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Subcontract Report:
TECHNOLOGY AND COST OF THE MY2007 TOYOTA CAMRY HEV – FINAL REPORT

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OAK RIDGE
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TECHNOLOGY AND COST OF THE MY2007 TOYOTA CAMRY HEV FINAL REPORT

Energy and Environmental Analysis, Inc.
an ICF International Company

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Energy and Environmental Analysis, Inc.

Technology and Cost of the MY2007 Toyota Camry HEV

Final Report

Submitted to:

Oak Ridge National Laboratory

Oak Ridge, TN

July 2007

Submitted By:

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1 OVERVIEW

The Oak Ridge National Laboratory (ORNL) provides research and development (R&D) support to the Department of Energy on issues related to the cost and performance of hybrid vehicles. ORNL frequently benchmarks its own research against commercially available hybrid components currently used in the market. In 2005 we completed a detailed review of the cost of the second generation Prius hybrid. This study examines the new 2007 Camry hybrid model for changes in technology and cost relative to the Prius.

The work effort involved a detailed review of the Camry hybrid and the system control strategy to identify the hybrid components used in the drive train. Section 2 provides this review while Section 3 presents our detailed evaluation of the specific drive train components and their cost estimates. Section 3 also provides a summary of the total electrical drive train cost for the Camry hybrid vehicle and contrasts these estimates to the costs for the second generation Prius that we estimated in 2005. Most of the information on cost and performance were derived from meetings with the technical staff of Toyota, Nissan, and some key Tier I suppliers like Hitachi and Panasonic Electric Vehicle Energy (PEVE) and we thank these companies for their kind co-operation.

2 CAMRY HEV DESIGN

2.1 VEHICLE DESCRIPTION

The model year (MY) 2007 Toyota Camry hybrid electric vehicle (HEV), see Figure 2-1, is derived from a conventional 2.4L Camry with the Toyota's Hybrid Synergy (THS) second generation system incorporated within existing body packaging.

Figure 2-1. MY2007 Toyota Camry HEV.

Highlights of the Camry HEV technology are as follows:

- 2.4L 147hp Atkinson cycle L-4 aluminum block and head engine;
- THS drive with 105kW electric motor;
- 245V nickel metal hydride (Ni-MH) battery pack;
- Electrically variable continuously variable transmission (CVT) free wheeling diodes (FWDs) transaxle;
- 143kW (192hp), 275N-m total system rating;
- 0–60 mph in 8.9 seconds;

- Advanced Technology – Partial Zero Emission Vehicle (AT–PZEV) emissions certification;
- EPA label fuel economy 40/38/39 (city/highway/combined);
- Steel unit body design with steel closure panels;
- Vehicle aerodynamic drag coefficient C_d of 0.27; and
- Produced in Toyota's Georgetown, Kentucky plant.

The Camry HEV is certified to Super Ultra Low Emission Standards (SULEVs), California's classification for exhaust emissions, which is the most stringent current standard for conventional internal combustion-powered vehicles. The add-on hybrid components were designed to qualify the vehicle as an AT–PZEV (a classification used in California emissions control programs), but the AT–PZEV requires a longer warranty period, so Toyota decided to classify the Camry as a SULEV.

Compared to the regular 2.4L Camry with 5-speed automatic transmission (EPA FE rating 24/33mpg), the hybrid improves city fuel economy by 67%, but highway improvement is only 15%. Some of the fuel economy improvements are attributable to the body add-on features such as underbody fairings which reduce aerodynamic drag from 0.28 to 0.27.

2.2 THE HEV SYSTEM LAYOUT

The Camry's high voltage hybrid system operates the electrical motor, generator, A/C compressor, and inverter/converter. All other devices, including the electric power steering, are supported by a conventional 12V battery. As a result, the vehicle utilizes four electrical systems:

- Nominal 12V DC;
- Maximum 34V AC;
- Nominal 245V DC; and
- Maximum 650V AC.

Figure 2-2 illustrates how these circuits interact. The main system battery stores power at 245V DC. This voltage is used directly to drive the A/C compressor. An inverter/converter contains a circuit that boosts the battery voltage to 650V DC. The inverter packaged in the same housing creates three-phase AC current (variable to max 650V AC) to power the traction motor and generator in the transaxle. The 34V AC circuit is used for electric power steering.

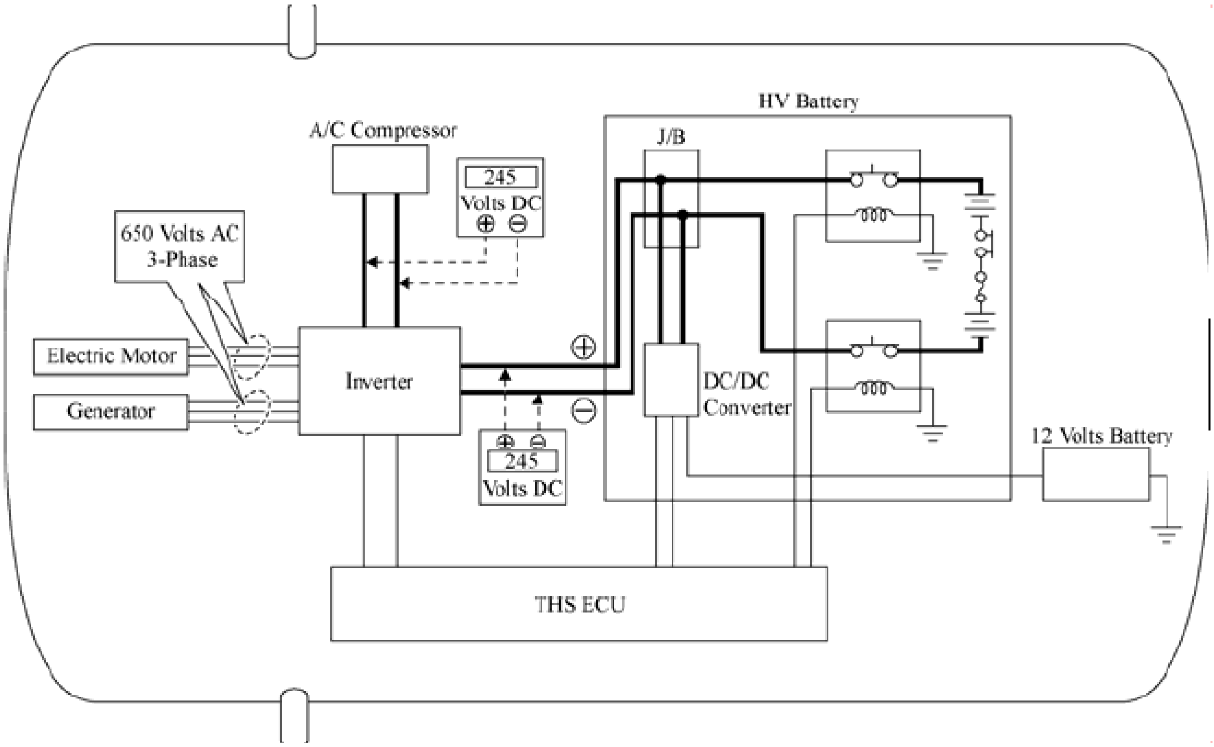
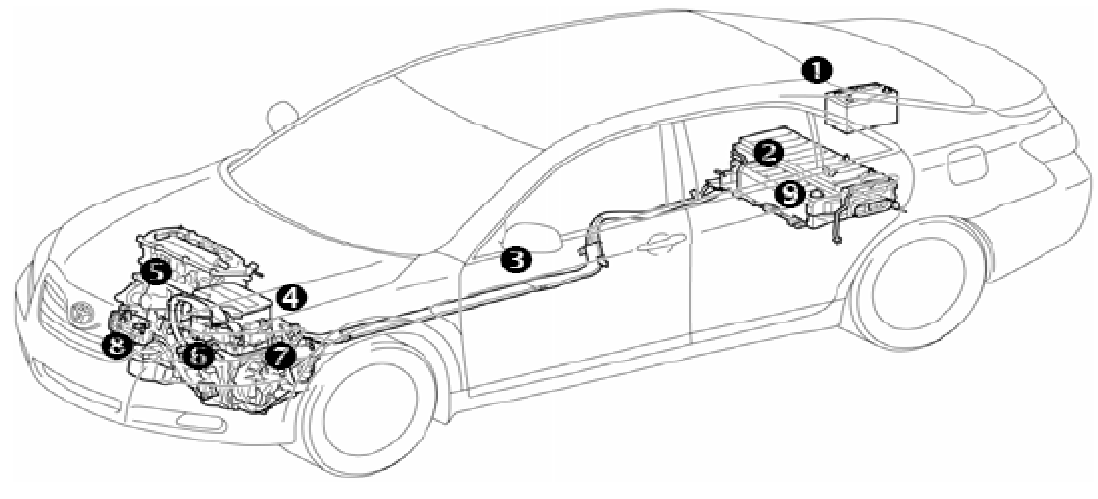
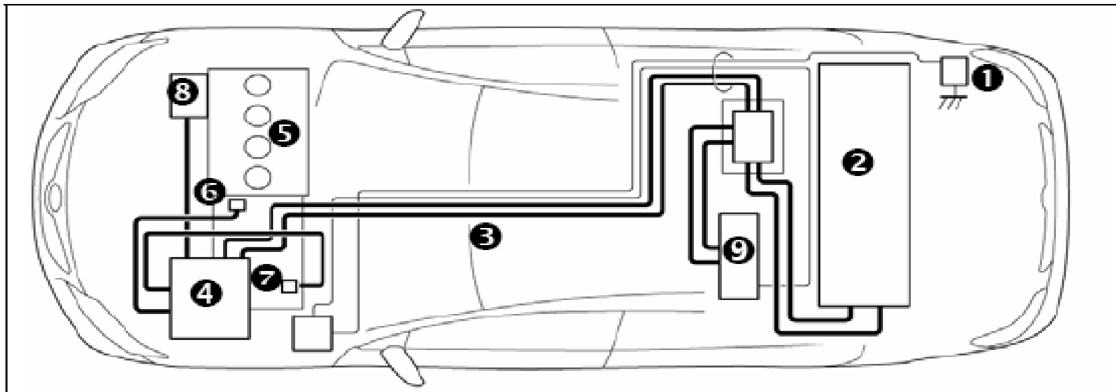


