power points. To achieve the highest thermal efficiency, a relatively high brake mean effective pressure (BMEP), which is calculated by dividing the work of one cycle by the engine displacement, is required. Also, a high EGR of up to 30% is typically used for the target value.

Considering the low speeds when driving on local roads, the engine operating point for the optimum brake specific fuel consumption (BSFC) for normal charging operations was fixed at a lower speed of 2000-2400 rpm so that the engine could maintain quietness. Because of the consideration of lower friction and lower engine noise (as for the BSFC operating point), the engine speed for the maximum output power was set to 4800 rpm, which is a relatively low speed compared to general engine operating points. To fulfil these requirements, early Miller cycles, a cooled EGR system, and a turbocharger dedicated to e-POWER were adopted in the engine concept. Figure 24 shows a schematic of the valve timing in the engine concept. To maintain the pumping loss, which requires sucking a sufficient amount of air and shortening the cam length, a roller-rocker type intake valve system was used. Figure 25 shows the influence of the timing of the intake valve closure (IVC), which was calculated using the 1D simulation software GT-POWER, on the in-cylinder temperature at the end of the compression stroke. An analysis showed that the in-cylinder temperature decreased when the timing of the IVC was small, which effectively mitigated knocks at both the highest thermal efficiency point and the maximum output power point.

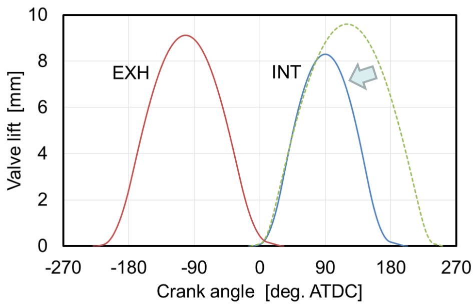


Fig. 24 Valve lift curve of conventional late IVC and E-IVC

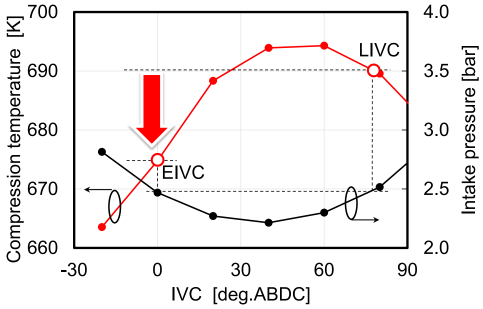


Fig. 25 Effect of IVC on the compression end temperature

A cooled EGR system can effectively achieve a high theoretical thermal efficiency and high specific heat ratio, and can also mitigate knocks. To ensure a high EGR rate at the maximum thermal efficiency point, a combustion stability estimation and EGR feedback control system was developed. The turbocharger was optimized for charging under a high EGR rate and a supply of fresh air at the maximum thermal efficiency point, and was designed to handle a high output power. Figure 26 shows a schematic of the pumping loss reduction achieved by using the newly designed large turbocharger dedicated to e-POWER, which reached an indicated thermal efficiency of 45%. The figure indicates that the dedicated large turbocharger reduced the pressure ratio required at the maximum thermal efficiency point and, in turn, reduced the pumping loss.

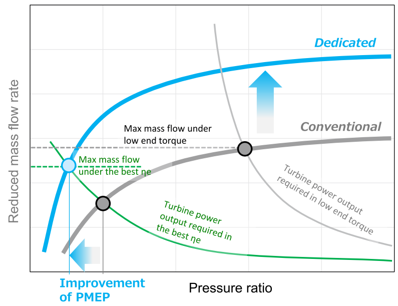


Fig. 26 Pumping loss reduction with e-POWER dedicated turbocharger

Figure 27 compares the pressure-volume (P-V) diagrams of the conventional and new dedicated turbochargers at the maximum thermal efficiency point. For an EGR of 30%, the new dedicated turbocharger achieved a pumping mean effective pressure (PMEP) of -14 kPa, which represents a significant reduction in the pumping loss. Using the new combustion concept, STARC, and the new air intake system that combines these technologies, an indicated thermal efficiency of 45.0% was achieved.

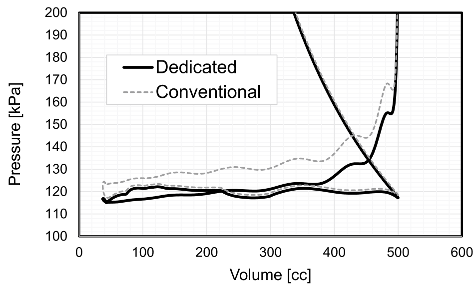


Fig. 27 Comparison of low pressure part of P-V diagram between conventional turbo-charger and dedicated turbocharger

4.3 Friction reduction

Friction reduction is a basic technological approach useful for increasing the thermal efficiency of engines. Accordingly, this study also aimed to reduce the friction by taking advantage of e-POWER in the new engine concept. Figure 28 illustrates the friction reduction techniques used in the new engine dedicated to e-POWER. A friction reduction of 46% relative to a conventional 2.0-L L4 turbocharged engine was achieved via downsizing, the removal of a front-end accessory drive (FEAD), downspeeding, a low-end torque cut, and the utilization of new low-friction technologies.

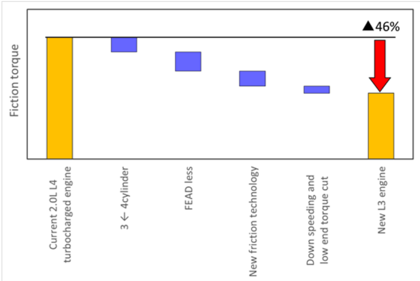


Fig. 28 Friction reduction of new e-POWER dedicated engine

Owing to the combustion design and air intake design dedicated to the series hybrid operations, the speed of the engine at the maximum power output was reduced to 4800 rpm as it reached a specific power output of 85 kW/L at λ=1. This downspeeding minimized the piston ring tension, valve spring rate, and bearing width. In addition, the reduction in the low-end torque region shown in Fig. 2 relaxed the demand from the turbocharger and piston oil jet, thereby allowing the use of a smaller oil pump. A typical case for the adoption of low-friction materials is the smoothed bearing of a textured crankshaft. The bearings were still under mixed lubrication conditions in the vicinity of the maximum combustion efficiency point. Therefore, the friction can be effectively reduced by smoothing the bearing surface. Figure 29 shows the experimental results for the influence of the bearing surface roughness on the friction at 2000 rpm. The figure indicates that the friction was reduced by approximately 10% after the bearing surface was smoothed. However, smoothing the bearing surface can result in adverse events (e.g., bearing seizures) because of the lack of lubricant oil remaining on the bearing surface. To suppress seizures, the crankshaft pin/journal surface was textured using a new design. Figure 30 shows the external appearance of the prototype textured crankshaft. To form miniscule dimple textures, various production processes, including machining, roll forming, shot blasting with masking, and laser methods, were trialed. Texturing processes are effective in reducing the friction of not only the crankshaft, but also other lubricating parts, including the piston skirts and piston rings.

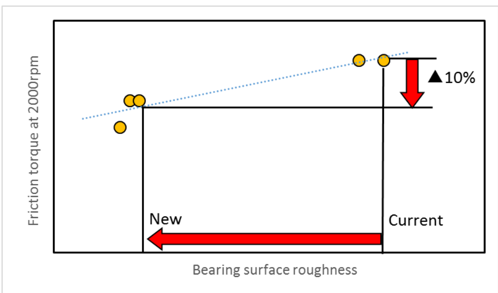


Fig. 29 Friction sensitivity by bearing surface roughness

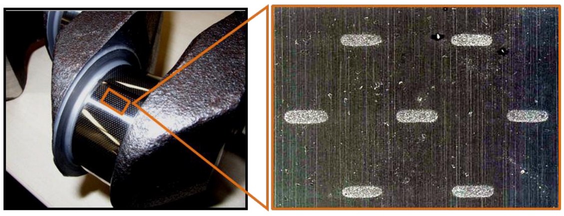


Fig. 30 Texture crankshaft surface

4.4 New combustion control

Because of the limited engine operating points and quasi-steady-state transient operation of e-POWER, achieving a higher EGR rate at the optimal thermal efficiency point during battery charging is possible. In contrast, conventional engines require additional resources for combustion stability to ensure an effective engine response and suppress misfiring during transient operations. However, this requirement introduces challenges when utilizing a high EGR rate. Because of the slow transient operation characteristics of e-POWER, its EGR intake volume can be higher than that of conventional engines. To achieve further BSFC gains, a new combustion stability target EGR/ignition timing feedback control system was developed to secure a higher EGR rate near the stable combustion limit. Figure 31 shows the effects of the EGR rate on the IMEP and BSFC. The target intake EGR rate was assigned with a margin for the stable combustion limit, and the EGR rate was increased during the operation up to the stable combustion limit. Once the combustion stability exceeded the standard level, the target EGR rate was reduced to enable the operation to always be at the EGR rate near the combustion limit. Because of this new combustion control, e-POWER can utilize the maximum thermal efficiency at the optimum thermal efficiency point, regardless of the variations in the ambient conditions and mass-produced parts.

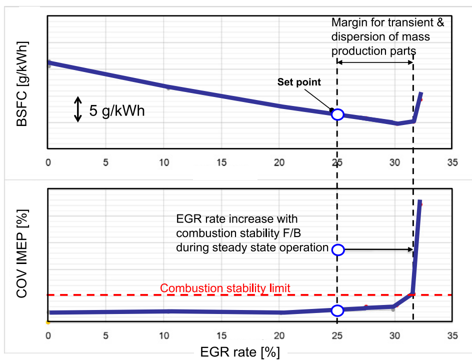


Fig. 31 Improvement of BSFC realized by e-POWER EGR set point and combustion stability feedback EGR target control

4.5 Verification of the brake thermal efficiency of a multi-cylinder engine

To comprehensively verify the new combustion concept, air intake system, and friction reduction technique, experiments were conducted on a multi-cylinder prototype engine. Figure 32 shows the BTE as a function of the ignition timing. The figure shows that a BTE of 43.4% was achieved under the trace knock condition using RON98 fuel. Assuming that the difference between the MB50 crank angles for the RON95 and RON98 fuels under the trace knock condition was 3 degrees, a BTE of 43.0% was expected for the RON95 fuel. In addition, a specific output power of 85 kW/L at $\lambda=1$ was achieved using a multi-cylinder prototype engine with RON95 fuel.

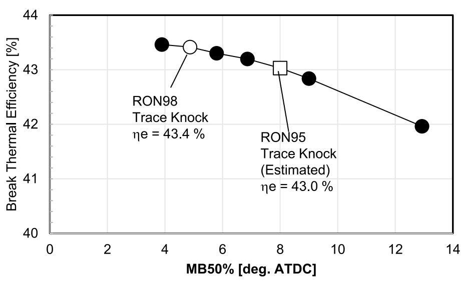


Fig. 32 Validation result of brake thermal efficiency with a multi-cylinder prototype engine (Engine speed 2000 rpm, BMEP 12 bar, RON98 fuel)

5. Prospect for 50% efficiency with e-POWER

5.1 Increasing the thermal efficiency of the engine dedicated to e-POWER

The series hybrid operation of e-POWER provides an opportunity to further improve the engine's thermal efficiency via lean combustion with a high excess air rate. Lean combustions in conventional spark-ignition engines are technically challenging in terms of controlling the torque and NOx emissions during lambda-switching between lean operation modes ($\lambda>2$) and during standard operation modes with a stoichiometric gas mixture ($\lambda=1$). The series hybrid operation of e-POWER does not require adjusting the air-to-fuel ratio (A/F) because the engine operation mode can be limited to the lean combustion region by combining the engine with a battery system. The new combustion concept enables stable combustions for A/F values with $\lambda>2$ without modifying the design of the combustion chamber or intake port. Figure 33 shows the influence of the A/F on the concentration of NOx in the exhaust gas and on the covariance of the IMEP for homogeneous lean and weak stratification lean combustions when using a single-cylinder engine. To assist the ignition of weak stratification lean combustions, the equivalence ratio around the spark plug was increased by injecting a very small amount of fuel before ignition during the compression stroke. For homogeneous lean combustions, a stable combustion limit of up to A/F=26 ($\lambda=1.8$) and a low NOx concentration of approximately 100 ppm were observed. In contrast, for weak stratification lean combustions, a stable combustion up to A/F = 36 ($\lambda=2.5$) and a NOx concentration below 30 ppm were achieved. The weak stratification lean combustions reached a thermal efficiency of over 48%. In addition, the analysis that used the GT-POWER software indicated a maximum BTE of 46% was achieved in a 1.5-L three-cylinder turbocharged engine, a result that accounted for the pumping loss during the gas exchange and the friction discussed in Section 4.3 (Fig. 34).

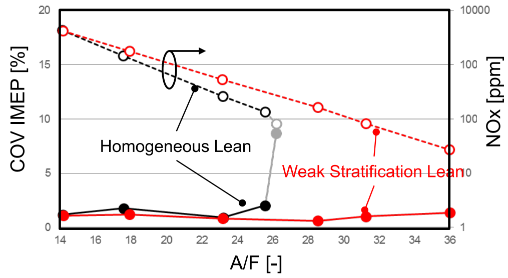


Fig. 33 COV of IMEP and engine out NOx in relation to Air fuel ratio (A/F)

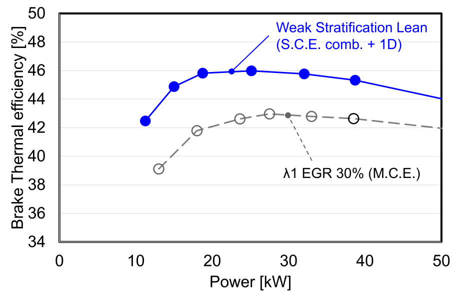


Fig. 34 Brake thermal efficiency vs Power with Lambda=1 and Lean burn (lambda=1 : Result of M.C.E., Lean: S.C.E combustion + 1D-Code Air-path)

5.2 Waste heat recovery system

When the thermal efficiency is increased, maintaining a low exhaust gas temperature is difficult. In particular, for lean combustions, retaining the activity of the exhaust gas after treatment system (ATS) is challenging. Therefore, maintaining a high heat transfer rate from the combusted gas by reducing the heat transfer to the combustion chamber, exhaust port, and exhaust components in front of the ATS is important. This means using more heat insulation and reducing the heat transfer to the exhaust components and coolant. Therefore, by accounting for the after-exhaust treatment when arranging the heat insulation of the cooling components and the heat transfer from the combustion components, further improvements in thermal efficiency can be achieved using a thermal management system that incorporates waste heat recovery.

The e-POWER system's specific engine operations and steady-state operations at particular operating points are also suitable for waste heat recovery. Figure 35 shows an example of a medium-temperature (MT) Rankine cycle heat recovery system suitable for high-speed and high-load operating conditions.

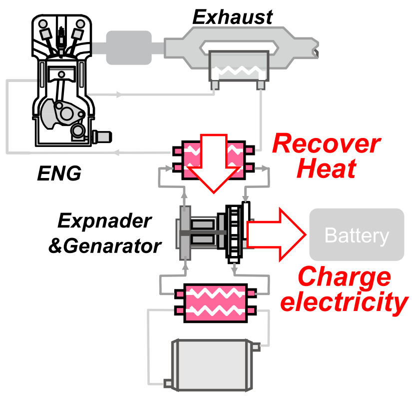


Fig. 35 Medium temperature rankine cycle heat recovery system

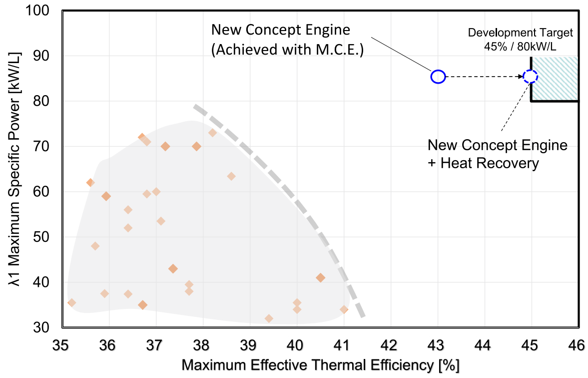


Fig. 36 Validation Results of the new engine concept

The MT Rankine cycle system operates between a high-temperature (HT) coolant circuit that cools the engine and a low-temperature (LT) e-PT coolant circuit, and it contains a boiler, expander equipped with a generator, condenser, and pump. The MT Rankine cycle system improved the thermal efficiency by approximately 4-5%, particularly in high-speed and high-load conditions. The efficiency is expected to improve by 4.6% for an e-POWER vehicle in the worldwide harmonized light vehicle test cycle (WLTC) extra-high mode. By combining the MT Rankine cycle with an exhaust heat recovery system, the thermal efficiency is expected to improve by an additional 2% (Fig. 35). Therefore, a thermal efficiency of 46% under lean combustion conditions can reach up to 48% by implementing a waste heat recovery system. A thermal efficiency of 48% is speculated to be the maximum achievable value using a 5-kWh e-POWER system, considering the current battery size. In the future, when electrification evolves further and a larger capacity battery is installed, the thermal efficiency may approach 50% if the engine operating points can be limited to one or two specific charging operations. Currently, the power output from the battery alone is insufficient for acceleration; hence, the battery's output is supplemented with electricity generated by the engine. If the capacity and output power of the battery satisfy the acceleration requirements, the engine can still select the optimal compression ratio specific to its thermal efficiency by ceasing to generate the torque and power required to assist the electric power output. Moreover, at the minimum operating point, simultaneously controlling the maximum engine speed and maximum in-cylinder pressure Pmax during combustion is possible, and it would significantly reduce the friction. By optimizing the design of the engine and its operations dedicated to electric charging, Nissan will continue its technical development toward a thermal efficiency of 50% as the ultimate target.

6. Conclusion

In this study, a new engine concept dedicated to Nissan's e-POWER system was developed to reduce the WtW CO_2 emissions for future sustainable mobility, and the following results were obtained.

- A new combustion concept, STARC, was developed to stabilize the ignition and minimize the cycle variation by combining a new in-cylinder flow design and a high-energy ignition system for ultra-lean combustion. The new combustion system delivered an indicated thermal efficiency of 45.6%.
- A new air intake system dedicated to the series hybrid operation of e-POWER was developed, with a focus on achieving the maximum thermal efficiency and maximum specific power output. By using cooled EGR, a turbocharger dedicated for e-POWER, and a new combustion stability target (the EGR/ignition timing ratio) with a feedback control system, obtaining an EGR rate of 30% was possible, and it resulted in a maximum indicated thermal efficiency of 45.0%.
- Mechanical friction was substantially reduced because of the confined operation region and slow transient operations of e-POWER. Many friction reduction technologies were successfully used to decrease the friction by 46% compared to the current 2.0-L turbocharger engine. A multi-cylinder engine equipped with the technologies described above exhibited a maximum brake thermal efficiency of 43.0% and a specific output power of 85 kW/L for λ=1. The addition of a waste heat recovery system increased the prospect for reaching a brake thermal efficiency of 45%.
- By adopting the new STARC combustion concept for lean combustions, a brake thermal efficiency of 46.0% was achieved for a multi-cylinder engine. When a waste heat recovery system was added, a thermal efficiency of 48% could be reached. In the future, when the progress in electrification delivers batteries with increased capacities and output powers, achieving a thermal efficiency of 50% may be possible by confining the engine operation to the maximum thermal efficiency point, introducing additional friction reduction technologies, and increasing the specific compression ratio.

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Authors

Tadashi Tsurushima

Special Feature 2:Advanced Driver Assistance Systems (ADAS) & autonomous driving

1. Advanced Driver Assistance Systems (ADAS) & autonomous driving

Takashi Kimura*

1. Introduction

In recent years, various companies have introduced technologies that support automated driving via electronic control of the vehicle's movement. This was achieved by using electronic technologies that have rapidly developed since the 1980s to solve social issues stemming from the development of motorization, such as traffic crashes, environmental degradation, and traffic congestion.

To further support these endeavors, Nissan has defined its ultimate goal of "Zero Fatality," wherein the number of fatalities caused by traffic crashes involving Nissan cars is reduced to virtually zero. Since the early stages of the development of electronic control technologies, Nissan has been working to decrease the number of crashes by making vehicles intelligent, and Nissan has also recognized the importance of these technologies for revolutionizing mobility. Accordingly, Nissan has developed advanced driver assistance systems, such as ProPILOT Park, which automates parking operations, and ProPILOT Assist 2.0, which enables hands-off driving on highways. These technologies were not developed overnight, but were realized through a vast amount of technological expertise accumulated over many years. This article provides an overview of the company's long-standing efforts and technological foundations.

Nissan's efforts to advance autonomous driving and driver assistance technologies can be divided into the following three general time periods: (1) the early days of technology research (in the 1990s) when the foundations of environment recognition technologies were consolidated while a mechanical framework for controlling vehicle movements was built, (2) the adaptation and commercialization period (in the 2000s) when many preventive safety technologies were put into practical use based on the advancement of environment recognition technologies and the creation of the "Safety Shield" concept, and (3) a progressive period since the mid-2010s when various driving support technologies were implemented for specific driving scenarios, such as highway driving and parking. The following sections provide an overview of Nissan's efforts during each period and the key aspects of the corresponding technology.

2. Evolution of driver assistance technologies

Since the late 1980s, the control of driving functions has been performed electronically. This update enabled the brake oil pressure and drive torque to be adjusted according to the road conditions, thus preventing the wheel from locking while braking and from slipping while accelerating. In addition, improving the maneuverability and stabilizing the turning motions has become possible via sensing the motion of the vehicle and generating a moment in the rotational direction by finely steering the rear wheels and controlling the brake hydraulic pressure individually for each wheel. Nissan has introduced various electronic control devices, including the anti-lock braking system (ABS), traction control system (TCS), high capacity actively controlled steering (HICAS), and vehicle dynamic control (VDC)[(1), (2), (3), (4)].

This period also witnessed the introduction of new technologies, such as camera image processing and distance measurements made by emitting laser light and capturing the reflected light (i.e., light detection and ranging, or LiDAR). At the end of the 1980s, Nissan commenced basic research on the technology required to detect white lines on roads via camera images and to measure the distance between vehicles using laser light.

One outcome of this basic research and development effort that has been incorporated into the modern autonomous driving capability was the function to automatically follow the vehicle ahead and drive in the center of the lane, which was manifested in the Advanced cruise-assist Highway Systems (AHS) project led by the former Ministry of Construction. In September 1996, a autonomous driving demonstration was jointly conducted with other companies on a section of the Joshinetsu Expressway before it was opened for regular use,, demonstrating the possibility of stable and smooth autonomous driving[(5)].

By initiating early efforts, Nissan was able to swiftly use these technologies for practical applications. In 1997,

*Mobility and AI Laboratory

Nissan implemented adaptive cruise control coupled with brake control, which could regulate both regulates the driving and braking forces to maintain a safe distance from the vehicle ahead[6],[7]. In 2001, a lane-keeping support system, which used a charge-coupled device camera to detect white lines on the road and assist in the steering operations to help ensure the car stayed inside the lane, was implemented in commercial applications[8].

Nissan expects these electronic control technologies to gradually support or automate vehicle control and to enable autonomous driving in the future. To sequentially build these functions, Nissan positioned each function of the control system hierarchically in relation to the mechanisms responsible for human motor control (as shown in Fig. 1).

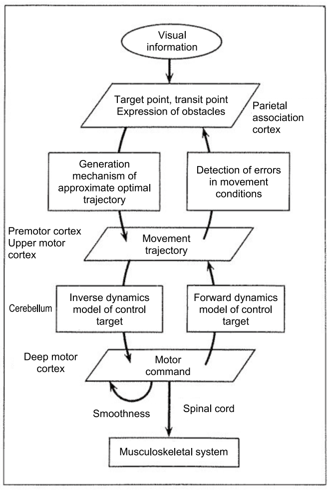


Fig. 1 Hierarchical model of human neural circuit[9]

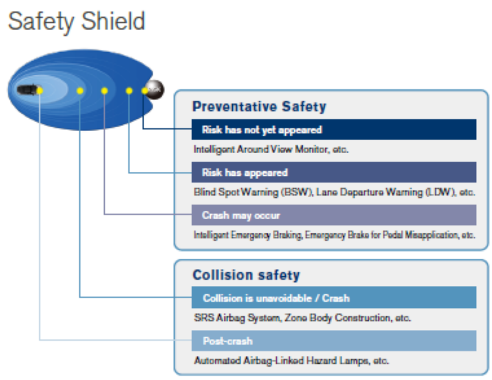
The control system of the human body consists of a musculoskeletal system that performs fine force adjustments based on spinal reflexes, a motor control system in the cerebellum that accounts for the dynamics of the object under control, and an upper-layer control system that determines target values based on visual information, generates trajectories, and provides error feedback. The vehicle control system can be correlated with that of a human as follows: ABS and TCS, both of which adjust the tire slip ratio, and the rear wheel angle servo in HICAS, which accurately controls the tire angle, correspond to the lower-layer musculoskeletal system; VDC and HICAS, which control the rigid body motion of a vehicle by accounting for the vehicle dynamics, correspond to the middle-layer motion control system; and driving assistance, which controls the distance between vehicles and the position within the lane based on external information, corresponds to the function of the upper layer.

In these early stages of technological development, Nissan built the lower- and middle-layer functions to control acceleration, deceleration, and yaw motion according to the target values without compromising vehicle stability. This laid the foundation of vehicle control technologies, which led to future driving assistance and autonomous driving capabilities, which in turn resulted in the subsequent development of many practical driving assistance systems.

3. Adaptation and commercialization of preventive safety technologies

The use of an environment recognition function that detects vehicles and white lines on the road ahead, along with functions that control the braking force, driving force, and steering angle, enabled the development of adaptive cruise control and lane-keeping support systems. These environment recognition technologies are rapidly progressing. For example, they can accurately detect vehicles and objects not only ahead but also behind and on the sides, as well as vehicles and objects further ahead. Based on these technologies, Nissan has developed the concept of "Safety Shield," which aims to support the safety of occupants based on the idea that cars should protect people[11].

In this concept, environmental conditions are categorized into the stages labeled as "risk has not yet appeared," "risk has appeared," "crash may occur," "crash is unavoidable," "crash," and "post-crash." In each stage, the features optimized for the risk factors are activated, which provides comprehensive assistance to the driver in avoiding the risks and protecting the passengers.



