

Development of a Parallel Hybrid System for RWD Vehicles

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ABSTRACT

In December 2006, Nissan announced its Nissan Green Program 2010 (NGP 2010), a mid-term environmental action plan that includes initiatives to reduce vehicle emissions. In line with this plan, the company intends to introduce a new and original hybrid system in fiscal year 2010. Specifically, this system-called the “Infiniti Direct Response Hybrid”-is a one-motor, two-clutch parallel hybrid system that eliminates the need for a torque converter. It will be featured in the 2012 Infiniti M35 Hybrid and provides the following advantages.

1. Significant improvement in fuel economy even in Highway driving
2. Better response and a more direct feeling
3. Lightweight and low cost

This one-motor, two-clutch system without torque converter possesses a simple but highly capable architecture that is new to the passenger vehicle segment. The successful development of this system hinged on breakthroughs in the following areas.

1. High speed control of switching between charging/discharging
2. Immediate and high-output power assist
3. Smoothness at engine start

Nissan has developed the following proprietary technologies to realize the development of this system.

- High-output and high-speed lithium-ion battery
- Innovative high-speed and precise motor control

This paper provides an outline and description of this new one-motor, two-clutch parallel hybrid system as well as the key breakthrough technologies that made it possible.

INTRODUCTION

There is wide recognition that carbon dioxide (CO₂) levels must be significantly reduced in the long term. Based on NGP 2010, Nissan estimates that it will be necessary to reduce CO₂ emissions from new vehicles by approximately 70% from 2000 levels by 2050. In the short- to mid-term, internal combustion engines (ICEs) have the potential to reduce CO₂ levels by up to 30%, and therefore, improvement in the fuel efficiency of ICEs seems the most practical and immediate way to address the issue of carbon emissions. Along this line, a number of technologies have been recently introduced, including direct fuel injection, variable valve event and lift, clean diesel, and efficiency improvements in continuously variable transmissions (CVTs). Intelligent transportation systems are also expected to play an important role in reducing CO₂ emissions through traffic controls and other integrated measures (Figure 1). However, in order to reduce carbon emissions in line with Nissan's long-term goal, the company will need a product lineup made up of largely electric drivetrains. Accordingly, it plans to introduce battery electric vehicles, additional hybrid vehicles, and fuel cell vehicles.

As part of its CO₂ reduction strategy, Nissan developed its own original hybrid system. After examining and contrasting various system configurations (Table 1), it was determined that the one-motor, two-clutch parallel hybrid system without torque converter achieved the best balance in terms of cost, weight, size, fuel economy, and acceleration performance. However, a number of issues had to be overcome in the application of this system to luxury rear-wheel drive (RWD) vehicles, for which smooth driving performance is an important requirement (Figure 2).

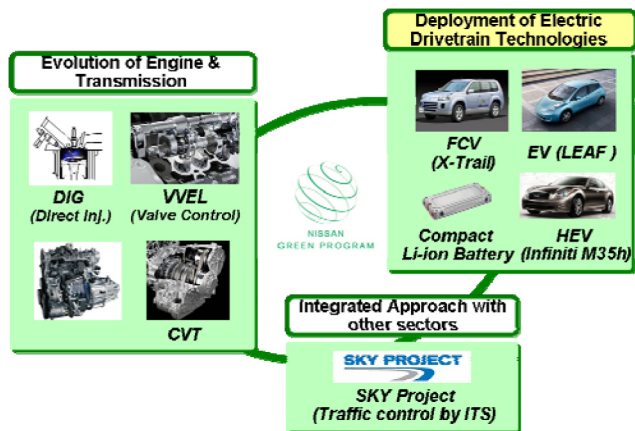


Figure 1 . CO2 reduction activities

Table 1 . Examined hybrid system configurations

System	Unit Architecture
Series-Parallel (1-mode)	Engine Motor Planetary Gear $\times 1$ (Reduction Gear $\times 1$)
Series-Parallel (2-mode+Multi Fixed Gear)	Planetary Gear $\times 3$ + Clutches & Brakes
Parallel (1-Motor 1-Clutch)	AT/CVT
Parallel (1-Motor 2-Clutch)	AT/CVT
Parallel (2-Motor 2-Clutch)	AT/CVT

