DEPARTMENT OF GENERAL SERVICES
OFFICE OF FLEET AND ASSET MANAGEMENT

# PLUG-IN HYBRID ELECTRIC VEHICLE RETROFIT DEMONSTRATION PROJECT

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## FINAL REPORT TO THE CALIFORNIA ENERGY COMMISSION

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Department of General Services
Office of Fleet and Asset Management
1700 National Drive, Sacramento, CA 95834
www.ofa.dgs.ca.gov

# Department of General Services
# Office of Fleet and Asset Management
# Project Team

Rick Shedd, Assistant Chief
Asset Management

Gary Fujii, Assistant Chief
Fleet Operations

Katrina Valentine, Manager
Fleet Operations

Phil Guenther, Analyst
Asset Management

John Musser, Analyst
Asset Management

# Table of Contents


| | |
|---|---|
| **Executive Summary** | **4** |
| **Deployment** | **4** |
| **Operating Costs** | **6** |
| **Vehicles' Days of Use** | **6** |
| **Miles Driven** | **6** |
| **Energy or Fuel Consumption** | **7** |
| **Vehicle Performance** | **7** |
| **Greenhouse Gas Emission Reduction** | **10** |
| **Petroleum Displacement** | **11** |
| **Operator Feedback** | **12** |
| **Malfunctions** | **12** |
| **Meeting State Business Transportation Needs** | **13** |
| **Conclusion** | **13** |

**Executive Summary**

The Department of General Services (DGS) is pleased to present the final report about the Plug-in Hybrid Electric Vehicle (PHEV) Retrofit Project to the California Energy Commission (CEC). In December 2009 fifty 2009 Toyota Prius' were converted to PHEVs and deployed throughout California to measure their ability to produce higher than normal fuel economy results while being operated by a variety of drivers in a host of driving conditions. This project was funded by the CEC and DGS. The federal Department of Energy's Idaho National Laboratory monitored each vehicle through GPS and engine telemetry and provided statistical feedback monthly. A standard 2009 Prius is rated at 46 miles per gallons (mpg) combined city/highway. This demonstration has shown that the partnership between the vehicle operators and the PHEV's plays a crucial role in a PHEV's ability to achieve significant fuel economy. For example, sixteen of the fifty PHEV's achieved better than average fuel economy with seven averaging between 50 and 56 mpg. Several other PHEV's, however, fell below the average mpg ratings for a non-converted Prius as a result of being operated at higher speeds and without regard to battery charging. Those drivers that operated the PHEV's in low-speed intercity conditions and who were vigilant about charging the vehicles' batteries on a daily basis achieved the best results. The less efficient results tended to center around those drivers that exceed the PHEV's speed limitations and operated their vehicles primarily on the internal combustion engine and/or neglected to routinely charge their batteries. Driving the PHEV's above 35 mph nullified the vehicles' ability to operate on battery power as did failing to charge the batteries. The increased weight that the PHEV battery pack added to the vehicle in those cases became a detriment to achieving optimal fuel economy. There were very few problems reported by the PHEV operators other than two Original Equipment Manufacturer (OEM) battery failures and a vehicle accident, both unrelated to PHEV retrofits. Overall, the PHEV demonstration project has confirmed that the technology is able to achieve higher than average fuel economy when the vehicles are driven at lower speeds by operators that charge the batteries frequently.

**Deployment**

Table 1 (see below) lists each PHEV location and the State agency operating the vehicle.

**Table 1**

| Vehicle | Location | Agency |
|---|---|---|
| A1 | Sacramento | Peace Officers Standards and Training |
| A2 | Sacramento | CA Dept. of Education |
| A3 | Sacramento | Dept. of Military |
| A4 | Sacramento | CA Energy Commission |
| A5 | Sacramento | Water Resources Control Board |
| A6 | Los Angeles | Dept. of General Services |
| A7 | Sacramento | Dept. of General Services |
| A8 | Sacramento | State Chief Information Office |
| A9 | Sacramento | State Chief Information Office |
| A10 | San Francisco | SF Bay Conservation |

