2005-01-3827

Design and Development of a Parallel Hybrid Powertrain for a High Performance Sport Utility Vehicle

A. Singer-Englar, R. Kamisky, P. Erickson, A. Frank, W. Allan, C. Bangar, C. Carde, A. Dalal, D. Garas, J. Holdener, N. Meyr and C. Nitta
University of California, Davis

ABSTRACT

A plug-in, charge-depleting, parallel hybrid powertrain has been developed for a high performance sport utility vehicle. Based on the Ford U152 Explorer platform, implementation of the hybrid powertrain has resulted in an efficient, high performance vehicle with a 0-60 mph acceleration time of 7.5 seconds. A dual drive system allows for four-wheel drive capability while optimizing regenerative braking and minimizing electric motor cogging losses. Design of the system focused on reducing petroleum use, lowering greenhouse gas emissions, and reducing criteria tailpipe emissions. Additionally, this vehicle has been designed as a partial zero emissions vehicle (PZEV), allowing the driver to travel up to 50 miles in a zero emission all-electric mode. High-energy traction battery packs can be charged from the grid, yielding higher efficiencies and lower critical emissions, or maintained through the internal combustion engine (ICE) as with a traditional hybrid vehicle. The ICE is primarily used to provide average power and maintain state of charge (SOC). The ability to use the electric energy from the grid allows the most inexpensive way of driving the vehicle and reduces the dependence on petroleum. Electric power created at a large-scale power plant is produced more efficiently than by an ICE. However, to allow a long range and the option (rather than requirement) for using the plug, one has the capability to utilize liquid fuel through the ICE as well. Fuel consumption is reduced by more than 80% over the stock vehicle, resulting in average city usage of roughly 29 mpg (gasoline equivalent). Full functionality of the stock vehicle has been maintained, including four wheel drive, tow, and acceleration capabilities, as well as driver comfort, with no loss in cabin space and a small increase in vehicle weight. Analysis shows a final cost lower than comparable performance competitors. This paper details the design and implementation of this powertrain, and compares the hybrid vehicle response to that of the stock vehicle.

INTRODUCTION

The University of California, Davis FutureTruck team participated in the 2004 FutureTruck competition, sponsored by Ford Motor Company and the U.S. Department of Energy. In response to international concern regarding the potential of Greenhouse Gas (GHG) emissions to cause global warming, the competition goals challenged student teams to redesign a midsize Sport Utility Vehicle (SUV) as a Hybrid Electric Vehicle (HEV), reducing equivalent Greenhouse Gas Index (GHGI), criteria tailpipe emissions, and fuel consumption. These goals were to be met without compromising vehicle safety, performance, utility, or value. In addition, UC Davis focused on qualifying for 80% Partial Zero Emissions Vehicle (PZEV) credit under the California Low Emissions Vehicle II amendment[i]. UC Davis competed in the 2004 FutureTruck competition with *Yosemite*, a redesigned 2002 Ford Explorer. Figure 1 illustrates the vehicle's configuration and Table 1 lists the team's design goals for 2004.

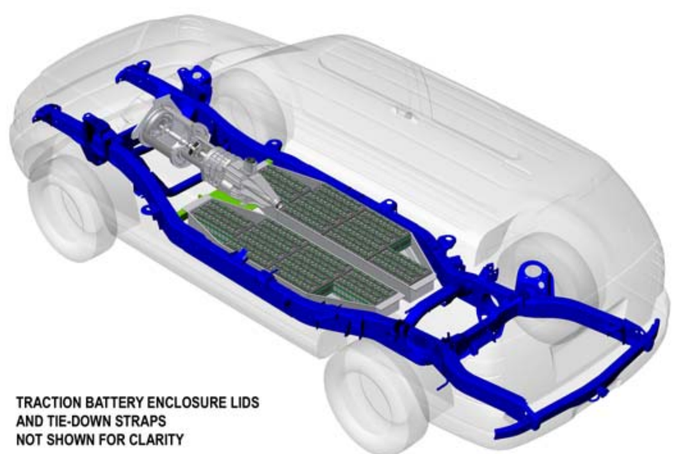

Figure 1. Yosemite design layout.

Table 1. Yosemite design goals

Greenhouse Gas Emissions	67% reduction
Petroleum Consumption	80% reduction
Fuel Economy	30 mpgge
0-60 mph acceleration	7.0 seconds
Emissions	California SULEV

The FutureTruck Challenge places an emphasis on reducing greenhouse gases (CO_2, CH_4, and NOx), which suggests the use of electricity as the primary fuel due to its low fuel-cycle emissions[ii]. A charge-depletion control strategy maximizes electrical power usage by using energy from off-board charging. The vehicle automatically shifts to a charge-sustaining mode during extended use and during trailer towing. In addition to improved efficiency, *Yosemite* also demonstrates best in class acceleration, competitive towing capacity, an advanced driver interface, and four-wheel drive (4WD) capability.

DESIGN PHILOSOPHY

HYBRID POWERTRAIN CONFIGURATION

Three powertrain configurations dominate HEV research. These are series, dual-hybrid and parallel configurations. A *series* hybrid configuration was eliminated due to unnecessary and inefficient energy conversions. A *dual-hybrid* design has lower conversion losses than a series configuration, but can be costly, heavier, and mechanically complex. As such, researchers at the UC Davis HEV Center concluded that a *parallel* hybrid configuration was the best choice for *Yosemite's* powertrain.

In a parallel configuration, the internal combustion engine (ICE) and electric motor (EM) drive the vehicle in tandem. The ICE was sized to meet steady state highway loads while the EM was used for low speed driving and transient conditions. Therefore, the size of the ICE can be greatly reduced in comparison to the stock vehicle without sacrificing performance. This set up allows the engine to operate at higher average thermal efficiency and within its ideal operating region, thereby increasing fuel economy.

Reducing ICE size necessitates an increase in available electric power. To compensate, *Yosemite* uses a high capacity battery pack and a 150kW electric drive system. The size of the battery pack was motivated by an Electric Power Research Institute (EPRI) study indicating that 54% of US motorists drive 45 miles (72.4km) or less daily[iii]. Realizing zero tailpipe emissions over this range implies plug-in, zero emissions capability; improving the air quality in densely populated regions.
An all-electric, independent front powertrain provides 4WD capability and maximizes regenerative braking efficiency. This design eliminated the energy losses typical in a mechanical transfer case. *Yosemite* is therefore drivable as an electric vehicle (EV), a conventional vehicle, or as an HEV in two or four wheel drive configurations.

