Special Feature 2 : Constantly advancing e-POWER

1. Spreading the appeal of electric drive with e-POWER

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1. Introduction

In 2016, Nissan introduced the NOTE, which features an electric power system called e-POWER, to the Japanese market. e-POWER is 100% motor-driven, with all the power being generated by the engine. Since then, Nissan has continued to increase the number of e-POWER vehicle models. As part of the electrification strategy of Nissan, e-POWER has become an integral component of its electric vehicles as a sustainable technology that achieves sufficient environmental and driving performance simultaneously. This paper covers the history and values of e-POWER, including the technical challenges and future developments.

2. Belief in the proliferation of electric drive

Electrification and intelligence strategy of Nissan ahead of CASE

Nissan commenced its electrification and intelligence study as a technical development strategy in approximately 2005. The strategy was publicized outside the company prior to launching the Nissan LEAF in 2010. Although CASE is a common technology that is currently used by all automotive companies, in 2005, the strategy of Nissan was challenging because it involved the battery electric vehicle (hereinafter referred to as BEV[*2]) and autonomous driving as the core technologies of electrification and intelligence, as shown in Fig. 1. For electrification, Nissan intended to achieve a 100% electric drive in the long run, while gradually increasing the ratio of electric drive vehicles.

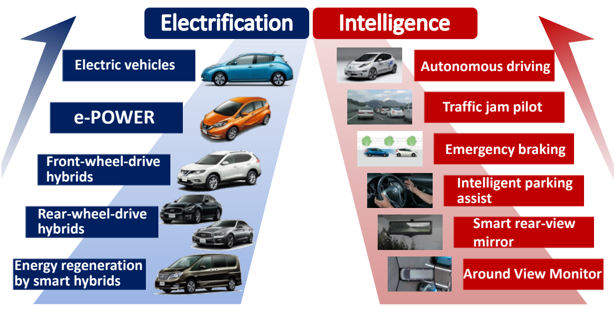

Fig. 1 Electrification and intelligence strategy

Shared motor drive regardless of energy source

The birth of e-POWER was supported by the research and development of power-generating electric vehicles (hereafter referred to as EVs[*1],) which have been promoted as catalysts for the proliferation of BEVs. To achieve an ultimate low-carbon society through electrification, Nissan has researched and developed technologies based on various energy sources, as shown in Fig. 2. These include direct hydrogen fuel cell technology (H2 FCEV), which uses hydrogen as the fuel; reforming fuel cell technology (e-Bio Fuel-Cell) using reformed biofuel for power generation; and internal combustion engine-based power-generating systems with gasoline as the fuel. All these technologies have been intended to expand the options for energy sources based on technologies for improving BEVs and have aimed at achieving a 100% motor drive.

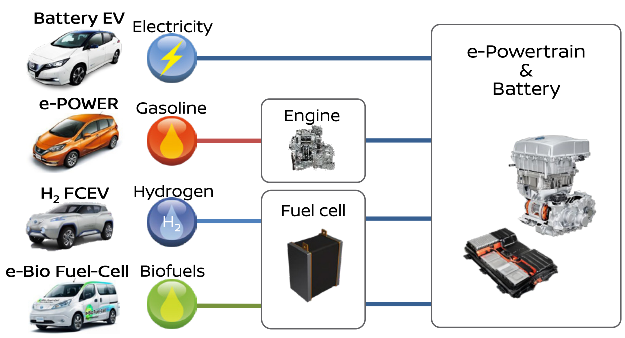

Fig. 2 Energy options for 100% motor-driven systems

Among these options, H2 FCEV and e-Bio Fuel-Cell show significant potential for the future. However, enhancing their proliferation requires further cost reduction and improvements in convenience, including infrastructure.

By contrast, engine-based power-generating systems can extend the driving ranges of range-extender EVs. These use high-capacity EV-dedicated batteries and

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engines as supplementary power-generating systems. Indeed, Nissan initiated the advanced development of range-extender EVs alongside the product development of the LEAF launched in 2010, as shown in Fig. 3.

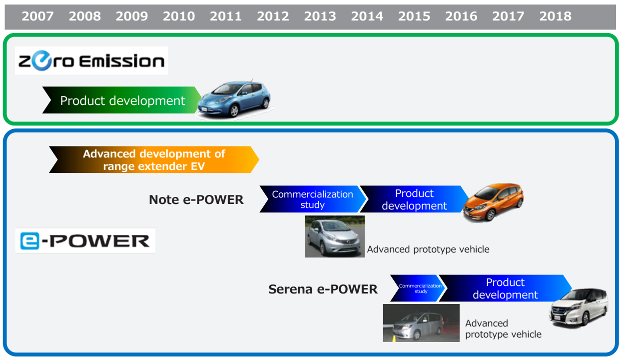

Fig. 3 Development histories of BEVs and e-POWER

For the practical use of e-POWER, Nissan employed the control technology developed for LEAF and the energy management and noise and vibration technologies developed for the range-extender EV. In addition, Nissan needed new breakthroughs such as high-power-density batteries, which will be discussed later in this article.

Improved response and smoothness of Nissan EVs through the development of LEAF

Essential factors for the proliferation of BEVs include a sufficient driving range, charging convenience, and realistic retail prices. In addition, our predecessors at Nissan strived to provide drivers of motor-driven vehicles with a powerful response and comfortable, smooth driving at the highest level, to ensure that the drivers were enthralled once they drove the vehicles. They were capable of satisfying drivers by expressing the excellence of the systems and control in the form of vehicles.

LEAF was launched globally in 2010 and gained an excellent reputation owing to its driving comfort and high level of quietness, which distinguished it from other motor-driven vehicles. The general BEV models vibrated noisily during acceleration, similar to carts; by contrast, LEAF provided a smooth driving experience even during rapid acceleration and deceleration. Thus, the superiority of LEAF was evident. Furthermore, after a trial ride, all the drivers were smiling; internally, this smile was called the “LEAF smile.”

3. Practical use of e-POWER with the main model in Japan

Start of development aiming at EV-ness[*3]

When Nissan decided to launch the NOTE e-POWER in 2014, the hybrid vehicle of a competitor had a significant market share in the compact vehicle segment in Japan. To launch electrification technology as a follower, Nissan needed to improve the fuel economy and also express the uniqueness of this vehicle. Thus, e-POWER, the main driver behind the electrification strategy of Nissan, was developed to define the characteristic of “EV-ness,” which represents the good driving performance of the Nissan LEAF.

Challenges different from those of range-extenders

Fig. 4 depicts the e-POWER system. The system is simple and consists of a BEV with an additional engine for power generation. The system configuration is similar to that of the range-extender EV described above; however, some parts are significantly different. Range-extender EVs supply power to the motor from the battery, similar to BEVs. Likewise, e-POWER vehicles also supply power from the battery under normal usage conditions; however, under high-load usage cases in which a high motor output is required, they supplement power by generating it from the engine. Because a smaller battery capacity, as compared to that in a range-extender, is required, the batteries can be downsized, which is advantageous for vehicle installation.

Conversely, achieving a BEV-equivalent “response” necessitated supplying the necessary power as quickly as possible; therefore, the battery output was increased by reducing its internal resistance. Hence, Nissan needed to devise a breakthrough solution to achieve a higher battery power density and create batteries that leveraged the characteristics of e-POWER.

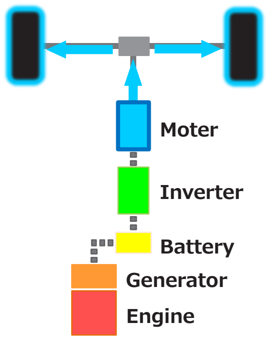

Fig. 4 e-POWER system

Because the system required 100% power generation, the efficiency of the power-generating engine was crucial, and Nissan improved it exclusively for e-POWER. It was also a new challenge to establish noise, vibration, and emission performances under the unique fixed-point operation at the maximum efficiency point, which will be detailed in a later article.

In the system configuration of e-POWER, the motor that drives and the engine that generates power are mechanically separated from each other. Accordingly, Nissan assumed that LEAF-equivalent EV-ness could be achieved easily. However, as the system supplies the maximum power when combining the two types of power from the battery and engine, as discussed earlier, if the power generation of the engine is delayed, the response of the motor is also delayed. By contrast, if the engine is continuously operated to be ready for the power output, the EV-ness will be impaired, leading to poor fuel economy. Solving such trade-offs proved to be a considerable challenge for Nissan, which the range-extender EVs had not posed. The pertinent details will be discussed in a later article.

Driving SERENA with a 1.2L engine

The next challenge was to achieve EV-ness with SERENA, which was a larger vehicle than the NOTE. Hence, higher torque and output are required. The motor output and torque were optimized according to the vehicle model, as per the basic specifications shown in Table 1. To optimize the specifications using an engine and motor of the same type, Nissan implemented a modular design by varying the number of cells combined in the battery and the current capacity of the inverter.

		 NOTE	 SERENA	 KICKS
Motor (EM57)	Maximum output	80 kW	100 kW	95 kW
	Maximum torque	254 Nm	320 Nm	260 Nm
Engine (HR12)	Maximum output	58 kW	62 kW	60 kW
Battery capacity		1.5 kWh	1.8 kWh	1.5 kWh

Table 1 Basic specifications of 1st-generation e-POWER

The battery ratio of the SERENA is higher than that of the NOTE. However, the challenge was to achieve EV-ness by managing energy and power, as discussed above. Therefore, it was essential to conduct a simulation and also perform a feeling evaluation using an actual vehicle, in order to confirm practicality. As Nissan could not evaluate the SERENA under development on a public road, the vehicle was tested late at night at the reserved Hakone Turnpike several times to evaluate feelings and practicality. Although the concept of driving a SERENA with a 1.2L engine, as described in the presentation materials, was difficult to understand, Nissan improved the EV-ness of the mini-van to the optimal level through repeated driving tests. Nissan performed the final evaluation after the relevant executives experienced the ride comfort during the late-night trial rides at the Hakone Turnpike.

Ride comfort of e-POWER that stimulates purchase intention once experienced

During the development of clear EV-ness while working on the breakthroughs mentioned above, the key for the successful launch of e-POWER was its simplicity. This characteristic enabled the engineers involved in the development and the concerned internal parties to quickly discover the superiority and difference of e-POWER, as compared to competitors' HEV systems, during the trial rides. They were satisfied with the technology, as evidenced by the LEAF smile described above, and showed the intention to purchase. Although fuel economy is an important factor when purchasing a vehicle, Nissan shifted the point of the discussion to a more important factor, that is, how the ride comfort of the vehicle could be conveyed to the customers to stimulate their intention to purchase. Nissan needed to convey the following three benefits to customers:

- Linear and smooth acceleration, with the feel of an EV.
- High level of quietness
- Top-level fuel economy in the class

In fact, Nissan held almost 20 test ride events with the concerned internal parties before finalizing the launch of the NOTE and SERENA. Thus, they developed confidence in the vehicles as intended through exceptional performance during the physical demonstrations.

As discussed above, the promotion of EV-ness and the provision of appropriate energy and power management were challenging but exciting aspects of the development of e-POWER. During its development, every step was challenging, including the study of the trade-offs and the judgment criteria that were completely new to Nissan. The details of these challenges will be discussed in future reports.

4. Contribution to building of the Nissan brand

Brand strategy of Nissan evolved from electrification and intelligence

The brand strategy of Nissan, "innovation for excitement," is not only the value that is intended to be offered to customers but also the brand promise.

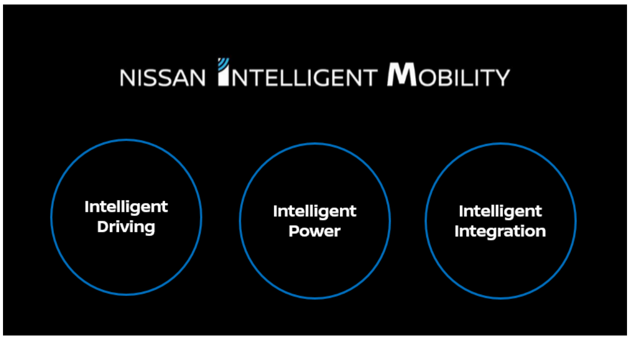

Fig. 5 Nissan Intelligent Mobility

To deploy this strategy in a more competitive manner, Nissan adopted a differentiator, Nissan Intelligent Mobility (NIM), as a slogan. NIM is a generic name for innovations conveying futuristic visions and is composed of the three elements shown in Fig. 5. The three elements are shown in parallel; however, the concept is that the electrification (intelligent power) and intelligence (intelligent driving) described earlier evolved first to create an integrated value (intelligent integration). To summarize, NIM is built on the developed electrification and intelligence strategies.

Strengthening of the Nissan brand using technology

With the intelligent power of NIM, the objective is to accelerate the enjoyment of clean, quiet, and powerful driving that is unique to Nissan by offering dynamic driving experiences through electrification technology.