Figure 2-2. Camry HEV System Schematic.

Figure 2-3 identifies the key hybrid components on the vehicle layout. Table 2-1 summarizes each component function and location.



Hybrid Synergy Drive Components



Components (Top View) and High Voltage Power Cables

Figure 2-3. Camry HEV Component Layout.

Table 2-1. Camry HEV Component Description and Function

Numbers are labeled on Figure 2-3.

Number	Description	Location	Function
1	Lead acid 12V battery	Trunk area.	Powers low voltage devices, including electric power steering (EPS).
2	Ni-MH battery pack	Behind rear seat.	Powers high voltage devices.
3	Power cables	Under passenger floor and engine compartment.	Carry high voltage DC and AC current between battery pack, inverter/converter, motor, generator, and A/C compressor.
4	Inverter/converter	Engine compartment.	Boost and inverts the high voltage DC current from the battery pack to three-phase AC current and vice-versa. Powers the A/C compressor.
5	Engine	Engine compartment	Powers the vehicle and generator.
6	Generator	Transaxle	Recharges battery pack.
7	Motor	Transaxle	Powers front wheels.
8	A/C compressor	Engine compartment.	Powers A/C system.
9	12V DC-DC converter	Battery pack.	Steps-down 245V DC from battery pack to 12V to recharge the low voltage battery.

2.3 CAMRY HEV POWER TRAIN

The Camry HEV is equipped with a modified 2.4L I4 double overhead camshaft (DOHC) electronic fuel injection (EFI) engine and electronically controlled CVT. The FWD transaxle has two built-in motor/generators (MGs). The vehicle is designed around the THS II “full” hybrid architecture which provides propulsion in five modes depending on the battery state of charge:

1. During light acceleration and low speeds the vehicle is powered by the electric motor.
2. During normal driving, the vehicle is mainly powered by the gasoline engine. Some power from the engine drives the generator to charge the battery.
3. During high loads, both the engine and motor power the vehicle.
4. During braking or deceleration, regenerative braking charges the battery.
5. While the vehicle is stopped, the motor and engine are off and the battery powers accessories.

2.3.1 Engine Details

The Camry’s 2.4L I4 engine was modified for hybrid duty and operates as an Atkinson cycle engine. The cycle modification was possible because of the variable valve timing (VVT) and electric motor assist availability. The Atkinson cycle engine offers higher thermal efficiency and lower pumping losses due to independent control of the compression and expansion stroke duration. If conditions are favorable, the ECU delays the intake valve closing, effectively delaying the start of compression. This feature maintains relatively high compression ratio availability and, therefore, higher overall thermal efficiency at the expense of peak power.

Figure 2-4 compares the Atkinson and conventional cycle engines on a Pressure-Volume (P-V) scale. In addition to pumping loss reduction, the Atkinson engine allows peak efficiency improvement from 35–38%. However, this thermal efficiency comes at a peak power penalty. The HEV Camry 2.4L I4 delivers 147hp while the conventional Camry peaks at 160hp (about 7% higher). This tradeoff is possible on a hybrid because the engine peak power loss is compensated through electrical power assist capability.

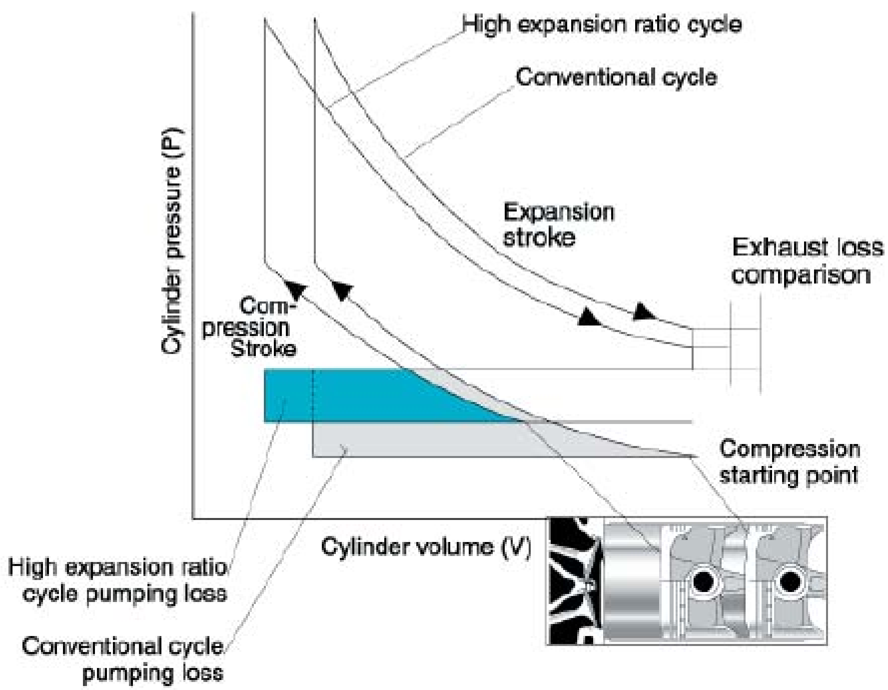


Figure 2-4. Atkinson Cycle Engine P-V Diagram Compared to Conventional Otto Cycle.

Toyota targeted other engine changes to improve fuel economy and noise vibration and harshness (NVH) response on the Camry hybrid version. Intake and exhaust manifolds were reworked for easier flow, including large diameter passages and thinner walls. Pistons and intake camshaft were revised for lower weight and higher strength. Adapting the engine to hybrid operation has also enabled elimination of belts and other components related to power steering, A/C, and the alternator.

Table 2-2 summarizes key characteristics of the 2.4L engine used in the Camry HEV. The modifications resulted in a very high expansion ratio engine (12.5:1). Due to the Atkinson cycle employed, peak power is down from 160 hp on the conventional Camry to 147 hp, but peak efficiency increases from about 34–37.5%.