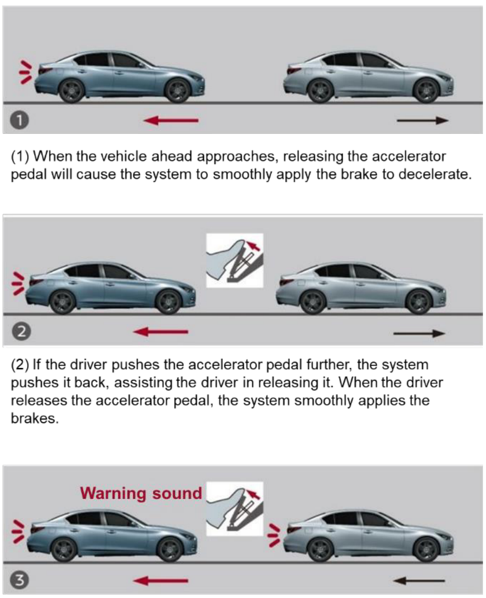
Risk has not yet appeared ProPILOT (ProPILOT Assist / ProPILOT Assist with Navi-link/ ProPILOT Assist 2.0) ProPILOT Park (ProPILOT Park/ ProPILOT Remote Park) Intelligent Distance Control Navigation-enabled Intelligent Cruise control with fullspeed range following capability Adaptive Front-Lighting System (AFS) Intelligent Around View Monitor Intelligent Rear View Mirror	elps the driver drive with peace of mind
Risk has appeared Intelligent Forward Collision Warning Lane Departure Warning Intelligent Lane Intervention Blind Spot Warning Intelligent Blind Spot Intervention Intelligent Back-up Intervention Intelligent Driver Alertness Rear Cross Traffic Alert	Helps the driver avoid or lessen the severity of an accident
Crash may occur Intelligent Emergency Braking Anti-lock Braking System (ABS) Vehicle Dynamics Control (VDC) Emergency Brake for Pedal Misapplication	
Crash is unavoidable Front Pre-Crash Seatbelts	Helps reduce injuries when a collision is unavoidable
Crash Zone Body Construction SRS Airbag Systems Pop Up Engine Hood	
Post-crash Automated Airbag-Linked Hazard Lamps SOS Call (HELPNET)	

Fig. 2 Safety Shield concept

As shown in Fig. 2, the concept has adopted many driver assistance technologies. Although such technologies are very effective in mitigating risks during driving, the driver may distrust the system because of unexpected vehicle motion caused by the system, or the driver may be too confident in the system owing to excessive expectations of the system's effectiveness. Therefore, to develop these technologies, Nissan has actively addressed human factor issues.

Intelligent pedals, a technology used in Safety Shield, are an example of a system that fully accounts for human factors (Fig. 3). In intelligent pedal technology, the perceived risk from an approaching vehicle ahead is quantified and transmitted to the driver through the reaction force on the accelerator pedal, and the deceleration is controlled in response to the driver's operation of the accelerator pedal. Essentially, it incorporates the driver into the control loop to maintain a safe distance from the vehicle ahead. The system easily enables a safe distance from the vehicle ahead to be maintained; thus, it reduces the burden on the driver, even in traffic situations in which vehicles frequently accelerate and decelerate[12].

This technology was realized by accounting for various human factors, including the driver's risk perception caused by the relative speed and distance from the vehicle ahead, the driver's judgement exercised in response to the changes in the reaction force exerted by the accelerator pedal, the changes in the driver's driving behavior and vehicle-to-vehicle distance caused by the use of the system, and the quantitative evaluation of the changes in the driver's cognitive load resulting from the use of the system[13],[14].



(1) When the vehicle ahead approaches, releasing the accelerator pedal will cause the system to smoothly apply the brake to decelerate.

(2) If the driver pushes the accelerator pedal further, the system pushes it back, assisting the driver in releasing it. When the driver releases the accelerator pedal, the system smoothly applies the brakes.

(3) When the system determines that the driver needs to push the brake, the driver is alerted via the display and various sounds. Subsequently, the system pushes the accelerator pedal back to prompt the driver to push the brake pedal instead.

Fig. 3 Intelligent pedal technology

4. Development of driver assistance technologies

In the previous sections, various driver assistance technologies were introduced. These technologies provide separate assistance for each driving behavior and risk category, such as maintaining a safe vehicle-to-vehicle distance, drifting from the center of the lane, and approaching vehicles from the side or rear. For example, ProPILOT Assist, which was introduced in 2016, integrated driver assistance technologies for single-lane driving on expressways[15].

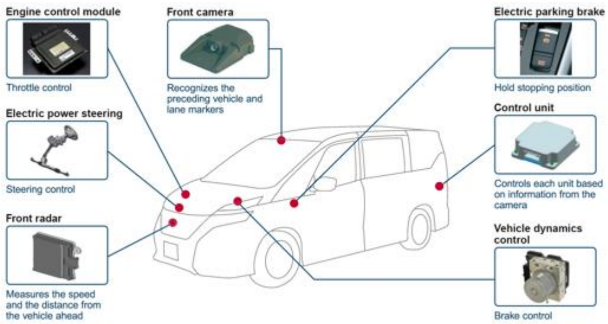


Fig. 4 Components of the ProPILOT Assist system

The ProPILOT Assist system significantly reduces the operational load of the driver when cruising on expressways or driving in traffic jams. This is accomplished by recognizing the road and traffic conditions using advanced environment recognition technology and automatically controlling the entire system, including the accelerator, brakes, and steering.

As driver assistance technologies become more advanced, the driver's understanding of the state of the system and the kind of assistance available will become increasingly important. In ProPILOT Assist, a dedicated display indicates the system status in a way that can be easily understood.

In 2019, ProPILOT Assist 2.0 was introduced to assist driving on multiple-lane highways in conjunction with navigation. Under certain conditions, it also assists with hands-free driving within the same lane and steering when switching lines[16]. Once a destination is selected, ProPILOT Assist follows the navigation system to provide comprehensive driving assistance while on the expressway.

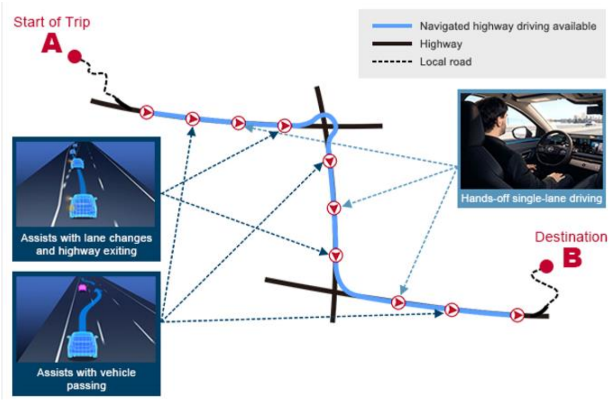


Fig. 5 Navigation-linked route generated by ProPILOT Assist 2.0

Fig. 6 ProPILOT Park

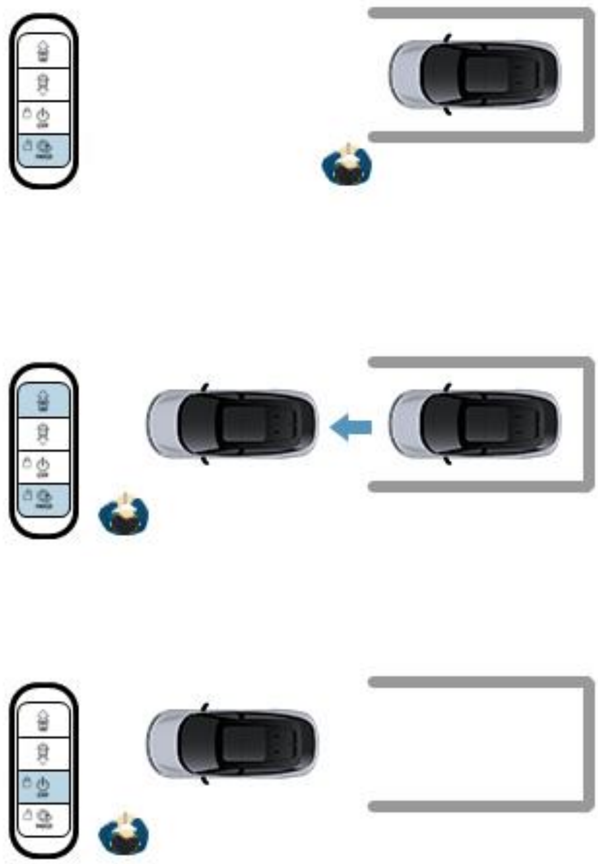


Fig. 7 ProPILOT Remote Park

Furthermore, ProPILOT Assist 2.0 can obtain information 360° around the vehicle using cameras, radar, sonar, the global navigation satellite system (GNSS), and 3D high-definition maps. This combination identifies the exact positional relationships between the vehicle and road and recognizes the road structure, including the number of lanes and whether they are merging, branching, or crossing. Additionally, a driver monitor checks whether or not the driver is paying attention to the road ahead, and a dedicated human-machine interface (HMI) clearly communicates the status of complex systems.

The aim for ProPILOT Assist 2.0 was not to simply upgrade the functions but to provide new value that allows driving on expressways to be safe, secure, convenient, and comfortable. This was achieved by adding a steering control mechanism that performed more smoothly than an experienced driver and by using an HMI to clearly communicate to the driver the system's environmental perceptions and its decision-making algorithm[(17),(18),(19),(20),(21),(22)].

ProPILOT Assist and ProPILOT Assist 2.0 deliver comprehensive driving assistance on expressways. In addition, ProPILOT Park[(23)] and ProPILOT Remote Park[(24)] are driving assistance functions that automate parking operations.

With a simple switch, the ProPILOT Park automatically controls the steering, accelerator, brakes, gear shift, and parking brake, assisting the driver until parking is completed. Control is executed by calculating the driving distance according to the surroundings of the vehicle (including for reversing vehicles), and by precisely maneuvering the vehicle through the coordination of the accelerator, brakes, steering, and gear shift. Similarly, ProPILOT Remote Park assists in moving the vehicle in and out of a narrow garage via a remote control with an intelligent key held outside the car.

Thus, by combining sensor, control, navigation, HMI, and other technologies, Nissan has been producing comprehensive driver assistance technologies applicable to various driving scenarios, including expressway cruising and parking.

5. Future work

Through constant efforts over the past 30 years, Nissan has been advancing its technologies and moving toward its ultimate goal of "Zero Fatality." However, approximately 300,000 traffic crashes occur annually in Japan, resulting in the loss of many lives[25].

To decrease the number of traffic crashes while continuing to increase the application of existing technologies, Nissan is developing a more advanced driving assistance technology called ground truth perception, which will contribute to preventing multidimensional and complex crashes. With this technology, cognitive abilities are upgraded to the next level using stable and smooth next-generation LiDAR[26]

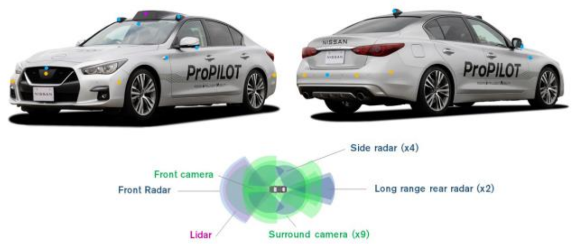


Fig. 8 Ground truth perception

As autonomous driving technologies continue to be developed, cars are becoming a major component of social infrastructure that supports people's mobility, which improves their quality of life in both cities and rural areas.

Nissan is currently working on Easy Ride®*, a mobility service that utilizes autonomous driving technology. Feasibility experiments were started in the Yokohama area in 2017[27],[28].

(*Easy Ride® is a trademark of DeNA Co., Ltd. and Nissan Motor Co., Ltd.)

Fig. 9 Easy Ride®

Currently, demonstrations of SAE Level 2 autonomous driving technology are being conducted by Nissan with an onboard driver to help ensure safety. In the future, while continuing to develop technologies and accumulate track records, Nissan intends to promote autonomous driving technologies to provide sustainable transportation services that support movement between cities and rural areas.

Furthermore, Nissan has been collaborating with NASA (USA) to develop a Seamless Autonomous Mobility (SAM) system that supports autonomous driving mobility services by making full use of AI in the cloud[29].

In this system, when an autonomous vehicle faces an unexpected situation, such as a crash or road obstacle, humans can intervene by remotely controlling the vehicle and connecting all related vehicles to collect information in the cloud and guide the vehicles to safety.

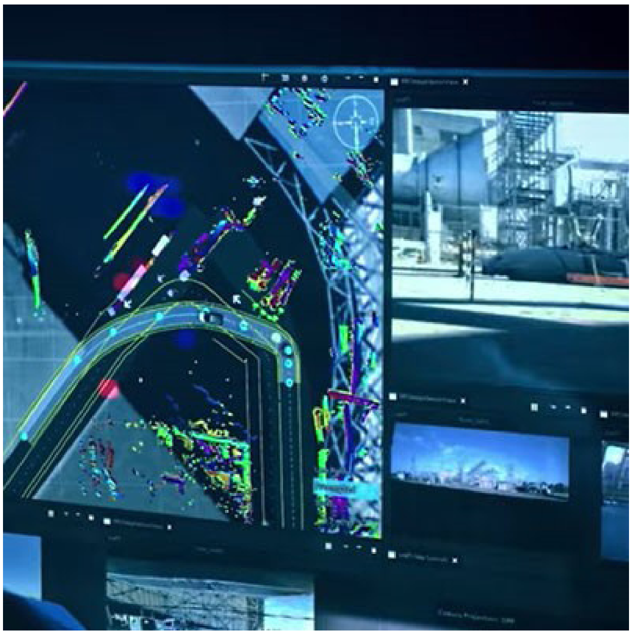


Fig. 10 Seamless Autonomous Mobility (SAM) system

6. Summary

In an effort to reach its ultimate goal of "Zero Fatality," driver assistance technologies that electronically control vehicle driving functions and promote their advancement are being developed by Nissan. To further decrease the number of future crashes, Nissan is improving driver assistance technologies to prevent multidimensional and complex crashes. Nissan will also continue to work on mobility services using autonomous driving vehicles to provide sustainable transportation in cities and rural areas.

In recent years, the capabilities of technologies known as the third and fourth AI revolutions, which originated from deep learning technologies, have been increasing daily. Detecting objects via environmental recognition and predicting the behavior of other vehicles and pedestrians are now possible. Furthermore, with faster wireless communications and the prevalence of cloud computing, accumulating and learning from a large amount of driving data and improving system functionality on a daily basis has become possible as well. By introducing these new technologies without delay and further advancing driving assistance and autonomous driving functions, Nissan will continue its efforts to deliver sustainable transportation and to decrease the number of traffic crashes in pursuit of its "Zero Fatality" goal.

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(参照日:2023年12月1日)

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2. ProPILOT Assist

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1. Introduction

For more than 20 years, Nissan has developed many world-first technologies to lead technological innovation as a pioneer in driver assistance technologies. In 2016, Nissan commercialized ProPILOT Assist (Fig. 1), an integrated driving assistance technology for single-lane highways, and in 2019, Nissan launched ProPILOT Assist 2.0 (Fig. 2), which operates in conjunction with the navigation system to offer the world's first driving assistance system that enables vehicles to follow a route on multi-lane highways while, under certain conditions, performing hands-off driving within the same lane. This chapter introduces the ProPILOT Assist and ProPILOT Assist 2.0 technologies.

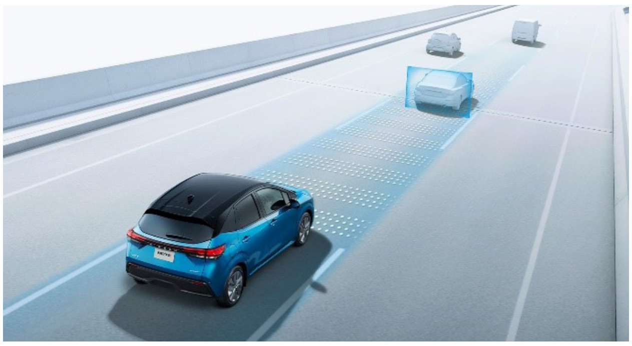

Fig. 1 Illustration of ProPILOT Assist capabilities

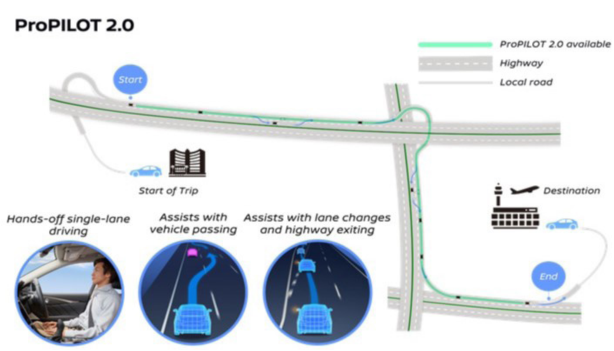

Fig. 2 Illustration of ProPILOT Assist 2.0 capabilities

2. ProPILOT Assist

This section provides an overview of the functions, driver interactions, and recognition and control technologies associated with ProPILOT Assist (PPA 1.0).

2.1 System overview

By automatically and simultaneously controlling the accelerator, brakes, and steering, PPA1.0 reduces the driver's burden in two of the most stressful situations on the highway: traffic jams and long-distance cruising. It utilizes a front camera and radar to recognize the exterior environment as well as a vehicle control unit, electric power steering unit, brake control unit, and electric parking brake, all connected to an advanced driver assistance system controller that manages each unit based on the sensor information (Fig. 3). As a result, PPA1.0 can recognize the vehicle in front as well as the white lane marking in three-dimensional space, use that information to accurately control the vehicle, and provide a comfortable drive.

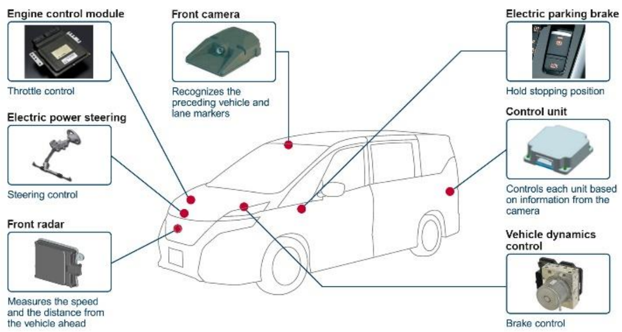

Fig. 3 Structure of the PPA1.0 system

*AD/ADAS Advanced Technology Engineering Department

2.2 Functions of PPA1.0

PPA1.0 provides two functions: vehicle speed and distance control and lane keeping.

2.2.1 Vehicle speed and distance control

The vehicle speed and distance control function maintains the speed set by the driver. When the system detects a vehicle ahead, it controls the vehicle speed to maintain a safe inter-vehicle distance using the speed set by the driver as the upper limit. The PPA1.0-equipped vehicle stops when the vehicle ahead stops and can resume moving with the vehicle ahead up to 30 s after that. Furthermore, in conjunction with the navigation system, PPA1.0 assists the driver's speed adjustment operations by switching the set speed when the speed limit changes and controlling deceleration according to road features such as tight curves and freeway off-ramps.

2.2.2 Lane keeping

The lane-keeping function of PPA1.0 helps the driver to maintain the vehicle in the middle of the driving lane on straight roads by controlling the steering wheel, though the driver must remain engaged with the wheel at all times.

2.3 Driver engagement

To prevent the driver from neglecting to take appropriate actions in response to the surrounding traffic conditions while driving with PPA1.0, a steering torque sensor or steering touch sensor is used to confirm that the driver is actively operating the vehicle. If the system determines that the driver is not, it issues a warning that prompts the driver to act. If the driver does not respond, the system issues an emergency warning, slows down, and stops the vehicle while alerting the surrounding vehicles using the hazard lights. These safety measures allow drivers to use the PPA1.0 advanced driver assistance system with peace of mind.

The next section details the sensors and vehicle control technologies employed to achieve safe and comfortable driving using PPA1.0.

2.4 Recognition and control technologies

To achieve seamless driving while controlling the distance to the vehicle ahead, it's position and movement must be accurately detected. Thus, PPA1.0 promptly and accurately detects the vehicle ahead by processing sensor signals and maximizing on the advantages of the front camera and radar systems: the front camera excels at recognizing the type of object and detecting its lateral position in and positional relationship with the lane; while radar systems excels at detecting the distance and relative speed of objects at farther distances with high accuracy. By combining these advantages, PPA1.0 can appropriately respond to vehicles a long distance ahead, which is necessary when driving at highway speed. Simultaneously, the system can suitably respond to certain movements of vehicles a short distance ahead, such as cutting-in and lane changes.

In addition, the lane-keeping function provides feedback based on vehicle information to properly respond to changes in conditions, such as roadway cant. For example, when overtaking a large vehicle such as a truck, the resistance to lateral position control changes owing to the changes in airflow, but PPA1.0 recognizes the truck in the adjacent lane and feeds this information forward to the steering control, which suppresses any disturbances in lateral position to pass alongside the larger vehicle safely.

Moreover, using navigation map data and global navigation satellite system (GNSS) signals, PPA1.0 obtains information such as the current location and attributes of the road ahead, including curve tightness, branching points, and speed limits, allowing it to control the vehicle speed according to the traffic environment. This eases the driver's workload, making driving safer and more comfortable.

3. ProPILOT Assist 2.0

This section provides an overview of the functions, technological features, and driver interactions of ProPILOT Assist 2.0 (PPA2.0).

3.1 System overview

While following the route set by the navigation system when a destination is entered, PPA2.0 assists a wide range of driving operations from when the driver gets on the main highway until they get off. It collects information not only from in front of the vehicle but also virtually 360° around the vehicle as well as the precise vehicle location on the road using seven cameras, five radars, and twelve sonars installed on the vehicle together with GNSS and three-dimensional high-definition (3DHD) map data. The 3DHD map data describe the road structures, number of lanes, and locations of merging, branching, and crossing points. This information allows the vehicle to be controlled according to the road conditions ahead and provides smooth driving similar to that performed by an experienced driver. The PPA2.0 system also constantly monitors whether the driver is paying attention to the situation ahead using an installed driver monitor camera. Figures 4, 5, and 6 show the PPA2.0 sensor locations, a representation of the 360° sensing coverage, and a 3DHD map image, respectively.

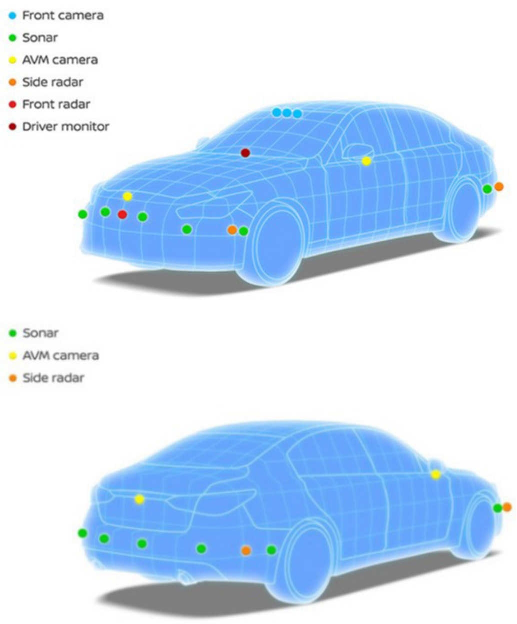

Fig. 4 Sensor locations for PPA2.0

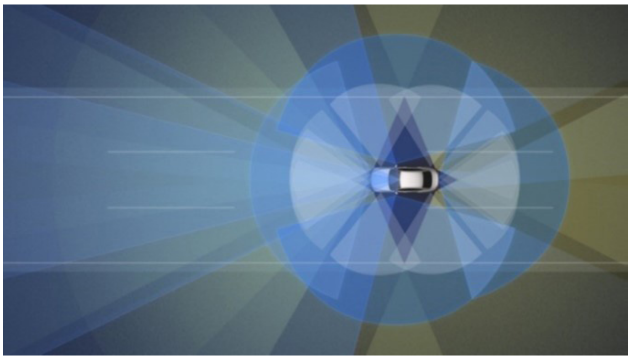

Fig. 5 360° sensing with PPA2.0

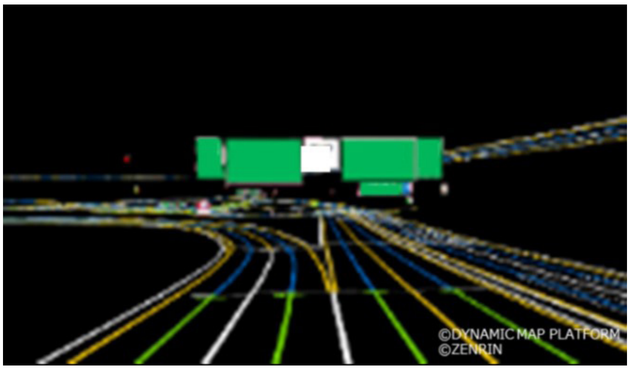

Fig. 6 3DHD map for PPA2.0

3.2 Functions of PPA2.0

In addition to providing the vehicle speed and distance control and lane-keeping functions of PPA1.0, PPA2.0 includes lane-change assistance, route-following assistance, and overtaking assistance functions.

3.2.1 Vehicle speed and distance control

As in PPA1.0, the vehicle speed and distance control function of PPA2.0 maintains the vehicle speed set by the driver. When the system detects a vehicle ahead, it controls the vehicle speed to maintain a safe inter-vehicle distance using the speed set by the driver as the upper limit. The PPA2.0-equipped vehicle stops when the vehicle ahead stops and can resume moving with the vehicle ahead for up to 30 s thereafter. In addition, PPA2.0 uses the 3DHD map and navigation route information to control the vehicle speed according to the present road configuration as well as the road conditions after a branching point.

3.2.2 Lane keeping

As in PPA1.0, the lane-keeping function of PPA2.0 helps the driver to keep the vehicle in the middle of the traveling lane on straight roads by controlling the steering wheel. Furthermore, PPA2.0 make allows the driver to take their hands off the steering wheel as long as they are constantly attentive to the road ahead and can immediately operate the steering wheel in response to road, traffic, and vehicle conditions.