FUEL SELECTION

The Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) model version 1.5a indicates that the use of electricity as vehicle fuel can significantly reduce the greenhouse gas production associated with automobiles. Simulations show that the biofuel E85 (85% ethanol, 15% gasoline by volume) decreases GHG emissions by 33g/mi relative to Reformulated Gasoline (RFG). Accordingly, electricity and E85 are *Yosemite's* primary fuels. *Yosemite's* flexible fuel capability also permits the use of RFG[ii].

ENERGY MANAGEMENT

A plug-in parallel hybrid design maximizes energy efficiency. Allowing the combustion engine to directly power the rear wheels reduces recirculation of power through the traction battery. A plug-in vehicle also has the unique advantage of recharging the traction battery with efficiently generated grid power.

Electrical energy is depleted to power the wheels under low speed driving conditions whereas the ICE is used under steady, high speed driving conditions. At higher speeds, constant power output from the ICE is desirable, so transient loads are met by electric power. This strategy reduces inefficient engine idling and transient operation.

VEHICLE MODELING

Vehicle systems models were used to determine component sizes and evaluate improvements to vehicle control strategies. Advisor 3.2 and the PNGV Systems Analysis Toolkit (PSAT v4.1), were used to model the 2004 UC Davis FutureTruck.

Advisor was used to determine the approximate powertrain component sizing to meet basic vehicle performance criteria. Advisor also provided an estimate of the average power required for steady state driving, gradeability, trailer towing requirements, as well as expected fuel economy.

The backward-facing modeling system employed in Advisor determines the acceleration required throughout a driving cycle and calculates the powertrain torque required at each instant. In contrast, a forward-facing model such as PSAT employs a 'virtual driver' that compares the trace speed with the actual vehicle speed and compensates with an adjusted torque command. This latter method of modeling is a more realistic simulation of vehicle performance. Consequently, control strategies are more accurately modeled in PSAT.

PSAT component model and control strategy parameters were modified to better represent *Yosemite* components. A single Simulink S-Function encapsulated the C language Vehicle System Control (VSC) code. This enabled rapid development of control strategies as new algorithms could be easily tested in the simulation and transferred directly back to the vehicle without modification to the VSC code.

POWERTRAIN DESIGN

ENGINE SELECTION

The engine selection process focused on technologically advanced, high efficiency, low emission engines. Compression ignition (CI) engines have an advantage in thermal efficiency over spark ignition (SI) engines; however, minimizing criteria pollutants mandated the use of an SI engine. The researchers concluded that while modified CI engines might meet the strict emissions criteria in the future, several manufacturers already offer SULEV SI-powered models[iv].

Simulations determined that a minimum engine power of 90 kW was required to meet steady-state freeway targets. Suitable engine candidates were identified and benchmarked on efficiency, emissions, availability, technical support, packaging, and weight. A Saturn 1.9L DOHC (Dual Overhead Camshaft), was chosen as the ICE for the vehicle.

ENGINE MANAGEMENT

The stock engine control unit (ECU) was designed for use in a conventional vehicle, limiting its performance in a hybrid powertrain. A third party Motec M48 ECU was implemented to improve control over low-level engine operation. The Motec ECU allows for complete engine calibration for improvements in cold start emissions, as well as high-load conditions with fast-response, closed-loop Lambda control utilizing a Bosch LSM-11 wide-band oxygen sensor.

ENGINE COOLING SYSTEM

The engine cooling system was designed around an electric water pump (EWP), reducing parasitic engine losses, especially at high engine speeds. The EWP controller modulates pump speed to control the temperature of the coolant, providing significant additional power savings.

A double pass aluminum radiator, sized to match the engine, was packaged in the stock location. A single Spal 530L/s electric fan mounted on a shroud provides airflow when vehicle speeds are inadequate or when the Heating Ventilation and Air Conditioning (HVAC) system is active.

ELECTRIC MOTOR SELECTION

Vehicle simulations were used to set electric motor requirements. The UQM SR218N 75kW was chosen for the primary powertrain on the basis of efficiency and packaging.

A dual motor powertrain (one per axle) provides 4WD capability with improved traction, optimized regenerative braking, and enhanced drivability during transmission shifts. For the front powertrain, a directly coupled motor with a minimum gear reduction of 7:1 was required to achieve adequate braking force. A shortened 75kW UQM SR218HSS brushless DC permanent magnet motor was coupled to a transaxle with an incorporated helical gear reducer. The transaxle provided a 7.99:1 gear reduction, which met the required parameters. This system delivers a maximum of 1917Nm of wheel-end torque for acceleration and regenerative braking, and incorporates a set of WARN Integrated Wheel End disconnects (IWE's). By utilizing the IWE's, the half shafts can be disconnected from the wheel ends at high speed, or when motive power and braking are not required. The option to disconnect the front drive allows for improved fuel economy by reducing mechanical drag.

TRANSMISSION SELECTION

A manual transmission was chosen over a conventional automatic transmission for its higher efficiency and compact, lightweight packaging. Advisor Simulations showed that a five-speed manual transmission with a low first gear, a wide gear set, and a 4.10:1 differential would accommodate all driving requirements.

New Venture's 3550 five-speed manual transmission, with a 4.10:1 final drive met the vehicle selection criteria. Its torque capacity was sufficient to handle *Yosemite's* primary powertrain loads. The 3550 utilizes a top-mounted shift tower and does not have an integrated clutch housing. The presence of synchronizers in all forward gears, with special dual-cone synchronizers in first and second gear positions, makes shifting easier and smoother. Table 2 shows the reduction for each gear.

Table 2. Gear Ratios and Final Drives

Gear Number	Ratio	Final Drive
1st	4.02	16.47
2nd	2.32	9.50
3rd	1.40	5.74
4th	1.00	4.10
5th	0.78	3.19

POWERTRAIN IMPLEMENTATION

Limited underbody space and increased component volume (battery enclosure, electric drive systems, high voltage components) created packaging constraints. Full chassis, body, powertrain, and accessory CAD/CAE solid models assisted in packaging and allowed for effective mount designs, cooling line and wire routing, weight distribution, and maintenance access.

REAR WHEEL POWERTRAIN

The rear wheels are driven by a 1.9L DOHC Saturn engine and a 75kW UQM SR218H brushless permanent magnet electric motor, as shown in Figure 2. The total rear powertrain output is 167kW at 6000rpm with a maximum rear axle torque of 6669Nm at 2500rpm in first gear.