Table 2-2. Toyota Camry HEV 2.4L Engine Details

Displacement and type	2.4L I4 Atkinson cycle
Expansion ratio	12.5:1
Compression ratio	9.6:1
Construction	Aluminum alloy head and block
Valve train	DOHC, four valves/cylinder with VVT-i
Engine peak power	147 hp @ 6,000rpm
Engine peak torque	138lb-ft @ 4,400 rpm

2.3.2 Electric CVT Transaxle

The CVT functionality in the Camry FWD transaxle is achieved using two motor-generators. The transaxle is a compact three shaft design and uses two sets of planetary gears. No clutches, bands, or hydraulics are required to control the system.

Figure 2-5 details the transaxle schematic and cutaway view. The first MG (MG1) is geared to the engine and primarily acts as generator, but also provides power for speed control and engine starting. The second MG (MG2) is geared directly to the drive and acts as the traction motor but also can act as a generator for regenerative braking.

The engine-side gear set in the transaxle acts as the power split device. Its sun gear is connected to the MG1, while the planet carrier is connected directly to the engine. The ring gear is connected to the counter gear to transmit power into axle. The traction motor-side gear set acts as a speed reduction device with the sun gear connected to the MG2 rotor. The carrier is grounded while the ring gear is connected to the counter gear. It should be noted that in high power demand modes, the generator output powers the motor, while during low demands the battery directly supplies the motor (MG2).

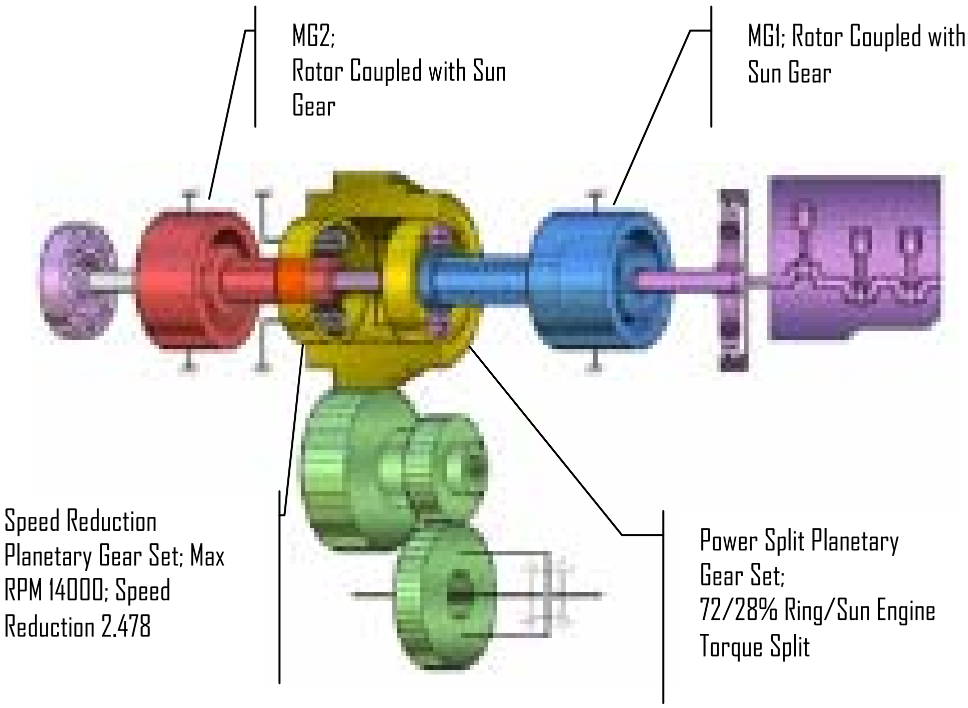


Figure 2-5. Camry HEV Transaxle Schematic and Cutaway View.

Table 2-3 summarizes the MG specifications. Both electrical machines are permanent magnet (PM) AC synchronous-type and operate at a maximum of 650V AC. The traction motor MG2 develops a maximum power of 105kW at 4,500rpm. A maximum torque of 270N-m is available immediately after starting to 1,500rpm.

Table 2-3. Camry HEV MG Specifications

MG types	PM water/oil cooled, AC synchronous
MG maximum voltage	650V AC
MG1 max speed	14,000rpm
MG2 max speed*	4,500rpm
MG2 max output	105 kW/4,500rpm
MG2 torque	270N-m/0–1,500rpm

*-Toyota documentation reports this figure as maximum MG2 speed, but it likely includes the speed reduction gear. The speed reduction planetary set maximum speed is 14,000rpm, which must correspond to maximum MG2 rotor speed since the sun gear of this set is connected directly to the rotor.

2.4 THE BATTERY PACK

The Camry HEV uses a Ni-MH battery (see Figure 2-6) which, like the Prius battery, is manufactured by PEVE, a joint venture between Panasonic and Toyota. The battery module is installed behind the rear seat and includes the battery pack, monitoring unit, system main relay, service plug, and DC-DC converter. High voltage circuits in the battery are controlled by 12V normally-open relays. The DC-DC converter transforms 245VDC to 14VDC for auxiliary loads and to charge the 14V auxiliary battery. The Camry HEV retained the 14V lead acid battery possibly because cold start of the engine remains a concern with Ni-MH batteries alone with the 2.4L engine. In contrast, the lead acid battery is eliminated in the Prius.

Figure 2-6. Camry HEV Battery Module.

The batteries key specifications are summarized in Table 2-4. The battery pack consists of 34 low voltage sealed (7.2V) modules connected in series to produce approximately 245V total voltage. The electrolyte is an alkaline mixture of potassium and sodium hydroxide. As a safety feature, the module venting is designed to expel gases directly outside the vehicle through a vent hose if overcharging is detected.

Table 2-4. Camry HEV Battery Key Specifications

Manufacturer	Panasonic EV
Type	Ni-MH
Battery pack weight [lbs]	114.6
Pack dimensions [in]	8 x 34 x 19
Nominal pack voltage [VDC]	244.8
Nominal pack capacity [A-hr]	6.5
Peak power [kW]	30
Number of modules	34
Module connection	Series
Module weight [lbs]	2.3
Module dimensions [in]	5 x 1 x 11
Nominal module voltage [VDC]	7.2
Cells in one module	6
One cell nominal voltage [VDC]	1.2

2.5 POWER CONTROL UNIT

Camry HEV's inverter/converter, or power control unit (PCU), represents one of the newest generation inverters which is more compact, lighter, and more efficient than the Prius or Highlander design. The PCU was designed to fit in space freed-up by the 14V battery transferred to the trunk compartment. As a result, the PCU is sized and shaped similar to a 14V battery.

The PCU's main function is to boost the battery DC voltage and convert it to three-phase AC to drive the MGs. Figure 2-7 illustrates the PCU's basic design. It incorporates a voltage boost converter, ECU, smoothing capacitor, and intelligent power module (IPM).

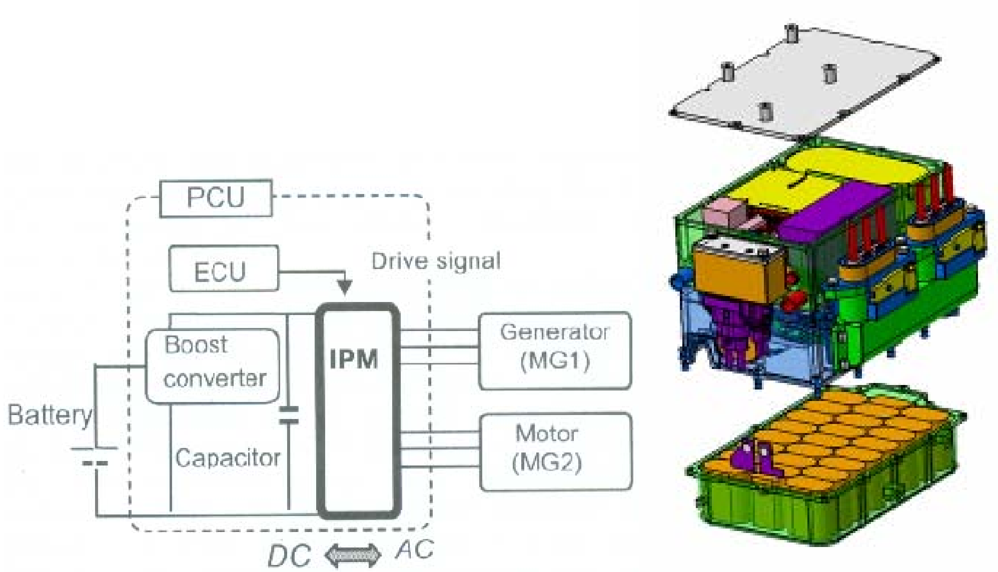


Figure 2-7. Camry HEV PCU Schematic and Exploded View.

