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Toyota PRIUS: focus on Continuous Variable Transmission and battery costs

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Abstract — Toyota PRIUS: focus on Continuous Variable Transmission and battery costs —
Toyota PRIUS is the first large diffusion hybrid vehicle. A lot of information is available on the developed technology [1]. The goal of this presentation is to focus on the impact of the high efficiency electrical continuous variable transmission on the engine fuel consumption. Another important aspect is to estimate the real cost of the battery used in the vehicle in microcycle mode, in comparison with other battery strategy and dimensioning

INTRODUCTION

In CEA-LITEN, the fuel cell system laboratory (LPAC) develops fuel cell systems for automotive applications, off-road ones and stationary gensets. One other activity is monitoring actions of existing electric or hybrid vehicles. The goal of these actions is to know the real behavior and dimensioning of existing vehicles to have technical feedback and to provide expertise for new vehicles.

The Toyota PRIUS is the first large diffusion hybrid vehicle. A lot of information is available on the developed technology. Because of the complexity of the technology and the different aspects involved, Toyota PRIUS technology is difficult to summarize. The goal of this presentation is to give the point of view of power electronics specialists and engine one on the concept. The discussion is focused on the electromechanical transmission and on the battery use and cost of battery use. Because of two battery laboratories on CEA, and one of these laboratories dedicated to battery use for photovoltaic application, there is some know-how in CEA on real cost of battery utilization in different applications. The main information used for this synthesis is extracted from Oak Ridge National Laboratory studies [1] ordered by US Department of Energy.

The Toyota PRIUS hybridation (parallel hybridation with power derivation) is first presented as an electromechanical high efficiency electrical continuous variable transmission. This high efficiency electrical continuous variable transmission allows using the engine only in the high efficiency zone to provide low fuel consumptions. The other important aspect presented in this paper is the battery use in microcycle mode in the vehicle and an estimation of the real cost of the battery used in microcycle mode. This cost is compared with other battery strategy and dimensioning too.

1 CONTINUOUS VARIABLE TRANSMISSION WITH HIGH EFFICIENCY

To explain the low consumption of the Toyota PRIUS, the first key point is not due to the battery use, but the use of a high efficiency electrical continuous variable transmission. The all transmission is presented in figure 1.

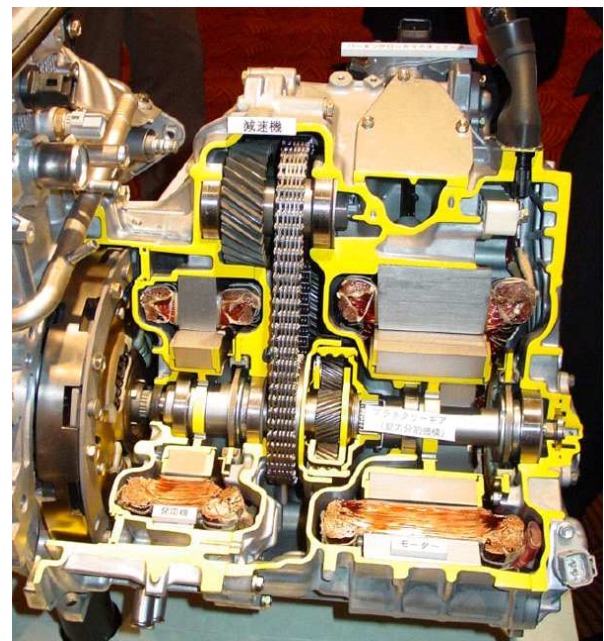


Figure 1

The different parts of this transmission are the power split device, the generator, the two inverters (generator and motor ones), and the electrical motor.

The figure 2 details the different mechanical parts.

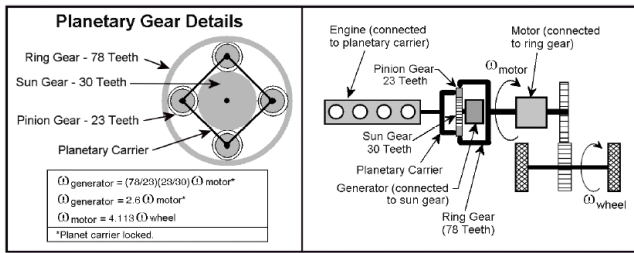


Figure 2

The engine is connected to planetary carrier of the split device.
 The generator is connected to the sun gear of the split device.
 The ring gear of the split device is the mechanical output axle.
 The electrical motor is directly connected to this mechanical output axle. It's able to provide additional torque, up to four times the one of the engine.

The figure 3 presents the system configuration involved. In fact there are two inverters, one for the generator and one for the motor in the same box. In this part of the presentation, we present the nominal mode, and the battery is not used. In nominal mode, there is no energy exchange with the battery.

