Special Feature 1:Electrification

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

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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)

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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.

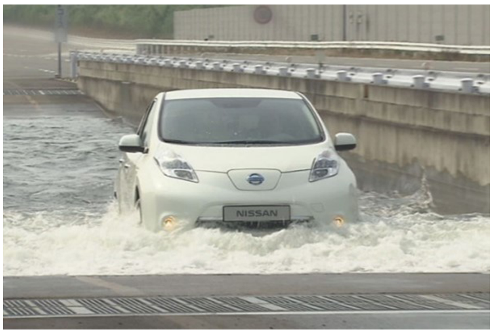

Fig. 9 Flooded road driving test

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.

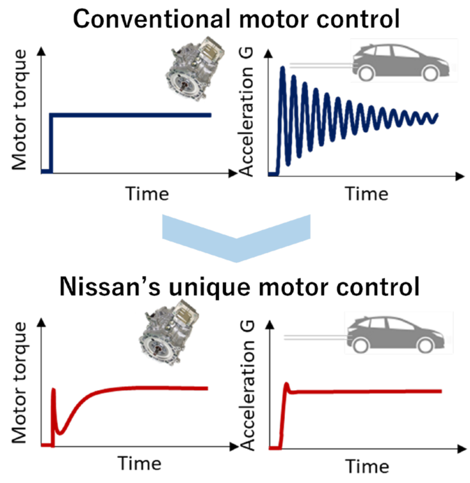

Fig. 10 Smooth acceleration by vibration control

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)

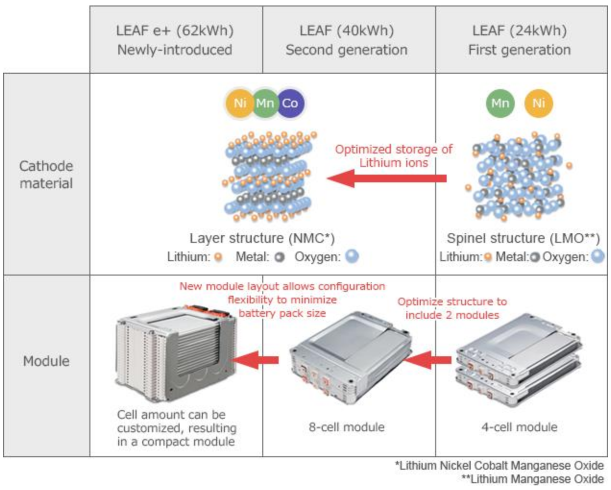

Fig. 13 Evolution of battery in "LEAF"

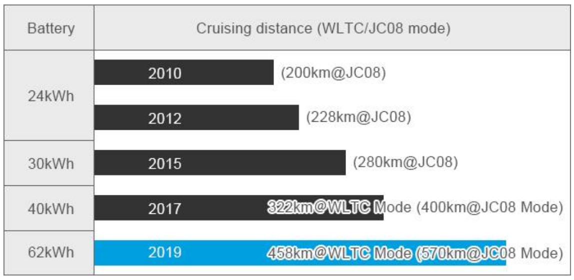

Fig. 14 Evolution of driving range

"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.

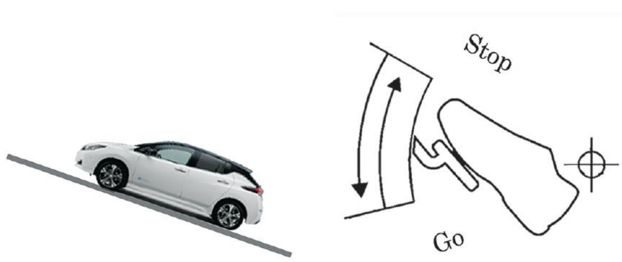

Fig. 15 Conceptual illustration of the e-Pedal operation

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)

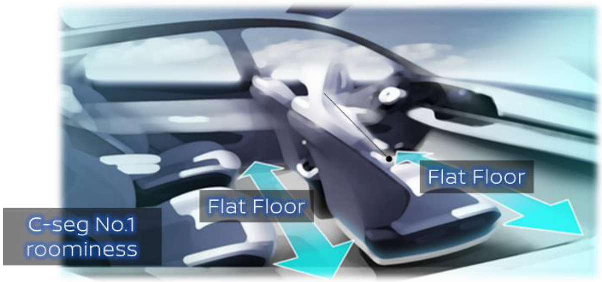

Fig. 17 Aim for great roominess and a completely flat floor

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.

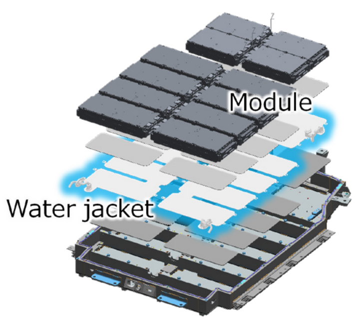

Fig. 18 Battery pack with integrated bottom and cooling plates

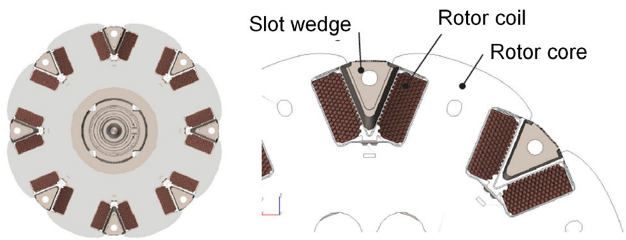

Fig. 19 Eight-pole rotor structure

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."

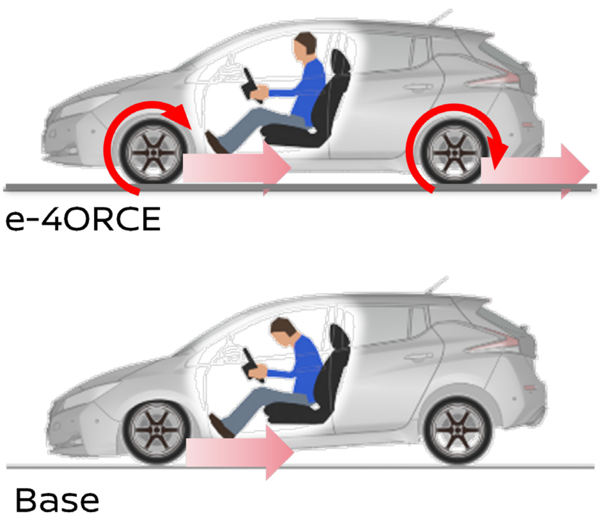

Fig. 20 Posture control during deceleration

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)

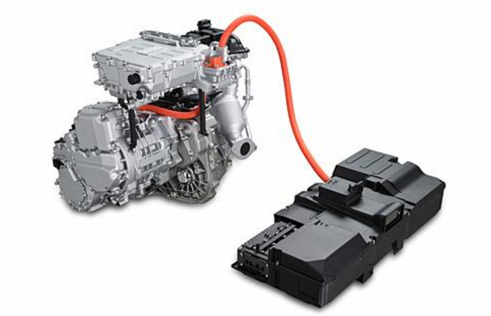

Fig. 24 First-generation "e-POWER" system

"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.

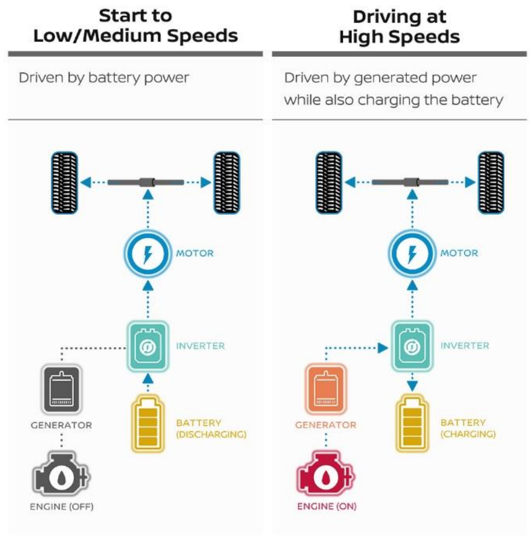

Fig. 25 Conceptual illustration of the "e-POWER" system operation

"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”

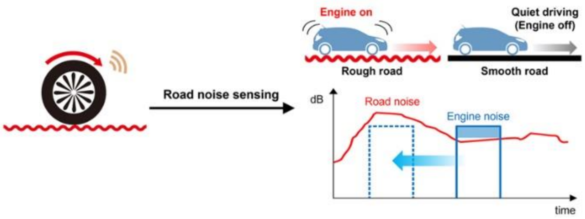

Fig. 27 The system controls engine operation with the addition of road surface information.

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

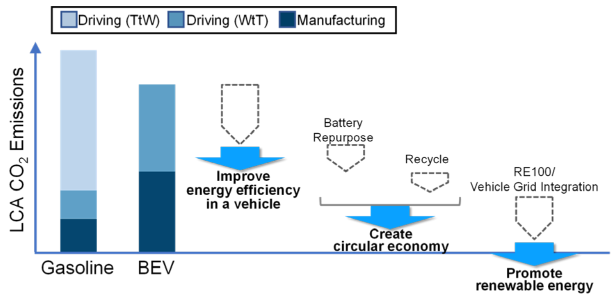

Fig. 29 Toward carbon neutrality and a sustainable society

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.

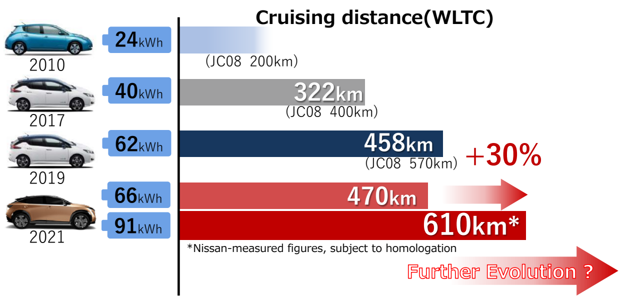

Fig. 30 Evolution of driving range for mass-produced electric vehicles

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.