The boost converter is capable of increasing the battery voltage to maximum 650V DC. The mid-section of the PCU houses the IPM with two sets of inverters controlling each of the two MGs. The insulated gate bipolar transistors (IGBTs), which are Toyota's in-house product, are used to perform DC-AC conversion (see Figure 2-8).

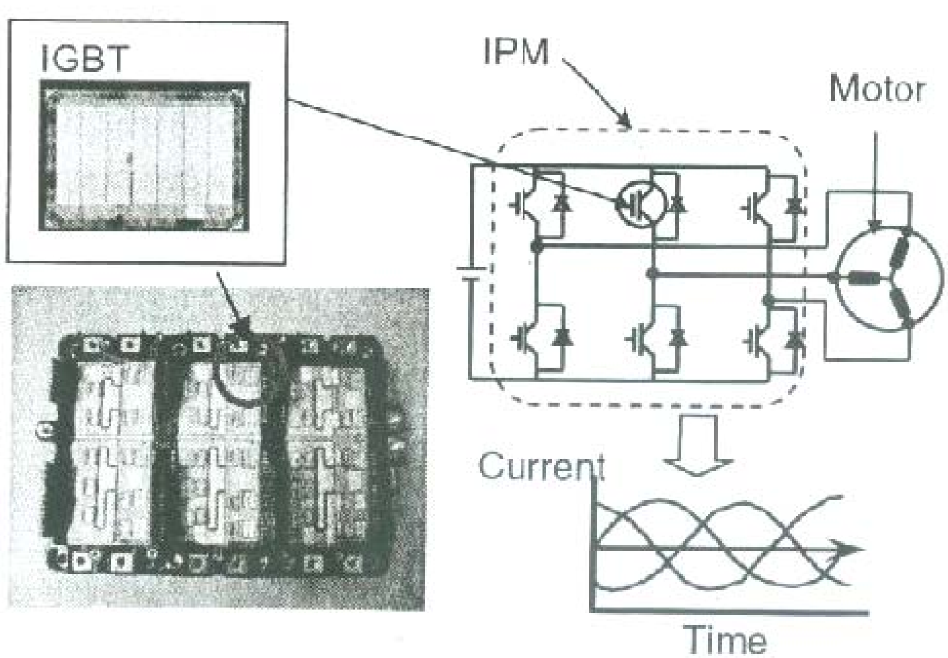


Figure 2-8. Camry HEV IPM Schematic and Installation.

Toyota continuously refines its IGBTs with each generation of IPM and new hybrids to achieve higher power density, size reduction, and loss reduction. Toyota claims in 2005 they were the only company in the world to manufacture IGBTs from eight-inch wafers, which resulted in lower costs since the technology yields more chips per wafer than conventional five-inch wafer technology.

Figure 2-9 illustrates the IPM layout. The IPM includes the module portion, which handles the high voltage and current. This module contains the heat sink, insulating substrate, IGBTs, and FWDs. The IGBTs and FWDs are paired in parallel to form a reverse-conducting switch. The circuit portion is packaged in the same area and controls the IPM functions.

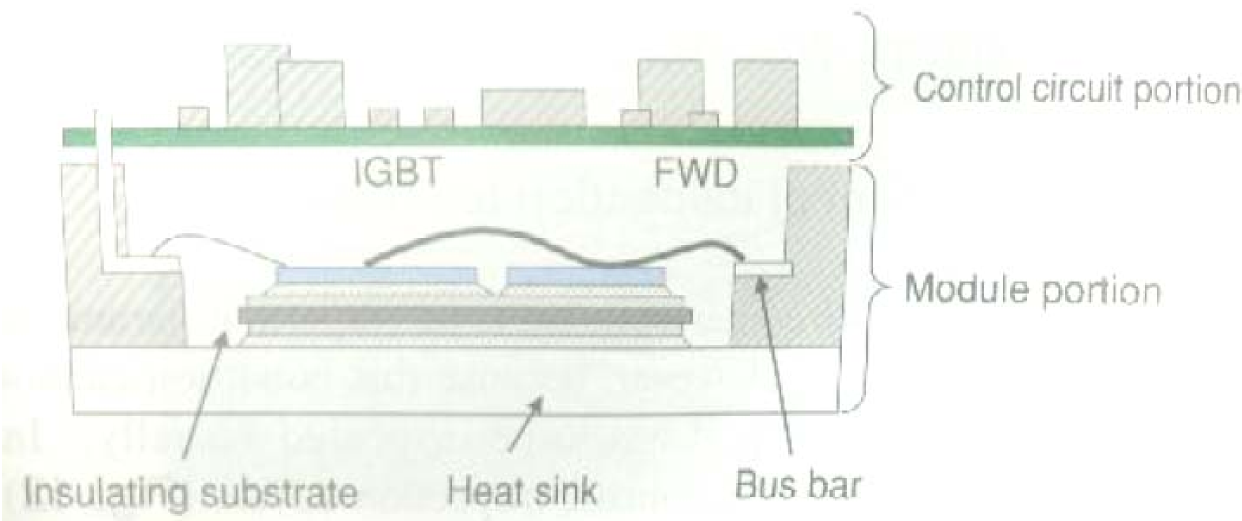


Figure 2-9. Toyota Camry HEV IPM Layout.

IGBTs used in the Camry were first installed on the Lexus RX400h followed by the GS450h. All IPMs in this group belong to a common 120kW class. In order to reduce the size and increase power and voltage capacity (650V nominal rating), Toyota changed the IGBT design from the “planar gate” design used in 50kW class IPM in Prius which operates at up to 500V voltage to the “trench” structure (see Figure 2-10). This structure contains deep vertical trenches in which gate electrodes are embedded. Compared to the Prius planar IGBT, the trench design can be packaged in a smaller surface area. Furthermore, this design also eliminates an ineffective region immediately below the P-region found in the planar IGBT (marked as area A).