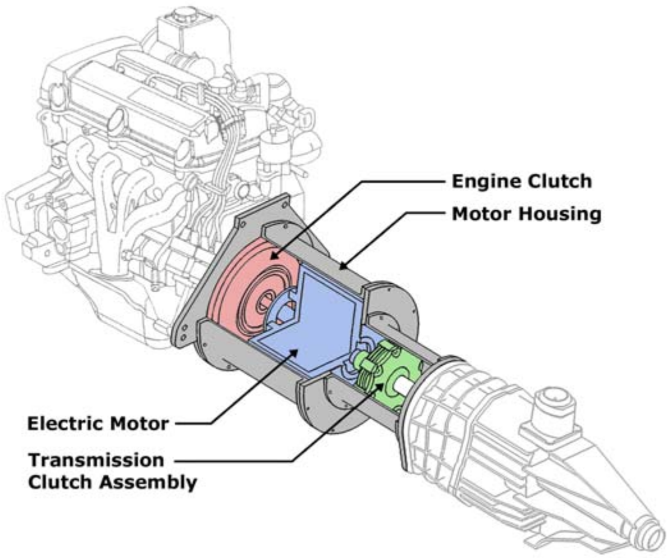

Figure 2. Primary powertrain diagram

Design of the motor and clutch housing was based on a force and moment analysis under peak torque loading. A structural housing was required to isolate the UQM motor from the reaction torque of the ICE, as the motor lacks a structural case. The housing aligns the electric motor with the engine output and provides an interface to the transmission. Plates were manufactured for the ICE, EM, and transmission to accommodate the different component bolt patterns. A shaft adapting the electric motor output to the transmission clutch was manufactured with hardened 4130 steel.

Space constraints dictated that the rear wheel powertrain be placed as high in the vehicle as possible. To accommodate this requirement, the transmission bell housing was designed to be as small as possible and the transmission tunnel was modified. A Tilton 14cm two-plate clutch was selected based on housing space constraints. This raised the rear wheel powertrain enough to accommodate the front axle electric drive system.

ENGINE MODIFICATIONS

Several significant engine modifications were performed. Due to a slight variation of engine orientation from the stock configuration, the coolant vent was relocated to the front of the cylinder head, requiring modifications to the water inlet housing of the engine block. Timing cover modifications were subsequently required to accommodate the new cooling vent. Separately, a required magnetic camshaft sensor was installed for proper Motec ECU operation. To reduce the mass of the engine block, extraneous mounting locations for components such as the power steering, and AC were removed.

EXHAUST SYSTEM

The stock cast iron exhaust manifold was replaced with a custom mild steel header. The 2.72kg header incorporates equal length runners and a close-coupled catalyst (CCC). The lightweight design lowered the thermal capacity of the header. A ceramic coating was applied to the manifold, increasing the exhaust gas velocity and improving heat retention. These attributes reduce catalyst light-off time, lowering cold-start emissions.

ENGINE CONTROL HARDWARE

The Motec ECU manages the injection and ignition of the ICE. The stock injection system was designed to operate on a conventional vehicle where the injection system enriches the air/fuel mixture in order to provide power during transient operating conditions and startup. These enrichments have been eliminated with the Motec calibration constants. Additionally, cold-start emissions have been eliminated as well, and tuning was performed to calibrate the Motec system for optimum emissions.

VEHICLE CONTROL STRATEGY

The vehicle control strategy manages the operation of the ICE and EM systems to provide optimal vehicle performance and efficiency through every operating condition. Performance criteria include increased fuel economy, reduced emissions, maximum component life, excellent drivability and transparent powertrain operation.

Four distinct vehicle operation modes, NORMAL, EV, 4WD and TOW, were introduced to meet these performance goals. NORMAL mode accommodates typical, low-load driving situations. 4WD mode is used when the vehicle requires more traction and power. EV mode is a driver-selected mode used if the driver expects to travel less than 45 miles (72.4km), and is not available when the battery state of charge has dropped to 20%. TOW mode is automatically triggered when the vehicle detects an attached trailer.

DRIVER INPUT AND CONTROL

The Powertrain Control Module (PCM) receives driver commands from the accelerator, brake, and clutch position sensors. The accelerator pedal commands a percentage of the total torque available, regardless of the vehicle operation mode. The brake pedal controls the amount of regenerative and mechanical braking while the clutch pedal position sensor informs the PCM of driver gearshifts.

NORMAL MODE

NORMAL mode is essentially two-wheel drive during propulsion and four-wheel drive during braking. Driving torque is provided primarily to the rear wheels while braking is accomplished by blending mechanical and regenerative braking. Regenerative braking is divided between front and rear EM systems.

NORMAL mode has three regions of operation, shown in Figure 4. The EV region, not to be confused with EV mode, is used for vehicle launch and lower speed driving. The charge depletion region uses a hybrid strategy that attempts to supply the vehicle load demand with ICE power operating at optimum efficiency while allowing use of the electric motor for acceleration. The engine does not actively charge the battery in this region, so state-of-charge (SOC) generally decreases. Charge sustaining operation actively maintains SOC above 20% when required.

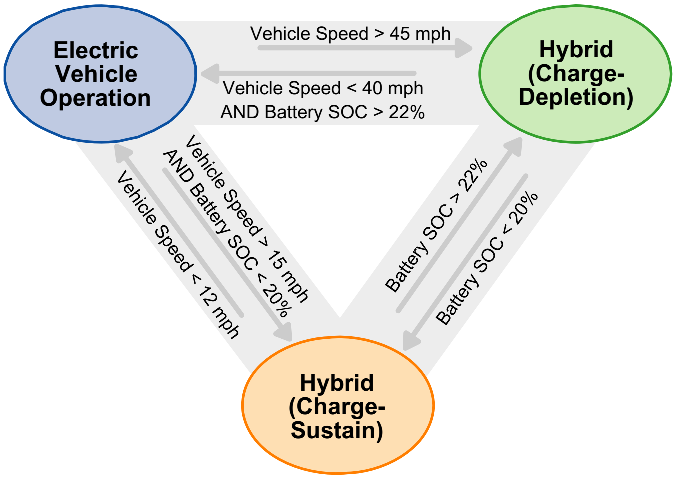

Figure 4. NORMAL mode operation.

NORMAL operating mode switches between these three regions based on feedback of vehicle speed, driver demand, and battery SOC. With sufficient battery SOC, the vehicle operates as an EV below the engine turn-on speed. Above the engine turn-on speed, the vehicle operates in the charge depletion region. When SOC drops below 20%, the engine turn-on speed decreases and the vehicle operates in the charge-sustaining region. The vehicle switches back to charge depletion operation when the battery SOC rises above 22%. The vehicle is always launched in the EV region.

The NORMAL mode includes a 'kick-down' feature that is triggered when the driver commands wide-open throttle. Under this condition, the controller commands full torque from all powertrain components, regardless of the vehicle speed or battery SOC. This feature is important to ensure that the driver can always access full powertrain torque in any NORMAL operating region.

