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Development of Battery Pack and Systems for Plug-in Hybrid Vehicle

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Abstract

In recent years, many energy sources have been investigated as replacements for traditional automotive fossil fuels to help reduce CO_2 emissions, improve energy security, and reduce emissions of air pollutants in urban areas. Toyota Motor Corporation considers the plug-in hybrid vehicle (PHV), which can use electricity efficiently, to be the most practical current solution to these issues. Toyota began sales of the Prius Plug-in Hybrid in early 2012 in both the U.S. and Japan. This is the first PHV to be mass-produced by Toyota Motor Corporation. Prior to this, in December 2009, Toyota sold 650 PHVs through lease programs for verification testing in the U.S., Europe, and Japan. Toyota has developed a new battery pack system for the mass-produced PHV. The system of the recently launched mass-produced vehicle underwent major improvements in response to the results of this verification testing. As a result of newly developed high-capacity battery cells and a lightweight aluminum frame structure, this system is approximately 50% lighter and 50% smaller in volume terms than the system in the verification vehicles. This paper discusses the development of the new battery pack and system for this mass-produced PHV.

Keywords: battery, lithium battery, PHEV (plug in hybrid electric vehicle)

1 Introduction

Various issues related to automobiles, such as reducing CO_2 emissions and resolving energy security problems (i.e., instability in the supply of fossil fuels) must be solved in order for people to continue to enjoy the convenience of the ability to move freely and the pleasure of having the comfortable moveable space that automobiles currently provide.
Hybrid vehicles (HVs) are one of the most effective countermeasures to these issues. The fuel consumption reduction effects of HVs (i.e., those achieved through regenerative braking, idling stop when the vehicle is not moving, and driving in EV mode at low and/or constant speeds) have achieved major improvements in fuel efficiency and reductions in exhaust emissions compared to a gasoline vehicle.
Furthermore, the introduction of electric vehicles (EVs) is another means of reducing CO_2 and other exhaust emissions. By charging the EV battery using electricity from the power grid, it is possible to reduce emissions of CO_2 and air pollutants to zero during driving. However, even when using the latest Lithium-ion (Li-ion) battery technology, specific energy is limited to about 1/50 of that of fossil fuels, and the full-charge driving range is short. While the driving range can be increased in accordance with the size of the battery,

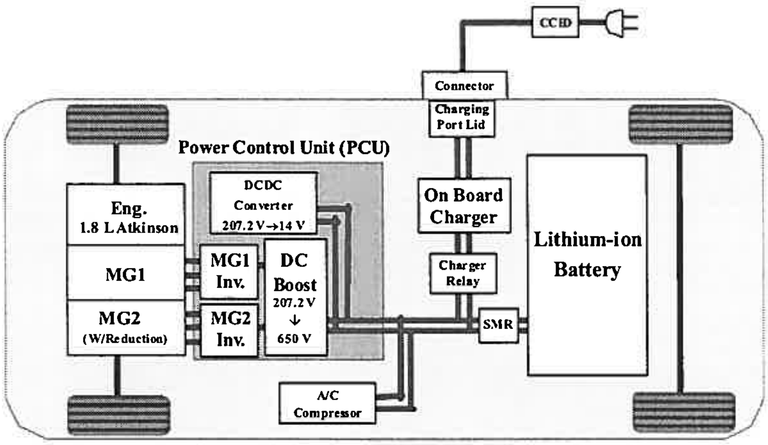

Figure 1: System configuration of newly developed PHV system

this means sacrificing some of the cabin and luggage space to increase the battery to a size that will ensure driving range equivalent to that of a gasoline vehicle. Also, larger batteries lead to drastic increases in the weight and cost of the vehicle, and therefore are not practical. Additionally, charging a large capacity battery from an external source in a short period of time would require a DC external charger with capacity for high electric output, which requires the installation of dedicated infrastructure. Accordingly, when considering these limitations, it appears that EVs probably will not totally replace the conventional gasoline vehicle, now or in the near future. It is assumed that, in the short term, the EV will function as a commuter vehicle that covers short distances.

The plug-in hybrid vehicle (PHV) is a potential solution for these issues. A PHV can run mainly on electrical energy as an EV over short distances and as a conventional HV using the engine when required once the battery is depleted. It combines the merits of an EV, since it has zero emissions during driving with electric power, with the merits of an HV, since it does not sacrifice any of the practicality of a standard vehicle. For example, driving range is equal to or better than that of a conventional gasoline vehicle. Currently, various types of PHVs have been proposed by different manufacturers. It is possible to separate these PHVs into two types based on the hybrid system, namely series hybrid system PHVs, and series parallel type PHVs. Toyota selected the series parallel type system for its PHV because the plug-in hybrid system could be configured at a relatively low cost by effectively using components of the base vehicle (i.e., the Prius HV). In addition, once the battery energy is depleted and the system shifts to HV mode, higher system efficiency and better HV mode fuel efficiency can be achieved. With the combination of EV/HV mode, the merit of this PHV system can be fully brought out [1].

