

Study of the Functioning of a Hybrid Vehicle converted into a Plug-In Vehicle. Performance Study and Docking of Extra Batteries

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Summary - This work describes an investigation carried out on a hybrid vehicle to which a battery pack has been added to increase the capacity originally installed. It will attempt to demonstrate the performance benefits of the PLUG-IN System.

I. NOMENCLATURE

MG: Motor generator
 HV: Hybrid Vehicles.
 EV: Electric Vehicles
 PHEV: Plug in Hybrid Electric Vehicles
 ICE: Internal Combustion Engine
 ECU: Electronic Control Unit
 SOC: State of Charge
 MG1: Motor-generator 1
 MG2: Motor-generator 2

II. INTRODUCTION

Hybrid vehicles are currently one of the products whose market has grown significantly in the United States and Latin America. The increase in fuel prices and its high consumption - product of congestion in cities - have been a very important factor in determining the purchase of this type of technologies by motorists. In this regard, manufacturers daily surprise us with modern developments applied for energy savings in terms of its use and optimization.

The use of an electric motor-generator or MG (as we know it) with an ICE: internal combustion engine, still compel the use of fuel, not permanently but under certain driving conditions, so the need for a 100% electric vehicle becomes stronger to solve these situations.

Whatever automotive technology is used, there is a big problem that so far has generated worldwide discussion issues: The batteries' capacity and charge storage.

For this reason, we have developed an investigation whose result is a final product that shows how effective is the conversion of a conventional hybrid vehicle into a Plug-In vehicle.

To explain this in other words: Providing more battery capacity to a hybrid vehicle by using an additional high voltage battery that will work together with the original of the vehicle, under a specific management. Thereby, we will try to decrease the fuel consumption on an initial trip (20kms or 12 miles, aprox.), after a complete battery's charge done from an 110 V outlet.

An important point is the adaptation of a charging outlet or plug in the vehicle. Which means, an electronic switching charger that will permit the charging of the extra battery through the electricity network of our home.

It is proven that the majority of drivers travel no more than 70 kilometers a day; usually, as much as 60 kilometers.

Therefore, it is about optimizing this initial trip (20kms or 12 miles, aprox.) using a hybrid vehicle with a higher capacity battery, that was loaded previously to travel.

Then, and of course, if it runs more than those initial kms/miles, it will be a normal hybrid vehicle and fuel will be used as the main energy source.

This is the motivator idea of the PLUG-IN System and in this study we will prove its convenience.

The development and implementation of this system includes also a study of the control stage that will allow us to manage the additional battery, to couple it in the most effective and possible way, optimizing the SOC calculated by the ECU's system.

III. INITIAL CONSIDERATIONS

SOC – State of Charge

SOC - State of charge is defined as the available capacity of a battery, and this could be compared to the fuel tank in a vehicle. It is represented as a part of the percentage of a full load, and must be updated periodically by the system.

The state of charge's estimation is essential for achieving an optimum performance of a system that

controls electric or hybrid cars, to maximize the use of the electric motor in relation to the combustion engine.

There are no direct ways to measure the state of charge (SOC) of a battery. There are indirect ways to estimate it but each one suffers from limitations.

One of the most important factors affecting the estimation of a battery's SOC is aging. Due to the charge and discharge cycles, the capacity of the cells making up the battery decreases with time. This fact leads to update the maximum state of charge available for the battery periodically, as it is the reference for calculating the above percentage. If taking in consideration the nominal value of the battery capacity, this estimate might contain weight errors. Other factors involved in the SOC estimation are the following:

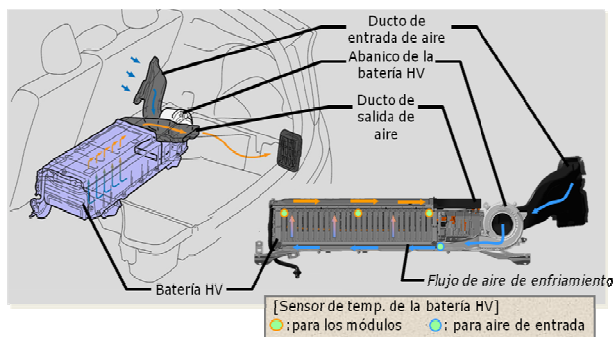
Charge and Discharge Rate

When charged and discharged, the electrochemical process within the cells always takes a finite time and is not always less than the electrical stimulus that charges the battery. During the charging process, a discharge pulse may take place, stopping the process and might result in inaccuracies in the SOC estimation. In addition, both charging processes consume energy and the energy supplied by the battery will be less than the one used for charging. This ratio is called Coulombic Efficiency and may affect up to 3% of the available capacity.