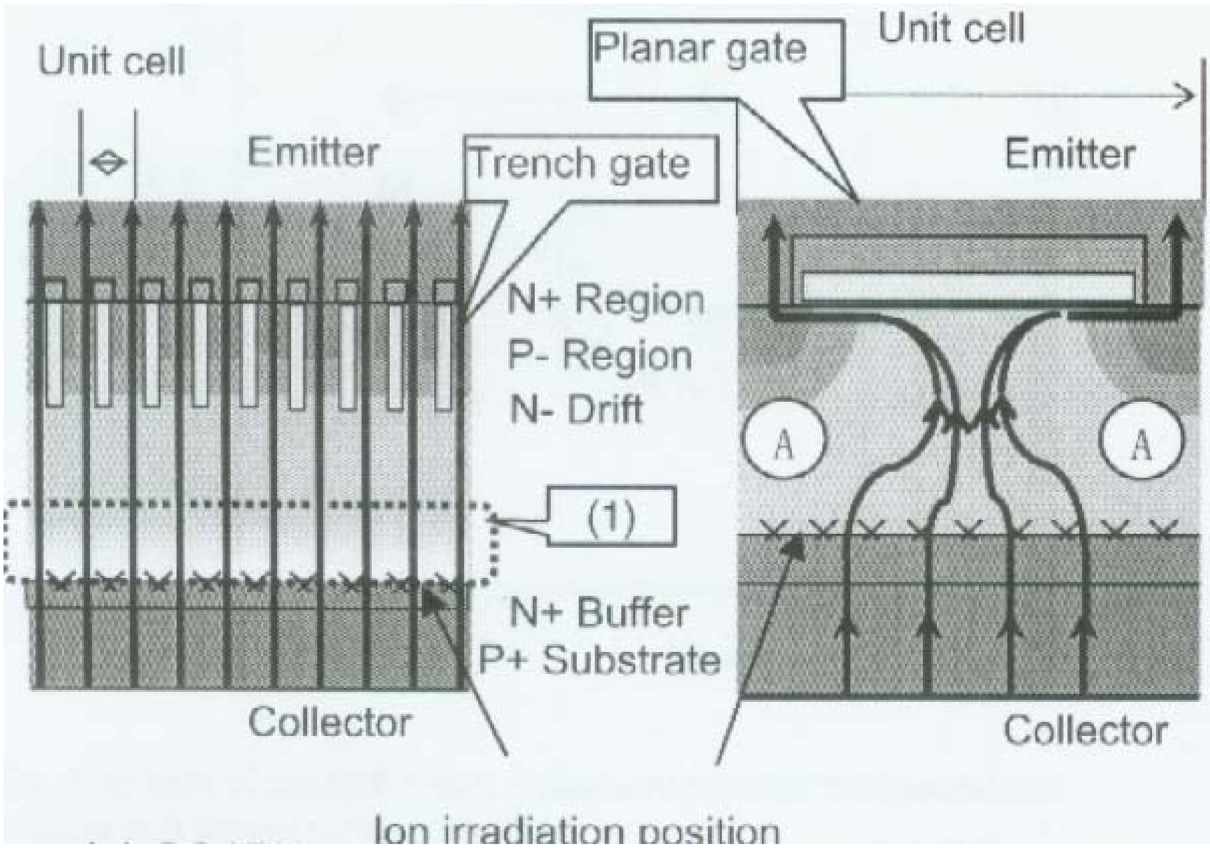


Figure 2-10. IGBT Design for GS450h (left) vs. Prius II (right).

Because of the higher peak voltage, Toyota had to refine the IGBT structure to minimize the electrical losses by adding the "concentration optimized" (shown as (1)) layer. The redesigned wafer structure enables the devices to operate with a higher reverse breakdown voltage.

The IGBTs are designed to operate at currents up to 200A. Toyota had to further modify the trench IGBT to deal with the increase in short-circuit current which degrades the resistance to surge current. The emitters of IGBT were arranged in a stripe-like structure and the gate width was decreased (see Figure 2-11).

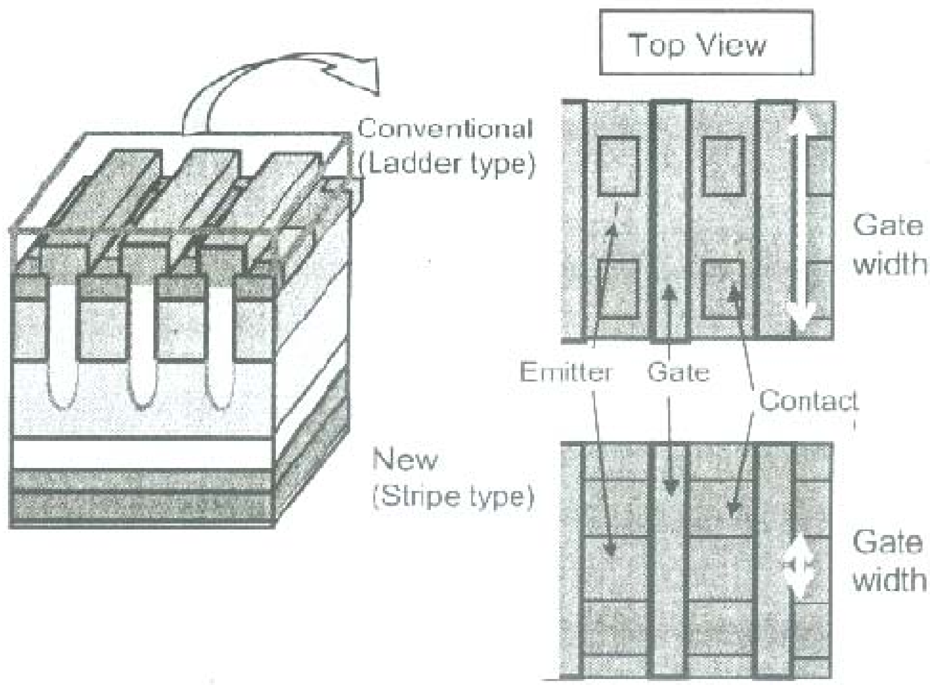


Figure 2-11. Toyota Trench IGBT Modifications.

The IGBT has a maximum junction temperature limit of 150°C. The heat sink and cooling circuit design was a special challenge given the PCU's packaging requirements. Figure 2-12 details the IPM cooling design. The silicon chips are soldered to a direct bonded aluminum (DBA) ceramic substrate, which is brazed on a Cu-Mo alloy base plate. The base plate is bolted on a water-cooled heat sink with thermal grease to conduct heat. The top surfaces of the silicon chips are connected to electric terminals by aluminum bonding wires.

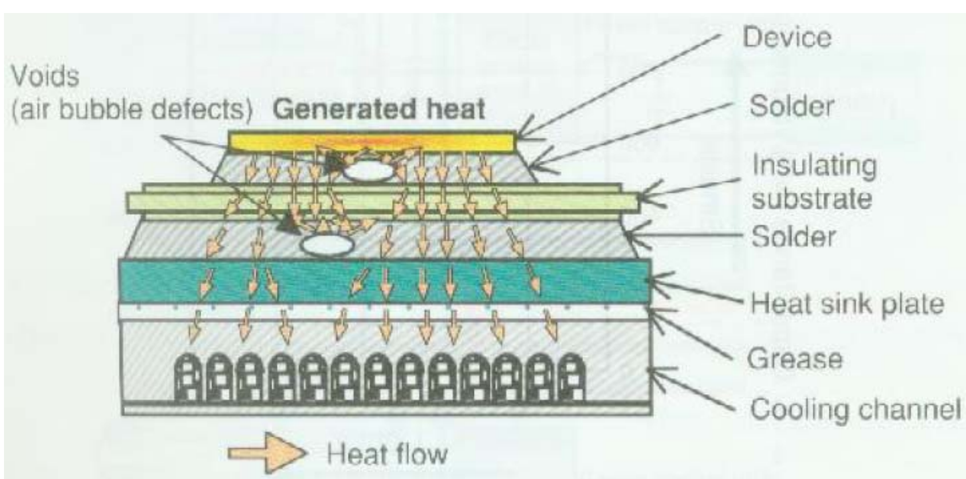


Figure 2-12. Heat Dissipation Structure for IPM Chips.

Toyota indicated that they use special soldering techniques to avoid trapped ambient gas "bubbles" (shown in the Figure 2-13), which can greatly reduce the thermal conductivity of the device. The technique involves a special soldering foil that exhibits discrete softening and melting temperature characteristics. Heat is applied gradually to flatten the solder while trapped gases are purged from the joint. After flattening and some delay, the solder is then melted quickly to complete the joint. However, this technique does increase cycle times.

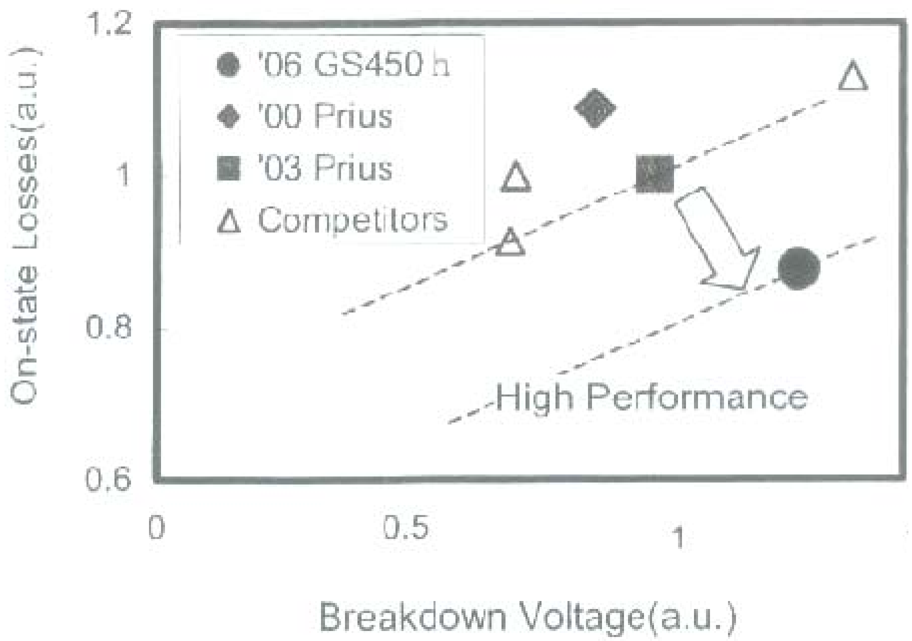


Figure 2-13. Toyota 2007 IGBT Design Performance Compared to Older Generations and Competition.