1.1 New PHV system for 2012 model

The PHV system for the 2012 model adopts the same series parallel configuration as the 2009 model [2]. The engine is connected to the wheels by a continuous power transmission system. Figure 1 shows the newly developed PHV system configuration. The major changes from the base HV are as follows.

1) The battery pack uses high-capacity Li-ion battery cells.
2) An external charge system compatible with AC 120 V/240 V is installed.

1.1.1 Performance of new model PHV

The EV range of the developed 2012 model was set at 11 miles under U.S. test cycle driving conditions. The EV range can be extended by increasing the batteries, but this would result in several trade-offs, such as reduced cabin and luggage space and higher system costs. The EV range of 11 miles was set after considering these trade-offs. With the assumption that the battery will be fully charged once per day, 11 miles is sufficient to cover around 25% of the total daily driving distance in the U.S. market. If the battery is charged twice per day, the percentage of coverage increases to around 43% (excerpt from SAE J2841, Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using Travel Survey Data).

Furthermore, the fuel efficiency of the 2012 model PHV is also greatly improved compared to the Prius HV. The Japanese Ministry of Land Infrastructure and Transport (MLIT) defines the plug-in combined fuel efficiency based on the utility factor (UF: the estimated proportion of a vehicle's EV driving range in relation to its total driving range assuming one full charge per day), which is calculated from real world driving distance distribution data. This combined fuel efficiency identifies the harmonic mean of the vehicle's EV mode fuel efficiency (i.e., until a fully charged battery is depleted) and its subsequent HV mode fuel efficiency. With an EV range of 11 miles, the plug-in combined fuel efficiency in the JC08 test cycle (the Japanese fuel efficiency measurement test cycle) is 87% better than that of the base Prius HV (Fig. 2) [1].

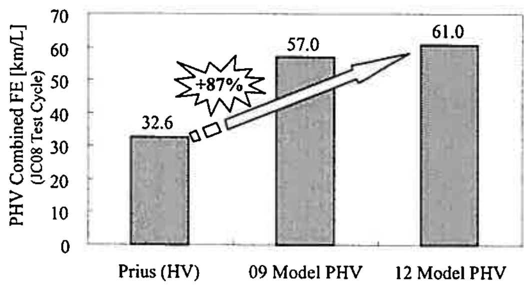

Figure 2: PHV combined fuel efficiency (Japanese JC08 test cycle)

Since PHVs provide a potential solution to the issues of cabin and luggage space and EV range, it is important to improve the overall fuel efficiency in consideration of a variety of driving conditions. These characteristics are closely related to the details of the battery pack and system. In other words, how the battery pack and system are designed in consideration of cost, weight, cabin space, and the like has a major effect on improving the overall fuel efficiency of a PHV.

The Prius Plug-in Hybrid is the first PHV to be mass-produced by Toyota and represents a feasible way of addressing these issues. This paper describes the development of the PHV battery pack and system.

2 Objective of New Battery Pack System for 2012 Model PHV

The battery pack was newly developed for the 2012 Prius Plug-in Hybrid. Various improvements were adopted in the mass-produced PHV system to increase its practicality. These improvements were identified as a result of a series of verification tests carried out in the U.S., Europe, and Japan in December 2009 prior to the start of the development. The size and weight of the battery pack system were reduced and the development aimed to use the results of the verification tests to ensure both the usability of the vehicle and the durability of the battery.

The objectives of the battery pack system development described in this paper were as follows.

- Reduce the weight and size of the PHV system by developing new high-capacity Li-ion cells
- Reduce the cost of the PHV system by commonizing parts with the Prius HV
- Secure durability of the battery system

3 Battery Pack and System

3.1 Li-ion battery cell

High-capacity and high specific energy Li-ion battery cells with characteristics suited for a PHV were newly developed for this vehicle (Fig. 3 and Table 1). The capacity is four times greater than the cells used in the verification model in 2009. These cells have sufficient input and output power to achieve the necessary vehicle performance (i.e., EV mode driving, cold engine start, etc). These battery cells drastically reduced the system weight and cost compared to the 2009 model.

