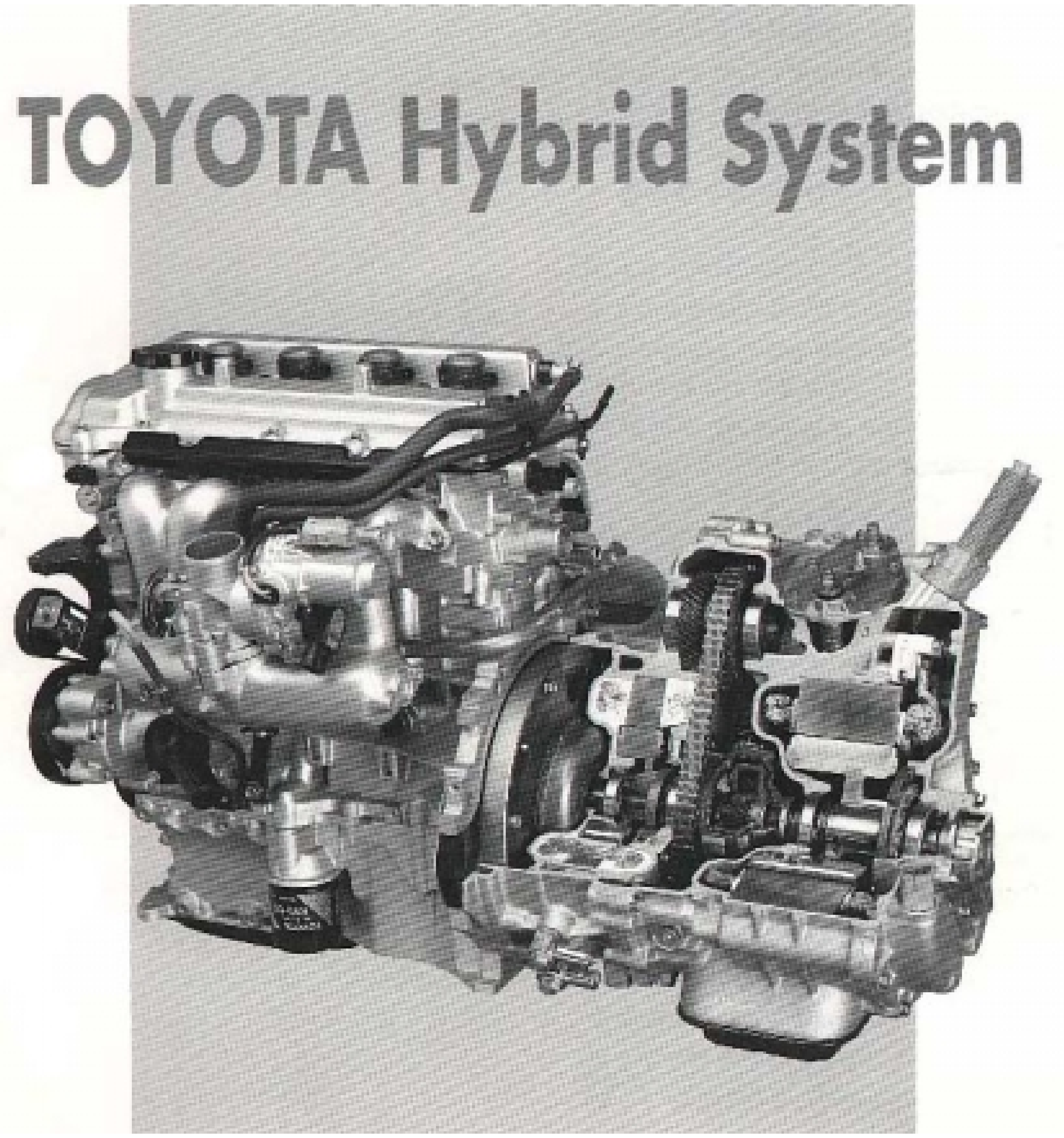
TOYOTA
PRESS INFORMATION '97



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Contents

Introduction

Reducing carbon dioxide (CO_2) emissions to alleviate global warming has become an international issue in recent years. From an automaker's point of view, the most important factors in reducing CO_2 emissions are improving fuel economy and achieving cleaner exhaust emissions.

Toyota's mission is to supply customers worldwide with safe, clean vehicles. Responding to environmental concerns has been a top priority for many years, and we continue striving to achieve a balance between a clean Earth and a prosperous society.

Spurred by global oil crises, efforts to improve fuel economy have covered a wide range of technologies: improving combustion efficiency, reducing friction loss, improving transmission efficiency, improving aerodynamics, and reducing vehicle weight, just to name a few. These efforts paid off with fuel economy improvements totaling about 25% between 1978 and 1990.

Improving fuel combustion directly affects CO_2 emissions. In this area, we set the pace for the auto industry with the development of electronic fuel injection (EFI) and the practical application of multivalve twin cam engines, which improve both fuel economy and performance. We also showed the way in developing more efficient transmissions.

Our successes include the 1984 introduction of the world's first vehicle equipped with a lean-burn engine. We continued to improve our lean-burn technology, amassing a considerable store of technology. For example, in 1992, we introduced a new-generation lean-burn engine that incorporated the world's first mass-produced combustion pressure sensor. Two years later, the development of an NOx storage-reduction catalytic converter helped relieve the NOx emission problem that had plagued lean-burn engines. By 1995, accumulated production of vehicles with lean-burn engines topped the 200,000 mark.

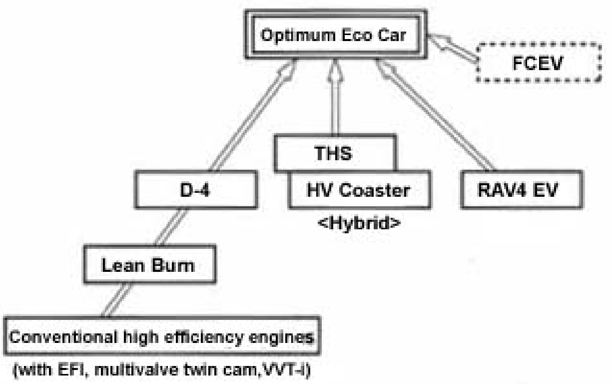
We achieved even more dramatic improvements in combustion efficiency with the development of a high-efficiency direct-injection gasoline engine, the Toyota D-4, which showcases our most advanced technologies. In the Toyota D-4, fuel is injected directly into the cylinder, enabling combustion of ultra-lean air-fuel mixtures. Vehicles featuring the D-4 engine and an automatic transmission that incorporates a state-of-the-art high-efficiency flex lock-up system went on the market in Japan in 1996.