4WD AND TOW MODES

The 4WD mode utilizes the same energy management strategy as the NORMAL mode, except that torque is split between the front and rear wheels during propulsion and braking. If either the front or rear torque commands approach saturation, the difference between the maximum torque and the torque requested is routed to the unsaturated powertrain to maintain consistent throttle response. TOW mode is a charge-sustaining hybrid mode that maintains a high battery SOC for towing.

EV MODE

EV mode disables the engine so the driver can make trips of up to 45 miles (72.4km) as a pure Zero Emissions Vehicle (ZEV). The same two-wheel drive propulsion and four-wheel drive braking algorithm from NORMAL mode is used in EV mode. The kick-down feature is identical to that of NORMAL mode, allowing engine engagement for emergency acceleration. When the battery state of charge has depleted to 20% the vehicle automatically switches to NORMAL mode to sustain battery charge.

VEHICLE ENERGY MANAGEMENT STRATEGY

The UC Davis energy management strategy maximizes EV distance traveled while maintaining the full range of a conventional vehicle. All operating conditions fall under two energy management strategies: a charge-depleting strategy and a charge-sustaining strategy. While the charge-depleting strategy allows the battery to deplete, the control system actively maintains battery SOC when operating in charge-sustaining mode.

During charge-depleting operation, the ICE engages when vehicle speed exceeds 45mph (72.4kph). This turn-on speed is chosen to maximize vehicle distance traveled. Regenerative braking uses the EM to capture the energy that otherwise would be lost in the mechanical braking system. During the charge-depletion mode only the energy recovered through regenerative braking charges the traction battery. Figure 5 illustrates the transition to charge-sustaining operation that occurs at low SOC. When this happens, the ICE turn-on speed is reduced to 15mph (24.1kph). During this mode of operation, the ICE generates more power than the driver requests, and the EM captures this extra power to maintain traction battery SOC.

The traction battery is likely to be charged externally before depleting below the charge-sustaining threshold. The plug-in hybrid concept stipulates that the traction battery is never fully recharged while driving because charging externally from a wall socket is more efficient. On long trips, range is only limited by fuel tank size.

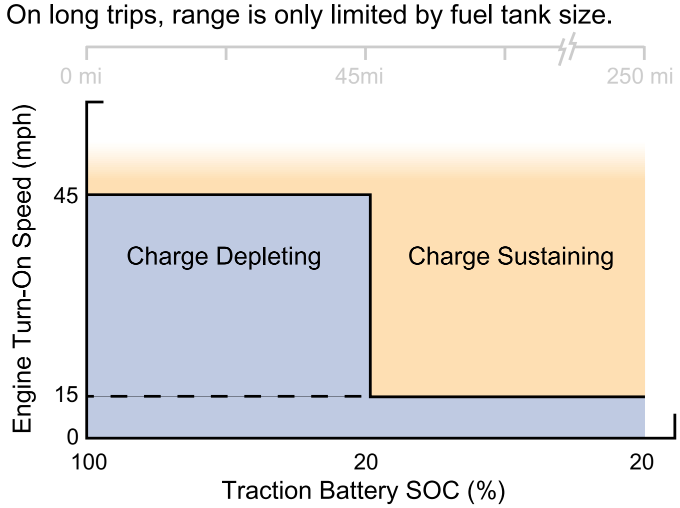

Figure 5. Charge sustaining, charge depletion regions.

GEAR SHIFTING STRATEGY

The Powertrain Control Module (PCM) determines current system efficiency based on quasi-steady-state component efficiency maps. The PCM constantly computes whether vehicle operation would be more efficient in the gear above or the gear below the current gear. If a different gear would be more efficient, the controller signals the driver to shift via shift lights in the instrument cluster.

POWERTRAIN CONTROL OPTIMIZATION

The PCM uses an artificial neural network (ANN) to continuously find optimum points of ICE and EM system operation, refining the powertrain blend based on internal system models. Optimization of powertrain control outputs for energy efficiency depends upon powertrain speed, driver torque command, battery SOC, and battery voltage.

Artificial neural networks are capable of approximating any function while using less space than a lookup table and calculating the result faster than an exhaustive search[v]. An ANN is used in the PCM to approximate the optimized powertrain torque map. The ANN supplements the powertrain control logic by determining the ideal operating settings for the ICE. While the ANN determines ideal settings, drivability is attained through conventional control logic. The large training time required by an ANN was done in simulation before integration into the vehicle.

CONTROL SYSTEM

DESIGN PHILOSOPHY

Yosemite features a UC Davis designed distributed control system. A majority of the stock vehicle's control modules have been removed, and the remaining stock controllers function independently or interact with UC Davis controllers. In this way, the UC Davis system functions as a dominant overlay.

The distributed architecture offers numerous benefits to the design process while improving system reliability, maintainability and reducing wiring complexity. Localized signal processing and control vastly reduces the potential for electromagnetic interference—a significant source of failure in vehicles employing electric traction systems[vi]. A distributed architecture requires control system functionality to be partitioned into modules at an early stage, facilitating the concurrent development of each module by independent workgroups.

SYSTEM ARCHITECTURE

Yosemite's control system is composed of networked, task-specific microcontroller modules. A Controller Area Network (CAN) bus provides fault-tolerant, deterministic-time control and data signaling at 250 kbps. The high-level powertrain and energy management strategy is executed by the Powertrain Control Module (PCM), a UC Davis designed module powered by a Motorola MPC565 microcontroller. The other controllers are a mix of modules containing either Motorola HC12 or HCS12 microcontrollers. An in-dash telematics system based on a National Semiconductor x86 processor provides an attractive Graphical User Interface (GUI) to vehicle occupants as well as an intelligent gateway to the vehicle's Internet Protocol (IP) network and the larger Internet.

CONTROL SOFTWARE

UC Davis designed a comprehensive set of software drivers for the series of microcontrollers. High-level application code is compact, readable and hardware-independent. In line with UC Davis's rapid development approach, the drivers reduce the amount of time that module developers must spend learning the intricacies of a microcontroller's hardware. Should a new microcontroller be chosen in the future, the driver's flexible Application Programming Interface (API) facilitates the easy migration of legacy code to the new platform. Support is integrated for advanced features such as soft power-moding and firmware programming over the CAN bus.

ELECTRONIC THROTTLE CONTROL

A conventional vehicle produces a significant portion of its emissions during transient operation. Yosemite's electronic ICE throttle is decoupled from the accelerator pedal, enabling the PCM to keep the ICE on its ideal operating line while commanding the EM to handle transient demands. The results of this system are a cleaner, more efficient vehicle.