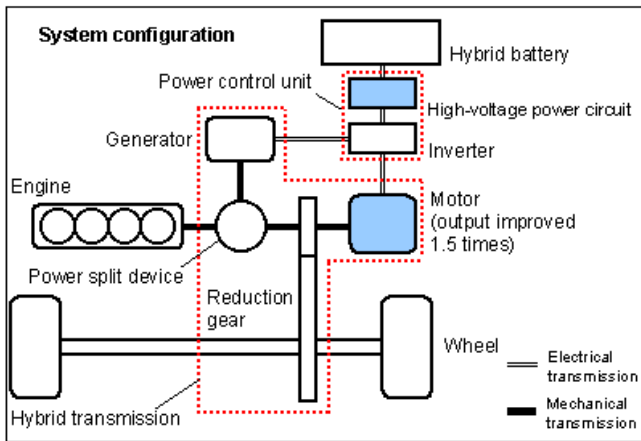


Figure 3

The power split device separates the engine mechanical power in two parts, a first one is used as a mechanical power; the second one is transformed in electricity by the generator.
 This electrical power is converted by the generator inverter in a high DC voltage (high voltage DC bus). The second inverter uses this DC voltage to supply the motor.

The figure 4 presents the mechanical transmission and the electric transmission:

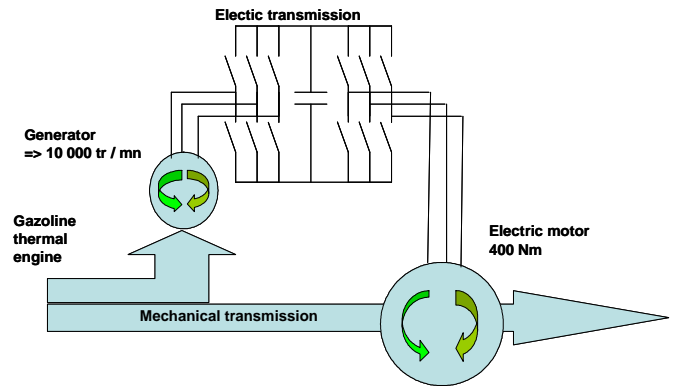


Figure 4

In the Toyota Prius, the gasoline engine provides a maximum torque of 115 Nm. The electrical motor has a maximum torque of 400 Nm at low rotation speed. So this motor can provide the adequate level of torque to start and accelerate the vehicle, as a mechanical gear box on the first transmission ratio.

Because of electric motor property, this component can provide enough torque up to the maximum speed of the vehicle.

The figure 5 presents the power and torque of the electric motor for the first Toyota Prius (THS) and the 2004 version (THS II). The differences between the two versions will be explained later.

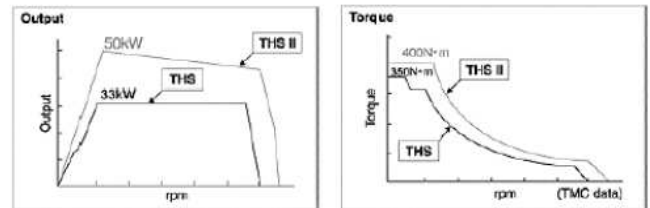
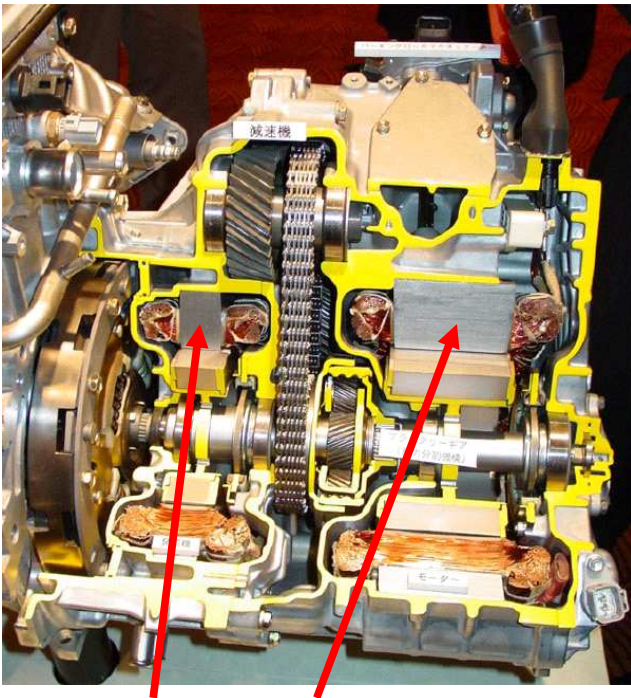


Figure 5

The generator is a high speed (10 000 r/mn) and low torque electric machine. The motor is a high torque and medium speed machine (5000 r/mn). The magnetic surfaces are very different, because surfaces are proportional to maximum torque value.