The company claims that the new IGBTs enabled 41% higher breakdown voltage (compared to Prius IGBTs). At the same time the IGBT losses were reduced by 14%. The resulting new inverter is lighter and smaller, requiring 10% less surface area.

Toyota has released information about the newest PCU design used in the LS600h, which shows that further power density increases can be expected from their new generation PCU designs. Because of even higher power requirements and more constrained packaging (once again, the space freed up by the 14V battery), the LS600h PCU achieved yet another leap in performance. Figure 2-14 (provided by Toyota) illustrates the relative power density of the LS600h PCU (MY2007) compared to older generations. The performance for MY2006 corresponds to that of the Camry/GS450h. The MY2005 is the design utilized in the RX400h, while the MY2004 data represents the 2004 Prius. Toyota was able to increase the power density of the newest PCU design by more than four times compared to the 2004 Prius.

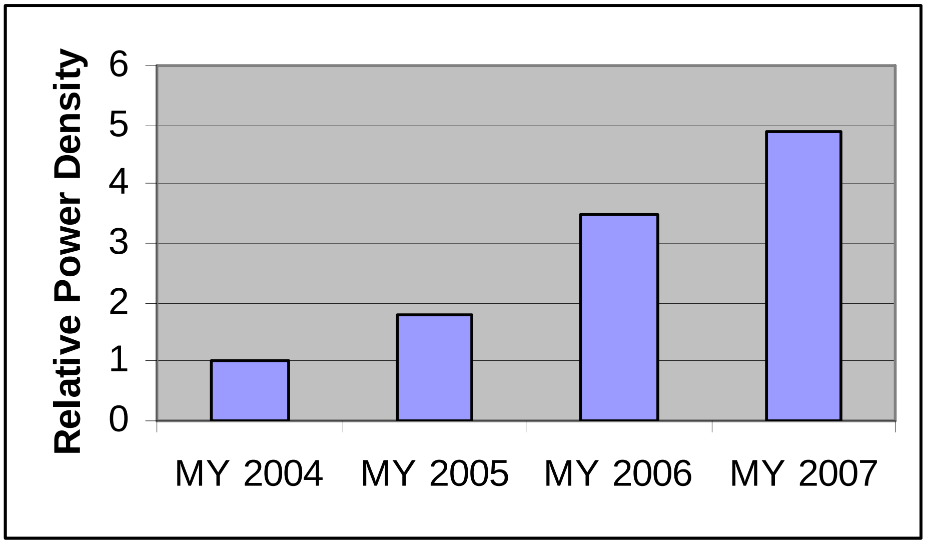


Figure 2-14. Toyota PCU Power Density Progression with Each New Hybrid.

To achieve this, Toyota has developed a new cooling design called the double-sided power modules (DSPM) stack. Figure 2-15 illustrates the new approach. The power chips have oxide-free copper heat spreaders soldered on both sides. Silicon nitride ceramic insulators, with heat conducting spacers in the chip area, are stacked on top of the copper spreaders, also on both sides. The resulting DSPMs are inserted into the gaps between cooling plates with thermal grease. The aluminum cooling plates are stacked into a cooler assembly following an assembly approach similar to an A/C evaporator.

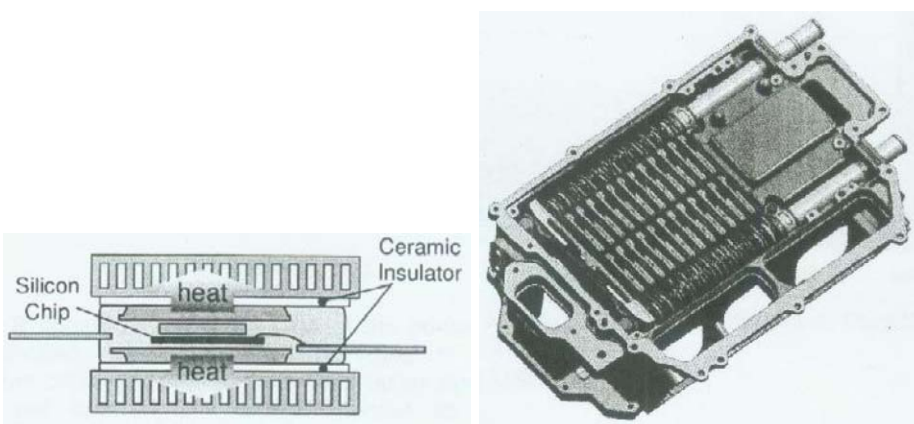


Figure 2-15. Lexus LS600h Double-Sided Cooling Design and View of IPM Assembly.

Toyota's new DSPM design doubles the heat sink area per chip. Because of thermal resistance reduction (less than half of a single-sided cooling design), Toyota was able to increase the maximum chip current from 200A to more than 300A. The result is that LS600 PCU requirements were achieved with only 24 IGBT/FWD modules. To achieve the same performance using a conventional one-sided cooling design, 40 modules at 200A rating would be required. However, Toyota told us that the assembly process is quite complicated and difficult for high volume production and they do not expect mass market vehicles like the Prius or Camry to incorporate this type of cooling in the near future.

2.6 OTHER CAMRY HEV DESIGN FEATURES

Because of compact and high power PCU design requirements, the Camry HEV is using a dedicated water pump for PCU cooling. A separate water pump was retained for passenger compartment heating.

The Camry HEV A/C compressor is electrically driven using 245V DC. Compared to the regular Camry, the hybrid vehicle's A/C was modified to include the "ECO – HEAT/COOL" switch on the dash, which further enables fuel economy increase. When the switch is activated, the system decreases the maximum cooling target temperature and decreases the cool-down time. The system then allows the engine to shut down, when the vehicle is stopped, under a wider range of conditions. The ECO option also reduces the peak heating temperature of the heating, ventilation, and air conditioning (HVAC) system and accelerates the engine warm-up cycle for reduced emissions. The system prevents running the engine for passenger heating when stopped.

The Camry HEV has an electric resistive heater, powered by the battery, to warm the heater core during the engine warm-up cycle. This feature supports AT–PZEV emission levels during cold-start and allows the engine shut-down when stopped.

The Camry HEV is equipped with a 34V AC assist motor EPS system. The EPS computer generates 34V from the 12V electrical system (see Figure 2-16) using a separate uni-directional DC-DC converter.