As shown in Fig. 6, Nissan embodied clean, quiet, and powerful driving in e-POWER technology to offer customers. In addition, e-4ORCE, which offers a new driving experience by driving with motors on both the front and rear wheels, and e-POWER Drive and e-Pedal, which enable deceleration with the accelerator pedal, are particularly compatible with the electrification technology of 100% motor drive. In this way, they deliver a unique driving experience together with the EV and e-POWER.

Fig. 6 Core technologies of intelligent power

As discussed above, e-POWER has been a key technology for supporting the brand building of Nissan. This is expected to contribute to the strengthening of the brand in the future and to offering new value to customers through technical innovations.

5. Delivering to customers worldwide

Achieving the No. 1 sales position in the segment with first-generation e-POWER

The first-generation e-POWER vehicles, as shown in Fig. 7, quickly impressed customers with the same driving feeling as BEVs, which stimulated their purchase intention and ensured their satisfaction after purchase. The following four points were highly evaluated, which exceeded the expectations of Nissan during development:

- Linear and smooth acceleration, providing the feel of an EV
- High level of quietness
- Top-level fuel economy in the class
- New driving feeling created by the acceleration and deceleration using accelerator pedals

Regarding the sales results, the NOTE achieved the No. 1 sales position in Japan in November 2016 for the first time in 30 years, after which the NOTE and SERENA achieved the highest sales volumes in their respective market segments. As of January 2021, the cumulative sales volumes of the NOTE and e-POWER are 440,000 units, and the sales volume of a subsequent model, KICKS, also shows a favorable trend.

Fig. 7 Lineup of first-generation e-POWER vehicles

Pursuing further EV-ness in second-generation e-POWER vehicles

The new NOTE, to be fully remodeled in 2021, is an e-POWER-dedicated model equipped with an improved second-generation e-POWER system. With this model, e-POWER has evolved in an ideal direction by providing improved power performance, smoothness, and quietness and creating a more EV-like feeling. To achieve these features, Nissan has improved the motor, inverter, battery, and engine constituting the system to enhance not only the output and torque but also the fuel economy. Quietness has been further improved by reducing the engine operation frequency, optimizing the engine operation timing, and adopting a new control that operates the engine according to road noise. An electric AWD model has also been added to harness the benefits afforded by precise control.

Power train strategy based on inseparable technologies BEV and e-POWER

As discussed above, e-POWER is inseparable from BEV in the power train strategy of Nissan. These technologies show potential for further improvement and are promising in terms of covering wide segments and regions. This promise is attributed to their practicality, which enables the sharing of parts and control technologies, and also their flexibility, which allows for a modular configuration. Nissan will continue to focus on the driving feeling, quietness, and excellent environmental performance provided by these 100% motor-driven systems.

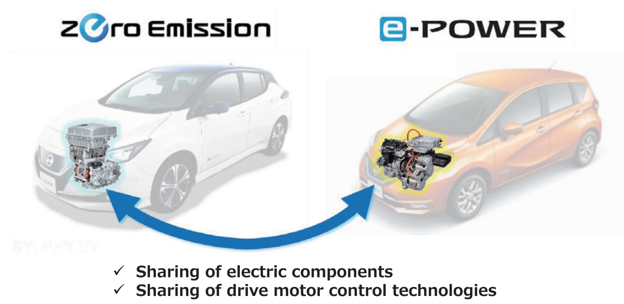

Fig. 8 Inseparable technologies in power train electrification strategy

6. Conclusion

Amid the growing global interest in environmental issues, it is said that the automotive industry faces a major once-in-a-century change. Even under these circumstances, Nissan will continuously strive to deliver the pleasure and comfort of a seamless driving experience to customers, while also achieving environmentally friendly fuel economy and emission performance. To attain these goals, Nissan has been expanding the range of e-POWER-equipped vehicle models from the NOTE to the SERENA, the KICKS, and the new NOTE that was launched recently. Nissan will continue to spread the appeal of the electric drive to ensure that customers worldwide can experience the LEAF smile.

Explanation of terms

*1 EV: Vehicle driven by an electric motor alone.
*2 BEV: EV driven by battery power alone.
*3 EV-ness: The quiet, powerful, and smooth driving feeling unique to electric motor drives
*4 EV driving: Driving with e-POWER operated by the battery power alone, with the engine stopped.

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Special Feature 2 : Constantly advancing e-POWER

2. Characteristics of e-POWER system and future development

Naoki Nakada*

1. Introduction

This article introduces the electric powertrain, e-POWER, which has been newly developed to enable good driving performance of the Nissan LEAF. e-POWER is 100% motor-driven with 100% power generated by the engine. The following topics are covered in this article: Overview of the system, characteristics unique to BEV*1-like and new features that have been developed by solving various trade-offs at a high level, system design to achieve them, and future expansion.

2. 100% motor-driven e-POWER system

The BEV system comprises a drive motor, inverter, lithium-ion battery, and battery charger. For the e-POWER system, while the drivetrain is the same as the BEV, the following alterations have been made: significant reduction of the battery capacity as a power source, elimination of the energy charging function, and the addition of a power-generating gasoline engine and a generator as an alternative power source. It is a simple system that is 100% motor-driven with 100% power generated by the engine. As a 100% motor-driven vehicle, e-POWER can be defined as an EV*2 similar to the BEV. The good driving performance of the BEV is inherited, and the fuel economy can be improved by intensively using the optimum fuel consumption range because the power-generating engine is separated from the tires.

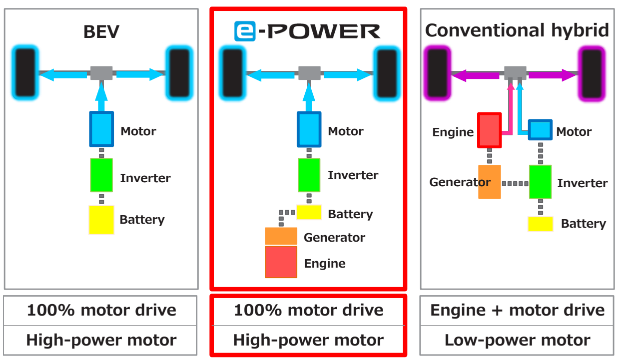

Fig.1 e-POWER system

Thus, e-POWER is an electric powertrain with great flexibility and various possibilities.

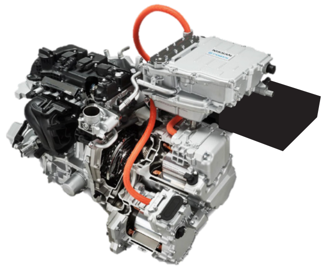

Fig.2 Appearance of e-POWER

Fig.2 shows the appearance of the NOTE e-POWER powertrain. As the engine is used for power generation only, it does not need to be positioned near the drive motor. However, we have integrated all the parts as much as possible to fit them compactly in the existing engine compartment.

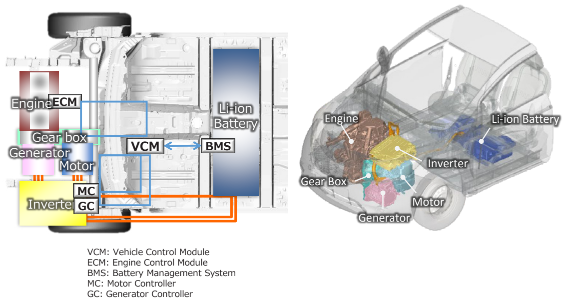

Fig.3 System configuration and layout

The engine is coupled to the generator via the speed increaser and the drive motor to the drive shaft via the speed reducer. Nissan put these two gear sets in a gear box to integrate the drivetrain- and generator-related components. The inverters for the drive motor and generator were placed in a single casing and installed inside the vehicle. A compact battery was installed under the front seat. By adopting this layout, Nissan not only fitted the e-POWER system in the platform of the compact

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vehicle, NOTE, but also achieved the comfort and ease of loading equivalent to those of gasoline-powered vehicles.

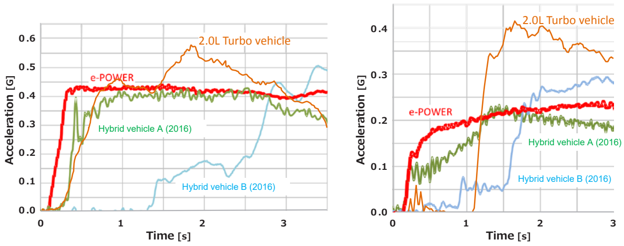
The e-POWER system is controlled by the main controller, the vehicle control module (VCM). The VCM works in conjunction with the MC (Motor Controller), GC (Generator Controller), BMS (Battery Management System), and ECM (Engine Control Module) to perform energy management and traction control by optimum power generation at all times.

3. Achievement of BEV-ness and pursuing new values

EV-ness[*3] - Smooth, High Response, Quiet
Fuel economy satisfying driving performance - Top level fuel economy
e-POWER Drive - Easy driving

Challenge of achieving responsive BEV driving

e-POWER achieves responsive, powerful, linear, and smooth acceleration when the accelerator pedal is depressed. By utilizing the characteristics unique to 100% motor drive, a maximum torque can be generated at low revolutions and no transmission mechanism is necessary. This is based on Nissan's motor controlling technology (motor damping control corresponding to the torsional resonance of the drivetrain) achieved through the development of the LEAF. This is a tremendous benefit that conventional hybrid vehicles have never had and is the primary feature of e-POWER.



Acceleration profile at standing start

Acceleration profile at passing from 60 km/h

Fig.4 Smooth acceleration of 100% motor drive

The keys to achieving such an excellent performance are the sharing of the power output from the energy-supplying battery and engine and the control of power generation. We have achieved them by optimizing the use of battery energy, engine start timing, and traction characteristics for various acceleration scenes. The details are described in Article 2.

Achievement of BEV-like quietness and fixed-point operation

The power generation by the engine that supplies and stores energy can be controlled separately from the drivetrain. Using this mechanism, we achieved BEV-like quietness. In practice, we have achieved it by adopting the following main concepts: active stopping of the engine in the low vehicle speed range and power generation with engine speed at which the driving noise masks the engine noise in the relatively high vehicle speed range. If a vehicle is driven at a low vehicle speed constantly, the battery energy decreases and the engine must be started to generate power. To address this, power is also instantly generated at an optimum fuel consumption rate with a relatively higher power of 2400 rpm × 76 Nm, 19 kW, which is equivalent to a NOTE's driving load at 120 km/h and is the operation point with a constant engine speed and load (fixed-point operation). In this way, the engine operation time is reduced to extend its stop time. Thus, we were able to stop the engine by approximately 90% at a vehicle speed of 25 km/h or less. However, in this fixed-point operation, we found two issues. One was the discomfort when vehicle speed and engine speed were not synchronized, which did not occur in conventional gasoline-powered vehicles. The other was the gap between EV driving[*4] and driving during the engine's fixed-point operation at a relatively high engine speed. The former is a characteristic of e-POWER, accepted in the market. We have evolved and improved the latter to apply it to the SERENA and KICKS based on the data and knowledge obtained from the NOTE. This is also described in Article 3. Other technologies for quietness are introduced in Article 5.

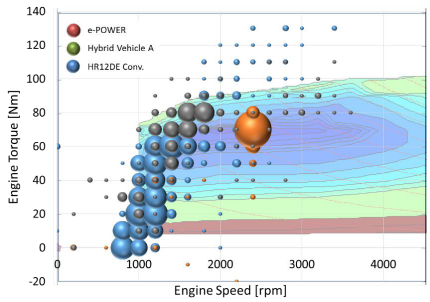


Fig.5 Incidence of engine operation points

Enhancement of fuel economy by fixed-point operation

With the power generation control based on fixed-point operation, Nissan has achieved the top-level fuel economy in its class by generating power for the energy required for driving at the point of best fuel consumption ratio, as much as possible. We have designed power generation control in such a way that the most fuel-efficient operation point is selected within the permissible ranges of various requirements. These include power, drivability, noise and vibration, exhaust emission, cooling, air heating, brake booster negative pressure, component protection, and diagnosis. Fuel economy-related information is detailed in Article 4.

Pursuing deceleration energy regeneration performance with e-POWER Drive

A new feature offered by e-POWER includes e-POWER Drive, which provides a new driving feeling. Because the driver can control the vehicle by operating only the accelerator pedal, driving will become easier and enjoyable. During the development of the 1st-generation LEAF, Nissan studied the recovery of deceleration energy based on cooperative regeneration with the brake. To improve the efficiency of energy recovery, Nissan also studied the one-pedal system that performed strong regeneration using only the motor. The main points observed from the development of this strong regeneration system are as follows: discomfort in drivability with respect to accelerator pedal operation, uselessness of strong regeneration mode that cannot be used even though the energy regeneration is large, and the setting of margins for safety and braking force limit on slippery road surfaces. For the 1st-generation LEAF, we set 0.08 G as the upper limit of the deceleration force by the motor regeneration in the ECO-B mode. Then, we further evolved the control of deceleration energy regeneration to generate a deceleration approximately three times that of gasoline-powered vehicles by optimally controlling the regenerative power according to vehicle speed, accelerator pedal operation, and slip ratio between the road surface and tire. Thus, we achieved drivability that allowed the driver to control acceleration and deceleration as intended by depressing and releasing the accelerator pedal. Accordingly, the NOTE e-POWER system did not use the cooperative regenerative system that has been a standard for electric vehicles. Through these efforts, Nissan has developed e-POWER Drive that about 70% of the deceleration of daily driving can be covered by only accelerator pedal operation. This significantly reduces the frequency of accelerator-brake pedal transfer, increases the energy regeneration amount, and offers driving pleasure and fuel economy at the same time.