| | | |
|---|---|---|
| A11 | San Diego | Dept. of Public Health |
| A12 | Sacramento | Dept. of General Services |
| A13 | Concord | Dept. of Industrial Relations |
| A14 | Sacramento | Dept. of General Services |
| A15 | Chico | Dept. of Social Services |
| C16 | Irvine | UC Irvine |
| C17 | Irvine | UC Irvine |
| C18 | Irvine | Dept. of Transportation |
| C19 | Los Angeles | Public Utilities Commission |
| C20 | Santa Ana | Dept. of Industrial Relations |
| C21 | Irvine | UC Irvine |
| C22 | Irvine | UC Irvine |
| C23 | Los Angeles | Public Utilities Commission |
| C24 | Irvine | UC Irvine |
| C25 | Los Angeles | Dept. of Corrections and Rehabilitation |
| A26 | Berkeley | Dept. of Toxic Substances Control |
| A27 | Sacramento | Dept. of Fish & Game Purchased |
| A28 | San Francisco | Public Utilities Commission |
| A29 | Sacramento | Dept. of General Services |
| A30 | San Francisco | Dept of Justice |
| B31 | Chico | Dept. of Social Services |
| B32 | Sacramento | Dept. of General Services |
| B33 | Sacramento | Dept. of General Services |
| B34 | Sacramento | Dept. of General Services |
| B35 | Sacramento | CA Integrated Waste Mgmt. Board |
| B36 | San Diego | Dept. of Fish and Game |
| B37 | Indigo | Dept. of Corrections and Rehabilitation |
| B38 | San Diego | Dept. of Industrial Relations |
| B39 | Fresno | Dept. of Parole Hearings |
| B40 | Sacramento | Dept. of General Services |
| A41 | Richmond | Dept. of Public Health |
| A42 | Richmond | Dept. of Public Health |
| A43 | Sacramento | Dept. of General Services |
| A44 | Sacramento | Dept. of Motor Vehicles |
| A45 | Sacramento | Dept. of General Services |
| B46 | Sacramento | Dept. of Fish & Game |
| B47 | Sacramento | Dept. of General Services |
| B48 | San Francisco | CA Public Utilities Commission |
| B49 | San Francisco | Dept. of General Services |
| B50 | San Francisco | Public Utilities Commission |

**Operating Costs**

- Gasoline

  From December 1, 2009 to March 31, 2011, the PHEVs in this demonstration project averaged $0.066 per mile to operate for a total of $46,924. This total was achieved using the following calculations:
  - 700,807 (total miles) divided by 46 (overall average mpg) = 15,235 gals of fuel
  - 15,235 multiplied by $3.08 (average price of CA gasoline, all grades, from 12/01/09 to 03/31/11)[1] = $46,924.
- Electricity

  From December 1, 2009 to March 31, 2011, the total dollar amount spent on electricity to charge the PHEVs was $2,060. This total was achieved using the following calculation:
  - 15,836 AC kwh (total charging energy) multiplied by .13¢ (average price of electricity, per kwh, in the State of California, from 12/09 to 04/11)[2] = $2,060.

The total amount spent on gasoline and electricity from December 1, 2009 to March 31, 2011 was $48,984.

**Vehicles' Days of Use** [3]

In order to obtain the objectives of this project, it was vital that the PHEVs be driven on a regular basis and under a variety of driving conditions. This is why the DGS crafted the driver selection process to include drivers who would operate the vehicles on a daily, consistent basis. The monitoring of the vehicles' daily use allowed for the re-assignment of vehicles that were being under-utilized. The total number of days of use/average per vehicle is listed below, as are the total number of trips/average per vehicle.

From December 1, 2009 to March 31, 2011:

- Total number of days of use = 11,387
- Average number of days of use per vehicle = 228
- Total number of trips = 51,370
- Average number of trips per vehicle = 1027

**Miles Driven**

The amount of miles driven by each PHEV is as equally important as the days of use and total trips made in determining whether PHEVs are a viable tool in reducing petroleum

[1] U.S. Energy Information Administration
http://tonto.eia.doe.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=mg_tt_ca&f=a
[2] U.S. Energy Information Administration
http://www.eia.doe.gov/cneaf/electricity/epm/table5_6_b.html
[3] See Tables 2 through 5, Information gathered by the Idaho National Laboratory.