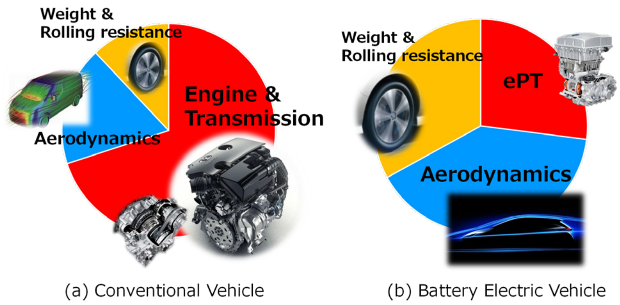

Fig. 31 Ratio of energy loss in vehicles

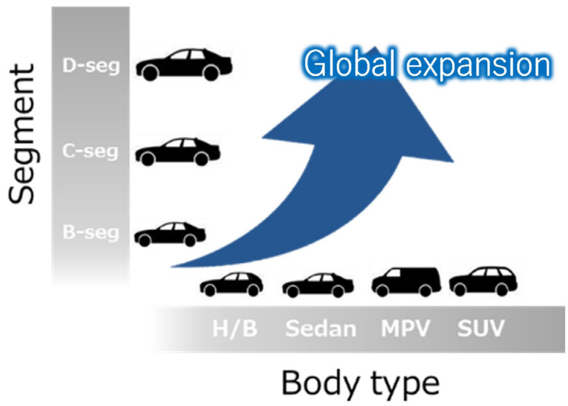

Fig. 32 BEV model deployment in the future

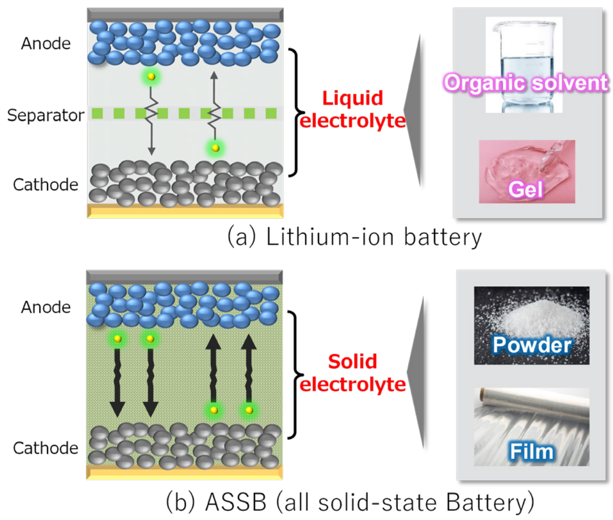

Fig. 33 Comparison of a lithium-ion battery and an ASSB

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.

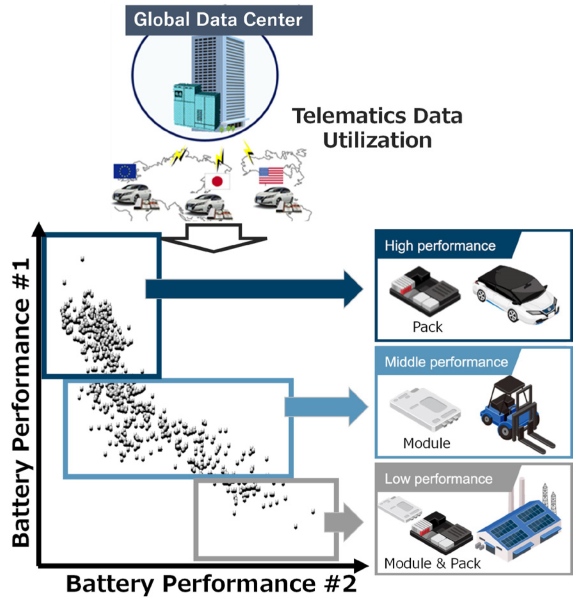

Fig. 36 Concept of the state of health of battery and applications

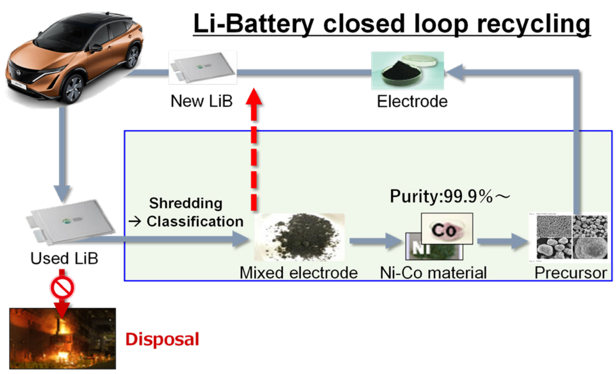

Fig. 37 Battery closed-loop recycling

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.

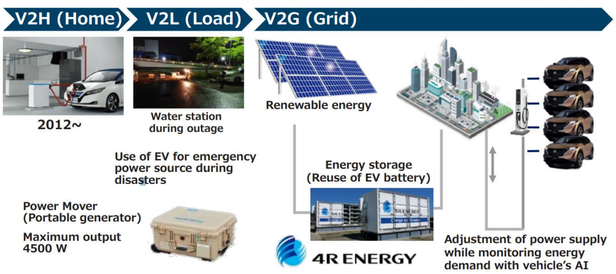

Fig. 38 Nissan's V2X initiative

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.

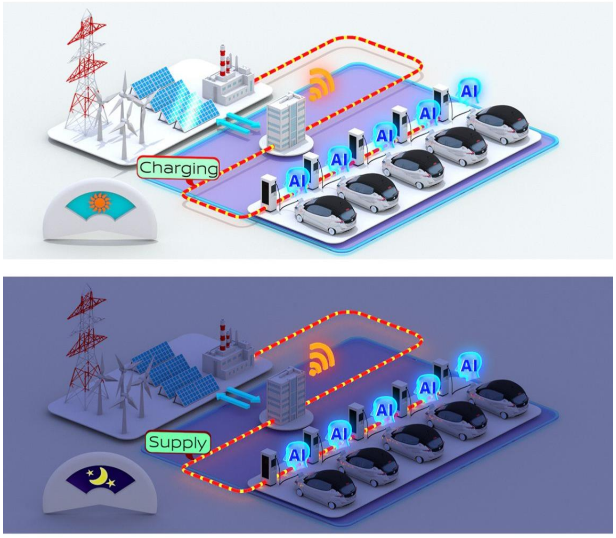

Fig. 40 Concept of Nissan energy management system

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.

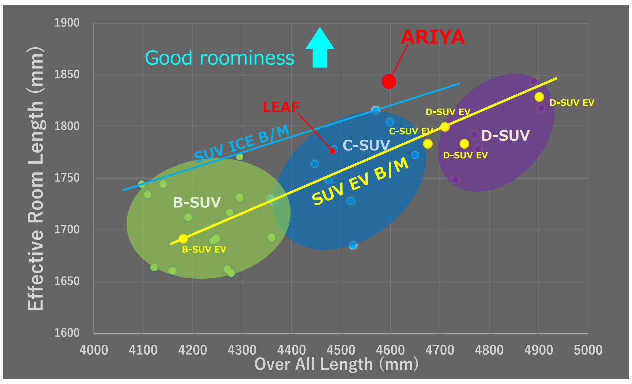
(1) Roomy interior space in the front-to-rear direction (which can be achieved using a compact powertrain).
(2) Completely flat interior floor (without using an exhaust system or propeller shaft).

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).

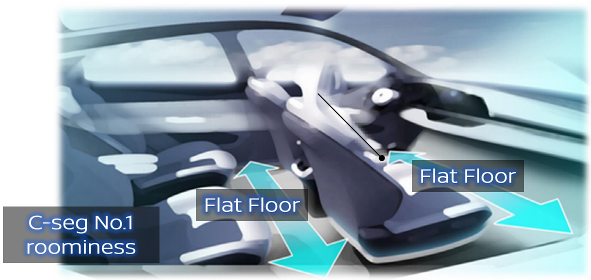


Fig. 3 High space efficiency achieved by the completely flat floor in the ARIYA

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.

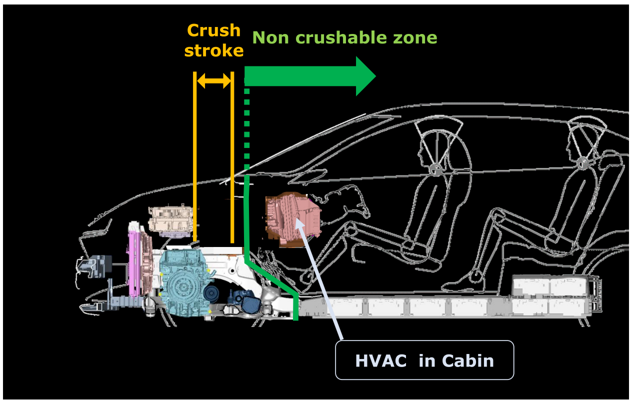


Fig. 4 Conventional arrangement of the air-conditioning unit and crush stroke

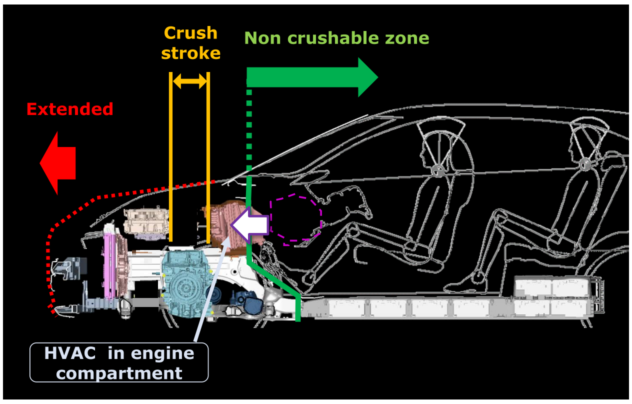


Fig. 5 Shifting the air-conditioning unit and extending the engine compartment

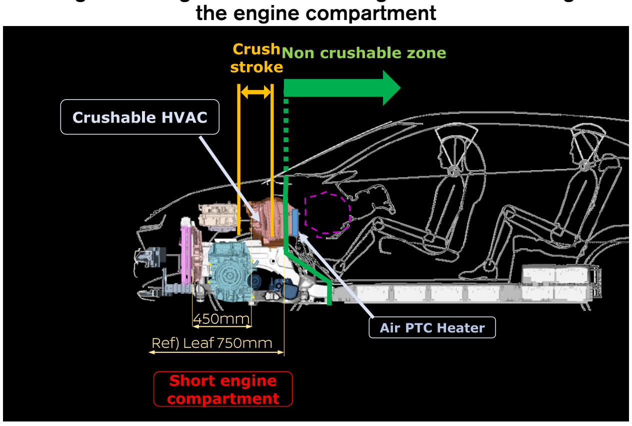


Fig. 6 Crush stroke based on the assumption that the air-conditioning unit will be crushed

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.

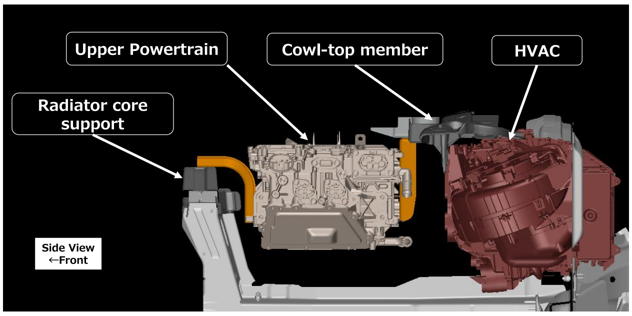


Fig. 7 Layout of the engine compartment designed for the CMF-EV

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.

