# Final Report

## Development and Evaluation of a Plug-in HEV with Vehicle-to-Grid Power Flow

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## 1. Abstract

Plug-in hybrid vehicles connect to the power grid while parked so they can operate on electricity from the grid as well as on petroleum-based fuel. This distinguishes them in a fundamental way from the plugless hybrid vehicles currently produced or planned by automakers which rely 100% on petroleum-based fuel. A plug-in hybrid can reduce emissions three ways, zero-emission driving, elimination of cold starts, and clean generation of electricity. The contractor designed, built, and tested an innovative plug-in-hybrid power system and installed it in a vehicle to demonstrate these capabilities.

The project vehicle provides 35 miles of battery-only range with highway performance capability so operation on grid electricity can eliminate operating emissions and one or more cold engine starts per day. The project vehicle can re-charge its traction battery from the grid in less than one hour. The hybrid power unit in the project vehicle can sustain battery charge at highway speeds providing long distance travel unconstrained by battery range. The hybrid power unit in the project vehicle can also generate electricity while the vehicle is parked. In this stationary mode, the hybrid power unit can operate on gasoline stored on the vehicle or on low-pressure natural gas piped to the vehicle from the gas main. While parked, the power generated can be exported as alternating current electricity either to the grid or to stand-alone loads. Interactions between the vehicle and the grid, including power export, can be controlled from remote locations via wireless internet connection. These capabilities are demonstrated in stationary testing and 6000 miles of on-road use.

## 2. Executive Summary

Plug-in hybrids differ from the hybrid vehicles now in production, such as the Toyota Prius, in that they can connect to the power grid and use grid-supplied energy as well as energy from onboard storage of petroleum-based fuel such as gasoline or diesel. In this sense, plug-in hybrids are true dual-fuel or alternative fuel vehicles because grid electricity is produced mostly from non-petroleum energy resources including natural gas, hydroelectric, wind, solar, geothermal, coal, and nuclear.

AC Propulsion has designed and developed electric propulsion systems for battery electric vehicles that combine high performance, high efficiency and a bi-directional power interface that allows electric power to flow in to and out of the vehicle. Electric vehicles are range-constrained and this limits, to some degree, their commercial potential. The goal of this project was to develop a hybrid vehicle that would combine characteristics of a pure electric vehicle with the unconstrained range of a conventional vehicle. This was accomplished by developing a compatible auxiliary power unit including a purpose designed alternator (APU), integrating the propulsion system and APU into a vehicle, and demonstrating emission reduction and commercialization potential.

The plug-in hybrid developed for this project demonstrates four capabilities that differentiate it from plugless hybrids as well as from conventional vehicles. The project vehicle can:

1. Provide full performance and 35-mile range with electric propulsion only
2. Substitute grid energy in place of petroleum energy
3. Serve as a distributed electric power resource
4. Use natural gas for generation of electric power

As a result of the project car’s ability to utilize three fuels, electricity, gasoline, and natural gas, it has been referred to as a “tri-fuel” hybrid.

Based on the results of testing conducted under this project, these capabilities can reduce vehicle emissions. Importantly, these capabilities demonstrate potential economic and energy benefits that can assist the commercialization of plug-in hybrids that is necessary to realize actual air quality improvement.

### The Vehicle Technology

A Volkswagen Jetta was converted to electric propulsion using a 100 kW drive system and an eight kWh lead-acid battery. The battery charger is integrated with the drive system and operates on grid power at 100 to 250 VAC. Charge power up to 20 kW is possible. The charger operates bi-directionally, allowing conversion of electricity from the high-voltage DC bus to 60 Hz AC current at up to 15 kW. The AC power can be fed to the grid, or to other external loads. A custom-built auxiliary power unit (APU) using a small automobile engine was designed and developed specifically for this project. The APU feeds the high-voltage bus with up to 30 kW of DC current. This power level allows charge-sustaining operation at any speed up to 80 mph. The APU is series-connected, it never drives the wheels directly. The APU can operate as a generation source, with its output fed from the vehicle to external loads including local or large area power grids. Equipped with a wireless internet connection and control algorithms developed under a separate CARB research contract, the power system in the project vehicle can be controlled remotely to provide grid support functions.

Development of the APU was a major element of this project. The emission-controlled engine drives a light-weight, high-efficiency alternator designed and developed to meet the power, noise, and weight requirements of this application. The engine burns gasoline when it operates while the vehicle is being driven. The engine is also equipped to operate on low-pressure natural gas, and the vehicle is equipped with a gas connection that allows the APU to draw fuel directly from gas mains while it is parked. Connecting the project vehicle to an offboard gas source allows it to generate electric power continuously without depleting the onboard fuel supply or discharging the battery.

### Vehicle Capabilities

The project vehicle was built to demonstrate usability, functionality, and convenience in daily use as well as the unique capabilities of plug-in hybrids. Driveability, simple controls, and seamless operation of the hybrid system all received development effort under this project. Vehicle features include cruise control, power brakes, regenerative braking, power steering, traction control, and bi-directional power. The vehicle has been tested and evaluated for emissions, efficiency, audible noise, and power quality in stationary operation; and emissions, range, fuel economy, acceleration, and driveability in mobile operation.

The completed vehicle provides 35 miles of range on batteries. The battery charger allows charging from 110V, 208V, or 240V outlets. A standard 50A electric outlet allows charging in one hour. Fuel economy of 30 to 35 mpg gives gasoline range of over 500 miles using gasoline. Up to 30 kW DC electric power is produced by the APU. This power level allows charge sustaining operation at up to 80 mph. Top speed is governed at 85 mph. Acceleration from 0-60 mph can be achieved in 8.5 seconds.

The project vehicle demonstrates full functionality as a replacement for a conventional car that may be used locally or for long-distance travel. (Loss of storage capacity, which was sacrificed for packaging expediency, is not a compromise inherent to plug-in hybrids).

### Results

In dynamometer tests conducted by CARB at their El Monte, CA test facility, the project vehicle produced emission levels near current ULEV standards over the standard UDDS test cycle. In separate tests, emissions were measured at steady state operating points, and these brake-specific emission rates, measured in gms/kWhr are very low as shown in Table 1, below, and repeated in Table 16 in Section 5. It is interesting to note that, because APU operation is de-coupled to some degree from the actual driving cycle, the UDDS emissions can be estimated just by multiplying the brake specific emmisions rates times the energy required by the vehicle over the driving cycle. Such theoretical calculations suggest that SULEV emission levels over the UDDS should be achievable, and that the relatively high emissions measured over the actual UDDS test are the result of poor cold-start emission control.

The measured brake specific emissions rates also can predict the emissions from the APU when it is used as a stationary power source. Comparing the brake specific emissions from the project APU to emissions from other power generating sources shows that the project APU operates with significantly lower emissions than microturbines or conventional gensets, neither of which benefit from the sophisticated and highly developed emission control systems that are typical of current automotive engines.

**Table 1. Project Car APU Operating Data, Stationary Mode, Gasoline Fuel**

| | **Fuel gal/kWh** | **Efficiency** | **NMHC gm/kWh** | **CO gm/kWh** | **NOx gm/kWh** |
|---|---|---|---|---|---|
| Project Car APU 5 kW (gasoline) | 0.148 | 20.5% | 0.011 | 0.254 | 0.154 |
| Project Car APU 15 kW (gasoline) | 0.116 | 26.0% | 0.003 | 0.232 | 0.048 |
| Capstone Microturbine 30 kW [1] (natural gas, max output) | NA | NA | 0.078 | 0.603 | 0.223 |
| US Generation Avg[1] (fossil fuel) | NA | NA | NA | NA | 2.54 |
| CA Generation Avg [2] (fossil fuel) | NA | NA | NA | NA | 0.20 |
| CARB DG Standard[3] 2003 | NA | NA | 0.45 | 2.7 | 0.23 |
| CARB DG Standard[3] 2007 | NA | NA | 0.009 | 0.045 | 0.03 |

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[1] source: Capstone White Paper March 6, 2000

[2] source: CEC Environmental Performance Report, 2001

[3] Distributed Generation Certification Program, Sec. 94203 California Code of Regulations

## 3. Introduction

The California Air Resources Board (CARB) promulgated a zero emission vehicle (ZEV) mandate in 1990 as part of an extensive regulatory effort to reduce the negative effects of automobiles on air quality. ZEVs were then, and now still are seen as electrically-propelled vehicles that use electricity from batteries or fuel cells. In the past year, the ZEV mandate regulation has been modified to allow other vehicle technologies to earn ZEV credits because true ZEV technology in the form of battery electric vehicles (BEVs) or fuel cell electric vehicles (FCEVs) has not yet been commercialized.

One development leading to the recent changes in the regulations governing the ZEV mandate is the reduction of tailpipe emissions from conventional vehicles. The state of the art in tailpipe emission controls has produced such low emissions that some question whether true ZEVs are necessary to meet air quality goals. That question depends in part on factors including levels of upstream emissions from refining and refueling, correlation between real world emissions and test emissions, and the maintainability and durability of the emission control systems over time, and it is beyond the scope of this report. No matter how low the emissions from conventional vehicles, however, ZEVs still promise an unambiguous reduction in emissions from vehicles, if they can be commercialized.

At the same time as improvements in vehicle emission control technology were reducing the impact of automobiles on air quality, the effects of automobile use on a variety of energy-related factors were assuming increasing importance in national and international policy considerations. Petroleum depletion, greenhouse gas emissions, energy security, balance of trade, and national security are all affected by the huge amount of energy consumed by the automotive fleet as a whole. Automotive energetics, the sources and uses of energy for automobiles, now joins emissions as a major consideration in the design and development of future automobile propulsion systems.

One non-ZEV vehicle technology that can earn ZEV credits under the current CARB regulations is hybrid drive which combines elements of electric propulsion with conventional vehicles. Hybrid vehicle systems can be designed different ways, and the different configurations have different capabilities with respect to their effects on emissions, on energetics, and on the long term commercialization potential of electric propulsion. Hybrid vehicle technology is likely to play an increasingly important role in automaker efforts to improve the energetics of their products. The purpose of this project is to demonstrate innovative hybrid vehicle technologies that can improve on the early generation hybrids now in production.

### 3.1 The Connected Car

A major distinction among different types of hybrid vehicles is whether or not they can plug into the grid. The hybrid vehicles available today from Honda and Toyota, and those planned for production by GM, Ford, and Chrysler do not plug in. They use gasoline only. This approach does not allow the vehicle to use electricity from the grid, and neither does it reduce emissions significantly below those of the cleanest conventional vehicles. The primary advantage of plugless hybrids is improved fuel economy, an important factor in automotive energetics.

Among hybrid designs, plugless hybrids deviate least from the engineering designs and customer expectations of conventional vehicles. Presumably, this is one factor in the universal adoption of plugless designs by automakers so far. They are conservative in their design directions and have good reason to be. Nonetheless, the use of energy from the grid to substitute, in part, for petroleum as a transportation fuel, offers potentially compelling benefits in the realms of emissions, energetics, and economics. Demonstration of these benefits is an important step in overcoming barriers to the commercialization of connected cars – cars that plug in to the grid.

### 3.2 Distributed Energy Resources

Besides their ability to substitute grid electricity for petroleum, connected cars can, by way of their connection to the grid, play a potentially significant role in an evolving concept known as distributed energy resources. DER includes non-centralized, relatively small sources of electric power including home solar arrays, generation for commercial buildings, wind and other non-conventional power sources. The development of rules, standards, and regulations, as well as economic and business models for DER is an intensely active area of endeavor that involves both the public and private sector.

The role of automobiles in the DER arena is yet to be defined, but the potential is huge simply by virtue of the size of the automobile fleet. A small percentage of the fleet could still represent a significant power and energy resource. The economic potential is also intriguing because the automobile represents an un-utilized asset most of the day while it is parked. If that asset can be put to good use while it is parked it may be possible to create an economic benefit. If an asset whose cost is allocated to transportation can be used for another purpose entirely, as a distributed energy resource, then the capital cost associated with DER can be decreased.

Prior studies have demonstrated the technical and economic potential of vehicle-to-grid (V2G) functions using battery electric cars to source and sink electric power in modes that do not involve a net discharge of the vehicle traction battery. In this project, the vehicle will be capable of net generation of electricity using the onboard APU. The project vehicle is the first hybrid vehicle to be demonstrated with V2G functionality.

### 3.3 Commercialization

The project realizes an appealing concept, the charge-sustaining, plug-in hybrid, and applies design and technology innovations to improve its commercial viability. The vehicle can feed electricity from its integrated power system to offboard loads including power equipment, buildings, other cars, and the grid. The power flow can be controlled by the user or remotely via wireless internet connection, opening up many opportunities for the vehicle to serve as a distributed energy resource. This new capability, available only with connected cars, may clear a path to commercialization of connected cars as its potential is developed in the near to mid term.

A grid-connected hybrid vehicle with bi-directional grid interface has the potential to produce electric power with lower emissions than other available fossil-fueled DERs. An automobile-based powerplant is exceptionally clean because the engine is built to comply with automotive emission standards. The engine in the project car, typical of modern emission controlled engines, operating in steady state, produces almost no exhaust emissions. Automakers now claim that in some modes, the exhaust coming out the tailepipe is actually cleaner than the air going into the engine.

As a distributed generation resource, a vehicle would have low capital costs due to both automotive economies of scale and splitting the cost allocation between transportation and energy. It would be located where the demand is – at work sites during the day and at residences in the evening. The vehicle power would be highly available – the average automobile is idle for 23 hours a day. Finally, it would be affordable. The incremental costs specific to power generation on the project vehicle are under $300.