consumption and GHGs. Too few miles driven can result in an incomplete or inaccurate conclusion, where as, excessive miles driven can give a more accurate picture of performance. Again, the GPS tracking system allowed the DGS to reassign any vehicles that weren't being driven a satisfactory number of miles. The total number of miles driven and the average miles driven per vehicle are as follows:

From December 1, 2009 to March 31, 2011:

- Total miles driven = 700,807
- Average per vehicle = 14,016
- Average miles driven per vehicle/per month = 876

**Energy or Fuel Consumption**

The GPS tracking devices installed in each PHEV allowed the DGS to monitor the amount of electrical energy each vehicle used. In addition, each individual charging event was also recorded. These factors were crucial in examining the use of each PHEV and in determining whether the vehicle was being used in the most fuel efficient manner. The data shows that regular recharging of the batteries resulted in better performance and a higher overall mpg. The totals and averages for each PHEV are as follows:

From December 1, 2009 to March 31, 2011:

- Total charging energy (AC kwh) = 15,836
- Average charging energy per vehicle per month = 18.9
- Total number of charging events = 5,402
- Average number of charging events per vehicle per month = 6
- Overall gasoline fuel economy (mpg) = 46
- Lowest fuel economy = 28 mpg
- Highest fuel economy = 56 mpg

**Vehicle Performance**

While the 50 vehicles involved in this project achieved an overall mpg average of 46, several vehicles accomplished a much higher average up to 56 mpg. There were some occasions where drivers turned off the battery kit contained within their PHEV. During these times those vehicles did not have an opportunity to operate under the PHEV battery power and functioned solely on the OEM hybrid gasoline/electric mode. There were also vehicles that were not plugged in daily or were driven at higher than optimal speeds. Tables 2-5 on the following pages display average mileage as grouped by performance. DGS provided additional feedback to those drivers that were not charging their PHEVs regularly. In some cases charging intervals increased but some drivers failed to increase their charging practices after being notified repeatedly. This inaction by a subset of the vehicle operators demonstrates the critical relationship between the PHEV and a motivated operator to maximize the fuel economy potential of the vehicle.

Table 2, Idaho National Laboratory Information

| 50 – 56 MPG | | | | | | |
|---|---|---|---|---|---|---|
| VEHICLE | DAYS OF USE | MILES DRIVEN | TRIPS | CHARGING ENERGY (AC kwh) | CHARGING EVENTS | OVERALL MPG |
| DGSB38 | 280 | 32214 | 1580 | 698.9 | 147 | 56 |
| DGSA4 | 321 | 9173 | 2233 | 1396.8 | 521 | 53 |
| DGSA10 | 229 | 10310 | 849 | 786.9 | 223 | 52 |
| DGSA28 | 219 | 8888 | 734 | 712.0 | 181 | 51 |
| DGSA5 | 166 | 9758 | 509 | 460.8 | 166 | 50 |
| DGSA15 | 258 | 21553 | 1122 | 887.9 | 221 | 50 |
| DGSC25 | 192 | 19516 | 761 | 460.4 | 156 | 50 |
| Totals | 1,665 | 111,412 | 7,788 | 5,403.7 | 1,615 | Average mpg = 51.2 |

Table 3, Idaho National Laboratory Information

| 47 – 49 MPG | | | | | | |
|---|---|---|---|---|---|---|
| VEHICLE | DAYS OF USE | MILES DRIVEN | TRIPS | CHARGING ENERGY (AC kwh) | CHARGING EVENTS | OVERALL MPG |
| DGSA2 | 117 | 939 | 360 | 241.0 | 124 | 49 |
| DGSA12 | 146 | 3686 | 469 | 367.2 | 121 | 49 |
| DGSB31 | 261 | 25118 | 1193 | 921.1 | 227 | 49 |
| DGSC20 | 278 | 17825 | 1166 | 1143.9 | 255 | 48 |
| DGSA3 | 282 | 6139 | 785 | 639.2 | 211 | 47 |
| DGSA13[4] | 111 | 3765 | 341 | 0 | 0 | 47 |
| DGSA26 | 183 | 11420 | 613 | 218.8 | 103 | 47 |
| DGSA30 | 188 | 17625 | 626 | 411.7 | 122 | 47 |
| DGSB35 | 213 | 15610 | 811 | 390.4 | 149 | 47 |
| Totals | 1,779 | 102,127 | 6,364 | 4,333.3 | 1,312 | Average mpg = 47.7 |

[4] There were no charging events recorded by this vehicle.