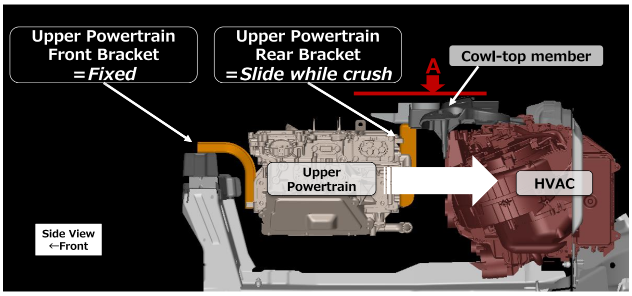
(2) When the upper powertrain unit retracts, the rear fixing point bracket is detached to allow the upper powertrain unit to retract.

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.



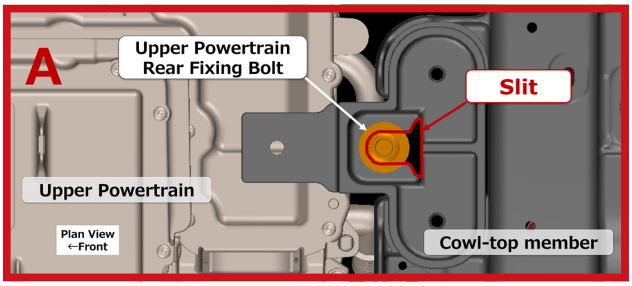


Fig. 8 Intended unit motion during a frontal collision (top) and the slit structure of the fastening point (bottom)

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).

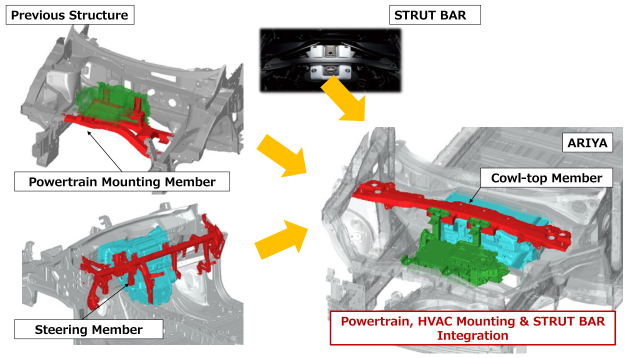


Fig. 9 Integration of functions into the cowl-top member

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.

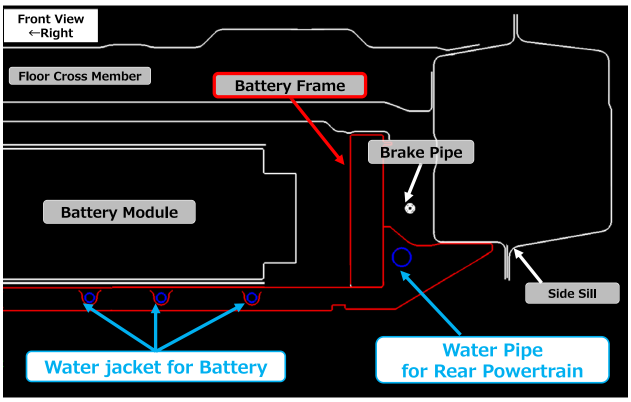


Fig. 10 Integration of the cooling water pipes into the high-voltage battery frame

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.

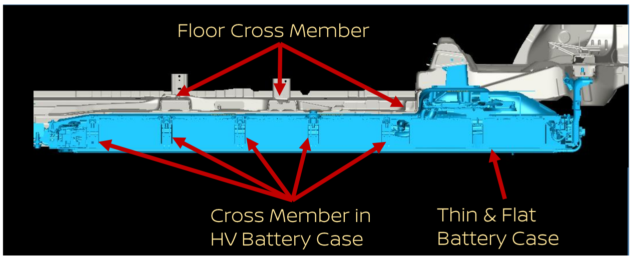


Fig. 11 Relative positions of the vehicle floor and high-voltage battery frame

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.

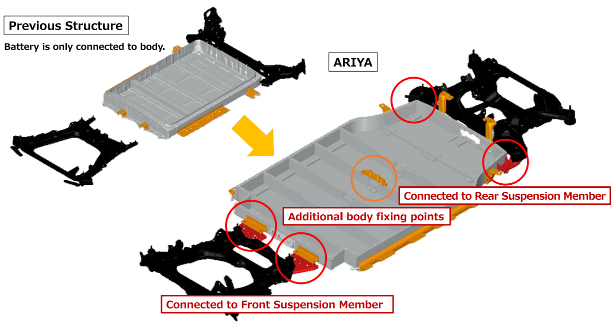


Fig. 12 Strengthening the coupling between the suspension and high-voltage battery

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.

Authors

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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.

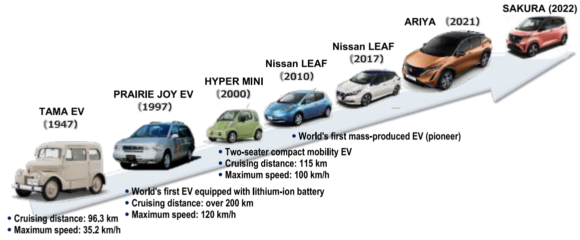

Fig. 1 History of Nissan EV development

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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.

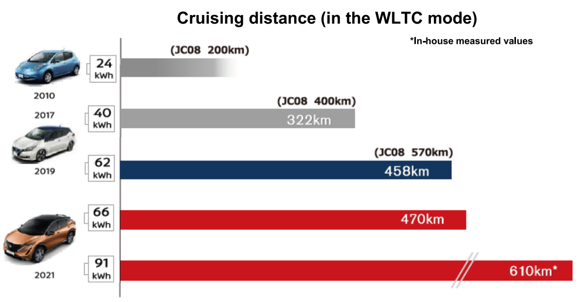


Fig. 2(a) Driving ranges of the LEAF and ARIYA

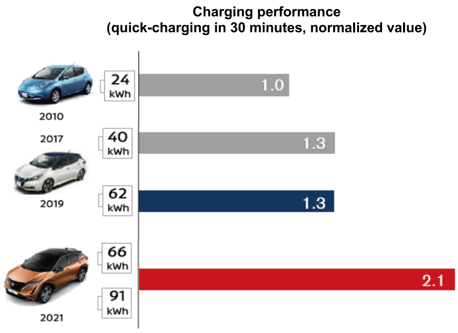


Fig. 2(b) Charging performances of the LEAF and ARIYA

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.

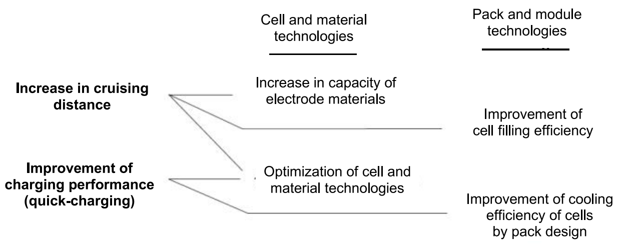
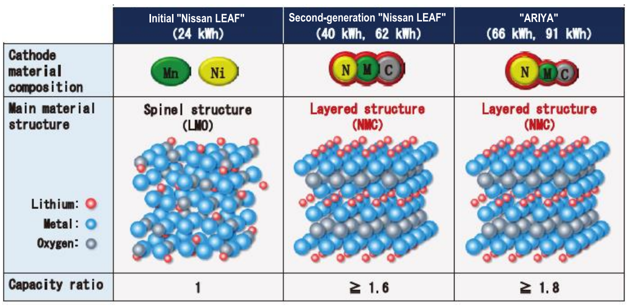


Fig. 3 Key technological challenges faced when evolving the driving range and charging performance of EV batteries



	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.

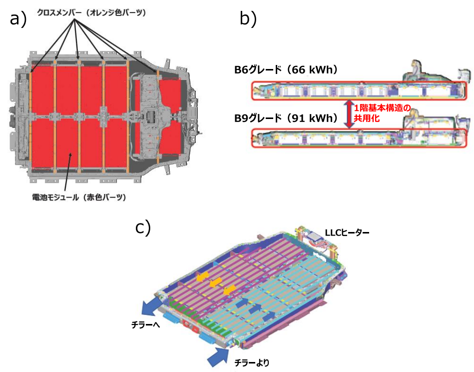


Fig. 5 (a) Battery pack layout for the ARIYA (B6 grade)
(b) Side views of the battery packs for the ARIYA (B6 and B9 grades)
(c) Bottom plate of the battery with LLC flow channels for the ARIYA (B6 grade)

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.

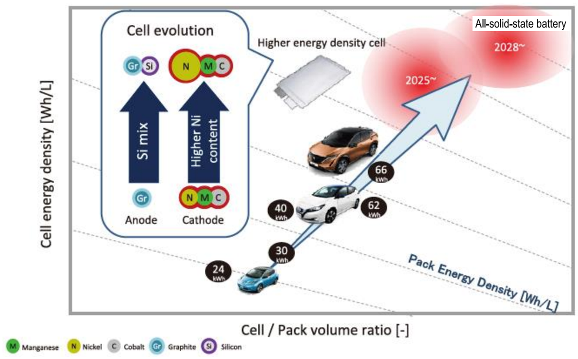


Fig. 6 Nissan's battery roadmap

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.

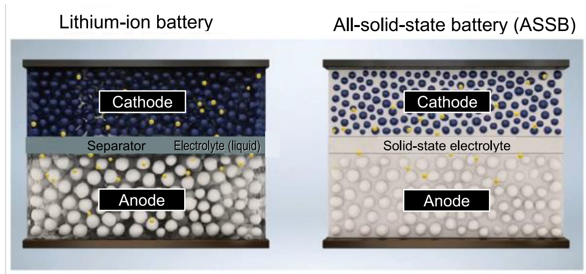


Fig. 7(a) Cell structures of a lithium-ion battery (left) and an ASSB (right)

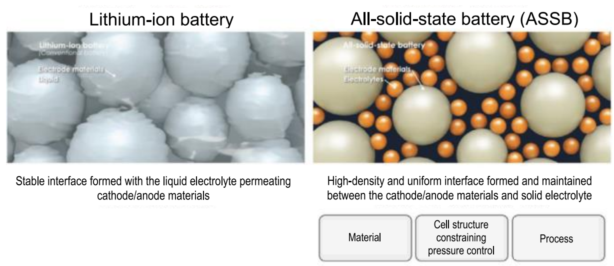


Fig. 7(b) Challenges of ASSBs (right) as compared to lithium-ion batteries (left)

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, CO2 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.