Generator and motor magnetic surface

Figure 6: magnetic dimensioning

The all system (power split device, generator, generator inverter, motor inverter, and high torque motor) associated with adequate controller provides a continuous variable transmission with a very good efficiency and speed variation.

On the Toyota PRIUS, there is no additional manual gear box or automatic one. There is only a mechanical reduction with constant ratio with a metallic chain and gears with fixed reduction ratio.

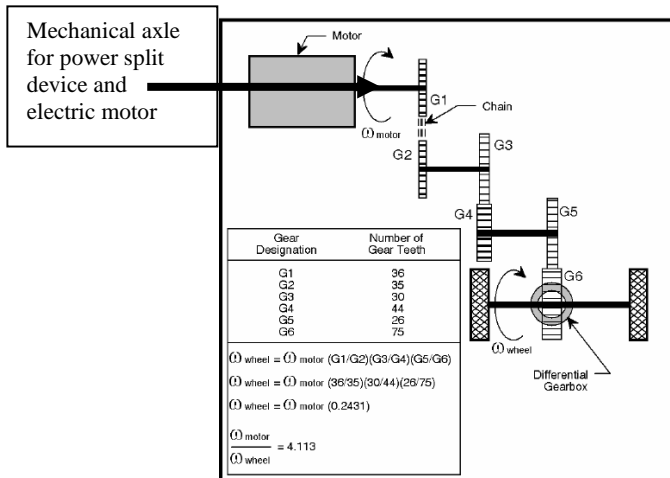


Figure 7: Mechanical transmission

The electrical motor is directly connected to the wheels with only constant reduction gear. So, it will be possible to provide additional power from the battery for transient phase. For example, for quick acceleration, it's not necessary to wait for gasoline engine acceleration to provide more power (as it's the case when there is only mechanical continuous variable transmission). Additional power could be provided instantaneously by battery to the motor to provide fast acceleration. This point will be detailed later in the presentation.

The ORNL expertise proves that the two electrical machines, and associated converters, have very good efficiency.

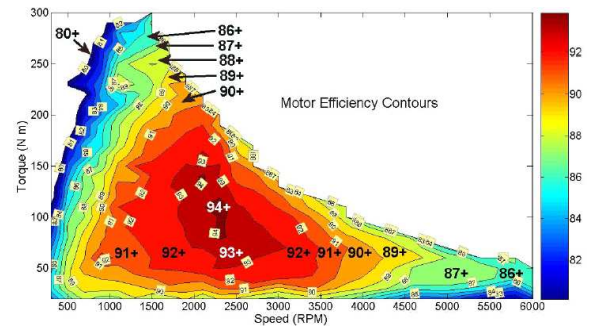


Figure 8: Motor efficiency

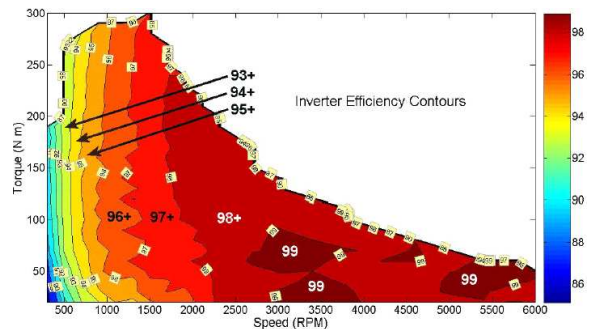


Figure 9: Motor inverter efficiency

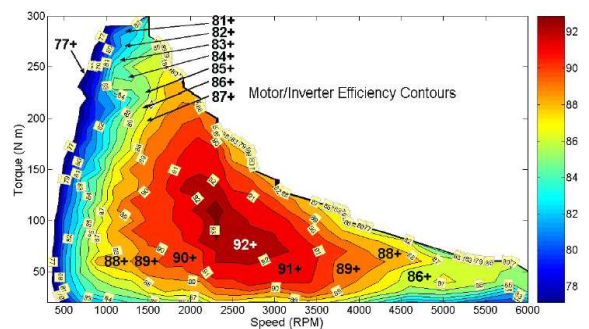


Figure 10: Motor and inverter global efficiency

The global electromechanical continuous variable transmission has a global good efficiency. The efficiency value is related to transmitted power, engine rotation speed and vehicle speed because the power is transmitted with two links: the mechanical one and the electric one, and the efficiencies are different and not constant.

2 ENGINE IS USED ONLY IN THE HIGH TORQUE AND HIGH EFFICIENCY ZONES

With a continuous variable transmission, it's possible to use the engine in a high torque zone where the specific consumption is low. This point is described now.