4. System design for achieving BEV-ness

e-POWER delivers high reliability because of its simple system configuration and ensures a high-quality level due to being equipped with the same system components as those of the LEAF and the conventional NOTE composed of an engine and CVT.

The components shared with the BEV include the drive motor, inverter, 12 V DC/DC converter, and speed reducer. Technologies are also shared for high-voltage safety, sequence control of system start/stop, and traction control. This indicates that e-POWER, like BEV, is also highly advantageous in terms of compatibility with intelligent technologies such as autonomous driving.

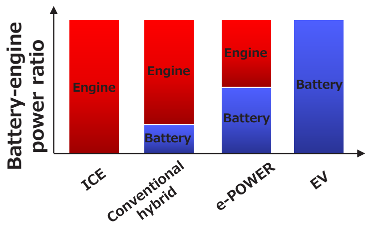


Fig.6 Sharing of battery power and engine power

However, compared with BEV, whose performance is highly dependent on the performance of the battery as an energy source, the performance of e-POWER is highly dependent not only on the battery's performance, such as output and capacity, but also on the power generation performance of the engine as another source of energy. Fig.6 shows an image of driving power sharing. The battery power of e-POWER accounts for approximately half of that of BEV, and the rest is covered by the engine. The battery capacity required for recovering regenerative energy and extending the EV driving time is 1.5 to 1.8 kWh, which is about a thirtieth of BEVs, although it is larger than that of other hybrid models. When designing the e-POWER system, it was important to properly select the specifications of the drive motor, the battery and engine powers, and the ratio between them to match the vehicle's concept.

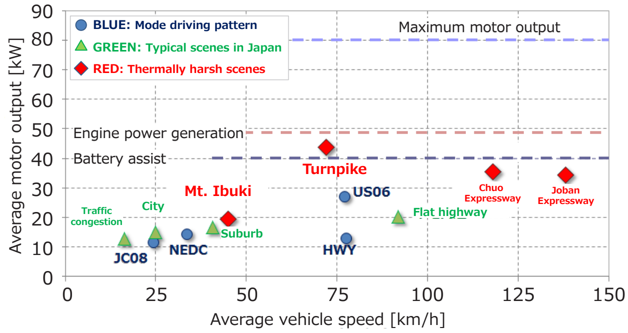


Fig.7 Balance between energy consumption and supply

A vehicle with e-POWER can only run on battery power in the typical driving scenes shown in Fig.7. In a scenario scenes that require a large driving force, powerful acceleration is achieved by adding the power from the generator. Fig.7 shows that the system has been designed to ensure sufficient driving performance even when the energy of the battery depletes and only the power generated by the engine is available. Nissan has optimally designed the power balance between the battery and power-generating engine for the driving power required for the vehicle. This has enabled Nissan to carry over the motor of the LEAF and the gasoline engine of the conventional NOTE.

The performance gets closer to that of the BEV by adopting a larger motor than that of conventional engine-dependent hybrid models and increasing battery power and capacity. However, doing so would increase the system cost and mass and threaten the feasibility of the layout. For this reason, Nissan must not only work on the cost/weight reduction, integration of electric components but also actively solve issues such as improving the efficiency of the integrated layout with the vehicle. In addition, it is important to select appropriate combinations of component specifications according to individual vehicle concepts factoring in the advantages and disadvantages discussed above.

5. Future expansion of e-POWER

The compact car, NOTE, and the mini-van, SERENA, both equipped with the EM57 motor and HR12 engine, satisfy their performance requirements by a change in battery capacities. As this example shows, the components of e-POWER are versatile, and the configuration allows system deployment in a modular manner. The components

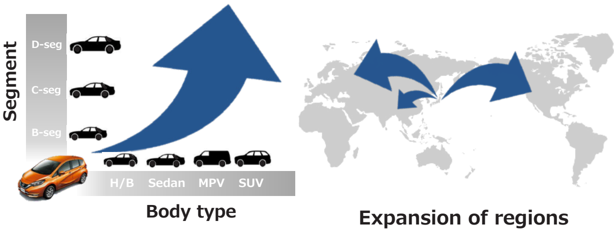


Fig.8 Future expansion of e-POWER

can be used for models in various segments and body types according to the combination of drive performance, power generation capacity, and battery capacity. The combination of the above motor and engine is also adopted in the compact SUV, KICKS.

The good driving performance of e-POWER's 100% motor drive is highly valued in the Japanese market. Due to congestion, the average vehicle speed is low and e-POWER enjoys a good reputation because it is quiet and fuel-efficient enabled by the combination of power generation at the point of best fuel efficiency and motor driving. To increase sales in the global market, Nissan must further improve fuel economy,adapt exhaust regulations and provide solutions for high-speed and high-load driving considering overseas environments. The flexibility of e-POWER has huge potential, allowing system selection and calibration tailored to region-specific usage and customer needs. For future expansion, it is essential to develop electric AWDs that utilize 100% motor-driven e-POWER and add value to e-POWER. The technical direction of the electric AWD system is introduced in Article 5.

6. Conclusion

e-POWER is a series hybrid that shares its drive system with the LEAF and uses the existing gasoline engine as its power-generating engine. Accordingly, it can be continuously enhanced along with the evolution of both BEV technology and engine technology.

In the future, expansion of the high-efficiency ranges of electric components and improvement in their efficiency during high-speed driving as well as in the thermal efficiency of the engines is expected. In addition, because e-POWER uses the engine for power generation only and the operation area can be reduced, the engine

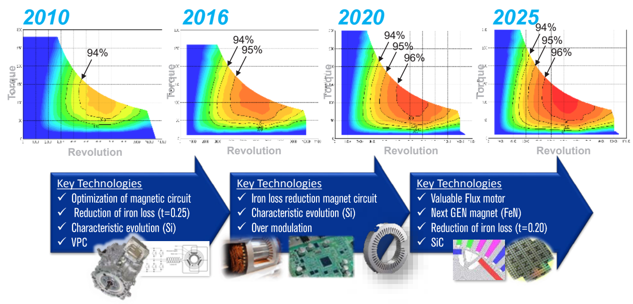


Fig.9 Technological evolution of electric components

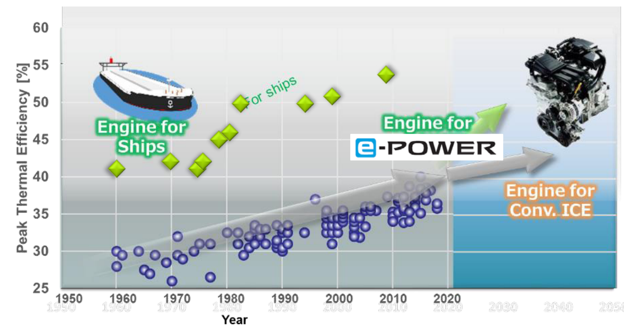


Fig.10 Technological evolution of e-POWER-dedicated engines

has greater potential than conventional engines in terms of efficiency improvement and can be simplified by focusing on the efficiency of fixed-point operation. Nissan will keep striving to develop solutions that only e-POWER can provide thanks to its configuration.

Explanation of terms

*1 BEV: An EV driven by battery power only
*2 EV: vehicle driven by electric motor only
*3 EV-ness:Quiet, powerful, and smooth driving feeling unique to electric motor drive
*4 EV driving:Driving with e-POWER, operated by battery power only with the engine stopped

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Author

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

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1. Introduction: EV-ness as the goal of e-POWER

Nissan has been developing e-POWER with the basic concept of providing customers comfortable driving utilizing the high-power motor of EV*[1]. This article discusses the technologies for embodying EV-ness*[3] in e-POWER equipped with a power-generating engine.

In Nissan, there are three key elements for EV-ness.

- Quietness: Exceptional quietness that conventional engine vehicles cannot offer
- Smoothness: No-shock, smooth feeling at acceleration and deceleration
- High response: Torque characteristic that allows for quick response to driver's operation and accurate link with driver's operation amount

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

For quietness, energy management is essential to reduce the discomfort the engine start-stop operations performed with operation noise in response to the request for power generation . For smoothness and high response, power management and energy management are essential for calculating the motor torque command in accordance with the driver's request and optimally supplying the power for the calculated torque command from the engine and battery. This article discusses energy management and power management that are the basic control functions of the e-POWER system.

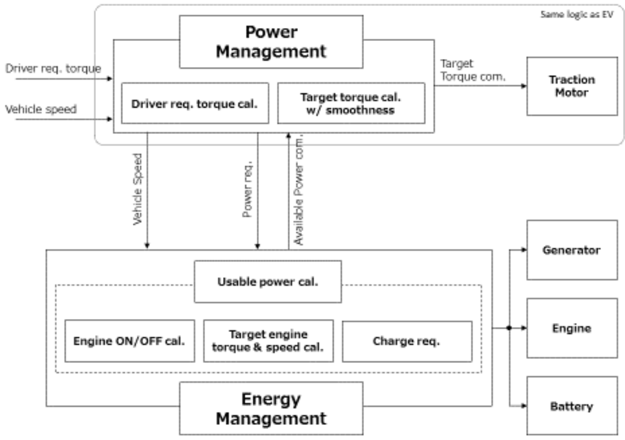

Fig.1 Conceptual diagram of e-POWER's system

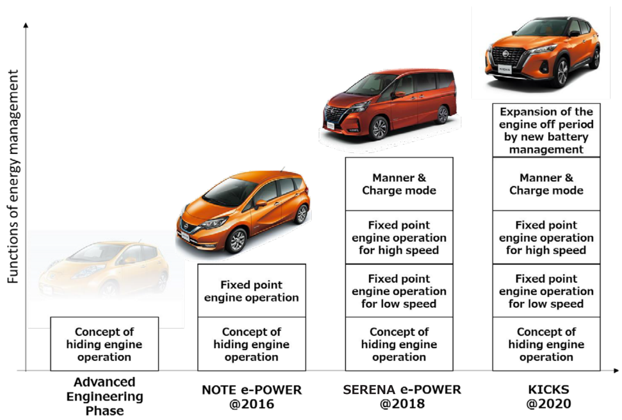

Fig.2 Evolution of energy management

2. Outline of e-POWER's system control

Fig.1 outlines the system control of e-POWER.

This system has been designed based the BEV*[2] which is also a motor-driven vehicle. Also, the power management for calculating traction is controlled in the same control logic as that for BEV. As for the energy management, the BEV's method has been adopted for the battery. For the combination of the engine and generator, e-POWER's own control block has been added. A charging system is provided for the BEV in place of the engine and generator above.

Because the power management of BEV is used in the traction calculation, the smooth and highly responsive traction characteristics accumulated through the development of the Nissan LEAF are achieved in e-POWER.

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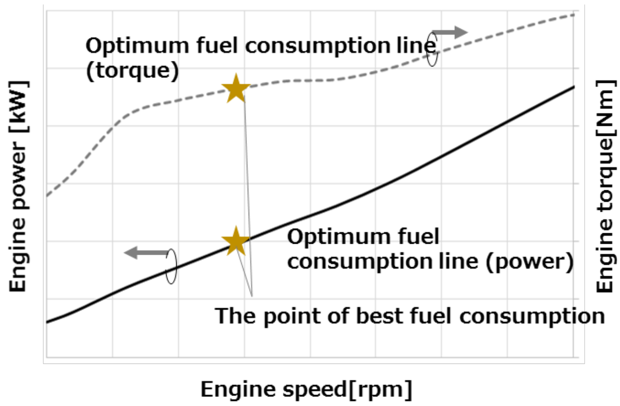

Fig.3 Optimum fuel consumption line and operation

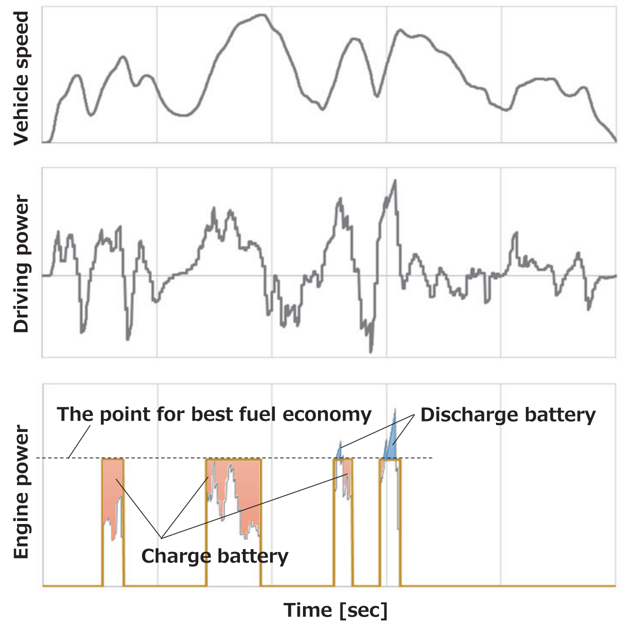

Fig.4 Determination of engine operation points

3. Development of energy management: Trade-offs between quietness and power

In e-POWER, the operation of controlling the engine and battery affects various functions and performances, such as fuel economy, acceleration performance, and the heating/cooling function. These functions for controlling engine operation and battery charging/discharging amounts are called energy management. The evolution of e-POWER technology is strongly linked to the improvement of this energy management. Fig.2 shows the evolution.