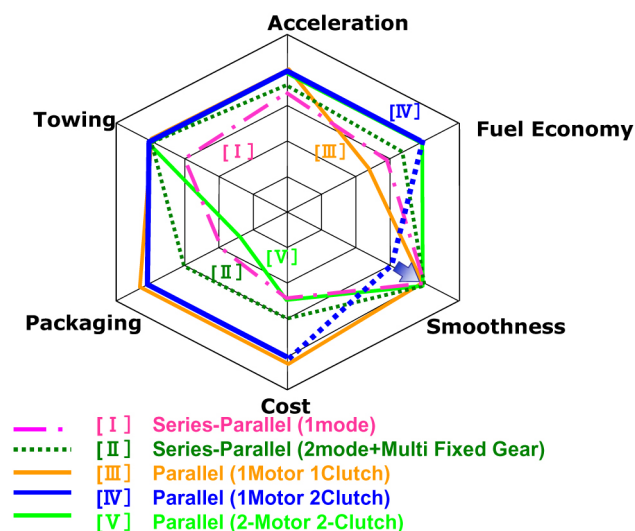


Figure 2 . Summary of hybrid system study

1. OUTLINE OF THE NISSAN PARALLEL HYBRID SYSTEM

1-1. HYBRID SYSTEM ARCHITECTURE

The hybrid system architecture is shown in Figure 3. The parallel hybrid unit is built into the base structure of the seven-speed automatic transmission, and the electric motor and dry single plate clutch (clutch 1) with hydraulic actuator are positioned in place of the torque converter. This system is equipped with a compact, high-power lithium-ion battery that delivers exceptional charge/discharge efficiency and is mounted behind the rear seatback. The inverter is minimized to a size equivalent with the 14 volt auxiliary battery thereby allowing it to be directly mounted in the engine compartment. Power steering, A/C compressor, and other auxiliary systems are electronically driven as full hybrid. A newly developed regenerative brake system was also incorporated into the hybrid system architecture.

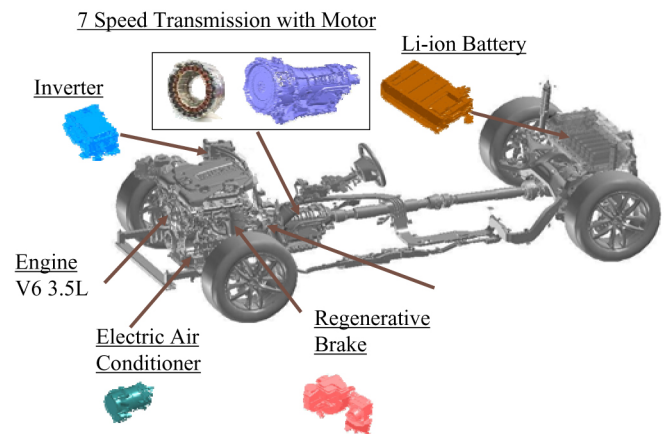


Figure 3 . Hybrid system architecture

1-2. POWERTRAIN UNIT ARCHITECTURE

Clutch 1 (dry single plate) and the drive motor are positioned in the conventional location of the torque converter, and the actuator for clutch 1 is packaged inside the motor rotor, ensuring full motor performance. In addition, the motor has a soft mount architecture-unique to hybrid systems-that acts to suppress motor noise. At engine off, required hydraulics are supplied by the 14 volt-driven electric sub-oil pump, which is positioned on the lower side of the motor housing. Clutch 2 (wet multi-plate) is commonized with clutches used in conventional seven-speed automatic transmissions (ATs), resulting in significant cost-savings and compactness. Clutch 2 performs comparably to typical seven-speed ATs also in terms of shifting, and it functions as a starting element in place of the torque converter. Furthermore, it helps to stabilize driving torque during engine start operation when there are momentary fluctuations in engine and motor torque.

Section 3 provides more information on the function of clutch 2 as well as on gear shift performance, start to move, and engine start operation. Functional integration of clutch 2 and elaborate packaging allow for a hybrid transmission that is equivalent in length to conventional seven-speed ATs, ensuring compatibility with passenger vehicles (Figures 4 and 5).

