Toyota's Newly Developed Electric-Gasoline Engine Hybrid Powertrain System

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Abstract

Toyota has developed a hybrid powertrain system based on a new concept. This system includes a drivetrain which features a planetary gear mechanism for dividing the drive force and two motor/generators. Computer control is used to optimize engine fuel consumption, minimize exhaust emissions, stop and start the engine and apply regenerative braking. The system also uses newly developed, high-output Ni-MH batteries.

Test vehicles fitted with this new hybrid system realized approximately twice the fuel economy of the conventional model and exhibited a high level of potential in terms of minimizing exhaust emissions.

1. Background

Man-made CO_2 is thought to be one of the contributors to global warming. To minimize the automobile's impact, industry continues to develop powertrains that consume less fuel and thus create less CO_2. This has the added benefit of lessening the consumption of non-renewable fossil fuels. This trend is evidenced by examples such as the PNGV program in the United States and the 3-liter per 100 km car project in Europe. At Toyota, research for creating a powertrain system that consumes less fuel suggested the possibility of adopting a hybrid system consisting of an electric motor and a gasoline engine.

Previous hybrid systems that have been considered were generally classified as either series or parallel type. Our powertrain is based on the parallel type. However, to optimize the engine's operation point (for minimum fuel consumption), it includes a system that enables a series-like operation through the use of a generator and a motor that are independent of each other.

2. System configuration

Figure 1 shows the configuration of the Toyota Hybrid System. Following are sections describing the basic elements of the system.

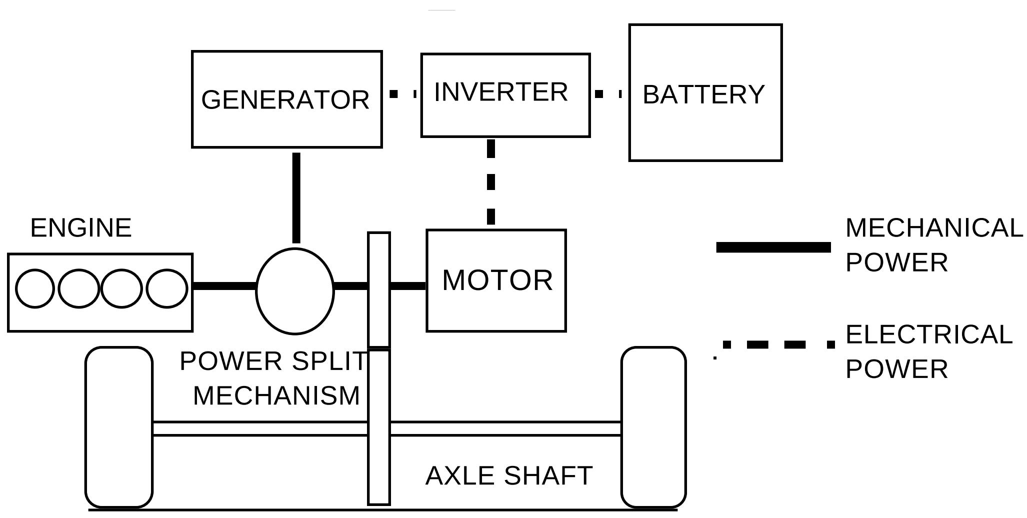

Fig1 Toyota Hybrid System Configuration.

2-1. Hybrid transmission

The transmission consists of a single planetary gear set to divide the engine's output plus a generator and a motor. The planetary gear set divides the engine's drive force into two forces: one that is transmitted via the ring gear to drive the axle shaft and the other that drives the generator through the sun gear. The electrical force, produced in the generator, is re-converted into mechanical force through the motor. Since the motor is also connected directly to the ring gear, this force is transmitted to the axle shaft. In addition, batteries provide supplemental drive force to the motor as needed. The batteries also recover and reuse the braking energy through regenerative control.

2-2. Engine

As for the engine, we developed a new 1.5-liter gasoline engine that achieves high combustion efficiency through the application of the high expansion ratio Atkinson cycle. Because the electric motor can assist in meeting peak drive force requirements, we optimized the engine for a high level of efficiency rather than peak power output. Specifically, we designed an engine in which friction loss is dramatically reduced by lowering its maximum speed. Further, we used the VVT-i (Variable Valve Timing-intelligent) system to finely control the intake timing, thus ensuring maximum efficiency.

2-3. Batteries

The nickel metal hydride battery developed for the electric vehicle (EV) application features the superior characteristics of higher power density, lighter weight, and longer life. New batteries were developed building on these attributes but optimized for the hybrid application. The new battery has more than three times the power of the EV battery per unit volume.