Energy management of NOTE e-POWER

When Nissan started the NOTE e-POWER project, which was scheduled to be launched in 2016, we aimed to develop a system with a greatly reduced battery power and capacity so that the system would satisfy the assembly and cost requirements of a compact car. Two new concepts were developed for achieving high fuel economy based on the concept of masking the engine's

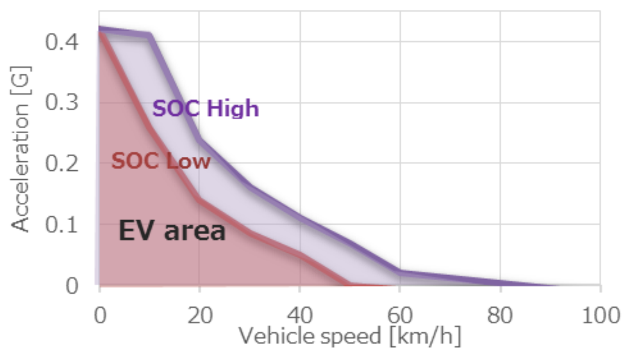

Fig.5 EV range responding to vehicle speed and battery's SOC

operation noise by the vehicle's ambient noise, which had been developed for advanced vehicles.

Concept 1: Improvement of fuel economy
⇒ Increase in the use of the point of best fuel consumption by fixed-point power generation and reduction of the frequency of engine starts
Concept 2: Achievement of EV-ness
⇒ Satisfaction of both response and smooth engine starts
The following describes the above two concepts.

Concept 1: Improvement of fuel economy

The basic concept of energy management is to ensure that the power required for driving by generating power is achieved at optimum efficiency. Fig.3 and Fig.4 outline the operation. Fig.3 shows the relationship between the fuel consumption rate characteristics and the power of the engine. The optimum fuel consumption line is a line connecting the operation points per engine power where fuel consumption is the lowest, and the point of best fuel consumption is an operation point where the combustion efficiency is the highest. Because, in case of e-POWER, engine operation points can be flexibly selected regardless of vehicle speed, power can be generated at the operation points on the optimum fuel consumption line according to the required vehicle power. In addition, by compensating for the difference between the required vehicle power and the power generated at the point of best fuel consumption using the battery's charge/discharge power, the use of the point of best fuel consumption is increased to improve fuel economy.

In the low-speed range, the engine's power generation is stopped and EV driving*4 is performed by battery power only. Thus, when a battery's state of charge (SOC) is high, EV driving can be performed in the higher speed range as well. As the engine operation conditions are not constrained by vehicle speed, e-POWER enables EV driving at higher vehicle speeds.

By adopting this control, e-POWER allows for driving at the point of best fuel consumption more frequently than other systems, as per the distribution of engine operation points shown in Fig.5 in the previous article.

Concept 2: Achievement of EV-ness

The battery power of e-POWER is higher than that of conventional hybrid models, which is intended to provide

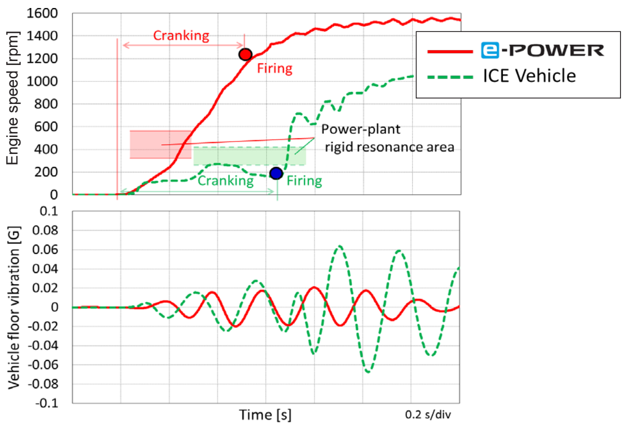

Fig.6 Relationship between engine ignition timing and floor vibration

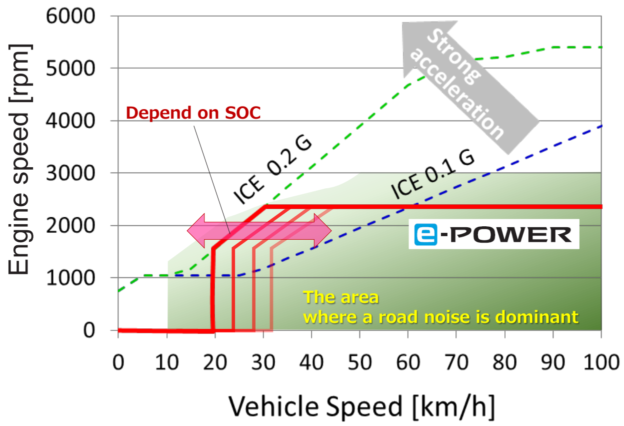

Fig.7 Conceptual diagram of road noise in NOTE e-POWER with respect to engine revolution

customers with the EV's responsive acceleration and quietness as if the engine is not operating. As shown in Fig.5, EV driving is performed during low-speed driving and continues up to high vehicle speeds with the engine stopped.

Because a high-power generator is used as an engine starter, the resonance vibration of the power train is quickly dissipated, as shown in Fig.6., which suppresses the vibration at the start of the engine.

Fig.7 shows the conceptual diagram of the engine revolution control of the NOTE e-POWER. Nissan achieved quietness by disabling the engine in the low-speed range to mask the noise by the ambient noise as far as possible. When rapid acceleration is required, Nissan achieved smoothness by increasing the engine revolutions to securely generate the power required for driving. Through these measures, Nissan achieved EV-ness with e-POWER.

Energy management of SERENA

For the SERENA, Nissan aimed for a control that satisfies both the quietness in the low-speed range and guarantees energy supply in the high-speed range. This aimed to enhance the image of the large mini-van, wherein family members and friends can enjoy traveling time.

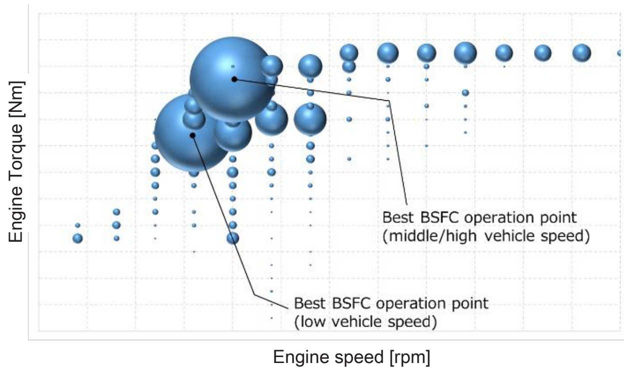

Fig.8 Operation ratios of SERENA's engine operation points

Nissan improved the engine, expanded the optimum fuel consumption range, and provided a point of optimum fuel consumption rate for low vehicle speeds and middle-to-high vehicle speeds. When driving in cities at low vehicle speeds and low loads, quietness was prioritized and power was generated at the point of best fuel consumption on the low revolution side. Because the revolution is low, the output at the point of best fuel consumption decreases, and the power generation for recovering the battery SOC takes longer. However, Nissan has provided measures against vehicle noise and suppressed engine operation noise to a comfortable level. When driving on suburban arterial roads, higher power is generated at the point of best fuel consumption on the high revolution side to expedite SOC recovery so as to quickly respond to a request for high acceleration.

In addition, the SERENA is equipped with a battery with a capacity higher than that of the NOTE and by charging and discharging the battery more actively, engine operation points are controlled at the point of best fuel consumption, although the overall mass of the SERENA is greater.

Fig.8 shows the distribution of engine operation points used when a vehicle is driven in fuel economy mode in Japan. Nissan has precisely controlled the engine operation points by improving the energy management control derived from the development of the NOTE to satisfy both quietness and fuel economy of the mini-van.

Nissan provided the SERENA e-POWER with new functions namely, charge mode and manner mode. Because the engine and drivetrain are not mechanically connected with each other in e-POWER, power can be flexibly generated regardless of the vehicle speed . Utilizing this characteristic, Nissan has developed a function that allows for forcible battery charging regardless of timing and driving mode (charge mode) and a function that allows for quiet, battery-powered driving with the engine stopped (manner mode).

The charge mode can maintain the battery's SOC at a high level, so that it is useful on mountain roads where acceleration force is continuously required. When the driver requires less acceleration, surplus power is actively charged to the battery to maintain the SOC at a high level to provide for an acceleration request in the future. In addition, by using this mode until just before selecting the manner mode, EV-like quietness can also be enjoyed

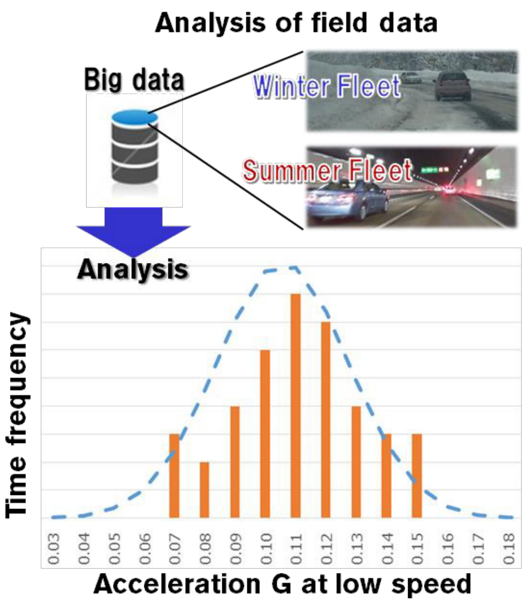

Fig.9 Distribution of accelerations in the Japanese market

for a longer time.

The manner mode is mainly intended to actively stop the engine. Other HEV models also have this type of engine stopping mode, but because e-POWER uses a high-capacity battery, the effect of this mode is large. Combined with the charge mode above, an unparalleled driving experience is provided with the engine stopped.

Energy management of KICKS

The energy management of the NOTE and SERENA is based on the intention for acceleration and focuses on the relationship between acceleration and engine start. To enhance EV-ness, Nissan has modified this concept for the KICKS and developed a control that performs SOC management while expanding the range when the engine is stopped.

Analyzing from actual driving data, Nissan assumed that the amount of power that the engine needed to generate to recover SOC was small because only small amounts of energy were required in scenarios where relatively brief acceleration would do. These included turning right at intersections and standing start when a traffic light changes. Accordingly, Nissan has maintained EV mode up to the lowest possible SOC to offer the quietness of EV driving to the driver and has set this control as the concept of energy management.

The criteria for the above control are the upper-limit of acceleration for maintaining EV driving and the setting method of permissible SOC. Unless these criteria are optimally balanced, adverse effects would occur, such as lowering of battery assist power during acceleration and continued power generation when the engine has to be stopped.

To optimize the permissible EV range, Nissan collected actual driving data for the NOTE and SERENA over hundreds of thousands of kilometers. The data was analyzed to investigate the distribution of driver acceleration patterns within the Japanese market. Fig.9

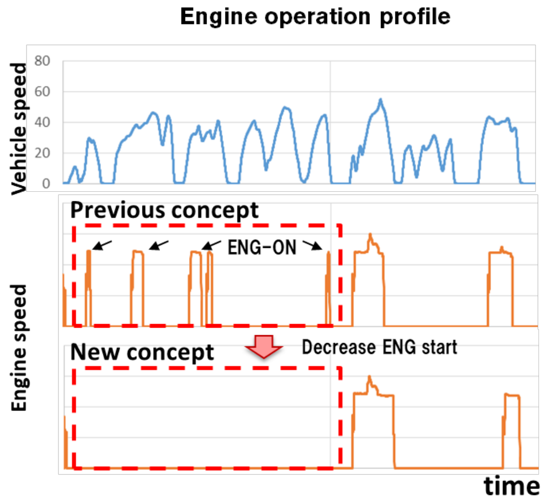

Fig.10 Comparison between new and previous engine operation concepts

shows the distribution of accelerations in the low speed range of approximately 30 km/h or less in the Japanese market. Fig.9 shows that generally, engine start can be avoided during normal driving by maintaining EV driving with an acceleration of approximately 0.15 G. Nissan also obtained data such as the consumption energy per acceleration–deceleration for each required vehicle speed range, which enabled us to optimize the engine start point.

By adopting the energy management of a new concept based on market data analyses, Nissan shifted the supply timing of the energy generated by the engine to a higher-vehicle speed.

Shifting the energy supply timing to a higher vehicle speed has the following two effects. The first is the reduction in the frequency of starts at low vehicle speed where ambient noise is low (reduction of the frequency of engine “start and stop within a short time period”). The second is the reduction of the frequency of engine start/stop by generating power all at once at a high vehicle speed to make effective use of the power generation system.