Figure 9 present the hybrid drive system associated to the gasoline engine.

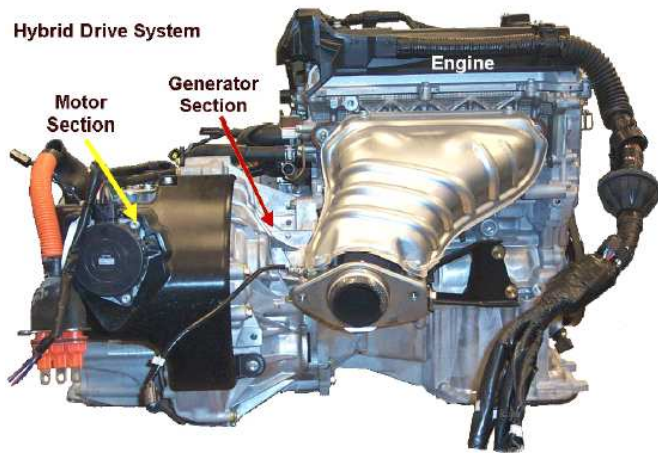


Figure 11

Compared to diesel engine, the gasoline engine has a lower efficiency due to Carnot law because of its lower compression ratio and lower combustion temperature. But this theoretical efficiency difference is lower than the real fuel consumption difference (in liters).

One additional point is the difference of energy between one liter of diesel and one liter of gasoline.

The last and important point is that the gasoline engine has a lower efficiency, far from theoretical one, because of air aspiration losses at low charge (low torque). At low charge, the throttle is only partially open, to have the adequate quantity of air to be stoichiometric. In a diesel engine, there is no throttle and no additional losses. The diesel engine works with air excess.

Without a continuous variable transmission (and with additional power for transient acceleration) the driver uses the gasoline engine in low charge (low torque) for

long times, to have adequate level of safety margin for the accelerations.

The figure 10 presents the Toyota PRIUS gasoline engine cartography [2]. This engine is a specific optimized one, but the rules between efficiency and torque are the same than standard ones.

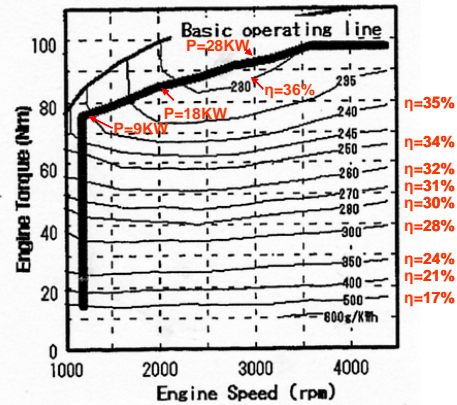


Figure 12

With a standard manual or automatic gear box, the engine is used mainly in low torque zone to have safety margin to provide acceleration if necessary.

For example, 9 kW is adequate to provide 80 km/h speed, but there is no gear box with 70 km/h for 1000 rotation per minute. Standard manual gear boxes are 35 km/h / 1000 rpm for gasoline engine and 45 km/h / 1000 rpm for diesel engine. With such a too long ratio it would be very difficult to drive because it's necessary to change the gear box ratio for each power demand variation.

The hybrid drive system of the Toyota Prius is firstly a high efficiency electrical Continuous Variable Transmission and secondly it provides the safety margin for acceleration instantaneously by the battery. So the engine can be used only in high charge zone with high efficiency. The consumption is lower. In this case, the global efficiencies of diesel and gasoline engine (associated with hybrid drive system) are the same. The **energy consumptions** are the same. The consumptions in liters are different because of the difference of density between the two fuels:

- For diesel, the energy is 10 kWh/l, CO2 emission is 2.6 kg.
- For gasoline, the energy is 9 kWh/l, CO2 emission is 2.4 kg.

If the price was related to energy or CO2 emission, the price for diesel fuel should be 10% more than gasoline one.

The first key point of the Toyota PRIUS is a high efficiency controlled variable transmission constituted from a power split device, a generator, a generator inverter, a motor inverter and a high torque power motor. The second key point is the electrical motor directly linked to the wheels and additional power battery to provide safety margin for acceleration without delay. The third key point is that with this CVT, the gasoline engine is used only in the high efficiency zone at high charge (torque).

The Toyota PRIUS has an Atkinson/Miller cycle. This is an optimization of the gasoline engine with controlled valve with angle control. This is not a key point. This kind of technology (controlled valve with angle control) is now developed in new Japan or European gasoline engine to minimize air aspiration losses and for global higher efficiency.