**Table 4, Idaho National Laboratory Information**

| 46 MPG | | | | | | |
|---|---|---|---|---|---|---|
| VEHICLE | DAYS OF USE | MILES DRIVEN | TRIPS | CHARGING ENERGY (AC kwh) | CHARGING EVENTS | OVERALL MPG |
| DGSA1 | 265 | 3192 | 970 | 202.2 | 100 | 46 |
| DGSB32 | 262 | 28073 | 1316 | 243.0 | 80 | 46 |
| DGSB34 | 247 | 27225 | 1282 | 299.0 | 102 | 46 |
| DGSA44 | 261 | 22150 | 1097 | 343.1 | 113 | 46 |
| DGSB46 | 78 | 4961 | 400 | 17.3 | 5 | 46 |
| DGSB49 | 261 | 25362 | 1424 | 448.9 | 147 | 46 |
| Totals | 1,374 | 110,963 | 6,489 | 1,553.5 | 547 | Average mpg = 46 |

**Table 5, Idaho National Laboratory Information**

| 45 MPG & UNDER | | | | | | |
|---|---|---|---|---|---|---|
| VEHICLE | DAYS OF USE | MILES DRIVEN | TRIPS | CHARGING ENERGY (AC kwh) | CHARGING EVENTS | OVERALL MPG |
| DGSA6 | 202 | 3982 | 615 | 117.8 | 49 | 41 |
| DGSA7 | 278 | 37944 | 1487 | 370.3 | 91 | 45 |
| DGSA8 | 252 | 6305 | 1020 | 308.4 | 280 | 45 |
| DGSA9 | 207 | 6354 | 1546 | 13.8 | 11 | 39 |
| DGSA11 | 340 | 16384 | 1257 | 42.1 | 22 | 45 |
| DGSA14 | 226 | 10251 | 926 | 229.8 | 64 | 45 |
| DGSC16 | 226 | 2146 | 1481 | 146.2 | 45 | 31 |
| DGSC17[5] | 26 | 181 | 69 | 24.1 | 13 | 42 |
| DGSC18 | 269 | 20127 | 1529 | 384.5 | 151 | 42 |
| DGSC19 | 284 | 15158 | 1285 | 347.8 | 149 | 45 |
| DGSC21 | 243 | 2445 | 969 | 48.0 | 46 | 32 |
| DGSC22 | 194 | 1688 | 587 | 142.9 | 38 | 35 |
| DGSC23 | 284 | 23639 | 1175 | 500.3 | 165 | 44 |

[5] There were data transmission failures from this vehicle from March 1, 2010 through December 31, 2010.

| | | | | | | |
|---|---|---|---|---|---|---|
| **DGSC24** | **252** | **2017** | **1583** | **111.6** | **59** | **28** |
| **DGSA27** | **291** | **10363** | **883** | **36.7** | **11** | **45** |
| **DGSA29** | **236** | **19978** | **1097** | **145.2** | **76** | **44** |
| **DGSB33** | **277** | **33533** | **1504** | **97.6** | **47** | **45** |
| **DGSB36** | **264** | **12731** | **1221** | **314.2** | **85** | **45** |
| **DGSB37** | **377** | **17773** | **2269** | **57.8** | **15** | **39** |
| **DGSB39** | **125** | **13579** | **436** | **12.5** | **7** | **44** |
| **DGSB40** | **221** | **9294** | **1202** | **76.3** | **61** | **43** |
| **DGSA41** | **174** | **2369** | **486** | **41.7** | **11** | **39** |
| **DGSA42** | **76** | **1944** | **178** | **57.5** | **24** | **45** |
| **DGSA43** | **220** | **21225** | **1123** | **117.0** | **47** | **45** |
| **DGSA45** | **246** | **23642** | **1356** | **212.2** | **83** | **44** |
| **DGSB47** | **207** | **21061** | **1421** | **93.1** | **92** | **45** |
| **DGSB48** | **336** | **18556** | **1362** | **280.4** | **111** | **45** |
| **DGSB50** | **236** | **21640** | **1022** | **215.4** | **75** | **44** |
| **Totals** | **6,569** | **376,309** | **31,089** | **4,545.2** | **1,928** | **Average mpg = 41.8** |

**Greenhouse Gas (GHG) Emission Reduction**

Out of the 50 vehicles, the PHEVs in Table 2 achieved the highest average mpg and the highest reduction of GHG emissions, followed by the vehicles in Table 3. The following charts compare the amount of GHG emissions produced by a standard 2009 Prius to that of a 2009 PHEV Prius.