Toyota is also developing a number of technologies to enhance energy conservation and diversification, key issues in this era of dwindling fossil fuel resources. These efforts include alternative energy vehicles, which run on compressed natural gas (CNG) or other fuels instead of gasoline or diesel fuel, as well as electric vehicles (EVs). We began marketing practical EVs on a limited basis in Japan in 1996. That same year, we developed a fuel cell electric vehicle (FCEV) fueled by hydrogen, a clean, efficient source of energy. Our long-term FCEV research aims at bringing these vehicles to the practical application stage in the next century.

These clean-energy vehicles each have peculiar advantages, which should result in a certain degree of popularity. At the moment, however, many technological issues remain to be solved, such as vehicle cost and operating range, and infrastructure issues, such as the development of fuel or charging stations.

Toyota has now completed a new power train for passenger vehicles, the Toyota Hybrid System, or THS for short. This system combines a gasoline engine with an electric motor. Unlike EVs, it does not require battery charging facilities, so it can operate within the existing infrastructure. What's more, experimental THS vehicles offer twice the fuel economy of conventional gasoline-powered vehicles.

■ Toyota's concept for CO_2 Reduction (Fuel Economy)



Hybrid Power Train

Automotive power trains that use a combination of two sources are called hybrid systems. In a hybrid system, each power source is intended to maximize its advantages, while offsetting the disadvantages of the other.

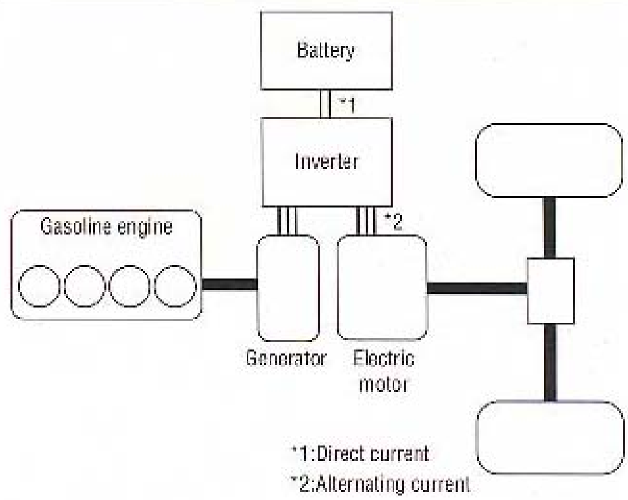
For example, electricity generated by the engine is used to drive the motor, and the system can choose to power the vehicle with either the engine or the electric motor, depending on speed and driving conditions. This reduces exhaust emissions, maximizes fuel economy, and helps overcome the EV's inherent range limitations. These advantages have attracted increasingly attention in recent years.

There are two of hybrid systems:

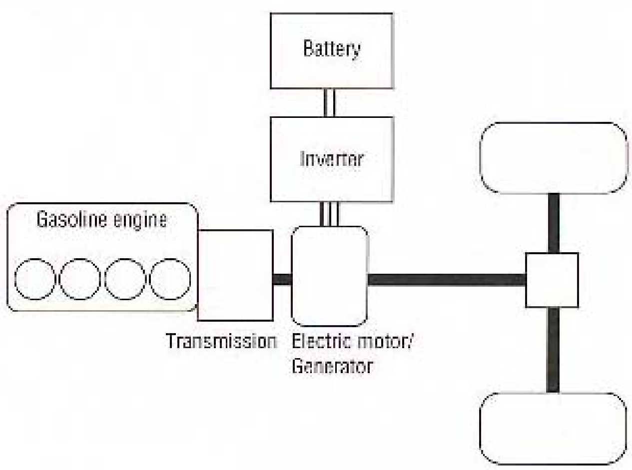
(1) Series hybrid systems

In this type, the engine drives a generator, which produces electricity that powers a motor to drive the wheels. It is called a series hybrid because the power flows in a straight line. The series hybrid system operates a small engine at its most efficient speed, resulting in superior fuel economy and reduced emissions.

■ Series Hybrid System (Fig.2-1)



■ Parallel Hybrid System (Fig.2-2)



(2) Parallel hybrid systems

In this type, both the engine and motor drive the vehicle. Because the power flows along two paths, it is called a parallel hybrid system. This system also allows the engine to recharge the battery while powering the vehicle.

Toyota Hybrid System Objectives

The objectives of THS are to achieve twice the fuel economy of conventional gasoline-powered vehicles, to reduce exhaust emissions significantly, and to assure smooth, powerful, responsive performance.

1. System schematic

THS offers the advantages of both parallel and series hybrid systems.

It is driven by both an engine and a motor, with the engine providing the primary power. The system divides the engine's power with a power split device that uses a planetary gear to send power to both the drive shaft and the generator. Some of the electricity from the generator drives the motor; the remainder, after being converted to DC by an inverter, is stored in the battery.

The THS transmission, consisting of such components as the power split device, motor, generator, and reduction gears, is compact enough for a passenger car.

- ■ Engine: High-efficiency 1.5-liter gasoline engine
- ■ THS transmission

  Power split device: Allocates power via the planetary gear system

  Motor and generator: Permanent magnetic synchronous type
- ■ Battery: Nickel-metal hydride

2. Achieving revolutionary improvement in fuel economy

(1) Highly efficient engine

The primary power source is a newly developed 1.5-liter engine with a high-efficiency high expansion ratio cycle, based on the Atkinson cycle (see p.8), for remarkably low pumping and friction loss.

(2) Improved engine operating range

The engine achieves its best fuel consumption per unit of output when operating in the high torque ranges. Therefore, depending on conditions, the system controls the division of power between engine and motor so the engine always operates in its maximum torque range. The engine also automatically operates within a constant rpm range to maximize fuel economy.