3.2.3 Lane-change assistance

When the driver places their hands on the steering wheel and activates the turn signal in the direction of the desired lane, PPA2.0 controls the steering and assists with the operations necessary to change lanes.

3.2.4 Route-following assistance

After the driver has provided a destination to the navigation system, PPA2.0 suggests lane changes required to continue following the predetermined route, such as at exit ramps or branch points or where the number of lanes decreases. When the driver places their hands on the steering wheel and presses the lane-change assist button, the turn signal is activated in the direction of the desired lane, and PPA2.0 controls the steering wheel to assist in changing lanes accordingly. If the vehicle must change lanes multiple times to reach the desired lane, PPA2.0 can assist in consecutive lane changes.

3.2.5 Overtaking assistance

If PPA2.0 detects a vehicle ahead, that is slower than the speed set by the driver, it suggests that the driver overtakes the vehicle. When the driver places their hands on the steering wheel and presses the lane-change assist button, the turn signal is activated in the direction of the desired lane and the system controls the steering wheel to assist in changing lanes. Once the slower vehicle is passed, the system suggests that the driver returns to the original lane. When the driver presses the lane-change assist button, the left-turn signal is activated, and PPA2.0 controls the steering wheel to assist the driver in returning to the original lane.

The next section discusses the use of 3DHD map data, which are essential for the lane-change, route-following, and overtaking assistance functions.

3.3 Application of 3DHD map data to the lane change assistance function

This section explains how the PPA2.0 lane-change assistance function uses 3DHD map data to determine the feasibility of lane changes and plan lane-level driving.

3.3.1 Determination of lane-change feasibility

One of the challenges of implementing lane-change assistance is obtaining adequate information describing the lane conditions ahead. When a lane change begins, the camera could be unable to collect comprehensive lane information from the point at which the lane change will end, such as lane markings indicating the disallowance of lane changes. Thus, the information the camera provides may be insufficient to inform safe lane changing. However, 3DHD map data contain information such as road curvature and lane markings at the local level, allowing for the assessment of road configurations beyond the camera's detection range and enabling PPA2.0 to determine whether lane changes are possible by considering the starting and ending points of the relevant lanes.

3.3.2 Lane-level driving plan

The lane-change assistance function determines the appropriate timing for suggesting lane changes to assist in overtaking or following the route the navigation system recommends. This determination is enabled by creating a lane-level driving plan using the lane-level data in the 3DHD map. The driving plan determines which lane the vehicle should use in which road section and decides how to guide the vehicle to that lane.

Figure 7 illustrates the process of generating a lane-level driving plan. First, when a branching point, such as an exit ramp, exists on an expressway, the system calculates the number of lane changes required to move to the route recommended by the navigation system as well as the distance along the road to the branching point, then selects a lane accordingly.

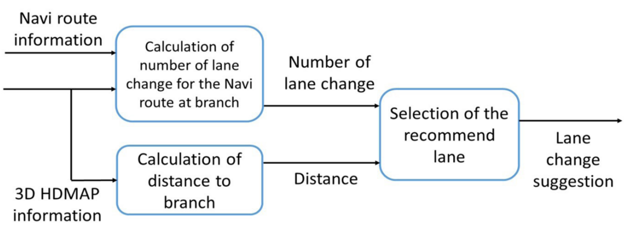

Fig. 7 Block diagram depicting the generation of a lane-level driving plan

For example, Fig. 8 shows a schematic road configuration near a highway junction. The route recommended by the navigation system is set to proceed to exit P in the diagram at the exit ramp. If the vehicle is in the rightmost through-traffic lane when it approaches the exit, PPA2.0 suggests changing lanes to the left until it is in lane A. The system does not recommend moving to lane B because doing so would increase the number of lane changes needed to exit at point P. If the vehicle initially travels in lane B, PPA2.0 suggests a lane change to the right and guides the vehicle to lane A. In this manner, regardless of the lane in which the vehicle is traveling, a lane-change proposal is ultimately made to guide the vehicle to exit P.

In addition, using a lane-level driving plan allows PPA2.0 to provide suggestions when overtaking a vehicle at appropriate times. For example, if the route to be followed requires taking a branch road to the left and the distance to the branching point is small, the system does not suggest overtaking.

Thus, constructing a lane-level driving plan using 3DHD map data allows PPA2.0 to determine the most desirable lane to follow the navigation route, facilitating the suggestion of lane changes at the appropriate times.

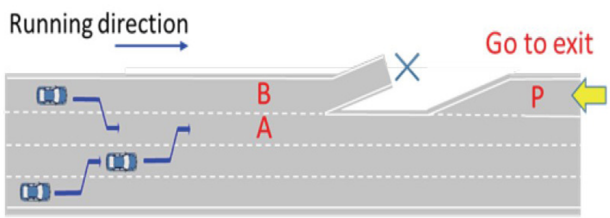

Fig. 8 Planning of a lane-level driving near a branching point

3.4 Off-board linkage function

To provide functions such as updating 3DHD map data, PPA2.0 has an off-board linkage function that enables constant telematic communication with the map server. This off-board linkage function comprises vehicle-side data storage for the 3DHD map, a 3DHD map electronic control unit (ECU) for outputting map data, a telematics control unit for communication, and a server for storing and distributing the latest map data (Fig. 9).

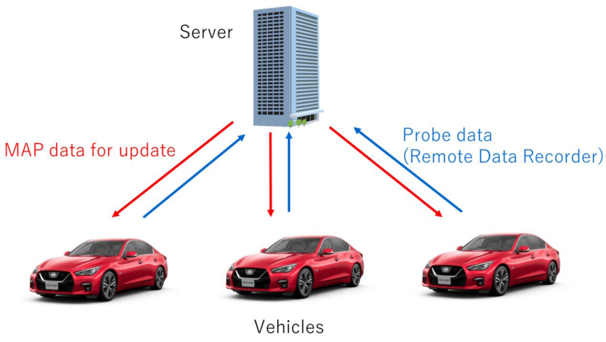

Fig. 9 Off-board linkage function

The 3DHD map data are updated several times a year to help ensure that the latest maps matching the actual road configuration are available promptly, even when the road configuration changes owing to construction or other reasons.

The 3DHD map ECU checks for differences between its map and the latest map version on the server for each operation. If the ECU map version is already updated when the navigation destination is set, priority is given to the map on the ECU, whereas when no destination is set, the latest map for a location close to the vehicle is downloaded from the server to update the ECU map. This help ensures that the latest 3DHD map data are always used for driver assistance.

3.5 Relationship between PPA2.0 and the driver

The intelligent interface for PPA2.0 is a unique human–machine interface (HMI) designed in-house at Nissan to facilitate the appropriate use of its advanced driver assistance functions. The intelligent interface comprises a heads-up display (HUD), meter display information, steering wheel button operations, and driver monitoring system warnings (Fig. 10).

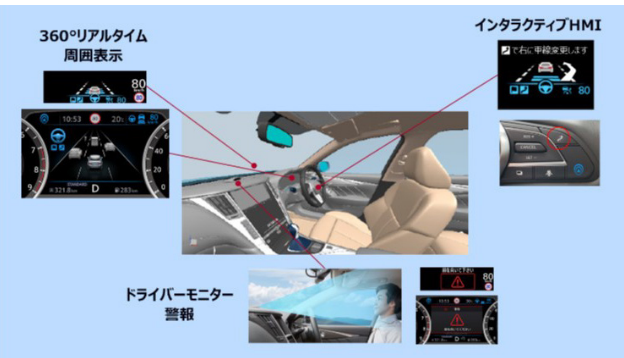

Fig. 10 Intelligent interface

There are three activation states in PPA2.0 compared to the two in PPA1.0, owing to the addition of the hands-off function for single-lane driving. These three modes comprise intelligent cruise control (ICC) mode, in which only the vehicle speed and distance control are activated; hands-on mode, in which vehicle speed and distance control, as well as steering control, are activated, but the driver must maintain steering control at all times; and hands-off mode, in which vehicle speed and distance control as well as steering control are activated and allow the driver to take their hands off the steering wheel in certain situations, assuming that they maintain attention on the road ahead and remain ready to take over vehicle operation when required. To facilitate mode identification, Nissan adopted different color schemes for display elements such as icons and indicators on the HUD and meter displays: ICC mode is white, hands-on mode is green, and hands-off mode is blue (Fig. 11).

Fig. 11 Color schemes indicating operation status

Furthermore, a driver monitoring system is included to help ensure that the driver remains attentive to the road ahead. If they do not, the system warns the driver to be more attentive, thereby preventing them from neglecting to monitor the surrounding traffic conditions when driving in hands-off mode (Fig. 12).

Fig. 12 Warning issued by the driver monitoring system prompting the driver to attend to the road ahead

3.5.1 Interactive HMI

During the branching or overtaking stages of navigated-route driving, PPA2.0 considers the planned route, the speed of the vehicle ahead, and surrounding traffic conditions to suggest the use of lane-change assistance at appropriate times via the HUD and meter displays (Fig. 13).

Fig. 13 Suggestions from the lane-change assistance system

Arrow-shaped graphics in the HUD provide suggestions for lane-change assistance, and text at the top prompts for driver approval. The number of display elements in the HUD was minimized to help ensure the driver can readily recognize system suggestions while retaining their forward view. Each lane-change assistance suggestion is also provided on the meter display to allow the driver to confirm its necessity. Upon reviewing the suggestion, the driver checks the safety of their surroundings and presses the lane-change assist button. Because this button often operates relatively quickly after the driver receives a system suggestion, the suggestion is located in the upper region of the display near the periphery of the steering wheel to link its visibility with button operability. Thus, once the driver is familiar with button operation, it can be pressed without looking.

During lane-change assistance, the driver must place their hands on the steering wheel to override the system. Therefore, once lane-change assistance is initiated, the color of the HUD and meter display change from blue for the hands-off mode to green for the hands-on mode to prompt the driver to grip the steering wheel. Indeed, the color-coding scheme is most effective in this situation. From the time the driver's approval is received until the lane change begins, an arrow-shaped graphic on the HUD is animated to flow from front to back while a text message is displayed urging safety confirmation. Furthermore, when PPA2.0 flashes the turn signal and initiates a lane change, the arrow-shaped graphic on the HUD turns green and flashes at the same frequency as the turn signal, indicating that a lane change is in progress (Fig. 14).

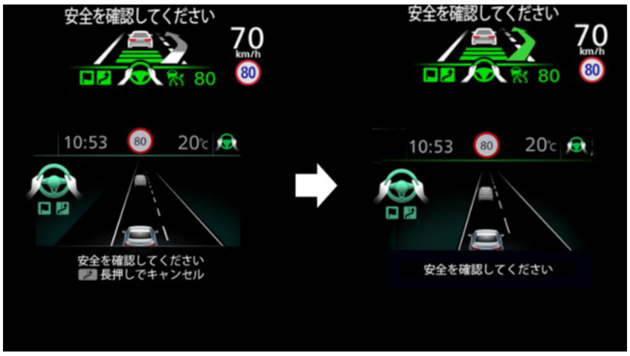

Fig. 14 Display during lane-change assistance

3.5.2 360° real-time surrounding display

To provide the driver with an accurate understanding of the capabilities of PPA2.0, the detected road environment and traffic conditions are shown in real time using a virtual 360° view on the meter display. To depict the road environment, PPA2.0 uses the 3DHD map data and front camera to display the presence or absence of lanes adjacent to the traveling lane and the type of lane marking (single or double solid/dashed white lines and solid/dashed yellow lines), as shown in Fig. 15.

Fig. 15 Example of 360° real-time surrounding display (distinguishing line markings)

To depict the traffic situation, PPA2.0 displays the other vehicles detected in the traveling and adjacent lanes according to vehicle type (passenger car, truck, motorcycle, or unknown) using fusion processing of sensor data from the front camera and front and side radars. The locations and sizes of these depicted vehicles are repeatedly tuned using nonlinear scaling such that the apparent distance to the other vehicles on the display approximately matches the actual surroundings. This allows the driver to develop an intuitive understanding of the detection range and identification capabilities of the system by comparing the actual and displayed spaces.

Therefore, the virtual 360° real-time display helps drivers to gradually learn the capabilities of PPA2.0 as they experience various situations, promoting the appropriate use of and fostering a sense of trust in the system.

4. Summary

The ProPILOT Assist system has been developed considering the concepts of “wider situations,” “easier use,” and “more users.” By commercializing ProPILOT Assist and ProPILOT Assist 2.0, Nissan provides customers with a safer, more comfortable, and stress-free driving experience that has received great positive feedback.

Nissan will continue developing such technologies to assist driving operations in a broader range of situations and provide new benefits toward realizing a safer motorized society.

Authors

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3. ProPILOT parking

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1. Introduction

Parking is a difficult driving operation for many drivers. Because they must appropriately plan their turning locations based on the shape of the parking spot and the presence or absence of adjacent vehicles. In particular, when parking in a narrow space, the driver must turn the steering wheel repeatedly while shifting the vehicle forward and backward. Therefore, research and development on parking assistance is being actively conducted. Memory functions have recently been developed to detect parking locations without markings, such as those in residential environments. These functions allow the driver to register the parking location, allowing the system to detect the parking location and provide parking assistance automatically. In one type of memory function, the driver registers the parking location by operating the cursor on the navigation screen; in another, the driver's parking route is memorized and accurately reproduced.

2. Nissan ProPILOT Park

ProPILOT Park was first installed on the second-generation LEAF released in 2017. A parking assistance system(2) automatically detects the target parking location and calculates the optimal parking route, including forward and reverse pull-ins, by detecting parking space lines using the Around View System(1) and assessing the available space, such as between vehicles, using sonar. The driver presses the “parking start” button, and the system automatically controls the driving operations (steering wheel, accelerator, brakes, and shift switching) to assist the parking process at the target parking location (Figs. 1 and 2). ProPILOT Park was later installed in SAKURA, X-TRAIL, and ARIYA.

In 2023, Nissan’s first ProPILOT Park with memory functions was installed in SERENA (Fig. 3). This chapter introduces the latest memory function technology used for registering and detecting parking locations.

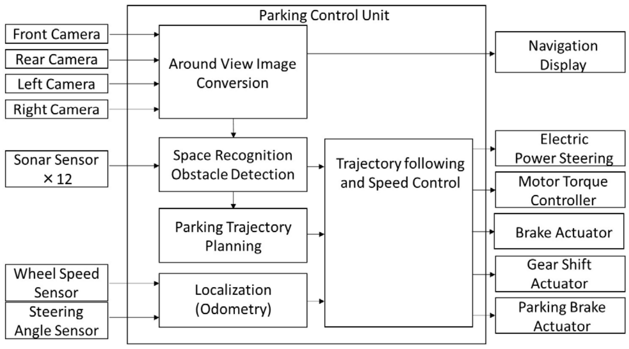
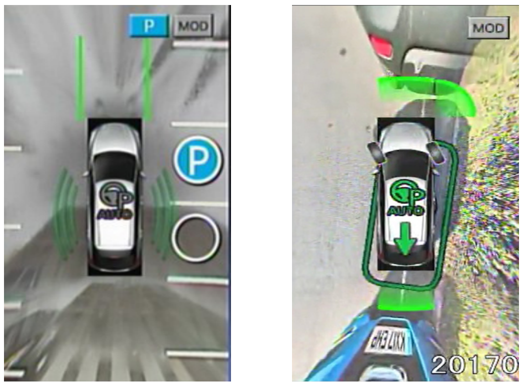


Fig. 1 System configuration of ProPILOT Park



Detection of target parking location　　Parking control (parallel parking)

Fig. 2 Parking location detection and parking control

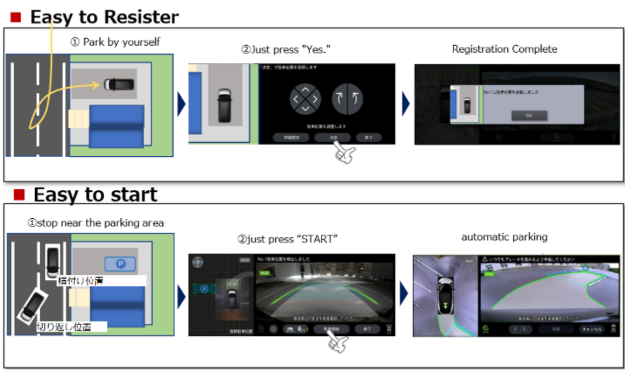


Fig. 3 ProPILOT Park with memory function

*AD/ADAS Advanced Technology Engineering Department

3. ProPILOT Park with memory function*

The memory function was designed that the driver can register a parking location easily and seamlessly transit from normal driving operation to parking assistance. This system is running in the background automatically while the driver is driving at low speeds. And drivers can do one-touch registration of the parking location. (Fig. 3, top). Afterward, whenever the driver stops near the registered parking location, the system automatically detects the parking location via the global navigation satellite system (GNSS) and automatic memory selection (Fig. 3, bottom) to initiate parking assistance. The system can detect the registered location as long as the vehicle is near it in a standstill condition.

*equipped in Serena (as of July 2024).

4. System configuration

Fig. 4 shows the configuration of the ProPILOT Park system with a memory function. Equipped with a newly developed 3-megapixel around view camera, this system captures detailed images of nearly the entire vehicle surroundings, including the road surface. In addition, the left and right door mirrors are equipped with infrared light emitters for nighttime sensing. Furthermore, GNSS information is acquired, linked to the memory information, and used to detect the parking location automatically.

5. Registration and detection of parking location

The memory function uses the around view camera to capture the road surface images and extracts its features. Then it compares the registered road surface features with the current ones to determine the parking location. These features are mapped and saved for a maximum distance of approximately 40 m, near the parking location. Using this wide-area road surface map, the parking location can be detected from the parallel position and forward and reverse pull-in positions (Fig. 3, bottom).

5.1 Road surface maps

The road surface map is consist of keypoints and their descriptors with each coordinates along the driving route. Two different types of the maps are employed for registration and detection. In the registration phase, the map is created up to 20 m regarding forward and backward maneuvering from a switchback point, respectively. It includes all parking pathways from the switchback position on the road to the parking location (Fig. 5, Fig. 6(a)). In the detection phase, the map is created to specify registered target position and its range is consecutive 20 m including the vehicle position at the time of detection (Fig. 6(b)). The system automatically accumulates around view images at fixed distance intervals when driving at low speeds. Drivers do not need to perform any operations to begin recording or detection.

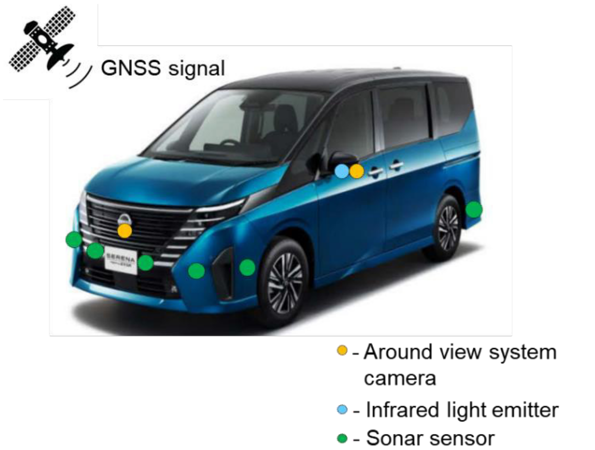


Fig. 4 Arrangement of the components of ProPILOT Park with memory function

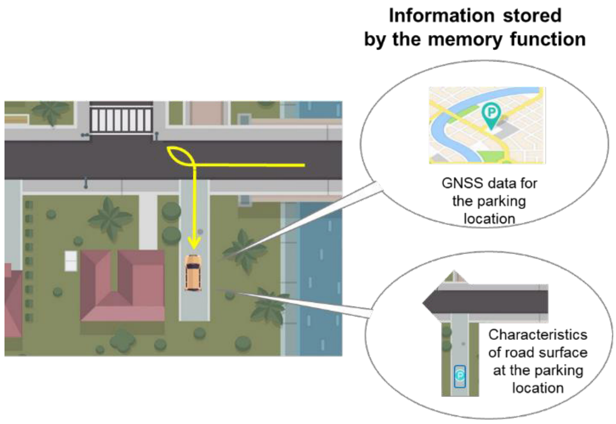


Fig. 5 Information registered in the memory function

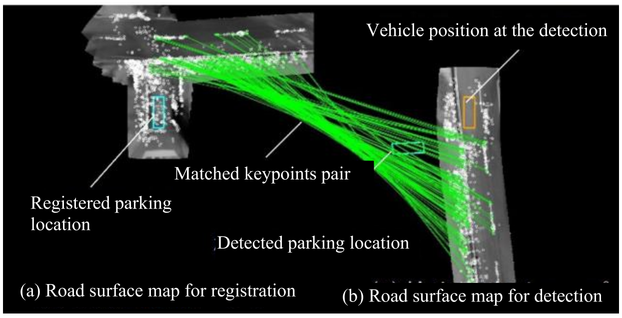


Fig. 6 Comparison of road surface maps

5.2 Detection of parking locations

The system compares the detected road surface with the registered road surface map to detect the parking location and connects the most similar pairs of image features. Here, an “image feature” refers to keypoints indicating the locations of corners, edges, etc., in the road surface map and the feature descriptors for identifying these points. However, if there are changes in the images owing to shifting 3D objects such as parked vehicles or bicycles or changes in sunlight conditions in the morning, day, or night, the performance of this comparison process can be poor. To overcome this issue, the automatic detection process is designed to extract robust keypoints(3).

5.3 Automatic detection of registered parking locations

At the registration of a parking location, the system links to and saves the GNSS location information (latitude, longitude, and vehicle orientation) obtained from the navigation system. After registration, the system automatically searches for a registered parking location within a certain distance from the vehicle using the present GNSS location information. When the vehicle stops near the registered parking location, the system automatically compares the detected road map with the registered one to identify the parking location. It displays it on the navigation screen (Fig. 7). If there are multiple registered locations within a certain distance from the vehicle, all registered locations within the range are compared with the detected road map, and the location with the closest distance is preferentially displayed. The driver can also manually select a parking location from the system memory.

5.4 Real-time correction

During the parking manuever, the parking location is detected by sequentially comparing the registered road surface map with the current image. As the vehicle approaches the parking location, this image can be directly compared to the parking location, thereby improving the accuracy of the parking operation. (Fig. 8)

6. Summary

This chapter describes the functions of Nissan ProPILOT Park and the latest recognition technologies enabling its memory function. This function allows the driver to register a parking location with a simple operation after parking and thereafter have the vehicle automatically detect when it approaches the same location (Figs. 9, 10, 11) to provide easy-to-operate parking assistance.

Fig. 7 Display when a parking location is automatically detected

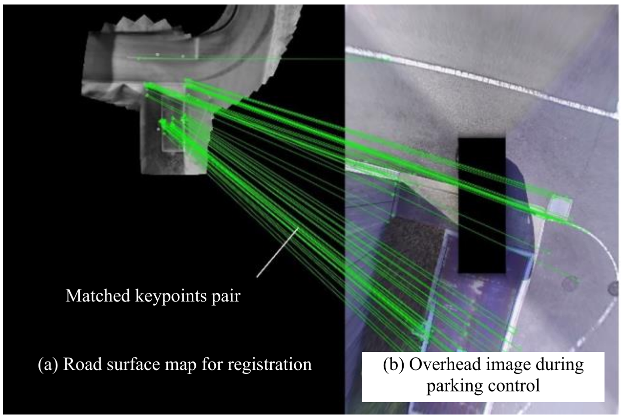


Fig. 8 Comparison of road surface maps with real-time correction

Fig. 9 Detection from the side-facing position

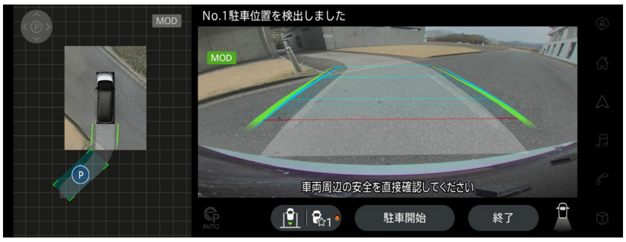


Fig. 10 Detection from the switchback position

Fig. 11 Detection of a deep parking position

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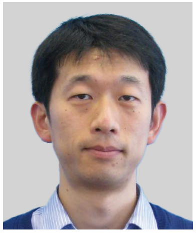
Authors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Special Feature 2:Advanced Driver Assistance Systems (ADAS) & autonomous driving

4. The latest driver assistance technology aimed at achieving zero accidents

Nariaki Etori*

1. Introduction

In pursuit of its Nissan Ambition 2030 long-term vision, Nissan is developing high-performance next-generation LiDAR-based vehicle control technologies that will help to reduce traffic crashes significantly. As customers will need to use their cars confidently in the approaching era of autonomous driving, driver assistance technologies must be improved to avoid multi-dimensional and complex crashes that can occur in the real world. Nissan is working to provide higher levels of safety in real-world situations through two initiatives (Table 1).

The first initiative for ensuring a high level of safety is to clarify the nature of real-world traffic situations. A wide variety of crashes occur in the real world, ranging from frequent and simple to infrequent and highly complex situations. Due to the inherent challenges of conducting a comprehensive desktop study encompassing all potential complex scenarios that may result in severe crashes, statistical methods are often regarded as viable alternative research approaches. Nonetheless, the implementation of these statistical methods presents its own set of challenges. For instance, in the context of Japan, traffic crash statistics reveal an average distance traveled of approximately 240 million meters per fatal accident. This distance is equivalent to the total annual mileage of approximately 30,000 vehicles. Thus, many datasets are required to model infrequent crashes situations, and Nissan is working to collect data from mass-produced vehicles and conduct driving experiments accordingly.

The second initiative is to improve safety performance through automation. Under the “Safety Shield Concept,” Nissan is developing and commercializing technologies appropriate to the likelihood of different collision risks.