Fig.10 shows the engine operation modes of the new and old energy management concepts. Nissan has reduced the frequency of engine starts in the low-speed range, particularly the frequency of engine start and stop within a short time period. In the range of 30 km/h or less, Nissan reduced the engine starts to about 70% of that of the old energy management. This control has significantly contributed to the improvement of quietness, which is one of the major features of e-POWER.

4. Development of power management: Satisfaction of both smoothness and response

The traction control derived through the development of the Nissan LEAF is well accepted in the market, and the power management of e-POWER has been derived from that control. However, because e-POWER receives power from the battery and engine unlike an EV, where

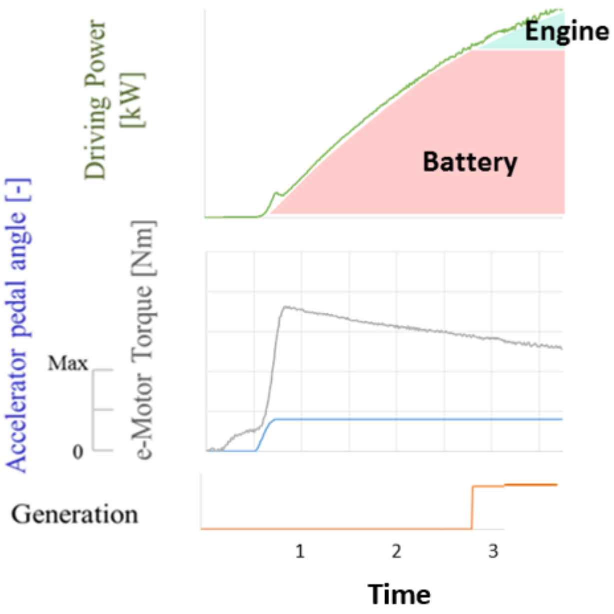

Fig.11 Power distribution when SOC is high

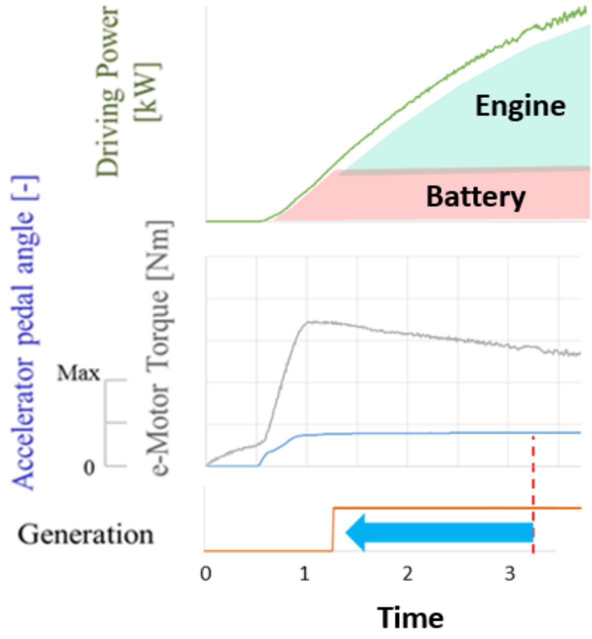

Fig.12 Power distribution when SOC is low

power is supplied from the battery only, the delay of power from the engine affects the acceleration performance.

In this section, we discuss the measures against such issues and the high response and smoothness that provides EV-ness to e-POWER.

4.1 Achievement of acceleration performance independent from SOC

The point of improvement for the power management of e-POWER, which is driven by the power from the engine, unlike the BEV, is the control that does not create the feeling of acceleration drop even when battery power is lowered.

Fig.11 shows the condition at the engine start during acceleration when the battery has sufficient power with a high SOC. EV driving is maintained while suppressing the engine's power generation as long as possible. In contrast, Fig.12 shows the condition when the SOC is low and sufficient power cannot be secured just from the battery. The power generation of the engine is started early so as not to create a feeling of acceleration drop. Through such control, the same acceleration feel is achieved regardless of the system condition.

4.2 Satisfaction of both acceleration feel and fuel economy

As discussed above, e-POWER satisfies the power required by the vehicle by jointly using the engine when the need for acceleration is high.

e-POWER can flexibly control engine revolution, although the increase in the engine's operation noise goes against the quietness of EV-ness. For e-POWER, we have varied engine revolutions so that acceleration feel can be created according to the driver's intended acceleration level suggested by the accelerator opening.

Fig 13 shows the engine revolution behavior at each accelerator opening position. Because fuel economy is also important, the opening position, if small, is controlled to maintain the point of best fuel consumption so as to satisfy both the required fuel economy and quietness. The increased rate of revolution and target revolution enhances the acceleration feel according to the level of the intended acceleration, and the acceleration feel is brought about by engine sound while securing the power required for driving.

5. Pursuing further EV-ness

The energy management and power management discussed above have been adopted in the new NOTE after further improvement.

Further evolution of e-POWER deepens the EV-ness.

To improve the quietness, Nissan has been exploring the possibility of extending the engine stop time. In the future, Nissan may be able to combine it with other systems, such as ANC (Active Noise Canceller) that actively deadens the noise. Because the e-POWER's unique power generation control at the point of best fuel consumption can be easily used as the target of the quiet zone of ANC, Nissan assumes that the ANC will be compatible with e-POWER.

To improve the smoothness, Nissan will further optimize the balance between the output characteristics of the engine and battery. When a high-power engine is installed, in particular, the power generated by the engine takes up a large share of driving power, and the output characteristic of the engine affects the smooth drive characteristic. As for engines, Nissan will continuously improve both specific fuel consumption and output characteristics.

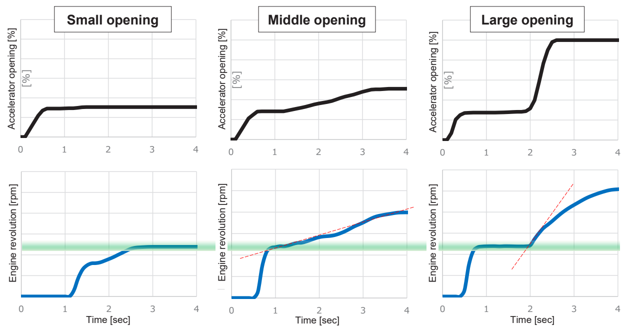

Fig.12 Power distribution when SOC is low

To improve the responsiveness to the driver's intended acceleration as with the BEV, Nissan will suppress shock and vibration and aim to actively control the vehicle posture.

Explanation of terms

*1 EV: Vehicle driven by electric motor only
*2 BEV: An EV driven by battery power only
*3 EV-ness: Quiet, powerful, and smooth driving feeling unique to electric motor drive
*4 EV driving: Driving with e-POWER, operated by battery power only with the engine stopped

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4. Fuel saving technology that satisfies e-POWER's driving performance

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1. Introduction

Nissan developed the electric power train system, e-POWER, which satisfies both fuel economy and the pleasure of a 100% motor drive. In 2016, the system was installed in the compact car, NOTE, for the first time. Since then, additional vehicle models have been added including the mini-van, SERENA in 2018, the SUV, KICKS in 2020, and the new NOTE in 2021.

This article introduces the fuel saving technologies that utilize the characteristics of "e-POWER system" that are inseparable from the electric vehicles in Nissan's power train strategy.

2. e-POWER system and operation mode

Fig.1 shows the system configuration of the e-Power. The biggest characteristic is that the power generation system and drivetrain are completely separated from each other. Thus, the operation points of the engine and generator can be flexibly determined regardless of the mode of the drivetrain. Nissan has also developed a new driving mode "e-POWER Drive," which fully utilizes the advantages of 100% motor drive. As shown in Fig.2, in the market, 90% or more of the deceleration is covered by the accelerator pedal to recover deceleration regenerative energy and enable the driver to control the vehicle with only the accelerator pedal, which achieves the feeling of "Fun to drive." *(1)

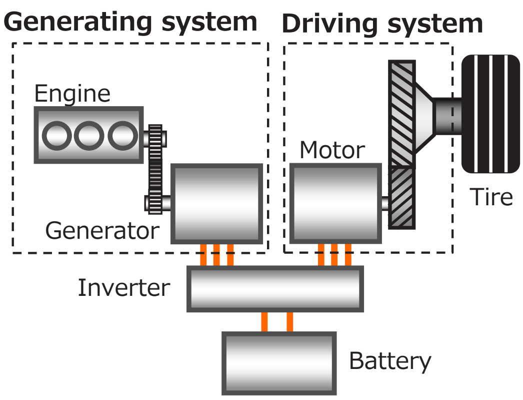

Fig.1 Diagram of system configuration

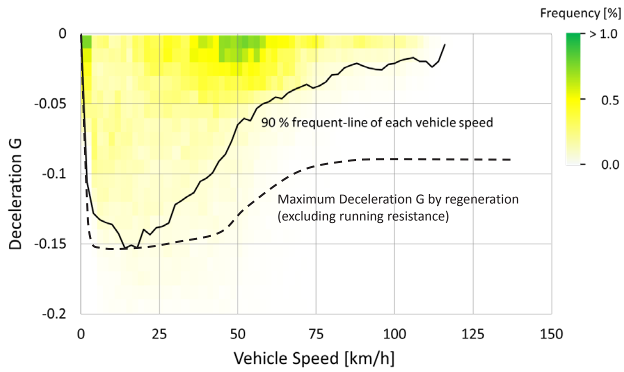

Fig.2 Deceleration frequency in the market and deceleration characteristics of e-POWER Drive

The system's operation is composed of the following six modes: Fig.3 illustrates each mode. Modes (1) to (5) are for basic operation and mode (6) is optional.

(1) The engine is stopped, and traction is achieved just by the power of the lithium battery.
(2) The vehicle is driven by the power generated by the engine, and surplus power is used to charge the lithium battery.
(3) The vehicle is accelerated using the power generated by both the engine and the lithium battery.
(4) The vehicle is driven by the power generated by the engine.
(5) The engine is stopped, and the coast deceleration regenerative energy is recovered to the lithium-ion battery.
(6) The engine is rotated by the generator used as motor to discharge power from the lithium-ion battery (for generating brake M/V negative pressure, performing OBD, and preventing battery overcharge).

3. Elements for fuel economy improvement commonly required for e-POWER

e-POWER converts the mechanical power of the engine into electric power by means of a generator and generates traction with the motor using electric power. Because of this mechanism, loss occurs during the conversion between mechanical power and electric power. To improve fuel economy, it is essential to devise measures

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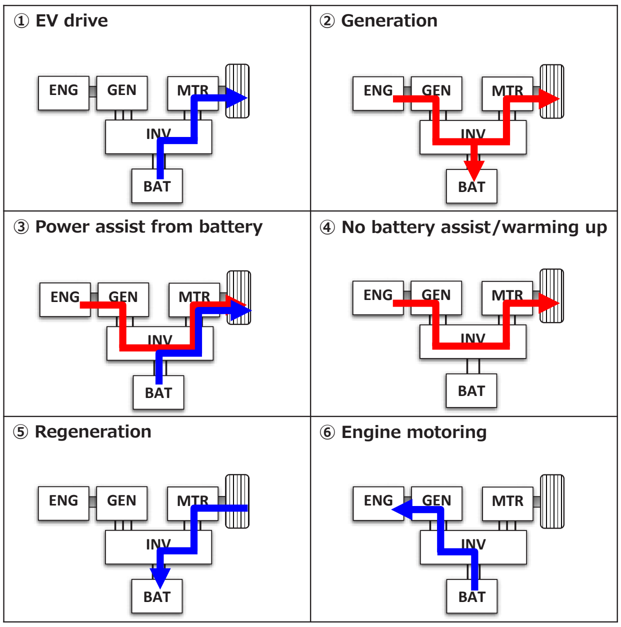

Fig.3 e-Power System operation modes

for efficiently generating power by the engine and improving the efficiency of the entire system at the same time.

Thus, Nissan has thoroughly improved the power generation efficiency of the engine by utilizing the characteristics of e-POWER, based on the operations at set operation points, where the efficiency of the power generating system is high (hereinafter called fixed-point operation (mode (2) in Fig.3).

3-1. Fuel economy improvement by fixed-best efficient point operation

Fig.4 shows the line α connecting the operation points per revolution, where efficiencies reach the highest. Because, in conventional hybrid systems, engine revolution is bound by vehicle speed and required traction, the systems are controlled by tracing this line, and thus, fewer operation points need to be used in the low revolution range.