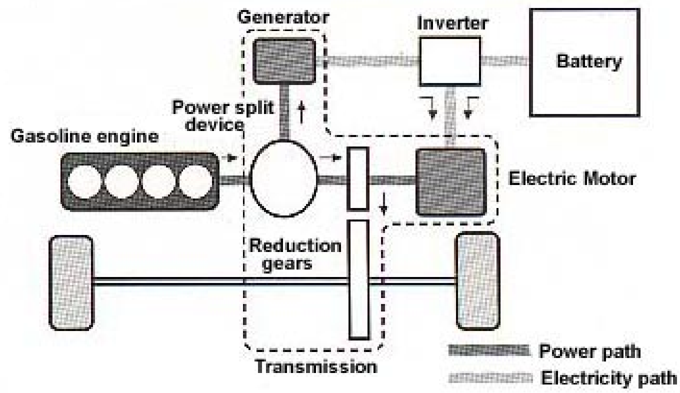
(3) Engine shut-off system

When the vehicle is stopped or decelerating at a low speed, the engine automatically shuts off to save fuel and reduce exhaust emissions.

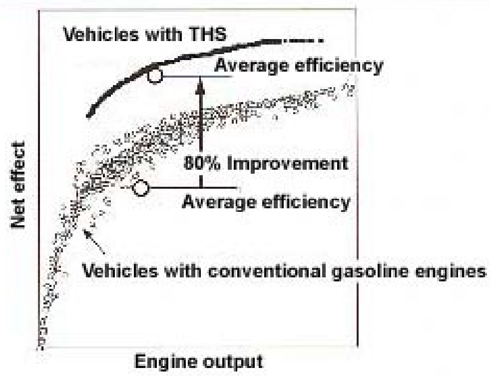
(4) Regeneration and reuse of braking energy

When the vehicle decelerates, the motor serves as a generator, converting the vehicle's kinetic energy into electricity and sending it through an inverter to be stored in the battery.

■ System (Fig.3)

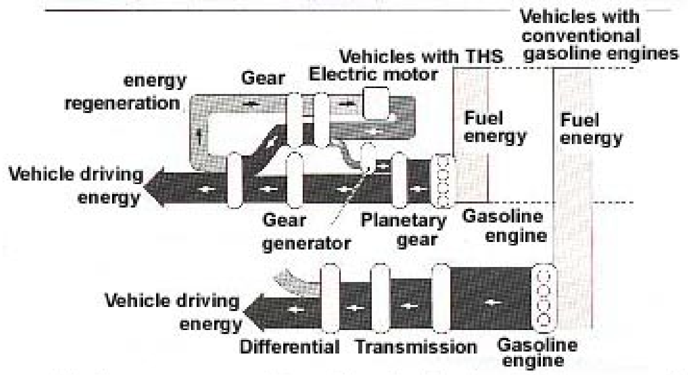


■ Advanced System Control(Fig.4)



This figures compares the net efficiency (conversion efficiency of fuel energy, including the use of generated electric power) of the THS engine with conventional gasoline-powere vehicles, under city driving conditions. As the engine operates in it's most energy-efficient range, it is 80% more efficient than conventional vehicles.

■ Energy Regeneration (Fig.5)



This figure uses energy flow patterns to show how THS improves efficiency. THS doubles the fuel economy of conventional vehicles - in other words, it offers a 100% increase in fuel economy. Engine efficiency, including the use of generated electricity, improves by 80% (see Fig.4), while energy recovery during acceleration adds another 20% improvement.

3. **Achieving smooth acceleration and deceleration**

Because the THS transmission function as an electronically controlled continuously variable transmission and the electric motor assists the engine, a THS vehicle achieves smooth acceleration and deceleration, as well as excellent response.

In particular, initial acceleration takes advantage of the motor's characteristics -- high torque at low speeds. For maximum acceleration when the throttle is fully opened, power from both engine and motor drives the vehicle, with energy from the battery boosting the motor's output.

(System operating conditions)
Starting out/light load

When starting out, driving at extremely low speeds, going down a moderate slope, or operating in other conditions in which the engine is not at peak efficiency, the engine shuts down and the motor drives the vehicle. (A)

Normal driving

The power split device separates the engine power into two paths. One path drives the wheels. (B)

The other drives the generator to produce electricity for the motor, which provides additional driving force to the wheels. (C)

The system controls the ratio of power to each path for maximum efficiency.

Full-throttle acceleration

During full throttle acceleration, the battery also supplies power, boosting the motor's output. (A)

Deceleration/braking

During deceleration and braking, the inertia of the wheels turns the motor, which then acts as a generator. The recovered electricity is stored in the battery. (A)