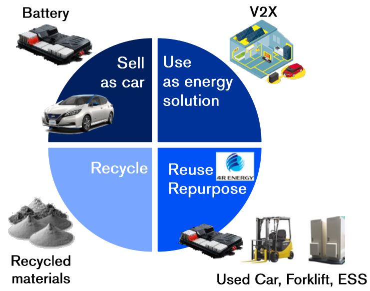


Fig. 8 Sustainable eco-cycle for recycling EV batterie

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(3) https://www.4r-energy.com/

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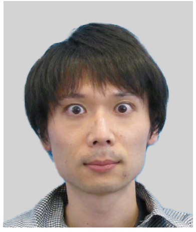

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Special Feature 1:Electrification

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).

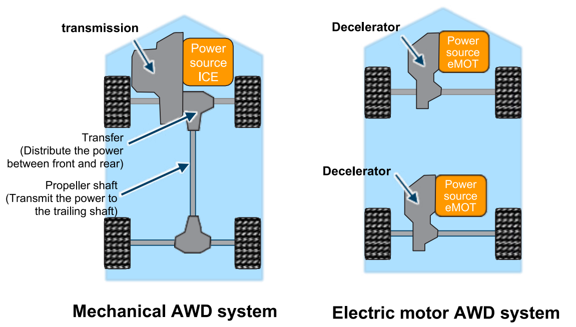

Fig. 1 Comparison of AWD systems

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).

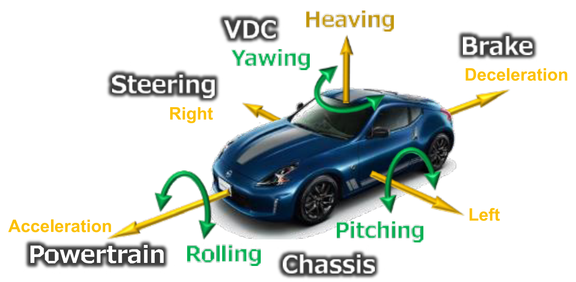

Fig. 2 Vehicle movement and system roles

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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).

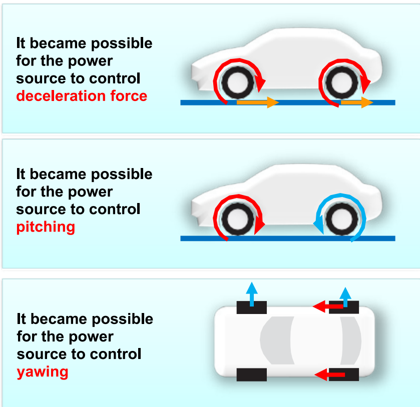


Fig. 3 Movement of electrified AWD

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).

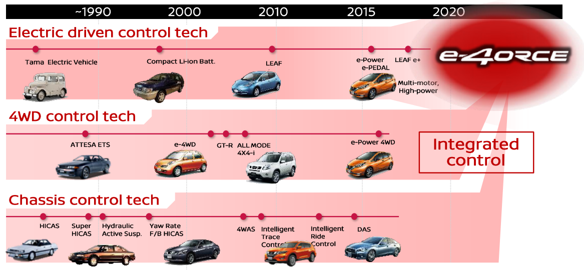


Fig. 4 Technical flow of e-4ORCE development

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.

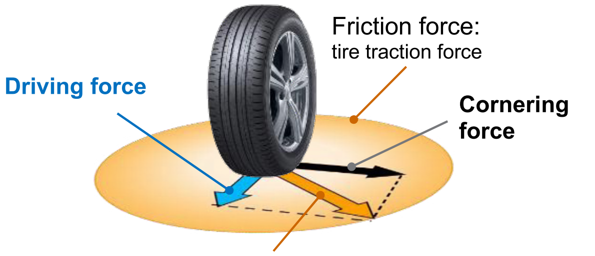


Fig. 6 Tire traction and driving forces

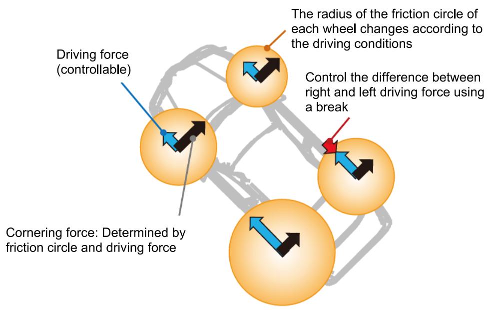


Fig. 7 Control of the force to turn each wheel using driving force

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.

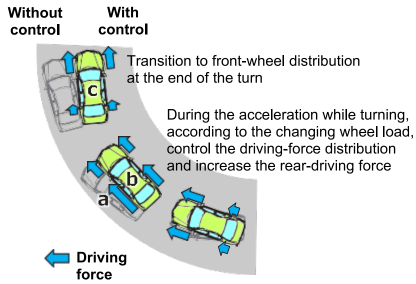


Fig. 8 Control of driving force distribution during turning acceleration

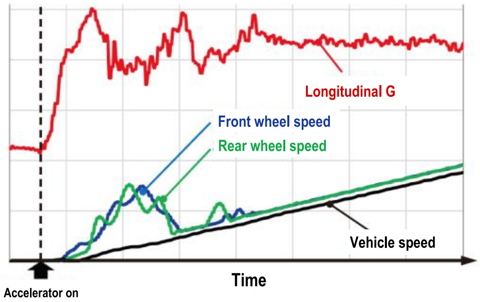
Starting on a slippery road

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.

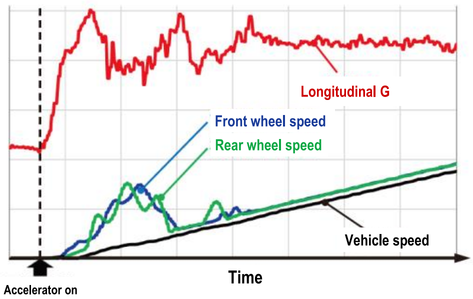
Fig. 9 Slippery road (image)

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

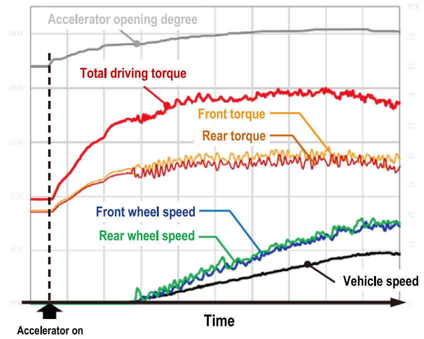
A sufficient driving force is required to overcome the running resistance caused by the tires being buried in the snow when the road is covered with deep snow in which the tires sink. However, the frictional force between the tires and road surface is small, and an excessive driving force can cause the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

Fig. 11 Driving through deep snow road (image)

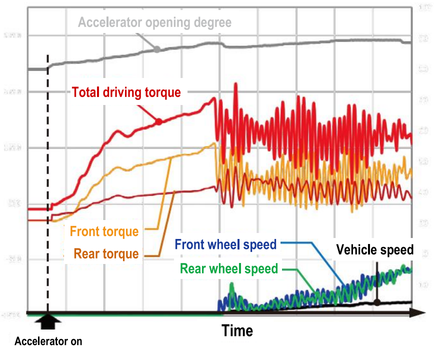
It is necessary to provide sufficient driving force to overcome the running resistance, and simultaneously, a precise control of the motor torque is necessary to prevent excessive tire slippage in such circumstances. The e-4ORCE controls the optimal front and rear motor torques according to the ground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

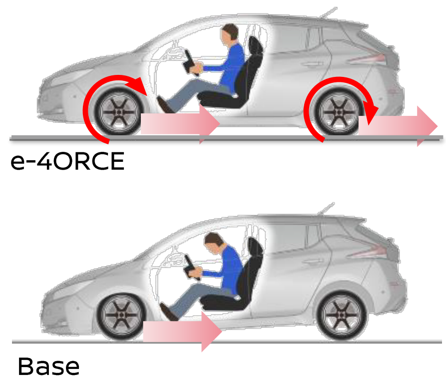
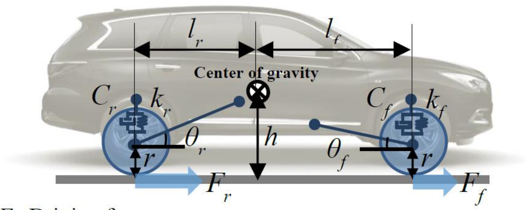


Fig. 13 Posture control during deceleration

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.

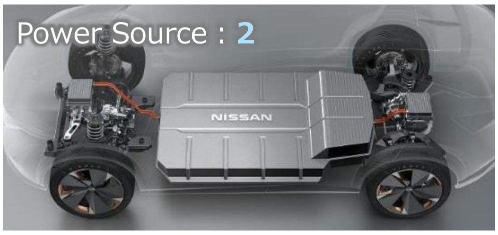
4. Summary and future prospects

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.

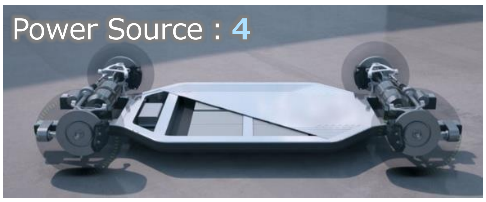
The aim of e-4ORCE is to bring out the full potential of the two onboard electric motors. However, it is believed that its full potential has not yet been realized. There is still room for improvement in the e-4ORCE, and Nissan aims to further develop this technology to enhance the benefits of vehicles.

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.

