Hybrid Vehicles
Lessons Learned and Future Prospects

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ABSTRACT

There exist many environmental and earth resource problems to be solved for the 21st century. Hybridization of both internal combustion powertrains and fuel cell powertrains holds great promise for next generation vehicles. This paper describes the lessons learned during design, development, production and marketing of nearly 700,000 hybrid vehicles to date. We review the evolution of major components with a focus on reducing cost, mass and volume while increasing power and efficiency. We also describe the future prospects for hybrid vehicles.

INTRODUCTION

Between the launch of Prius in December 1997 and June 2006, Toyota sold nearly 690,000 hybrid vehicles in the global market, Figure 1.

Figure 1 Toyota Global Hybrid Sales

Toyota had captured 80% of the global hybrid market, but many competitors have announced aggressive plans for ever broadening hybrid sales.

Looking forward, Toyota global hybrid sales should pass the million unit market in 2007. With a stated goal of 1 million units per year early in the next decade, it is reasonable to expect additional product launches and increased volume of current product.

As shown in figure 2, US sales exceeded 350,000 cumulative units at the end of June 2006 and were rapidly increasing. It is expected that the US market will represent ~60% of Toyota global hybrid sales in the future.

Figure 2 Toyota US Hybrid Sales

With five models in the US market, Toyota has the most diverse hybrid product offering in the US market. As of July 2006, Toyota had over 68% of the US hybrid market, Figure 3. But many other manufacturers are now joining the hybrid race and the future will see intense competition in this arena as in all other segments.
This paper discusses lessons learned over the last 8 years and speculates about future direction.

DEFINITION OF HYBRID

A hybrid vehicle is defined as “a vehicle in which propulsion energy is available from two or more kinds of energy stores, sources or converters.” Practical developments have been achieved with combinations of internal combustion engines, electric motors and hydraulic motors, but given the background development of electric vehicles, electric motors, batteries and their controlling technologies developed rapidly, and ICE-electric hybrids have become mainstream. A full hybrid is further defined as a hybrid having the ability to use either the engine or motor independently or in combination. It should be pointed out that all Toyota hybrid systems sold to date in the US are of the “full” hybrid configuration.

TOYOTA HYBRID SYSTEMS

Currently marketed as Hybrid Synergy Drive there have been several improvements both in overall system and individual components since December of 1997. Figure 4 shows the current Prius system configuration.

All of Toyota’s US market hybrids feature what has been called a series/parallel configuration with an input planetary gear power split device. The planetary carrier is linked to the engine, the sun gear to the generator, and the ring gear to final drive. In different applications the motor is either directly connected to the ring or connects through a gear system to increase torque and lower rotational speed. The major components of the system include the engine, the battery, the motor/generators, the power electronics, the gear system and the control system. Auxiliary systems include air conditioning and power steering.

COMPONENT LESSONS LEARNED

The following sections look at the various components of a hybrid system and discuss improvements made over time.

ENGINES

When designing a hybrid system, there are three basic engine choices driven by desired power performance and fuel efficiency goals for the vehicle. For maximum efficiency, the engine can be downsized and perhaps use a more efficient combustion strategy (like Atkinson cycle). For a mixture of enhanced performance and improved efficiency, you could keep the same displacement, but employ a more efficient combustion strategy. Finally, you would keep the same high performance engine and supplement it with a hybrid system for even greater performance and a more modest improvement in efficiency. We have used each of these approaches to achieve different objectives. Table 1 summarizes the engine specifications, performance and fuel economy of various products.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prius</th>
<th>Camry HV</th>
<th>RX 400h / Highlander</th>
<th>GS 450h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration</td>
<td>L-4</td>
<td>L-4</td>
<td>V-6</td>
<td>V-6</td>
</tr>
<tr>
<td>Displacement</td>
<td>1.5 l</td>
<td>2.4 l</td>
<td>3.3 l</td>
<td>3.5 l</td>
</tr>
<tr>
<td>Rated Power</td>
<td>57 kW</td>
<td>110 kW</td>
<td>165 kW</td>
<td>218 kW</td>
</tr>
<tr>
<td>Rated Torque</td>
<td>111 N-m</td>
<td>187 N-m</td>
<td>288 N-m</td>
<td>362 N-m</td>
</tr>
<tr>
<td>Combustion</td>
<td>Atkinson</td>
<td>Atkinson</td>
<td>Otto</td>
<td>Otto</td>
</tr>
<tr>
<td>0-60 mph</td>
<td>10.1</td>
<td>8.5</td>
<td>6.9</td>
<td>5.2</td>
</tr>
<tr>
<td>Combined FE</td>
<td>55</td>
<td>39</td>
<td>29</td>
<td>26</td>
</tr>
</tbody>
</table>

Table 1 Engine specifications, performance and FE

BATTERIES

Significant progress has been made in specific power and attendant mass and volume over the years. Figure 5 shows the improvement over three generations of Nickel Metal Hydride batteries for a Prius-size 25 kW peak power pack.
In addition to improvements in specific power, an alternative packaging form was developed to allow placement under the second row seating in an SUV. For this application the historic 6-cell plastic case module was reconfigured into an 8-cell metal case structure to allow a longer, lower height profile with improved cooling.

**MOTOR/GENERATORS**

Although all Toyota hybrids have used permanent magnet motor/generators, several improvements have occurred in power, efficiency and rotational speed. Table 2 summarizes the specifications for the drive motor in products released to date.