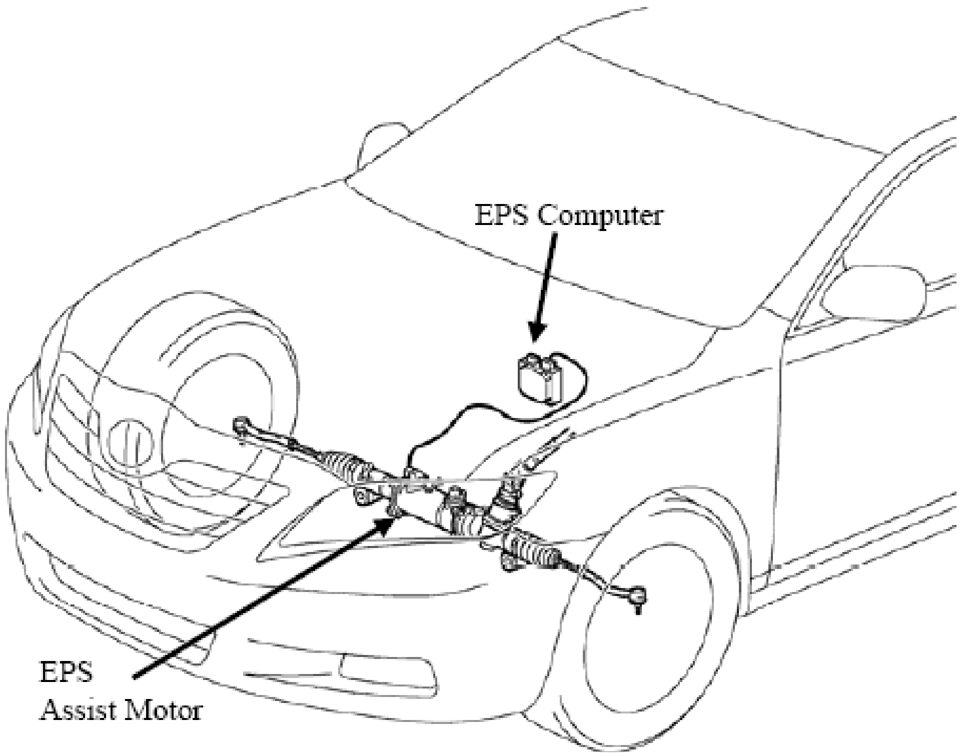


Figure 2-16. Camry HEV EPS System Layout.

2.7 SECTION SUMMARY

The new Camry HEV overall hybrid architecture is similar to the Prius II, while the body design is similar to the regular Camry. However, the key hybrid components including the battery pack, inverter/converter, motor, and generator were upgraded substantially to accommodate higher power requirements and the 2.4L engine used. As a result, the hybrid component-level design features are similar to Toyota "performance" hybrid vehicle designs, such as the Lexus GS450h.

The hybrid battery pack is assembled from the same type of cells used in other Toyota HEV offerings. The size of the battery was increased and the 14V DC-DC converter was built-in the battery housing.

The Camry is using a new PCU introduced in the Lexus HEV and designed to fit in the existing 14V battery space. The PCU design was upgraded substantially from the Prius design, including new trench IGBTs. The system maximum voltage was increased to 650V.

Table 2-5 compares the Camry HEV key specifications with those of the Prius and the regular 2.4L Camry. The electrical MGs used in the Camry are over twice as powerful compared to the Prius and the battery is about 50% larger. Toyota decided not to downsize the basic 2.4L I4 engine which is used on the conventional Camry. Instead the engine fuel economy improvements were derived from the adoption of the Atkinson cycle and other modifications for hybrid duty.

Table 2-5. MY2007 Camry HEV Specifications Compared to Prius and Regular Camry

	MY2007 Camry HEV	MY2007 Camry 2.4L	MY2007 Prius
Engine			
Gasoline engine	2.4L I4	2.4L I4	1.5L I4
Valve train	Twin-cam, four valve/cyle w/VVT-i	Twin-cam, four valve/cyle w/VVT-i	4-valve/cyle w/VVT-i
Engine power	147 hp @ 6,000rpm	160 hp @ 6,000rpm	76 hp @ 5,000 rpm
Engine torque	138lb-ft @ 4,400 rpm	161 lb-ft @ 4,000 rpm	82lb-ft @ 4,200 rpm
Emissions	AT–PZEV	PZEV-CA	AT–PZEV
Electrical Motor			
Motor type	PM AC synchronous	-	PM AC synchronous
Motor output	105 kW/4,500rpm	-	50 kW/1,200–1,540 rpm
Motor torque	199 lb-ft @ 0–1,500 rpm	-	295 lb-ft @ 0–1,200 rpm
Transmission			
Transmission	E-CVT	5-Speed automatic	E-CVT
Battery			
Battery type	Ni-MH	-	Ni-MH
Nominal voltage	244.8V (204 cells, 1.2V/cell)	-	201.6V (168 cells, 1.2V/cell)
Capacity	6.5 ampere hour	-	6.5 ampere hour
Battery peak horsepower rating	40 hp (30Kw)	-	28 hp (21Kw)
System			
System voltage	650 volts max	-	500 volts max
Combined system net power	192 hp (143 kW)	158	110 hp (82 kW)
Coefficient of drag	0.27	0.28	0.26
Curb weight [lbs]	3,680	3,307	2,932
EPA Fuel Economy (city/highway)	40/38	24/33	60/51

Figure 2-17 compares the acceleration of the Camry HEV versus the conventional 2.4L Camry (five-speed AT). The HEV provides almost instantaneous torque due to the electric traction motor capabilities with smooth acceleration due to the CVT. The result is that Camry achieved performance advantages with acceleration improvement by about 15% overall compared to the conventional Camry.

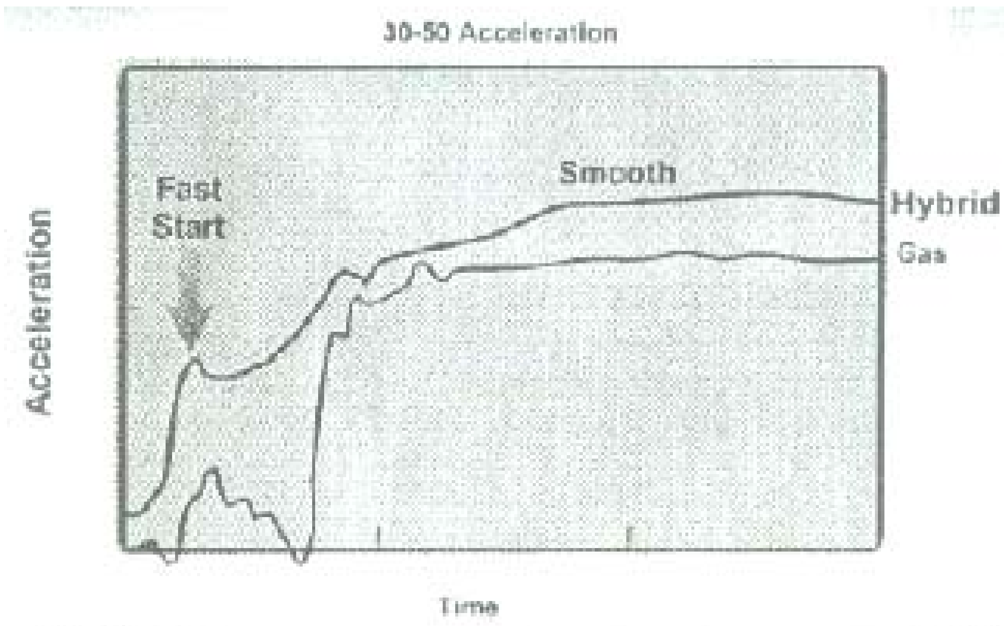


Figure 2-17. Camry HEV Acceleration Performance Compared to Conventional 2.4L Camry.

3 CAMRY HEV COST ANALYSIS

3.1 OVERVIEW

The overall cost of the hybrid drive train in the Camry HEV is the incremental cost of the electrical components less the cost savings from part elimination. Similar to the cost data shown in the previous Prius report, the "cost" data shown are variable cost/unit without any fixed cost burden from Toyota or its in-house divisional suppliers for amortization of R&D cost nor the engineering and tooling costs for the vehicle, or any intermediate profit margin for the "supplier" which may be in-house division or an external supplier. Typically these unit costs are very strong (inverse) functions of production volume and have important ramifications at low volume. The Camry hybrid is being produced at a rate of about 4,000 units per month whereas the Prius is being produced at a rate of about 20,000 units per month; hence, there are cost differences associated with scale. However, the Camry IPM is quite similar to the one used in the Lexus GS450H and the next-generation RX so that effects of scale are not as large.

Typically, the economies of scale follow a logarithmic dependence on production volume and studies indicate that a tenfold volume increase results in a 25–30% reduction in cost. The volume difference of a factor of four translates into a 15–18% increase in cost for hybrid components, which has not been included in this analysis. We excluded this cost because of uncertainty regarding total planned volume for components and because many components, such as IGBTs, are shared across many hybrid product lines. The overall cost of the hybrid drive train in the Camry is the incremental cost of the electrical components less the cost savings from part elimination. EEA has used this methodology to estimate the incremental cost of the first generation Prius and the second generation Prius.