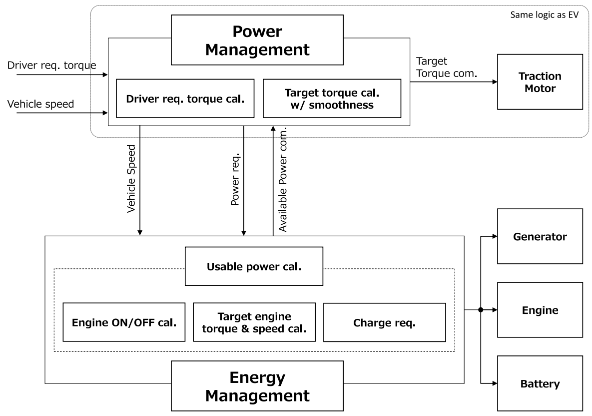

Fig. 1 Conceptual diagram of the e-POWER system

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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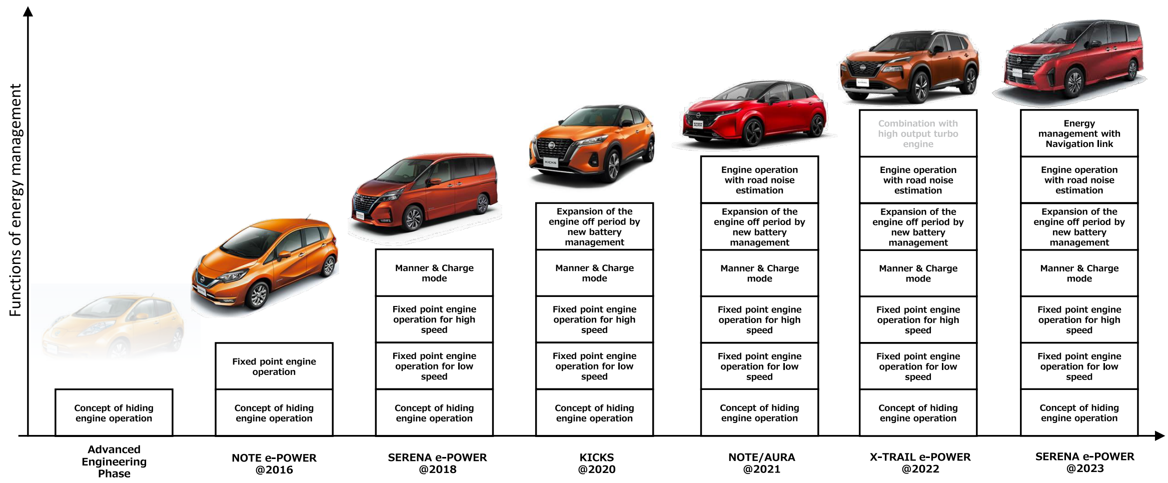

Fig. 2 Evolution of Nissan's energy management systems.

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.

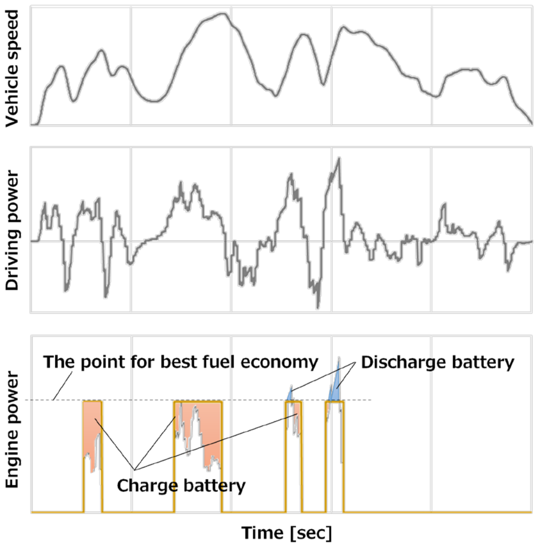

Fig. 4 Determination of engine operating points

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.

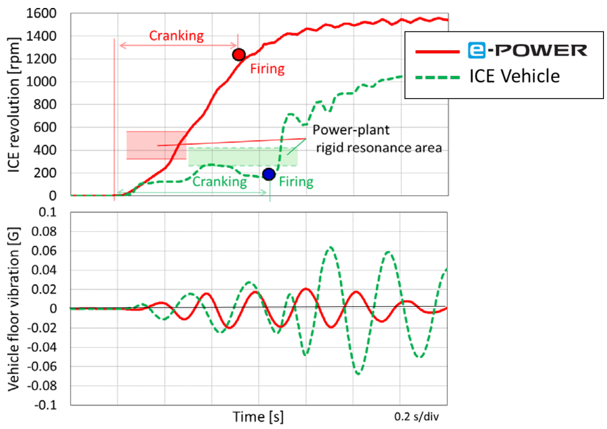

Fig. 5 Relationship between the timing of the engine ignition and the vibration of the floor

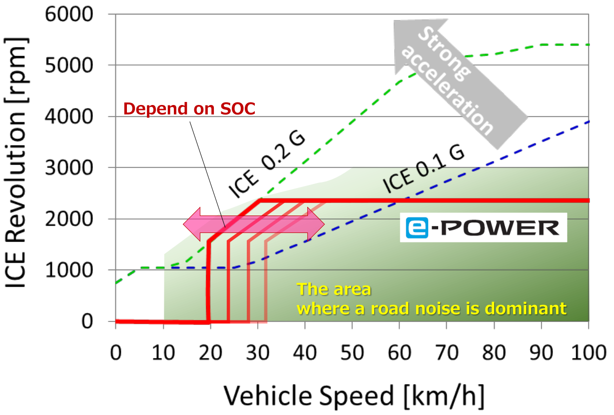

Fig. 6 Conceptual diagram of road noise in NOTE e-POWER with respect to engine revolution

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.

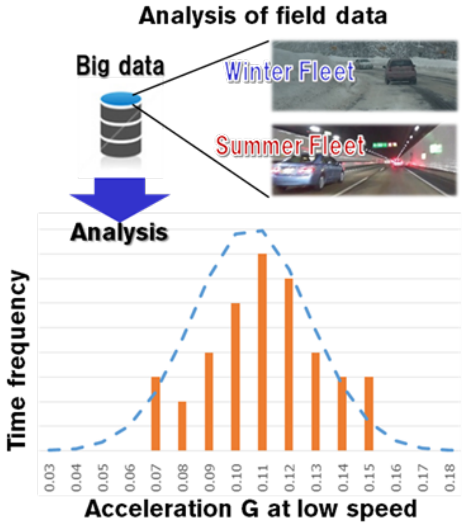

Fig. 7 Distribution of vehicle accelerations in the Japanese market

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.

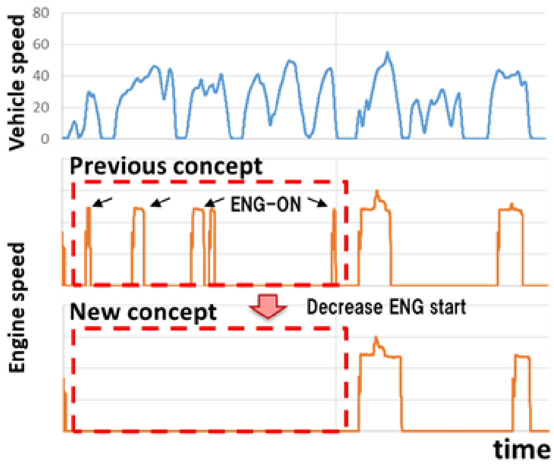

Fig. 8 Comparison between new and previous engine operating points

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.

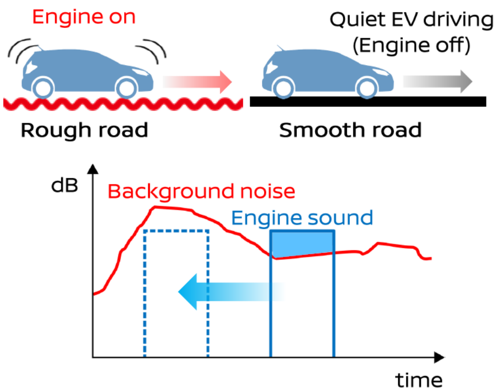

Fig. 9 Energy management concept based on the estimated road noise

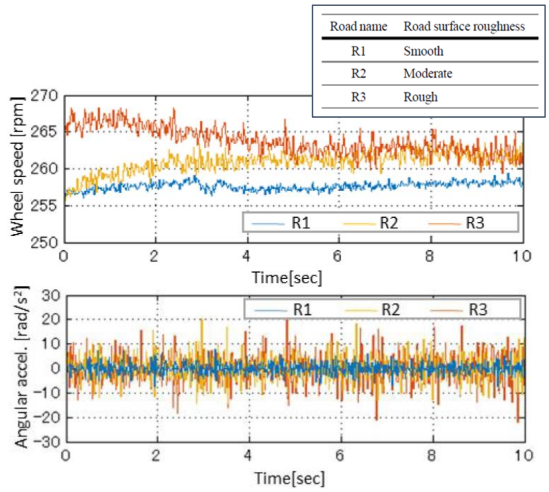

Fig. 10 Relationship between the road surface roughness and the angular acceleration of the wheel

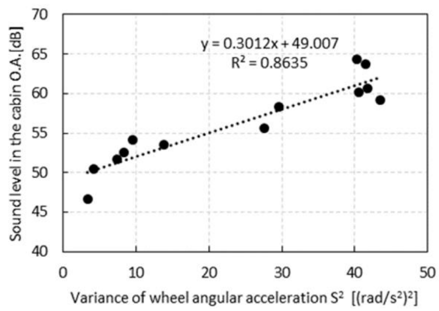

Fig. 11 Relationship between the angular acceleration of the wheel and the road noise

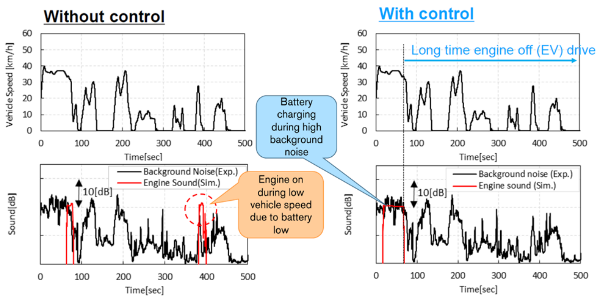

Fig. 12 Comparison between engine starts with and without road surface detection control

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.

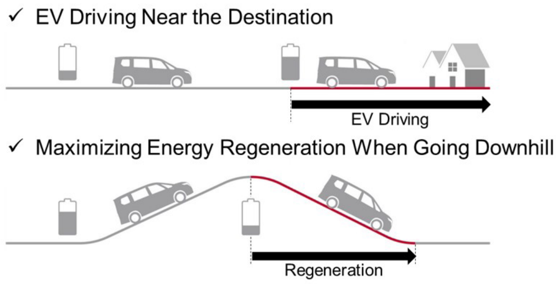

Fig. 13 Concept of predictive charging/discharging control

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

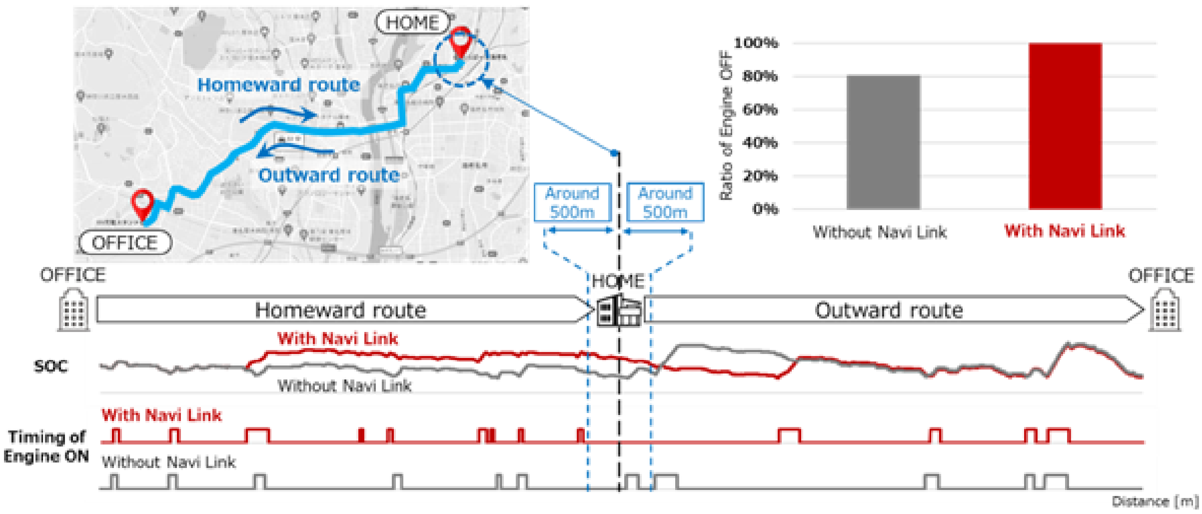

Fig. 15 Effect of predictive charging/discharging control (for enabling EV driving mode near the destination)

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.