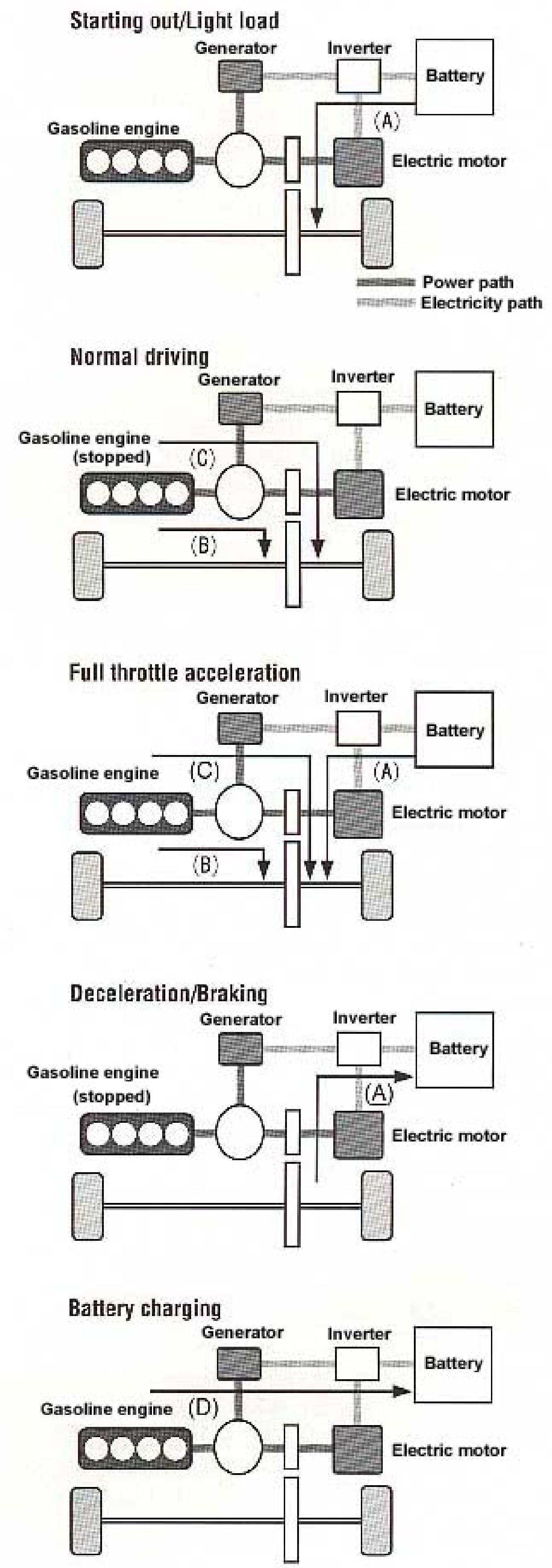
Battery recharging

The battery is regulated to maintain a constant charge. When the battery gets low, the generator routes power to recharge it. (D)

Stopped

The engine automatically shuts off when the vehicle is stopped.

■ How The System Works (Fig.6)



THS Transmission

The THS transmission consists of the power split device, the generator, the motor, and reduction gears. The power split device divides the power from the engine, sending one portion to the drive shaft, and the other to the generator. In other words, engine power is transmitted to the drive shaft via a mechanical path and an electrical path.

The THS transmission also functions as an electronically controlled continuously variable transmission by smoothly adjusting the speed of the engine, generator, and motor when accelerating or decelerating.

1. Power split device

The power split device uses a planetary gear.

The rotating shaft of the planetary carrier is connected to the engine, and uses a pinion gear to transmit power to the outer ring gear and the inner sun gear. The shaft of the ring gear connects directly to the motor and to the drive shaft through reduction gears, driving the wheels. The shaft of the sun gear connects to the generator.

2. Engine, generator, and motor operations

The following graph shows how the engine, generator, and motor operate under different conditions.

(1) Stopped

The engine, generator, and motor are stopped. (A)

(2) Engine start up and vehicle starting out

The generator acts as a starter to crank the engine. After the engine starts up, the generator begins to produce electricity, operating the motor, which supplies power for the vehicle to start out. (B)

(3) Normal driving

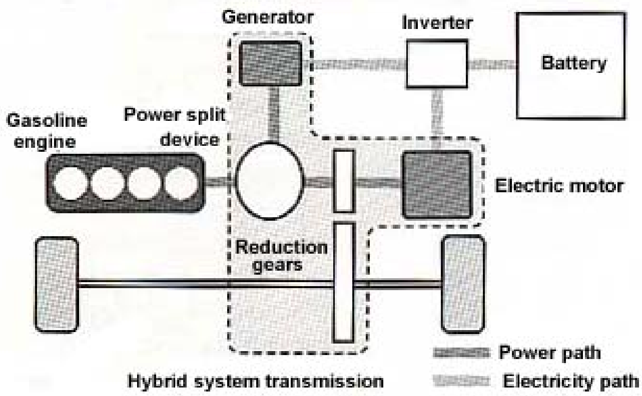
The engine supplies enough power for normal driving conditions, so there is virtually no need to generate electricity. (C)

(4) Acceleration

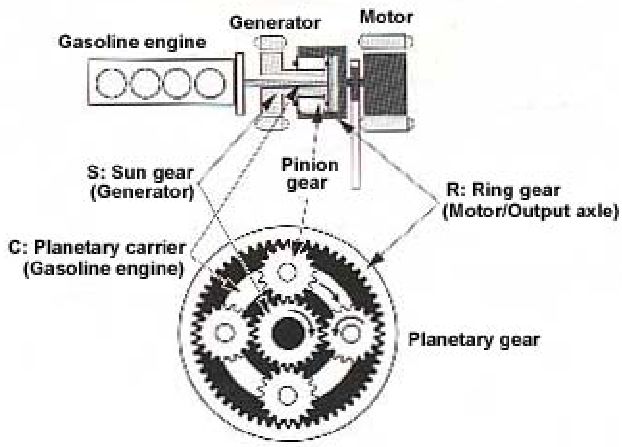
As the vehicle accelerates from cruising speeds, engine speed increases, the generator produces electricity, and the motor sends additional power to the drive shaft to assist the acceleration. (D)

The system can change the engine speed by controlling the generator's revolutions. And some of the engine's output is transmitted to the motor via the generator as supplemental power for acceleration. This means that the system does not need a conventional transmission.

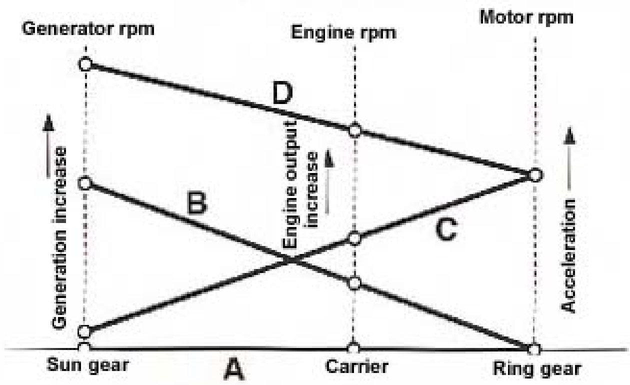
■ Hybrid Transmission (Fig.7-1)



■ Power Split Device (Fig.7-2)



■ Power Interaction Diagram (Fig.7-3)



The three vertical lines in the diagram show the revolutions of three shafts in the planetary gear.

3. Engine stopping system

When the vehicle is stopped or decelerating from a low speed, the engine automatically shuts down to conserve energy.

When starting out, the motor propels the vehicle; then the engine starts. At very low speeds, or under other conditions in which the engine would operate inefficiently, it shuts down to save fuel. The vehicle is then powered entirely by the motor.