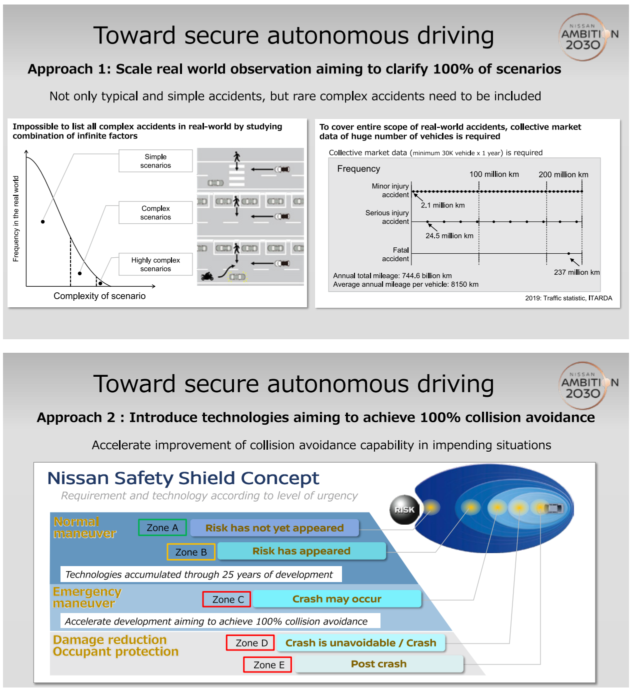

Table 1 Activities for delivering safe autonomous driving

Following approximately 25 years of technological advancements, Nissan is making significant strides towards achieving automation in regular usage. Nevertheless, there is a pressing need to expedite the development of accident avoidance technologies. This chapter introduces Nissan’s latest work on ground truth perception technology to further the automation of accident avoidance maneuvers.

2. Examples of complex crashes

Figures 1 and 2 show two examples of rare, complex crashes. In Fig. 1, the left lane is congested at a certain distance from a vehicle pulling a trailer. The vehicle notices the congestion late, swerves suddenly, and overturns the towed trailer, blocking three lanes in front of the vehicle of interest (autonomous driving vehicle).

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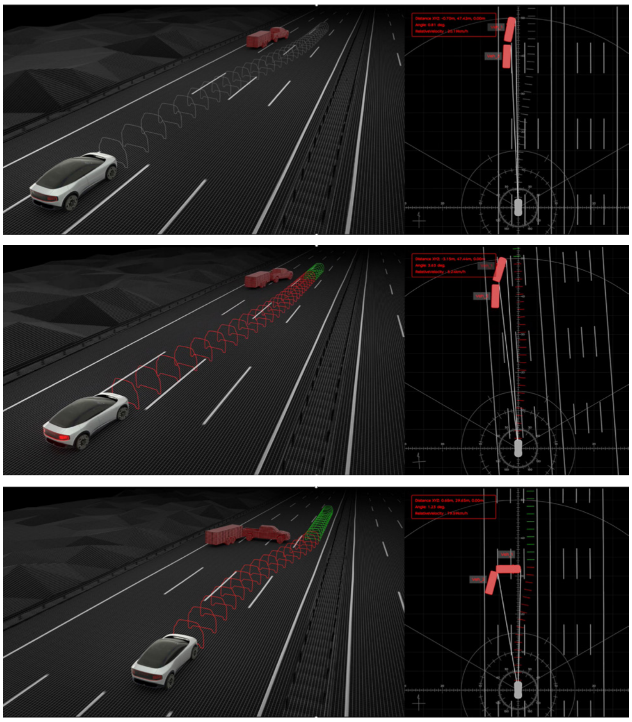

Fig. 1 Complex accident example 1

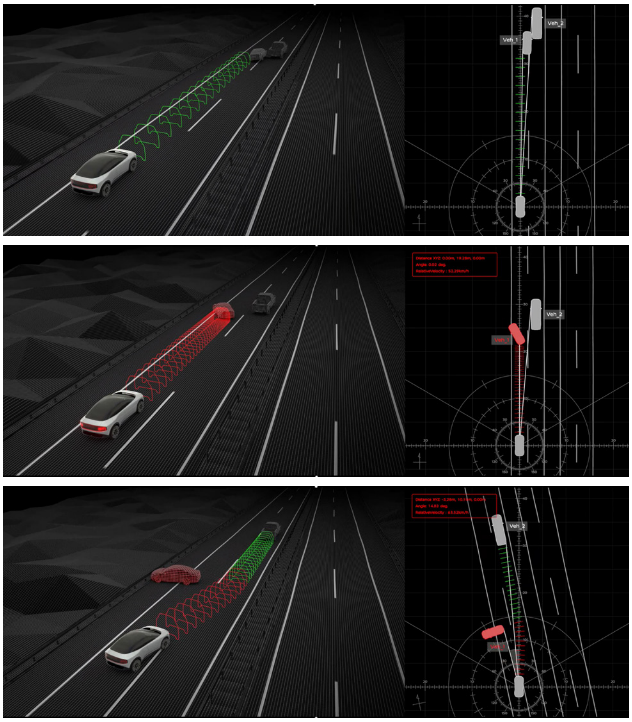

Fig. 2 Complex accident example 2

An autonomous driving vehicle should react to such a scenario by first attempting to avoid the trailer using the steering wheel as the trailer initially veers into the vehicle's traveling lane. However, further avoidance is required because the trailer overturns and blocks three lanes of traffic. Thus, the autonomous driving system must grasp the constantly changing situation accurately and near-instantaneously to take the appropriate evasive action.

In the second example, the vehicle running in front of the autonomous driving vehicle is distracted and collides with a truck in the adjacent lane, then slows down and collides with a guardrail, causing it to come to halt more abruptyly than anticipated. (Fig. 2)

In this situation, the autonomous driving vehicle should first attempt to avoid collision by braking because the vehicle in front slows down after its collision with the truck. However, the vehicle in front subsequently stops suddenly, requiring the autonomous driving vehicle to avoid collision by making an urgent avoidance maneuver. Given that the vehicle in front veers into the traveling lane of the autonomous driving vehicle, the steering wheel is used in this maneuver. Again, the constantly changing situation must be grasped accurately and near-instantaneously to inform evasive action according to the situation.

As indicated by these examples, the accident avoidance maneuvers required of autonomous vehicles involve accurate and rapid recognition of space and objects in three dimensions and the performance of continuous evasive maneuvers based on instantaneous judgments under ever-changing conditions.

3. Ground truth perception technology

Innovation in recognition performance is critical for delivering the accident-avoidance maneuvers required from autonomous driving vehicles. Thus, Nissan’s newly developed ground truth perception technology uses next-generation high-performance LiDAR in addition to conventional cameras and radar to gather data describing the vehicle surroundings, as shown in Fig. 3.

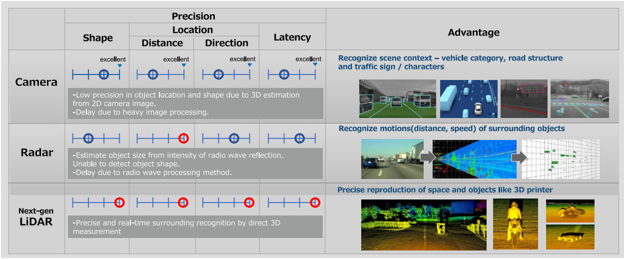

Fig. 3 Features of camera, radar, and LiDAR systems

As cameras capture a large quantity of information, they can clarify the meaning (context) of a situation. However, shape and position accuracy is lost when creating 3D information from 2D images. In addition, the algorithms for converting camera data into 3D information are complex. Therefore, cameras are unable to track objects during sudden changes in situation. Furthermore, though radar is excellent at capturing the movement of objects, it cannot determine accurate shapes because the strength of the radio wave reflection can only be used to determine the size of an object. The complex algorithms employed for radar data processing also make tracking objects difficult when they move suddenly. In contrast, LiDAR can directly measure spatial structures without requiring complex interpretation, allowing it to quickly follow changes in the situation and reproduce spatial structures in the processor of an autonomous driving vehicle analogous to the accuracy of a 3D printer. By integrating and maximizing the advantages of these three sensor types, autonomous driving vehicles can expand their capabilities to match or exceed those of humans.

While conventional LiDAR cuts space into extremely thin angles, hindering its understanding of space and objects and thereby limiting its potential capabilities, next-generation high-performance LiDAR can capture the environment from a wide angle, similar to cameras, with a vertical detection angle of 25° or more. Furthermore, next-generation high-performance LiDAR can achieve a detection distance of 300 m, more than twice that of conventional LiDAR. This increased distance allows vehicles at the tail end of traffic jams to be detected early and subsequently avoided by making normal lane changes at speeds of up to 130 km/h, the typical maximum speed on highways worldwide. Because doubling the detection distance causes the LiDAR beam to spread farther, its resolution must also be doubled and reached 0.05° or less in next-generation LiDAR systems accordingly (Fig. 4).

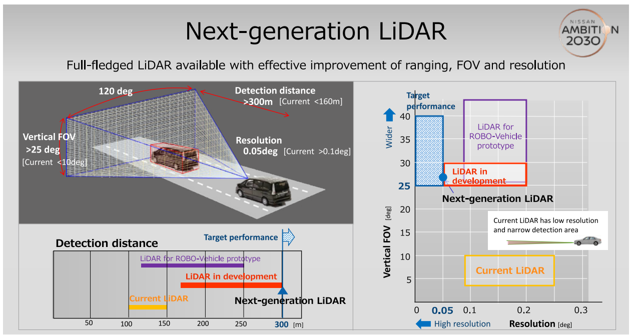

Fig. 4 Next generation LiDAR

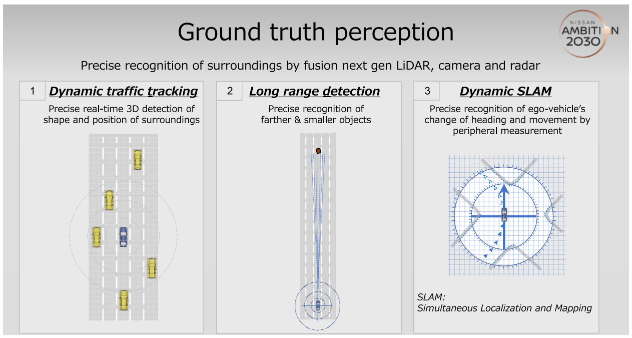

Fig. 5 Ground truth perception

Sensing technology combining cameras, radar, and next-generation LiDAR enables dynamic traffic tracking, long-range detection, and dynamic simultaneous localization and mapping (SLAM), as illustrated in Fig. 5.

Dynamic traffic tracking accurately captures road configurations as well as the movement of surrounding vehicles without delay, improving emergency response performance. Long-range detection identifies vehicles more than 300 m away, facilitating the management of most incidents on highways. Finally, dynamic SLAM detects obstacles in the area by accurately measuring the surrounding space and tracks the vehicle's movement based on changes in its spatial view. This accurate tracking of self-movement allows autonomous driving even in areas where no map is available, such as hotel premises, making door-to-door driving functions possible.

4. Ground truth perception prototype vehicle

This section introduces a prototype vehicle equipped with ground truth perception technology. The vehicle system configuration is shown in Fig. 6.

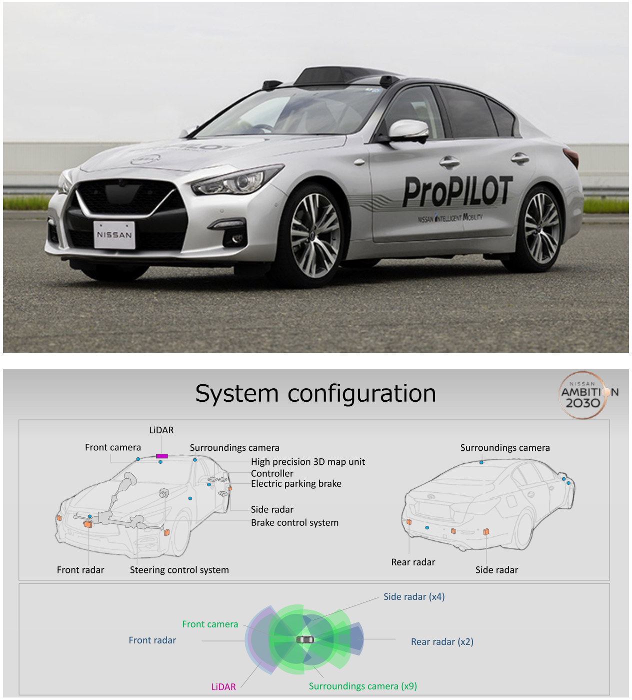

Fig. 6 Appearance and system configuration of the prototype vehicle

This prototype vehicle was equipped with seven radars, ten cameras around the car body, and a next-generation LiDAR mounted on the rooftop to help ensure that surrounding vehicles do not block the beam and provide long-distance spatial recognition.

5. Latest driver assistance technologies using ground truth perception technology

This section describes the performance of the prototype vehicle in three scenarios.

The first scenario (Fig. 7) involved avoiding a vehicle being backed out of a parking lot along the road and then making an emergency stop responding to a pedestrian suddenly appearing ahead. In this scenario, the shape and position of the surrounding objects were accurately recognized without delay, and emergency operations were continuously performed based on instantaneous judgments, thereby allowing automated continuous maneuvers to avoid the backing vehicle and pedestrian.

Fig. 7 Automated emergency maneuvers to avoid a vehicle and pedestrian

The second scenario (Fig. 8) considered a rolling tire detached from a vehicle running in the oncoming lane. First, the tire approached the front of the prototype vehicle, and then the oncoming vehicle (without its tire) crossed the median strip into the traveling lane. In this scenario, the system accurately recognized the shapes and positions of the surrounding objects without delay and again conducted successive avoidance maneuvers based on instantaneous judgments.

Fig. 8 Detection and avoidance of an approaching tire

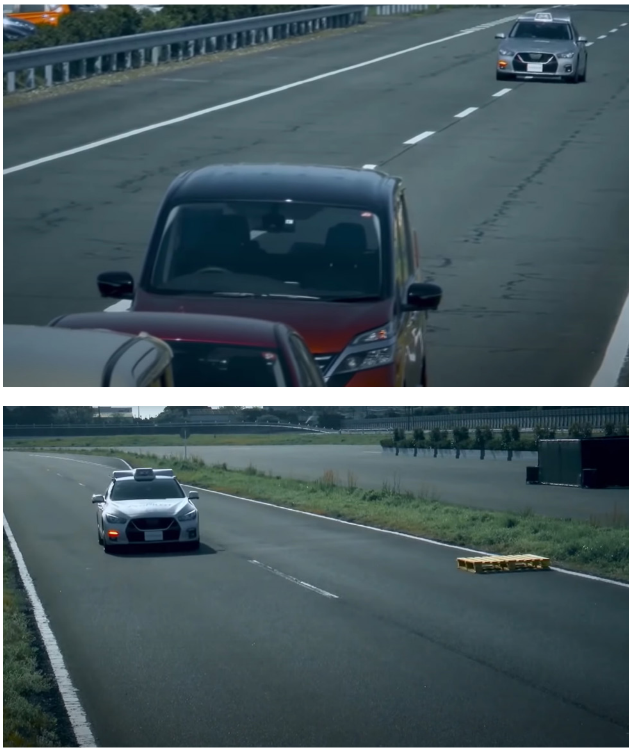
Fig. 9 Avoidance of traffic jams and obstacles on the road via lane-changing operations

In the third scenario, the prototype vehicle quickly detected the end of a traffic jam as well as obstacles on the road while driving at high speed (Fig. 9). The vehicle first moved to a safe lane using a normal lane-changing operation, then recognized the surrounding road structure on an unmapped road, calculated the route to take, and autonomously traveled to the destination the front of a door (Fig. 10).

These scenarios illustrate the evolution of driver assistance technologies by developing ground truth perception technology, which will eventually realize address-to-address autonomous driving.

Fig. 10 Automated emergency maneuvers of the prototype vehicle to arrive at destination

6. Conclusion

Nissan believes that the automation of accident avoidance maneuvers is the first task that must be achieved to deliver a reliable autonomous driving experience and intends to accelerate further the progress of technological development introduced here to advance the evolution of autonomous driving technologies steadily.

Authors

Nariaki Etori

Special Feature 3:Connected service

1. Overview of Connected Cars and Services

Toshiro Muramatsu*

1. Introduction

For more than 260 years since the invention of automobiles, the initial development of automotive technology was primarily focused on the technologies directly required for transportation, such as moving, turning, and stopping. However, with the development of wireless communication technology in the latter 10% of the history of automobiles, connectivity was added as a new function. In particular, telematics, a portmanteau that represents the interplay between telecommunications and informatics, provides various services to vehicles via a wireless communication system based primarily on a mobile phone network.

Vehicles equipped with this system are called "connected cars," and the services provided by this system are called "connected services." Continual innovations in these technologies and services benefit from the ongoing development of information and communication technology (ICT). This article describes Nissan's connected cars and services, mobility services, and its vision for the future.

2. Connected cars and services developed to date

Nissan's connected services began in 1998 as Compass Link. This system was designed to supplement the large volume of information processed by in-vehicle navigation systems, which started to spread in the mid-1990s. The system used a large-scale database located at an operation center to eliminate the inconvenience of finding destinations, and it featured a search service provided by a human operator and search results for navigation destinations, which was the first service of its kind in the world. Customers were able to find their desired destinations by talking to an operator via hands-free voice calls, and the navigation system automatically set the destination. This service required both voice and data communications and utilized a technology called Data and Voice (DV)*1, which split the 9.6-kbps bit rate into two channels: one for voice and the other for data communications. The customers' mobile phones were used as wireless communication devices. This system enabled the vehicle side to transmit customer and vehicle identification information to the operation center, and enabled the latter to transmit search result data to the vehicle side while the customer and operator were on a voice call.

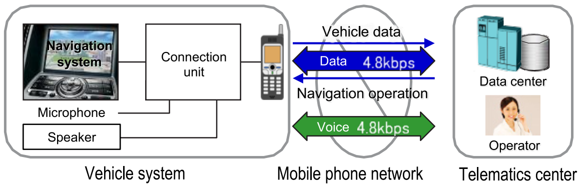

Fig. 1 System overview of the Compass Link service

In response to the spread and development of mobile phone-based information searches, CARWINGS was launched in 2002 as a service dedicated to customer experience, offering enhanced information services in addition to the aforementioned human operator service. This service included the "Information Channel," which provided a variety of content, the ability to receive e-mails, the "My car is here" service (which allowed users to send their vehicle's current location by e-mail), and the "Fastest Route Guidance" service (which searched for the quickest route to a destination based on traffic information). Instead of using the abovementioned DV technology, this service switched between voice and data communications because of the greater proportion of data communications available in such a setup. Drivers could utilize these services relatively undistracted by employing voice recognition technology for sending commands and text-to-speech technology for playing back the content downloaded to their vehicles. Since then, human-machine interfaces (HMI) have been continuously developed along with the systems and services that use them.

The CARWINGS service has also started utilizing information obtained from vehicles themselves (probe data). The abovementioned "Fastest Route Guidance" service combined traffic information obtained from the Vehicle Information and Communication System (VICS) Center with probe data to generate detailed real-time

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traffic information, using both estimated and statistical traffic information to calculate the fastest route. The service was also used to conduct a demonstration in which anti-lock braking system activation data (i.e., time and location) were collected, anonymized, and distributed as "slip information" to warn drivers about the road conditions and provide the information to road administrators.

Fig. 2 Examples of CARWINGS services

In 2010, Nissan launched the world's first mass-produced electric vehicle (EV), the LEAF, into the global market. To prepare for this world-first challenge, an in-vehicle telematics control unit (TCU) was deployed globally to monitor the quality of lithium-ion batteries in the market and relieve customer concerns about using EVs. Data on how vehicles were used in the market and the conditions of lithium-ion batteries were collected and centrally managed by the Global Data Center (GDC), which monitored the quality of vehicles and batteries to prepare for possible malfunctions and obtain information useful for subsequent EV and battery development. Customers were concerned about using EVs because of the cruising distance and insufficient number of charging stations. To allay these concerns, the cruising distance was calculated using information on the actual electricity consumed by the vehicle, and the range was displayed on the navigation map, which facilitated the search for information on nearby charging spots. Mobile phone applications were also improved to allow the driver to remotely activate the vehicle's air conditioner before entering the vehicle and to check the driving history after exiting it, which were functions only available in EVs. Since then, seamless functions that customers can enjoy while driving the vehicle as well as before and after using it have enhanced the user experience, and the technology has been integrated with the Internet of Things (IoT), which has now become widespread.

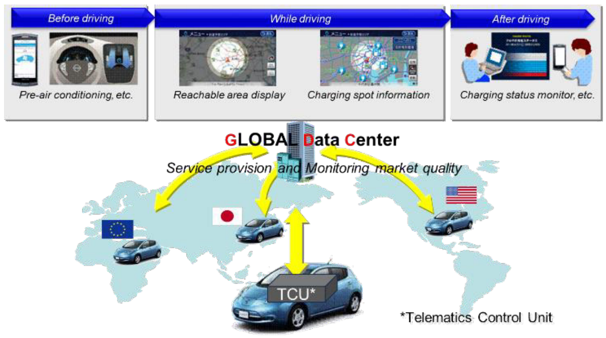

Fig. 3 Conceptual illustration of the GDC and EV services

3. Current connected cars and services

The development and commercialization of Nissan's vehicles, especially its EVs, have been carried out in line with changes in social acceptance and the evolution of technologies relevant to vehicles, such as advanced driver assistant systems (ADAS) and ICT. In 2019, the NissanConnect services were launched by linking connected cars to a cloud system called Alliance Intelligent Cloud, which was the result of an alliance with Renault. Although this system of connected cars was an off-board data center, the development and operation costs were hindrances for the connected service business; thus, the aim was to reduce the unit cost by leveraging the volume effect of the alliance and by shifting from an on-premise server to a cloud server. The vehicle components were also shared within the alliance and among its global operations to decrease the system and service development costs and to enable speedy deployment in the global market.

As smartphones are increasingly becoming the center of customers' digital lives, smartphone apps will be improved to enhance remote functions, such as the remote monitoring of vehicle information and remote operation of door locks. In addition, collaborations with business-to-business (B2B) services and third-party services such as Google and Amazon via cloud systems have been established.

One of the key values provided by connected cars is the provision of access to the latest information, through which the data and software for an in-vehicle system can be updated to the latest version. Based on this arrangement, navigation maps and software for the navigation system, as well as over-the-air (OTA) remote updates of high-definition maps used for ProPILOT 2.0, have been implemented. The ARIYA and later Nissan models also offer OTA updates of the vehicle electrical control unit (ECU) software. This update is called software over-the-air (SOTA) or firmware over-the-air (FOTA), depending on the software level, and is an important vehicle function.

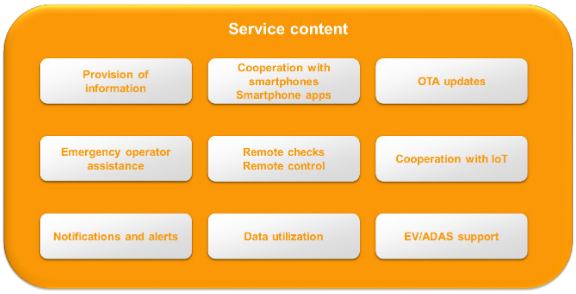

Fig. 4 Connected services of the ARIYA

In addition, the operations of in-vehicle systems are being expanded from simple navigation functions to multimedia functions, and applications and widgets are also being introduced. Accordingly, the conventional real-time OS (RTOS) has been transitioned to a general-purpose OS with high functional scalability, such as Linux. Nissan has adopted Android as the new OS for its in-vehicle infotainment system and will also provide built-in Google services. The services will perform navigation using Google Maps and utilize Google Assistant for the voice interface. It will also be possible to select and download applications through Google Play.

4. Vision for the future

Connected cars and services will continue to expand B2C/B2B/B2B2C services and to evolve HMI through the use of generative AI. However, as mentioned above, connected cars will not only be used to provide such connected services, but will also serve as a platform for future vehicles, services, and businesses to support the following initiatives.

・Mobility services

Starting with a car-sharing demonstration conducted in 1999 using HYPERMINI EVs, Nissan has demonstrated a number of mobility services, such as “Choimobi,” “e-sharemobi,” “Namie Smart Mobility” (in Namie-machi, Fukushima Prefecture), “Easy Ride ®” (for future self-driving services), and “robot taxi service” (in Suzhou, China). For such services, the remote monitoring of vehicle movement, including that of conventional rental cars, is necessary for effective management of the vehicles. Similarly, future automated mobility services will also require remote monitoring of the movement, surroundings, and interior of the vehicles. Moreover, in case of emergency, remote operation will be essential.

・Energy management

As vehicles shift to EV designs, they require more electric power, and their batteries are expected to temporarily store electric power. Nissan has already launched its “LEAF to Home” system, which uses the electricity stored in the LEAF for household electricity. LEAF to Home is expected to become part of the power system linked to large-scale systems, such as vehicle-to-building (V2B) and vehicle-to-grid (V2G). The connected car system can also be utilized to remotely monitor the power stored in EVs and remotely control the charging and discharging of the battery.

・Software-defined vehicles

Because vehicles are already electronically controlled, they are controlled by a combination of software and actuators. However, the recent attention on software-defined vehicles (SDVs) is based on the fact that innovations in vehicle electronic architecture, software that utilizes vehicle data, and OTA updates are becoming increasingly available. Automotive intelligence can be promoted by utilizing connected cars as a platform in which the ECUs, which are provided for each function, are integrated. Hence, the software of the integrated units will become increasingly important, and the software will need to be developed and improved by training it with actual vehicle data.

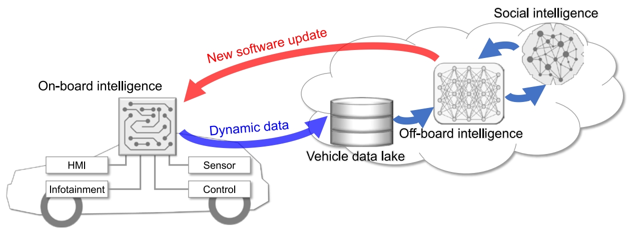

Fig. 5 Conceptual illustration of the automotive intelligence system of an SDV

In addition, the increasing number of connected cars has resulted in their exposure to cybersecurity risks. Although appropriate measures have already been taken in response to the UN-R155 cybersecurity regulations, it is necessary to closely monitor the latest trends and continue to implement countermeasures.