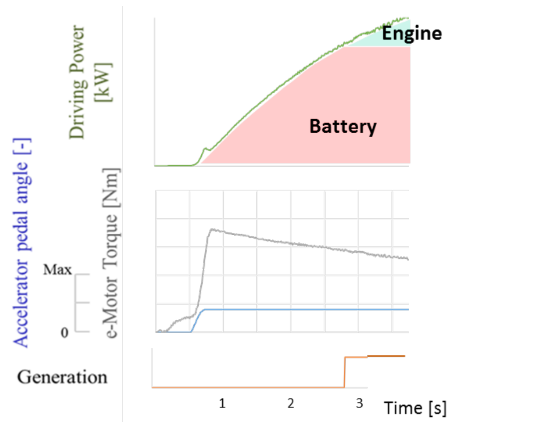

Fig. 16 Power distribution when the battery's SOC is high

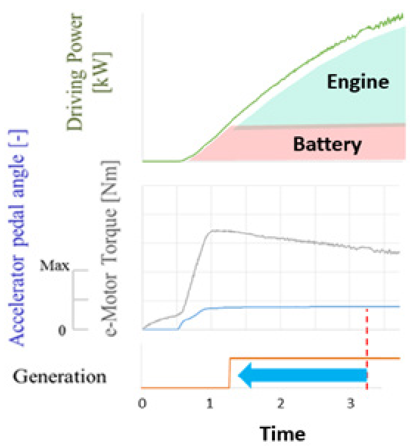

Fig. 17 Power distribution when the battery's SOC is low

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.

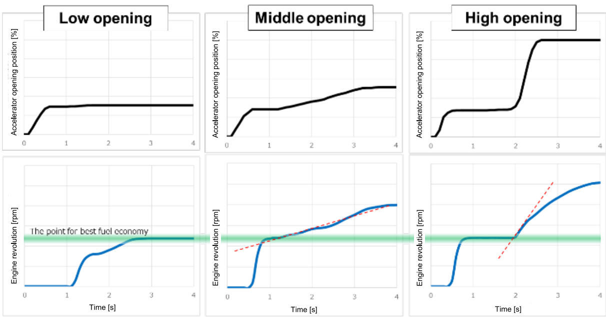

Fig. 18 Engine revolutions according to the intended acceleration

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.

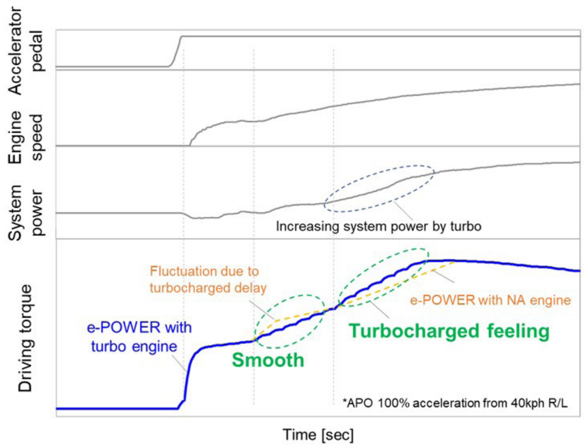

Fig. 19 Acceleration characteristics of e-POWER when combined with the VC-TURBO engine

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.

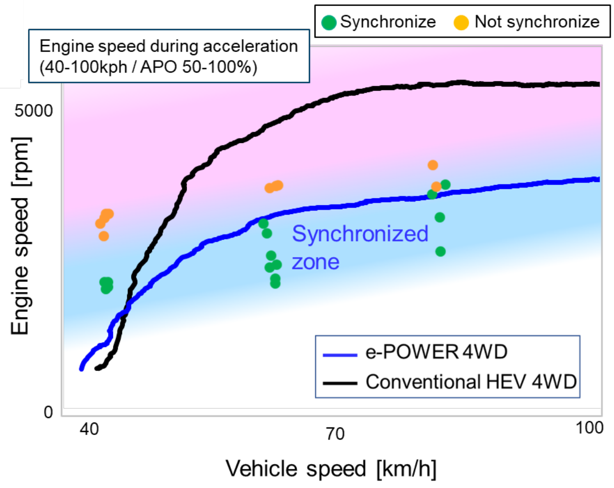

Fig. 20 Comparison between the engine revolutions of the e-POWER 4WD and a conventional HEV 4WD. The green dots indicate when the evaluator detected a synchronization between the increase in engine revolutions and the vehicle's acceleration, and the orange dots indicate when they did not detect such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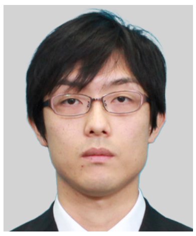
Hidekatsu Akiyama


Azusa Ito

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.

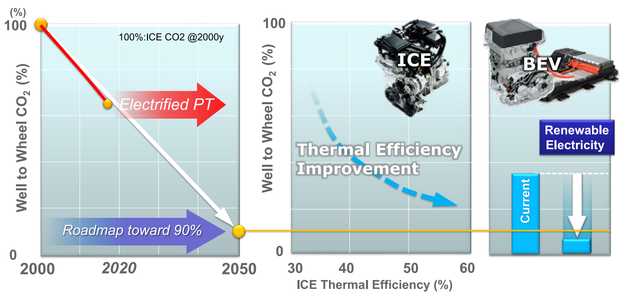

Fig. 1 NISSAN WtW CO_2 reduction strategy

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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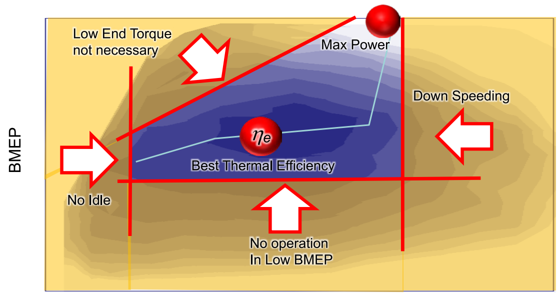

Fig. 2 Schematic of e-POWER engine operation and dedicated engine concept

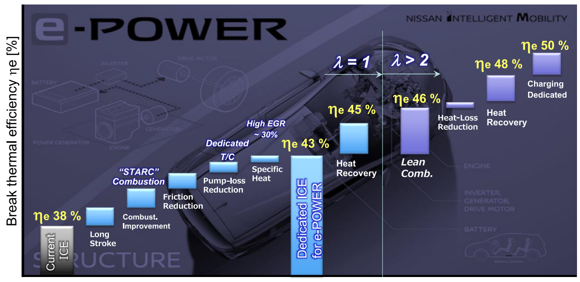

Fig. 4 Thermal efficiency roadmap toward 45% with lambda=1 and 50% with lambda > 2 (RON95)

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.

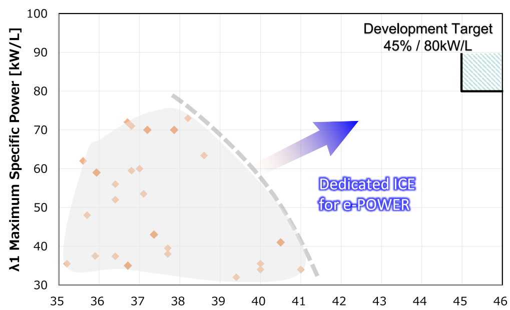

Fig. 3 Positioning of the new concept engine development target in brake thermal efficiency vs maximum specific output power (lambda=1) scatter band

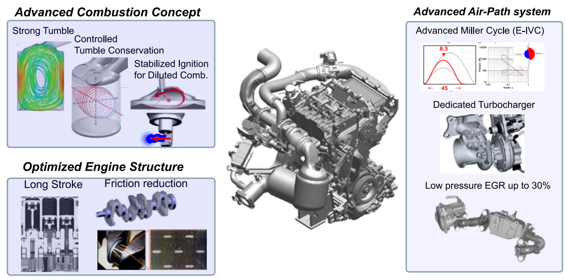

Fig. 5 New engine concept dedicated for e-POWER

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.

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%.

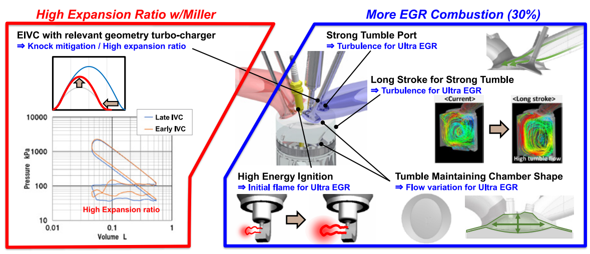

Fig. 6 New combustion concept “STARC” for highly diluted combustion

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.

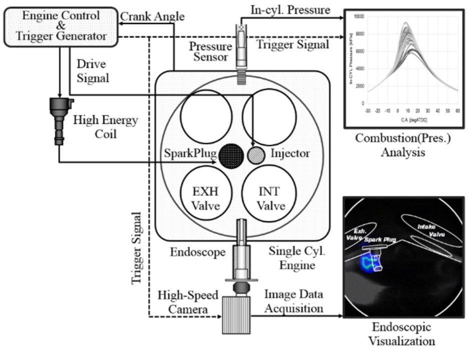

Fig. 7 Visualization system of spark discharge channel and initial flame kernel

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.