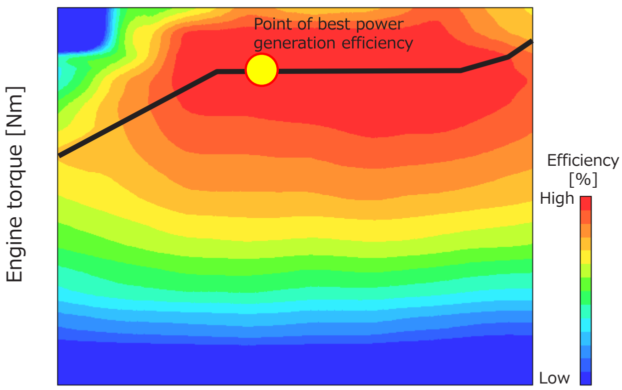

Fig.4 Efficiency characteristic of power generation system

Conversely, because the drivetrain and engine are completely independent of each other in e-POWER, operation is controlled regardless of the mode of the drivetrain. In this way, the most power generation-efficient operation point is selected within the permissible ranges of various requirements, such as mechanical power, drivability, noise and vibration, emission, heat, air heating, brake negative pressure, component protection, and diagnosis. During the control, the optimum amount of power for motor output is adjusted by charging and discharging to/from the lithium battery, as shown in Fig.5 (modes (2) and (3) in Fig.3)[*(4)].

When driving in cities or similar scenarios where the

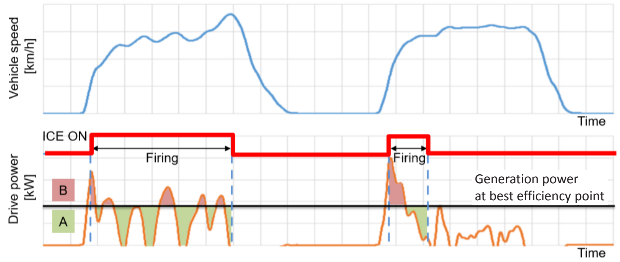

Fig.5 Concept of energy management

required traction is small, the engine is operated at fixed points and surplus power charges the lithium battery (mode (2) in Fig.3). Then, the stored electric energy is used to start the EV drive (mode (1) in Fig.3).

Fig.6 shows the result of fuel economy improvement achieved by switching fixed-point operation and EV drive. The figure shows that the fuel economy has improved to approximately twice that of the operation mode with the engine always on (mode (4) in Fig.3).

In scenarios where the required traction is large, such as when driving at a high speed or accelerating for passing, the electric energy in the lithium-ion battery that has been stored from surplus power is used to supplement the necessary power for acceleration. This maintains fixed-point operation as much as possible and minimizes fuel consumption (mode (3) in Fig.3).

3-2. Improvement of power generation system

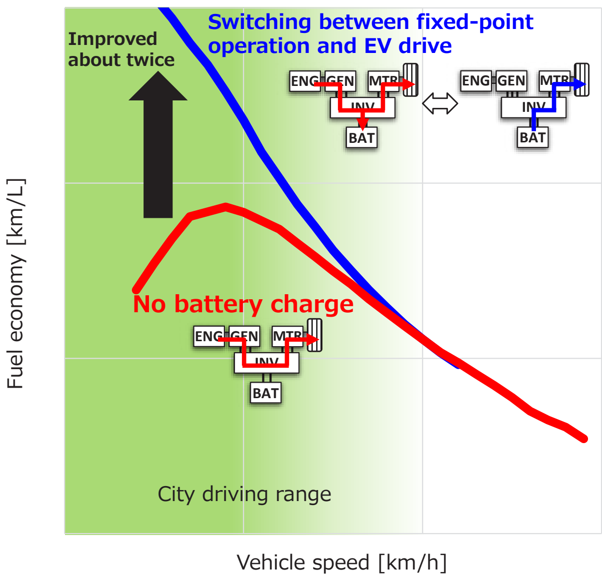

Fig.6 Result of fuel economy improvement achieved by cruising at a constant speed

(engine + generator)

Fig.7 shows the characteristics of the specific fuel consumption of the engine. Nissan has developed an engine for e-POWER, based on the 3-cylinder 1.2-L gasoline engine, HR12DE. By adopting cooled exhaust gas recirculation (EGR) and electrified accessories such as water pumps and air compressors, Nissan reduced friction to improve the optimum fuel consumption rate. *(2)

Fig.8 shows the efficiency characteristics of the generator (overall efficiency including the inverter). The generator has also been tailored to e-POWER to cover the maximum torque and output of the engine. *(3)

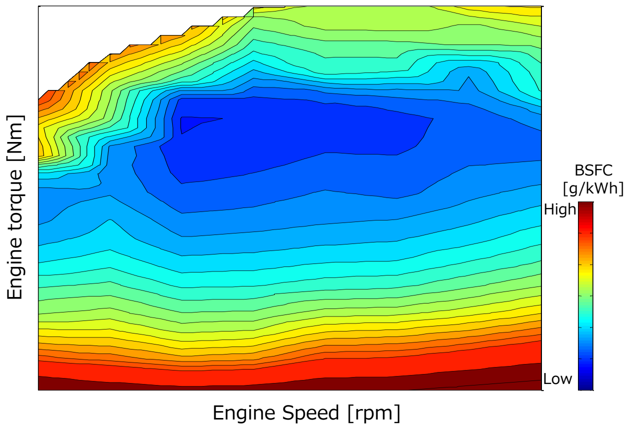

Fig.7 Specific fuel consumption of engine

Because the high-efficiency ranges of the engine and the generator are different from each other, Nissan set 0.6 as the gear ratio of the speed-increasing gear. This is provided in-between the engine and generator to bring power generation efficiency to the maximum within the range of the maximum allowable revolutions of the engine and generator.

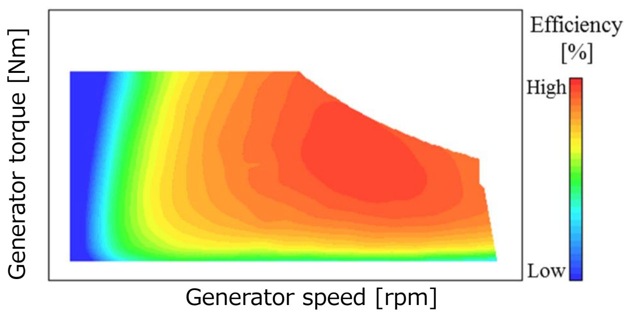

Fig.8 Efficiency characteristics of generator (including inverter)

3-3. Improvement of battery system

Improvement in fuel economy is also attributable to the evolution of lithium battery technology and the following parameters:

- By reducing the internal resistance of the lithium-ion battery, the losses at charging and discharging power were significantly reduced.
- By reducing size and weight, the high-capacity lithium battery can fit in a compact car. This significantly reduced the frequency of engine starts and enabled longer EV driving with the quietness equivalent to BEV.
- By enhancing the cooling performance, high-power and long charging/discharging became available.

Thus, Nissan have achieved top-level fuel economy and quietness for this class of vehicle.

4. Engine operation control of improved e-POWER

As discussed above, e-POWER basically reduces fuel consumption by fixed-point operation during engine operation. Nissan has provided the three measures described below to improve engine operation control and has adopted them in KICKS and the new NOTE.

4-1. Further reduction of the frequency of engine start

Nissan focused on the fuel consumed when the engine is started and then reaches the point of fixed-point operation where the efficiency of the power generation system reaches the maximum as well as on the electric energy consumed at the engine start. Nissan reviewed the conditions of engine start based on user data and significantly reduced the frequency of engine starts so that the EV drive is maintained when low-speed driving and short acceleration are expected. Although the fuel economy degrades immediately after the engine is started until it reaches the point of fixed-point operation, the process is completed in an extremely short time. However, because this transition to the point of fixed-point operation occurs every time the engine is started, reducing the frequency of engine start is effective for fuel reduction.

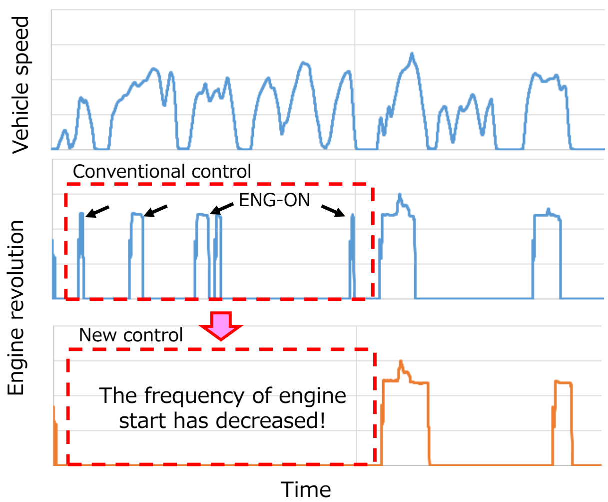

Fig.9 Reduction of the frequency of engine start

4-2. Addition of points of fixed-point operation during engine warm-up

For cold starting, Nissan used to generate waste heat to facilitate warm-up, using the operation range where the engine's thermal efficiency was poor. Instead, Nissan has now adopted the point of best power generation efficiency, where a heat source is not required.

In addition, by focusing on the fact that the point of best power generation efficiency varies before and after engine warm-up, Nissan set the points of fixed-point operation for warm-up such that the points of fixed-point operation can be switched according to the warm-up status. As a result, the actual fuel economy at short-distance driving has improved.

4-3. Change of engine operation points for heater operation in winter

e-POWER uses the waste heat from the power-generating engine as a heat source for heating. It is an important issue to efficiently manage the air conditioning environment in the vehicle compartment to maintain comfort.

Conventionally, power generation efficiency is prioritized as a fixed-point operation after engine warm-up, even when the heater was used in winter. Because the engine needed to be continuously powered during heating, when the storage capacity of the lithium-ion battery was exceeded, forced discharge was performed with the engine motoring (operation mode (6) in Fig.3). Accordingly, Nissan could not achieve an optimum fuel economy.

This time however, Nissan controlled the operation point of power generation according to the battery level and heating requirement and secured a minimal amount of heat, so that both heating performance and fuel economy are satisfied.

5. Approach for zero emission

Nissan has achieved the top fuel economy in the vehicle class by sharing the evolved technologies of the ICE and EV and providing an energy management system unique to e-POWER. For the new NOTE, Nissan has improved the efficiency of the e-POWER system by improving the thermal efficiency of the engine and adopting a technology that improves the transmission efficiency of the electric components shared with EVs.

In the future, Nissan will strive for further improvement of the e-POWER engine dedicated to power generation for higher thermal efficiency, downsizing and weight reduction, loss reduction, efficient energy generation for heating, and advanced control corresponding to the component evolution. We will also maximize the efficiency of the system through the next-generation of energy management in conjunction with navigation systems and IT/ITS.

Through the innovation of these fundamental technologies, Nissan aims to drastically reduce CO2 emissions and bring the amount of emission gas to a near-zero level, which will enable us to contribute to global environmental protection. Nissan will continue development so that we can provide more customers with the e-POWER system that delivers pleasant driving with the unique 100% motor drive.

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Special Feature 2 : Constantly advancing e-POWER

5. Noise and vibration technologies of new NOTE supporting the EV-ness of e-POWER

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Ryuugo Chiba* Takanobu Sawada** Toru Nakada*** Masaya Gotou****

1. Introduction

e-POWER uses common drive motor with battery-driven electric vehicles (hereinafter called BEV[*1]); hence, it delivers a smooth acceleration feel similar to the BEV and the quietness equivalent to that of high-grade vehicles, particularly from standing start to mid-speed driving, which is driven by the motor only with the engine stopped (hereinafter called EV driving[*3]).

The following are important factors in individual driving scenarios when pursuing quietness with this system.

In an EV driving scenario, high-frequency noises caused by the motor and speed reducer are dominant. In addition to the reduction of the motor's own exciting force, the radiative characteristics of e-POWER must also be suppressed factoring in the location where the generator and engine are integrated. The BEV does not have this problem.

It is also important to devise measures to muffle the engine operation noise during power generation. Nissan assumed noise and vibration issues would arise in the following operation scenarios and took measures accordingly.

(1) During EV driving: Reduction of the noises of the motor and speed reducer gears

(2) During driving with the engine on: Reduction of engine noise, rattle noise, and other noises due to the speed increaser gears, and considered quietness at engine start

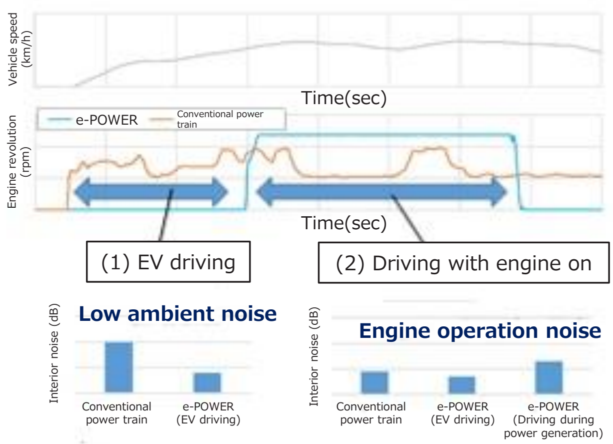

Fig.1 Driving scenarios that hinder the quietness of e-POWER

This article describes the design concept of the e-POWER system considering the key noise and vibration phenomena in the important scenarios above and the technical solutions that have been adopted to the new NOTE.

2. Improvement of quietness during EV driving

2.1 Issues during EV driving

During EV driving, the high-frequency noises of the motor and gears that have been masked by engine noise manifest themselves as unpleasant noises. For this reason, a high quietness level equal to that of BEV vehicles is required.