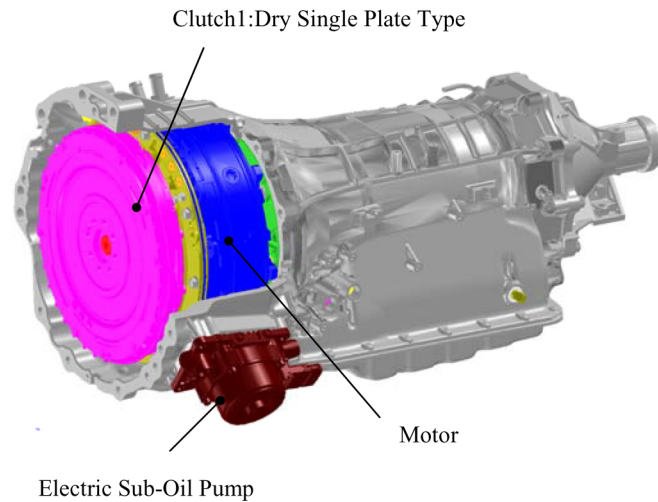


Figure 4 . Overview of hybrid transmission (seven-speed AT with motor)

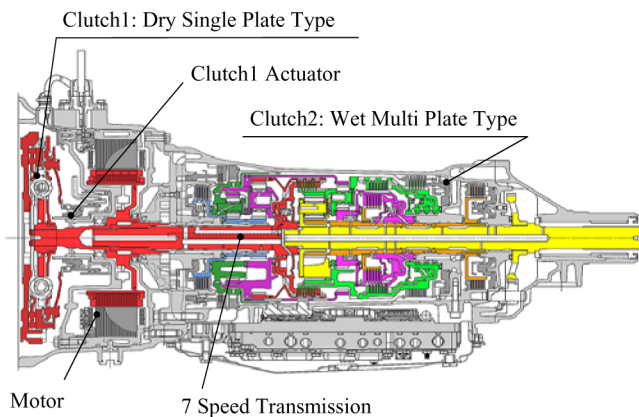


Figure 5 . Cross-section of hybrid transmission (seven-speed AT with motor)

The main specifications of each system component are shown in Table 2. Weight reduction and a high final gear ratio contribute significantly to improved vehicle fuel economy. The permanent magnet AC synchronous motor adopted in this hybrid system ensures high motor performance through high torque density and efficiency. In terms of the battery, the utilization of a spinel-structured cathode and laminated cells results in a level of power density approximately two times that of conventional nickel-metal hydride (NiMH) batteries. Characterized by fast charge/discharge response, the battery features compactness, exceptional cooling performance, and

high reliability. In addition, battery output increases momentarily to roughly 60 kW when more power is required, i.e. at engine start.

Table 2 . Main specifications of each component

Item		Unit	Value (or Details)
Engine	Type	-	VQ35HR
	Max. Power	kW/rpm	225/6800
	Max. Torque	Nm/rpm	350/5000
Motor & Inverter	Type	-	Permanent Magnet AC Synchronous Motor
	Max. Torque/Power	Nm/kW	270 / 50
Battery	Type	-	Laminated Lithium-ion Battery (Manganese Cathode)
	Voltage	V	346
	Capacity	kW·h	1.4
	No. of Cells	-	8Cells / Module, 12Modules
	Max. Power (at System)	kW	60kW (in Short Time)
Transmission	Gear Ratio 1st/2nd/3rd/4th /5th/6th/7th/Reverse	-	4.783/3.103/1.9846 /1.371/1/0.871/0.776 /3.859
	Final Gear	-	2.611

1-3. OUTLINE OF SYSTEM OPERATION

Typical system operations are shown in Figure 6. These operations are designed to shift in accordance with driver operation and the condition of specific components, such as the battery state of charge (SOC). Examples of system operations are provided as follows.