3. System operation

Figure 2 shows a schematic diagram of the system. The engine is connected to the planet carrier, the generator is connected to the sun gear and the motor is connected to the ring gear. Ring gear output is connected to the axle via a differential and counter-gear.

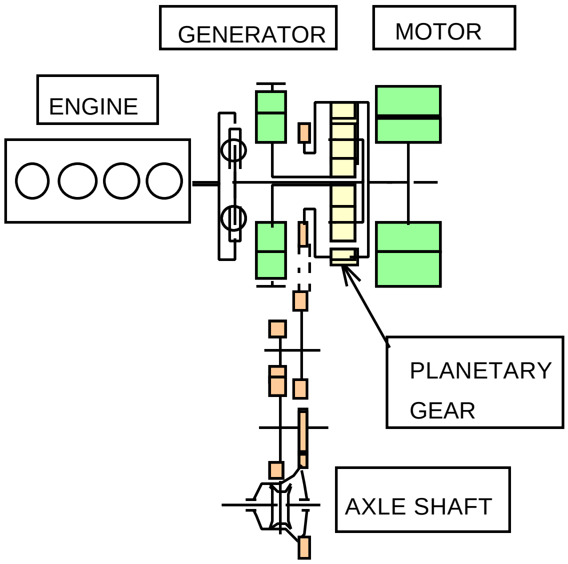

Fig.2 A schematic representation of the Toyota Hybrid System

System operation is described below using the following symbols:

Powertrain Component	Engine	Generator		Motor	Axle
Planet Element	Carrier	Sun	Ring		
Speed	ne	ng	nr	nm	
Torque	Te	Tg	Tr	Tm	Ta

ρ : planetary gear ratio = number of sun gear teeth / number of ring gear teeth
Gr : reduction gear ratio = nr / na

3.1 Colinear relationship

Relative shaft speeds for the planetary gear set elements are given by equation (1).

$$\rho * ng + nr = (1 + \rho) * ne \quad (1)$$

Generator and ring gear torque at steady state is obtained as follows:

$$Tg = (\rho / (1 + \rho)) * Te \quad (2)$$

$$Tr = (1/(1 + \rho)) * Te \quad (3)$$

3.2 Relation between Engine output and axle shaft output (CVT function)

Since the generator output is fed back into the motor, total power available at the axle can be expressed as shown in equation (4). (For simplification, the conversion efficiency from the generator to the motor is assumed to be 1).

$$na * Ta = nr*Trnm*Tm \quad (4)$$

$$nr * Tr nr * (1 / (1+))*Te \quad (5)$$

$$nm*Tm Ng * Tg ng * (/ (1+))*Te \quad (6)$$

Consequently, using formula (1), and formulas (4) through (6) result in:

$$na * Ta \ (1+)*ne*(1 / (1+))*Te$$

$$ne * Te \quad (7)$$

Thus, it is evident that the engine output has been converted into axle shaft output. Moreover, based on formula (1), by fixing ng, the relationship between na and ne will be:

Gr * na(1+) * ne * ng (1) '

Therefore, between axle shaft speed na and engine speed ne stands the speed conversion in which the parameter is generator speed ng.

As described above, due to the output saving function given in formula (7) and the speed conversion function given in formula (1)', it is evident that this composition is that of a CVT (Continuous Variable Transmission).

3.3 Engine start/stop

To attain the target engine speed ne^ regardless of whether the vehicle is at a standstill or moving, it will suffice to control the generator speed by applying formula (1).

Hence, rendering ng^ as the target generator speed, executing the generator speed control so that:

ng^ ((1+) * ne^- nm) / (8)

Then, it will become possible to render the engine speed to be ne^, thus enabling the engine to be started by injecting and igniting the fuel.

4. System Control

Figure 3 shows the configuration of the hybrid control system.