A Visteon Electronic Throttle Body (ETB) is driven by the UC Davis designed, CAN connected Electronic Throttle Controller (ETC). In the event of a power or communication failure between the PCM and ETC, fail-safe conditions disable fuel injection and double return springs ensure that the throttle fully closes.

FUEL SYSTEM

The fuel system was designed to be compatible with the corrosive nature of E85 and to provide the increase flow rate necessary to compensate for E85's lower energy density as compared to RFG. The lower heating value (LHV) of RFG is 31.5MJ/L, while the LHV for E85 is 28% lower at 22.6MJ/L. The increase in static flow needed to compensate for the LHV of E85 is represented in the following equation:

$$v_{85} = 1 - \frac{RFG_{A/Fratio}}{E85_{A/Fratio}} = 1 - \frac{14/7}{10} = 45.5\%$$

To accommodate the higher required fuel flow rate, the original Delphi fuel injectors (176cc/min) were upgraded to 225cc/min injectors. Fuel system pressure was increased from 2.96 to 3.44 bar to improve atomization.

FUEL SYSTEM HARDWARE

Yosemite's fuel system hardware was selected to ensure corrosion resistance to ethanol-based fuels, reduce evaporative emissions, and to allow quick removal of the fuel tank. All flexible fuel lines are composed of a braided stainless steel hosing with a Teflon inner core. The fittings are Army-Navy (AN) style anodized aluminum. Zero-loss quick-release disconnects allow easy and quick tank removal. A 9.5mm hard-line routed along the inner passenger side frame rail, delivers fuel from the tank to the regulator and returns excess fuel back into the tank. Fuel is delivered by an ethanol compatible gerotor style Mallory fuel pump that delivers 36GPH through a high flow stainless steel mesh fuel filter. Both the fuel filter and pump are mounted on the rear passenger side frame rail. An integrated charcoal canister relieves tank pressure and is purged by the stock Saturn evaporative emissions system.

FUEL TANK

The position of the stock Ford Explorer's fuel tank – under the passenger floorboards on the inside of the frame rail – could not be maintained due to the placement of the battery pack. The new fuel tank is located between the frame rails behind the rear differential. The tank was designed around the existing spare tire and spare tire cranking mechanism in order to maximize volume and not encroach upon the rear crumple zone. The tank was manufactured from stainless steel, ensuring no reaction between the ethanol and the tank.

EMISSIONS CONTROL

The stringent SULEV emissions standard requires a system approach to emissions control. *Yosemite's* emissions control strategy combines a sophisticated engine management system, high-level hybrid systems control strategy, and a sophisticated exhaust after-treatment system. A system analysis resulted in the following list of key areas to address:

1. Minimize cold start hydrocarbon (HC) emissions.
2. Transient control of HC emissions, especially during hybrid stop-start operation (warm starts).
3. NO_x emissions at high engine load.
4. CO emissions during engine startup and at load

Yosemite's exhaust aftertreatment system consists of a CCC, a metal foil EHC, and a larger underfloor catalyst, Cold start emissions are handled by the EHC, a 186 cell per square centimeter metal foil unit with a .04mm wall thickness. The low thermal mass of this design provides a faster warm-up and a high surface area for improved gas interaction[vii,viii]. The 12-volt catalyst reaches a light-off temperature of 275°C in 30 seconds. The EHC is controlled by the Active Emissions Module (AEM) which monitors catalyst temperature and fires the EHC to maintain light-off temperatures for engine operation.

TRACTION BATTERY

Selection and integration of the traction battery is important in maximizing the efficiency, emissions characteristics, and cycle life of an HEV. The batteries must have a high specific energy to provide adequate storage for a significant all-electric range. A high specific power is required for maximum recovery of regenerative braking energy and full power accelerations. A high energy density minimizes packaging and weight requirements.

BATTERY SELECTION

A Nickel Metal Hydride (NiMH) battery pack from Ovonic Battery Company was selected for its high energy and power density characteristics, as well as its sealed cell design, illustrated in Figure 6. The battery pack consists of 24 11-cell modules. Module capacity is 50 Ahr and pack voltage is 317V.

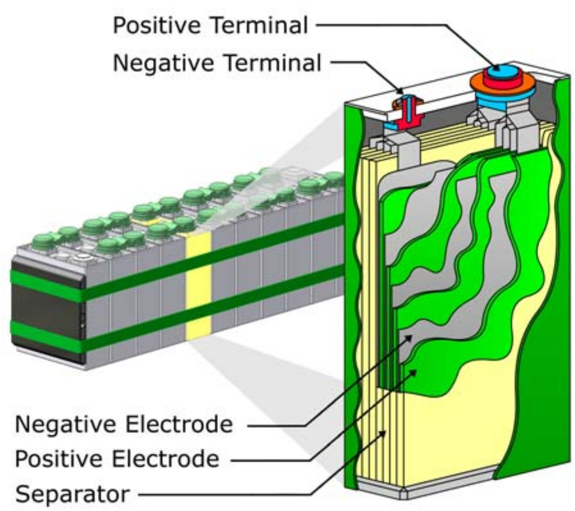

Figure 6. Ovonic NiMH battery cell[ix].

This specific NiMH chemistry demonstrates up to 750W/kg of peak power density. These high power batteries are extremely efficient, and are capable of battery energy in-out efficiencies exceeding 93%. The moderate energy density of 55Whrs/kg provides an all-electric range of up to 45 miles (72.4km).

BATTERY INTEGRATION

The traction battery pack was integrated to maintain the structural integrity and safety systems of the vehicle. The traction batteries are split into two packs of 12 modules each. These packs are located between the frame rails on either side of the rear driveshaft. This arrangement of the batteries allows for even distribution of the weight across the centerline of the vehicle, while lowering vehicle center of gravity by 5cm, improving vehicle stability. The base of the battery pack is higher than the low point of the frame rails, maintaining high ground clearance and allowing the frame to act as vertical and side impact protection. The battery packs are mounted on two cross members between the frame rails. A 1.25cm clearance between the battery pack and the frame allows for frame flexure and pack movement.

BATTERY ENCLOSURE FABRICATION

Battery enclosure geometry is driven by the curvature of the frame rails to accommodate the Independent Rear Suspension system, shown in Figure 1. The enclosures must package 24 battery modules and provide sufficient plenum geometry for uniform battery cooling while packaging compactly within frame rails and between the transmission mount and rear differential.