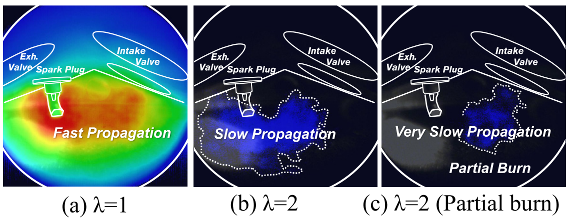

Fig. 8 Initial flame propagation with lambda=1 w/o dilution (a), lambda=2 slow propagation (b), lambda=2 very slow propagation (c)

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.

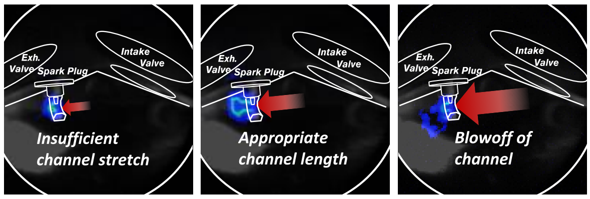

Fig. 9 Spark channel behavior under different flow velocity at the spark gap

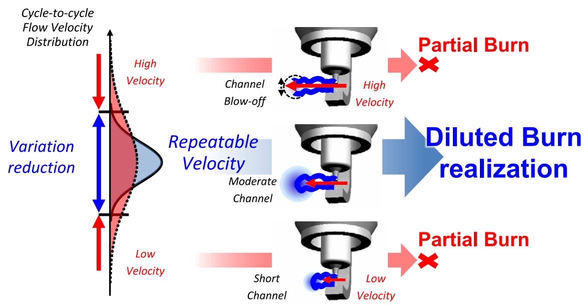

Fig. 10 Desirable flow to realize stabilized ignition for highly diluted combustions

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.

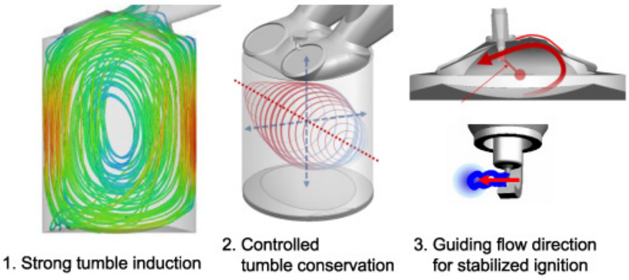

Fig. 11 In-cylinder charge motion design to realize STARC combustion concept

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.

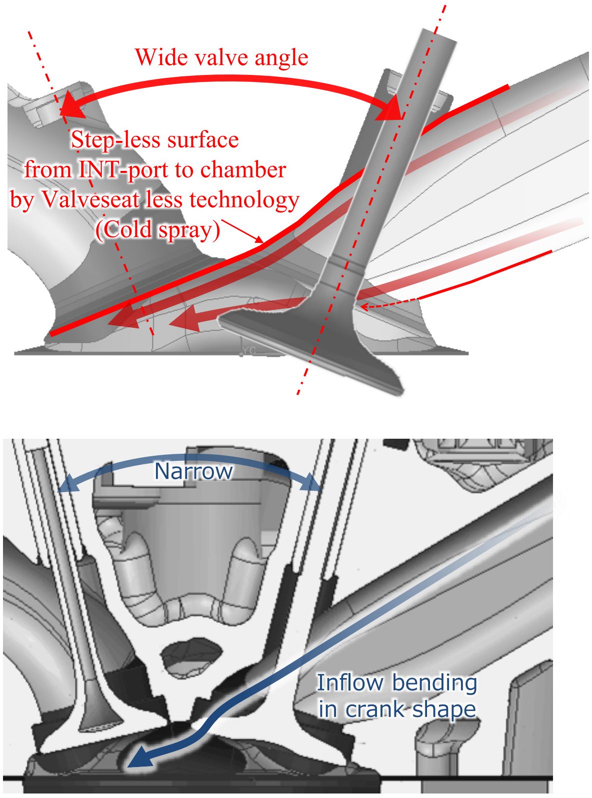

Fig. 12 Comparison of design concept of intake port and combustion chamber (New design with cold spray valve seat (left), current design (right))

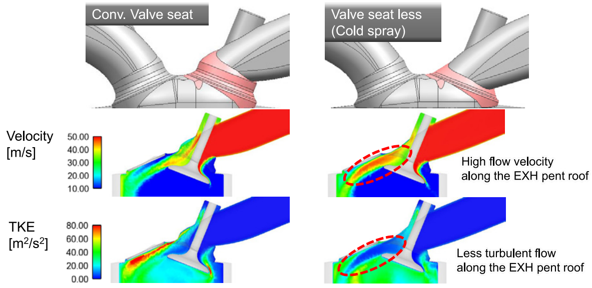

Fig. 13 Flow velocity and TKE distribution (CFD)

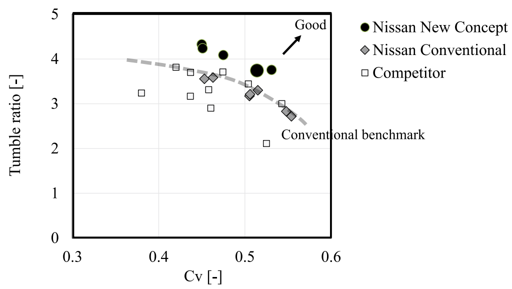

Fig. 14 Improvement of tumble-ratio-to-flow coefficient with new designs of intake port and combustion chamber equipped with a cold-spray valve seat

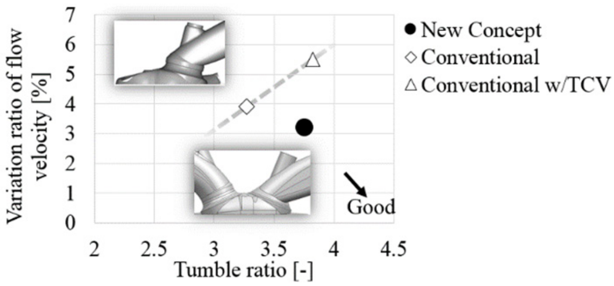

Fig. 15 Tumble ratio vs variation ratio (Air-flow test result)

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.

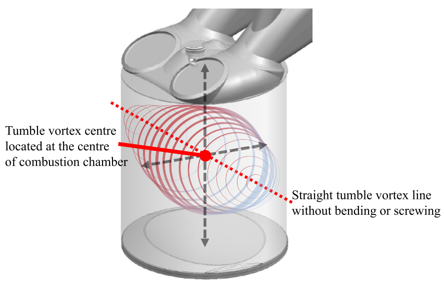

Fig. 16 In-cylinder charge motion design to maximize tumble conservation

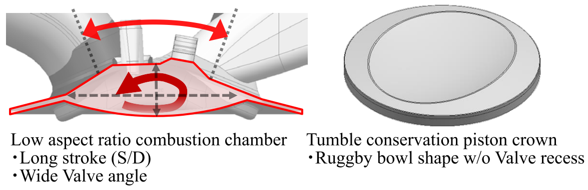

Fig. 17 Combustion chamber and piston crown design for tumble conservation

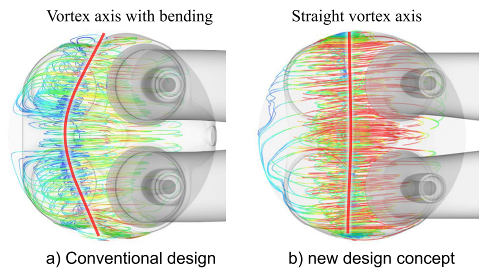

Fig. 18 CFD results of in-cylinder charge motion with conventional design (a) and new design concept (b).(2400 rpm, middle of compression stroke)

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.

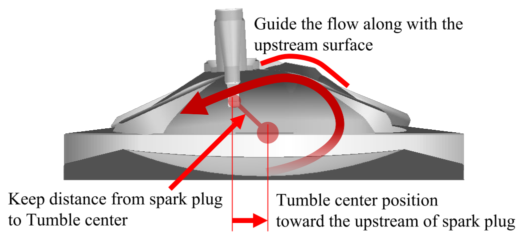

Fig. 19 Combustion chamber design to guide flow direction for appropriately stretched robust ignition channel

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.

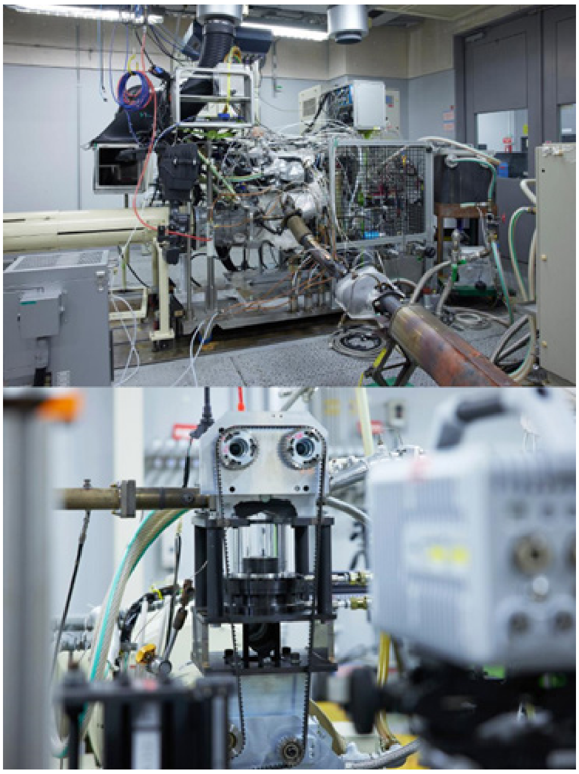

Fig. 20 Experimental equipment for new engine concept

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).