The keys to commercialization of electric propulsion are desirability and affordability. This project has developed a plug-in hybrid that endeavors to demonstrate both.

## 4. Design, Integration, and Development

The design, integration, and development of the project vehicle included nine milestone tasks in three areas of work, 1) installation of the electric propulsion system and battery, 2) design and construction of the APU, and 3) installation and integration of the APU in the vehicle. Of these three, the design and construction of the APU represented the project's most significant development effort and had a major impact on the performance of the complete vehicle.

The architecture of the project vehicle is essentially that of a pure battery EV with the addition of the APU – a gasoline-fueled generator that feeds DC electricity directly into the high-voltage battery bus. The propulsion is pure electric with no mechanical connection between the gasoline engine and the wheels.

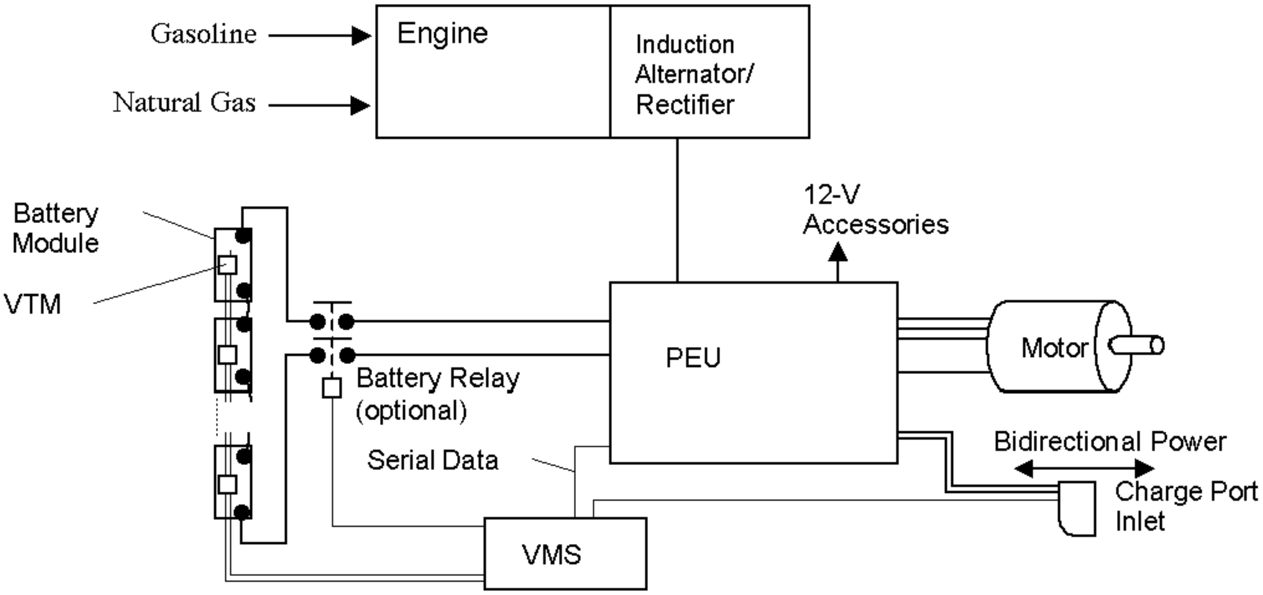

Figure 1. Power System Architecture

The location and orientation of all major components in the vehicle conversion was determined and documented in layout drawings showing the overall vehicle package. The electric propulsion system including inverter, charger, 12V DC power supply, motor and transaxle are located at the front of the vehicle in the space formerly occupied by the engine and transaxle. The traction battery is located in a specially constructed enclosure occupying the floorpan tunnel and space under the front seats. The gasoline tank remains in its original location under the rear seat.

The hybrid power unit including combustion engine, alternator, alternator controller, cooling system and exhaust system is located at the rear of the car, in an enclosure behind the rear seat. For this vehicle, the entire trunk space was dedicated to housing the APU. This eliminates use of that volume for carrying anything and also eliminates the spare tire stowage. These compromises are not inherent in the design of plug-in hybrids, but rather result from choices made for project expedience. As discussed below, the engine selected for the APU power source could not be packaged in a horizontal orientation which would have been more space efficient. A vehicle designed as a plug-in hybrid could achieve improved packaging.

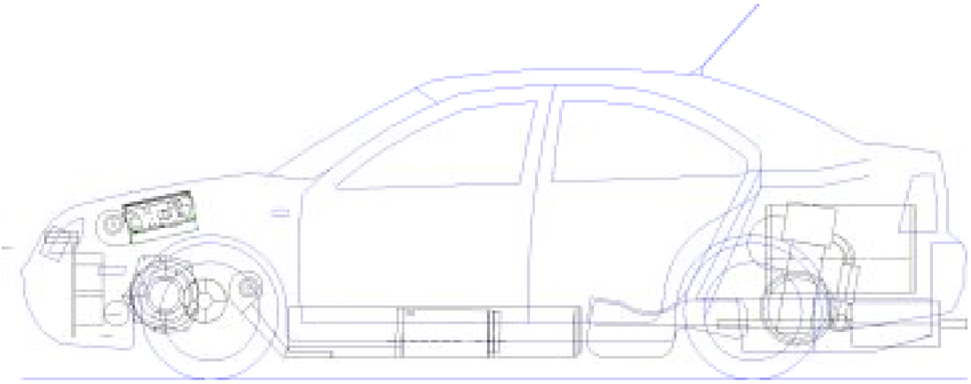

**Figure 2. Plug-in Hybrid Component Packaging**

## 4.1 Propulsion and Battery System

The Volkswagen Jetta base vehicle was disassembled including removal of the engine, transmission, exhaust system and all interior hardware and trim. Following practice already developed by AC Propulsion for conversion of Volkswagen Golf-platform vehicles, the propulsion system was installed in the space formerly occupied by the engine. The standard transmission was modified to operate as a fixed-ratio speed reducer. The traction motor was bolted directly to the transmission, and the entire assembly was installed in the original transmission location using slightly modified VW mounts. A fabricated bracket supports the transmission and accepts the torque reaction loads. The integrated power electronics unit (PEU) mounts on this same bracket. For this project, the AC150 Gen 2 PEU is installed because it provides the bi-directional power interface required for V2G functions. The AC150 was electronically “detuned” to 100 kW peak power consistent with the current capability of the 8-kWh battery pack. Electrically-powered accessories were installed to provide power brakes, power steering, and air conditioning. Normally the charge inlet is located in the fuel filler opening. For this project, that location was retained for gasoline refueling, so the charge inlet was positioned in the front grille behind a fabricated cover door.

The Panasonic HEV 1225 PbA battery was selected for the project vehicle on the basis of low cost and good power-to-energy ratio. The battery layout is adapted from designs successfully used in battery electric vehicles. For this vehicle, the battery is approximately half the size and weight, and each module is half as long as a typical full size EV battery. This allows the entire 29-module pack to fit in the central tunnel and under the front seats without any intrusion into the fuel tank area and minimal intrusion in the passenger compartment. Battery mass is centralized, low, and as far forward in the vehicle as possible. Access for battery installation and service is from inside the vehicle.

**Figure 3. Electric Drive System Installed**

The battery box was fabricated outside the vehicle. Then a section of the vehicle floorpan was cut out and the battery box welded in. The seats mount to the top of the battery box, and inner seat belts anchors and the parking brake mechanism attach to side of battery box tunnel. For these reasons, the box is built as a structural element of the vehicle. Box design, material selection, and installation procedures were specified according to this requirement.

Within the battery box, the battery installation includes the battery location and hold down system, the battery management system (BMS) and wiring arness, and power cables. The battery modules are located in individual trays that are an integral part of the battery box. The trays secure each module against horizontal movement. Hold-down rods attached to the trays prevent vertical movement of the modules. A battery monitor module and equalizer is located on top of each battery. These monitors are wired to each battery and connected by a communications harness. The battery contactor is located under the hood in the in the power electronics unit.

**Figure 4. Battery Installed**

The battery cooling system is an integral part of the battery box. A blower mounted near the vehicle firewall provides air to a duct and plenum system at the bottom of the battery box. The air is distributed to the battery modules and flows up between the modules along their long dimension. Locator plates and baffles ensure good heat transfer along the full length of each module. The plenum inlet duct is designed with adjustable dividers to allow some tuning of airflow among the right, left, and center sections of the battery box. The plenum has been sized for the required airflow provided by a 12V centrifugal blower.

Once the propulsion system and battery system were installed, the vehicle was driven more than 200 miles as a battery EV to determine that the power system and battery system performed satisfactorily. With about half the battery of a typical full function EV, the Panasonic modules work harder. This testing demonstrated brisk acceleration and strong regenerative braking capacity even at close to full SOC. The vehicle charging tested satisfactorily over three discharge/charge cycles using the bi-directional charger to discharge into the grid and then re-charge the battery from the grid. The charging is controlled by the battery management system and the vehicle management system. In both drive and charge modes, battery temperatures have stayed in equilibrium with <4 ºC between hottest and coldest module.

## 4.2 Auxiliary Power Unit

The auxiliary power unit comprises the thermal engine, alternator and inverter, and ancillary systems and is a critical element in achieving hybrid performance objectives including emissions, efficiency, and long-distance capability.

### APU Engine

The APU design began with a survey of automotive engine technology to identify candidate powerplants for the hybrid generator. The survey looked at engines in the 0.5 to 1.5 liter displacement range and considered power requirements, low-emissions potential, packaging considerations, and availability. Selection criteria included adequate sustainable cruising speed, acceptable levels of noise and vibration in both highway and stationary operation, attractive size and weight dimensions, high efficiency, and high expectation that emissions can be controlled to low levels under the planned operating conditions.

Based on vehicle simulations and performance objectives, operating targets of at least 30 kW electric power output and maximum engine speed of 3600 rpm were established. The power and speed targets effectively eliminated from consideration engines below 1.2 liter displacement. This precluded the use of engines from the Japanese mini-car class (0.6 – 0.8 l), many of which offered excellent packaging dimensions. It also eliminates most motorcycle and recreational engines (outboard marine, personal watercraft, snowmobile), most of which would have also presented significant emission control challenges.

A large number of automotive engines in the 1.2 to 1.5 liter displacement range are available, although mostly in vehicles not sold in the United States. Engines that have been recently launched as all new or major redesigns were sought on the assumption that such engines will embody the most up-to-date emission control and efficiency enhancing technology. The search narrowed to four engine families, Volkswagen Lupo, Toyota Prius/Echo, Honda Insight/Civic Hybrid, and the new Ford (Europe) Fiesta. The Volkswagen

Lupo 1.4 liter engine was selected for the hybrid power unit on the basis of availability and access to parts and technical information as a result of Volkswagen of America's support of this project.

**Table 2. VW Lupo 1.4 L Engine Specifications**

| | |
|---|---|
| Engine type | 4-cylinder inline engine with aluminum block and head, dual overhead cams, 4 valves/cyl, roller cam followers |
| Displacement | 1390 cc, 86 $in^3$ |
| Bore x stroke | 76.5 x 75.6 mm, 3.01 x 2.98 in |
| Fuel/emission system | Port fuel injection with lambda control |
| Power | 55 kW @ 5000 rpm |
| Torque | 126 Nm @ 3800 rpm |

Three versions of the Lupo engine were considered, the direct injection FSI engine, and two power levels of the 1.4L conventional engine. The FSI requires low-sulfur gasoline that is not reliably available in California, and the direct injection feature would not be beneficial at the relatively high-load operating points planned for this application. The 1.4L engine is available in two power ratings. Because the lower-power 55kW-rated version is biased toward torque at lower rpm it may provide somewhat better efficiency in the intended application. This is the engine selected for the project.

To qualify and characterize the engine early in the program, baseline emission testing was conducted on the complete Lupo vehicle as received from Volkswagen. The tests were conducted at the CARB emission test facility in El Monte, CA. A matrix of test points was selected corresponding to the expected range of the engine operation as an APU powerplant. These points ranged from 5 to 35 kW and from 1000 to 3600 rpm. The test points were translated into road load and road speed points so that the chassis dyno in CARB's emission test facility could be properly programmed for the steady-state tests. Appropriate dynamometer road load curves were developed, and the tests were run at steady speed ranging from 18 to 63 mph. All tests were conducted in fourth gear.

The baseline tests accomplished three objectives. First they confirmed that the engine and emission system in the donor vehicle can operate satisfactorily at the projected operating points of the APU. Second, the baseline data provides benchmarks of emissions versus APU control settings for comparing to changes and developments to the emission control system as installed in the project vehicle. Third, the tests demonstrated that ULEV or possibly even SULEV emissions are achievable during continuous operation.

The greatest concern prior to the baseline tests was whether the engine calibration would control emissions in continuous operation at high load levels. The tests showed that the planned operating output can be achieved at engine operating points that do not require fuel enrichment or open-loop operation. According to the OBD II system monitor, none of the test points resulted in open-loop operation. At four very high relative torque points, elevated CO measurements indicated that some controlled fuel enrichment may have been occurring. With this data, the operating curve of the APU was specified to avoid operation where enrichment occurs.

## APU Alternator

APU Alternator specifications were established based on selected engine speed and power targets. The alternator was specified as a 16-pole design with a stack diameter of 308 mm and rotor diameter of 254 mm. The 16-pole design allows for small back iron area to minimize iron losses and allow compact end turns. This design offers both high efficiency and the versatility to operate in high power for on-road use and lower power for stationary use. The lamination stack length is 77 mm. The in-house designs for laminations and the rotor bars were fabricated by outside vendors.