Designed to incorporate low-mass, high strength, and safety, the battery enclosures were constructed from composite materials. The layering for the enclosure is shown in Figure 7. The outermost layers are carbon fiber and integrated closed cell polyurethane foam with rectangular cross-section for increased longitudinal stiffness. The bottom surface has a thin layer of structural foam, which increases enclosure rigidity and safety from vertical impact. The interior of the enclosure is lined with fiberglass to electrically isolate the batteries from chassis ground. To reduce stress concentrations at the outer edges of the enclosure, strips of angled foam were incorporated.

To allow for airflow below and around battery modules, four fiberglass box tubes raise the battery modules above the floor of the battery pack. The spacing between the batteries is retained using machined ABS plastic trays, while the top of the batteries are secured using tie-downs across the row of modules. These two methods of securing the batteries ensure that there will be no vertical or planar module movement. Mounting flanges are reinforced with aluminum strips to prevent bolts wearing through the composite layers over time.

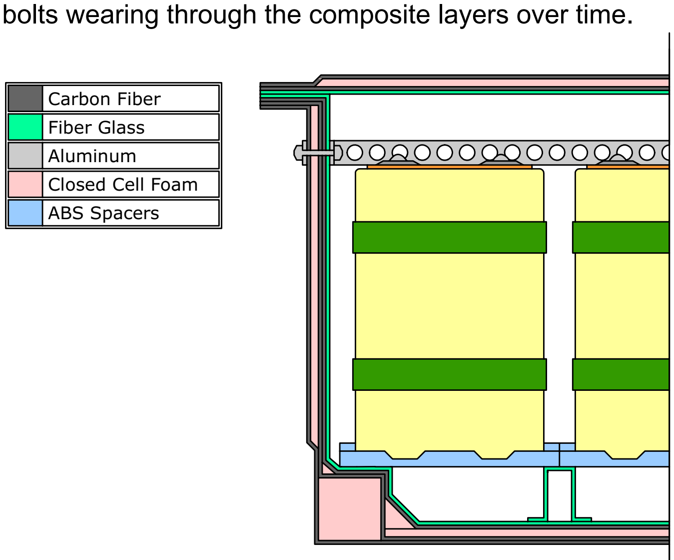

Figure 7. Battery enclosure cross section.

THERMAL MANAGEMENT

The battery thermal management system is designed to meet temperature specifications set by the Ovonic Battery Company. Filtered air is drawn into the batteries through an HVAC evaporator at the lower front of the battery box. Two 245L/s fans, controlled by the CCM, draw cooling air longitudinally through the battery enclosure, exceeding the recommended minimum airflow requirements. Air exits through ducts located near the top rear of each battery pack, preventing gas build-up. In addition, the inlet volume is lower than the exit volume so that the pressure drop is constant through the length of the enclosure. The BMS requests battery cooling, proportional to average module temperature, from the CCM. If battery cooling by the CCM alone is insufficient, the BMS also requests conditioned air from the HVAC system. In the case of continued temperature increases, the PCM limits battery current preventing battery pack damage.

BATTERY CHARGING

Battery charging is performed via the Ford EV-Ranger conductive charger. This charger is capable of charging the battery from 20% (minimum SOC) to 100% SOC in 2.4 hours from a 240V outlet and 10.2 hours from a 120V outlet. The lower voltage option reduces home infrastructure costs and provides for more convenient charging sites, as an electrical plug and cord are all that is needed.

HIGH VOLTAGE SYSTEM

A robust high voltage system design is critical to vehicle reliability and safety. *Yosemite's* traction battery pack is electrically isolated from the vehicle by internal contactors under the control of the BMS. A central high voltage distribution box supplies power to each load. Fusing is located within the battery box to ensure complete isolation during serious shorting conditions. An interlock loop passes through each high voltage connector as well as inertial and emergency disconnect (EDS) switches. The battery contactors will open if the interlock look is interrupted. A controlled high voltage start sequence prevents this system from repeated hard starts in the case of transient interlock failures.

ACCESSORY SYSTEMS

INSTRUMENT CLUSTER

The stock instrument cluster (IC) was intended for a conventional vehicle and would not convey the status of the hybrid powertrain to the driver without significant modification. A new instrument panel was designed to better communicate the status of the hybrid vehicle systems information while simplifying the physical and control system integration process. The instrument cluster design fully complies with Federal Motor Vehicle Safety Standards sections 101 and 102[x].

Using the stock IC housing and designing a new graphic overlay with the same dimensions simplified integration of the new instrument panel. The new IC design incorporates programmable stepper-motor modules, which provide a high-level software interface to each gauge on the instrument panel. Electro-luminescent material is used for the backlight, saving power over traditional incandescent backlighting. Only five electrical signals are needed to provide the necessary information to the IC, greatly reducing wiring complexity. Information formerly provided by the stock vehicle's networks along with discrete signals are now provided by the CAN bus.

The new dashboard includes an innovative power meter that gives the driver an intuitive feel for power flow in the vehicle. More comprehensive vehicle information is available on an integrated dot-matrix vacuum-fluorescent display (VFD). The VFD can display several screens including a trip computer, navigational cues, and powertrain energy flows. Three buttons on the steering wheel scroll through the display screens. Critical indicators for system faults and safety problems override the default displays when necessary.

Figure 8. Dashboard instrument cluster

CLIMATE CONTROL SYSTEM

The HVAC system is the largest accessory load. Electric air conditioning (AC) systems have proven to be more efficient than engine-driven systems[xi]. A Sanden electric compressor replaces the stock mechanical AC compressor. The Sanden system is a scroll compressor with a 600rpm - 7800rpm speed range, a 33cc displacement and an inverter operating at 320VDC. An electric compressor is more flexible as it is not engine driven and provides cooling independent of engine speed.

The compressor housing is an integrated motor/compressor assembly, which reduces risk of refrigerant leakage compared to a conventional system. The 4kW DC brushless motor has a cooling capacity of approximately 6kW (20,000 BTU/hour).

A HeaterCraft hybrid heater core replaced the stock heater core. The hybrid heater core allows for heating during both EV and HEV vehicle operation. During EV vehicle operation the heater core is electrically heated through the 42V system. The heater core uses engine waste heat during HEV vehicle operation as a conventional heater core.

The HVAC Control Module (HCM) receives passenger commands through the stock dashboard HVAC controls. The HCM operates in two modes: manual and automatic. In automatic mode the HCM maintains the cabin at a passenger specified temperature. Automatic mode allows for more precise temperature control, resulting in lower power consumption. Manual mode allows the user to specify heating or cooling, but not final temperature of the cabin.