5. Conclusion

Since the launch of connected cars and services in 1998, Nissan has continuously innovated in response to the evolution of vehicles and ICT in society as well as the changes in customer needs. Connected, which is the "C" in "CASE," the keyword recently used to refer to the current once-in-a-century period of transformation, will soon be a normal characteristic of vehicles in addition to moving, turning, and stopping, and it will enable vehicles to connect to a wide range of systems and services. Vehicles will then be integrated into social systems, which will facilitate the continual development of technologies required to create such a future.

Authors

Toshiro Muramatsu

Special Feature 3:Connected service

2. HMI evolved by connectivity

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1. Introduction

In 2020, ARIYA adopted an integrated interface display and intuitive graphical user interface (GUI) to realize a human–machine interface (HMI) (Nissan Technical Review No. 88). The HMI allows easy access, even while driving, to in-vehicle infotainment information, which is increasing with changes in use cases and user experience (UX), as well as to vehicle system information, which is diversifying as driver assistance technologies evolve. In the years since, Nissan has expanded its range of vehicle models, adopting these HMI technologies.

This chapter describes the development of display contents such as the GUI and camera images as well as voice recognition technologies, together representing HMI-related technologies that assist the delivery of increasingly diversifying services and contents.

2. HMI adopted in ARIYA

2.1 Interface for combined visibility and operability

In ARIYA, the infotainment and meter displays are integrated into a unified information display area, as shown in Fig. 1. The dead angle created by the steering wheel was considered when arranging these displays and their contents.

Fig. 1 Integrated interface display

Meter information required for driving is displayed at a convenient distance from the driver to help ensure clear visibility. In contrast, infotainment information is displayed within easy reach of the driver to facilitate operation (Fig. 2). These two information panels are adjacent to each other because the human visual field is approximately 1.5 times wider in the horizontal direction than in the vertical direction. Eye movements in the horizontal direction are easier (Fig. 3).

The integration of these displays creates an HMI that is in harmony with the futuristic design of the cockpit interior.

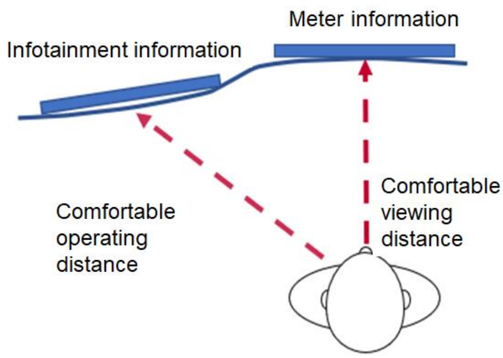

Fig. 2 Layout of information displays

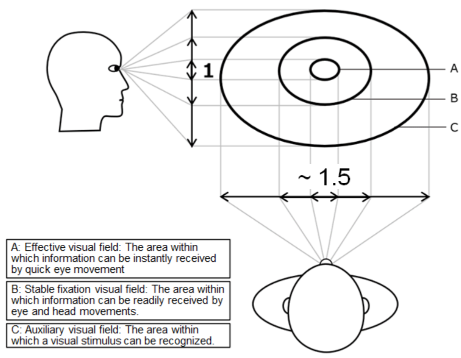

Fig. 3 Characteristics of the human visual field

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In addition to providing an effective layout and structure, integrating the two displays into a single display area achieves a sense of unity while allowing the displays to show different contents depending on the use case. To enable the driver to view map and audio information easily, a linkage function using Ethernet communication instantly transfers information from the infotainment display to the meter display through an intuitive swipe operation, illustrated in Fig. 4. This function supports various use cases such as displaying a map on the meter display. At the same time, a passenger enjoys other content on the infotainment display.

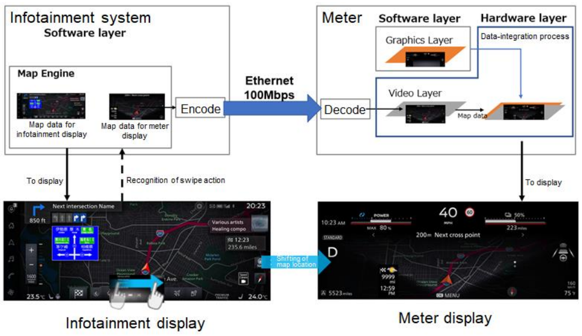

Fig. 4 Information integration of two displays using Ethernet

2.2 Simple and intuitive GUI

Because humans cannot process large volumes of information, the number and positions of the displayed menu items were carefully designed to help ensure ease of recognition. Furthermore, the recognizability and operability of each function were improved by displaying the corresponding widgets and tile menus in larger sizes and optimizing their numbers (Fig. 5).

As the ease of identification of interface users (defined as the rate of correct answers) differs depending on the number and arrangement of menu items, a four-column by two-row configuration was developed, resulting in a correct answer rate greater than 90% (Fig. 6).

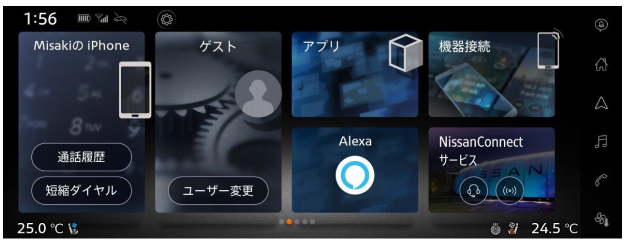

Fig. 5 Home widgets on infotainment display

Fig. 6 Four-by-two tile menu

3. Further evolution of UX

3.1 Display performance with emotional values

To provide emotional value to customers along with highly operable basic functions, Nissan developed approximately 50 interactive animations for ARIYA, including a full-screen opening animation when starting the system and a parallax effect animation when browsing widgets.

These emotional performances have further evolved to add comfort and fun to the new UX. For the GUI in the latest CONNECTED system, Nissan provided a sense of depth to the graphics on the display when browsing widgets on the home screen. Several techniques, including changing the widget size in conjunction with the current operation, adjusting the widget transparency, adding moving shadows on the background, and creating a background image that provides a sense of depth, were combined to make the widgets appear as if they are moving in the z-axis (depth) direction during browsing (Fig. 7).

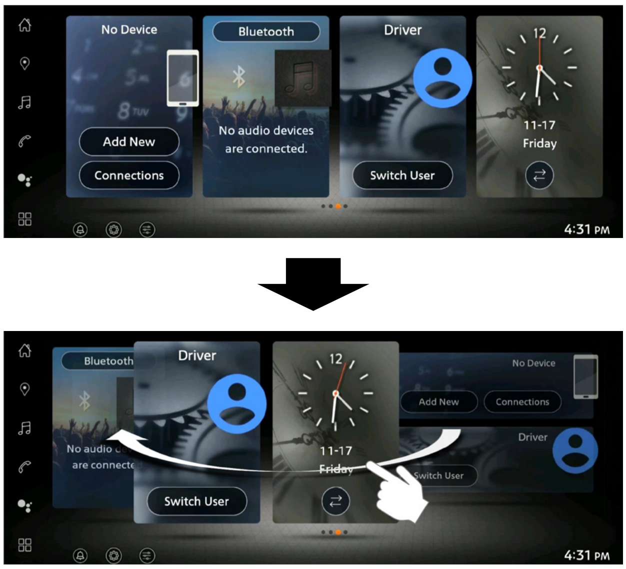

Fig. 7 Widget movement gives a sense of depth

3.2 Realistic camera display and its benefits

Many vehicles have adopted around view monitors that assist parking operations by providing images that appear to look down on the vehicle from directly above. In the latest camera systems, this conventional overhead image is augmented by 3D-view technologies developed to display real-time 3D 360° images.

As shown in Fig. 8, this technology creates a virtual 3D space by mapping the images captured by conventional cameras installed on the four sides of the vehicle onto a curved canvas wrapped around a representation of the vehicle.

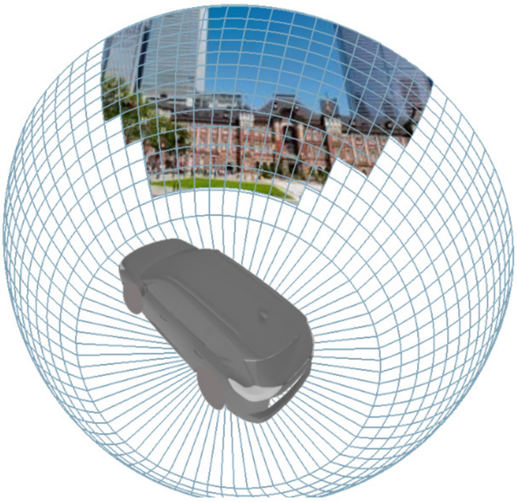

Fig. 8 3D image mapping

This virtual 3D space enables intuitive stereoscopic recognition of surrounding objects that are difficult to display using conventional around view monitors. In addition to these functional benefits, this technology provides a new, immersive experience by projecting panoramic images around a representation of the vehicle (Fig. 9).

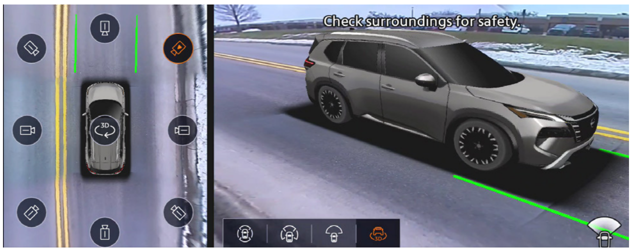

Fig. 9 3D view of vehicle surroundings

4. Evolution of voice recognition technologies by CONNECTED

Nissan has developed various voice recognition technologies to reduce the workload required to use infotainment functions while driving. Conventionally, a stand-alone system is used with a voice recognition engine and dictionary data installed in the vehicle. In contrast, ARIYA realizes voice command operations with ordinary and natural speech expressions (hereafter referred to as natural language) by adopting a server-based voice recognition method.

In this approach, natural-language speech is captured by a microphone and transferred to an off-vehicle server via an in-vehicle voice signal processing device. This signal is subsequently processed to first conduct word/sentence recognition followed by intention estimation (Fig. 10).

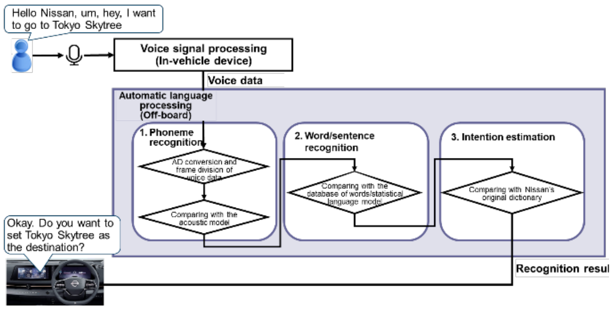

Fig. 10 Flow of natural-language speech recognition process

4.1 Word/sentence recognition

Word/sentence recognition utilizes the abundant computational resources available to the off-vehicle server as well as a statistical language model that learns the probability of transition from one word to another within a sentence (Fig. 11).

This system first selects a group of possible words by analyzing the chronological word arrangement in the collected speech, then identifies the most probable word from this group by finding a word pair that maximizes the sum of the probabilities of word-to-word transitions. For example, when the input "I want to go toukyou sukai turii" is provided, the system can recognize the accurate sentence "I want to go to the Tokyo Skytree," which has the highest probability of word-to-word transitions within.

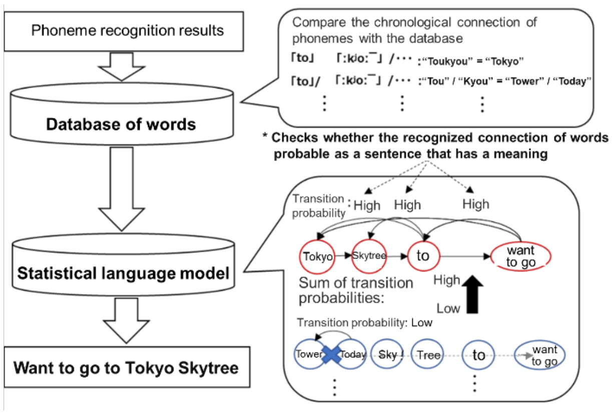

Fig. 11 Speech recognition using a statistical language model

4.2 Intention estimation

Because drivers must focus on driving tasks, their speech may include unnecessary words with no meaning, or they may express the same intention differently. Therefore, filtering is performed to remove unnecessary words (e.g., "um...," "hey"), selectively extract only the necessary words (e.g., "Tokyo Skytree," "want to go"), and correctly estimate the driver's intentions accordingly. In addition, Nissan's original dictionary database was developed to accommodate different expressions with the same intention, such as "I want to go to..." and "set the destination at...". This database contains learned data from approximately 3,000 speech patterns collected in actual driving environments. Together, these technologies enable ARIYA to achieve a voice recognition rate of approximately 85% (Fig. 12).

Fig. 12 Intention estimation

4.3 Vehicle linkage function

By improving voice recognition rates using the various technologies discussed in this section, the adoption of voice control can be expanded beyond infotainment functions such as navigation and audio to include vehicle command functions. As a result, the new SERENA now allows voice commands, including "close the windows" and "turn on the air conditioner."

5. Summary

Since the introduction of ARIYA, Nissan has facilitated easy access to information by improving the UX with HMI technologies, broadening the adoption of integrated display packaging to deliver both visibility and operability and refining the GUI to structure the increasing amount of available information in an easy-to-understand and easy-to-use manner.

In future development efforts, Nissan intends to further evolve the cockpit HMI into a driving concierge that closely supports every user by linking it with various peripheral technologies under development.

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3. Software update

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1. Introduction

The automobile industry is amid a major transformation defined by electrification, automation, and connectivity. The evolution of electronic components and software is at the heart of this transformation; today's vehicles are controlled not only by traditional mechanical components such as engines, transmissions, and brakes but also by sophisticated electronic devices and complex software.

1.1 Increasing number of electronic components and complexity of vehicle software

The world's first vehicle to incorporate microcomputer control utilized GM's engine control system (with a 10-bit custom microcomputer) in 1977; the first such vehicle in Japan was the Nissan CEDRIC (with an 8-bit Motorola 6802 microcomputer manufactured by Hitachi) in 1979. Since then, the number of electronic control components installed in automobiles has continuously increased. These components are essential for improving vehicle performance, energy efficiency, and driving experience. Multimedia infotainment systems, telematics units, and vehicle control systems for driving, turning, stopping, and, in recent years, driver assistance now operate at the core of a vehicle, providing many benefits to drivers and passengers.

Complex software programs manage electronic control unit (ECU) components and work together to maximize safety, performance, and efficiency. Critically, although software has provided major contributions to new features and performance improvements, its increasing scale and complexity make quality control more crucial than ever.

1.2 Advent of over-the-air updates

In 2012, Tesla used over-the-air (OTA) technology to update the software of the various ECUs installed in customer-owned Model S vehicles. Subsequently, OTA updates have rapidly spread to become a standard feature in the automobile industry. OTA updating allows vehicle software to be updated wirelessly, providing rapid benefits to customers without requiring them to take their vehicles to a dealership. Indeed, by streamlining the update and repair of vehicle software, OTA updates improve the quality of service and increase customer security.

Beginning with the implementation of OTA update functionality in the in-vehicle infotainment unit of the North American X-TRAIL (2018), Nissan Motors has expanded OTA updates to the telematics unit of LEAF (2019) and vehicle-control systems such as the driver assistance systems of ARIYA (2022) and SERENA (2022). This chapter introduces the technologies related to the OTA update functionality provided in ARIYA and SERENA (Fig. 1).

Fig. 1 OTA software updating

2. OTA Software update system for vehicle control systems

2.1 Goals and features

Three major goals for OTA vehicle control system software updates were defined as follows:

- Eliminate the hassle of requiring customers to visit the dealership to troubleshoot problems or add functionality.
- Avoid causing customers to feel anxious when updating software or requiring special knowledge or

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skills to do so.
- Help ensure that the OTA system can be operated stably under any circumstances.

Three basic features were required to achieve these goals:
A. Vehicle OTA software updates must be supported for infotainment systems as well as most ECUs related to vehicle control systems.
B. The vehicle immobility time during a software update must be extremely short.
C. Vehicle OTA updates must support accepted cybersecurity practices.
These three features are explained in detail below.

A. OTA software updates for control-related ECUs

In certain cases, it is desirable to update the ECU software for various vehicle systems to fix software issues and improve vehicle functionality and performance. There are 33 OTA-updatable ECUs in ARIYA and 22 in SERENA (C28). The ECUs of both models cover the in-vehicle infotainment, automated driving/advanced driver assistance, chassis, body electrical, and powertrain systems. Internal combustion engine (ICE), hybrid electric vehicle (HEV, e-POWER), and battery electric vehicle (BEV, Battery-EV) powertrains are all compatible with OTA updates.

B. Minimizing vehicle immobility during software updates

During updating of a smartphone's operating system, the device is non-operational for a period ranging from several minutes to over an hour. OTA systems also have non-operational periods ranging from several minutes to an hour. In contrast, Nissan’s OTA updating system requires only a short non-operational period, achieved by providing OTA-updatable ECUs with a dual-bank memory structure comprising a primary execution-memory area and a sub-memory OTA area. Thus, the software update downloaded from the server is stored in the sub-memory area instead of the primary execution-memory area employed while the vehicle runs. This structure allows software updates to be downloaded without affecting the various vehicle control systems that are active while driving. In other words, the system allows an update to be downloaded when the vehicle is in use and only requires the vehicle to be immobile when the software is switched from the execution memory to the OTA memory to install the update, as the vehicle-control functions become non-operational at this time. When tested on ARIYA (FE0), the immobility time was approximately 1 min.

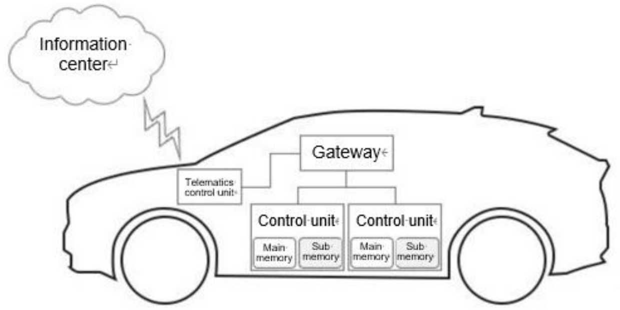

Fig. 2 Dual-bank memory configuration

C. Supporting accepted cybersecurity practices

Cybersecurity has become a critical issue in the automobile industry. Security measures must be included when providing OTA updates to prevent unauthorized software from being written to the vehicle. Therefore, the authenticity and completeness of the software update delivered by the server and the accompanying information must be verified. The following measures have been implemented accordingly:
- The updated software and accompanying information are packaged, and the entire package is protected with an electronic signature.
- Each package is layered and digitally signed with a different key.
- Multistage verification is provided such that signature verification for each package layer is carried out by different ECUs.

If a signature verification error is detected, it is sent to the information server, where it is stored along with a record of which vehicle and OTA update triggered it.

2.2 System configuration

The OTA updating system consists of an off-board side (information center in Fig. 2) outside the vehicle and an on-board side (information and communication, gateway, and control units in Fig. 2) inside the vehicle.

2.2.1 Off-board system

OTA- and dealer-applied software updates require an off-board system to manage software delivery to the appropriate vehicles. In addition, the same vehicle model can have different ECUs with different software versions according to the trim level, sales period, or individual circumstances, such as whether previous software updates have been implemented. This type of information must be managed individually for each vehicle.

The software update to be delivered is developed by each ECU supplier and is version-controlled off-board. When planning a software update, content such as objective, changes, etc. and its scope such as vehicle model, ECU and version of the software should be updated are defined. This information is registered in the off-board system.

The off-board system communicates with the on-board system (customer's vehicle); obtains information such as vehicle ID number (VIN), ECU, and software version; compares this information with the update scope to identify the vehicle for software distribution; and generates a delivery package accordingly. This delivery package includes information in addition to the update itself, such as the update content and electronic signatures.

After the update package is delivered to the target vehicle and the software update is completed, the history of software updates issued to the target vehicle, including update success/failure, is recorded by the off-board system. A summary of the off-board system functions is provided in Table 1.

Table 1 Off-board system functions

Function	Objective
Administration of vehicle information	Manages the VIN of the customer vehicle, installed ECUs, and software version of the ECUs in each vehicle history.
Administration of software version	Manages the software version for each ECU installed in the vehicle.
Administration of content and scope	Manages update scope information such as updated vehicles, delivered software, and links with recall notifications as necessary.
Creation of delivery packages	Creates a software update package appropriate for the target vehicle.
Generation of electronic signatures	Generates and attaches a signature to the delivery package.
Communicate with the on-board system	Exchanges a variety of information with the on-board system, including the version information of ECUs and software, update packages, and software update status.

2.2.2 On-board system

Regardless of the presence or absence of an OTA update, the vehicle information managed by the on-board system, including the VIN and each ECU, and its software version is sent to the off-board system. If a vehicle software is eligible for an update, the appropriate software package is received from the off-board system, and multi-step signature verification is performed. The timing of update activation (switching the software from the old version to the new version), which requires rebooting the ECU software, is determined by monitoring the vehicle speed and the status of each ECU; activation is only performed after the vehicle is confirmed to be in a safe state. At the time of activation, the updated content and operation restriction information are presented to the customer, and customer consent is sought. After activation is completed and the vehicle is switched to the new software version, a completion notification is sent to the off-board system. If the activation of a new software version fails owing to a signature verification error, the off-board system is notified of the error, and the old software version is retained. A summary of the on-board system functions is provided in Table 2.

Table 2 On-board system functions

Function	Objective
Communication with off-board system	Exchanges a variety of information with the off-board system, including the version information of ECUs and software, update packages, and software update status.
Human–machine interface (HMI) status reporting	Displays the status and contents of software updates, update acceptance, update success/failure, etc.
Package signature verification	Verifies the signature attached to the package delivered by the off-board system.
Writing to the ECU	Writes the software update to the target ECU.
Activation and rollback	Switch the executed software to the new version or revert to the old version if an error occurs.
Administration of vehicle condition	Monitors the vehicle status to determine whether an update process can be performed and manages the progress of the update process from downloading to activation.

2.3 OTA updating system flow

The full OTA updating process flow is summarized in Table 3. An OTA software update generally proceeds from preparation to inventory, downloading packages to the vehicle, transferring the updated software to sub-memory areas of the target ECUs (installation), and activating new software versions (activation). Note that the original equipment manufacturer performs update preparation in collaboration with the supplier, and inventory is conducted regularly regardless of the existence of an OTA update.

All steps in this process except activation can be conducted while maintaining the normal use of vehicle control functions, and customer consent is obtained immediately before activation when vehicle-control functions must be disabled.

Table 3 Full OTA updating system flow

Step	Action type	Objective
Preparation	Posting of software	Posts the software update to the delivery server that will deliver it to the target vehicle.
Preparation	Creation of the OTA update	The off-board system determines whether software delivery is necessary and creates an update according to the targeted models, updates contents, etc.
S1	Inventory	Shares vehicle information between the on-board and off-board systems and updates individual vehicle information in the off-board system.
S1-1	Inventory	Collects the software versions of installed ECUs and periodically sends the collected version information from the on-board to the off-board system.
S2	Updating	Updates the software of the target ECUs.
S2-1	Downloading	The off-board system sends the package to the vehicle, and the vehicle verifies the received package.
S2-2	Installation	The on-board system writes the updated software to the target ECUs.
S2-3	Obtaining customer consent	The HMI presents the updated contents and operation restriction information to the driver and obtains their consent.
S2-4	Activation	The on-board system activates the new software version
S2-5	Notification of software update completion	The HMI displays the results of the OTA update to the customer, the on-board system notifies the off-board system of the results, and the off-board system updates the vehicle history.

2.4 Package parameters tailored to vehicles and ECUs

Several parameters are defined during the creation of software updates and included in the delivery package to apply the OTA system to different vehicle powertrains and use cases.

One such parameter is the condition of data transfer when the power switch is turned off (Table 4). When transferring (installing) a new software version from the off-board server to the sub-memory area of each target ECU, stable power must be supplied to the ECU. For a BEV with a large battery capacity, sufficient power can be supplied to ECUs even when the power switch is turned off; thus, the data transfer can continue regardless of the state of the power switch. However, in an ICE vehicle with a small battery capacity, data transfer can only be conducted when the power switch is turned on; thus, data transfer and processing are paused when the power switch is turned off. Such cases must be considered at the time of update creation, and the corresponding parameters must be defined as part of the package according to the individual vehicle information managed by the off-board system and the contents of the delivered update.

Table 4 Example of installation conditions

Installation parameter	Customer use case
Only when power is on	When ICE vehicles are running
When power is on or the BEV battery charge level is above a certain level	When BEVs are running or parked

2.5 Safety measures

As described previously, OTA-updatable ECUs use dual-bank memory such that the updated software can be written to an unused sub-memory area separate from the executed software, allowing the software in the primary memory of the target ECU to be executed normally. This prevents vehicle from being affected by update package downloading and installation while driving. However, activation requires the swapping and rebooting of the target ECU software, which causes the functions associated with that ECU to become temporarily unavailable, albeit for an extremely short time. Therefore, the following safety measures are implemented during the activation process.

2.5.1 Customer notification of activation

An activation notification is provided on the in-vehicle display when the software update can be activated, the signature verification and installation have been completed, and the vehicle is safe. The information provided in this notification comprises

- a summary of the updated contents,
- a statement that some functions may not be available during activation,
- a statement that the vehicle cannot be driven during activation,
- appropriate safety warnings
- the time required for activation.
- appropriate safety warnings

As shown in Fig. 3, the customer's consent is sought at the bottom of this notification, allowing the customer to select from three options: “Activate now,” “Set timer within 24 hours,” and “Postpone until next time.”

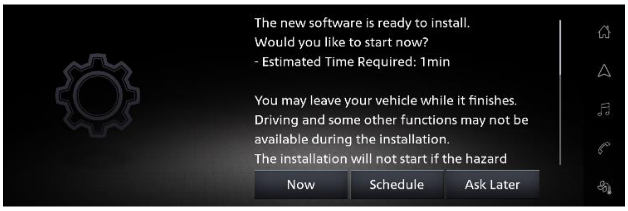

Fig. 3 Notification of software update activation (in-vehicle display)

2.5.2 Prohibition of engine start

To avoid potential destabilization of the power supplied to the target ECU owing to the operation of equipment that consumes a large quantity of power, such as the cranking motor of an ICE vehicle, and because update-targeted ECUs cannot be used during activation, engine-start prohibition control is applied to prevent the vehicle from being driven (Fig. 4). To inform drivers of this status, a message is provided on the meter display stating that the power cannot be turned on when they press the power switch during the activation process. Once activation is complete, the engine-start prohibition control is canceled, and the vehicle becomes operational with the new software version.