Special tooling was developed for stator winding. A copper/iron rotor, 246 mm in diameter, was fabricated at AC Propulsion. Rotor construction requires using a proprietary brazing technique that has been well-established in production of AC Propulsion traction motors. The larger diameter rotor for the APU alternator required construction of a new, larger brazing furnace. The rotor construction with low-back-iron laminations optimizes efficiency in this application.

The alternator is designed to mount directly to the back of the APU engine. An adapter plate secures the stator and alternator housing to the engine block. The shaftless rotor bolts directly to a crankshaft-mounted adapter. At the opposite end of the rotor, a steel hub rotates in a roller bearing mounted in the housing endplate. Both the rotor and alternator housing are electrically isolated from the engine/chassis using proprietary mounting hardware. The isolation prevents safety hazards during grid-connected operation.

**Figure 5. Stator and Rotor**

**Figure 6. APU Complete**

The alternator stator and housing were constructed following AC Propulsion practice. The air-cooling system uses a hub-mounted centrifugal fan blowing into an axial duct surrounding the alternator housing. The duct directs air through copper cooling fins bonded to the housing. The heated air is directed out the duct at the engine-end of the alternator. The overall dimensions of the alternator are 345 mm diameter by 250 mm long.

The alternator was dyno-tested to establish an operating calibration and power and efficiency data, before being assembled to the engine for initial APU testing.

In order to assure proper operation of the engine and all emission control systems after removal from the donor VW Lupo, all related components and wiring were also removed from the Lupo during disassembly. This included cooling, emissions, fuel, evaporative, and exhaust systems. All sensors and wiring, including anti-theft interlocks required to start the engine were retained with the engine. The complete engine system was mounted on a test stand that provided a close approximation to the orientation of systems and components of the APU as it will be installed in the project vehicle. Unneeded wiring and hardware from the Lupo were removed from the APU engine on the test stand. All systems checked out, including the OBD II communications port that allows real-time monitoring of engine operating parameters.

Upon completion of the dyno testing, the alternator was mounted to the engine on the APU test stand using a dummy housing without a stator. Preliminary tests without the stator using an auxiliary starting system consisting of a high torque DC motor and a belt drive to the engine crankshaft pulley demonstrated that the alternator to crankshaft coupling can withstand the loads imposed by engine reciprocation and torque pulsation.

The alternator was removed and re-assembled to the engine using the real stator and the complete APU assembly was installed on the test stand. The inverter and an artificial load were wired up to allow a full range of operating conditions to be simulated on the test stand. The artificial load was provided by an electric vehicle battery pack and a 20 kW dissipative load. Since the EV pack is bigger than the pack in the project vehicle, it allows longer run durations before the battery must be discharged. The APU was successfully operated under manual control over the intended range of speed and power outputs. Engine start using the alternator was successful. Engine speed and output were controlled by simulating the throttle pedal signal. With this level of control established, the APU was ready for control system and emission control calibration and testing. A matrix of operating points was established to span the expected range of operation and to serve as a base for emissions and efficiency tests.

**Table 3. APU Operating Points**

| RPM | Manifold Pressure “Hg abs | kW |
|---|---|---|
| 1850 | 16.0 | 5 |
| 2340 | 18.8 | 10 |
| 2700 | 21.4 | 15 |
| 2970 | 24.0 | 20 |
| 3135 | 26.2 | 25 |

| | | |
|---|---|---|
| 3280 | 28.5 | 30 |

### APU Control

A versatile APU control system was developed that provided automatic control of the APU with user selectable operating modes and programmable control parameters. The critical control parameter is battery bus voltage, the APU cannot be allowed to operate if module or pack voltage exceeds operating limits established by the battery manufacturer. Accordingly, the APU limits output according to bus voltage. A fast response is necessary to quickly reduce output in deference to regenerative braking current.

The overall control scheme provides for APU operation along a pre-selected operating curve of engine speeds and loads according to battery state of charge and battery current. The control algorithm results in APU output that follows load over time but is smoothed and averaged resulting in gradual engine transients. APU operation below about 5 kW is inefficient and is not allowed under normal operating conditions.

The APU control is complex but it provides a simple driver interface with two operating modes, EV mode and HEV mode. These are described below in Section 5.1. In stationary generation, the APU operates under the same control algorithms whether under manual or remote control. In generation mode, for example, the vehicle battery responds to generation demand, and the APU operates to sustain battery SOC within a narrow range.

## 4.3 Vehicle Integration and Test

The APU system includes the combustion engine, the alternator and inverter, and the associated sub-systems for cooling, fuel supply, and exhaust along with the wiring and plumbing associated with controls, electric power, fuel, and coolant. System installation required attention to noise and heat insulation between the APU compartment at the rear of the car and the passenger cabin.

The APU is mounted to substructures permanently attached to the primary vehicle structure. The APU is supported on three rubber isolation mounts bolted directly to the APU substructure. The APU is mounted transversely with the engine on the right side of the vehicle. This orients the engine induction system to the rear of the vehicle allowing access and clearance for the natural gas fuel components that are added to the engine.

Based on the results of baseline emission testing of the Lupo engine as originally installed in the donor Lupo, the Lupo exhaust system components including the light-off catalyst, main catalyst, and muffler have been retained. An exhaust system incorporating these components and fitting below the APU compartment was fabricated from stainless steel tubing. Extensive heat shielding reflects exhaust system radiant heat away from the APU.

A firewall between the APU compartment and passenger cabin is fashioned from glass fiber composite molded into the vehicle body. Felt, foam, and reflective materials applied to the firewall provide sound and heat insulation. The APU inverter is located in a pocket formed by the firewall between the back seat and the APU compartment. Ducts in the firewall allow inlet and exhaust of cooling air for the inverter supplied by a blower drawing air from a vent in the right rear fender.

Air supply for cooling and induction is ducted from an opening in the left rear fender to the coolant radiator, alternator fan inlet, and engine inlet. Air exhausting from the radiator and alternator exits the APU compartment at the rear of the car assuring positive ventilation of the APU compartment during both mobile and stationary operation. Gasoline for the APU is supplied from the original Jetta fuel tank in its original location. The Jetta fuel vapor canister is used in its original location at the rear of the vehicle.

**Figure 7. APU Installed**

For stationary operation, a low-pressure natural gas fuel system was installed. The system included a quick-connect inlet at the front of the vehicle, a supply hose running to the rear of the vehicle, two safety shut-off valves, a pressure regulator, an electronically controlled gas mixer, and closed-loop controller for the mixer.

**Figure 8. Natural Gas Fuel System Components**

The controller adjusts fuel flow to maintain a stoichiometric mixture based on signals from an exhaust gas oxygen sensor mounted in the exhaust manifold. The mixer mounts directly to the engine throttle body. The natural gas supply always comes from offboard the vehicle. No natural gas is stored on the vehicle. Safety shutoff valves assure that gas does not flow when the APU is not running.

After 10 days of shakedown testing, the vehicle was driven to Sacramento and back in late March, 2003. This 1100 mile round trip confirmed the basic functionality, reliability, and long range capability of the vehicle. The completed vehicle invited comparison to production hybrids such as the Toyota Prius, and the comparison reveals that although the modes of operation of the project car and the Prius differ significantly, the hardware content of the two vehicles is remarkably similar.

**Table 4. Plug-in Hybrid vs Prius**

| Component | Project Car Plug-in Hybrid | 2004 Prius |
|---|---|---|
| Engine | 1.4 liter, 35 kW | 1.5 liter, 56 kW |
| Generator | 30 kW | 20 kW (est) |
| Traction Motor | 110 kW | 50 kW |
| Transmission | Fixed ratio | Planetary |
| Battery | PbA, 8 kWh, 650 lb | NiMH, 2 kWh, 100 lb (est) |
| Charger | 20 kW, bidirectional | none |
| Charge port | conductive | none |

The primary differences are in the sizing and interactions of the components. Although the battery weight difference is significant, that reflects the different chemistries as much as the different energy capacity. Although detailed cost analysis is not a part of this project, it appears that the design cost of these two different approached should not be dissimilar.

## Testing and Validation

The completed hybrid vehicle was delivered to CARB's El Monte emission test lab on April 23 for a series of dyno tests to measure emissions, fuel consumption, and all-electric range. Over two testing periods, April 23 – May 9, and May 19 – May 22, CARB staff conducted both standard tests and a series of special tests.

The purpose of the testing was threefold. First, the tests were intended to characterize the performance of the vehicle in order to provide quantitative comparative evaluation of its capabilities. Second, the test results provide operating data to help optimize automatic control algorithms for emissions and efficiency. Third, the tests provide some insight into the potential air quality benefit of plug-in hybrids and how regulations may be constructed so as to encourage that potential.

Jeff Wong of ARB supervised the tests, all of which were conducted in Cell 7 at CARB's El Monte test facility. The standard tests were conducted according to CARB testing protocol. The special tests were variations of standard tests intended to provide information about specific modes of operation. Where possible standard testing procedures were observed.

**Figure 9. Vehicle Testing at CARB – El Monte**

Three different standard tests were conducted.

All Electric Range-Urban Test – This test is conducted without running the APU. The vehicle is pre-conditioned and fully charged the day before the test then soaked at ambient (laboratory temperature) overnight. For the test, the vehicle is operated over the UDDS starting cold. Successive UDDS cycles are driven with a 10-minute soak between each cycle. For this test, the driver was instructed to stop the test when an audible low-battery-voltage warning sounded continuously for 3 seconds.

All Electric Range-Highway Test – This test is conducted without running the APU. The vehicle is pre-conditioned and fully charged the day before the test then soaked at ambient (laboratory temperature) overnight. For the test, the vehicle is operated over two HFEDS with a 15-second key-on stop between tests and a 10-minute soak after every two tests. For this test, the driver was instructed to stop the test when an audible low-battery-voltage warning sounded continuously for 3 seconds.

Federal Test Procedure (FTP) Emission Test – This test is conducted over the UDDS with special provisions for hybrid vehicles. The test comprises a cold start test and a hot start test following the cold start test after a 10-minute soak. At the completion of the test, the battery state of charge must exceed the state of charge at the start of test according to specified state of charge net change tolerances. For this test, the auxiliary power unit (APU) was controlled with a LabView interface from a laptop computer, but the test was conducted so as to portray fully automatic control of the APU with an algorithm intended to benefit fuel efficiency.

In addition, three special tests were designed and conducted to generate specific data for the purposes of design and analysis.

> Steady-state emissions – The APU was operated at continuous output levels of 5, 10, 15, 20, 25, and 30 kW of DC power. The vehicle was driven at a steady speed on the chassis dyno at a load setting that would approximately offset the APU power output. Emissions were sampled for 300 seconds starting with the APU in stabilized operation at the specified power level. Actual electric power output was measured to allow calculation of specific emissions and fuel economy in terms of grams/kWh and gallons/kWh respectively.
>
> APU Transient Tests – The APU controls itself in order to limit voltage on the battery bus. For example, when the APU is operating and the driver decelerates, regenerative braking generates current that flows to the battery causing bus voltage to increase. In order to prevent excessive voltage but still allow maximum recapture of braking energy the APU reduces power according to a predetermined algorithm. These APU transients may occur even though the APU is operating in an essentially steady output mode. When battery SOC is relatively high, these transients occur more often. In order to characterize and roughly quantify the effect of transients on emissions, UDDS 505 cycles (1st bag test) were run at 80% SOC and at 20% SOC. At the high SOC, the APU had to assert control frequently to avoid excessive voltage. At the low SOC, such control transients were much less frequent.
>
> APU “Cool-start” Tests – In some types of driving, the APU may shut down for extended periods while the vehicle is being driven. A series of tests was designed and conducted to measure the effect of different length shut downs on emissions. The APU was started and operated at 15 kW steady output for 300 seconds after sitting off for periods of 5, 10, 20, 30, 40, and 60 minutes. Emissions samples were taken for each 300 second test including the APU start up.

With the assistance of CARB technical staff, working around the laboratory’s testing schedule, all of these tests were completed over a one-month period.

**Table 5. Emission Testing Schedule**

| Date | Test | Comments |
|---|---|---|
| April 23, 2003 | All electric range - urban | Valid test |
| April 24, 2003 | All electric range - highway | Valid test |
| April 30, 2003 | UDDS | Valid test |
| April 30, 2003 | Steady state emissions tests | Valid tests |
| May 2, 2003 | UDDS | Invalid test, test equipment malfunction |
| May 8, 2003 | Transient tests | Valid tests |
| May 9, 2003 | UDDS | Invalid test, APU malfunction |
| May 9, 2003 | “Cool-start” tests | Valid tests |
| May 21, 2003 | UDDS | Valid test |

| | | |
|---|---|---|
| May 22, 2003 | UDDS | Valid test, APU operation timed to capture cold start emissions in first bag of second cycle |

## 5. Results

Since the project vehicle was first driven as a hybrid on March 12, 2003, it has covered more than 6000 miles, including two Los Angeles to San Francisco area round trips, dynamometer testing, and stationary generation testing. In September, the vehicle competed in the Michelin Challenge Bibendum in Sonoma, California where it successfully completed against other environmental vehicles in a series of tests measuring its performance, emissions, and efficiency. Most recently, it was demonstrated in the Ride-and-Drive at EVS-20, November 15-19, in Long Beach California. At the Ride and Drive more than 75 attendees drove the car over a 1.3 mile course. The testing and extended usage allow vehicle operation to be characterized in both quantitative and qualitative terms.