Temperature and Discharge Rate

The dependency of the available capacity in a battery with temperature is direct. For this reason, if the temperature increases, inaccuracies may occur in the SOC and this could even lead to an explosive phenomenon of the cell or battery.

For this reason, all hybrid and electric cars come with a cooling system only for the high voltage battery to avoid this type of inconveniences. Figure 1



Auto- Discharge

Over time, a battery undergoes a process of self-discharge that is typically less than 3% per month. This energy consumption can be appreciable in cases of long periods between charging processes.

Charging Procedures. Charge and Discharge Cycles

We know it is possible to generate energy through a chemical reaction. Among these energies, we are interested in the Electric Power. The systems capable of storing Electric Power as a chemical energy are called Electrochemical Cells. The fundamental structure of an electrochemical cell consists of two electrodes (metallic in most cases) inserted into a conductive solution or electrolyte: Positive Electrode, called the Cathode and Negative Electrode called Anode.

The characterization of the materials used as electrodes is based on observations of their behavior after several charge and discharge cycles, called 'cyclability'. Some terms used to characterize are:

Charge Factor:

Is the ratio between the discharge curve capacity and the charge curve capacity.

Cycle Efficiency:

Is the ratio between the discharge curve energy and the charge curve energy.

Average Life:

Is the number of charge-discharge cycles an electrochemical cell can be submitted before disposal.

Memory Effect:

Effect through which in each recharge, the charge's capacity is limited.

SOC Estimation Methods

There are several methods to estimate the batteries' state of charge that have been developed and improved. These depend on the battery type and the possibilities each one present. Among the most important are:

a- Estimation Based on Voltage

This method is based on a direct relationship between the current battery voltage and its available capacity. This method is imprecise due to the nonlinear behavior

of many types of batteries in relation to voltage, like the lithium ion in a range of intermediate values.

b- Measurement of Specific Gravity

Also known as relative density measurement. To measure it is necessary to access the electrolyte internal liquid of the battery. The relationship between the density of water and the electrolytic substance decreases linearly with the discharge of the battery cell. Therefore, an estimate of the SOC cell can be obtained by measuring the electrolyte density. Although this is a fairly accurate method, it is not capable of determining the total battery capacity.

c- Estimation Based on Current or Intensity

It is also called Coulomb Counting. Involves the integration of incoming and outgoing current into the battery. This method integrates over time, the intensity that loads and unloads the cells and its results are the charge stored in the interior the cells. This is rated as the most accurate method for estimating the SOC due to the direct measurement of charge.

IV. HYBRID OPERATION

HV - Hybrid Vehicle Operation

A hybrid vehicle is a vehicle where its propulsion energy comes from two different sources: The fuel and the electrical energy stored in batteries. When moving, the hybrid vehicle behaves according to the load demand required by the driver, so it can operate:

- In EV - Electric mode only (Electric Vehicle).
- In a combining mode, using the combustion engine and the electric battery. HV (Hybrid vehicle)
- And in a mode only powered by the combustion engine.

The operation modes are more than these 3 described, since in each case the system can be charging the battery or absorbing current from it. All these operation modes alternate without the driver perceiving which is the source of propulsion.

In the events where there is a surplus of energy delivered by the combustion engine, this is used to charge the high voltage battery, which later will be available to deliver its accumulated energy and take

action on every occasion that the combustion engine is powered off.

Events like braking are used to recharge the battery, passing part of the energy of motion into electrical energy.