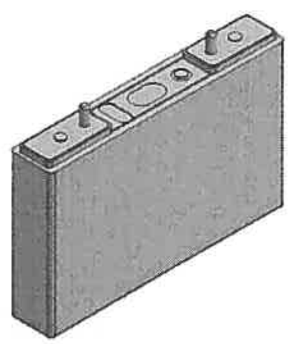

Figure 3: Lithium-ion battery cell

	09 PHV	12 PHV
Nominal Capacity	5.0Ah	21.5Ah
Specific energy	73Wh/Kg	110Wh/Kg
Energy density	103Wh/L	193Wh/L
Weight	245g	726g
Dimensions	110.3mm(W) 13.8mm(T) 91.8mm(h)	148mm(w) 26.5mm(T) 91mm(h)

Table 1: Cell specifications

3.2 Battery pack

The same frame construction as the 2009 model was adopted for the battery pack to ensure high strength and rigidity (Fig. 4). Additionally, the 2012 model adopted an aluminum extruded material to reduce weight as well. The combined effects of this frame construction and the high-capacity high specific energy cell reduced both the weight and volume of the battery pack by approximately 50%. As a result, the specific energy of the new battery pack is substantially greater than the 2009 model. Consequently, despite increasing the total battery energy to more than three times the base Prius HV, the Prius Plug-in Hybrid has the same cabin and luggage space.

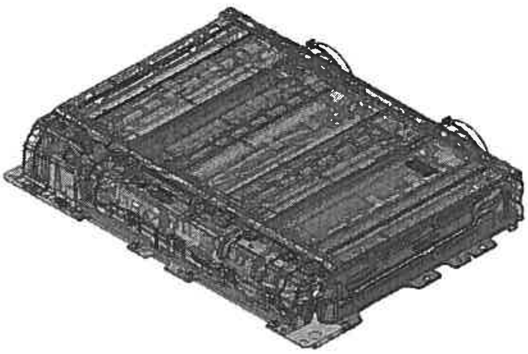

Figure 4: Battery pack structure

	Base HV	09 PHV	12 PHV
Dimension	387mm(L) 1011mm(W) 225mm(H)	807mm(L) 911mm(W) 378mm(H)	700mm(L) 950mm(W) 170mm(H)
Weight	42kg	160kg	77kg
Battery Cell	Ni-MH	Li-ion	Li-ion
Cell Quantitiy	168cell	288cells	56cells
Nominal Capacity	1.3kWH	5.2kWH	4.4kWH
Nominal voltage	201.6V	345.6V	207.2V
Laggage Space	446L	403L	443L

Table 2: Battery pack characteristics

The battery pack consists of 56 cells, a monitoring unit and other auxiliary devices, and two air cooling fans. The 56 cells are divided into four stacks of 14 cells each, and each stack is fixed within the battery pack, which ensures that the pressure applied to the cells is constant. The two air cooling fans were installed to ensure sufficient battery cooling performance and prevent battery deterioration, considering the harsher usage conditions for batteries in PHVs compared to HVs. The simple structure with four stacks and the auxiliary devices located at the front of the battery pack also greatly improves the ease of maintenance. The stack structure allows individual stacks to be replaced, thereby reducing repair costs for the user. The auxiliary devices can also be accessed for repair by simply removing the top cover. Furthermore, by matching the total battery voltage with the base Prius HV, the input voltage of the high voltage components connected in parallel to the battery (the DC/DC converter and air conditioning inverter) was set at the same level, enabling the use of common parts and contributing to reducing the PHV system cost.

3.3 Battery monitoring and control

The voltage of Li-ion batteries must be monitored for each cell and equalized. For this reason, in addition to the battery monitoring system for each block (a group of cells) used in the NiMH battery pack of the base HV, the PHV battery system also includes an additional monitoring unit that functions to monitor and equalize the voltage of all cells (Fig. 5). The battery monitoring unit monitors the voltage of each cell and prevents over-charging or over-discharging.

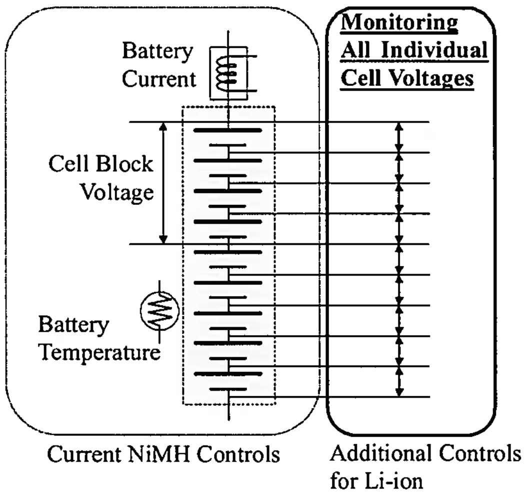

Figure 5: Schematic diagram of Li-ion battery monitoring

The method of estimating the state of charge (SOC) in the 2012 model battery system was also modified. Conventionally, SOC is estimated based on the block voltage, conduction current, etc. For the new model, a method was developed that identifies the battery capacity loss and adds this information to the SOC calculation method to greatly improve the estimation accuracy. This enables the battery energy to be used close to the upper and lower SOC limits, which was not possible in the conventional control for reasons related to estimation accuracy. In other words, this new control has enlarged the usable SOC range of the battery. As a result, although Table 2 shows that the total energy of the 2012 model battery pack is approximately 14% lower than the 2009 model, the 2012 model has a longer EV range (Fig. 6).