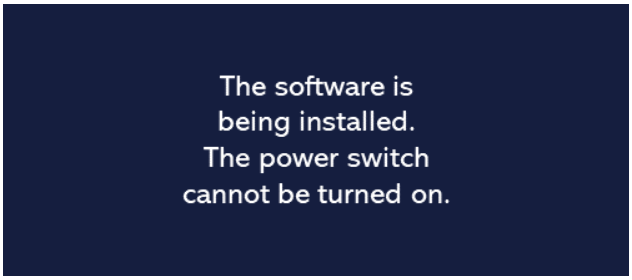

Fig. 4 Engine-start prohibition message on the meter display

2.5.3 Confirmation of vehicle stoppage using multiple ECUs

One of the prerequisite conditions for beginning update activation is that the vehicle must be in the stopped state. Multiple ECUs are used with multiple criteria to judge the vehicle-stop status. Specifically, the gateway ECU and target ECU have the different conditions to determine the vehicle-stop status. The determination process is made redundant by considering the input values for both the gateway and target ECU. Activation is prevented if either the gateway or target ECU determines that the vehicle is not stopped.

2.5.4 Rollback

After signature verification, if problems such as memory failure or data-bit corruption occur during data transmission through the on-board system, unintended data could be written to the target ECU’s sub-memory. Therefore, when first booting a new software version after activation, the gateway and target ECUs confirm whether the intended version of the software is present. If data corruption or memory failure occurs, this version verification will fail, and the on-board system reactivates the previous software version retained in the primary memory. This process, called rollback, restores the vehicle to its state before the OTA software update is performed, keeping the vehicle operational for the customer. The customer is notified "successful" or "failed to update, run previous version software.

3. Postscript

Under Nissan Ambition 2030 long-term vision, Nissan strives to provide driving experiences that are defined by confidence and excitement, which can strengthen connections between people and society and expand mobility possibilities. Under this vision, Nissan intends to continue improving the customer experience by developing personalized services and innovative vehicle technologies, such as electric vehicles and advanced driver assistance. As software-defined vehicles can deliver these technologies and services, software is no longer simply a developmental means for improving vehicle functionality and performance but rather an elemental technology that continually excites customers. The development of software-defined vehicles typically requires first defining the services that can be continuously provided, then identifying the infrastructure required for such services, deciding on the ECU and electrical/electronic architecture, including connected services for their provision, and finally developing the software specifications.

Instead of following this procedure for each service and software function, OTA software updates can be applied to continuously update the vehicle software after it has been delivered to the customer. As an infrastructure function, OTA updating can aid the development of strategies for the future deployment of services and software, fully realizing the advantages of the software-defined vehicle; this dynamic moment in the history of its development is quite exciting.

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Special Feature 3:Connected service

4. The Present and Future of IoT Collaboration Services Provided by Connected Cars.

Naoya Oka* Toshimitsu Ishii*

1. Introduction

In recent years, the CASE (Connected, Autonomous, Shared, and Electric) concept has attracted increasing attention in the automobile industry. In particular, the “connected” attribute is the driving force behind the technological development and adoption of the Internet of Things (IoT) in automobiles. As connected vehicles are equipped with many communication devices and sensors, they can be considered mobile IoT devices. Connected vehicles can also provide services linked to external devices through on-board navigation systems and off-board smartphones. This chapter discusses examples of services offered through IoT linkages with external devices and explores the future prospects of this technology.

2. Amazon Alexa linkage services

Amazon Alexa (hereafter referred to as Alexa) *1 is a voice recognition service that allows control of a target device through voice commands. Owing to strong customer demand in the vehicle market for compatibility with Alexa, the Nissan business team requested the development of this feature using a different approach than conventional vehicle body development. This approach allowed the development, testing, and release of the service without depending on the vehicle release schedule and facilitated completely separate development from that of the vehicle itself.

Table 1 List of Alexa linkage functions

Function	Explanation
Account link	Links NC account with Amazon (Alexa) account
Conformation of battery status	Monitors the remaining battery level
Remote charging	Starts/stops remote charging
Remote air-con	Starts/stops remote air-conditioning, sets/cancels the air-conditioning timer
Route transmission	Transmits route search results to the vehicle

The Connected Car Off-board Development and Operations Department developed and released a function allowing voice control of vehicles from Alexa by linking the Amazon Alexa and NissanConnect (NC) services. Table 1 presents a list of NC services that can be operated via Alexa and have been released to the market. Alexa compatibility was developed using the agile development method to quickly release the product by first determining the minimum necessary function or minimum viable product. According to user feedback, this initial development stage was followed by lifecycle updates to improve functionality. Thus, the Alexa linkage service can be constantly improved to incorporate market requirements in a timely manner through lifecycle updates, which allow for the development of services in an agile manner and represent a critical ability for digital services essential to increasing customer satisfaction and preventing disinterest.

*1 [AMAZON BRAND], [AMAZON BRAND], and all related marks are trademarks of Amazon.com, Inc. or its affiliates.

3. Garage door opener linkage service

Conventional garage door opener linkage services use physical buttons located in the vehicle, as shown in Fig. 1. Although this technology makes it possible to open the garage door from inside the vehicle, the constraint on the physical distance between the garage door unit and buttons requires the vehicle to be near the garage door. In other words, the driver must first arrive at home, then press a button and wait for the garage door to open before finally entering the garage, representing a usability issue in that the driver cannot enter the garage smoothly.

*Connected Car Off-board Development and Operation Department

Fig. 1 Map lamp linkage

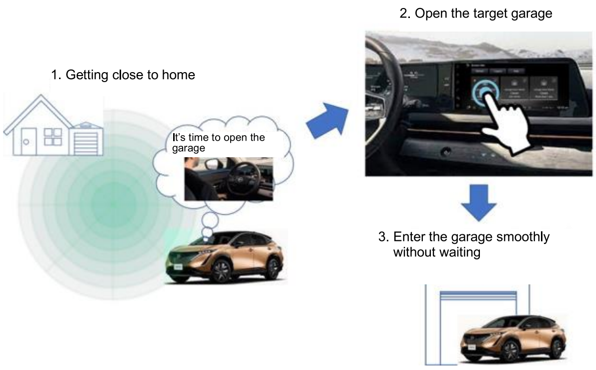

Fig. 2 Use case with IVI linkage

To address this issue, a new garage door opener service will be introduced in the North American market that uses telematics services in connected vehicles equipped with the CCS2 platform and works with the in-vehicle infotainment (IVI) system. Fig. 2 shows the use case of a garage door opener service using an IVI linkage. When the driver approaches the target garage, they can change the garage door status from closed to open by pressing a button on the IVI screen, as shown in Fig. 3. By relying upon telematics, this feature allows drivers to control the target garage door from anywhere within wireless data service coverage. In addition, because multiple garage doors can be registered in the system, this feature can be made available at home and work, assuming the systems are compatible. Thus, the IoT linkage services included in connected vehicles can provide new value to customers from a usability perspective.

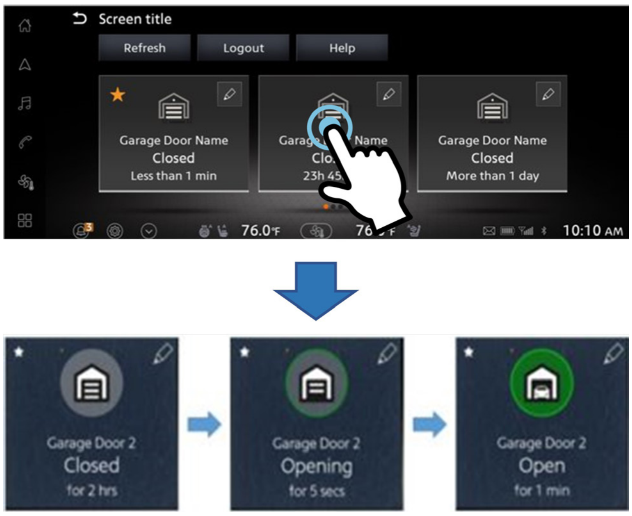

Fig. 3 Image of IVI display

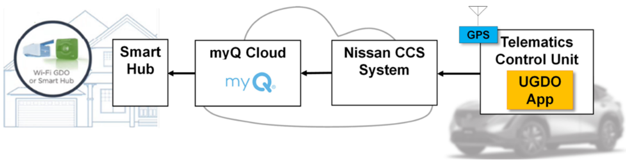

Fig. 4 System configuration

Fig. 4 shows the system configuration diagram for connected vehicles' garage door opener linkage service. As the Chamberlain Group has gained a significant market share in the sale of garage door opener units and solutions, Nissan will launch its connected service using a linkage with the myQ Cloud provided by this manufacturer. The content of communications with the myQ Cloud using this IoT connection service comprises:

2-1) Registering the target garage door
2-2) Obtaining the status of the garage door
2-3) Opening and closing the garage door.

The target garage door can be operated on the IVI screen while driving through communication between the in-house cloud (Nissan CCS System) and external cloud (myQ) using publicly available APIs to perform the control actions described above. By linking the Nissan CCS System and myQ Cloud using IoT technology, the connected vehicle can communicate with devices and solutions widely used in the market, making it possible for customers to operate their devices and services which they normally use in different and more convenient ways. Since customers often resist using completely new products and are more likely to accept improved versions of products they are familiar with, this IoT linkage capability can improve the convenience and recognition of Nissan's connected vehicles and create new business opportunities for collaboration with other companies.

4. IoT home appliance linkage service

The application of IoT technology to home appliances has been advancing since before vehicles were connected to network environments. Today, the control of appliances from outside the home has become commonplace. Nissan is actively creating services to improve convenience by connecting IoT home appliances to vehicles.

Fig. 5 depicts a use case for several of the functions of the NC service that Nissan has implemented to connect vehicles to a smartphone app of the same name (the NC app). This app provides new value to users by linking them to various IoT-based home appliances. In a practical application, the user connects their NC account identification (NCID) to the home appliance manufacturer's account identification (appliance ID). The user can subsequently select which actions to send to their IoT devices out of the various notification functions offered by the NC service, listed in Table 2. For example, the car alarm function in the crime prevention category envisages a user experience in which a “Car alarm” notification is sent to a home device (TV, etc.) when the user is at home away from their vehicle, creating new value by linking vehicles to devices other than smartphones.

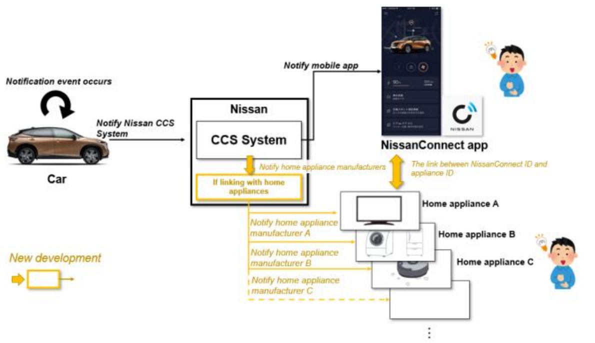

Fig. 5 IoT home appliance linkage use case

Table 2 List of notification functions

Category	Notification
Charging	Charging timer started
	Charging stopped
	Stop error
Navigation	Pre-departure reminder
Air conditioner	Recommendation of air conditioner use before boarding
Crime prevention	Power switch on
	Car alarm
Zone alert	Return home notification

When translating business requirements into system design, the user experience, or how users will use the system, must be emphasized. The following aspects were considered in the system design and function delivery accordingly.

4.1 Improvement of user experience

The IoT linkage service is intended to improve user convenience and value by connecting IoT-based home appliances with the notification functions of NC services delivered by connecting the NC app and Nissan vehicles. The system running this service was designed to provide intuitive and stress-free functions to customers. To achieve this goal, highly experienced and knowledgeable professionals in web/information technology fields, including user interface and user experience designers, backend engineers, mobile application engineers, product owners, and project managers, worked together as a team to create customer journey design, system, and operation designs by streamlining the development from the NC app to the backend. As a result, Nissan has achieved service development using a method centered on user experience, which would be difficult to achieve through the traditional vertical division of labor by function.

4.2 NCID linkage with external IoT-based home appliances

To connect to IoT-based home appliances, users must link their NCID with the appliance ID managed by each manufacturer. This linkage allows Nissan's system to recognize which users are linked to which home appliances using authentication and authorization protocols, such as OpenID Connect*, ensuring the security of system connections between companies. (*Other authentication/approval technologies may also be introduced depending on the linked home appliance manufacturer.)

4.3 Close-yet-sparse linkage with external IoT-based home appliances

Though technologies such as OpenID Connect can be used to closely link NCIDs with appliance IDs, situations in which NC services become unavailable to the connected vehicle system because of linkages with external IoT-based home appliance systems must be avoided. Therefore, Nissan adopted the system architecture shown in Fig. 6 to separate the notification function for home appliance IoT linkages from the existing connected vehicle system. This keeps the existing NC service protected, as it will be unaffected even if a problem occurs with Nissan's linkage system (IoT adapter) or an external home appliance system.

4.4 Scalability and versatility considering business development

When designing the system architecture, the aforementioned close-yet-sparse linkage with home appliance IoT systems was not the only critical consideration; the system's scalability and versatility were also considered in the context of business development. In the digital world, a common software development approach is to quickly release services in small batches and then grow and expand these services based on user feedback. Nissan introduced a versatile system architecture that was not limited to a single company, and it accommodated the possibility of business partnerships with various home appliance manufacturers. The tactics used to realize this architecture included the introduction of commonly used authentication and authorization technologies, such as OpenID Connect, and modularizing functions that link with external home appliances by creating new microservices in the existing connected vehicle system. This has resulted in a versatile system that can scale to future business development.

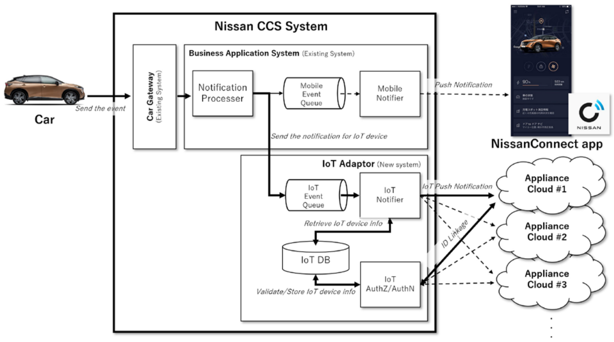

Fig. 6 System configuration

4.5 Introduction of development and operations program

As the IoT linkage system is intended to be constantly improved based on user feedback, system development does not end with a single release. This necessitates introducing a development and operations (DevOps) program that considers the potential for post-release issues from the development stage onward. To implement this program, quality improvement was automated to the extent possible using continuous integration/continuous delivery, creating an environment in which ongoing software releases can be quickly issued. In particular, system monitoring and log collection were strengthened to enable early detection and troubleshooting of problems, leading to further improvements and better user experience.

In this manner, Nissan has created a home appliance IoT linkage system that emphasizes user experience while providing versatility and scalability, anticipates future business development, and minimizes any impact on existing connected vehicle systems.

5. Conclusion: The future of IoT linkage services

New products and services are created daily in the web/information technology and consumer product industries. The ability to perform IoT linkages in a network environment that connects vehicles with widespread devices and services represents a major point of evolution and can only be realized by the connected vehicle system. This ability can also significantly expand the possibilities of automobiles. While the conventional vehicle manufacturing business generates profits by selling vehicles and providing maintenance, connected vehicles can deliver new conveniences to customers after the vehicle sale, thereby providing new value and additional profits to the business. Under this model, customers are charged for the necessary services when they want them through a corresponding subscription. This mode of operation represents a new revenue source for Nissan and changes how customers relate to their vehicles. The case studies discussed in this chapter are part of the IoT linkage system that connects Nissan vehicles with other companies' services, and Nissan plans to continue introducing similar services to the market. These efforts to expand the capabilities of connected vehicles will create a new circular business model that encourages customers to buy another Nissan by offering them a more enjoyable and engaging everyday life with their vehicle.

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Special Feature 3:Connected service

5. Mobility service

Susumu Fujita* Takeshi Kimura* Naoki Miyashita**

1. Introduction

The history of mobility services research and development at Nissan Motor Co., Ltd. dates back to September 1999, when joint experiments on electric vehicles were first conducted. In response to potential future social issues such as population decline, aging, and rural depopulation, Nissan quickly recognized the promise of the sharing economy concept, not just from the perspective of improving usability for individuals but also as a means of solving regional issues. Therefore, Nissan has developed carsharing as one of mobility services. Furthermore, Nissan is investigating the multi-purpose use of electric vehicles, including carsharing and power interchange between vehicles and buildings. Nissan has also worked to develop ridesharing in recent years, exemplified by an on-demand vehicle dispatch service presently operated in the Coastal region of Fukushima Prefecture. This chapter describes the ongoing development of these mobility services at Nissan.

2. History of mobility services

Mobility services began with carsharing, in which multiple individuals jointly own a vehicle. This section first explains the differences between carsharing and ridesharing, then describes the mobility as a service (MaaS) concept that seamlessly connects all means of mobility except privately owned vehicles, including public transport.

2.1 Carsharing

The carsharing concept began in the 1970s in Zurich, Switzerland, when the government implemented large-scale vehicle influx restrictions and provided high-frequency, high-quality public transportation services through trams, buses, and trains. Residents who could no longer own cars in the city center began to own cars in the suburbs jointly, and carsharing began. In Japan, Seeds Co., Ltd. introduced carsharing services specializing in foreign cars in 1988. However, carsharing was not widespread until recently, when it was commercialized in earnest. Today, the mobility and transportation industries are rapidly changing, and MaaS businesses are diversifying and expanding to include bicycles, motorcycles, and electric scooters.

2.2 Ridesharing

In the United States, carpooling in private vehicles has become a common means of transportation for people commuting to a workplace from the same origin. With the continued progress of motorization and changes in the flow of people, carpooling has expanded into ridesharing. There are two types of rideshare: conventional, in which people share a ride to travel to the same destination, and transportation network company (TNC) services that match people to rides using a mobile app (1)(2).

Traditional ridesharing includes carpooling, vanpooling, and casual carpooling but excludes taxis that collect fares. In San Francisco, carpooling has become a primary mode of transportation. Today, people can search for carpooling opportunities at any time using smartphones, and drivers are generally allowed to collect fees to cover their actual expenses, such as fuel costs. Similarly, vanpooling uses a larger shared vehicle to transport many people, and the costs are borne by the passengers or subsidized by companies and governments. Finally, casual carpooling is a form of ridesharing in which the driver of a private vehicle picks up a commuter from a queue at a roadside stop; it is characterized by the fact that the driver and the passenger do not know each other.

The TNC is a new type of transportation service that began in San Francisco in 2012 and has developed rapidly since. In this type of rideshare, the TNC service does not operate as a means of transportation but mediates between passengers and drivers of private vehicles through a digital platform to provide paid transportation. The reservation, evaluation, and payment processes are performed using a mobile app , and fares, often quoted before the ride is initiated, are determined by region and vehicle type according to travel distance and time. Typical examples of TNCs include Uber and Lyft in the United States and DiDi in China.

The Road Transportation Act in Japan states that common taxicab operators must obtain a license to operate paid transportation businesses that use

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passenger vehicles. Private paid passenger transport, in which ordinary drivers transport passengers for a fee, is given special permission limited to sparsely populated areas where transportation services are

otherwise poor. Currently, the government is evaluating options for expanding the applicable areas for private paid passenger transport or allowing such transport when taxis are in short supply. Considering the progress of such legal reforms, various companies are conducting field tests of ridesharing services under names such as "mobi," "KnowRoute," and " AI Unkou Bus®."

2.3 MaaS

The MaaS concept seamlessly connects all forms of transportation except private vehicles, including public transportation and ridesharing, to integrate the services of multiple transportation operators and handle everything from route search to reservation and payment in a single application. For example, MaaS Global Ltd began operating the MaaS app named as "Whim" in Finland in 2016.

In Japan, the Toyota Motor Corporation released the MaaS app named as "my route" in Fukuoka City and Kitakyushu City in 2019. This app integrates various transportation-related functions, including searching for transportation, booking reservations, and making payments, to provide multimodal mobility services that support smooth movement around the city. It also describes nearby stores and event spots that contribute to the vibrant urban atmosphere.

3. Nissan Motors initiatives

This section describes several examples of Nissan's efforts to develop carsharing, including a park-and-ride trial of a vehicle-sharing system using HYPERMINI, Choi-Mobi, and e-Share m

obi, and discusses the Namie Smart Mobility and Easy Ride® ridesharing services.

3.1 Carsharing initiatives

3.1.1 Shared usage systems using HYPERMINI

Since September 1999, Nissan has participated in two joint field test projects related to carsharing using HYPERMINI, a two-seater ultra-compact electric vehicle with a special body developed to serve the urban commuter (Fig. 1, Table 1).

Fig. 1 HYPERMINI

Table 1 Specifications

Dimension	Length x width x height (mm)	2665 × 1475 × 1550
	Wheelbase (mm)	1890
	Tread (mm)	1290 / 1270
Weight	Gross vehicle weight (kg)	840
Capacity	Passenger capacity (persons)	2
Performance	Minimum turning radius (m)	3.9
	Driving distance per charge (km)	115
Motor	Types	AC synchronous motor
	Maximum output (kW)	24
	Maximum torque (Nm)	130
Main battery	Type	Lithium-ion battery
	Capacity (Ah/3hr)	90
	Cell quantity (pcs)	4
Other	Drive system	Rear wheel drive
	Tire size	Front: 145/65R14
		Rear: 165/60R14
	Suspension	Front: Strut type
		Rear: Strut type
	Brakes	Front: Ventilated disc type
		Rear: Disk type
	Steering	Rack and Pinion type

The Downtown Rental Car System was a field test comprising 20 HYPERMINIs implemented in the Yokohama Minato Mirai 21 district and run by the Association of Electronic Technology for Automotive Traffic and Driving (now the Japan Automobile Research Institute). It attempted to promote the widespread use of electric vehicles to realize a new environmentally friendly intelligent transportation system emphasizing user convenience. Vehicles were rented and returned to an uncrewed vehicle station (Fig. 2). A control center accepted reservations, detected each vehicle's location and monitored its condition using intelligent transportation system functions, authenticated users, and communicated with the vehicle driver to send appropriate information to the vehicle. The vehicles were equipped with a navigation system that included functions to enable efficient and convenient communication between the vehicle, control center, and user.

Fig. 2 The Downtown Rental Car System station

In terms of usability, the vehicles were equipped with a "one-shot" button that allowed the driver to easily search for a route from their current location to the vehicle station by pressing a single button, a call button that contacted the control center in case of trouble, an environmental contribution display that displayed the CO_2 emissions prevented each time the vehicle was used, a battery level warning function that issued a warning before the vehicle was unable to return to the station on its remaining charge, and a customer service button that monitored user dissatisfaction, all of which helped improve usability during the test. In addition, after starting the field test, the service was adapted to provide sightseeing along the route between accommodation facilities and tourist attractions in the Yokohama Minato Mirai 21 district to improve the occupancy rate and environmental image of the district.

Similarly, the Ebina Project, conducted in Ebina City over the same period, was a park-and-ride experiment comprising 15 HYPERMINIs run by the Ministry of Construction, Kanagawa Prefecture, and Ebina City. This experiment elucidated the effects and problems arising from ridesharing by recruiting citizen volunteers to use the HYPERMINI for commuting in the morning and evening and as an official vehicle for city hall workers during working hours. Through actual field operation, including the use of an IC card-based system for vehicle management, an effort will be made to identify and resolve issues with an eye toward practical implementation of vehicle-sharing in the future. At the same time, the associated challenges were analyzed to expand the implementation area and extend ridesharing applications to the private sector.

3.1.2 Choi-Mobi

With support from the Promoting the Introduction of Ultra-Small Mobility project led by the Ministry of Land, Infrastructure, Transport and Tourism, Nissan and Yokohama City conducted a field experiment running Japan's first one-way carsharing service, Choi-Mobi Yokohama, for two years from October 2013 to September 2015. This service comprises 25 ultra-compact "Nissan New Mobility" concept electric vehicles (Fig. 3, Table 2). Its purpose was to promote low-carbon transportation, improve the quality of urban life and transportation, and develop tourism. The business entities involved were Nissan Motor Co., Ltd. and the City of Yokohama. The operating entity was Nissan Car Rental Solutions Co., Ltd., and Surge Co., Ltd. handled the carsharing system's development. Since the experiment, the service has been used as a rent-a-car operation for tourists and local businesses.

For approximately two years, from March 2017 to 2019, a new Choi-Mobi Yokohama round-trip carsharing service was tested in the vehicles and returned to the dispatch stations after use. Based on the knowledge accumulated in previous experiments, it promoted the concept of ultra-compact mobility closely connected to the local community and attempted to create a sustainable public–private partnership and business model. This service provided guided tours specializing in the central area of Yokohama and long-term rentals to local companies.

Renting and returning of vehicles were conducted at 14 stations in the central Yokohama area. Once a user registered as a service member through a dedicated website, the service was managed using a registered authentication card (driver's license, FeliCa-compatible transportation integrated circuit cards, or mobile terminals). Reservation was possible up to 30 min before the scheduled start time. In addition, 2 dedicated free parking spaces (23 spaces) were offered. A driver's license, smartphone, and credit card issued in Japan were required to use the service, and a user fee of 250 yen was charged every 15 min in addition to a basic fee of 200 yen; the maximum fee for a full day's use was 3,000 yen.