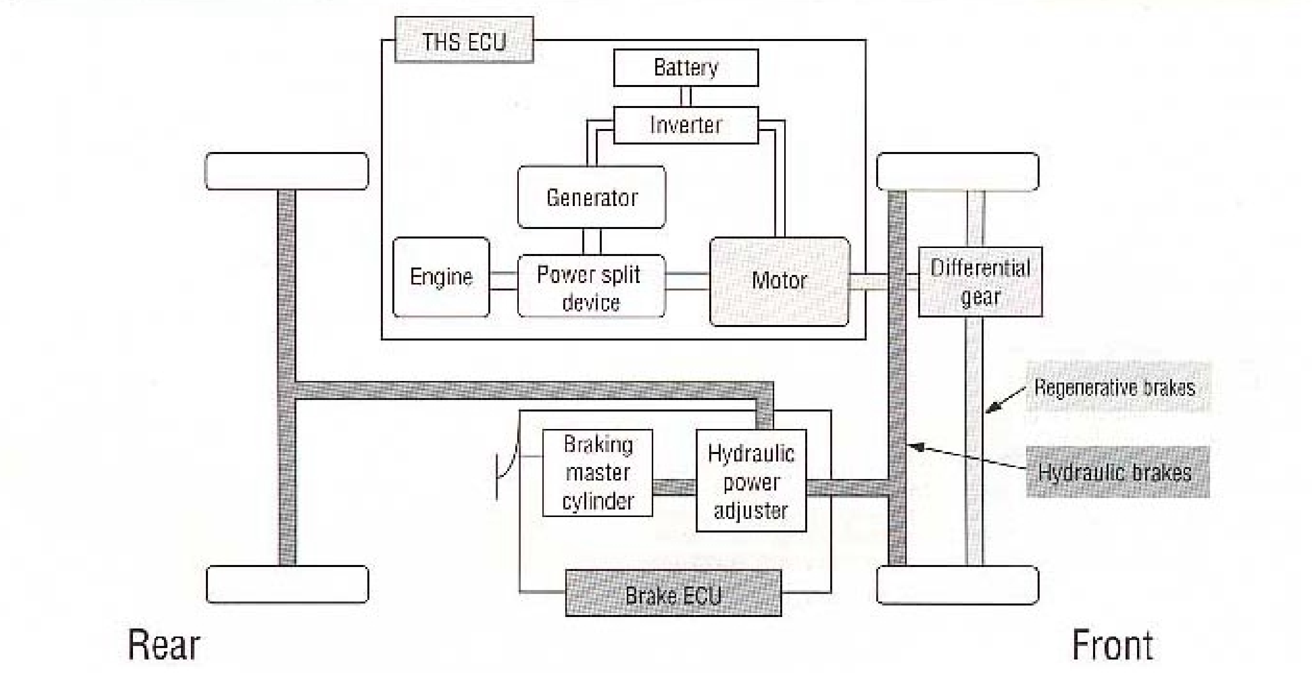
4. Regenerative braking system

When the vehicle slows down, either by engine braking or by applying the brakes, the motor acts as a generator and converts kinetic energy into electricity, which is stored in the battery.

This regenerative braking system is especially useful in the repetitive acceleration and deceleration of city driving, and is a very effective method of recovering energy.

When the driver applies the brakes, the hydraulic and regenerative braking systems are controlled in a cooperative manner to maximize energy regeneration.

■ **Interaction of Motor and Hydraulics (Fig.8)**



Highly Efficient Engine

THS gives the engine a boost with the motor whenever necessary, so the engine was developed to operate at maximum thermal efficiency rather than maximum output. This result in much better fuel economy.

1. High expansion ratio cycle

The new 1.5-liter gasoline engine uses a high expansion ratio cycle based on the Atkinson cycle for greater efficiency.

This engine has smaller combustion chambers and greater expansion ratio*1. As a result, the expansion stroke can be extended until the expansion pressure has virtually dissipated, converting much more of the combustion energy into crankshaft revolutions.

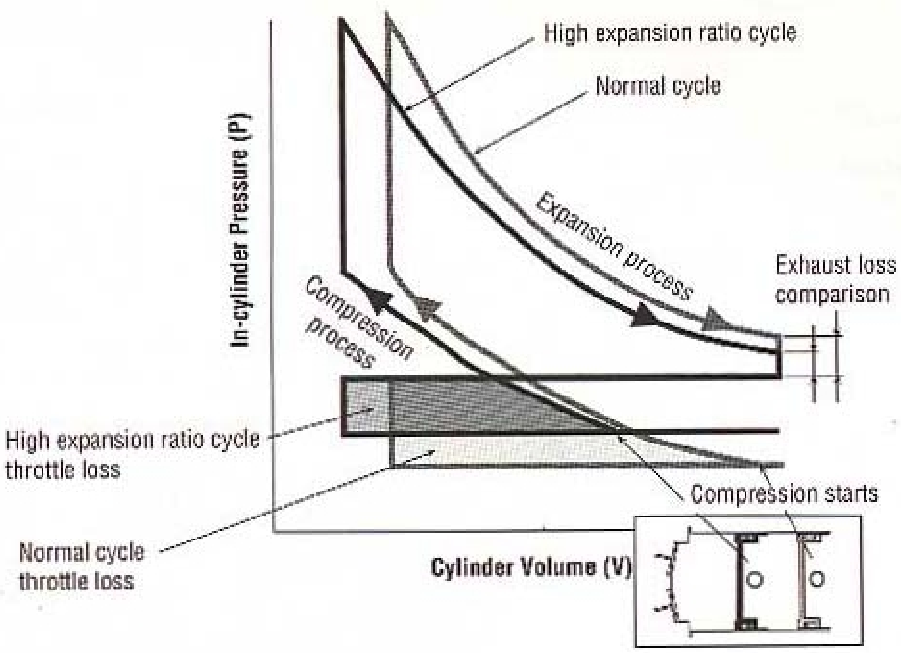
Conventional engines have virtually identical compression and expansion strokes, so the compression ratio*2 and expansion ratios are basically the same. As a result, raising the expansion ratio also raises the compression ratio. This causes knocking, which limits any increase in the expansion ratio.

If the intake valve is left open longer than ordinary at the beginning of the compression stroke, some of the air in the cylinder returns to the intake manifold, delaying the start of compression. In effect, this increases the expansion ratio without raising the actual compression ratio.

This allows a larger throttle opening, which reduces the pressure inside the intake manifold when the engine is under light load, reducing pumping loss.