The efficiency achieved by optimizing the use of the energy produced by the combustion engine is remarkable, and this shows up in a low fuel consumption. Especially in city trips, where consumption is better than in highways; contrary to what happens in conventional vehicles. Therefore, we may easily have a performance of 15 to 20 kilometers per liter in city, equivalent to 35 to 45 miles per gallon.

Anyway, and despite the extraordinary efficiency, the energy is still coming from fuel.

PHEV – Plug-In Hybrid Electric Vehicle Operation

The study of the PHEV – Plug-in hybrid electric vehicle incorporates the possibility of plugging or connecting it to the home electricity grid to charge the higher capacity battery. The vehicle is still a hybrid, but has an additional source of energy that while its load lasts, it will make the system make less use of the combustion engine, optimizing the performance even more during the first miles, trying to optimize in this project the first 20 kilometers.

When this battery is discharged, the vehicle should behave like a conventional HV – Hybrid Vehicle; which means, return automatically to its original condition.

For this study, we used a 2005 Toyota Prius equipped with a high voltage battery pack of higher capacity, and the objective of this study is to investigate its behavior and benefits to prove the plug-in hybrid theory and determine its convenience.

Operating Modes on a HV – Hybrid Vehicle

From investigations conducted, we have determined that nine operating modes - 9 modes - can be distinguished on a hybrid vehicle Toyota Prius or similar. (Series/Parallel System)

These modes can be checked in other hybrids of this manufacturer, as well as in other models where the design of the transmission and motor-generators disposition is similar. This corresponds to two motor generators MG1 and MG2, plus an internal combustion engine coupled to a planetary system.

The operating modes can be easily seen by observing the energy monitor screen available in the same car.



Engine: ICE - Internal Combustion Engine
 Battery: High Voltage Battery
 Electric Motor: MG1 and MG2 (Motor-Generators)

Arrow 1:

Outgoing Arrow: Battery discharge.
 Incoming Arrow: Battery charging.

Arrow 2:

Down: ICE moves to MG1 and charges the battery.

Arrow 3:

To the Left: MG2 moves the vehicle.
 To the Right: The vehicle movement is used to move MG2 and recharge the battery.

Arrow 4:

To the Left: ICE pushes the vehicle.

When a hybrid vehicle is turned on, a light in the panel indicates that it is ready to run. This is usually shown with a READY indicator.



The light turned on does not mean that ICE is running. It indicates only that it is **READY** to run, which means that when you press the accelerator the vehicle will move, previous "gear selection: **D – B o R**"

Status Indicator of the Battery's State of Charge or SOC



The state of charge - SOC - can be seen in the same energy monitor display or in the scanner.



According to the tests, we distinguish 9 modes of operation:

MODE 1: Vehicle stopped, sufficiently charged.

In this mode the vehicle is stopped and there is no need to turn on the ICE to charge the battery.

MODE 2: Vehicle stopped, ICE turned on, moved by MG1 which acts as an engine.

MODE 3: Vehicle stopped charging the battery; the ICE moves the MG1 and charges the battery.



MODE 4: Electric Vehicle in electric motion, this is called EV Mode and occurs at low demand of load.



MODE 5: Average speed, vehicle in motion, charging the battery. ICE pushes the vehicle and through MG1, charges the battery.



MODE 6: High Load, ICE and MG2 move the vehicle and MC1 charges the battery.



MODE 7: Full Throttle, ICE, MG1 and MG2 act as an engine.



MODE 8: Regenerative brake. On raised foot condition or braking MG2 charges the battery (in D gear). If the vehicle is in B gear, MG1 and MG2 charge the battery.



MODE 9: Reverse. MG2 rotates in reverse and the moving backward is electric.

V. PROJECT DEVELOPMENT

The following conclusions are obtained from the observation of the energy monitor and the SOC:

When the vehicle is stationary, ICE starts and begin to charge the high voltage battery. This occurs when the SOC drops below 40% - about two segments – on the indicator display.

When the SOC is close to 50%, ICE stops and stops charging the battery.

This corresponds to MODES 1, 2 and 3.

A direct observation of IB (battery's current intensity) in the scanner shows that the charging rate of the battery, with a stopped vehicle, is around 20 Amp. approximately.