POWER STEERING

A high-voltage electric power steering unit from a Ford EV-Ranger replaced the engine-driven stock unit. The electric power steering unit adjusts fluid pressure according to steering angle rate of change and vehicle speed. The stock rack-and-pinion steering is maintained without modification.

BODY AND CHASSIS MODIFICATIONS

MASS REDUCTION

Vehicle mass is an important factor in vehicle efficiency and safety. A modest mass reduction program was implemented to offset the added mass of the traction battery and other electric drive components. Use of lightweight composite materials and aluminum were key components of mass reduction, including: composite running boards and mounting brackets, as well as enclosures for high voltage components. The composite components are able to provide the strength and rigidity required, at a much lower mass than their metallic counterparts. Powertrain mass reductions include a lightweight engine flywheel and clutch, removal of extraneous casting material, integrated accessory mounts, and the engine thermostat housing.

VEHICLE DRAG

Aerodynamic modifications were considered that could provide a measurable improvement in vehicle drag coefficient without compromising the external appearance or integrity of the vehicle body. Research shows that after body drag at the rear of the vehicle is a significant factor in total drag. Reductions in after body drag can improve overall vehicle drag coefficient by up to 9%[xii].

An active front valence (AFV) provides additional down force at higher vehicle speeds. By deploying a composite section at the bottom of the valence once the vehicle reaches the turn on speed of 40 mph, vehicle aerodynamics can be varied. This results in an increase in vehicular stability at higher speeds, as well as reducing the aerodynamic drag on the vehicle, yielding an increase in fuel economy.

The stock Michelin P235/70R16 tires were replaced with more efficient Goodyear P255/70R16 Wrangler RT/S tires, reducing the tire coefficient of rolling resistance (C_{rr}) from 0.0078 to 0.0060.

CHASSIS MODIFICATIONS

Modifications were made to the frame cross members. Cross members 3a and 3b were removable without compromising structural integrity. Cross members 1b and 2 were removed and replaced with A (a mount for the Enova motor,) and B (a high voltage battery pack and transmission mount), respectively. Cross member C was added as a rear high voltage battery pack mount. These modifications are detailed in Figure 9.

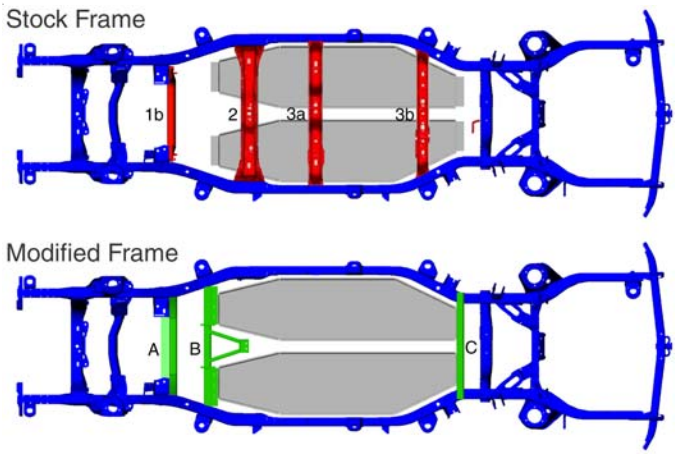

Figure 9. Frame modifications

SUSPENSION AND BRAKES

The stock suspension system was preserved wherever possible to maintain the stock Explorer ride and handling characteristics. Due to the location of the front powertrain, the front sway-bar was replaced with a custom manufactured torsion bar. The design utilizes a tubular torsion bar with adjustable rod ends to reduce weight and replicate stock spring rates.

The front wheel ends were modified to accommodate the SR218HSS motor. Due to the direct coupling of the motor to the wheels, vehicle top speed will be limited by the maximum rotational speed of the motor. Accordingly, a vacuum actuated wheel end disconnect has been implemented into the vehicle, allowing for a higher top speed as well as reducing the mechanical drag at higher speeds. The motor can then be coupled to perform regenerative braking or motive force once the vehicle speed has dropped below the maximum motor rotation.

Yosemite's braking system is enhanced through regenerative braking from the dual traction motors. When the brake pedal is depressed, initial braking force is generated by a ramp increase in negative torque from the electric motors. Torque is blended between front and rear systems. Mechanical braking is blended in with further pedal travel. Vehicle efficiency is improved by capturing a portion of the vehicle's kinetic energy with no overall loss in braking performance.

Full mechanical braking power is maintained by the addition of an electric vacuum pump that supplies a constant vacuum to the brake booster.
manufacturability and cost potential

COST ANALYSIS

There are many difficulties inherent in a cost analysis of an advanced vehicle design. Validated component cost data are difficult to determine accurately. Two significant efforts to understand and develop cost models for calculating Retail Price Equivalent (RPE) for advanced vehicles were undertaken by Cuenca, et al[xiii]. and Graham, et al[iii]. The steps for developing the cost model methodology include:

1. List conventional powertrain component costs.
2. Develop cost relationships for advanced system components.
3. Finalize vehicle glider cost (without powertrain).
4. Perform cost optimization during design process.
5. Calculate RPE of advanced vehicle design.

This cost model, in 2004 dollars, assumes a production volume of roughly 100,000 vehicles. Subtracting the costs of the deleted conventional components results in an estimated glider list price of $24,238. Adding the hybrid drive components featured in *Yosemite* and the telematics system raises the final predicted list price of the vehicle to $43,077.

The cost formulae for these components are linear approximations. The added components are then marked up by a factor of 1.5 to 2.0 to arrive at the predicted RPE.

The battery cost assumption used for this model was $280 per kWhr of energy storage. This assumption is drawn from cost/volume data compiled from several battery manufacturers[xiv]. Recent aggressive development in the field of advanced batteries indicates that mass production of all types of HEVs has the potential to lower prices to this level.

Table 3. Cost breakdown of stock and hybrid Explorer

Vehicle System	Stock XLT	Yosemite HEV
Explorer XLT Glider	$ 24,238	$ 24,238
Engine	$ 5,904	$ 3,524
Transmission	$ 2,400	$ 1,500
Transfer Case	$ 1,200	$ 0
Accessory Power	$ 488	$ 608
Electric Traction	$ 100	$ 4,900
Energy Storage System	$ 60	$ 6,617
Charging System	$ 0	$ 690
Telematics System	$ 0	$ 1000
Total Vehicle List Price	$ 34,390	$ 43,077

MANUFACTURING ISSUES AND POTENTIAL

Yosemite is intended for production on a standard U152 production line. The advanced hybrid drive systems are designed to replace existing powertrain components with similar packaging and mounting requirements. The design layout of the vehicle does not impact interior cabin volume or compromise the vehicle structure.