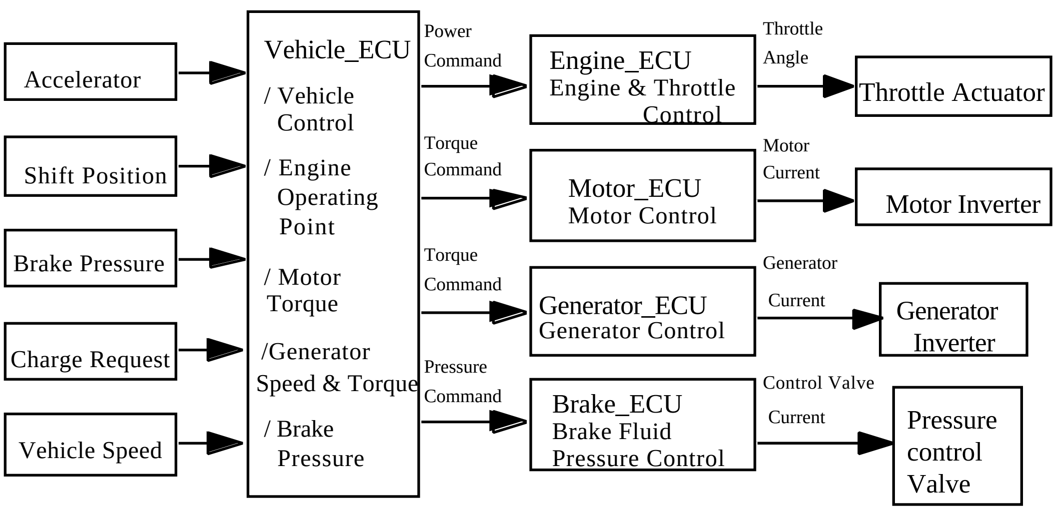

Fig.3 Hybrid Control System

Vehicle Control (Vehicle ECU)

Based on accelerator pedal angle, shift position, brake pedal effort and battery condition this ECU calculates the engine output, motor torque, and generator speed commands for the respective control devices. Furthermore, during braking, this ECU gives a regenerative control command to the motor and simultaneously gives a pressure reduction command, equivalent to the regenerative control command, to the hydraulic servo valve to provide the total braking force required.

Engine Throttle Control (Engine ECU)

Based on the engine power command from the Vehicle ECU, this ECU gives the actuator a throttle opening angle command.

Motor Control (Motor ECU)

The Motor ECU commands the motor to provide that portion of the total axle torque not met by the engine direct path torque. Hence, the sum of the engine direct path and the motor torque meets the accelerator pedal demand.

Generator Control (Generator ECU)

To control the engine speed, the Generator ECU controls the generator torque to achieve the target generator speed that was defined by the Vehicle ECU.

Hydraulic Brake Control (Brake ECU)

The Brake ECU commands the pressure control valve to provide brake energy in excess of regenerative potential to meet the total brake pressure requirement calculated by the Vehicle ECU.

This hybrid control system is extremely flexible and offers the following features:

- The engine can be started and stopped any time while the vehicle is being driven
- The CVT function enables the engine operating point to be controlled
- To meet braking demand, the system balance regenerative and hydraulic operation

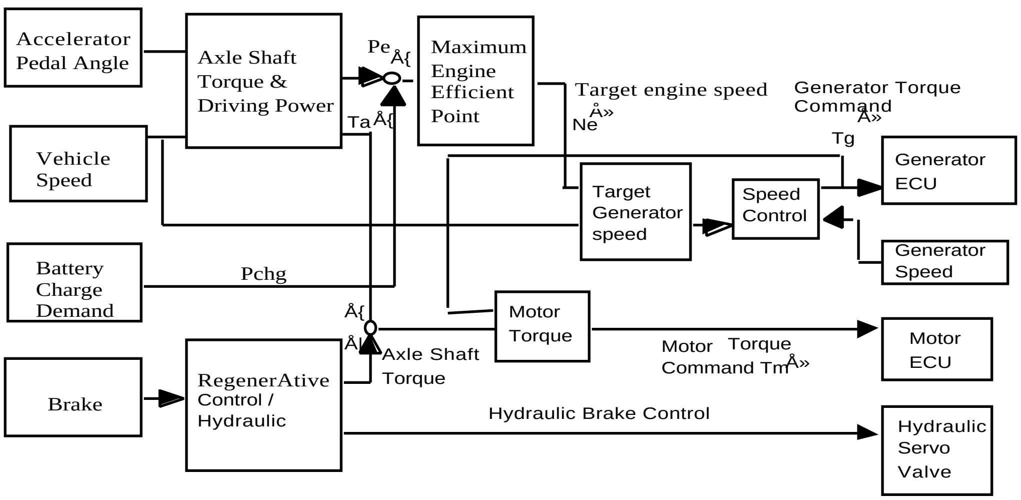

Fig4. Control Logic Block Diagram

Figure 4 is a block diagram of the control logic. Followings are features of the control system from the perspective of fuel consumption:

Engine operation and/or electric motor operation

Because engines are less efficient in the low-load region, it is more effective to stop the engine and operate the vehicle on its batteries when the driving power demand is low. Therefore, below a defined power demand, the firing of the engine is stopped.

Maximizing engine efficiency

Since the engine's maximum efficiency is usually obtained at its wide-open-throttle operating point, this data is stored and used to control the generator speed and the throttle opening angle.

Regenerative control

The brake system prioritizes regenerative braking by storing a table of available regenerative force and only demanding excess effort to the hydraulic brakes based on brake pedal effort.

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