The Prius Battery ECU – hosted on the same HV battery assembly – communicates with the main hybrid

equipments through the CAN bus. This ECU calculates and displays the battery voltage, the current that enters or leaves the battery by current sensor reading, the cells temperatures, the estimates of the State of Charge (SOC) and the maximum load and the discharge current, and other data... [3]

MODES 5, 6 and 7 are displayed when the vehicle is in motion; until the SOC rises, reaching a maximum of just over 80% in highway driving, where ICE is the main propulsion source of the vehicle. In this condition, the display turns green.

Estimating the SOC by the battery ECU is critical, since the hybrid controller maintains the SOC within a 40 to 80% (the lower and upper limits on the graphical display - non-linear) and tries to keep it around 60%. When the SOC is above 60%, the hybrid controller works to discharge the battery by using battery power (and less gasoline), even during normal cruising. This increases to about 30A (~ 6 kW) at 70% and above. When the SOC is below 60%, the hybrid controller operates to charge the battery, making ICE's job even more intense during normal cruising.

When the SOC is below 40%, unpredictable things might happen, and ICE is usually kept on.

For these reasons, if the battery's ECU sees a SOC above 60%, the system will operate with more tendency to discharge the battery. If this extra battery was of a higher capacity, we could achieve a longer driving time in this condition, which we will call PHEV Mode – Plug-In Hybrid Electric Vehicle Mode.

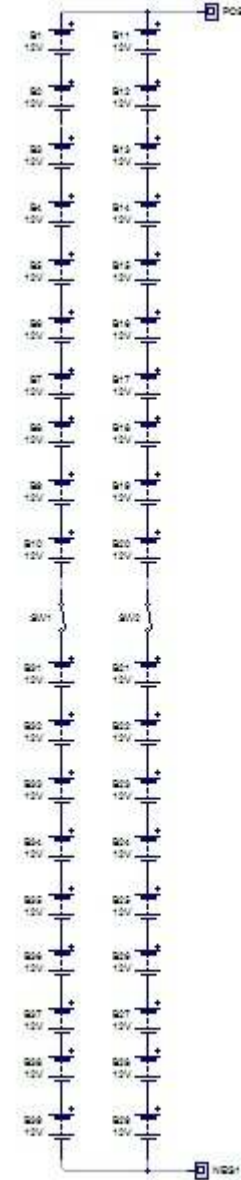
For this project on PHEV, the goal is to maintain a SOC of 60% or above until an extra battery is discharged enough to accept a new recharge or a load of low intensity on long rides.

The regenerative braking current will be left to replace the original battery, trying to keep as long as possible higher state of charges – SOC, preferably between 70-80% and in this way, force to use less gasoline even in EV Mode - only - until the actual state of charge of the battery has come close to its lower limit.

As presumed, this project consist on maintaining a high SOC using an additional battery pack.

In a second stage of this project, it will be also interesting to emulate the reading that the ECU of the battery does about the SOC; so it can make more use of the extra battery and while this happens, the ICE only reloads the original battery.

Unlike other similar projects, the additional battery pack consists of 38 Pab units of 12 Volts 7.2 A/hour in two parallel groups of 19 batteries each. Based on the followings mounting and electric scheme:



The result is a battery of a nominal voltage of 228V. Equal to 38 12-volt batteries in two sets of 19 batteries each.

In the middle of the series, two switches have been placed to disable the packages.
We can see the packages in the following photos:



Photo 1: Lower Battery Pack - Switches



Photo 2: Lower battery pack



Photo 3: : Wiring connection



Photo 4: Top Package

It was decided to place 38 batteries in 2 sets of 19, because in this way - and by the size of the batteries used - there would be no alteration in the trunk space of the original vehicle. Photo 4

Photos 1, 2, 3 and 4 correspond to the assembly of the auxiliary battery pack.

It has been divided in two parts: Lower one with 14 batteries and the upper one with 24 batteries.



Photo 5: Installing the 12 Volts 7.2 Amp/Hour batteries in Series.