### 5.1 Vehicle Operation

Although the operating logic of the project vehicle is complex, the control system seen by the driver is simple. It is designed to provide the same level of autonomous operation as a conventional vehicle. At the same time it is designed to encourage utilization of energy taken from the grid and to allow drivers some level of control over operating modes according to their preferences.

The vehicle operates in one of two modes, EV mode or HEV mode. The vehicle starts in EV mode each time the key is turned on. In EV mode, battery SOC is allowed to descend to a low-SOC threshold level. After that threshold level is reached, the control system automatically switches to HEV mode. Allowing for relatively deep discharges allows operation of 25 to 35 miles without use of the APU when starting with a fully charged battery. In HEV mode, the APU automatically operates according to a sustaining-SOC threshold of about 60%. The APU control algorithm sets APU on/off status and power level based on power consumption and battery SOC. The control algorithm has been tuned to keep the APU operating in a high-efficiency, low-emission envelope, and to reduce noise vibration and harshness (NVH) annoyance by limiting on/off cycle frequency and avoiding high-power operation at low speed.

A selector switch allows the driver to assert control authority for certain conditions if so desired. The driver may select HEV mode at any time. If SOC is below the sustaining-SOC threshold, the APU will start immediately and operate at high power to restore SOC to the threshold level. Once the threshold is reached, APU power will drop to a level that sustains SOC. If SOC is above the threshold, the APU will not start until the threshold is reached. Manual selection of HEV is never required, but it may be desirable for example when starting a long highway trip so as to avoid a deep battery discharge.

The driver may also select EV mode at any time. When EV mode is selected the APU will turn off if it is operating, and it will not turn on until the low-SOC threshold is reached. At the low-SOC threshold, the controller will automatically re-select HEV mode. Some drivers may prefer to select EV mode at the end of a trip when the remaining distance to a known charging opportunity is within the range of the remaining battery charge, or when in heavy traffic so as to enjoy the smooth and quiet characteristics of pure electric traction.

The project vehicle is equipped with one additional manually selectable control mode for the APU. When operating in EV mode the driver can manually control the APU. A rotary knob can turn on the APU and set the power level. This allows the driver to adjust APU power level to any acceptable level as simply as adjusting stereo volume. The power level setting always defaults to zero (APU off) when EV mode is selected even if the power control knob is not in the zero position. In this case, manual power control can be initiated by returning the control knob to zero for two seconds and then selecting the desired power level. The manual APU output control is intended for tuning, testing, and demonstration. In a commercial product, the customer value of this mode would have to be weighed against its potential effects on emissions.

A comprehensive user interface for APU operation is provided although the system will operate completely automatically without any user intervention. The user interface includes a selector switch to toggle between EV mode and HEV mode, EV and HEV mode indicator lights in the instrument panel, a rotary knob for manual control of APU output, an analog APU current meter, an analog APU temperature meter, and a selectable 4-line LCD screen that displays APU current, APU power, APU rpm, battery voltage, temperatures for APU engine, alternator, and inverter.

The other vehicle operating controls are similar to the controls for other AC Propulsion electric vehicles. Push buttons allow for selection of for forward, reverse, and neutral. The accelerator pedal sends a torque command to the system controller. The torque command can be for positive torque (acceleration) or negative torque (deceleration) allowing the accelerator pedal to control both tractive effort and regenerative braking. A slide lever allows the driver to adjust control sensitivity of the regenerative braking. Instrumentation includes speedometer, ammeter, voltmeter, an energy status LCD display, and a system control LCD display. The energy status display includes information about battery state of charge, energy consumption, speed, and distance. The system control display includes battery, charge control, and power system information.

### 5.2 Vehicle Driving Performance

Compared to the base vehicle, a Jetta 2.0L with automatic transmission, the project vehicle demonstrates equivalent or superior overall performance. At the EVS-20 Ride and Drive, most drivers offered spontaneous, unsolicited comments in praise of the acceleration performance and the regenerative braking. A sampling of those comments is included here:

> "I like this one, you have full accel and decel on one pedal"
>
> "very good acceleration, quite good, actually better than my Passat"
>
> "I do like the strong regen(erative braking). I didn't think I would. You really have much more control"
>
> "really amazing power, no shifting"
>
> "wow, wow, wow-wow-wow, it really goes. I'm amazed, wow, like a race car, unbelievable"
>
> "It's definitely the strongest EV I've ever driven"
>
> "it just drives beautifully"

The test drives were all conducted in HEV mode. Typically, the drive would start with the APU off and it would then turn on automatically about half way along the test route. Because the route was conducted on city streets with low overall power demand, the APU would restore SOC sufficiently and then turn off again. Most drivers did notice the APU once it was running, but, over the short duration of the test drive did not suggest that it was objectionable.

Observed performance for the project vehicle is compared to that of a standard Jetta below.

**Table 6. Performance and Fuel Economy Comparison.**

| | Project Vehicle | VW Jetta 2.0L auto. |
|---|---|---|
| 0-60 mph acceleration | 8.7 secs [1] | 12.0 secs [2] |
| Top Speed | 85 mph [3] | >100 mph |
| City fuel economy | 27 mpg [4] | 23 mpg [5] |
| Highway fuel economy | 34 mpg [1] | 29 mpg [5] |

1 measured
2 *Consumers Reports* test data
3 Governed by control system
4 CARB test result depreciated 10%
5 EPA label value

More detailed results of performance, energy consumption and emissions testing are included in the following sections.

### 5.2.1. Energy Consumption

Test data characterize energy consumption of the project vehicle in driving mode and of the APU in steady state operation.

1. Driving energy consumption is the electrical energy drawn from the battery bus to power the traction drive and accessory loads. It depends on the type of driving, the drive system efficiency, and the vehicle characteristics.

**Table 7. Driving Energy Consumption**

| | | |
|---|---|---|
| Dyno tests at CARB: | Urban cycle (UDDS) | 213 Wh/mi |
| | Highway cycle | 195 Wh/mi |
| On-road: | Highway loop – 65 mph avg | 210 Wh/mi |
| | Pomona Loop (suburban) – 22 mph avg | 220 Wh/mi |
| | Mountain loop – Cajon Pass, Mount Baldy | 240 Wh/mi |

2. Miles per gallon measurement must include allowance for changes in battery state of charge. In long distance drives, the fuel effects of battery energy are minimized.

**Table 8. Fuel Economy**

| | | |
|---|---|---|
| Dyno tests at CARB: | Urban cycle (UDDS) | 30.5 mpg |
| On-road: | Highway trip – 65 mph avg | 35 mpg |

3. Generation energy consumption is the fuel energy consumed by the APU to generate electricity into the battery bus. It depends on the power level and APU characteristics, but is not directly affected by the type of driving cycle or vehicle characteristics.

**Table 9. APU Energy Consumption**
**Steady-state Power Tests at CARB**

| Nominal Power Output (kW DC electric) | Energy Consumption gal/kWh | Overall Efficiency | Calculated Engine Thermal Efficiency [1] |
|---|---|---|---|
| 5 kW | 0.148 | 20.5% | 22.7% |
| 10 kW | 0.126 | 23.9% | 26.6% |
| 15 kW | 0.116 | 26.0% | 28.9% |
| 20 kW | 0.111 | 27.2% | 30.2% |
| 25 kW | 0.109 | 27.6% | 30.7% |
| 30 kW | 0.109 | 27.8% | 30.9% |

[1] based on measured average 90% APU electrical efficiency

### 5.2.2. Driving Range

Driving range in EV mode was measured over urban and highway driving cycles on the CARB dyno, and in real world on-road driving.

With the 15.5 gallon fuel tank capacity, total driving range in HEV mode can be calculated from dynamometer energy consumption data. Real world driving range was observed on the San Dimas to Sacramento road trip.

**Table 10. Driving Range**

| Mode and Driving Cycle | Driving Range |
|---|---|
| EV – Urban Electric (dyno) | 39.3 miles |
| EV – Highway Electric (dyno) | 38.0 miles |
| EV – City/Highway (observed) | 30 - 45 miles [1] |
| HEV – Highway (observed) | 547 miles [2] |

[1] EV range can vary greatly depending on the type of driving as the low-SOC threshold is approached.

[2] Highway driving at 65 mph until tank is empty plus additional 20 miles on battery.

### 5.2.3. Charge Sustaining Power

Charge sustaining operation means that the APU can sustain battery SOC indefinitely. The maximum charge sustaining speed occurs when road load equals the maximum output of the APU. For the project vehicle, the APU operating at a governed maximum of 30 kW provides enough power to sustain the battery charge at 80 mph.

Long distance trips and mountain driving confirm that 30 kW is adequate power for charge sustaining operation of the project vehicle under all but the most extreme conditions. Data from different on road driving conditions gives approximate values for power requirements of different speeds and driving conditions.

**Table 11. Observed Average Power Requirements For Project Vehicle** [1]

| Type of driving | Avg. Speed | Approximate APU Avg. Power Reqmt |
|---|---|---|
| Stop and go – city | 15 mph | 4 kW [2] |
| Stop and go – freeway | 25 mph | 6 kW [2] |
| Suburban | 25 mph | 6 kW |
| Freeway, level | 65 mph | 16 kW |
| Freeway, level | 80 mph | 27 kW |
| Freeway, 6% grade | 70 mph | 60 kW [3] |

[1] These values are based on observations while driving and should be considered as estimates only because variations in conditions including speed, terrain, traffic, and weather can greatly affect power requirement.

[2] Higher battery SOC can reduce average delivered power of the APU in stop and go traffic because the APU will back off when regen braking occurs.

[3] Climbing a 6% grade at 70 mph is an extreme condition. Starting with the battery at 60% SOC, the 30 kW deficit could be maintained for about seven minutes, about eight miles, before the battery charge was depleted.

The high-speed hill-climbing case shown above suggests one justification for allowing manual control of the APU. Approaching a long high-speed grade, the driver could manually set the APU for maximum output so as to “fill up” the battery before the ascent to give more battery reserve and allow a higher-speed up the grade.

On the major Interstate routes there are only a few grades that would require this degree of forethought. The well-known Grapevine Grade on southbound I5 in California sustains a 6% grade for only about five miles. The rest of the Grapevine ascent is much less steep. It will not be far in the future before GPS-based navigation systems will be able to anticipate battery SOC requirements and provide input for more sophisticated control of APU based on route and elevation data.

### 5.2.4. Emissions

In typical operation, the APU operates in an almost steady state mode, gradually changing output to match the average power requirement of the vehicle. When average power requirements change, for example, when moving from surface streets to freeway, the APU gradually adjusts power output so as to maintain battery SOC.

In the general case, vehicle emissions can be estimated by multiplying brake specific emission levels measured at steady operation, by the energy consumption of the vehicle as shown in the following equation.

brake specific emissions x vehicle energy consumption = vehicle emissions

or

grams /kWh x kWh/mi = gm/mi

Brake specific emissions data for the APU were generated on the CARB dyno by setting the APU to a fixed output and operating the vehicle on the dyno at a speed and load setting that matched the APU output.

**Table 12. Steady-state APU Emissions**
**CARB Test Results from the Project Vehicle**

| Nominal Power Output (kW DC electric) | NMHC gm/kWh | CO gm/kWh | NOx gm/kWh |
|---|---|---|---|
| 5 kW | 0.011 | 0.254 | 0.154 |
| 10 kW | 0.001 | 0.441 | 0.305 |
| 15 kW | 0.003 | 0.232 | 0.048 |
| 20 kW | 0.000 | 0.250 | 0.049 |
| 25 kW | 0.008 | 0.987 | 0.007 |
| 30 kW | 0.048 | 4.015 | 0.022 |

**Table 13. Calculated Driving Emissions**
**Based on CARB Steady-state APU EmissionsTest Results**
**And Project Vehicle UDDS Energy Consumption of 213 Wh/mi**

| Nominal Power Output (kW DC electric) | NMHC gm/mi | CO gm/mi | NOx gm/mi |
|---|---|---|---|
| 5 kW | 0.0023 | 0.0540 | 0.0329 |
| 10 kW | 0.0002 | 0.0940 | 0.0650 |
| 15 kW | 0.0007 | 0.0494 | 0.0103 |
| 20 kW | 0.0000 | 0.0533 | 0.0105 |
| 25 kW | 0.0017 | 0.2102 | 0.0014 |
| 30 kW | 0.0102 | 0.8551 | 0.0047 |
| ULEV I standard | 0.0400 | 1.700 | 0.2000 |
| SULEV standard | 0.0100 | 1.000 | 0.0200 |

The sweet spot for emissions is with the APU operating in the range of 15 kW to 20 kW, but this data portrays emission levels low enough to meet the ULEV I standard at any power level. These calculations also show the dependence of actual emissions on energy consumption. A vehicle with the identical APU, but with energy consumption of 250 Wh/mi, would have a calculated emission rate 17% higher.

Actual emissions differ from emission rates based on steady state test results because of cold starts and transients. Actual UDDS emissions were measured with the intact Volkswagen Lupo donor vehicle before it was disassembled, as well as on the completed project vehicle. The initial Lupo tests indicated that although it was calibrated to European emission standards, the control levels were low enough to achieve ULEV II emission levels. The same engine and emission control system produced significantly higher emissions when tested as an APU in the project vehicle, as shown below. The project vehicle met ULEV I standards for CO and NOx, but not for NMHC.