2.2 Motor noise

Motor noise is caused by the electromagnetic force between the stator and rotor. The components of this vibromotive force can be divided into two directions, the circumferential and radial directions of the motor. Their contributions vary according to the frequency range (Fig.2).

While reducing the electromagnetic force over a wide range, Nissan has optically designed a magnetic circuit that satisfies both efficiency and output at a high level. This followed simulation results of hundreds and thousands of design parameter combinations (Fig.3).

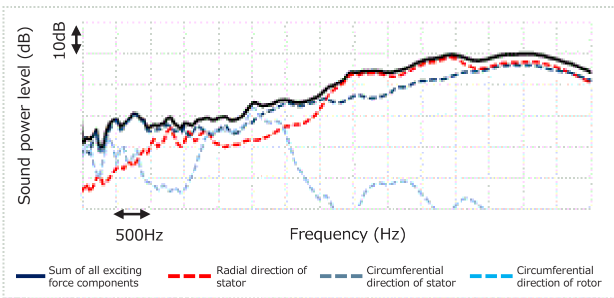

Fig.2 Analysis of the contribution of exciting forces by direction with respect to motor noise levels

*Powertrain and EV Performance Engineering Department **Powertrain and EV Advanced Technology Department
***Powertrain and EV Electrical Technology Department ****Customer Performance and Vehicle Test Engineering Department No.1

By focusing on reducing the level of the electromagnetic force in the vehicle low-speed range, we have adopted a magnetic circuit for the new NOTE e-POWER that efficiently reduces the components of the vibromotive force in the circumferential direction as well as iron loss.

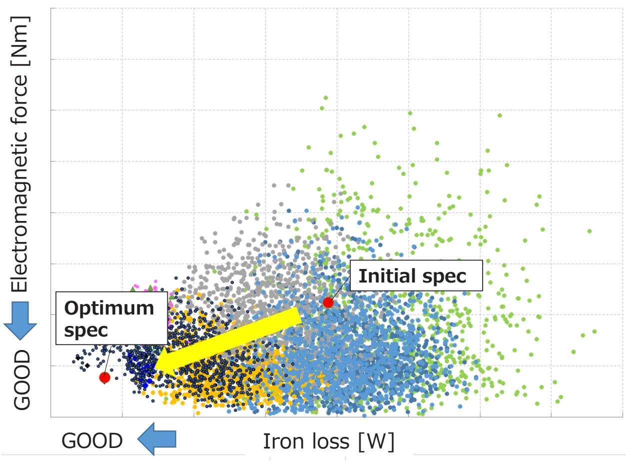

Fig.3 Optimum designing of magnetic circuit that satisfies both electromagnetic force and efficiency

Besides the reduction of the exciting force discussed above, Nissan also carried out further measures to efficiently reduce motor noise. For the structural components of the motor unit, the main cause of motor noise is radiation. Nissan conducted simulations to analyze the major contributors to the radiation noise and found that the inverter was the main contributor. Accordingly, we focused on improving the rigidity of the inverter case (Fig.4).

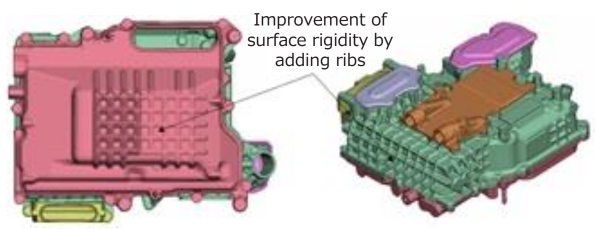

Fig.4 Measures to improve the rigidity of the inverter case

2.3 Noise of speed reducer gears

To ensure the quietness of the gears at a high speed, Nissan improved the noise level of the speed reducer gears by increasing the face width to enhance the contact ratio and provided additional honing to increase tooth precision.

3. Improvement of quietness during engine operation

3.1 Noise reduction during engine operation

3.1.1 Guidelines when designing for low noise during engine operation

To efficiently generate power in the e-POWER system, the engine is operated at high-load and low revolutions more often than the engines of conventional vehicles aiming at higher engine efficiency. Thus, Nissan designed the engine according to the following guidelines.

(1) Efficient reduction of the vibration level during engine operation in the vibration propagation paths to the vehicle compartment

(2) Muffling of engine noise by operating the engine in the range where tire noise and other ambient noises are higher

3.1.2 Measures provided for vibration propagation paths

The engine noise propagation paths to the vehicle compartment can be largely divided into two: paths that propagate vibration via parts such as the engine mount and paths that propagate noise by air from the engine compartment.

For the vibration propagation paths, Nissan improved the vibration level by installing the inverter directly above the motor unit to improve packaging efficiency and by adding the minimum necessary parts to significantly improve the rigidity of the entire power train.

Specifically, Nissan fixed the inverter and drive motor with bolts and added a gusset between the inverter and power generation motor to significantly improve the rigidity of the entire motor unit system (Fig.5). For the mount bracket on the left side of the vehicle, Nissan fixed the bracket and the above-mentioned inverter with a small stay by bringing the bolted portions to the top of the motor rear cover. With this improvement, we have greatly reduced the vibration level while controlling the weight increase of the bracket (Fig.6).

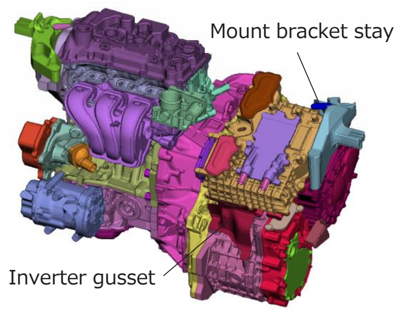

Fig.5 Major changes in the structural system of new NOTE e-POWER's motor unit

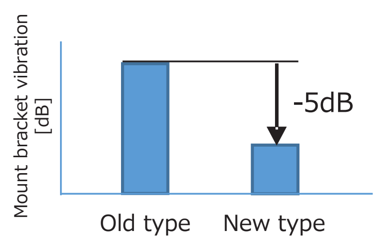

Fig.6 Vibration reduction by improving the rigidity of inverter case

3.1.3 Conditional control of engine start timing (road surface state discrimination)

Nissan has recently developed a function that controls engine operation by judging the increase in road noise when driving on a rough road surface. This function maintains a sufficient battery level by generating power in scenarios where the engine operation does not bother the driver. Thereby, the driver can enjoy quiet driving, unique to EV driving, more at standing start or when driving on a smooth road surface.

The old NOTE e-POWER was designed to operate the engine at high vehicle speeds, assuming that road noise increased in proportion to vehicle speed. However, in cities where vehicles repeatedly start and stop, scenarios where engine operation does not bother the driver are limited. For this reason, Nissan needed to control the scenarios where the engine operated during low-speed driving.

It is known that the roughness of a road surface affects the level of road noise more than vehicle speed. It is also known that in the driving environment in Japan, many road surfaces cause higher noise levels than the engines. Therefore, Nissan has developed an algorithm for estimating road noise based on the variation of tire revolutions. The algorithm helps control engine operation, which greatly contributes to the improvement of quietness.

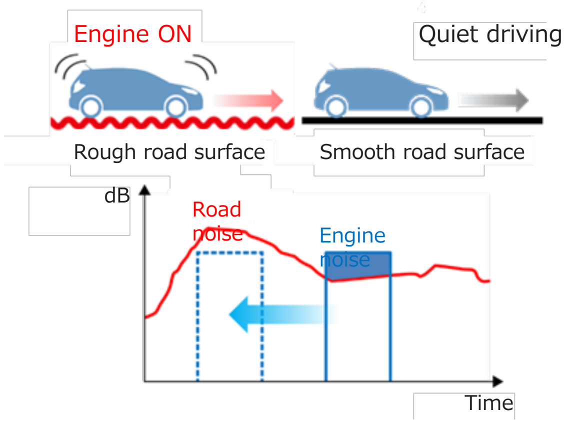

Fig.7 Outline of engine start control based on estimated road noise

3.2 Reduction of the rattle noise of speed increaser gears

3.2.1 Reduction of the rattle noise of the new NOTE's speed increaser gears

By reducing gear rattle noise with a new, low-rigid torsional damper, the quietness of the new NOTE e-POWER improved from that of the old NOTE e-POWER (Fig.8).

3.2.2 Rattle noise of speed increaser gears

The power generation system of e-POWER is composed of an engine, a generator, and a speed increaser. Each component is fixed with a spline, and a gap or backlash is present at each joint and gear meshing portion. In the gap or backlash, the teeth of the spline and gear collide with each other owing to the fluctuation of engine torque in the low-engine torque range, which generates noise (Fig.9).

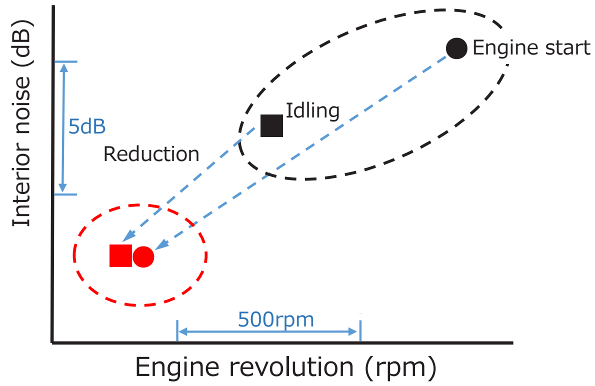

Fig.8 Quietness improvement by revolution reduction

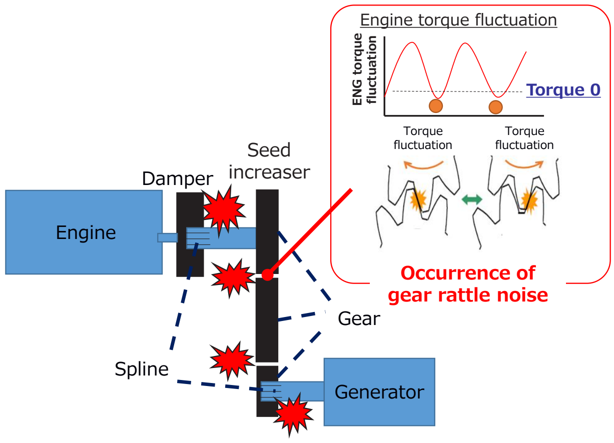

Fig.9 Occurrence mechanism of the rattle noise of speed increaser gears

3.2.3 Application of new, low-rigid torsional spring damper

The torsional spring rigidity of the old torsional damper installed between the engine and speed reducer had the characteristics of a single-stage type. However, as a measure to prevent the gear rattle noise discussed above, Nissan has developed a new damper with the characteristics of a double-stage type by reducing the torsional rigidity in the low-engine torque range that causes gear rattle noise (Fig.10). This development has enabled Nissan to significantly dampen the engine torque fluctuation input to the joints and gears and control gear rattle noise (Fig.11).

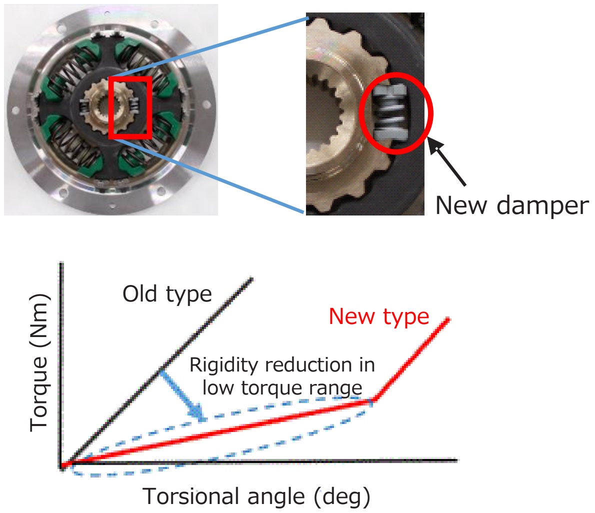

Fig.10 New low-rigid torsional damper

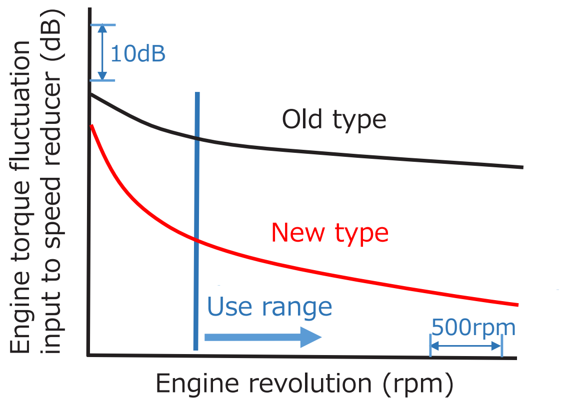

Fig.11 Improvement of the vibration characteristics between engine and speed reducer

3.3 Noise of speed increaser gears

Regarding the speed increaser connecting the engine and generator, one of the gears of the intermediate shaft between the engine shaft and generator shaft meshes with the gears of the engine shaft and generator shaft. Accordingly, the gear noise level tends to increase qualitatively. We can reduce the gear noise by optimizing the gear specifications and the layout of the gear shafts in such a way that the meshing phases between these two meshing points are mutually canceled out (Fig.12).