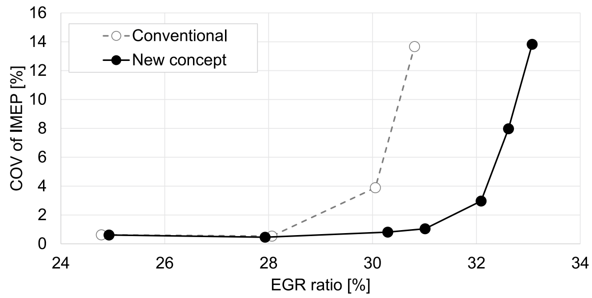

Fig. 22 Comparison of stable combustion limit against EGR between Conventional igni-tion system and new ignition concept with high energy ignition system

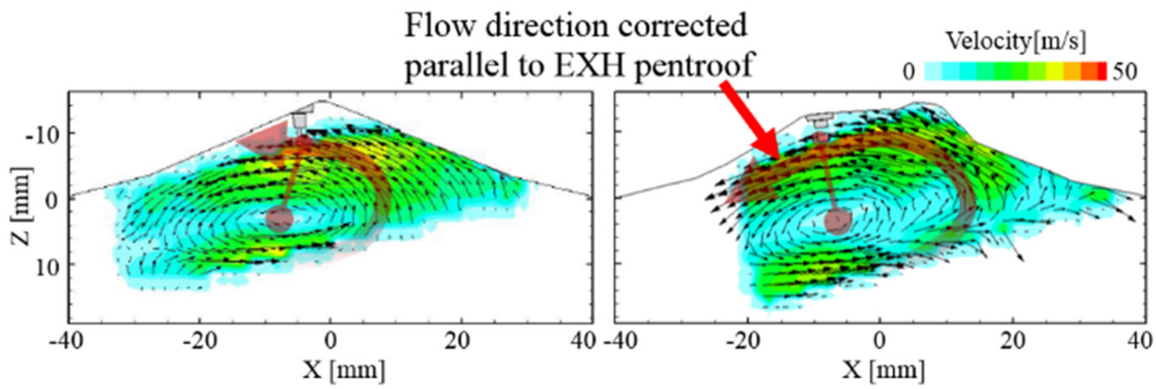

Fig. 21 Effect of the rectification pocket on the flow distribution around spark plug (PIV images, 2400 rpm, 40 deg. BTDC)t

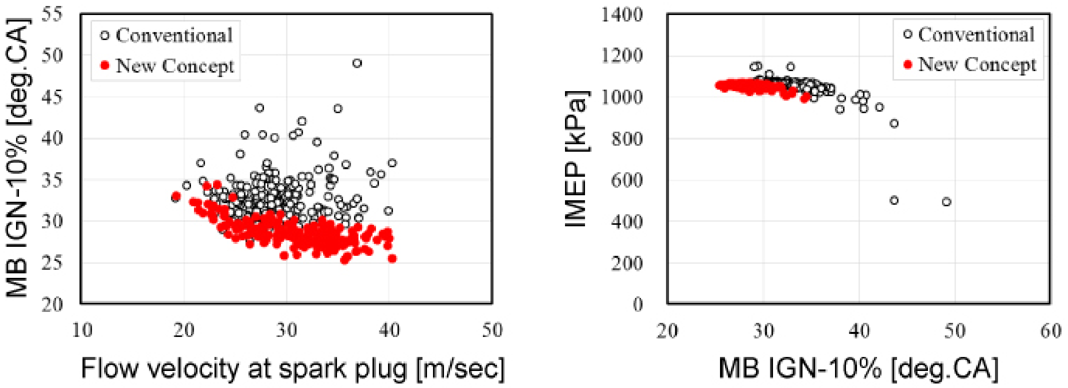

Fig. 23 Cyclic distribution of initial combustion period of CA ign-MB10% in relation to gas flow velocity at spark gap under EGR 30% conditions on same engine configuration except the ignition system

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.

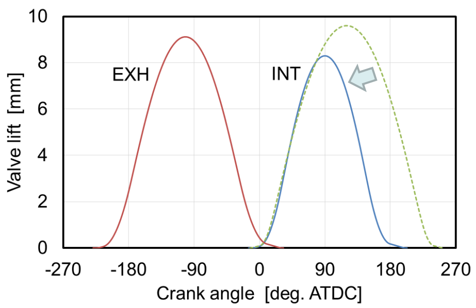

Fig. 24 Valve lift curve of conventional late IVC and E-IVC

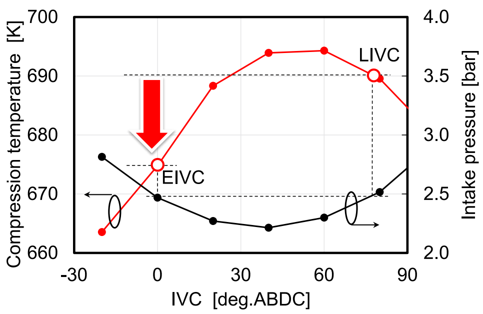

Fig. 25 Effect of IVC on the compression end temperature

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.

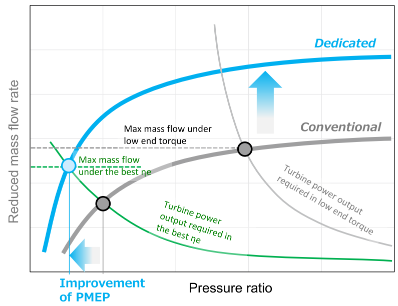

Fig. 26 Pumping loss reduction with e-POWER dedicated turbocharger

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.

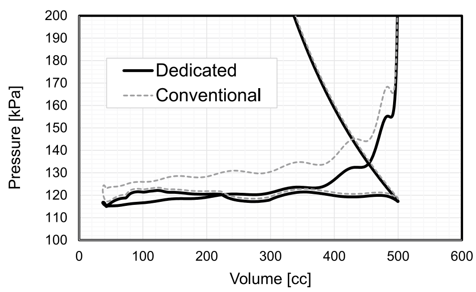

Fig. 27 Comparison of low pressure part of P-V diagram between conventional turbo-charger and dedicated turbocharger

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.

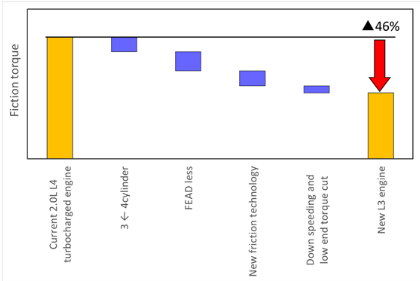

Fig. 28 Friction reduction of new e-POWER dedicated engine

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.

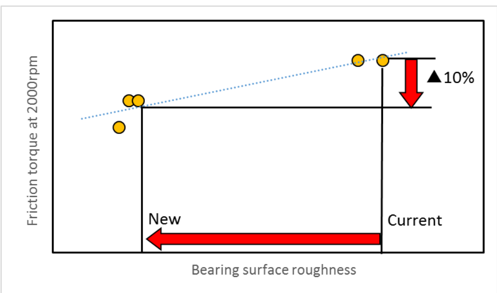

Fig. 29 Friction sensitivity by bearing surface roughness

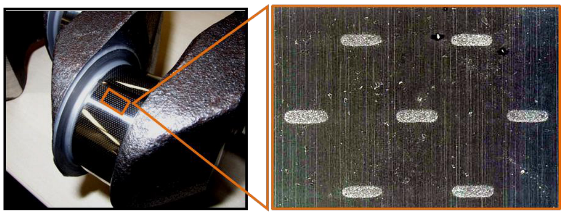

Fig. 30 Texture crankshaft surface

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.

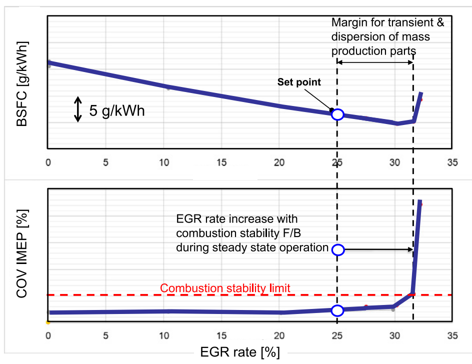

Fig. 31 Improvement of BSFC realized by e-POWER EGR set point and combustion stability feedback EGR target control

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 λ=1 was achieved using a multi-cylinder prototype engine with RON95 fuel.

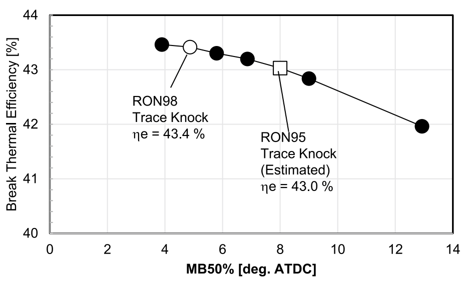

Fig. 32 Validation result of brake thermal efficiency with a multi-cylinder prototype engine (Engine speed 2000 rpm, BMEP 12 bar, RON98 fuel)

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 (λ>2) and during standard operation modes with a stoichiometric gas mixture (λ=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 λ>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 (λ=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 (λ=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).

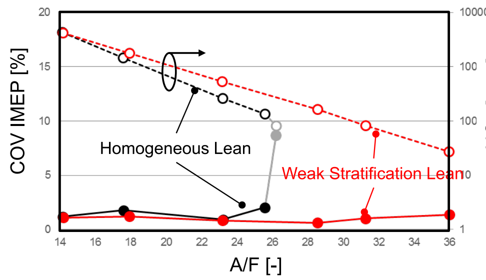

Fig. 33 COV of IMEP and engine out NOx in relation to Air fuel ratio (A/F)

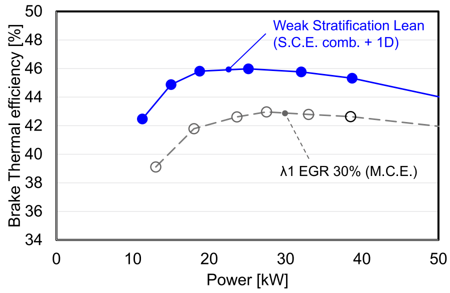

Fig. 34 Brake thermal efficiency vs Power with Lambda=1 and Lean burn (lambda=1 : Result of M.C.E., Lean: S.C.E combustion + 1D-Code Air-path)

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.

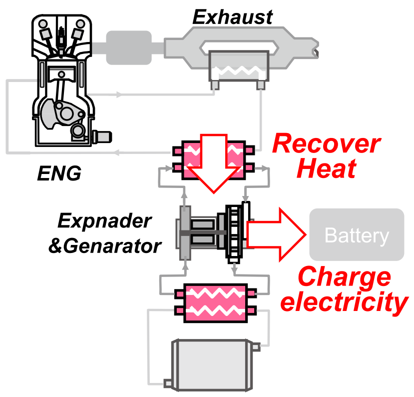

Fig. 35 Medium temperature rankine cycle heat recovery system

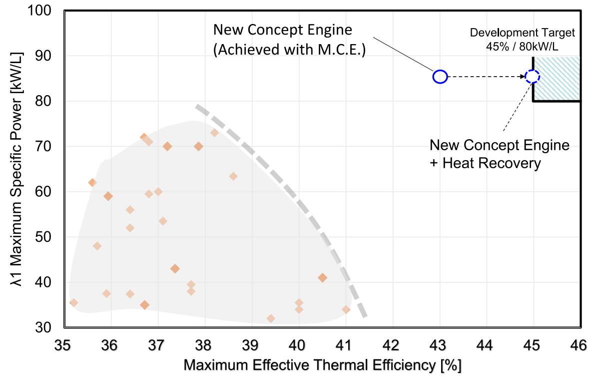

Fig. 36 Validation Results of the new engine concept

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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