**Table 14. Actual UDDS Emissions Measured at CARB**

| | NMHC gm/mi | CO gm/mi | NOx gm/mi |
|---|---|---|---|
| Project Vehicle, 3-test avg | 0.0740 | 0.218 | 0.0780 |
| VW Lupo base vehicle, 2-test avg | 0.0280 | 0.200 | 0.0330 |
| ULEV I standard | 0.0400 | 1.700 | 0.2000 |
| ULEV II standard | 0.0400 | 1.700 | 0.0500 |
| SULEV standard | 0.0100 | 1.000 | 0.0200 |

The higher emissions for the project vehicle are probably due to two factors. First, reflecting the actual weight difference between the cars, the project car tests were run at 4000 pound test weight setting versus a 2500 pound test weight setting for the Lupo test. Second, the cold start strategy for the APU resulted in a higher load sooner than would occur in a conventional car and this may have caused high emissions before catalyst light off.

To investigate the effect of cold start on overall emissions, a UDDS test was driven on the dyno, but the sampling was controlled manually. During the UDDS, the APU typically starts at 200 seconds. In this test, the first sample bag was timed to capture only the first 100 seconds of APU operation, representing the cold start and warm up only. The emissions from the first 100 seconds represented 96% of NMHC, 57% of CO, and 76% of NOx emissions for the entire test. If the cold start emissions could be reduced to a level equivalent to 100 secs of warmed up operation, with an electrically heated catalyst (EHC) for example, the project vehicle emissions would approach SULEV levels as shown below.

**Table 15. Projected Emissions without Cold Start**

| | NMHC gm/mi | CO gm/mi | NOx gm/mi |
|---|---|---|---|

| | | | |
|---|---|---|---|
| Project Vehicle, EHC simulation | 0.003 | 0.083 | 0.022 |
| SULEV standard | 0.0100 | 1.000 | 0.0200 |

Already, the cleanest cars are able to greatly reduce cold start emissions, although at some cost in hardware and complexity. It may be that a series hybrid with engine operation de-coupled from vehicle operation offers additional ways to reduce cold start emissions.

Related to cold start emissions are emissions from stop/start operation when the APU is cycling on and off during driving. A series of test was run to identify the maximum off time that did not result in elevated emissions upon restart. With the project car on the dyno operating at a steady speed, the APU was turned on after a ten minute off period and operated at 15 kW output for 6 minutes and emissions were collected. The test was repeated with increasing off periods of 20, 30, 40, and 60 minutes. The results, shown graphically below, suggest that emissions do not increase significantly when off time is kept below 30 minutes.

Normally, in HEV mode, the APU operates continuously once it is started to restore SOC. In very low speed operation, the APU may cycle on and off every two to three minutes, so APU off time in HEV mode should not be a factor in the emissions of the project car. If the car is operated in EV mode until the APU comes on, then the APU operates at high power to restore the battery to 60 % SOC, and this cycle is repeated, then the off time could lead to higher than necessary emissions.

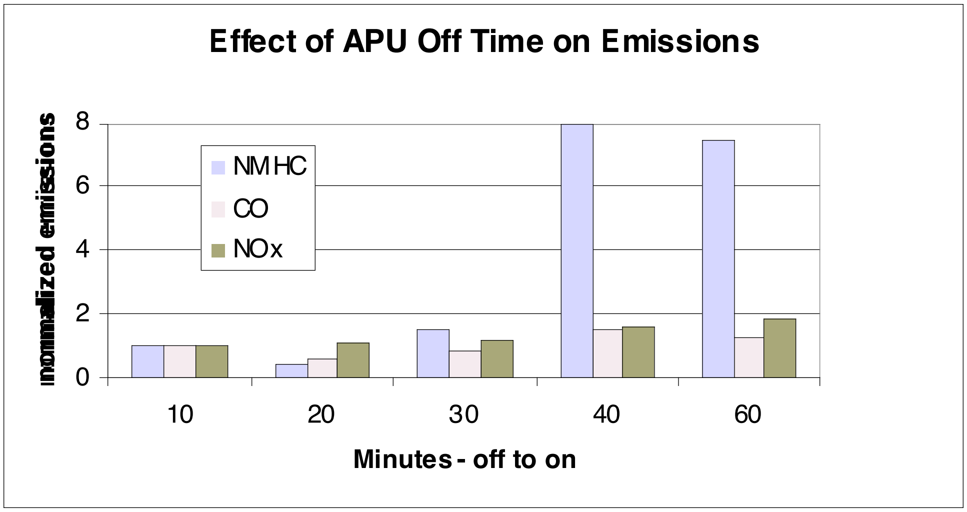

Figure 10. Effect of APU Off Time

Engine transients can effect emissions and efficiency, and transients are determined in part by battery SOC. At high SOC, battery voltage is higher, and the maximum voltage can be approached more readily under regenerative braking. In this situation, the APU may reduce output each time the vehicle decelerates.

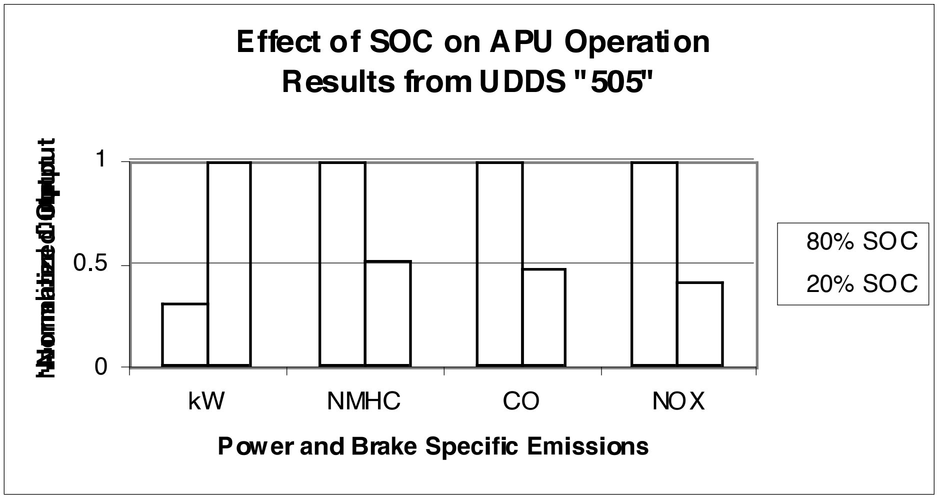

Figure 11. Effect of Battery SOC

To evaluate this effect, a series of “hot 505” dyno cycles was run, two with the battery at 80% SOC at the start of the cycle, and two at 20% SOC. The hot 505 is the first 505 seconds of the UDDS but run with a warmed up engine. For these tests, the APU output was set at 15 kW. The results, graphed in normalized form, show that emissions can essentially double in urban driving, if the APU is run at high battery SOC.

Interestingly, although the APU was set at 15 kW for all test, its effective output in the high SOC tests was reduced by about 70% because it was limited by battery voltage so frequently. The actual APU control algorithm reduces APU output as the SOC threshold is approached, so this test may tend to exaggerate the effect. It does suggest that a possible refinement to the control algorithm might be to allow SOC to drop in stop and go traffic and then to restore higher SOC once higher average speed is restored.

## 5.3 Vehicle-to-Grid Performance

The potential benefits of vehicle-to-grid (V2G) have been projected, and discussed in the literature. A CARB-sponsored V2G Demonstration Project (Contract number 01-313) conducted by AC Propulsion and completed in October 2002, concluded that “ ...integrating electric drive vehicles with the electric grid is technically practical and the concept has the potential to create an income stream that offsets a portion of vehicle ownership costs.” The vehicle demonstrated in that project was a pure battery EV with an 18 kWh battery.

The grid-connected hybrid developed for this project includes the same V2G capabilities demonstrated in the V2G Demonstration Project, but uses an 8kWh battery combined with an onboard generation source. As a result, the project vehicle maintains capability for providing grid ancillary services such as regulation, and has the additional capability of supplying a substantial level of electric power for grid support or other external loads. This energy can be supplied while still preserving adequate range capability.

### 5.3.1. Distributed Generation

Distributed generation was demonstrated feeding the grid and feeding external loads. In grid-tied operation, the vehicle sends a constant, commanded level of power into the grid. Feeding external loads, the vehicle acts as an on-site generator responding to power demand. Either way, the vehicle operates as if in HEV mode, but the drive system converts battery energy to AC electric power rather than to vehicle propulsion. The APU controller responds as it would under driving conditions – it controls battery SOC to a threshold level, and cycles on and off as required by the current drawn from the battery to provide AC power.

For grid-connected operation, the vehicle has a discharge mode that allows a fixed discharge current to be selected. When the vehicle is plugged in (as if to charge), and the discharge mode is enabled, the vehicle discharges at a fixed power level into the grid, matching the grid frequency and voltage. Safety systems similar to those employed with small distributed generation systems prevent the vehicle from feeding power into the grid when the grid power itself is down. Using a standard Level 2 charge port and Avcon connector, the maximum discharge current is 30A. Higher current levels are possible using higher-rated cable and connectors.

For stand-alone loads, such as providing backup power, work site power, or vehicle to vehicle charging, the vehicle has a UPS (uninterruptible power supply) mode that allows the vehicle to serve as a generator capable of responding to fluctuating current demands, supplying continuous power up to 15 kW and peak power up to 20 kW. For backup power, this means the vehicle can easily support the power needs of a house including turn-on loads for refrigerators, air conditioners and pumps. As a work site generator, the vehicle can provide the power to operate welders, air compressors and other machinery. A unique application, vehicle-to-vehicle charging, was demonstrated. The HEV served as a mobile charge station and fed AC electricity directly to the charging inlet of any EV equipped with an onboard charger. Operating at 15 kW, the HEV charged an EV at the rate of almost one mile per minute. In 10 minutes the stranded EV received enough energy to travel about 10 miles.

Operating as a stationary generator in discharge or UPS modes, the APU operates in essentially the same manner as when the vehicle is being driven. The vehicle traction battery supplies energy directly to support the load, and the APU operates at an appropriate power level and cycles on and off as necessary to sustain battery SOC. Discharge and UPS modes are enabled only when the vehicle is stationary. Discharge mode also requires connection to line. In both stationary modes, the APU output is limited to 15 kW for thermal and noise reasons.

Data for the project vehicle operating in generation mode are identical to the steady state data from dynamometer testing at CARB. They are summarized below and compared to micro turbines, utilities, and current ARB standards for small off-road engines.

**Table 16. Project Car APU Operating Data, Stationary Mode, Gasoline Fuel**

| | Fuel gal/kWh | Efficiency | NMHC gm/kWh | CO gm/kWh | NOx gm/kWh |
|---|---|---|---|---|---|
| Project Car APU 5 kW (gasoline) | 0.148 | 20.5% | 0.011 | 0.254 | 0.154 |
| Project Car APU 15 kW (gasoline) | 0.116 | 26.0% | 0.003 | 0.232 | 0.048 |
| Capstone Microturbine 30 kW [1] (natural gas, max output) | NA | NA | 0.078 | 0.603 | 0.223 |
| US Generation Avg[1] (fossil fuel) | NA | NA | NA | NA | 2.54 |
| CA Generation Avg[2] (fossil fuel) | NA | NA | NA | NA | 0.20 |
| CARB DG Standard[3] 2003 | NA | NA | 0.45 | 2.7 | 0.23 |
| CARB DG Standard[3] 2007 | NA | NA | 0.009 | 0.045 | 0.03 |

[1] source: Capstone White Paper March 6, 2000
[2] source: CEC Environmental Performance Report, 2001
[3] Distributed Generation Certification Program, Sec. 94203 California Code of Regulations

The brake specific emissions from the APU are significantly lower than for other typical generation sources. This reflects the high level of sophistication and development of emission control systems for automobile engines.

### 5.3.2. Operation on Natural Gas

Natural gas operation was demonstrated and tested. Parked in a location equipped with both a charging connection and a natural gas connection, the project vehicle was plugged into the grid and the gas supply, and was operated in discharge mode at up to 7 kW output using natural gas.

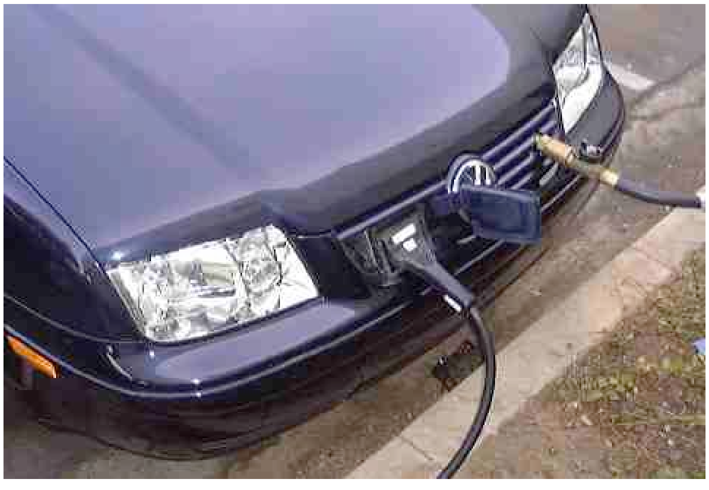

**Figure 12. Hookups for AC Power and Natural Gas Fuel**

The emission lab at CARB was unable to provide a set up capable of supplying natural gas to the vehicle in the emission lab, so emission testing was conducted at AC Propulsion using an Andros portable emission analyzer. In order to provide comparable data, the tests were conducted alternating between natural gas and gasoline so that relative emission values could be compared even though the accuracy of the absolute values could not be validated. The results, in the table below, show that NOx emissions operating on natural gas matched those operating on gasoline, but that HC and CO emissions were much higher with natural gas. The negative value for HC concentration on gasoline may be a calibration error, or it may reflect an actual reduction in HC concentration compared to the background at the time of the test.