In this hybrid system, fuel economy improvement is realized through more frequent decoupling of the engine. In the low- to mid-speed range, recurrent electric-mode driving is achieved without engine friction by releasing clutch 1 and stopping the engine. In the mid- to high-speed range, the engine is activated and driven only in its efficient operation area according to power requirements and charging status through additional engine load from charging and higher final gear ratio. During acceleration, faster response and gear downshifting are simultaneously realized by means of electric motor torque assist with its precise and immediate control of revolutions and torque. During deceleration, decoupling of the engine by clutch 1 allows for energy regeneration without loss. This maximizes the amount of kinetic energy that can be recovered to the lithium-ion battery.

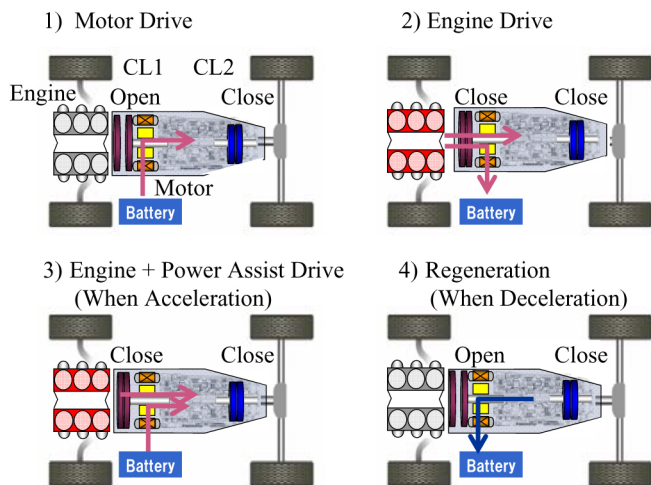


Figure 6. System operations

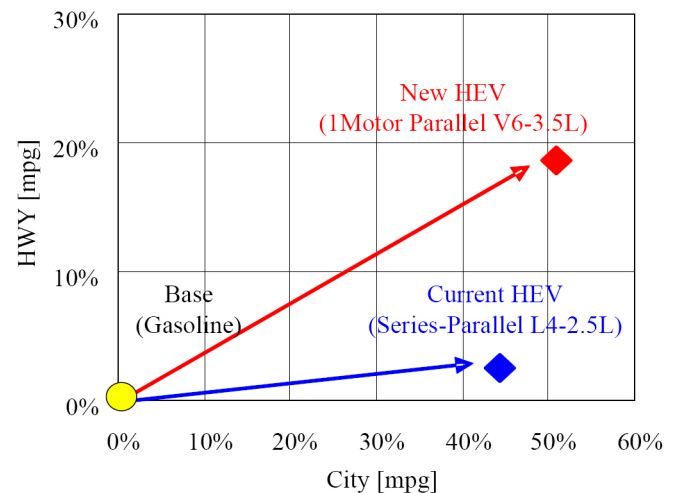


Figure 7. Improvement in fuel economy

1-4. VEHICLE PERFORMANCE

Nissan's new hybrid system ensures a high level of vehicle performance in terms of both fuel economy and overall driving experience. Estimated fuel economy label ratings are shown in Table 3 by destination (Japan, the U.S., and Europe). Although paired with a luxury vehicle and a 3.5-liter engine, this system achieves gas mileage comparable to that of a 1.8-liter front wheel drive compact car. Of particular interest is the improvement in highway fuel economy provided by this system over conventional hybrids, which have only demonstrated modest improvement in highway fuel economy compared to that of city driving. In terms of the overall driving experience, as marked by vehicle acceleration, the new hybrid outperformed a conventional 3.7-liter gasoline engine vehicle (Figures 7 and 8).

Table 3. Fuel Economy / CO2 emissions

USA			JPN	EUR
City (mpg)	HWY (mpg)	Comb (mpg)	10-15 (km/L)	NEDC (CO2 g/km)
*27	*31	*29	19.0	162
* Nissan internal estimate; official EPA figures not available at time of publication				