### Table 2 MG2 Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Prius</th>
<th>Camry HV</th>
<th>RX 400h / Highlander</th>
<th>GS 450h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>50 kW</td>
<td>105 kW</td>
<td>123 kW</td>
<td>147 kW</td>
</tr>
<tr>
<td>Max. RPM</td>
<td>6,700</td>
<td>12,400</td>
<td>12,400</td>
<td>14,000</td>
</tr>
<tr>
<td>Rated Torque</td>
<td>400 N-m</td>
<td>270 N-m</td>
<td>333 N-m</td>
<td>275 N-m</td>
</tr>
<tr>
<td>Max Voltage</td>
<td>500 VAC</td>
<td>650 VAC</td>
<td>650 VAC</td>
<td>650 VAC</td>
</tr>
</tbody>
</table>

Magnet placement has also been optimized to improve efficiency.

**POWER ELECTRONICS**

The signature feature of Hybrid Synergy Drive systems is the boost converter. Adopted first in the 2004 Prius this system variably boosts battery pack voltage to higher levels. This higher operating voltage allows more power from the electrical machines without increased size or the expense of carrying more current.
These power density improvements have allowed packaging in a wider variety of underhood environments.

GEAR SYSTEMS

All of Toyota’s US market hybrids have used an input power split topology. In this topology, the engine output is connected directly to the carrier of a planetary gear set. A motor/generator, commonly referred to as the Generator or MG1, is connected to the sun gear of the planetary set. The ring gear is connected to the gearing for the final drive. The output of another motor/generator, commonly referred to as the Motor or MG2, is also connected to the final drive either directly or through additional gearing.

Three discrete generations of transmission packaging have been developed. The Prius transaxle is a four-shaft configuration as shown schematically in Figure 9 and in cut-away in Figure 10. In this layout the Motor (MG2) is directly connected thru the ring gear to the final drive. Motor speed is output shaft speed and no torque multiplication/speed reduction occurs from motor to output.

For the RX 400h, Highlander Hybrid and Camry Hybrid a different layout shown schematically in Figure 11 and in cross-section in Figure 12 is used. In this configuration a more compact layout is used with only three shafts. A second planetary gear set connects MG2 to the output. The sun is connected to the Motor, the carrier of this planetary set is grounded and the ring connects to the output. The ring to sun ratio is 2.478, so significant torque multiplication/speed reduction occurs.

As shown in Figure 13, a unique gear called the multifunction gear combines both planetary ring gears with the counter drive gear and the parking pawl slots. This machined masterpiece has been referred to as a piece of mechanical art.
For the GS 450h an entirely new layout was necessary. Not only is the GS platform rear wheel drive, this was to be a high performance package. Fitting the transmission in the shadow of existing 6-speed transmissions required a smaller diameter MG2, while the performance requirement demanded more power. The adopted solution is shown schematically in Figure 14 and in cross-section in Figure 15.

![Figure 14 GS 450h transmission schematic](image1)

![Figure 15 GS 450h transmission cross-section](image2)

In this transmission MG2 is connected to the output via a Ravigneaux planetary system configured to provide two torque multiplication/speed reduction ratios. A 3.9 low gear and a 1.9 high gear were selected. The clutch to clutch shift is accomplished at approximately 80 kph. This arrangement yields a package that fits the available space without platform modification and provides great power for rapid acceleration.

CONTROL SYSTEMS

The hybrid control system has overall control of energy, electric supply power and vehicle drive power. This is done while sensing driver intentions, assessing the running condition of the vehicle and supervising the charge level of the battery. Based on total power requirement, the control system maintains optimum efficiency while meeting the vehicle performance demands. At the same time, the system continuously monitors the hybrid units, components and control systems to assure the system is fail-safe for the whole vehicle. Figure 16 shows the network configuration for the RX 400h hybrid control system.

![Fig.16 Network configuration for RX 400h](image3)

As shown in Figure 17, many controllers carry out synchronized, coordinated control. Overall control of the whole hybrid system is conducted by the hybrid ECU. All HSD systems now use a CAN bus layout. The fact that it has become possible to establish this kind of large-scale system for a mass production car has also brought about quantum leaps in electronics, information and control technologies. In the new Prius, the adoption of new functions, such as the smart key system, or shift-by-wire etc., in combination with the high voltage HSD, has revolutionized control systems.

![Fig.17 Schematic Diagram of Prius HSD Control](image4)

AIR CONDITIONING

Starting with the 2004 Prius we have adopted an electric air conditioning compressor for improved efficiency. In Prius the DC to AC inverter function is in the power electronics, but starting with RX 400h a new generation compressor has been used that moves the inverter function to the compressor itself. This reduces the volume requirement in the power electronics box. Figure 18 shows a cross-section of the latest electric a/c compressor.
POWER STEERING

From the first Prius for the Japan market, electric power steering has been used. The initial systems were electro-hydraulic units using an electrically driven hydraulic pump. Starting with RX 400h a pure electric power steering unit was adopted. Figure 19 shows a section view of this unique unit. The electric motor is actually wrapped around the steering rack. This system improves efficiency and has the added benefit of using no hydraulic fluid.

FUTURE FOR HYBRID

With increased emphasis on conservation of natural resources and concern for the environment, hybrid technology will earn a growing share of the market. Toyota is deeply committed to hybridization not only as a significant improvement for ICE power systems, but as a critical enabler of future fuel cell systems. We expect continuous improvements in all the components and new synergies in the system. With each new product, we introduce new or improved systems. As the single most expensive element in the system, batteries continue to receive particular attention. Opportunities exist for further improvements in motors and electronics and improved control systems also offer great promise. Toyota is committed to a further halving of the incremental cost of hybridization. Gaining market penetration requires a broader offering of products and we are working hard to expand the line up.

REFERENCES