**Table 17. Comparative Emission Concentrations Natural Gas vs Gasoline**

| | HC ppm | | CO % | | NOx ppm | |
|---|---|---|---|---|---|---|
| DC output | gas | petrol | gas | petrol | gas | petrol |
| 4 kW | 141 | -57 | 3.1 | 0.006 | 7 | 2 |
| 7 kW | 61 | -72 | 1.8 | 0.007 | 7 | 7 |
| 10 kW | 40 | -73 | 1.3 | 0.010 | 7 | 7 |

Although the natural gas fuel system included a closed loop controller to maintain stoichiometric air/fuel ratio, the emissions data suggest that the mixture was too rich by a significant margin. It may also be that the natural gas metering system, designed for use on industrial equipment was not well suited for application to advanced emission controlled gasoline engines. Time and budget constraints precluded efforts to tune the system to achieve better results.

## 6. Discussion

Automakers are taking an incremental approach to the introduction of hybrid vehicles into the market That the first hybrids use minimal electric propulsion systems and cannot be plugged in, reflects the technological and economic risks involved in introducing new products, not necessarily any determination of optimality. The vehicle developed for this project demonstrates a conceptually and technologically more innovative approach that seeks to achieve commercial viability by maximizing the capabilities of the electric propulsion system. In this section, these capabilities will be assessed according to their environmental benefits, their effectiveness in creating market appeal, and their potential for commercialization.

### 6.1 Emissions and Energy Benefits

The primary environmental benefits of the plug-in hybrid occur as a result of substituting grid energy for petroleum energy. Such substitution is not possible with hybrids that do not plug in. In California, according to CARB, grid energy, when used for automotive transportation, is cleaner than the cleanest combustion vehicles. Although this may not be true in every state, grid energy typically creates emissions away from population centers while the opposite is true for automobiles. Use of grid energy instead of petroleum also provides important energy diversity and balance of trade benefits that promote national security. Secondary environmental benefits of the plug-in hybrid are possible because the operating requirements of the combustion engine are de-coupled from the operation of the vehicle. This allows application of optimal emission control strategies to the combustion engine without creating inconvenient or unacceptable driving characteristics.

### 6.1.1. Fuel Substitution Benefits

Fuel substitution occurs whenever energy from the grid is used instead of gasoline. The magnitude of the benefit depends on the battery range, typical trip length, and availability and use of opportunity charging. The practical range of the project vehicle operating in EV mode is 25 to 35 miles. Without charging at work, this range is marginal for many commuters so the APU may operate at least once a day, typically on the trip home from work. With charging at work, most commuters could operate emission free all day, even with side trips.

It is worth noting that most tailpipe emissions come during the start and warmup periods of operation. The project vehicle test results demonstrate this. This means that emissions are more a function of number of cold starts than of total miles driven. Thus, in local driving, whether or not the APU comes on has a greater effect on emissions than how long it operates once it comes on and warms up. This has important implications for balancing emissions and economic factors in configuring vehicle and infrastructure.

Although typical vehicle usage is highly varied day to day and person to person, a large number of individuals drive a highly consistent pattern of say 30 miles at least five days a week. For such a driving pattern, at least one cold start a day can be eliminated if EV range is as little as 15 miles. Doubling the range to 30 miles would eliminate a second cold start, and beyond that, increasing range may continue to have customer appeal, but the emission benefit based on cold start elimination will begin to tail off.

It is not obvious that even the second 15 mile increment of range is cost beneficial compared to installation of workplace charging. With a battery cost of at least $80 per mile of range, (probably twice that for advanced batteries), that 15 miles of range would cost $1200 or more. It is likely that Level 1 or even Level 2 charging could be installed in an employer parking lot for less than $1200 per car. Furthermore, the long term benefits of new charging infrastructure would outlive the batteries. These benefits include reduced range anxiety and resistance to battery cars and increased potential for V2G implementation.

Battery advancements are moving toward the higher power-to-energy ratio batteries that will be necessary to provide adequate performance in a low-range vehicle. And looking at emissions from the cold-start elimination viewpoint, even plugless hybrids such as the 2004 Prius may be able provide this benefit to some degree by providing enough battery performance to “bundle” several short trips, each of which might have required a cold start, on one battery cycle and then start the engine just once to recharge the battery.

While the major emission benefits of hybrids come in chunks, each cold start eliminated is a chunk, the energy benefits do not. The more miles driven on grid energy, the less petroleum is consumed. So for the purpose petroleum consumption reduction, both bigger batteries and more charging locations are beneficial. The funding committed to fuel cell vehicle and infrastructure development primarily in the name of national energy security suggests that fuel substitution has a high value that may justify expenditures on both larger batteries and increased charging infrastructure.

### 6.1.2. Engine Operation Benefits

The project vehicle APU management system has been developed to achieve project objectives, but is not yet optimized. The emission testing confirmed that the APU engine operation in the 15 to 20 kW range is a good compromise between low emissions and high efficiency. The transient tests confirmed that operation at high battery SOC can increase emissions and reduce efficiency. The APU off-time tests showed that emission control is most effective if the APU off time between starts is less than 30 minutes.

These findings are reflected in the APU control algorithms. APU operation is prevented at low power levels or at high SOC. APU off time is not controlled directly, but in HEV mode, the SOC thresholds and programmed hysteresis result in typical off times of less than 5 minutes. Furthermore, the APU responds to every power request with a distinct speed and load. Although the speed load matrix is not fully optimized, it is based on a rough engine mapping conducted in the CARB dyno while the engine was installed in the donor Lupo. The result is that the steady state emissions of the APU result in the potential for projected driving cycle emissions to be consistent SULEV standards.

To reduce the achieved UDDS cycle emissions to these levels would require near elimination of cold start emissions. The use of a low-power electrically heated catalyst or other pre-heating technology might achieve this objective without the cost of fast warmup EHCs. Because the APU operation is de-coupled from driving requirements, the EHC can spend more time warming up without detracting from driveability.

### 6.1.3. Actual Emissions vs. Measured Emissions

The potential emissions reductions from eliminating many cold starts is a potentially significant air quality benefit from plug-in hybrids, but it is a benefit that may not be adequately recognized under hybrid vehicle test procedures specified under CARB regulations. These regulations require that the APU operate at least once during the emissions test which represents about 14.8 miles of driving. This is appropriate for conventional cars as it assumes two cold starts for 30 miles of driving, a reasonable average. For a hybrid, this assumption may overstate the number of cold starts in typical use, and thus underestimate the air quality benefits of plug-in hybrid vehicle use.

For drivers who average 25 miles or less per day, or for drivers who can access opportunity charging on a regular basis, the project vehicle can be operated for days on end without starting the APU. If the APU is used just once a week, the average emissions, assuming SULEV cold start emissions, would be 85% less than a conventional SULEV, but this would not show up in the emission ratings.

For conventional vehicles CARB uses an average of one cold start for every 15 miles to project vehicle tailpipe emissions. This is a reasonable accommodation between a best case – high mileage freeway driving, which in modern cars is almost emission free, and worst case – many short trips spaced hours apart each of which includes a cold start. The test procedure established for hybrids portrays more of a worst case scenario by assuming that the APU will start at least once every 15 miles regardless of its battery size, charging capability, and control logic. There is almost zero operating experience with plug-in hybrids to justify a worst case approach, and it may be counter-productive from an air-quality perspective by discouraging the pursuit of plug-in hybrid technology.

### 6.2 Distributed Generation

A fleet of plug-in hybrid vehicles parked in an employers lot during business hours could provide standby generation using the APU engine as the source of power. To allow for such generation without requiring more frequent gasoline refueling with its inconvenience and emissions, the project vehicle was equipped to demonstrate operation on low-pressure natural gas drawn directly from the gas main.

Prior studies have suggested that vehicles connected to the grid and capable of bi-directional power flow can participate in a broad variety of distributed generation and ancillary services functions that can have significant economic value including:

- Reliability in Service
- Transmission Loss Reduction
- Regulation (automatic generator control)
- Spinning and Non-Spinning Reserve Margin
- Peak Shaving
- Transmission and Distribution Deferral
- VAR Support/Power Quality
- Cogeneration Capability
- Improvement in Utility "Load Factor" Fuel Diversity
- Transmission line stabilization

There will also be other effects that utilities may value because of their secondary benefits. Reducing "Energy Congestion" on the grid will ultimately benefit the utilities since more of their transmission and distribution assets will be freed up and T&D construction will be reduced. The Electric Power Research Institute (EPRI) estimates that distributed generation (DG) will comprise up to 40% of all new generation by the year 2006. When these benefits can be provided by an asset whose capital cost is incurred for transportation, which is the case for the APU in a plug-in hybrid, the economic case may be attractive.

A 2001 study co-sponsored by CARB found that the value of vehicle-based grid support services can exceed their total cost including fuel, equipment wear and tear, and battery wear out. Part of this excess value can accrue to the vehicle owner, providing an offset to overall vehicle ownership costs. This real value will provide a sustainable economic incentive that will speed commercialization of electrically-driven vehicles.

A more recent CARB-funded project conducted by this contractor demonstrated the feasibility of wireless remote control of a grid-connected vehicle to provide grid regulation service. That study concluded that battery electric vehicles can provide grid regulation without discharge of the battery over time, and that the value of the regulation service provided could earn a positive net income for the vehicle owner.

This project applied the V2G systems developed for battery EVs to a plug-in hybrid that, by virtue of its onboard APU, could provide bulk energy to the grid. During the conceptual stages of this project, California was enduring supply uncertainties that raised the profile of backup power supplies for businesses where power interruptions can have major economic impacts. This situation led to the prospect of thousands of such businesses installing and operating diesel backup generators with high costs and undesirable effects on air quality. The concept of vehicle-based generation represents an alternative to such conventional backup power sources. The vehicles are used for transportation to and from work, and when parked at work they are plugged in to the grid and to a natural gas source. With authorization from the driver, and under command of the grid, the vehicles would provide a clean and efficient standby power resource.

The workplace connections would require installation of the charging stations, gas fueling connections, and the V2G communications network, and perhaps some incentives to the vehicle drivers, a relatively low investment and overhead. Even at the modest 7kW power level available through Level 2 charging hardware, 150 plug-in hybrids could supply 1 MW of power for an extended period, enough to operate a large building. An equivalent level of power with conventional backup generators, or advanced technology such as microturbines, solar panels, or fuel cells would require a significant investment in equipment and installation costs, and that investment would sit idle most of the time. With vehicle-based generation, the primary generating asset is a car that provides transportation value everyday, but is available for backup power when needed, a potentially superior allocation of resources.

A wide variety of technical, regulatory, and institutional issues are involved in the adoption of vehicle-based DG. The California Public Utilities Commission (CPUC) has approved Rule 21, which provides for the interconnection of distributed generation equipment to utility distribution systems. Many municipal utlities in California are adopting interconnection rules similar to Rule 21. Rule 21 covers the interconnection, operating, and metering requirements for interconnection with the grid. A multi-stakeholder working group drafted the current version of Rule 21, and this Rule 21 Working Group continues efforts to resolve ongoing issues. Rule 21 covers small scale generation such as residential solar panels, but is generally written to cover larger, semi-permanent systems. The requirements it lays out were not written to include vehicle-based DG, so they do not consider issues related to mobile distributed generation. Rule 21 requires reviews and approvals of individual sites and individual DG equipment. Widespread adoption of vehicle-to-grid will be difficult unless these procedures can be streamlined so as to apply to vehicle model lines rather than individual vehicles. So, although interconnection of DG sources is allowed and approved in California, regulations in place now will have to evolve to a significant degree in order to accommodate the several types of vehicle-to-grid interactions of which the project vehicle is capable.

The California energy crisis turned out to be artifact of a poorly conceived regulatory structure that invited market manipulation. Although electricity prices are higher now than before the crisis, they are not as high as during the crisis, and the threat of blackouts has receded. Accordingly, the incentive for business to invest in backup generation has largely disappeared, and with it the immediate driver for the development of a large-scale market for vehicle-based distributed generation. Nonetheless, the low emissions and high efficiency potential of vehicle-based distributed generation remain, and the project vehicle has demonstrated that vehicle-based generation is feasible.

In retrospect, it is worth noting that had vehicle-based generation been commercialized at the end of 2000, it could have prevented the energy crisis. Two hundred thousand vehicles, about 1% of the California vehicle fleet, each capable of generating 10 kW into the grid, would have collectively represented a 2 GW power resource. That power, 5% of California’s requirement would have given the California Independent System Operator a fast response, dispatchable, distributed power resource. With that resource directly under its control, the CAISO could have replaced the power that was being withheld by the market manipulators and avoided most, if not all of the Stage 2 power alerts that were issued during the crisis.

### 6.3 Market Appeal

Toyota has responded to its customers in the design of their 2004 Prius hybrid. The original Prius could go only one or two miles, at most, on the battery before the engine started automatically. Also, it was mechanically unable to go faster than about 35 mph with the engine off. The new 2004 Prius has increased capabilities in both electric range and speed reflecting the desires of Prius buyers and potential buyers who want these features. This suggests that electric propulsion itself, not the low-emissions aspect or the fuel-saving aspect, but the “touch, sound, and feel” of driving electrically has market appeal in and of itself.