**Table 2 Vehicles (50-56 mpg)**

| 12/01/09 to 03/31/11 | Total Miles Travelled | Combined MPG | Gallons of Gasoline | $CO_2$/gal[6] | Pounds $CO_2$ |
|---|---|---|---|---|---|
| Standard 2009 Prius | 111,412 | 46 | 2,422 | 19.4 | 46,987 |
| Table 2 PHEVs | 111,412 | 51.2 | 2,176 | 19.4 | 42,215 |

The PHEVs in Table 2 produced 42,215 lbs of $CO_2$, while a standard 2009 Prius driven the same amount of miles would produce 46,987 lbs of $CO_2$. This resulted in a reduction of 4,772 lbs of GHG emissions.

[6] http://www.epa.gov/oms/climate/420f05001.htm

**Table 3 Vehicles (47 – 49 mpg)**

| 12/01/09 to 03/31/11 | Total Miles Travelled | Combined MPG | Gallons of Gasoline | $CO_2$/gal[7] | Pounds $CO_2$ |
|---|---|---|---|---|---|
| Standard 2009 Prius | 102,127 | 46 | 2,220 | 19.4 | 43,071 |
| Table 3 PHEVs | 102,127 | 47.7 | 2,141 | 19.4 | 41,536 |

The PHEVs in Table 3 produced 41,536 lbs of $CO_2$, while a standard 2009 Prius driven the same amount of miles would produce 43,071 lbs of $CO_2$. This resulted in a reduction of 1,535 lbs of GHG emissions.

By capitalizing on the vehicles ability to operate on electric power alone, petroleum consumption was reduced and the vehicles produced less GHG emissions.

**Petroleum Displacement**

The PHEVs in Table 2 and Table 3 both achieved some petroleum displacement. The PHEVs in Table 2 used less gasoline (246 gals.) than a standard 2009 Prius would use over the same amount of miles, while the PHEVs in Table 3 used less fuel (79 gals.) than a standard Prius.

This petroleum displacement can be attributed to the higher mpg achieved by the vehicles, which, conversely, can be accredited to the additional battery power of the PHEVs. Frequent charging of the batteries helped play a role in reducing petroleum consumption. The data shows that there was a much higher fuel economy when the PHEVs were operated in charge depleting mode (58 mpg) than when operated in charge sustaining (44 mpg) modes. Charge depleting mode is where the entire trip had a charged battery pack to utilize while charge sustaining mode refers to when the battery is depleted and the vehicle is not using the battery to move forward. The higher ratings associated with charge depleting mode are what can be expected overall from the PHEV operators who kept the plug-in battery packs fully charged.

The nature in which the vehicles were used was also a factor in achieving a higher mpg. Vehicles that were driven primarily in the city maintained a greater mpg average than those which operated primarily on the highway. Highway speeds trigger the gasoline engine to engage where as the vehicle can operate solely on battery power at lower city speeds.

The vehicles in Tables 4 and 5 did not displace any petroleum due to their lower mpg averages. In addition to the highway driving conditions vs. city driving conditions mentioned above, there are other factors which contributed to a decreased overall mpg averages including the additional weight of the battery kit. The battery kit weighs 200 lbs. and a

[7] http://www.epa.gov/oms/climate/420f05001.htm

standard 2009 Prius has a maximum load capacity (passengers and cargo) of 810 lbs. The battery kit alone reduces the PHEV's maximum load capacity by almost 25% to 610 lbs. Given that the average body weight of a US adult is 179.70 lbs[8] and that the 2009 Prius seats 5 passengers, the PHEV's maximum load capacity could be easily exceeded when transporting a full accompaniment of passengers and related cargo.

In addition, certain operating procedures caused the PHEVs to function in gasoline-only mode. These included the use of the AC/heating units and rapid acceleration by the drivers. These dynamics resulted in decreased overall mpg averages for some vehicles.