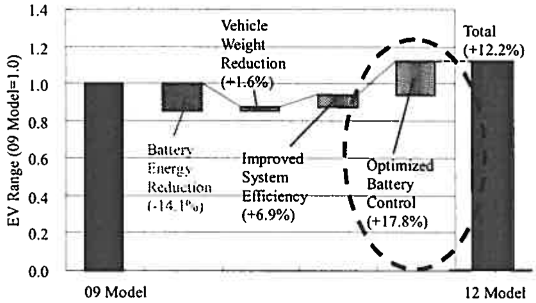

Figure 6: EV range improvement in U.S. city test cycle

3.4 Durability of battery system

Toyota carried out large-scale field tests to gather data on the battery system up to the sale of the 2012 mass-production model, in which more than 650 of the 2009 model PHVs were used in verification tests to confirm battery reliability. Durability was verified using reference data from HVs installed with Li-ion batteries and 100 2011 model Li-ion HVs.

The tests were carried out in a temperature range from -30°C to 40°C in various countries (Japan, the U.S., Canada, Germany, China, etc). The HVs were driven for more than 10,500,000 km. After analyzing the field data, the following results related to battery durability were obtained. Figure 7 shows the combined capacity data for the PHVs and HVs. It indicates that the PHVs and HVs have virtually the same capacity ratio, confirming that usage in a PHV does not result in abnormal battery capacity loss. It was also confirmed that the data on HV battery deterioration can also be applied to the PHV battery system.

However, differences in vehicle usage created variations in capacity for individual vehicles. For this reason, the mass-production PHV was also provided with a charging timer function to promote optimum usage for the customer. Toyota has also prepared various services to maximize the benefit of the vehicle to the customer, such as suggestions at the point of sale for how to best use the vehicle to reduce the stress on the battery.

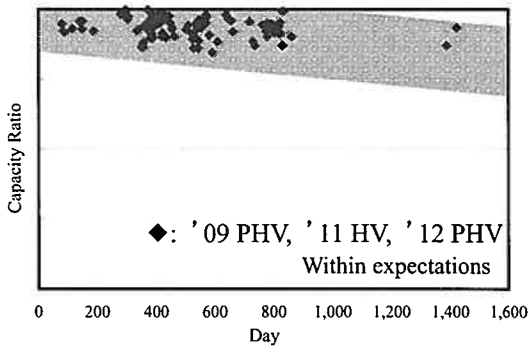

Figure 7: HV and PHV field test results for battery capacity

4 Future Outlook

The effective use of electricity as a source of drive power for automobiles will be indispensable in the future to help respond to various issues such as reducing CO_2 emissions and improving energy security. However, when considering current issues (i.e., battery issues such as cost and low specific energy, short range, the need to build new charging infrastructure, etc), it is likely that EVs will take more time to become a truly effective solution.

However, a PHV can use electricity as an energy source in the same way as an EV, while ensuring the same level of utility and convenience as a conventional HV. Additionally, it is possible to create a system configuration with a relatively low cost increase over that of a conventional HV by modifying the HV battery pack system for PHV use. Consequently, since the PHV is the most practical environmentally friendly vehicle for the near future, its popularity may well grow. In developing a highly practical battery and system, Toyota is aiming to further popularize the PHV.

The effective use of electricity is likely to become even more important in the future. Further improvements in battery technology (such as reducing size, weight, and cost, increasing specific energy, etc) will be necessary to both popularize the use of PHVs and enable the development of even more practical battery packs.

5 Conclusions

- Toyota has developed a new high-capacity Li-ion battery cell and greatly reduced the size and weight of the battery pack and system.
- System costs were reduced by minimizing changes to the battery pack from the base Prius HV.

- Including verification tests with the 2009 model, the results of field tests confirmed the reliability of the battery. No abnormal deterioration in battery performance (such as capacity loss and the like) occurred.
- The Prius Plug-in Hybrid is the first PHV to be mass-produced by Toyota and sales began in early 2012.

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