3 ELECTRIC MOTOR IS ALWAYS CONNECTED TO WHEELS, GAZOLINE ENGINE IS DECOUPLED

As said previously, the electric motor is always connected to the wheels, so it's possible to:

- provide additional acceleration with battery power,
- provide continuous torque without interruption (as an electrically control gear boxes with different transmission ratio),
- drive in pure electric mode.

The engine is not linked directly to the wheels. It's linked by the split device. If there is no torque demand on the generator, there is no torque on the engine axle. With the control command and the generator inverter, it's possible to decouple totally the engine of the wheels.

Compared to some other hybrid electric cars, the Toyota Prius engine can be totally decoupled. It's an advantage for energy saving in deceleration (no engine losses) and electric mode (no engine losses).

4 A 1.2 KWH BATTERY IN MICROCYCLE MODE

In the Toyota PRIUS, the battery is used only in some very specific conditions. This strategy is due to cost and reliability aspects. In this part, we will describe these points.

The Toyota Prius battery is from NiMH technology. The energy storage is around 1.2 kWh. The elements are small ones with a capacity of 6.5 Ah and the individual voltage is 7.2 Volts. Each element has 6 cells in series.

In the battery, 28 elements are connected in series, so the nominal voltage is 201 Volts.

In the first version of Toyota Prius, the elements are tubular ones. In the 2004 version the elements are prismatic ones.

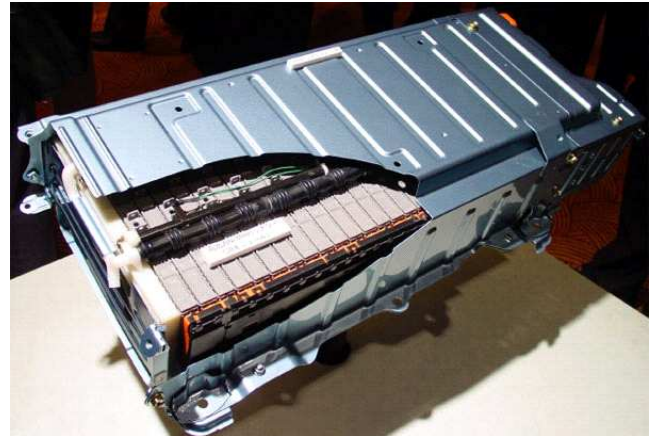


Figure 13

This 2004 version is very well optimized for thermal dissipation and temperature homogeneity. Air conditioning from the vehicle is used and spreads in parallel all the elements. Between the elements, there are only small spaces for air with corrugated surfaces. All this points are adapted for very good air exchange, with high speed of air and a lot of turbulences.

The electrical technical points are:

- the NiMH battery stores a maximum energy of 1.2 kWh,
- to provide a long life, the mean state of charge of the battery is 60%, for from the extremes,
- a state of charge windows of 20% is allowed around the mean value of 60%. This windows amplitude is 240 Wh.
- In most cases, the real cycle amplitude is only 5% in the windows of 20%. So most cycles have amplitude of only 60 Wh.

The specified maximum power for the battery is 21 kW. For this level of power, the 5% cycle correspond to 15 s of range.

5 MICROCYCLE: BATTERY USE COST IS DIVIDED BY FIVE

The use of a battery has a cost which is the investment cost divided by the number of cycles and the cycle amplitude. In most application, this cost is very high compared to the cost of the electricity.

For example, in photovoltaic application isolated from the main, for 30 years, the cost of the lead acid battery replacement is as important as the cost of photovoltaic modules. For 30 years, the cost of electricity is 0.5 € per kWh. The cost of the storage is about another 0.5 € per kWh.

For lead acid battery the cost of the battery use is around 0.5 €/kWh. This cost is approximately the same for high quality tubular lead acid battery for telecom or photovoltaic applications and for lower cost but lower number of cycle lead acid battery for starting vehicle. In this application the cycle amplitude may be maximum, around 80% and more, depending from the solar resource.

For the NiMH Toyota Prius, with high cycle amplitudes battery, the cost of use should be around 1.5 €/kWh (1500 €/kWh and 1000 cycles). This cost is prohibitive compared to energy provided by gasoline and efficiency of engine.

A good order of magnitude for mechanical or electrical energy provided by an engine supplied by a fuel is 0.5€/kWh (For example, gasoline to 1.4 €/liter, 9kWh/liter and a 30% efficiency for the engine). This value is continuously changing because of oil price variation.

For the NiMH Toyota Prius battery with high cycle amplitudes the cost of use should be three times the cost of gasoline use. This cost is prohibitive. With this level of cost a plug-in Prius is not competitive.

With a cost of use of 0.5 €/kWh, lead acid batteries are competitive. This technology is often used in small electric vehicle.

The battery strategy in the Toyota PRIUS is to be around 60% of state of charge (far from the extremes to provide long life time) in a window of 20 % of variation, and a great number of real cycles around 5%.