Photo 6: Cooling and ventilation fans

The additional battery capacity is equal to 7.2 A/H doubled, because it is composed by two sets of 19 batteries in parallel, resulting equal to 14.4 A/H

The power of this additional battery pack is as follows:

$$P_{ad} = ((19 * 12 \text{ V}) * 7.2 \text{ A/H}) * 2 = 3283 \text{ V*A/H}$$

$$P_{ad} = 3283 \text{ W} = 3.28 \text{ kW}$$

The original battery capacity is 6.5 Amp/ Hour. The original battery power is:

$$P_{ori} = (28 * 7.2 \text{ V}) * 6.5 \text{ A / H} = 1310 \text{ V * A/H}$$

$$P_{ori} = 1310 \text{ W} = 1.31 \text{ KW}$$

The total available power will be = (3.28 + 1.31) KW

$$\text{Total Power} = 4.5 \text{ KW}$$

When a battery is charged, its maximum voltage is approximately 20% more than the rated voltage.

This means:

$$\text{For an additional battery} = 228 * 1.2 = 273 \text{ V}$$

$$\text{And for the original battery} = 201 * 1.2 = 241 \text{ V}$$

Given this situation, the project seeks to charge both batteries – original and additional – when both are connected to the electricity grid for charging. This means, when plugged in.

A simple way would be searched to take both batteries – original & additional – to their maximum state of charge.

The following assembly shows all the proposed hypotheses and must have the following characteristics (See Figure 2):

1. When the vehicle is plugged in, the Charger is activated to load the extra battery at a current of 2 Amp/Hour. By activating the RL4 relay, a load of 0.5 Amp/Hour must be send to the original battery. A Control System will deal with the management of RL4 relay, sending positive to point B when the vehicle is charging.

2. When the vehicle is turned on - after pressing the START button, and once the SMR are coupled - it takes one minute to activate the RL1 relay through the Control system and this relay will allow the current of the auxiliary battery pass through the diodes; with no option to return to the original battery. The premise of placing diodes for their coupling is done with the idea that the auxiliary battery is used but not directly charged by MG1 or MG2 in regenerative

braking. It is considered at this point that the stored charge (while the vehicle was plugged in) should be use but not replenish by the vehicle, which in any case must charge the original battery.

3. Once the START button is triggered and the system is READY, the control system must enable the Relay RL4 which will allow the replacement of the extra battery & the original in long trips, through the R4 & R6 resistors, at a low rate current, less than 1Amp.

All these steps can be accomplished by students, technicians and professionals in the automotive area with the implementation of very simple electronic systems.

The following is an example of appropriate equipment for these practices. It is highlight the CHARGER and the CONTROL.

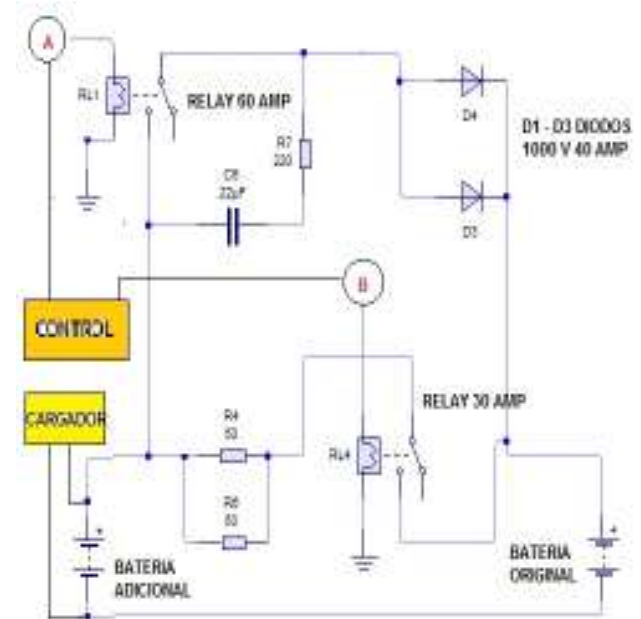


Figure 1: Coupling Circuit

Figure 1 shows the Coupling System.