Certainly EV drivers have testified to the joys of electric motoring, but for the broader car-buying public, range limits and range anxiety represent significant barriers to the commercialization of pure EVs. The plug-in hybrid overcomes these barriers and perhaps even more than the Prius and other plugless hybrids, the plug-in hybrid can serve as a market bridge to greater acceptance of electric transportation.

The project vehicle can provide both local and long distance travel without range constraints. In electric mode it is capable of use as a pure electric for much local driving, and in such operation it does not require any gasoline. In hybrid mode it provides better performance, higher fuel economy, and lower emissions than the base Jetta 2.0L automatic. Uniquely, the project vehicle can provide a wide range of electric generation and grid support functions. These functions may offer convenience value to some users now, and in the future may provide economic benefits as well.

At the same time, the project vehicle lacks trunk space, its fuel economy is not as good as the plugless hybrids already on the market, its emission levels have not been reduced to the lowest possible level, and, compared to the base Jetta, the additional propulsion hardware in the project vehicle would add cost. None of these shortcomings is insurmountable. The difficult question is what combination of configuration, cost, and features is the right one for the market.

### 6.3.1. Series vs. Parallel designs

Fuel economy can be improved by allowing the APU engine to drive the wheels directly in some modes of operation so that the conversion losses from electric generation and propulsion are avoided. This is done in parallel and combined hybrid systems such as the Prius. Compared to a series hybrid such as the project vehicle, the measured fuel economy gains can be significant, (the Prius is rated at 55 mpg), but the actual benefit to the user depends on the driving patterns and the relative prices paid for gasoline and electricity (Toyota admits that real world Prius fuel economy is typically 44 mpg). If, with a plug-in hybrid, half of total miles are driven on grid energy, then the petroleum fuel economy is effectively over 60 mpg. If three fourths of miles drive are electric, then the petroleum mpg is well over 100 mpg. With off peak rates of 8¢/kWh, the cost per mile of electricity is 1.7 ¢/mi compared to about 3.6 ¢/mi to buy gasoline for a Prius, so there is an incentive to use electricity instead of gasoline.

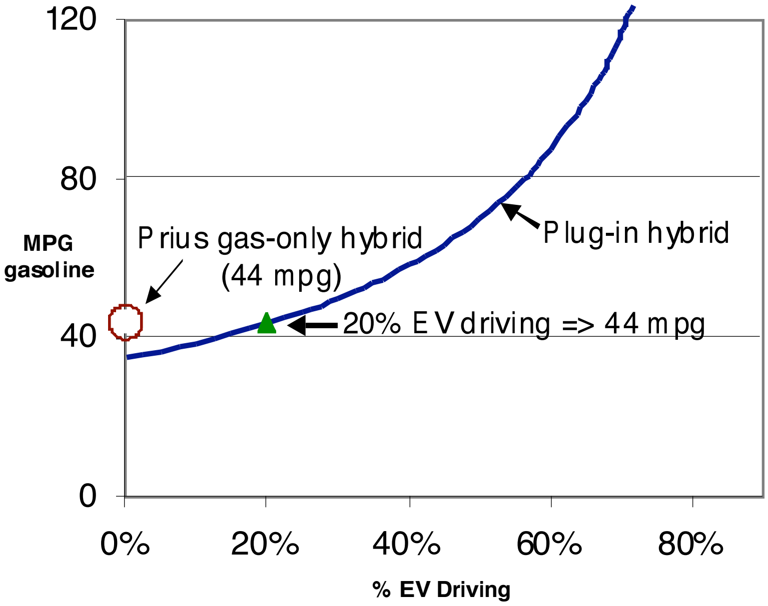

**Figure 13. Effect of EV Driving on Gasoline Fuel Economy**

The series-hybrid uses a less complex transmission than the parallel-hybrid and the cost savings can be applied to a larger battery that gives the series-hybrid greater electric range. The greater range in turn allows reduced reliance on gasoline and a greater sense of “driving electric”, two features with great appeal to potential hybrid buyers.  It may be that the cost penalty for parallel drives becomes low enough to allow plug-in hybrids with series/parallel drives, giving the customer the best of both technologies.

### 6.3.2. Packaging

The project vehicle successfully packages a 100 kW drive system, 8 kWh PbA battery, 15 gallon fuel tank, and 30 kW APU without loss of passenger space or comfort, but cargo and spare tire volume are sacrificed. These packaging losses were expedient for this project, but are not inherent in the project vehicle concept. The drive system is a 150 kW system turned down to 100 kW, so it is somewhat larger than necessary. The APU is designed around an existing engine and the APU compartment was converted from the vehicle trunk. A dedicated hybrid vehicle design would include componentry and architecture that use available space more efficiently. The Toyota Prius is an example of hybrid packaging that demonstrates what can be accomplished when both the vehicle and the hybrid hardware are designed into an integrated package.

### 6.3.3. Cost Factors

All of the questions relating to the costs of batteries, electric propulsion systems, research and development, and low-volume manufacturing for production of electric and hybrid vehicles are being answered by Toyota as it moves toward launch of its second generation hybrid Prius. The answer is that hybrids cost more, about $4,000, or 25%, more comparing a Toyota Corolla to a Prius, and that a large group of buyers will pay that extra cost.

If the project vehicle were in production, that same level of cost differential would be expected. The traction motor and inverter, battery, and APU alternator and inverter are all additional components whose costs are only partially offset by the lower costs of a smaller engine and less complex transmission. Comparing the Prius to the project vehicle, there is high correspondence among the major components although their relative power and size varies. Each car has an internal combustion engine, two electrical machines with controllers, a transmission, and a battery.

The feature that most differentiates the project vehicle from the Prius is the ability to plug in. This feature provides 30 to 40 mile electric range, at-home recharging, and the fundamental V2G capabilities. As implemented on the project vehicle, the onboard charger and grid interface is integrated with the drive system and has a projected incremental cost of less than $200. The charge inlet is a commodity component whose volume cost is estimated at less than $30. The 8 kW PbA battery probably costs about the same as the small NiMH battery in the Prius. In total, the plug-in feature should cost about the same as a plugless hybrid such as the Prius. With features that are attractive to hybrid buyers, and the potential to earn value from providing V2G services, at a cost no greater than the Prius, the value proposition for a plug-in hybrid such as the project vehicle would appear to be attractive.

### 6.4 Commercialization Potential

CARB has declared the emission reduction benefits of electric transportation. Those benefits can only be realized through commercial success of electric transportation. Automakers have rejected battery electric vehicles that operate entirely on energy from the grid, but increasingly they are developing and selling hybrid vehicles that use electricity generated onboard the vehicle. The grid-connected hybrid built for this project demonstrates the feasibility and advantages of a vehicle that can use electricity from either source. Based on stated preferences of hybrid and EV drivers, these advantages include:

- Extended ZEV range allows EV driving for most local trips
- Home recharging reduces trips to the gas station
- Unlimited range and automatic control eliminates range anxiety
- V2G capability provides convenience and economic benefits

Commercialization of hybrid technology ultimately requires the participation of the automotive OEMs because only they have the expertise and capability to produce emission certified engines for hybrids. These companies need to be convinced that the plug-in feature is desirable to their customers and cost-effective to produce. The project vehicle provides a property that can be used to demonstrate features to automotive customers and to demonstrate feasibility to automakers.

Short of commercializing the entire plug-in hybrid vehicle concept, the technology developed for this project has already created new potential business opportunities. The APU designed and built for this project may have stand-alone applications as a hybrid power unit for shuttle buses and other medium-duty vehicle applications. The alternator is an unusual hollow center design that can also be operated as an induction motor. A traction motor built from this design would offer light weight with torque and speed characteristics well suited to light trucks and other medium duty vehicles. Already, AC Propulsion has had inquiries about adapting the alternator from the project vehicle to other applications for a variety of uses.

## 7. Summary and Conclusions

The general hybrid vehicle concept combines conversion of onboard fuel with electric propulsion to achieve low emissions, high energy efficiency, and desirable vehicle attributes. The vehicle developed for this project demonstrates how this can be done using pure electric propulsion, conventional internal combustion engine, and innovative grid connection technology.

### 7.1 Work Completed

For this project, the contractor completed a course of work that included the following tasks:

- Convert a conventional vehicle to electric propulsion by installing a battery and an electric drive system with a bi-directional charger.
- Design and build a 30 kW alternator and integrate it with an internal combustion engine to make an auxiliary power unit or APU.
- Install the APU in the electric vehicle conversion with a control system that allows the APU to keep the EV battery charged, creating a hybrid vehicle.
- Fit the APU with a natural gas fuel system to allow operation on low-pressure natural gas as well as gasoline.
- Test the APU as a generator feeding up to 15 kW to the grid, to stand-alone loads, and to charge other battery vehicles.
- Test the APU for emissions and achieve low emission levels running at steady state and in dynamometer driving tests.
- Test the vehicle for range and efficiency
- Complete testing of over 6000 miles including local and long-distance driving.
- Observe reactions and comments in over 80 test drives

### 7.2 Summary of Results

In testing, the project vehicle achieved the following results:

**Emissions**

- Up to 40 zero emission miles per charge
- With opportunity charging, up to 80 or more zero emission miles per day
- ULEV I level emissions achieved over UDDS emission test
- APU capable of SULEV emissions
- Reduced emissions from stationary generation compared to microturbines and other combustion engine generators

**Energy**

- Tri-fuel operation that allows the use of electricity for local transportation, gasoline for extended trips, gasoline or natural gas for electric power generation

- Substitution of electricity for gasoline in most local driving
- Improved fuel economy compared to base vehicle
- High recapture of braking energy through regenerative braking
- Capability of providing grid support functions including regulation and generation through bi-directional grid interface

**Attributes**

- Improved acceleration and responsiveness
- Reduced noise and vibration in EV mode
- Refueling at home or at any electrical outlet
- Avoidance of engine operation and related emissions and gasoline consumption by operating in EV mode
- Use of vehicle as a back-up power source
- Potential for earning economic return by providing grid support services

## 7.3 Conclusions

Based on these results, the following conclusions can be drawn.

- By combining the driving characteristics of an electric car and the uncompromised range of a conventional car, the plug-in hybrid can satisfy a large segment of the automobile market.

- Charging from the grid provides important user benefits – up to 40 miles of all electric range and elimination of many trips to the gas station.

- Charging from the grid provides important emissions benefits – electric driving can reduce the number of cold starts, the greatest source of emissions. Also, emissions from the remaining cold starts can potentially be controlled more tightly because engine operation is de-coupled from vehicle operation.

- Charging from the grid provides an important energy benefit – driving on grid electricity substitutes secure, domestic, and often clean or renewable energy resources for petroleum.

- Comparing the project vehicle to plugless hybrids such as the Toyota Prius suggests that design costs are similar. The plug-in feature as implemented in the project car does not add significant cost.

- Supplying AC power from the vehicle to the grid or other loads is feasible and can provide a desirable convenience feature for some users. Combining the generation feature with remote control via wireless internet connection, as demonstrated in an earlier project creates the prospect of a multi-megawatt power resource available from a fleet of connected cars.

- The regulations for testing and calculating emissions from plug-in hybrids may be too conservative. By assuming the worst case operating scenario, i.e. that the car is never plugged in, even though there are behavioral and economic incentives to charge the vehicle from the grid, the regulations may be thwarting the potential emissions benefit available from plug-in hybrids.

# 8. Recommendations

## 8.1 Promote Connected Cars

Connected cars, battery EVs and plug-in hybrids, are those cars that can connect to the grid. Legislators, regulators, policy makers, and auto manufacturers should promote connected cars. The primary feature of a connected car is that it can draw energy from the grid, most of which is derived from non-petroleum resources, and substitute that energy for petroleum. Once a fleet of connected cars is established, vehicle-to-grid interactions, V2G for short, follow as a logical development. The benefits of V2G are enhanced by another kind of connection, a wireless internet communications link that allows the vehicle to serve as a fast response, dispatchable, distributed generation resource. The twin benefits of energy substitution and grid support address a variety of interrelated environmental, energy, and economic challenges including exhaust emissions, petroleum imports, energy security, power capacity and reliability, renewable energy utilization, and technology and infrastructure costs. Vehicles can provide these benefits, but only if they plug in to the grid.

## 8.2 Sustain charging infrastructure

California has developed a charging infrastructure for automobiles. That infrastructure should be preserved and maintained. Even though automakers have ceased production of electric vehicles, the infrastructure continues to benefit EV drivers, and if maintained, will present one less challenge to the re-introduction of connected cars to the market. The "chicken and egg" dilemma faces every effort to introduce alternative fuels. For electricity used as fuel, we now have the “egg” in the form of a basic charging infrastructure. Maintaining that infrastructure will help bring plug-in cars, including plug-in fuel cell cars, “the chickens” back to the market.

## 8.3 Study cold-start emission controls

Cold-start emissions are the biggest portion of tailpipe emissions from cars that meet ULEV and SULEV standards. In fact, some automakers claim that emission controls are so effective, once the engine is warmed up, that the exhaust coming out of the engine is cleaner than the air going in. Automakers spend great effort to further reduce cold start emissions, but in conventional cars these efforts must work around the customer requirements for immediate drive-off and uncompromised driveability after a cold start. Although automakers have achieved extremely low cold-start emissions from SULEVs, the plug-in hybrid vehicle gives a new degree of freedom to cold start emission control. Catalyst preheat time and engine warmup calibrations that affect driveability would be transparent to drivers of this project vehicle because vehicle performance is the same whether the combustion engine is running or not. An investigation of the potential for controlling cold start emissions from de-coupled engines would inform future regulatory treatment of these types of vehicles.