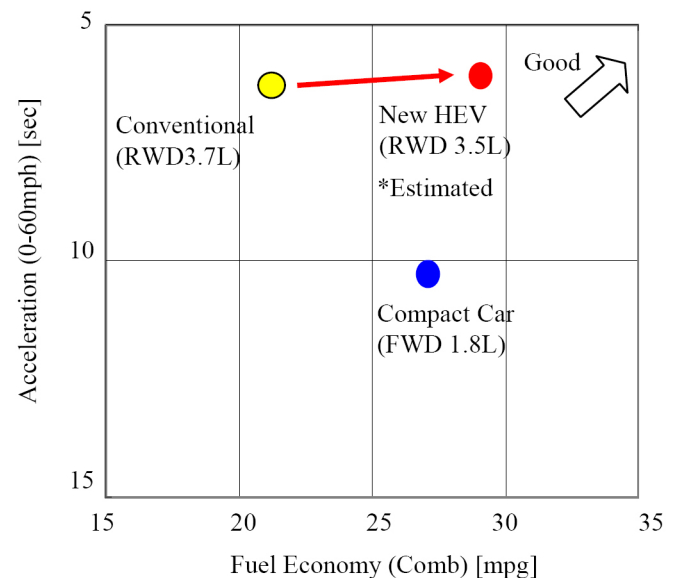


Figure 8. Performance of the new hybrid system

The main solutions to improved fuel economy in this hybrid powertrain system are as follows.

1. Improvement in powertrain efficiency
2. Improvement in engine efficiency through controlled operational conditions

Torque is transferred to the tires more efficiently as a result of the parallel hybrid system's higher gear efficiency. Electric conversion loss, which is inevitable with power-split hybrids, is also minimized. Furthermore, by using the drive motor and clutch as the starting elements in place of the torque converter, power transfer efficiency is improved.

This basic structure allows for a dramatic increase in the range of vehicle speeds in which the hybrid electric vehicle (HEV) can operate in full electric mode, allowing the engine to remain off even during highway driving. In testing, the engine remained off approximately 72% of the time in the hot condition of the Federal Test Procedure (FTP) and 42% of the time in the highway cycle (Figures 9 and 10).

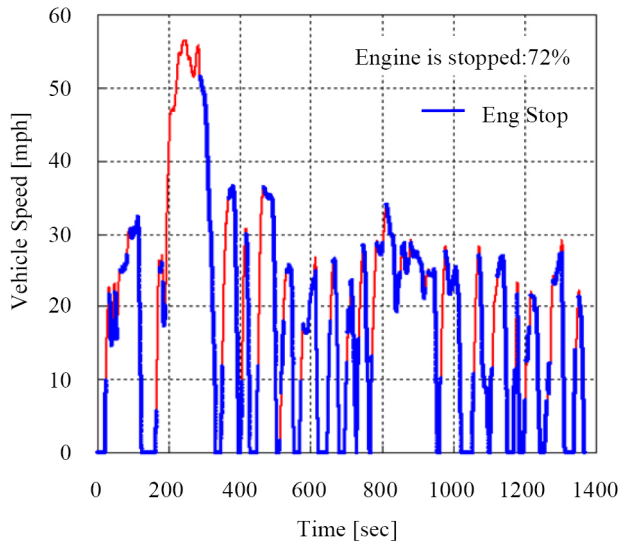


Figure 9 . System operation in the FTP hot cycle

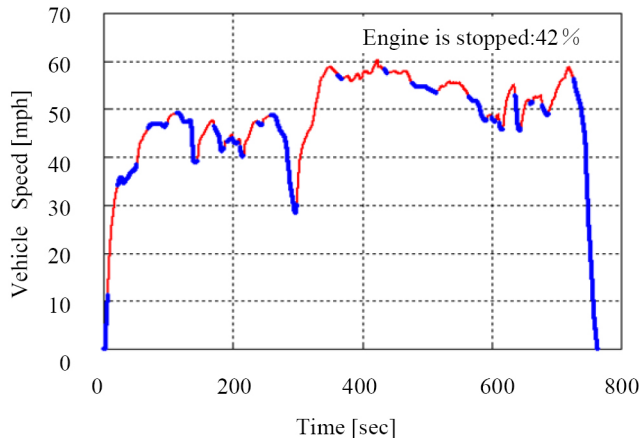


Figure 10 . System operation in highway cycle

Figure 11 illustrates the extent of fuel economy improvement in the FTP cycle from an energy standpoint. As illustrated, the system allows for a reduction of 35% in engine output energy as well as a reduction of 54% in fuel consumption.