**Operator Feedback/Education**

A questionnaire was sent to each of the PHEV users and 17 responses were received. Each user was asked the following questions:

1. What do you like about the PHEV most?
2. Have you come across any issues while operating the PHEV?
3. Have you come across any issues while charging the PHEV?
4. Do you feel that you were educated enough when the garage staff completed the PHEV demonstration for you?
5. Do you have any suggestions to improve the PHEV Program?

The responses were all generally very positive about their initial experiences with the PHEVs. The most common response regarding what they liked most about the PHEV (question 1) was the excellent fuel economy. No other response to the questionnaire repeated in any significant number except that six respondents indicated that they received little or no instructions from the garage staff when picking up the vehicle (question 4).

Driver feedback was provided during this project. The DGS monitored the use of each PHEV and maintained contact with each operator. This allowed the project team to stress the importance of plugging in the vehicles on a regular basis and offered the opportunity to remind drivers of the proper ways to operate the vehicles and keep the battery kits activated. In addition, vehicles that were underutilized were reassigned to drivers that could drive more miles during the demonstration.

**Malfunctions**

The following were the malfunctions reported since deployment of the PHEVs:

- Two had dead OEM batteries that needed replacing
- Two had telemetry problems (one had a loose wire, the other needed a new part)
- One did not hold an electric charge and was returned to the battery pack installer for repair/replacement
- Two were involved in accidents (one minor, one major and both needed to have their battery packs removed before body work could be done)

[8] Centers for Disease Control and Prevention
http://www.cdc.gov/nchs/fastats/bodymeas.htm

- Two were returned by their operators due to the inability to operate the heater without shutting off the battery.
- One required service on its electric plug connector

**Meeting State Business Transportation Needs**
The business needs of each potential PHEV assignment were examined prior to assigning the vehicle to ensure that there were no requirements that could not be met by a standard mid-side sedan. The PHEVs in this project met the State's business needs based upon the operator feedback.

**Conclusion**
All 50 PHEV's were deployed across California and served in a variety of government business uses. Operators were educated on proper driving techniques and encouraged to plug-in the PHEV's at every opportunity. A final interview was conducted with the drivers who achieved the highest fuel economy. There were several factors that the vehicle operators shared in common in achieving high mpg rates. All of the operators responded that their vehicles were used primarily by one driver. This is evidence that an operator practicing conservative driving habits can obtain a greater mpg. When asked whether the vehicles were driven primarily in the city or on the highway, the answer was unanimously "the city". This shows that the PHEV technology is best utilized at lower speeds. All of the operators responded that they made a conscientious effort to charge the vehicles on a daily basis. Again, the PHEV technology is best exploited when the vehicle is fully charged. Vehicle #DGSA2 achieved slightly less than 1,000 miles on a single tank of gas. Vehicle #DGSB38 had the highest overall mpg (56mpg) and also logged the third highest miles driven (32,214). Both of these drivers operated their vehicles at lower speeds and practiced regular charging. The lackluster fuel economy of the underperforming vehicles can be attributed to three conditions: undesirable driving habits such as rapid acceleration; inadequate battery charging; and, driving at higher speeds primarily on highways. This project has demonstrated that if the retrofitted PHEVs are utilized for low speed city driving and correct driving habits are employed, including keeping the batteries frequently charged, the PHEV technology is a viable method that the State could use to reduce its petroleum consumption and cut its greenhouse gas emissions.

The ability for the State to monitor PHEV performance on a large scale is problematic. This demonstration project pointed out that it is vital to monitor and provide drivers with feedback about their driving and charging habits. Even when this occurs it is difficult to change driving or charging habits that are detrimental to achieving higher than average fuel economy. The added weight that the PHEV's additional battery pack adds to a standard hybrid cannot overcome drivers that operate mostly on highways and fail to charge their vehicles' batteries with constant regularity. For State agencies to monitor the driving and charging habits of their staff, and then to manage changes where necessary would be challenging at best. While the PHEV technology has shown that it can outperform a standard hybrid's fuel economy ratings, it can only do so in the hands of conscience drivers operating in specific conditions. This may prove limiting to widespread adoption at the state level. However, should speed limitations be overcome in future PHEV offerings, this concern would become moot.