It's important to know, the real cost of use with this strategy.

The battery supplier's specifications are 100,000 cycles for 5% of state of charge variation. With such cycles the

cost of battery use is now:
 $1500 / 100,000 \times 0.5 = 0.3 \text{ €/kWh}$.

In microcycle mode, the cost of storage use is divided by five.

This cost is competitive compared to the energy provided by gasoline and efficiency of the engine.

The global battery energy is 1.2 kWh. A cycle of 5% is only 60 Wh, so the battery uses are limited to:

- acceleration assist (with high torque and high electrical power),
- energy saving in decelerations and braking,
- electric mode for short distances,
- sequence of electric mode for short distances on the battery, and recharge by restarting the engine for some tens of seconds, and again engine stop for pure electric mode, and so on. This sequence is used at low speed (< 60 km/h) in the cities or traffic jams.

But the energy is too limited so there are:

- almost no energy saving in downhill, only 5% or 2 or 3 cycles of 5% maximum,
- no assistance for long uphill. To provide the power, the engine rotation rate is high, and the efficiency decreases. There is a lot of noise compared with the standard conditions.
- no plug-in.

Because of the very low level of energy, plug-in has no sense.

In case of additional battery for plug-in in modified vehicles, the battery cycles are high and the battery use cost is five time higher. With the indicated costs, the plug-in vehicle is not competitive.

But:

- Because of Toyota Prius influence, the high energy batteries are produced in high volume. One million of vehicles were produced and this only battery is one half of the all NiMH world market.
- New technologies of batteries are emerging, with lower material costs than NiMH. In NiMH batteries, Lanthanum is often used in hydrides and is expensive. For example, the components of Iron phosphate lithium ion batteries are less expensive.

The cost of battery use is not competitive now, but the boundary is near. Quantity production, competition between manufacturers and higher number of cycles in real use are the key factors to have a competitive cost of battery use. Iron phosphate Lithium ion batteries can be a good candidate for cost and number of cycle point of view. This technology provides a high level of intrinsic security.

6 GAZOLINE CONSUMPTION AND POLLUTION EMISSIONS AT LOW SPEED IN THE CITY ARE REDUCED

As it was said before, at low speed the consumption is reduced because of:

- the engine is used in high torque zone with high efficiency,
- the sequence of electric mode for short distance on the battery, and recharge by restarting the engine for some tens of seconds (in high torque zone), and engine stop again for pure electric mode, and so on. This sequence is used at low speed (< 60 km/h) in the cities or traffic jams.

In the city, the consumption is limited:

- for standard gasoline vehicle, the city consumption is 50 to 60 % more important than the mean consumption,
- for standard diesel vehicle, the city consumption is 30 % more important than the mean consumption,
- for Toyota Prius, the city consumption is 20 % more important than the mean consumption,

On the Toyota Prius, at low speed, the stop and start of the gasoline engine is done with very low level of emission. As it was said before, the engine is totally stopped in electric mode, so there is no parasitic air input to cool the engine and the catalyst filter. These two components are kept at adequate temperature, so there is still a low level of emission when restarting.

7 POWER ELECTRONIC

All the power electronic components (generator and motor inverters, battery converters and air conditioning compressor inverter) are in the same enclosure.

The figure 12 presents the localization of the inverters and converters. There is only one water cooled cold plate. Motor and generator inverters and high power battery converter are on one face. The converter for the low voltage battery (13.2V) and the air conditioning compressor inverter are on the other face.

As for water cooled cold plate which is common for all the converters and inverter, there is only one big film capacitor which is common.

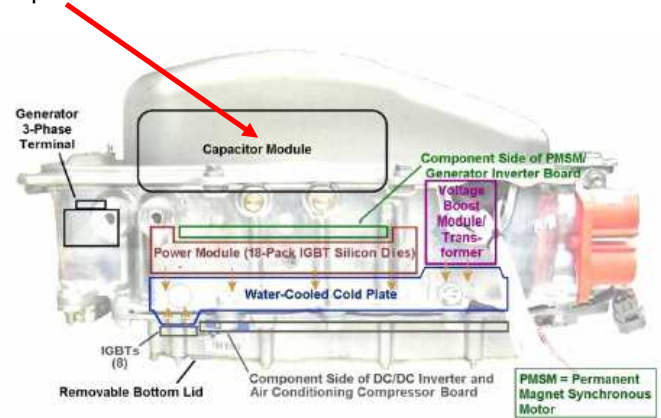


Figure 14

The figure 13 presents the first face, without the big film capacitor.