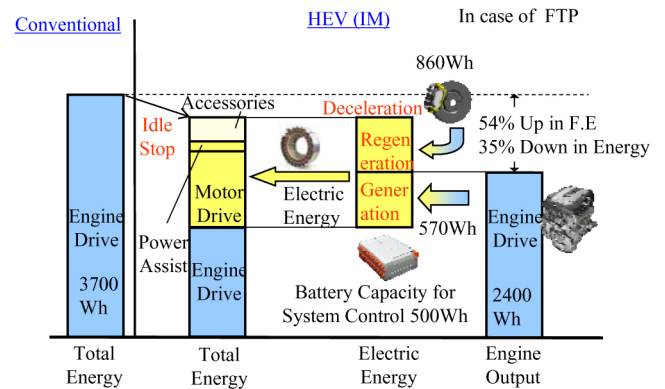


Figure 11 . Battery energy management

Using prototype vehicles, a validation of the frequency of electric mode driving under real-world conditions was conducted. Over the course of one year, data samplings were taken from four representative U. S. cities and regions (New York, Los Angeles, San Francisco, and Arizona). Results demonstrate that the Nissan HEV is capable of recurrent running with the engine deactivated under real-world driving conditions (Figure 12).

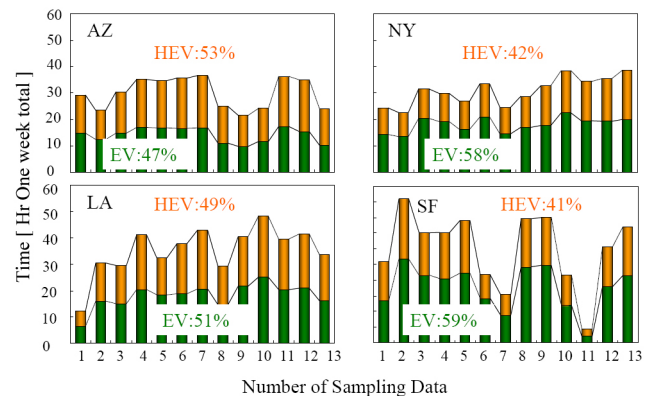


Figure 12 . Sampling of fuel economy data from representative U.S. cities

The potential benefit in terms of real-world gas mileage is also demonstrated by trip data taken from the Japan market, where the vehicle was released in November 2010 (Figure 13). In the figure, the dot plots indicate the fuel consumption variability per trip-blue for a Nissan FWD compact car equipped with a 1.5-liter engine and CVT and purple for the M35 Hybrid, which is a RWD luxury vehicle equipped with a 3.7-liter V6 engine. Variability for the M35 Hybrid is shown within the range of the orange bar. Results demonstrate that the real-world fuel economy of the Nissan HEV is nearly equal to the level of the compact car in all vehicle speed ranges.

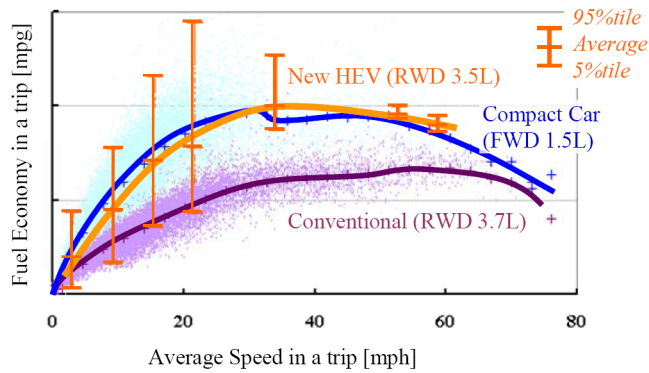


Figure 13 . Fuel economy and average speed per trip

Moreover, the Nissan HEV has a high level of acceleration performance—a necessity for RWD passenger vehicles. [Figure 14](#) compares standing-start acceleration between the new HEV and a conventional ICE vehicle equipped with a 3.7-liter V6 engine. As shown, faster acceleration response and direct acceleration delivery is achieved by means of the motor assist system, and even after standing start, the feel of acceleration is sustained without any significant drop from the initial peak. Furthermore, the high-response motor is used to control shifting between gears (described later). This not only enables shift performance that is quick and rhythmical, but it also improves the overall driving experience. High performance is also demonstrated when accelerating from high speeds, in which case the engine is boosted by the electric motor by means of a power-assist mode while engine revolution remains low ([Figure 15](#)).