ADDITIONAL BATTERY: Battery pack added.
ORIGINAL BATTERY: Set of original batteries.

It is important to mention that the connections on the original battery must be performed directly on the cells – specifically on its terminals.

Therefore, this connection remains in parallel before the current sensor and before the SMR relays. Photo7

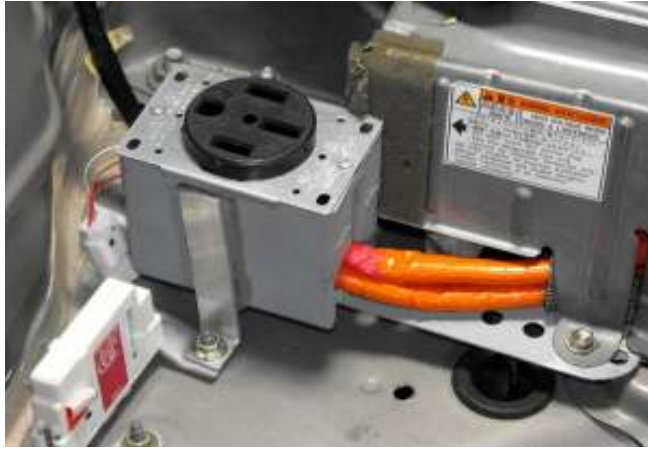


Photo 7: Connector for coupling the additional battery

The charger is one of the most delicate elements. It must charge the original and the additional battery at a constant rate of 2.5 Amp/Hour.

Because it is one of the most sophisticated components in this project, we will develop a special section further on, after the normal tests according to expectations. This charger will explain the Switching Charger development in Photo 8 and the CONTROL System. We used a Switching Charger that works by PWM.



Photo 8: Switching Charger used in the project

VI. PHEV – Plug-In Hybrid Electric Vehicle OPERATION

1 - Connection to the electricity grid - Plug in:

When connecting the vehicle – Photo 9 - the CHARGER is activated from a switch on the inside of the car. An amperemeter displays the current load which has been set 2.5 Amp. Photo 10.



Photo 9: Plug In Connector



Photo 10: Button for recharge and Amp Meter



Photo 11: View of the Assembly Process

By observing Figure 5, the PWM charger is activated and the CONTROL connects the RL4 relay so that 2 Amp. will circulate within the additional battery and 0.5 Amp will do within the original battery, through R4 and R6 resistors.

The assembly is shown in Photo 11.

At the same time, the battery fans should turn on. In our prototype, we have added a power supply which keeps the fan running in the original package, with 5 volts.

According to tests done, the entire set uses a current of 5.4 Amp. from the 110V electricity grid.

Since batteries do not drop below 50% of SOC, with this current rate is enough a charging of 3-5 hours max. to replenish the batteries.

2. Charger Switching OFF:

In this prototype, we have implemented a circuit that stops the charging process when a battery of 12 Volts – composing the additional package - reaches 14.2 Volts. This is performed with a voltage comparator circuit built around an OA Operational Amplifier as a comparator, so the charging process will stop under these circumstances. It is also equipped with a clock on top of the wall power outlet so the charging process will end after 4 hours, by stopping the electrical source supply. This cut should occur on the 110V AC current line.

Safety Standards are incorporated on the vehicle. These are:

- When connected to the electricity grid, the body vehicle remains grounded.

- When this vehicle is in Plug-In Mode, we have placed a relay that opens the interlock from the original battery. This makes it impossible for the vehicle to operate when it is charging. The aim of this last point is to immobilize the car if mistakenly the 110 V cable was not disconnected and there is an intention to drive it.

3. Operation:

When operating the system and pressing the START button, the SMR must be activated normally. The CONTROL should immediately activate the RL4 relay and a minute later the RL1. This minute is the time needed to equalize the slightly differences among voltages and lower the current flow, since the additional battery voltage is above the original battery. This process will be benefited because normally ICE starts a few seconds later after pressing the START button and charges the original battery a little bit more. Please, note that the diodes do not let the current go back, except the resistances that will give a throwback or eventually do a slow charging.

The CONTROL must activate the fans.