*1 Expansion ratio: (expansion stroke volume + combustion chamber volume)/combustion chamber volume
*2 Compression Ratio: (compression stroke volume + combustion chamber volume)/combustion chamber volume

■ **Engine/High Expansion Ratio cycle (Fig.9)**



Atkinson cycle
A heat cycle proposed by British engineer James Atkinson. It's configuration allows independent setting of the compression stroke and expansion stroke Later on, R.H. Miller of the United States improved the system by adjusting the timing of the intake valve opening and closing (the Miller cycle). Atkinson cycle engines offer much higher thermal efficiency than conventional engines, but have seen few practical applications because they require supercharging to produce sufficient power for conventional vehicles.

2. Reduced friction loss

The engine's maximum speed is 4,000 rpm, which results in low fuel consumption.

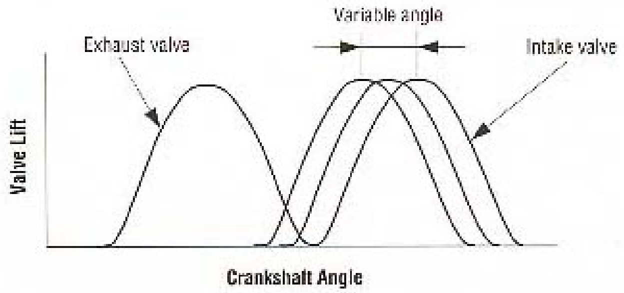
The low-rpm operation does not require components of the same strength as those in conventional engines. That allowed us to make them smaller and lighter. Our development work resulted in a thinner crankshaft, lower tensile strength piston rings, and reduced valve spring loads, all of which contribute to a great reduction in friction loss.

3. Advanced functions

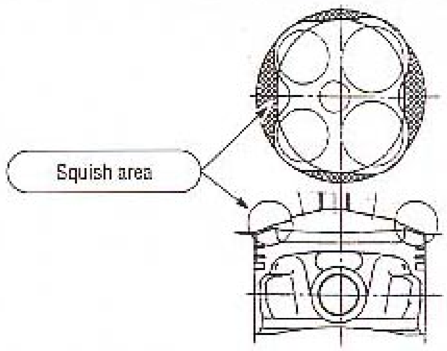
Variable Valve Timing-intelligent (VVT-i) adjusts the open/close timing of the intake valves to match operating conditions, helping the engine run at top efficiency at all times.

Another exclusive feature, the tilted squish-type compact combustion chamber, allows the ignition flame to spread quickly across the combustion chamber, further enhancing heat efficiency. Also, the aluminum alloy block, a compact intake manifold, and other such changes help reduce the engine's size and weight. This reduces overall vehicle weight and contributes to improved fuel economy.

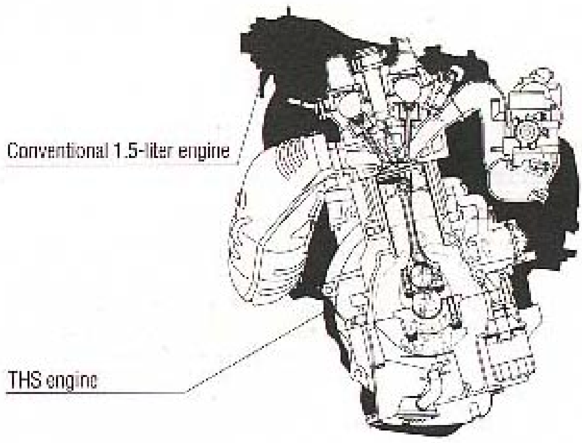
■ Valve Timing (Fig.10-1)



■ Tilted Squish-type Combustion Chamber (Fig.10-2)



■ Engine Cross-Section (Fig.10-3)



Other Major Components

Development work also led to performance improvements and size weight reduction in components such as the motor and the battery. This makes the system more practical and easier to mount on a vehicle.

1. Battery

The THS battery marks a further advance in sealed nickel-metal hydride technology, which was originally developed for EVs. It offers improved power output (triple the power of EV batteries), sealing, and durability, as well as reduced weight. These high-performance batteries are a perfect match for the Toyota Hybrid System.

The system controls the generator and motor to ensure that the battery maintains a constant charge. Unlike EVs, there is no need for recharging from an outside source.

2. Motor

The electric motor is a compact, lightweight, yet highly efficient AC permanent magnetic synchronous motor. It provides a power boost for the engine, ensuring smooth starts and powerful, responsive acceleration. In addition, when the regenerative braking system activates, the motor converts the vehicle's kinetic energy into electricity, and stores it in the battery.

3. Generator

THS uses a high-efficiency AC permanent magnet synchronous generator.

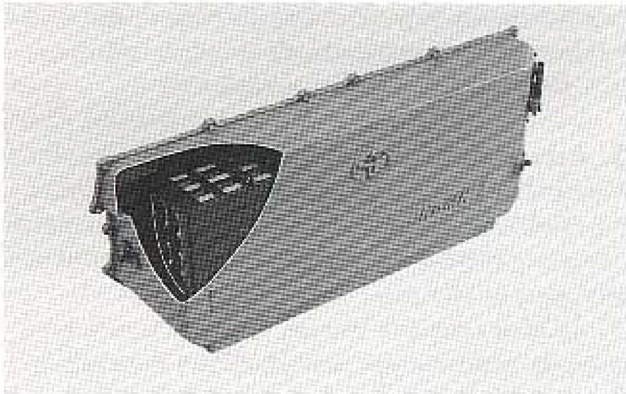
It generates electricity to drive the motor or recharge the battery. In addition, adjusting the generator's revolutions by controlling the amount of electricity generated in effect controls the ratio of power distribution from the power split device.

The generator also serves as the starter for the engine

4. Inverters

The inverters turn direct current from the battery into alternating current for the drive motor, and convert alternating current from the generator and motor to direct current that charges the battery. The circuit uses an intelligent power module to increase reliability.