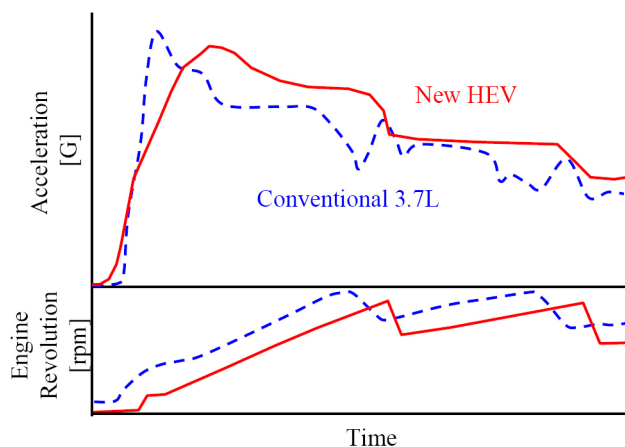


Figure 14 . Acceleration performance (0-60 mph)

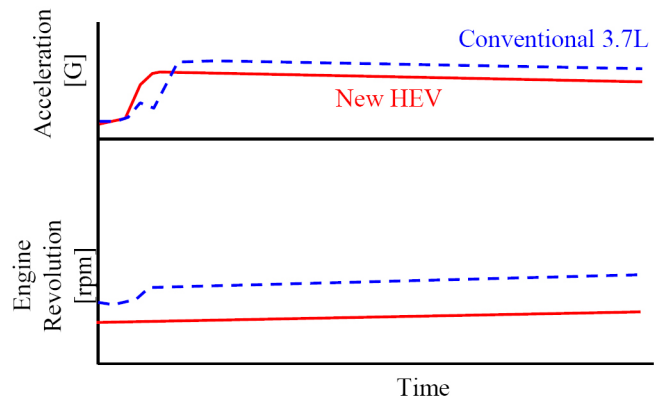


Figure 15 . 60 mph half-throttle acceleration performance

2. ENERGY MANAGEMENT

One of the technological keys to realizing full hybrid function in a one-motor parallel hybrid system involves the energy management of the high-voltage battery. Specifically, battery deterioration must be controlled while satisfying a variety of required vehicle performances, e.g. fuel economy, motive power performance, drivability, and noise, vibration, and harshness (NVH). In the case of this new hybrid, usage of the lithium-ion battery's electric power is greater per unit time than in conventional hybrids. This is caused by motor drive and regeneration functions as well as other factors such as 1) the extended electric-mode driving range, 2) an acceleration-assist function, 3) increased engine start cycles due to the increased frequency of electric mode driving, and 4) motor-assist gear shifting. Charge and discharge cycles must be performed quickly over a short amount of time in order to control the state of charge (SOC) in various driving scenarios. [Figures 16](#) and [17](#) show how energy is managed in highway driving. With the new HEV, the engine is frequently off and battery current is regularly input and output. The example provided indicates amperage of approximately four times that of conventional hybrids with a wider SOC distribution.

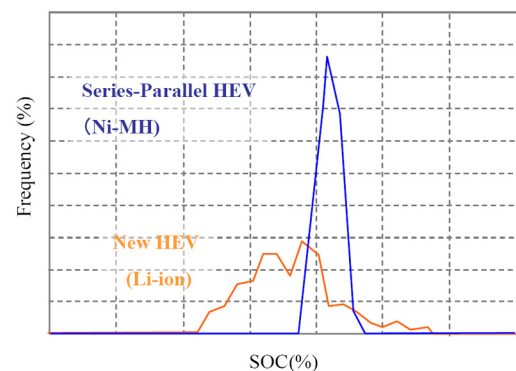


Figure 16 . Battery energy management (highway): SOC distribution