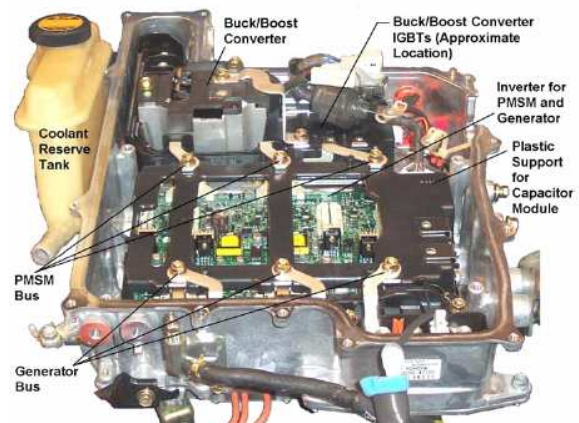


Figure 15

In the first Toyota PRIUS, there is no additional converter for the high power battery.

This enclosure is one of the 2004 version where an additional converter is added. This converter is a buck-boost one. When there is a power demand, the boost

mode is used to transfer energy of the battery to the higher voltage of the DC bus between the two inverters.

The figure 14 presents the IGBT module for the two inverters.

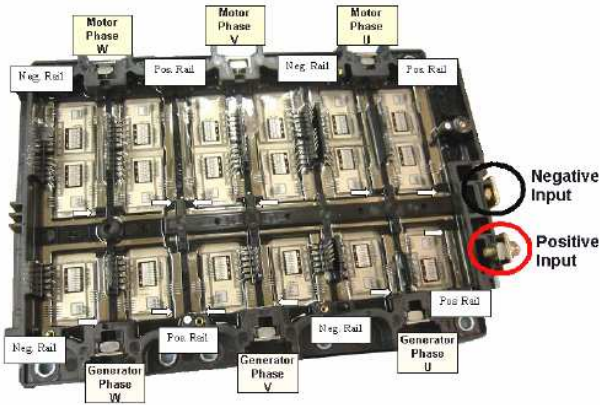


Figure 16

The generator is a medium torque electric machine, so there is only one IGBT chip and one diode per switch (bottom of the figure 14).

For the same mean power, the motor is a high torque electric machine, so two IGBT chips and two diodes are used per switch (top of the figure 14).

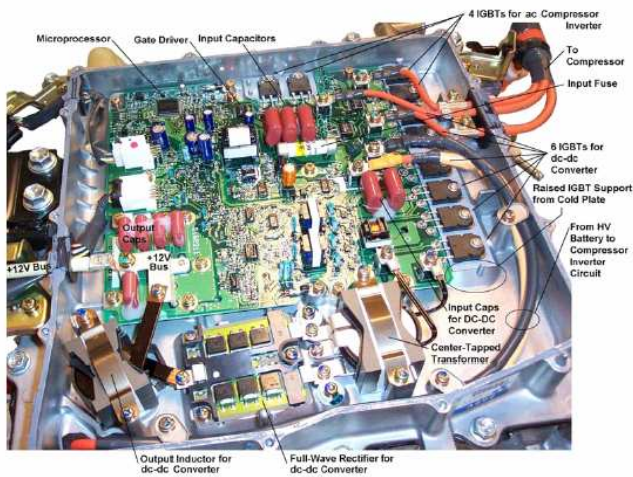


Figure 17

The figure 15 presents the second face of the water plate. This face is dedicated to the converter for low voltage network (13.2V) and the air conditioning compressor.

8 POWER ELECTRONIC EVOLUTION BETWEEN FIRST GENERATION AND 2004 VERSION

The first Toyota Prius has limited driving performances compared to the 2004 version. This high improvement is due to an electric architecture modification [3].

In the first Toyota Hybrid System (THS) the battery is directly linked to the high voltage DC network between the generator inverter and the motor inverter. With this electrical architecture, the motor is triangle coupling because of the low level of voltage, and torque is limited by the maximum current of the inverter. The current of each phase of the inverter is separated between two windings.

The figure 16 presents the two electrical architectures.

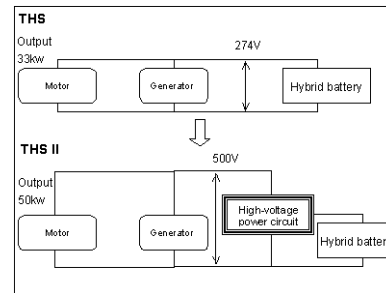


Figure 18

The architecture of the 2004 version is THS II. In this case, the voltage can go up to 500 volts. With this voltage, the same motor can be connected in star coupling. The same inverter, with the same maximum current, supplies only one motor winding per phase.

The maximum torque of the motor is improved from 300 Nm up to 400 Nm. The maximum power is improved from 33 kW up to 50 kW [4].