There are a number of important manufacturing issues that govern the introduction and market potential of hybrid electric vehicles. Crucial issues include the cost and longevity of advanced battery chemistries and the cost of high-power electric drive systems. Component manufacturers are striving to reduce the cost of these advanced systems. The *Yosemite* powertrain concept is highly compatible with the U152 platform. An ambitious program could conceivably bring this powertrain to production in a three-year period, culminating in the launch of an HEV Explorer based on the *Yosemite* concept in 2007 with an estimated list price of $43,077.

INTENDED MARKET

The UC Davis *Yosemite* is a premium sport-utility vehicle. Its buyers will demand class-leading power and performance, but will also appreciate the strong environmental statement made by the vehicle. Many of the first buyers will be technological early adopters intrigued by the hybrid drive system, dual use of electricity and flex-fuel, and telematics system. The vehicle is naturally positioned in the Explorer line above both the XLT 4.0L SOHC V-6 and the Eddie Bauer 4.6L SOHC V-8, as it surpasses both vehicles in acceleration performance, drivability, and fuel economy. Figure 10 and Table 4 illustrate *Yosemite's* premium performance compared to a BMW X5 4.4i V-8 with a list price of $54,000. The two electric drive systems provide exceptional low-end torque and outstanding acceleration performance across the board.

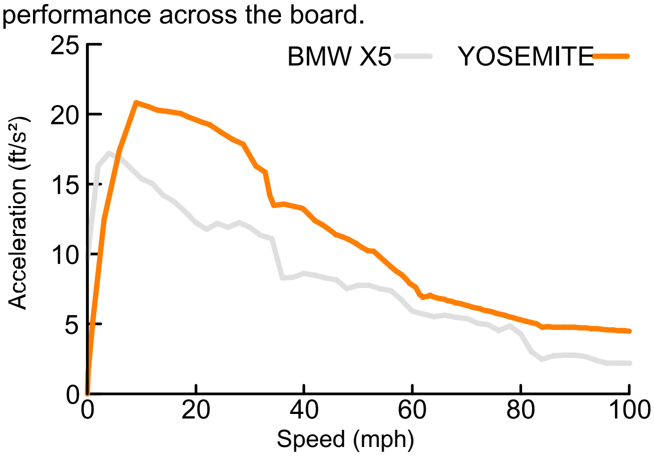

Figure 10. Acceleration comparison with BMW X5

Table 4. Acceleration comparison with BMW X5

Event	BMW X5	YOSEMITE
0 -30 mph	3.49	2.81
40 - 60 mph	3.92	3.01
0 - 60 mph	8.99	7.05
60 - 80 mph	5.76	5.48
1/8 mile	10.92	9.92
1/4 mile	16.65	15.15

The estimated list price of $43,077 is significantly higher than the Explorer XLT at $34,390 but similar to the Explorer Limited V8 at $43,325. This figure is comfortably within various manufacturer SUV list prices, and far below the class ceiling of $68,645 (BMW X5 4.6is). It is envisioned that the strong performance and unique technological appeal of this hybrid Explorer will demonstrate significant customer pull from other manufacturers. In addition, the environmental appeal of the vehicle's design will augment the brand name across the board.

CONCLUSION

The UC Davis FutureTruck team has developed a premium hybrid powertrain system for a 2002 Ford Explorer. The resulting vehicle, *Yosemite*, uses both renewable E85 and grid electricity to offer outstanding performance with minimal environmental impact. Energy efficiency predictions for *Yosemite* are shown in Table 5 below

Table 5. Energy efficiency predictions for Yosemite

Yosemite Energy Efficiency Modeling	EV Mode Range (mi)	Electric Energy Efficiency (Wh/mi)	Normal Mode Charge-Sustain HEV (mpgge)
Urban (UDDS)	49.51	302.6	32.1
Highway (HFET)	49.50	304.4	36.3
Highway (US06)	31.89	469.8	23.9

Safety considerations were dominant throughout *Yosemite's* design. Fabricated components underwent rigorous stress and failure analysis prior to implementation. The high voltage and control systems are designed for fail-safe operation. Consumer-oriented features such as the auxiliary vision and enhanced brake light systems further complement safety.

Yosemite's EV range of 45 miles can account for 54% of average annual miles driven. Its high equivalent fuel economy and ability to use renewable E85 fuel dramatically reduces the petroleum consumption and greenhouse gas impact of the vehicle. The vehicle's uncompromising performance and ability to drive extended distances in charge-sustaining mode, even while towing a trailer, maximize its utility.
Preliminary cost estimates indicate that this vehicle will cost approximately $8,687 more than a stock Explorer XLT. Wide pricing latitude in the SUV market combined with the premium performance and appeal of *Yosemite's* unique technology ensures a promising market potential.

REFERENCES

[i] .California Air Resources Board, "Description and Rationale for Staff's Additional Proposed Modifications to the January 10, 2004 ZEV Regulatory Proposal," March 5, 2004.

[ii] Wang, Michael, GREET 1.5a, Center for Transportation Research, Argonne National Laboratory, August, 1998.

[iii] Graham, R. *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options,* EPRI, Palo Alto, CA: 2001. 1000349

[iv] California Air Resources Board, "2003 Model Year Guide to Passenger Cars", 2003.

[v] Mitchell, T. M. (1997). *Machine Learning*. WCB/McGraw-Hill: Boston.

[vi] Ott, Henry W. *Noise reduction Techniques in Electronics Systems*. John Wiley & Sons, Inc. New York. 1988

[vii] Lafyatis, D.S., et al., "Use of High Cell Density Substrates and High Technology Catalysts to Significantly Reduce Vehicle Emissions", SAE Paper 2000-01-0502

[viii] Umehara, Kazuhiko, et al., "Prediction of Catalytic Performance for Ultra Thin Wall and High Cell Density Substrates", SAE Paper 2000-01-0494

[ix] GM Ovonic LLC, "The NiMH Choice", Troy, MI

[x] U.S. Department of Transportation, *Federal Motor Vehicle Safety Standards and Regulation,* Washington, DC

[xi] Bessler, Warren, et al., Electrically Driven Automotive Air Conditioner, presented at the International Congress and Exposition, Detroit, MI, February, 1987

[xii] Lansesr, W., Ross, J. Kaufman, A. "Aerodynamic Performance of a Drag Reduction Device on a Full-Scale Tractor/Trailer." SAE 912125

[xiii] Cuenca, R.M., et al., "Evaluation of Electric Vehicle Production and Operating Costs," Argonne National Laboratory, November 1999, ANL/ESD-41.

[xiv] California Air Resources Board, "2000 Battery Technical Advisory Panel – Final Report," 2000.