Fig. 3 Nissan New Mobility concept

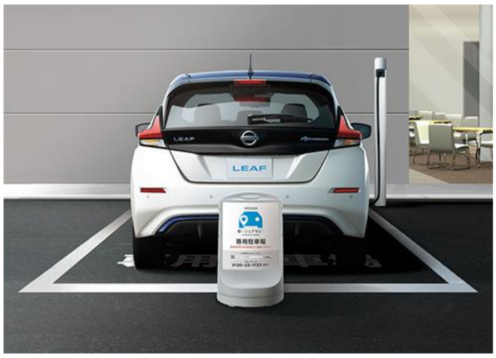


Fig. 4 Example of an e-share mobi station

Table 2 Specifications

Dimension	Length x width x height (mm)	2340 × 1230 × 1450
	Wheelbase (mm)	1685
	Tread (mm)	1095 / 1080
Weight	Vehicle weight (kg)	500 (with doors)
Capacity	Passenger capacity (persons)	2
Performance	Minimum turning radius (m)	3.4
	Driving distance per charge (km)	100
	Maximum output (kW)	Standard: 8
		Maximum: 15
Other	Tire size	Front: 125/80R13
		Rear: 145/80R13

3.1.3 e-share mobi

"e-share mobi" is Nissan's carsharing service that does not require membership fees or distance charges, providing a vehicle for 200 yen per 15 min of use. Because a rental license is required to operate this business, the service is provided jointly with Nissan Car Rental Solution Co., Ltd., which operates a rent-a-car business within the Nissan Group. The service began in January 2018 and was expanded to include 514 stations nationwide by the end of March 2019. As shown in Fig. 4, a station comprises a delineated parking space, a vehicle, and a sign cube. Nissan Group dealerships and Nissan Rent-A-Car stores are typically utilized to provide parking spaces, but securing spaces at suitable locations remains a critical issue as few such businesses near train stations. Currently, the SAKURA and LEAF electric vehicles and NOTE, AURA, KICKS, and SERENA e-POWER vehicles are available for rental; they all offer a fun and comfortable driving experience that is unique to electric vehicles as well as intelligent technologies such as autonomous drive assistance technology and automated parking functions.

As "Smart Oasis®," a registered trademark of Nippon Unisys Co., Ltd. (currently BIPROGY Co., Ltd.). has a proven track record as a carsharing service platform, it was customized and integrated into ".e-share mobi" The resulting system provides cloud-based functions to facilitate member management, operations management, and billing settlement, all of which are necessary for the business operations of mobility services. Customers who register online and reserve a vehicle can unlock the door by holding their driver's license over the card reader installed in the rear window of the vehicle parked at the station at the reservation date and time. Once in the vehicle, the customer can retrieve the smart key stored in the dashboard to use the vehicle, eliminating the need for formalities at a physical store.

3.2 Ridesharing

3.2.1 Field test in the Coastal region of Fukushima Prefecture

In February 2021, three local governments in Fukushima Prefecture (Namie Town, Futaba Town, and Minamisoma City) and eight companies, including Nissan Motor Co., signed the Collaboration Agreement for Community Development Utilizing New Mobility in the Coastal region of Fukushima Prefecture. Since February 2021, Nissan Motors has intermittently provided on-demand vehicle dispatch services as part of its efforts to provide mobility services as a new means of transportation. This service picks customers up at the appropriate time and transfers them to their destination when they indicate their need for immediate travel.

3.2.1.1. History of service

1) Approximately two weeks from February 2021

The acceptability of the service among residents and visitors was first evaluated as part of the Namie Smart Mobility Challenge. This field test comprised a hub-and-spoke type in-town public transportation service using Michi-no-Eki Namie as a mobility hub (connection base), town-circle shuttles to connect major locations within the town center, and spoke vehicles to connect Michi-no-Eki Namie with homes in the suburbs and other destinations (Fig. 5, top row). This service used two eNV200 vehicles as town-circle shuttles within the town center and three LEAFs as spoke vehicles for transportation to the surrounding regions. In addition, a shopping delivery service was offered in which products purchased in-store or ordered online were delivered using mixed passenger and freight transportation (Fig. 5, bottom row).

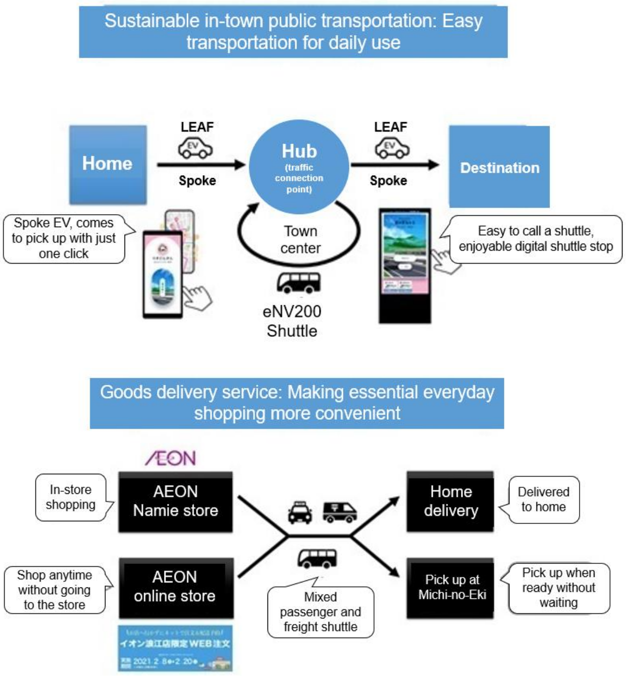


Fig. 5 Implemented mobility service (top: in-town public transport, bottom: delivery service for purchased goods)

Using the town-circle shuttle, customers could move within the town center by first verifying their identity at the digital shuttle stops at eight pick-up and drop-off points (Fig. 6) using facial recognition, then setting their destination. Each digital shuttle stop used a 43-inch digital signage board operating Android OS and running a vehicle dispatch app. Amazon Rekognition, provided by Amazon Web Services, was used for facial recognition.

Fig. 6 Digital shuttle stop

The spoke vehicles allowed customers to travel between the Michi-no-Eki Namie, their homes in the suburbs, and other destinations by specifying their boarding locations and destinations using the smartphone app. Without passengers, the town-circle shuttles and spoke vehicles remained parked at a predetermined waiting location.

2) Approximately two months from November 2021

The results of the two-week field test suggested that meeting the transportation needs of all customers in the service area was impossible with the limited number of boarding locations in the city center and that the waiting time for boarding was too long. Consequently, a two-month field test of the Namie Smart Mobility on-demand vehicle dispatch service was conducted with more advanced functionality. The waiting time for boarding was reduced by increasing the number of pick-up and drop-off points in the city center from 8 to 120 locations to allow travel to destinations within a one-minute walk. In addition, the service hours were extended on Thursdays and Fridays [to 9 pm, supporting a wider range of user needs, such as visiting restaurants in Namie Town. Again, one eNV200 and two NV350 vehicles were used. Starting in January 2022, to support the local economy, the Namie Virtual Shopping Street service began to offer delivery of goods by combining the virtual reality shopping support service provided by Toppan Printing Co., Ltd. (currently Toppan Holdings Co., Ltd.) with the Namie Smart Mobility service provided by Nissan Motors. This service allowed customers to view the sales floors of three companies in Namie Town (Shibaei Suisan, Michi-no-Eki Namie, and AEON Namie Store) online in real-time, check products, and place orders from the comfort of their homes (Fig. 7). The purchased products were delivered to the user's address by mixed passenger and freight shuttles. The field test validated the utility of remote purchasing to the home delivery service chain, improved the area's livability, and revitalized local businesses.

Residents were repeatedly interviewed to inform the

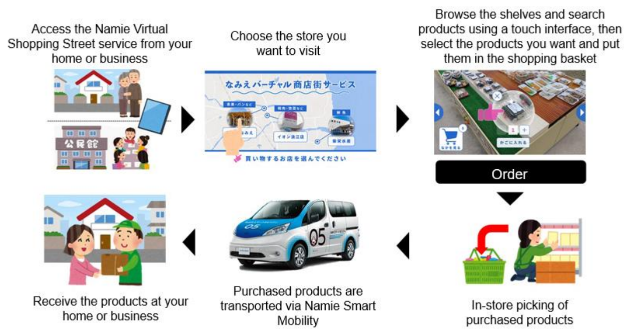


Fig. 7 Namie Virtual Shopping Street service

development of a smartphone app that allowed anyone, especially the aging population in Namie Town, to quickly request a ride and select their destination, even within the city center (Fig. 8).

Fig. 8 Mobile app for vehicle delivery

3) From June 2022 to end of 2023

Based on feedback from residents, the next field test was conducted for one year using two NV350s. Starting in October 2022, mini digital shuttle stops (Fig. 9) with user interfaces similar to those at the existing digital shuttle stops were installed at 14 locations, including major restaurants, landmarks, and hotels, to promote local residents' use of the service. These stops were specifically chosen to improve and expand user convenience while supporting customers' transportation to and from commercial areas. Critically, this service was offered to unregistered users.

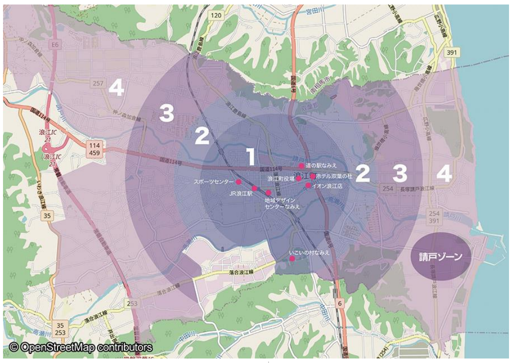
Fig. 9 Mini digital shuttle stop

Furthermore, the Suma-mobi Kids transportation service for children (Fig. 10) was launched in December 2022. In Namie Town, children generally travel between home and school on school buses, but if they want to visit children's facilities, they must be transported by their parents. Suma-mobi Kids attempted to reduce this burden on parents and encourage independent and active out-of-school activities to support the changing lifestyles of children. The service was made available for children without smartphones by providing them with keychains containing 2D codes read at special "kids shuttle stops." The information taken at the terminal device was linked to a control center, and parents were notified when their child entered or exited the facility or entered or exited a vehicle. Furthermore, the service allowed .parents to restrict where their child could go using a smartphone app. It also allowed parents to consent to their children coming home to avoid having them return when no parents were present. In addition, the driver kept an eye on each child from the time they got off the shuttle until they entered the house, allowing parents to use the service with peace of mind.

Fig. 10 Suma-mobi Kids
(top: reading 2D code, bottom: boarding the vehicle)

4) From January 5th, 2023

In January 2023, Nissan moved to the final field testing phase to verify how users and local communities accepted the paid transportation services. This step is necessary to design a commercialization scheme for sustainable mobility services, even in remote areas, considering future service expansion. Fig. 11 shows the service area and basic fares for Namie Town. The service area is divided into Zones 1–4, with Zone 1 representing central Namie Town. This service provides transportation within Zone 1 and also between Zone 1 and the other zones. As an exception, direct transportation service is provided to the Ukedo zone in Zone 4 for convenience, because there are earthquake ruins caused by the Great East Japan Earthquake in this zone and visitors are expected to travel around the area. The three companies operating the vehicles—Kanko Taxi, Tohoku Access, and Joko Taxi—received permission under Article 21 of the Road Transport Act to charge for the service, and fare payments can now be made via PayPay or cash.



Basic fare (per adult) Unit: Yen

Arrival / Departure	Zone 1	Zone 2	Zone 3	Zone 4
Zone 1	◉ 200	300	500	800
Zone 2	300			
Zone 3	500			
Zone 4	800			★ 300

Fig. 11 Service area (top image) and basic fare structure (bottom image)

3.2.1.2 Mobility service platform

In conventional taxis, when a customer requests a ride over the phone, the taxi company wirelessly asks all drivers if they can be dispatched, and then an available driver takes their vehicle to the customer's location. If a customer wishes to hail a running taxi, they must visually check the taxi's sign, which indicates whether it is available, rented, or out of service, and raise their hand to indicate their intention to take the taxi. The taxi driver must recognize the customer and determine a location to stop and pull up near the customer. Once the customer boards the taxi and informs the driver of the destination, the driver begins moving the vehicle toward the destination, where they again determine a nearby stopping location considering the surrounding conditions. Payment is processed before the door is opened, and the service is completed by the driver opening the door, allowing the customer to exit the taxi.

To realize Namie Smart Mobility, a mobility service platform (MSPF) was developed comprising the complete set of systems (vehicles, dispatch terminals, control systems, cloud-based dispatch systems, etc.) necessary to automate the aforementioned on-demand vehicle dispatch. Thus, customers can request a ride via a smartphone app instead of requesting a taxi over the phone or raising a hand to indicate the intention to catch a taxi. The fleet management system, a cloud-based vehicle dispatch system, receives the dispatch request from the app, determines the most suitable vehicle for the taxi company and the customer, and issues dispatch instructions. The dispatch of self-driving vehicles is supported by an autonomous drive gateway established to filter the required information. The overall configuration of the MSPF is shown in Fig. 12.

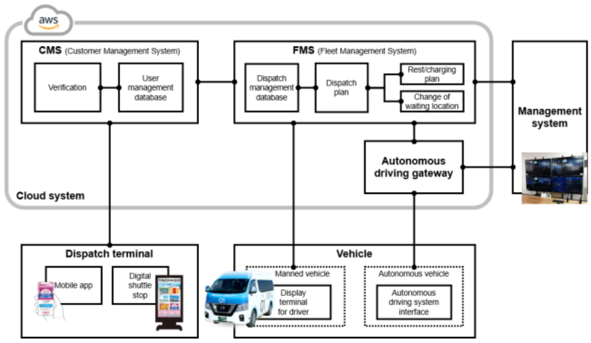


Fig. 12 Overall configuration of MSPF

The allocation of an available vehicle is determined by calculating the driving route of each vehicle from its current location to the customer's requested boarding location according to its present and predicted dispatch status. A trip is defined as the dispatch of a vehicle from the pick-up point to the destination, and a tour is defined as multiple trips arranged in chronological order. As shown in Fig. 13, assuming that there is currently no dispatch request and all vehicles are stationed at their waiting locations, when a new dispatch order is issued, driving routes are calculated for Trip A (travel from the current waiting location to the pick-up location), Trip B (travel from the pick-up location to the drop-off location), and Trip C (travel from the drop-off location back to the waiting location). As shown in Fig. 14, when ridesharing is enabled, if another customer requests a ride (Trip D), all possible insertion points of the pick-up and drop-off locations for Trip D are analyzed. It is inserted at the position where the traveling time is the shortest, while restrictions are placed on the maximum pick-up and drop-off times for the first customer to limit unnecessary waiting and riding times. When ridesharing is not enabled, Trip D is inserted into a trip when no customer is on board (i.e., from the waiting location to the pick-up location or from the drop-off location to the waiting location), and a tour with multiple drop-offs is created as shown in (1) and (6) in Fig. 14.

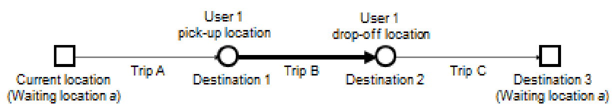


Fig. 13 Trip creation

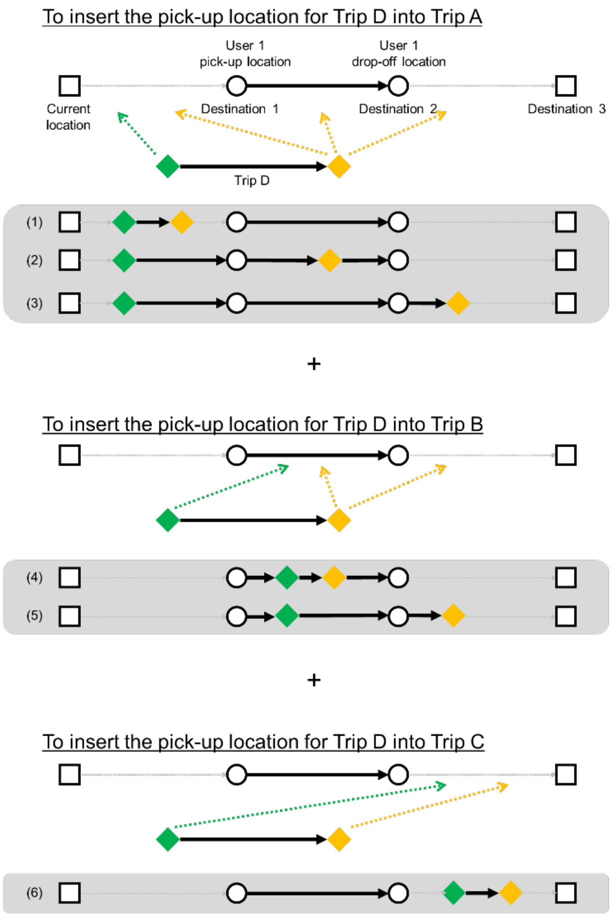


Fig. 14 Creation of a tour by inserting a trip
(Bold lines indicate trips with customers on board)

Notably, while conventional taxi drivers select their routes to travel in areas where demand is likely to occur based on the knowledge they have accumulated through practical experience, in an MSPF, vehicles are stationed in areas where demand is expected to enable services with high customer satisfaction and high dispatch efficiency.

3.2.2 Easy Ride®

Nissan Motors conducted a field test of a new transportation service using autonomous vehicle and ride-hailing technologies to explore the use of autonomous drive vehicles in the Yokohama Minato Mirai area. Created to enable increased freedom of mobility, Easy Ride®, a registered trademark of DeNA Co. Ltd. (hereafter referred to as DeNA) and Nissan Motor Co. Ltd., is a transportation service for anyone who wants to travel freely to their destination. In addition to providing a means of transportation, Easy Ride® also aims to facilitate encounters with local attractions.

1) FY2017 (from March 5th, 2018)

In collaboration with DeNA, Nissan Motors conducted a field test to identify issues related to the onboard experience of general users and identify and engage with the stakeholders who build the ecosystem around autonomous rideshare vehicles.

This field test was conducted for a round trip of approximately 4.5 km between Nissan Global Headquarters and Yokohama World Porters using LEAF-based autonomous drive vehicles. Approximately 300 participants were recruited through an official website and provided with basic services, such as setting a destination and dispatching a ride, as well as new riding experiences beyond transportation. For example, when passengers input "what they want to do" into the dedicated smartphone application via text or voice, it displays a list of recommended destinations. While the passengers were in the vehicle, an in-car tablet screen displayed a selection of nearly 500 recommended places of interest and events near the destination. In addition, approximately 40 discount coupons were offered to passengers for retailers in the area.

To develop an autonomous vehicle service that provides customers peace of mind, a remote monitoring center was established by combining Nissan seamless autonomous mobility technology and DeNA's service design and operation expertise. This remote monitoring center kept track of vehicle locations and cabin conditions and managed vehicle logistics and schedules.

2) FY2018 (February 19th to March 16th, 2019)

A field test was conducted in the Yokohama Minato Mirai and Chinatown areas (Fig. 15) using a newly developed autonomous drive vehicle based on the e-NV200. Because this vehicle was intended for daily use, no limit was set on the number of times it could be used during the test period, and users could choose a destination from 15 pick-up and drop-off points when requesting a ride. The vehicles were stationed at a waiting location at the northern end of the test area and dispatched upon customer request. Assuming that the service would be unmanned in the future, no staff was placed at the pick-up locations, and passengers were allowed to board the vehicle by scanning a QR code attached to the vehicle.

Fig. 15 Field test area

During the test period, the vehicles were dispatched 170 times, with one customer using them 16 times, indicating their use as daily transportation. However, several problems were identified related to long customer waiting times owing to the density of pick-up and drop-off points, the time it took to pick up and drop off, and the shortage of vehicles due to maintenance, resulting in cancellations.

3) FY2021 (September 21st to October 30th, 2021)

In collaboration with NTT DOCOMO, Inc., a larger field test was conducted in the area shown in Fig. 15, leveraging the latest technologies of both companies to solve transportation service issues faced by local communities, such as the shortage of public transportation drivers owing to the declining birthrate and aging population. This field test evaluated a future transportation service employing fully autonomous vehicles and verified its usefulness to approximately 200 participants recruited from Minato Mirai residents and workers. The test was conducted by combining the AI Unkou Bus® on-demand transportation system, which utilizes artificial intelligence for autonomous vehicle dispatch (Fig. 16). AI Unkou Bus® is a registered trademark of NTT DOCOMO, Inc., and uses the Smart Access Vehicle Service (3) developed by Mirai Share, Inc.

Fig. 16 Field test in collaboration with NTT DOCOMO

By incorporating an electronic control unit into the autonomous drive system and expanding the monitoring and diagnostic functions, the need for a human operator in the vehicle was eliminated, and the number of passenger seats was increased from two to three. In addition, the average pick-up time was shortened by setting up one vehicle-waiting location on the north side and another on the south side of the field test area and increasing the number of pick-up and drop-off points from 15 to 23. As a result, the number of users increased, and the vehicles were dispatched 513 times (approximately three times more than in FY 2018). Furthermore, a positive response rate of 84% was received for the in-vehicle experience with no driver. When asked about the fee for the mobile service, approximately half of respondents said that 500 yen/time was reasonable and that the use of a subscription service was preferable.

4. Conclusion

As the sharing economy becomes increasingly popular internationally, various carsharing and ridesharing instances have been implemented in the transportation field. This chapter described the shared mobility services that Nissan Motors has been developing. Nissan Motors will continue developing mobility service technologies that utilize autonomous vehicles to create a sustainable and convenient means of transportation.

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Technical Awards

2023 JSAE Award The Outstanding Technical Paper Award

Thick Diamond-like Carbon-coated Piston Ring Developed for Stainless Steel Thermal Spray Coating in Cylinder Bores

Introduction

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2023 JSAE Award The Outstanding Technical Paper Award

Thick Diamond-like Carbon-coated Piston Ring Developed for Stainless Steel Thermal Spray Coating in Cylinder Bores

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1. Introduction

Nissan's variable compression turbo (VC-TURBO) engine provides excellent fuel efficiency and superior power performance by adjusting the compression ratio. To improve the fuel efficiency of a VC-TURBO engine further, it is necessary to increase the exhaust gas recirculation (EGR) rate. However, this increases the exhaust condensate in the cylinder bore, which severely corrodes its thermal spray coat. The anticorrosion properties of cylinder bores have been improved by thermally coating the bores with stainless steel (Cr 12 wt%). Nevertheless, stainless steel coatings cause adhesion wear between the surface of the bore and the chromium nitride (CrN) coating on the outer surface of the piston ring. In this study, a thick hydrogen-free diamond-like carbon (DLC) coating with low hardness and fewer droplets was fabricated using a filtered vacuum arc (FVA) method. This DLC coating suppressed both adhesive wear and abrasive wear by eliminating the CrN coating and by improving the DLC deformation capability, respectively. An EGR rate of 20% was achieved by utilizing a thick DLC-coated piston ring and a stainless steel thermal spray coating for the cylinder bores. In addition, the fuel efficiency was increased by over 4% compared to a VC-TURBO engine (KR20DDET) with a conventional CrN-coated piston ring and an iron-based thermal spray bore.

2. Background

The VC-TURBO engine features a multilink mechanism that continuously varies the top and bottom dead center positions of the piston, allowing the compression ratio to be freely varied, thereby simultaneously achieving fuel efficiency and superior power performance(1). In recent years, the EGR has garnered considerable interest because of its potential for improving the fuel efficiency of gasoline-powered engines(2). Specifically, cooling losses can be reduced by lowering the combustion temperature, which can be achieved by mixing the gases exhausted as a result of the engine's combustion with the intake air.

When the EGR rate is increased to 20%, the combined effect of the exhaust condensate and piston sliding at the top dead center accelerates the corrosion wear of the thermal-sprayed bore. To overcome this problem, the substance used in the spray was changed from iron to stainless steel, which improved the corrosion resistance of the bore(3,4).

However, in conventional piston rings with a CrN coating on the outer surface and a DLC coating on top of that layer, the DLC coating wears off because of the prolonged sliding motion, which then exposes the underlying CrN coat. This causes adhesion wear between the exposed CrN coat on the piston ring and surface of the stainless steel-sprayed bore, which is composed of Cr. Figure 1 shows the adhesive wear on a piston ring after a number of sliding tests were carried out. To prevent this type of wear from occurring, this study developed a piston ring suitable for stainless steel-coated cylindrical bores by applying a thick DLC layer on the ring without an underlying CrN coat.

3. Concept of thick DLC-coated piston rings

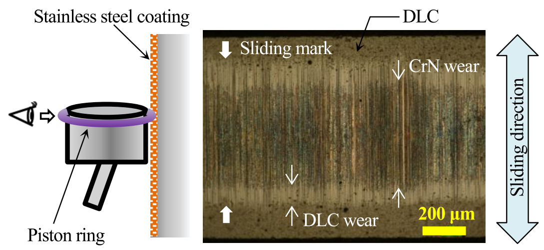

Fig. 1 Adhesive wear by exposed CrN after 1 μm thickness DLC wear out

Figure 2 shows the configuration of the thick DLC-coated piston ring. In general, a 20-μm thick CrN coating is applied on the outer circumference of the piston ring to avoid exposing the base material, and a 1-μm thick DLC coating is deposited on the outermost circumference to reduce friction, improve seizure resistance, and reduce the wear between the bore and the ring(5). The problems associated with eliminating the CrN coating and increasing the thickness of the DLC coating are: (1) the deterioration of the favorable sliding characteristics

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caused by the growth of droplets and (2) the progression of abrasive wear due to droplets that have fallen out. Problem (1) can be solved by reducing the number of droplets via the FVA method, and problem (2) can be solved by reducing the hardness of the DLC coating to improve the deformability of the droplets. The details are explained in subsequent sections.