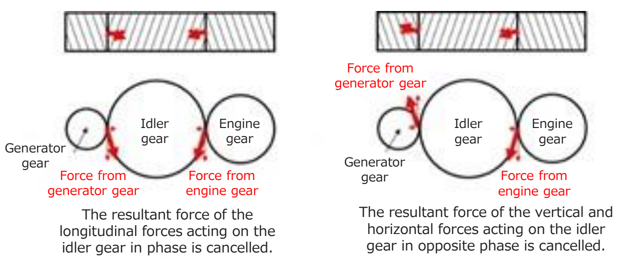

Fig.12 Conceptual diagram of the design for gear meshing phase difference

This design for optimizing phase differences has been adopted in the old and new speed increase of e-POWER so as to further reduce the level in the engine revolution range frequently used.

4. Pursuing further quietness

Assuming that e-POWER will be increasingly adopted in higher-power vehicles in the future, Nissan needs to modify the vibration transmission system for noise and vibration performance in accordance with the increase in the existing forces and enlargement of the power train due to the increase in engine and motor torques.

To achieve further quietness and pursuing EV-ness*4, Nissan aims to improve the quietness while fully bringing out the characteristics of the e-POWER system. This will be achieved by comprehensively designing from the main moving system and body structural system of the power train to the engine mount.

5. Summary

To achieve the quietness of high-grade vehicles that is a characteristic of e-POWER, Nissan has taken the following measures: (1) reduction of the high-frequency noise during EV driving, and (2) engine operation in a manner imperceptible to the driver. In addition, Nissan has made further improvements to the old NOTE e-POWER by focusing on controlling the rattle noise of the speed increaser gears.

- High-frequency noise during EV driving: We have reduced the noise level by optimizing the electromagnetic force by redesigning the motor’s magnetic circuit, efficiently improving the rigidity of the radiating portions, and improving the precision of the speed reducer gears.
- Noise during engine operation: We have improved the rigidity of the inverter case and newly adopted an engine start/stop control factoring in the driving scenarios where engine noise is muffled by ambient noise. We have also greatly reduced the rattle noise of the speed increaser gears by adopting the newly developed low-rigid damper. In addition, we have optimized the phase differences between two meshing points to address the gear noise caused by the double meshing of the speed increaser.

Explanation of terms

*1 BEV: An EV driven by battery power only*2
*2 EV: vehicle driven by electric motor only
*3 EV driving: Driving with e-POWER, operated by battery power only with the engine stopped
*4 EV-ness: Quiet, powerful, and smooth driving feeling unique to electric motor drive

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Special Feature 2 : Constantly advancing e-POWER

6. Electric AWD technology to add value to e-POWER

Ryozo Hiraku* Eigo Sakagami** Takeji Katakura**

1. Introduction

The conventional all-wheel drive (AWD) system functions by distributing the power generated by the internal combustion engine to the front and rear wheels through a mechanical system. However, recent EVs*1 have been adopting electric AWD with motors in both the front and rear , instead of using a single power source that distributes power to the front and rear. When combined with BEV*2, electric AWD has many advantages in vehicle design, such as fully independent control of the front and rear tractions and highly flexible layout. However, for combining with an internal combustion engine vehicle, electric AWD has some disadvantages such as a high-voltage battery system is required to obtain sufficient power, traction controllability is still limited even if the rear wheels are electric motor-driven because the front wheels are driven by the engine. In contrast, by combining with 100% motor-driven e-POWER equipped with a high-voltage battery system, the issues that arise when combined with conventional internal combustion engine vehicles are solved and the benefits of electric AWD can be gained as with the BEV.

This article discusses the technical direction of the 100% motor-driven AWD system combined with e-POWER, which is scheduled to be launched.

2. "e-4ORCE" as the evolution of electric AWD to Nissan

In the 2019 Tokyo Motor Show, Nissan publicized the direction of the evolution of new electric motor AWD, "e-4ORCE" (Fig.1), with the "Ariya Concept". For the control technology of "e-4ORCE," Nissan has developed the technologies of four-wheel traction control, chassis control, and electric power train, while combining the knowledge, which Nissan has accumulated over the years. Nissan has the knowledge to maximize the effects of the traction control, brake control, and chassis control acquired from the ATTESA E-TS (Advanced Total Traction Engineering System for All Electronic - Torque Split) of the "GT-R" and the intelligent 4 x 4 system of the "X-Trail". Furthermore, Nissan has also utilized its long experience in the development of motor drive and advanced four-wheel drive systems to develop an advanced system "e-4ORCE" equipped with two electric motors.

Fig.1 Ariya Concept in 2019 TMS

The aim of "e-4ORCE" is to bring (1) usability, (2) comfort, and (3) confidence to a level that cannot be achieved by conventional internal combustion engine vehicles, by re-defining the roles of individual vehicle systems based on electric motor drive and maximizing the high potential of the electric motor.

This is not merely the "transformation to AWD" from the front-wheel drive electric vehicles but an evolution aiming at a new direction of vehicle design. Only 100% electric motor-driven BEV and e-POWER can achieve this performance.

3. New dynamics control achieved by electric AWD

Basically, vehicles provide their dynamic performance "Run," "Stop," and "Turn" by controlling the power generated by the power source, internal combustion engine, and by using the functions of the steering and brake systems, respectively (Fig.2). However, because the electric motor is being used as an alternative power source, it is able to provide functions that the conventional power sources could not provide. For example, some of the functions that used to be provided by the conventional brakes can be covered by the electric motor by properly controlling the regenerative capability of the electric

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motor. In addition, unprecedented smoothness and usability can be achieved by properly utilizing the high controllability of the electric motor. One of the applications is the e-POWER drive adopted in the NOTE e-POWER.

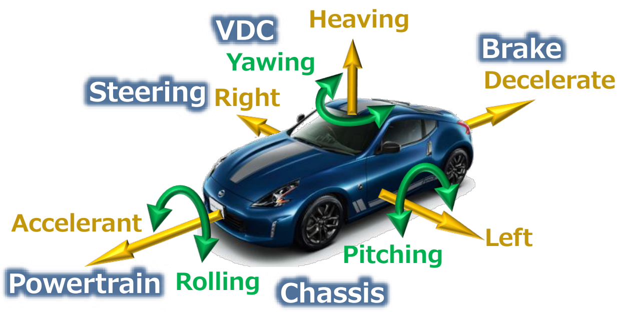

Fig.2 Vehicle's movement and role sharing of systems

Because electric AWD has two electric motors in the front and rear, the variety of movements increases owing to the motors use as power sources. For example, movements such as the vehicle's pitching and yawing can now be controlled by the electric motors to a limited extent, which is not what was expected before (Fig.3).

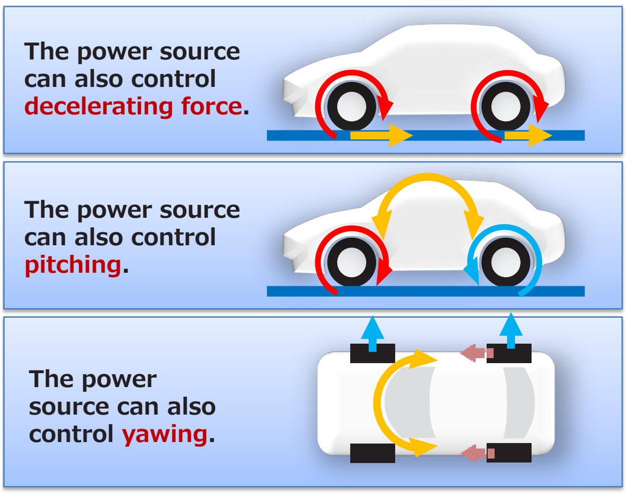

Fig.3 Movements achieved by using electrically driven AWD

4. Values offered by 100% motor-driven AWD

Fig.3 Movements achieved by using electrically driven AWD

4-1. Easy following path as per driver's expectations

Line traceability and accurate steering can be enhanced by the integrated control of the torques generated by the two electric motors, regenerative braking, and four wheels' hydraulic braking while optimally using individual roles. This control provides the driver with confidence. Such advanced control is particularly effective at cornering. Because the vehicle moves in accordance with the steering operation of the driver, the driver can enjoy smooth and comfortable driving.

For example, Fig.5 compares the behaviors of vehicles slaloming on a snowy road, when traction is properly distributed to the front and rear with integrated control, and when traction is fixed to the front and rear. The figure shows that the integrated control stabilizes vehicle behavior and allows the driver to constantly trace the ideal line as expected.

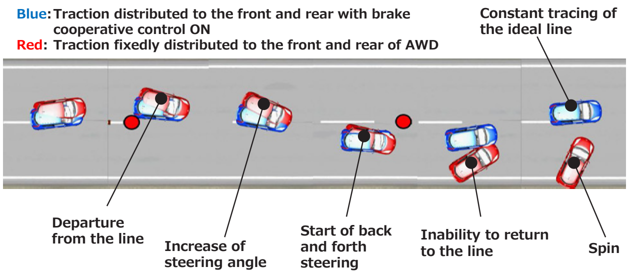

Fig.5 Comparison when slaloming on a snowy road

4-2. Comfortable ride for all

Electric motor-controlled regenerative braking also contributes to a comfortable ride.

Front-wheel-driven e-POWER applies regenerative braking using the electric motor located in the front, so that the front side of the vehicle deeply sinks when decelerated. Electric AWD vehicles optimally control the regenerative braking of the electric motor located in the front and rear to prevent the vehicle from front side sinking and oscillating, respectively, when decelerated (Fig.6). Accordingly, occupants do not feel the oscillations when the vehicle is repeatedly started and stopped or in similar situations, which reduces car sickness and delivers comfortable riding. This control provides not only the driver but also the occupants in the passenger seat and rear seats with stable and smooth ride comfort.

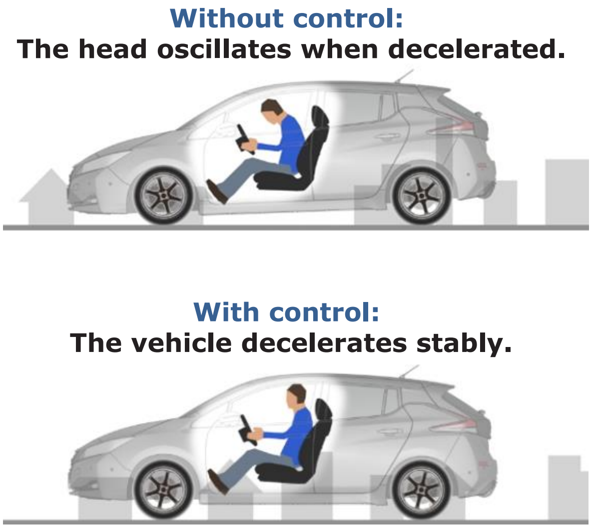

Fig.6 Attitude control when decelerated

4-3. Confidence anywhere

In scenarios where even an experienced driver feels stress such as when driving on a wet, frozen, or snowy slippery road, the tire' s road holding capability is maximized by integrated control of the outputs from the front and rear electric motors and the braking system in a precise manner to help stabilize the vehicle's movement. Thus, even when the driver excessively depresses the accelerator pedal on a slippery road, the vehicle properly controls the outputs so that the driver can securely control the vehicle.

The chart in Fig.7 compares a front wheel drive (FF) vehicle and AWD with or without the integrated control in a scenario where the driver lifts his foot off the accelerator pedal to decelerate the vehicle on a slippery road. By using integrated control, the road holding capability of the front and rear tires can be fully utilized to help secure a stable decelerating force.

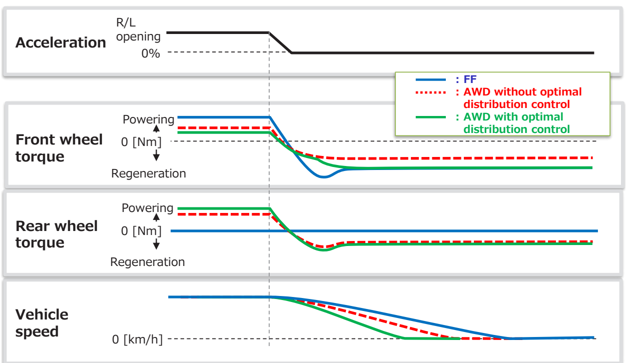

Fig.7 Slip control by motor

5. Summary

AWD has been widely known as a mechanism that provides confidence. With the electric AWD to be launched, Nissan not only offers the originally expected performance but also focuses on the performance enhancements "not just for some days but every day"'. In other words, we have not only refined rough road performance and limit performance but also enriched the performance that provides average drivers with comfort and ease of driving even during everyday driving on regular roads. We will continuously aim to advance performance toward the Nissan goal, which is ultimate intelligent mobility.

As a combination with e-POWER, the electric AWD combined with the new NOTE e-POWER is the first model, which is scheduled to be launched soon.

Explanation of terms

*1. EV: vehicle driven by electric motor only
*2. BEV: An EV driven by battery power only

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