After a few minutes, the display will be totally green and the SOC will be close to 80%.



Photo 12: High SOC - State of Charge on the Display

ITEM	Unico	Unico	Analogo
ETC borne distance	0		km
Component Monitor ENA	Enable		
Component Monitor CMPL	Completo		
+B	13.880		V
Running Time from MIL ON	0		min
ETC borne charge	30		min
State of Battery Charge(SOC)	78.5		%
Battery Current	1.79		A
Battery Block Vol-V01	16.91		V
Battery Block Vol-V02	16.94		V

SOC in 78 %

It can be seen how the charge in the additional and original batteries have raised the SOC system. Since the additional battery voltage is greater than the original battery, it will continue to pass electrical current and the SOC will rise further. Especially, if this happens while the vehicle is stopped.

VII. EVALUACION DEL PHEV

To verify the PHEV Operation, several test drives have been performed:

Test 1 - Comparison on a 5 Miles Initial Trip.

In this first test drive, we drove with the extra battery discharged, which means, the system behaved in its original form. The initial SOC was 45%.

After driving these 5 miles, the consumer monitor showed an average consumption of 30.9 MPG, after 15 minutes. Photo 13



Photo 13

Then we proceeded to charge the batteries and we drove with a SOC of 80% for the same test drive. The result were 48.8 MPG. Photo 14



Photo 14

Test 2 - Another test was done optimizing the driving, controlling the energy monitor and using the accelerator pedal looking for the best performance, starting with well charged batteries and 80% of SOC.

Initially, we proceeded to charge the batteries for 3 hours so, when pressing START, the additional battery would let the charge load go to the original battery and increase the SOC.

Here, it can be observed that the SOC is calculated in higher values as long as the tension in the batteries' voltage exceeds the 250Volts. That is, a high SOC can be emulated to the battery's ECU making this one read a high voltage between the ends of the series of batteries.

Starting from a high-load condition, the performance improves after a few minutes and passes load from the additional battery to the original one. Photo 15



Photo 15

In this test it was possible to achieve operational periods of 100 MPG . Photo 16



Photo 16

This image – Photo 16 – shows the vehicle running at 43 Miles/Hour and behaving like an EV – Electric Vehicle.

This test allowed us to drive the vehicle for 30 minutes in a 15-mile test drive obtaining a superior performance at 50 MPG. This consumption is considered amongst the best and lowest studied [4] in this type of vehicle.

VIII - CONCLUSIONS

Based on the tests performed, it is estimated that the PHEV – Plug In Hybrid Electric Vehicle is a very acceptable and rational solution for reducing fuel consumption.

In the test drives done, we have determined that the best performance is obtained when using the vehicle in PHEV Mode; which means, allowing the ICE engine run in combination with the motor-generators. This makes possible the replenish of the additional battery in

just three hours, at a very low charge rate and thereby, achieve a significant reduction in the first kilometers or miles of travel.

Even the PHEV performance is better than in pure EV Mode. In an EV Mode, even if fuel is not used, it will take the SOC of the battery to a very low level, whereby a significant load will be needed to replenish it.

It is estimated that the PHEV solution is the most suitable in all aspects, at least so far, until the 100% electric vehicle becomes more accepted. This will also require changes and upgrades in electricity networks.

The PHEV does not need high currents to be charged because the battery pack is not of high capacity.

After these tests, it is demonstrated that charging the extra battery capacity to 8 KW would increase the PHEV engine over 50 kilometers or 32 miles, which is enough to cover trips in the city burning less fuel in the ICE engine.

An 8 kW battery could be charged at a rate of 10 amps in a short time.

Moreover, the PHEV has unlimited autonomy while having fuel in the tank. The big advantage is that if the driver connects it daily to the electrical grid, the fuel consumption lowers considerably.

This work was developed using a real Hybrid Vehicle: a 2005 Toyota Prius which allowed us to perform the various tests and investigations mentioned.

As part of the project and in this particular case, remains the possibility of emulating the SOC, so the vehicle - when desire - may operate discharging the battery in PHEV Mode and with SOC levels lower than 60% , discharge more the additional battery.

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