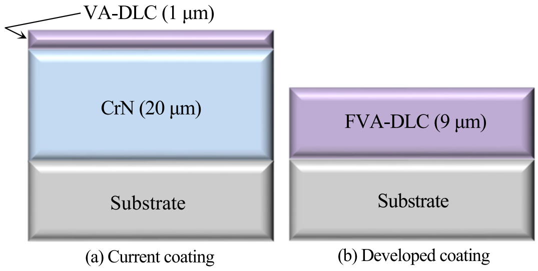


Fig. 2 Configuration of thick DLC coated piston ring

3.1 Reduction in the number of droplets via the FVA method

The vacuum arc (VA) method is typically used to fabricate DLC films. In this method, raw graphite in a vacuum is ionized by an arc discharge, and the carbon ions ejected by the discharge are accelerated by a bias voltage to form a film on a target material. During this process, both carbon ions and graphite particles may coat the target. Graphite particles act as nucleation sites where droplets grow on the surface of the DLC coating. Droplets scattered on the surface can degrade the sliding characteristics of DLC coatings lubricated with engine oil(6). To overcome this problem, the FVA method was used in this study because it reduces the number of droplets that form on the DLC coating(7,8). Figure 3 shows a schematic for the mechanism of the formation of films using the FVA method. The principle of the FVA method is similar to that of the VA method. A thick DLC coating can be deposited with fewer droplets by removing the graphite particles (preventing them from becoming nucleation sites for droplets) via a magnetic field applied to a curved filter, which ensures that only carbon ions are transported to the object to be coated.

Figure 4(a) shows a scanning electron microscope (SEM) image of a 9-μm thick DLC coating deposited using the FVA method (hereafter denoted as "FVA-9μm"), observed from above at a diagonal angle. For comparison, Fig. 4(b) shows a SEM image of a 6-μm thick DLC coating deposited using the VA method (hereafter denoted as "VA-6μm"). The figure demonstrates that the VA-6μm coating contained many droplets and no smooth areas on the surface, whereas the FVA-9μm coating contained fewer droplets and many smooth areas on the surface. However, the inflow of graphite particles was not completely suppressed, and the droplets on the surface of the DLC coating formed protrusions. As carbon ions are coated onto the areas surrounding graphite particle nuclei, the droplets grow and develop into conical shapes as their sizes increase(9). Even when the number of droplets is reduced using the FVA method, if a thick DLC coating is used, it is still necessary to smooth the protruding droplets via polishing(10).

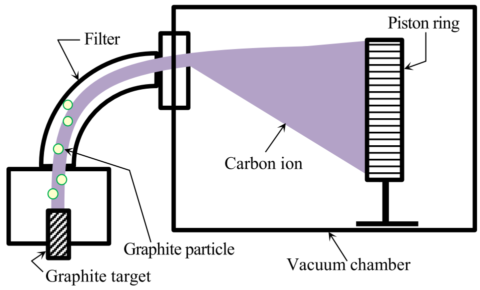


Fig. 3 Schematic representation of FVA system

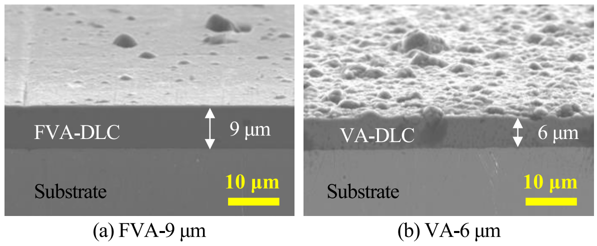


Fig. 4 SEM observations of FVA-9μm and VA-6μm from diagonally above

3.2 Improvement in the deformability of fallen droplets via a reduction in the DLC coating hardness

Even if the droplet protrusions are smoothed via polishing, if the remaining droplets on the DLC coating fall off in the process of sliding and abrasive wear occurs, seizures may occur because the underlying material is exposed(11,12). This study found that DLC coatings with low hardness have a high DLC deformability and that abrasive wear can be suppressed by elastically deforming the droplets that have fallen off in accordance with their shape. Figure 5 shows the mechanism by which the abrasive wear of low-hardness DLC coatings is reduced. Generally, the hardness of DLC coatings is determined by the ratio of the number of diamond bonds to the number of graphite bonds between the carbon atoms. The maximum hardness is a function of the bias voltage applied to the substrate during the formation of the film(13,14). If the proportion of the diamond bonds is increased, a DLC coating with a high nanoindentation hardness of approximately 70 GPa can be produced(15). In this study, by adjusting the bias voltage during the formation of the film and by reducing the proportion of diamond bonds, a DLC coating with a low hardness of approximately 20 GPa was produced, and its wear resistance against stainless steel-sprayed bores was evaluated(16,17).

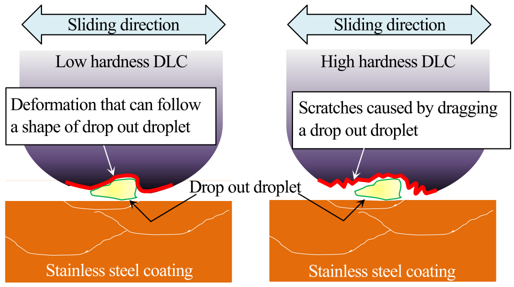


Fig. 5 Mechanism of DLC abrasive wear reduction

4. Experimental methods

Table 1 lists the deposition method, material properties, coating thickness, and surface roughness of the DLC coating deposited onto the piston ring used in the tests. The hardness and contact depth, which represent the elastic deformability, were measured using a nanoindentation method. The surface roughness was assessed using contact surface roughness measurements. To smooth the droplet protrusions on the DLC coating formed using the FVA method, four droplet specifications (FD1, FD5, FD6, and VD7) with different film formation methods, hardness values, and coating thicknesses were examined. The sizes and positions of the droplets were determined using surface SEM. For three droplet specifications (FD1, FD5, and VD7), the states of the droplets before and after polishing were assessed using cross-sectional SEM observations. For six droplet specifications (FD1, FD2, FD3, FD4, FD5, and VD7), the surface roughness before and after polishing was examined. To measure the sensitivity and wear of low-hardness DLC coatings, and to clarify the mechanism responsible for the wear progression of DLC coatings, wear tests were carried out on stainless steel-sprayed bores and 9-μm thick low-hardness DLC coatings (FD1, FD2, FD3, FD4) formed via the FVA method. The sections in which sliding occurred were then examined. The specimens used for the wear tests were fabricated by cutting the piston ring to the required length after polishing the outermost surface of the DLC coating to below an average roughness (Ra) of 0.05 μm and reduced peak height (Rpk) of 0.05 μm. Tests for measuring the reciprocating sliding wear against a stainless steel-sprayed cylinder bore were conducted on the specimens using an Optimol SRV® instrument. Figure 6 shows a diagram of the reciprocating sliding wear tests and the external appearance of the test specimens. Table 2 lists the test conditions. The depth of wear on the DLC coating was estimated by measuring the cross-sectional profile of the piston ring after 12 h of testing. The wear tests were interrupted after 1, 3, and 10 h, and the boundary between the sliding and non-sliding segments was observed using a microscope.

Table 1 DLC specifications

		(GPa)	depth (nm)	(μm)	As coating / After polish
FD1	FVA	22.1	287	9	0.34 / 0.04
FD2	FVA	25.8	265	9	0.33 / 0.04
FD3	FVA	26.7	260	9	0.34 / 0.03
FD4	FVA	27.7	255	9	0.32 / 0.04
FD5	FVA	50.0	185	9	0.37 / 0.13
FD6	FVA	22.1	287	1	0.12 / 0.03
VD7	VA	58.0	46	1	0.22 / 0.04

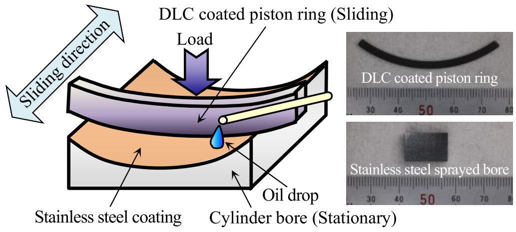


Fig.6 Schematic diagram of the reciprocating sliding wear test and test specimens appearance.

Fig. 6 Schematic diagram of the reciprocating sliding wear test and test specimens appearance.

Table 2 Wear test conditions

Load	450 N
Hertzian pressure	390 MPa
Frequency	25 Hz
Stroke	3 mm
Amount of oil	1 ml/h
Oil type	Poly-alpha-olefin (100 °C kinematic viscosity: 4 mm^2/s)
Test time	12 h (Observation of wear progress: 1 h, 3 h, 10 h)
Temperature	100 °C (Heating test table)

5. Results and discussion

5.1 Surface control of thick DLC coatings via the FVA method

Figure 7 shows SEM images of the surfaces of the FVA-9μm DLC coatings with hardness values of 22.1 GPa (FD1) and 50.0 GPa (FD5), as well as SEM images of the FVA-1μm (FD6) and VA-1μm (VD7) coatings. No significant differences in the sizes and positions of the droplets on the FVA-9μm coatings were observed. Small droplets (approximately 1 μm wide) were observed on the surfaces of the FD6 and VD7 coatings, but the FD6 coating had fewer droplets because of the filter. However, the droplets on the FD6 coating grew larger after the coating thickness was increased to 9 μm.

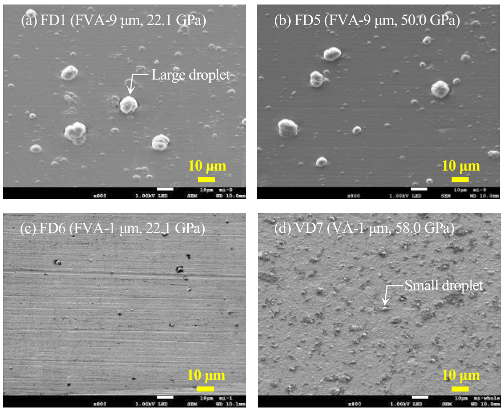
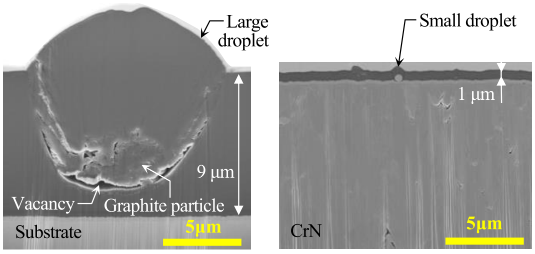


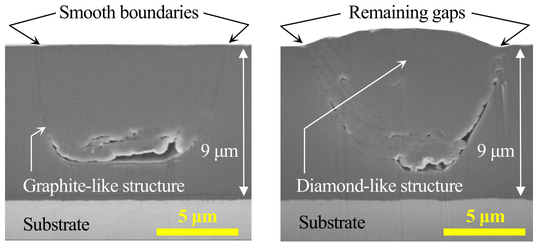
Fig. 7 Surface SEM observation of as-coated DLC with different process, hardness, and thickness

Figure 8 shows cross-sectional SEM images of droplets on the FVA-9μm (FD1) and VA-1μm (VD7) coatings. The droplets on the FD1 coating grew around the graphite particles that were deposited at the start of the film formation process, and voids formed below the droplets. The droplets became large, reaching a diameter of approximately 10 μm, and their lower sections penetrated to a depth just above the substrate and their upper sections protruded above the surface of the coating. Figure 9 shows cross-sectional SEM images of the droplets on the FVA-9μm DLC coatings with hardness values of 22.1 GPa (FD1) and 50.0 GPa (FD5) after they were polished for a period of time deemed suitable for mass production. After the FD1 specimen was polished, it exhibited a flat surface with no height discontinuities between the droplet and surrounding area. In contrast, the FD5 specimen did not form a flat surface, and the protrusion was only partially removed. At the interface between the droplet and DLC, the proportion of weak graphite bonds was high. Moreover, the droplets had the same diamond bond ratio as the DLC coatings. Therefore, when the hardness of the DLC coating was high, it was difficult to polish the droplet protrusions quickly. Figure 10 shows the effect of the DLC coating hardness on the Rpk of the DLC surface, which represents the height of the droplet protrusion. The figure indicates that, before polishing, the Rpk value of the FVA-9μm coating was over 0.3 μm, regardless of the DLC coating's hardness. Therefore, to decrease the Rpk to below 0.1 μm via polishing, the hardness of the DLC coating should be less than 27.7 GPa.



(a) FD1 (FVA-9 μm, 22.1 GPa) (b) VD7 (VA-1 μm, 58.0 GPa)

Fig. 8 Cross section SEM observation of droplet as coating



(a) FD1 (FVA-9 μm, 22.1 GPa) (b) FD5 (FVA-9 μm, 50.0 GPa)

Fig. 9 Cross section SEM observation of droplet after polish

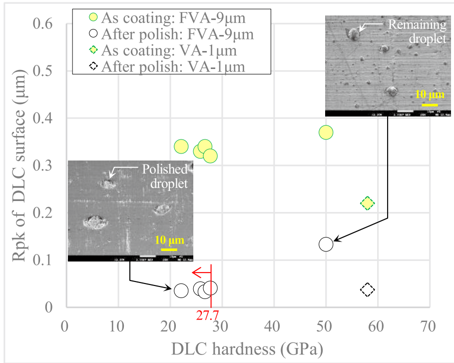


Fig. 10 Relationship between Rpk of DLC surface and hardness after as coating and polish (FD1, FD2, FD3, FD4, FD5, VD7)

5.2 Sliding wear tests on stainless steel-sprayed cylinder bore and DLC coatings

Figure 11 shows the relationship between the DLC coating hardness and wear depth after 12 h of testing. The cross-sectional profiles of the piston ring before and after the tests were used to calculate the depth of the wear. The wear on the DLC significantly increased when the DLC coating hardness was increased to over 26.7 GPa (FD3). For a hardness of 27.7 GPa (FD4), the wear on the DLC reached up to 4.5 μm. For hardness values of 22.1 GPa (FD1) and 25.8 GPa (FD2), the wear was 1 μm or less. Figure 12 shows the SEM surface images of the segments of the FD1 (hardness of 22.1 GPa) and FD4 (hardness of 27.7 GPa) coatings that were exposed to the sliding. The results of the surface roughness measurements are also presented. The FD4 specimen exhibited multiple scratches in the direction parallel to the sliding motion, which contributed to an increased Ra value of 0.08 μm. In contrast, the high-deformability FD1 coating exhibited mild and uniform wear over the entire segment. No scratches were observed in the direction parallel to the sliding motion, and the surface roughness did not increase.

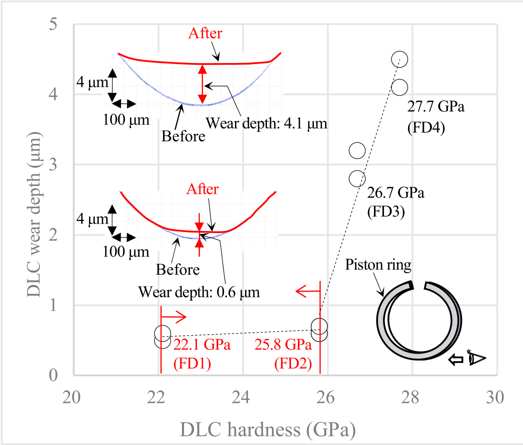


Fig. 11 Relationship between DLC wear depth and hardness after wear test (12 hours)

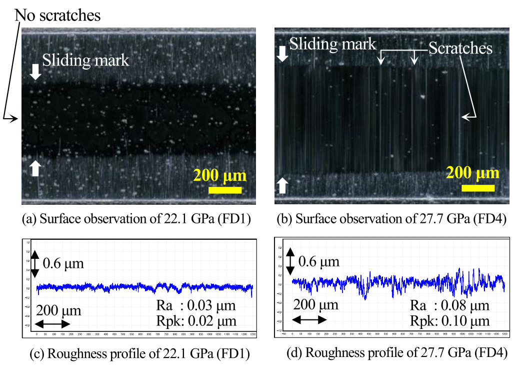


Fig. 12 Surface observation and roughness profile of DLC sliding area after wear test (12 hours)

5.3 Properties of the DLC after the wear tests

Figure 13 shows the SEM images of a location where a droplet fell out of the FD4 DLC coating (hardness of 27.7 GPa) after 3 h of wear testing. Figure 14 shows cross-sectional SEM images of the location where the droplet fell out, along with the results of the energy-dispersive X-ray (EDX) analysis. Scratches along the direction parallel to the sliding motion originated at the location where the droplet fell out. In addition, Fe and Cr, the main components of the stainless steel-sprayed bore, were detected at the locations where droplets fell out. These results indicated that the droplets fell out because of the sliding friction between the DLC coating and the stainless steel-sprayed bore, which dragged the droplets along the sliding direction and caused scratches. Additionally, the cross-sectional SEM images suggested that the droplets probably fell out because of cracks that originated at the interfaces between the droplets and DLC coating and that propagated toward the internal voids or vacancies. The ratio of graphite bonds was high at the interfaces between the droplets and DLC coating. Hence, the ease at which the droplets fell out was not strongly correlated with the hardness of the DLC coating. Large droplets remained at the bottom, but if the DLC coating had been worn further, these large droplets may have fallen out again and caused abrasive wear.

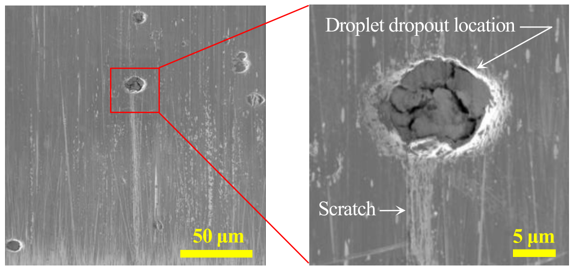


Fig. 13 Surface SEM observation of droplet dropout location after wear test (3 hours: 27.7 GPa (FD4))

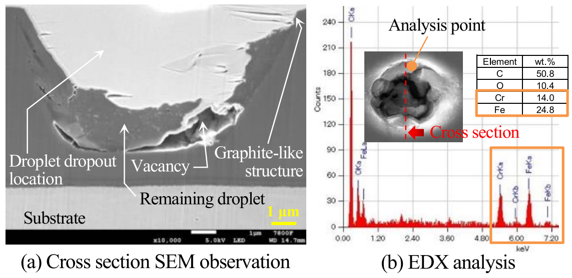


Fig. 14 Cross section SEM observation and EDX analysis of droplet dropout location after wear test (3 hours: 27.7 GPa (FD4))

5.4 Mechanism of DLC wear progression

Figure 15 shows the microscopic observations of the boundary between the sliding and non-sliding segments of the FD4 DLC coating (hardness of 27.7 GPa) after abrasion tests were carried out for 1, 3, and 10 h. The figure also shows the microscopic observations of the FD1 DLC coating (hardness of 22.1 GPa) after a 1-h wear test. The figure indicates that after 1 h of wear testing on the FD4 DLC coating, multiple scratches originating from the droplets appeared, and the boundary line between the sliding and non-sliding segments became jagged. After 3 h of wear testing, the scratches that appeared after 1 h either disappeared or became shallower. After 10 h of wear testing, the wear increased and new scratches appeared because of the droplets that had fallen out. However, the number of scratches was lower than that observed after 1 h of wear testing. In contrast, after 1 h of wear testing on the FD1 DLC coating, no scratches originating from the droplet positions were observed. The wear progressed uniformly, and the boundary line between the sliding and non-sliding segments exhibited minimal unevenness. In addition, polishing marks, which occurred during the polishing process, remained on the boundary between the sliding and non-sliding segments.

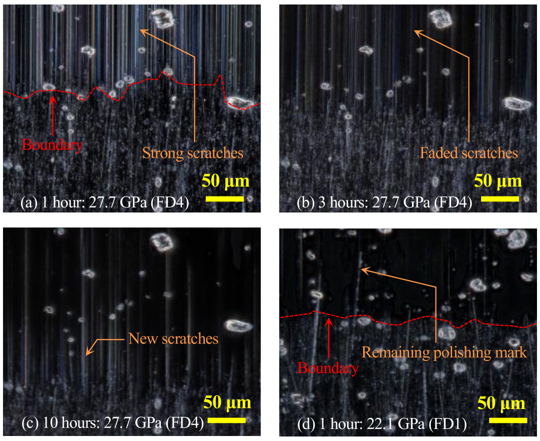


Fig. 15 Mechanism of DLC wear progressing by observing the boundary between sliding part and non-sliding part.

6. Engine durability test results and estimation of market-based DLC coating wear loss

Durability tests were conducted on a four-cylinder engine equipped with a piston ring coated with a 9-μm thick layer of FD1 DLC (hardness of 22.1 GPa) and a stainless steel-sprayed bore with a diameter of 84 mm. The tests were conducted using a maximum rotation speed of 5600 rpm, maximum oil temperature of 135 °C, and test duration of 500 h. Figure 16 shows a surface image of the sliding segment of the FD1 DLC coating after the durability test and the results of the surface roughness measurements. No signs of adhesive or abrasive wear were observed on the sliding segment, and no deterioration in the surface roughness was detected. Based on the depth of the wear on the DLC coating after the durability test and the survey results of the wear on piston rings recovered from vehicles that had been driven long distances, the market-based wear loss was estimated for the FD1 and FD4 DLC coatings, as shown in Fig. 17. The figure indicates that, at a standard mileage of over 150,000 km, the predicted wear depth for the FD4 DLC coating (hardness of 27.7 GPa) was 14 μm. This depth implied that the underlying material was likely exposed. For the FD1 DLC coating (hardness of 22.1 GPa), the predicted wear depth was 8 μm, which is less than 9 μm. Finally, an engine durability test was conducted at an EGR rate of 20%, and it confirmed that there were no abnormalities in the wear of the DLC coatings(4).

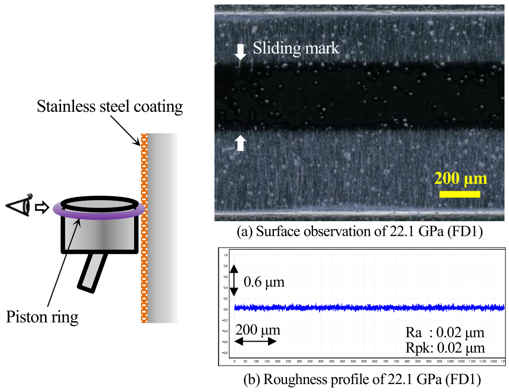


Fig. 16 Surface observation and roughness profile of DLC sliding area after engine durability test (500 hours: 22.1 GPa (FD1))

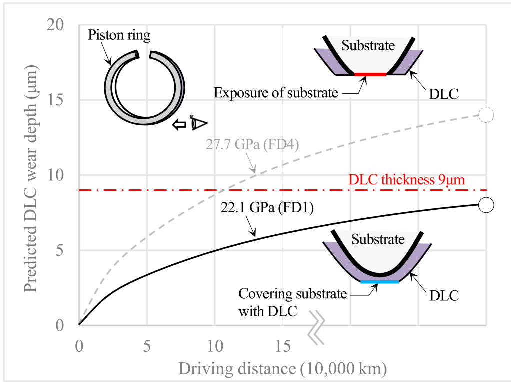


Fig. 17 DLC wear depth prediction

7. Conclusions

In this study, a piston ring compatible with stainless steel-sprayed bores was coated with a thick layer of various DLC coatings. The DLC coatings were fabricated with low hardness values and were deposited in thick layers with a small number of droplets. Adhesive wear and abrasive wear were minimized by eliminating the CrN coatings and by improving the DLC deformation capability, respectively. The findings of this study are summarized below.

1) If the hardness of the FVA-9μm DLC coating was 50.0 GPa (FD5), it was difficult to smooth out the protrusions of the droplets via polishing. Therefore, to quickly flatten the surface such that Rpk < 0.1 μm, the hardness should be less than 27.7 GPa.
2) In a 12-h wear test using a stainless steel-sprayed bore, the FVA-9μm DLC coating with a hardness of 22.1 GPa (FD1) exhibited a minimal wear loss (i.e., less than 1 μm). The entire sliding segment was uniformly and mildly worn and had no scratches in the direction parallel to the sliding motion.
3) After 500 h of engine durability tests on the FVA-9μm DLC coating with a hardness of 22.1 GPa (FD1), no signs of adhesive or abrasive wear were observed on the sliding segment, and no deterioration in the surface roughness was detected. In addition, through an estimation of the

market-based wear loss of DLC coatings, the expected wear depth for the FD1 DLC coating was 8 μm.

By adopting piston rings coated with 9-μm thick DLC coatings with a hardness of 22.1 GPa and using stainless steel-sprayed cylinder bores, an EGR rate of 20% was achieved and the fuel efficiency increased by over 4% compared to that of a VC-TURBO engine (KR20DDET) with conventional CrN-coated piston rings and iron-based thermal spray bores.

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Editorial Postscript

Thank you for reading Nissan Technical Review. 2023 marks the 90th anniversary of Nissan's founding, and this time, Nissan Technical Review also celebrates its 90th issue. As a commemorative edition, we featured three topics covering Nissan's advanced technology development: electrification, Advanced Driver Assistance Systems (ADAS) & autonomous driving, and connected service.

In the electrification section, we discussed the 75-year history and future prospects from "Tama" to "Ariya." For Advanced Driver Assistance Systems (ADAS) & autonomous driving, we explored the history of driver assistance development since the late 1980s. In the connected service section, we delved into the evolution of various services since the late 1990s. Each field was deeply explained with iconic technologies, making it a very informative special issue.

The contributors to these articles are at the forefront of Nissan's technical development. We express our respect to all the writers and editors who were involved with the desire to widely disseminate Nissan's technology.

The first article in Nissan Technical Review introduced research on engine technology related to valve mechanisms. While the content of technology will evolve with time, Nissan's DNA of "do what others don't dare to do" will remain unchanged, and we will continue to pursue cutting-edge technology. We sincerely hope that our advanced technologies being developed will be conveyed to all our readers.

Tomohiro Yamamura,
Research Planning Department,
Nissan Research Center

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Cover Concept

For the 90th issue of Nissan Technical Review and the commemorative issue of Nissan's 90th anniversary, we aimed for a fitting cover design that embodies the keywords "history" and "future."

When we think of "history," it brings to mind the technological history accumulated by Nissan engineers, but it also represents the history of Nissan Technical Review, which has reported on Nissan's technology every year.

By delving into Nissan Technical Review, one can touch upon the history of Nissan's technology, and the overlapping of the 90th anniversary and the 90th issue feels inevitable as we have walked this path together.

With these sentiments in mind, we decided to use the 90th anniversary logo as a symbol of the 90th issue of Nissan Technical Review and placed it beyond a collage of past technical images. Additionally, by overlaying this 90th anniversary logo with an endless horizon, we aim to evoke the image of Nissan's technology evolving continuously without change into the "future," as well as the role of Nissan Technical Review in conveying this evolution.

Nissan Creative Services Office Services Department
Katsumasa Tsubokura, Hirono Kamata

Nissan Motor Co., Ltd.