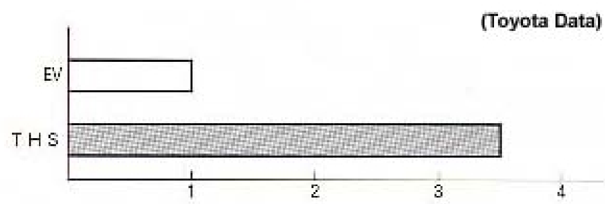
■ Battery



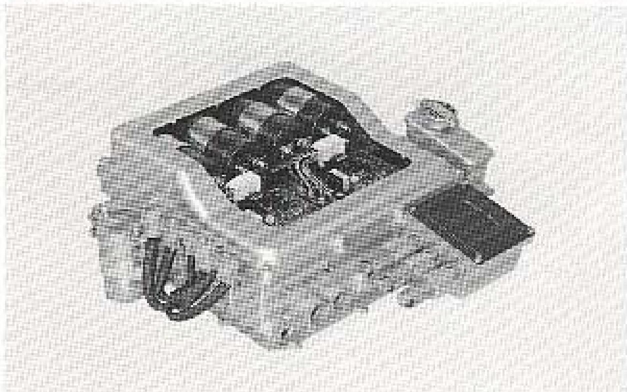
■ Types and Characteristics of Batteries (Fig.11-1)

	Pb - Acid	Ni - Cd	Ni - Mh	Li - ion
Energy density	△	○	○	◎
Power density	◎	◎	◎	◎
Durability	△	○	◎	○
Safety	○	○	◎	△
Cost	○	△	△	△

■ Comparison of Battery Output per Volume (Fig.11-2)



■ Inverter



Advanced System Control

THS calculates the desired operating condition and the current operating condition of the engine, motor, generator, battery, and other components, and controls them accurately in real time.

1. Engine operating control

By matching engine speed to operating conditions and the electronic throttle opening, the THS ECU keeps the engine operating in a predetermined high torque range, maximizing fuel economy.

2. Operational control

When the driver presses the accelerator pedal (1), the electronic throttle opens in response to a signal from the ECU (2); engine speeds are also controlled (3). At the same time, the ECU determines the allocation of engine power between the drive shaft and the generator (4). The carefully controlled combination of the engine's direct drive force and the motor's drive force propels the vehicle. If the battery gets low, the ECU commands the engine to provide output to the generator to recharge it (5).

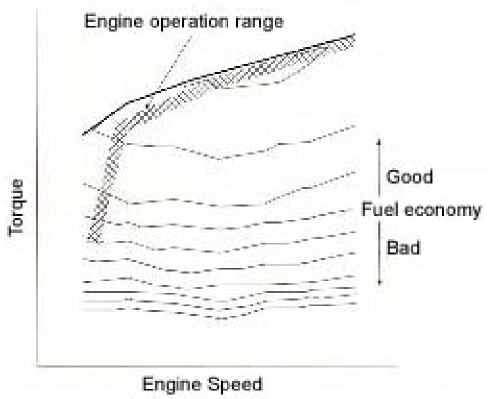
3. Driving force control

Performance of THS vehicles is determined by the sum total of:

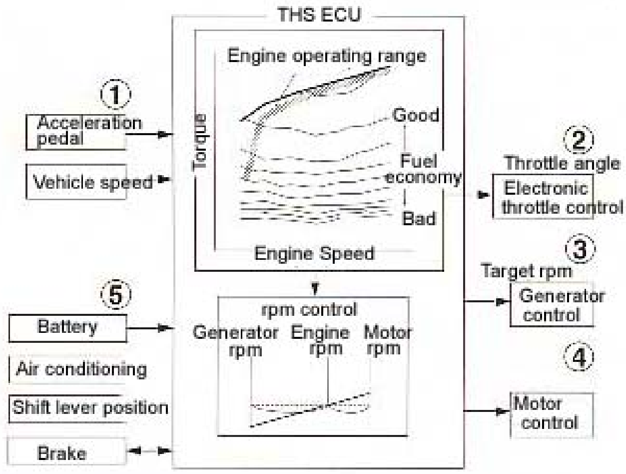
■ the engine's direct driving force
■ the driving force of the motor, powered by the generator and battery

At low vehicle speeds, this overall drive force is dominated by the motor. With the power split device functioning like an electronic continuously variable transmission, the vehicle achieves much smoother acceleration and deceleration performance than vehicles with conventional engines.

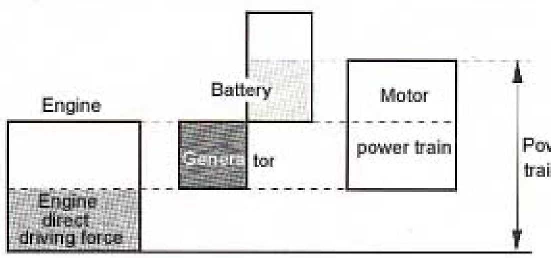
■ Engine Operation Range (Fig.12)



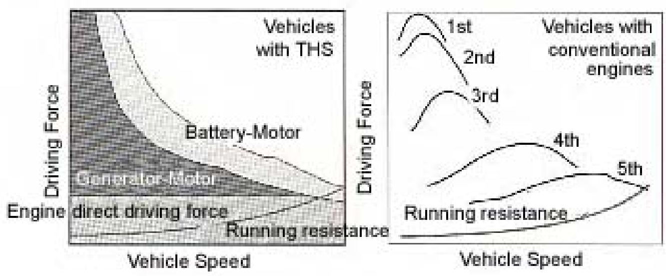
■ THS Control System (Fig.13)



■ THS Performance (Fig.14-1)



■ Performance Comparisons (Fig.14-2)

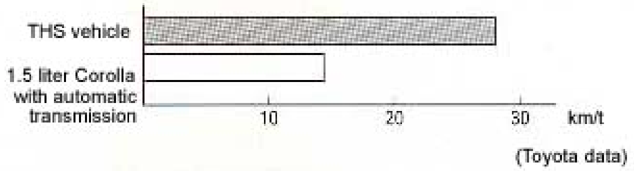


THS Performance

1. Fuel economy

Compared to vehicles with conventional engines and automatic, THS vehicles offer about twice the fuel economy, or about 28km/liter (according to in-house test results) in the Japanese test driving mode.