The "cost" data shown are variable cost/unit without any fixed cost burden from Toyota or its in-house divisional suppliers for amortization of R&D cost, nor the engineering and tooling costs for the vehicle, or any intermediate profit margin for the "supplier" which may be in-house division or an external supplier. Hence supplier prices to Toyota would be higher than the prices quoted here by a factor of 1.35–1. 40, while retail prices would be higher by a factor of 1.75–1.90.

3.2 COST DATA INPUTS

A detailed list of the components used to estimate the incremental cost of the hybrid drive train and includes the cost for the first and second generation models. The components list includes the following:

- the motor and generator,
- the IPM module including the voltage booster,
- cooling systems for the motor and IPM module,
- the bidirectional 14V/244V DC-DC converter,
- the battery,
- the battery box and cooling system,
- the battery monitoring and control unit,
- the electrical safety system, and
- the regenerative brakes.

The regenerative brakes in particular are not part of the hybrid drive train but are a significant contributor to overall fuel economy. The generator's increased power capability is one factor that allows greater energy recovery from braking energy normally lost to friction.

The detailed cost estimates were based on the following data received for this study. The cost of the motor and generator scale more according to the weight of the electrical machines rather than the power rating and the high power rating of the Camry motor has been achieved by going to higher rpm. The Prius motor was rated at 50KW at 1200 rpm and 295 ft-lbs of torque at 0–1200 rpm; while the Camry motor is rated at 105KW at 4500 rpm and 199 ft-lbs from 0–1500 rpm (the torque at 4500 rpm is 164 ft-lb to attain 105Kw output). At 42kg, the Camry motor is actually lighter then the Prius motor but needs a separate gear reduction to step down the rpm of the output shaft. The peak motor speed is about 14,000 rpm. Hitachi indicated that the peak power rating may be too optimistic as typical high rpm motor ratings were around 1.8–2kW/kg, making a peak rating of 70–80 KW for the Camry motor a more realistic 1 minute peak rating. According to our sources, the generator is also operated at a higher average rpm so that the costs do not scale with power. The Prius generator is rated at about 30KW while the Camry generator has a rating of about 60KW, but we understand that the weight has increased by only 10%. Also according to our sources, the costs of the motor and generator for the Camry were only slightly higher than those for the Prius. Our cost estimates for high rpm motors are consistent with the $10 per peak KW or about $18–$20 per kg estimates that motor suppliers had forecast.

However, material costs for motors have increased significantly since 2005. We understand that most of the rare earth magnetic materials are obtained from China and costs have escalated substantially over the last two years. PMs used to retail for $55–$60 per kg, but now retail for $90–$100 per kg. Costs of steel and copper have also increased by 40–50% over this period. Hence, the costs of the Prius motor and generator are estimated to have increased by about 25–30% since the 2005 study. In addition, the cost of the magnets accounts for about 15–20% of total motor cost. Based on our total motor cost estimate and the cost of magnetic material, this would imply a PM weight of about 1.4kg in the Camry motor.

Costs for power electronics have decreased on a $/KW (peak) basis due to the better performance of the trench IGBTs, as well as the higher voltage (650 vs. 500) relative to the Prius. Cost of power electronics are a stronger function of current than power and the 30% increase in peak voltage reduces current by 23% at high power outputs. A total cost reduction of about 25–30% on a $/kW (peak) basis is estimated for the motor/generator converter/inverter, but since the power handling capacity has doubled, absolute cost has increased by 40–45%. The voltage booster has benefited from a more modest cost reduction on a $/kW basis and the cost reduction is largely due to the 20% increase in battery voltage so that the 60% increase in battery power output translates to a 32% increase in current.

Another major component of the IPM is the capacitor. According to Hitachi, the cost of the capacitor for a 100kW system is about 8–10 % of the IPM cost. Hitachi did not state the actual value of capacitance but the context of this statement was in relation th the Camry IPM. Most auto-manufacturers have switched to film capacitors from electrolytic types, and the cost and size of these film capacitors are being reduced. Current film capacitors are rated at up to 105°C, and future capacitors are likely to improve both the thermal performance as well as the volumetric specific power rating due to improvements in the film material and reduction in film thickness.

Other system costs for cooling of the motor IPM and battery are quite similar between the Camry and Prius. One significant issue is the credit for the engine; since the performance of the Camry hybrid is quite similar to that of the V-6 Camry model, the engine cost reduction is based on replacing the 3.3L V-6 with the 2.4L 4-cylinder engine.

The battery cost of $1100 is controversial but is based on direct input from PEVE, the battery manufacturer. We interviewed their chief engineer in 1995 soon after the introduction of the second generation Prius and he confirmed that Toyota was getting the battery at ~$40/kw (peak). Since that time battery production has increased by a factor of 3 and cell design improvements have been made, so that a 10% cost reduction seems very likely. Hence the cost of the Camry battery was estimated as 30*40*0.9 and rounded to the nearest 50$, Note that the cost is a variable cost and the cost to a non-Toyota buyer would be approximately 1.35 times this value or about $1500.

3.3 INCREMENTAL COST ESTIMATES FOR THE CAMRY HYBRID

Based on the above observations and other inputs obtained form interviews, a cost estimate for the hybrid component list was derived. We emphasize that these estimates are based on a combination of subjective and objective analyses since actual costs are rarely disclosed publicly. Costs were derived from the estimates for the Prius corrected for material costs, changes in technology, and changes in power ratings. The detailed cost estimates are summarized in Table 3-1 for both the Camry and the new model Prius. The new Prius eliminates the 14V starter, alternator, and 12V battery; whereas the Camry retains the 12V battery and starter for jump starting and these factors are accounted for in the estimate shown. The hybrid component cost is estimated at $4720 but cost savings of $1300 are estimated for replacing a V-6 engine with a 4-cylinder and eliminating the automatic transmission. The net result is that the costs for the Camry model at $3,400 is about $600 higher than the original 2005 cost estimate for the second generation Prius, but only about $350 higher if corrected for the current high material costs in spite of significant increase in the power of the system. We discussed the estimates derived with two suppliers who stated that the numbers looked quite reasonable based on their own experience, but also stated that their own costs were about 10–15% higher since they had less scale economy than Toyota.

It should also be noted that all these cost figures are for variable cost, not the burdened cost with all the fixed cost amortization included. We obtained some confidential information from existing and prospective buyers for the entire hybrid system as purchased from Toyota at high volume (>10,000 systems per year). The cost quotes given by Toyota to these buyers we obtained were very consistent with the $4720 * 1.35 or about $6500, and serves as one validation of the cost data provided.

Table 3-1. Variable Cost Estimates for the Drive Train Components

Component	Camry 2007 Cost	Prius 2005 Cost	Comment
Motor	750	600 (750 in 2007)	Power increased by 110%.
Generator	550	400 (500 in 2007)	Power increased by 50%.
Inverter/controller	1300	900	Size reduction, higher voltage.
Voltage booster	325	250	About 30KW power rating on Camry, 20KW on Prius.
Bidirectional DC-DC converter	150	150	1.2KW unit.
Battery	1100	900 (-35 for 12V battery)	Number of modules increased in Camry, 12V battery retained.
Battery box and cooling system	150	120	Increased box size and more powerful cooling.
Battery control	80	65	Increased number of battery modules.
Electrical safety	40	40	Disconnects high voltage in case of accident.
Power harness	50	40	Increased voltage, current.
Electric Power steering +36V DC	65 + 40	65	Increment over hydraulic system.
Electric water pump	40	35	Larger engine.
Regenerative brakes	120	100	
Sub-Total	**4720**	**3630**	
Savings on transmission	(600)	(600)	Same as Prius.
Savings on starter and alternator	(50)	(80)	14V starter retained on Camry.
Saving on engine	(650) compared to V-6	(150)	Engine savings based on constant performance comparison.
Net Cost	**3420**	**2800m (+250 for 2007)**	

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