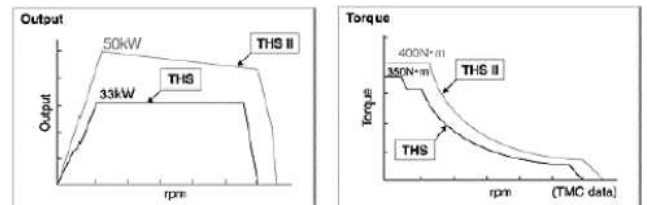


Figure 19

In the THS II architecture, an additional converter is used between the high voltage battery and the DC bus between the generator inverter and the motor inverter.

The voltage of the DC bus is variable between 200 Volts and 500 Volts. The voltage is proportional to the vehicle

speed in stabilized mode and goes to 500 Volts in transient mode.

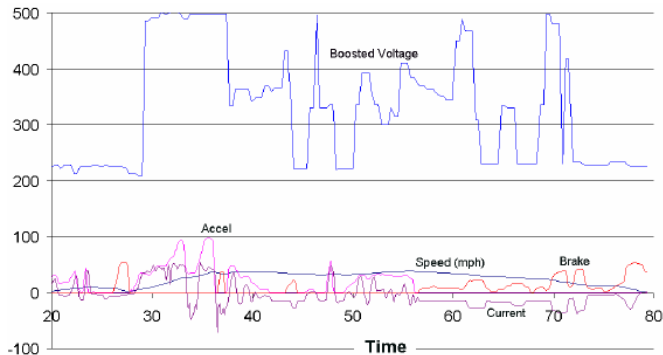


Figure 20

Between the first version and the 2004 version of the Toyota Prius, the electric architecture is modified to allow a variable voltage mode for the high voltage. An additional converter is associated with the high voltage battery. With this architecture, the maximum torque and power of the same electric motor provides a high improvement for driving performance.

CONCLUSION

The goal of the presentation is to focus on the key points of the Toyota PRIUS concept.

The first key point of the Toyota PRIUS is a high efficiency controlled variable transmission constituted from a power split device, a generator, a generator inverter, a motor inverter and a high torque power motor.

The second one is that this CVT allows using the gasoline engine only in the high efficiency zone at high charge (torque).

The third key point is the possibly to provide acceleration without delay by using the electrical motor and additional power provided by the battery. This possibility is due to the electrical motor directly linked to the wheels and a high power battery used for additional power for a short time.

The fourth one is battery strategy in the Toyota PRIUS:

- to be around 60% of state of charge (far from the extremes to provide long life time)
- in a window of 20 % of variation,
- and to have a great number of real cycles around 5%.

In this microcycle mode, the cost of storage use is divided by five (0.3 € compared to 1.5 €) and is

competitive compared to energy provided by gasoline and engine use.

In microcycle mode, the level of energy is very low, around 60 Wh. It's only compatible with:

- acceleration assist (with high torque and high electrical power),
- energy saving in decelerations and braking,
- electric mode for short distances,
- sequence of electric mode for short distances on the battery, and recharge by restarting the engine for some tens of seconds (in high torque and high efficiency zone), and engine stop for pure electric mode, and so on. This sequence is used at low speed (< 60 km/h) in the cities or traffic jams.

But the energy is too limited so:

- almost no energy saving in downhill, only 5% or 2 or 3 cycles of 5% maximum,
- no assistance for long uphill. To provide the power, the engine rotation rate is high, and the efficiency decreases. There is a lot of noise compared with the standard conditions.
- no plug-in.

With the indicated level of costs, the plug-in vehicle is not competitive.

The electric motor is always connected to the wheels, so it's possible to:

- provide additional acceleration with battery power,
- provide continuous torque without interruption (as an electrically control gear boxes with different transmission ratio for example),
- drive in pure electric mode.

The engine is not linked directly to the wheels. It's possible to decouple totally the engine of the wheels. It's an advantage for energy saving in deceleration and for electric mode. There are no engine losses in these two modes.

With the Toyota PRIUS concept, city overconsumption is limited compared with diesel and gasoline engine, with a very low level of pollution.

Between the first version and the 2004 version of the Toyota Prius, the electric architecture is modified to allow the high voltage DC bus to be a variable voltage mode. An additional converter is added to the high voltage battery. With this architecture, the maximum torque and

power of the same electric motor is much more important. It provides a high improvement for driving performances.

All the power electronic is in a unique block for the mutualism of auxiliary functions (water cooling cold plate, decoupling capacitors, input filters, command...). This kind of design allows cost saving.

For plug-in vehicles, the cost of battery use is not competitive now, but the boundary is near. Quantity production, competition between manufacturers and higher number of cycles in real use are the key factors to have a competitive cost of battery use. For us, Iron phosphate Lithium ion batteries technology can be a good candidate for cost and number of cycle points of view. This technology provides a high level of intrinsic security.

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