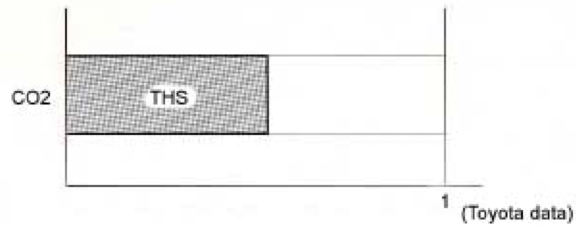
■ Fuel Economy (Japanese test driving mode) (Fig.15)



2. Exhaust emissions

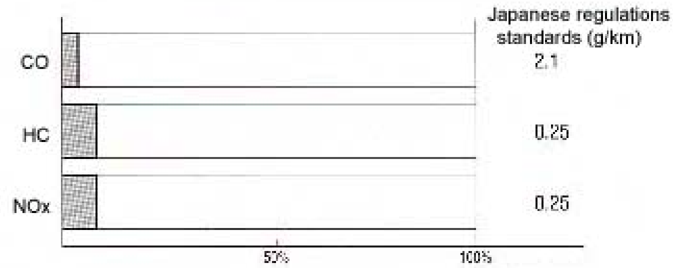
Compared to conventional gasoline-powered passenger vehicles, THS vehicles emit about half as much CO2 and about one-tenth as much CO, HC and NOx.

■ CO_2 Emission Volume (Fig.16-1)



Compared to vehicles w/ conventional gasoline engines

■ Emissions (Japanese test driving mode) (Fig.16-2)

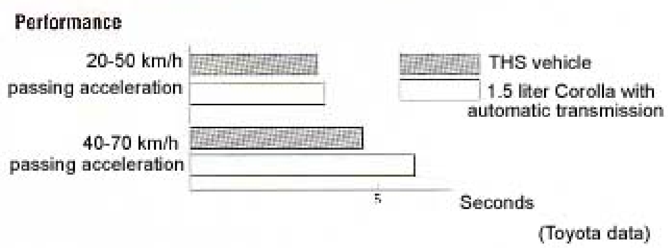


Compared to regulation standards (Toyota data)

3. Acceleration

THS vehicles offer passing acceleration that matches or exceeds that of conventional vehicles equipped with gasoline engines and automatic transmissions. What's more, acceleration is smooth, without the kick-down of conventional vehicles.

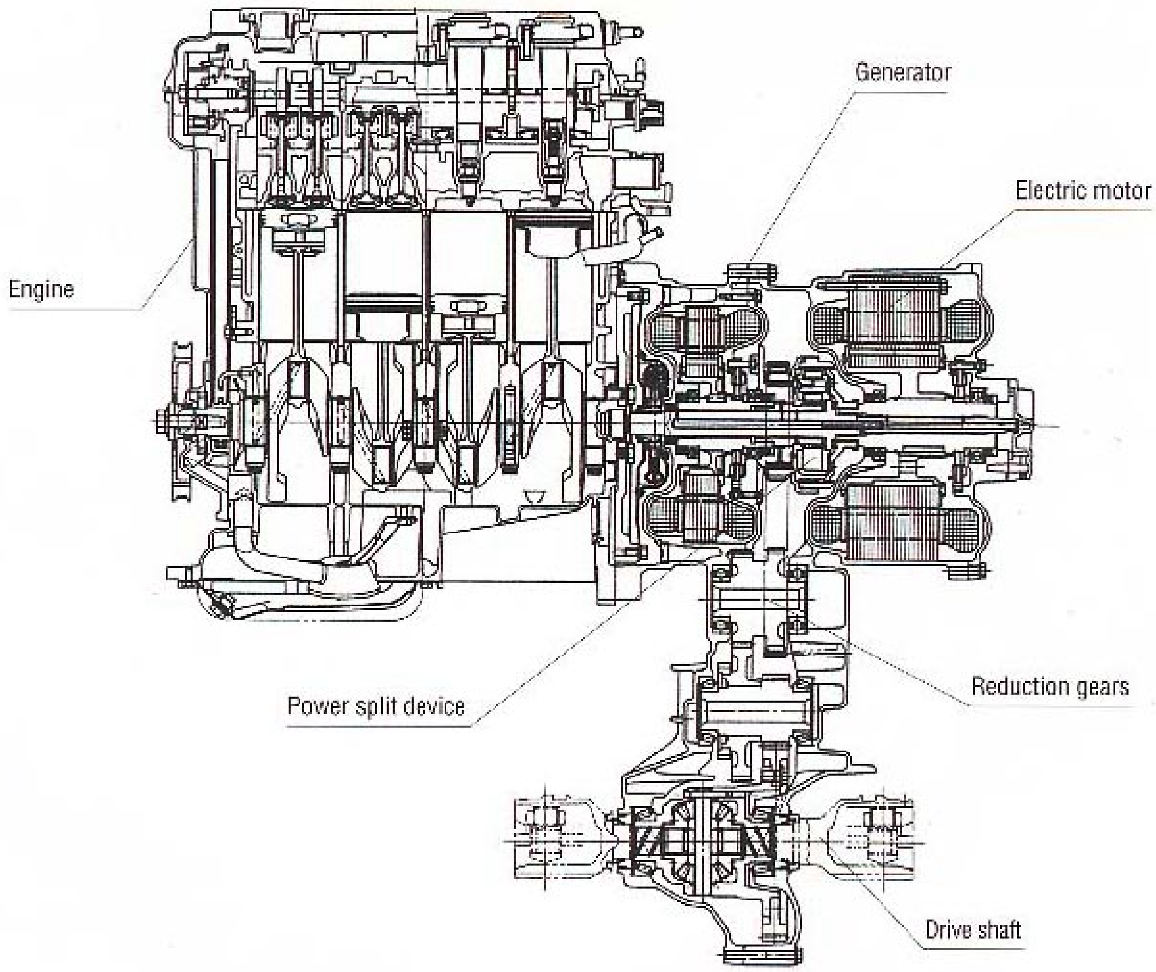
■ Acceleration (Fig.17)



■ Specifications

Engine	**Number of Cylinders**	**Direct 4-Cylinder**
	Displacement (*l*)	**1.5**
	Valve train	**DOHC, four-valve, VVT-i**
	Fuel supply system	**Pent roof type**
	Fuel	**EFI**
	Type	**Regular gasoline**
Motor	**Type**	**Permanent magnet synchronous**
Generator	**Type**	**Permanent magnet synchronous**
High voltage battery	**Type**	**Nickel-metal hydride**

■ Cross-Section of Engine and THS Transmission



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