## 8.4 Consider benefits of cold starts avoided

CARB should evaluate the benefit of “cold starts avoided”, especially at temperatures below those of the UDDS test which are often typical of the first start of the day. Exhaust emission control efforts have succeeded in reducing tailpipe emissions from warmed up vehicles to almost negligible levels, so cold start emissions are the major element of tailpipe emissions from ULEV and SULEV vehicles. This is also true of the project vehicle, but with 35 mile electric-only range, the project vehicle may commit 50% to 75% fewer cold starts than conventional vehicles with proportionate reduction in emissions. Current emission standards to not recognize this benefit and the result is a regulatory and economic disincentive for plug-in hybrids.

### 8.5 Investigate new hybrid battery technology for plug-in hybrids

Plug-in hybrid development work should include investigation of advanced batteries. The emission reduction and customer appeal of plug-in hybrids depends in part on electric-only range. Both of these benefits might be increased substantially by substituting an advanced battery for the project vehicle's PbA battery. Battery technology has advanced significantly since the inception of this project, and there may be opportunities for cost-effective improvements.

### 8.6 Encourage fuel cell plug-in hybrids

The plug-in hybrid configuration should be encouraged for fuel cell vehicles. Many of the cost, efficiency, range, complexity, and reliability challenges preventing early fuel cell vehicle deployment relate to cold starts and peak power requirements. A plug-in hybrid with a fuel cell APU would minimize these problems. By de-coupling fuel cell operation from vehicle operation, warmup can be slower and simpler, output can be optimized for efficiency, and size, power, and cost can be reduced. Higher efficiency reduces hydrogen consumption increasing range or reducing tank size. Battery-only range reduces hydrogen consumption and dependence on hydrogen availability. The fuel cell cost can be partially defrayed by zero emission power generation while parked. The development paths being pursued by automakers do not seem to recognize these benefits.

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## 10. Appendix I Vehicle Specifications

### Base Vehicle

| | |
|---|---|
| Type | VW Jetta, 4-door, 5-seat compact sedan, front wheel drive |

### Conversion

| | |
|---|---|
| Type | 4-door, 5-seat, front wheel drive, series hybrid |
| Layout | Drive system – front<br>Battery, fuel tank – underbody<br>Auxiliary power unit (APU) - rear |
| Weight | 3680 lbs, front 49%, rear 51% |

### Power System

| | |
|---|---|
| Propulsion | AC Propulsion Gen 2 AC-150 power system de-rated to 100 kW peak |
| Transaxle | Fixed-ratio, OA ratio of 10.1:1, standard location |
| Charger | Onboard, integrated, conductive, output from 1 to 20 kW |

### Battery

| | |
|---|---|
| Type | Panasonic PbA (HEV spec) |
| Capacity | 348 V, 25 Ah, 8.7 kWh |
| Max power | 110 kW |
| Weight | 650 lb |
| Thermal | forced air cooling, module-level electric heating |
| BMS | voltage/temperature monitoring with 5A/module equalization current |

### Auxiliary Power Unit

| | |
|---|---|
| Engine | Spark ignition, 4-stroke, 1.4 liter displacement |
| Fuel | Gasoline, port injection from onboard tank<br>Natural gas, low-pressure mixer, from offboard source |
| Generator | Direct-driven AC Propulsion inverter-controlled alternator |
| Output | 30 kW DC @ 280V – 400 V<br>15 kW AC 240 V (stationary) |

### Performance

| | |
|---|---|
| Efficiency | Electric drive: 180-250 DC Wh/mi estimate<br>Vehicle: 30-40 mpg (without battery depletion) |
| Range | Battery only: 30-45 mi<br>Fuel only (15 gal tank): 500 mi |
| Emissions | Battery: ZEV<br>HEV: SULEV capable<br>Stationary: Below current DG standard |
| Acceleration | 0-60 mph in 8.5 sec |
| Top Speed | 85 mph governed , 80 mph charge-sustaining |

### Features

Avcon charging inlet
Bi-directional power
Power steering
Regenerative braking

Cruise control
Power brakes
Traction control

## 11. Appendix II CARB Test data

**AC Propulsion VW Jetta Hybrid Preliminary Data Summary**
30-May-03 Proj 2R0101

**City All-Electric Range Test**
**Wednesday, April 23, 2003**

| **Test** | **Seconds** | **Miles** | **Tot Kwh** | **Reg Kwh** | **Amp Hr** | **Regen Amp Hr** |
|---|---|---|---|---|---|---|
| RJ-1 | 1451 | 7.4106 | 1.6127 | -0.556 | 4.5949 | -1.4306 |
| RJ-2 | 1392 | 7.4317 | 1.5277 | -0.5658 | 4.4069 | -1.4917 |
| RJ-3 | 1425 | 7.4372 | 1.5968 | -0.5667 | 4.7198 | -1.5232 |
| RJ-4 | 1419 | 7.4355 | 1.5265 | -0.5698 | 4.6265 | -1.5665 |
| RJ-5 | 1427 | 7.4392 | 1.5908 | -0.5789 | 5.0783 | -1.6265 |
| RJ-6 | 359 | 2.127 | 0.4992 | -0.1704 | 1.7428 | -0.4613 |
| **Totals** | **7473** | **39.2812** | **8.3537** | **-3.0076** | **25.1692** | **-8.0998** |

**Highway All-Electric Range Test**
**Thursday, April 24, 2003**

| **Test** | **Seconds** | **Miles** | **Tot Kwh** | **Reg Kwh** | **Amp Hr** | **Regen Amp Hr** |
|---|---|---|---|---|---|---|
| RHWY-1 | 1701 | 20.5254 | 4.005 | -0.3232 | 11.4119 | -0.8379 |
| RHWY-2 | 1393 | 17.5084 | 3.4066 | -0.3045 | 10.4662 | -0.8218 |
| **Totals** | **3094** | **38.0338** | **7.4116** | **-0.6277** | **21.8781** | **-1.6597** |

**FTP Weighted Emissions (g/mi)**

| Standards | | NMHC | CO | NOxC | Formaldeh | Particulate | Fuel Fuel Econc | Net Ah Increase | |
|---|---|---|---|---|---|---|---|---|---|
| Tier I | | 0.25 | 3.4 | 0.4 | --- | 0.08 | | | |
| TLEV | | 0.125 | 3.4 | 0.4 | 0.015 | --- | | | |
| LEV I | | 0.075 | 3.4 | 0.2 | 0.015 | --- | | | |
| ULEV I Std | | 0.04 | 1.7 | 0.2 | 0.008 | --- | | | |
| ULEV II Std | | 0.04 | 1.7 | 0.05 | 0.008 | --- | | | |
| SULEV | | 0.01 | 1 | 0.02 | 0.004 | 0.01 | | | |
| **Power Plant Emissions** | | **0.004** | | **0.02** | | | | | |
| **Assuming 350 Wh/mi** | | | | | | | | | |
| **g/kWh** | | **0.011429** | | **0.057143** | | | | | |
| Date | | | | | | | | | |
| | 4/30/03 | 0.072 | 0.28 | 0.068 | | | 30.393 | 0.004925 | |
| | *5/2/03* | *0.062* | *0.214* | *0.065* | | | *36.558* | *0.347* | 1 |
| | *5/9/03* | *0.073* | *0.229* | *0.286* | | | *30.708* | *0.18* | 2 |
| | 5/21/03 | 0.076 | 0.182 | 0.089 | | | 30.767 | -0.4233 | |
| | 5/22/03 | 0.075 | 0.191 | 0.078 | | | 30.329 | -0.3032 | |
| *Lupo Emissions Tests (Reference)* | | | | | | | | | |
| | 5/21/02 | 0.028 | 0.182 | 0.042 | | | | | |
| | 5/22/02 | 0.028 | 0.218 | 0.024 | | | | | |

*1 Invalid Test: Exhaust boot came loose, NOx analyzer calibrated 2% high*
*2 Invalid Test: APU control surged uncontrollably*

# Appendix II CARB Test data, continued

**Steady State Emissions Tests**

4/30/03

| Nominal Load (kW) (Power Plant Emissions Ref) | Estimated Load (kW) | Estimated speed (mph) | Nominal Speed (mph) | Veh F/E mpg | Distance (mi) | Time (sec) | Average speed (mph) | NMHC (g) | CO (g) | NOxC (g) | **NMHC (g/kWh)** | **CO (g/kWh)** | **NOx (g/kWh)** | **Engine F/E gal/kwh** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | **0.011429** | | **0.057143** | |
| 5 | 5.436076 | *40.40626* | 40 | 50.462 | 3.389 | 300.4 | 40.61385 | 0.005 | 0.115 | 0.07 | **0.011023** | **0.253522** | **0.154317** | **0.148055** |
| 10 | 10.5495 | *40.2611* | 40 | 30.098 | 3.362 | 300.7 | 40.25008 | 0.001 | 0.389 | 0.269 | **0.001135** | **0.441455** | **0.305274** | **0.126764** |
| 15 | 15.4258 | *40.41365* | 40 | 22.542 | 3.381 | 300.6 | 40.49102 | 0.004 | 0.299 | 0.062 | **0.003105** | **0.232133** | **0.048135** | **0.116444** |
| 20 | 20.58091 | *40.22463* | 40 | 17.544 | 3.365 | 301 | 40.24585 | 0 | 0.431 | 0.085 | **0** | **0.250466** | **0.049396** | **0.111462** |
| 25 | 25.09401 | *40.40801* | 40 | 14.707 | 3.381 | 300.5 | 40.50449 | 0.017 | 2.067 | 0.014 | **0.008116** | **0.986799** | **0.006684** | **0.109751** |
| 30 | 29.24093 | *40.16205* | 40 | 12.626 | 3.357 | 300.5 | 40.21697 | 0.117 | 9.799 | 0.054 | **0.047935** | **4.014658** | **0.022124** | **0.108931** |

**Constant speed Discharge**

Thursday, May 08, 2003

| 9:20:17 AM | Seconds | Miles | Batt Tot Kwh | Reg Kwh | Batt AmpHr1 | APU AmpHr2 |
|---|---|---|---|---|---|---|
| Constert speed Discharge | 1925 | 160794 | 1.7348 | -0.396 | 4.9309 | -1.014 |
| Constert Discharge 2 5.03 AH 3VW | 411 | 43883 | 0.357 | -0.131 | 1.0198 | -0.3436 |
| Constert Discharge 3 20.14 AH 3VW | 3439 | 382737 | 5.7417 | -0.2631 | 16.6303 | -0.7319 |
| Constert Discharge 4 20.14 AH 3VW | 998 | 109675 | 1.2149 | -0.3836 | 3.6769 | -1.0566 |
| Constert Charge 1 7AH 3VW | 1395 | 0.005 | -4.3402 | -4.3434 | -11.2573 | -11.2658 |

**Hot 505 tests**

5/8/03

| Includes hot cranking, no special loading<br>Thursday, May 08, 2003 | Seconds | Miles | Batt Tot Kwh | Reg Kwh | Batt AmpHr1 | APU AmpHr2 | NMHC (g/mi) | CO (g/mi) | NOxC (g/mi) | FE mi/gal |
|---|---|---|---|---|---|---|---|---|---|---|
| APU on 15 KW 80P SOC | 612 | 35938 | -0.511 | -0.8895 | -1.1529 | -2.2046 | 0.002 | 0.175 | 0.405 | 20.762 |
| APU on 15 KW 80P SOC | 542 | 3.595 | -0.6131 | -0.8931 | -1.4505 | -2.2155 | 0.007 | 0.234 | 0.404 | 20.737 |
| APU on 15 KW 20P SOC | 538 | 35951 | -1.3807 | -1.6142 | -3.6145 | -4.2927 | 0.007 | 0.174 | 0.493 | 15.191 |
| APU on 15 KW 20P SOC | 516 | 35911 | -1.3989 | -1.6173 | -3.6719 | -4.3091 | 0.004 | 0.308 | 0.349 | 15.091 |

**300 Sec 15 kW Load SteadyState Tests**

Friday, May 09, 2003

| 9:05:00 AM | Seconds | Miles | Tot Kwh | APU kWh | Reg Kwh | AmpHr1 | AmpHr2 | NMHC (g) | CO (g) | NOxC (g) | FE mi/gal | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0054-10 APU On After 10 Min | 365 | 32486 | 0.1531 | 1.270778 | -0.0557 | 0.4315 | 3.444626 | 0.05 | 0.813 | 1.535 | 21.642 | |
| *0054-11 APU On After 20 Min wait* | *338* | *3.19* | *0.11* | | *-0.08* | *0.33* | *3.45* | 0.023 | 0.453 | 1.759 | 21.186 | *Labview File not recorded* |
| 0054-12 APU On After 30 Min wait | 329 | 32532 | 0.1678 | 1.253912 | -0.0549 | 0.4825 | 3.441684 | 0.075 | 0.643 | 1.832 | 21.896 | |
| 0054-14 APU On After 40 Min wait | 353 | 32028 | 0.1485 | 1.239956 | -0.0596 | 0.4308 | 3.417705 | 0.398 | 1.249 | 2.535 | 21.528 | |
| 0054-13 APU On After 60 Min wait | 343 | 32341 | 0.1172 | 1.296141 | -0.1259 | 0.3594 | 3.56768 | 0.376 | 1.039 | 2.851 | 21.465 | |