Design and Development of the 2003 UC Davis FutureTruck

William Allan, Charnjiv Bangar, Christopher Cardé, Aashish Dalal, Dahlia Garas, Joseph Holdener, Nathaniel Meyr, Christopher Nitta, and Andrew Frank

University of California, Davis

ABSTRACT

Yosemite is an advanced hybrid electric vehicle built on the Ford U152 Explorer platform. The University of California, Davis FutureTruck team designed *Yosemite* to meet the following objectives:

1. Maximize vehicle energy efficiency
2. Reduce petroleum consumption by 80%
3. Reduce fuel cycle greenhouse gas emissions by 67%
4. Achieve California Super Ultra Low Emission Vehicle (SULEV) target
5. Deliver best-in-class performance

Yosemite meets these goals with an efficient hybrid powertrain, improved component systems, and an advanced control system. The primary powertrain combines a 1.9L flexible fuel engine with a 75kW brushless DC motor. A 60kW AC induction motor and reduction transaxle gearbox drives the front wheels. This powertrain configuration is compact, reliable, provides 4WD, and allows flexibility in control strategy. A 16.5kWh nickel metal-hydride traction battery pack powers the electric motors, providing up to 45 miles (72.4km) of all-electric range and the ability to tow cross-country without recharging. The high power hybrid powertrain allows *Yosemite* to achieve high efficiency under normal operating conditions while exceeding V8 Explorer performance in all categories. *Yosemite's* superior fuel economy, low operating cost, and high performance, combined with advanced composites and telematics make it a desirable and competitive vehicle in today's growing market for advanced vehicles.

INTRODUCTION

The University of California, Davis FutureTruck team is participating in the 2003 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 challenges 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 must be met without compromising vehicle safety, performance, utility, or value. In addition, UC Davis focuses on qualifying for 80% Partial Zero Emissions Vehicle (PZEV) credit under the California Low Emissions Vehicle II amendment[1]. UC Davis will compete in the 2003 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 2003.

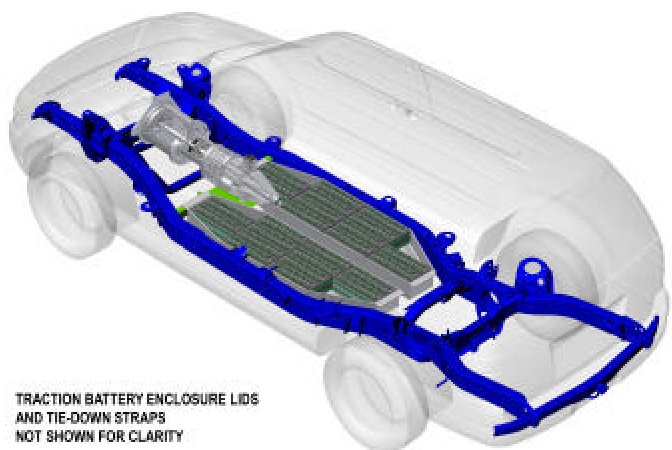


Figure 1. Yosemite design layout.

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 N_2O) which suggests the use of electricity as the primary fuel due to its low fuel-cycle emissions[2]. A charge-depletion control strategy maximizes electricity 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 excellent 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. A *series* hybrid configuration was eliminated due to unnecessary, inefficient energy conversions. A *dual-hybrid* design has lower conversion losses than a series configuration, but is costly, heavier, and mechanically complex. Ongoing research at the UC Davis HEV Center has demonstrated that a *parallel* hybrid configuration is 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 is sized to meet steady state highway loads while the EM is used for low speed driving and transient conditions. Therefore, the size of the ICE can be greatly reduced in comparison to the stock vehicle. This allows the engine to operate at higher average thermal efficiency and within its ideal operating region, increasing fuel economy.

Reducing ICE size necessitates an increase in available electric power. To compensate, *Yosemite* uses a high capacity battery pack and a powerful electric drive system. The size of the battery pack was motivated by an Electric Power Research Institute (EPRI) study indicating that over 54% of US motorists drive 45 miles (72.4km) or less daily[3]. Realizing zero tailpipe emissions over this range implies plug-in, zero emissions capability, improving the air quality of densely populated regions.

An all-electric, independent front powertrain provides 4WD capability and maximize 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) 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[2].

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 efficient 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 idle 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 2003 UC Davis FutureTruck.

Advisor was used to determine the approximate powertrain component sizing to meet basic vehicle performance criteria. Advisor also provides an estimate of the average power required for steady state driving, gradeability, trailer towing requirements, and 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 employs a 'virtual driver' that compares the trace speed with the actual vehicle speed and compensates with an adjusted torque command. This method of modeling is a more realistic simulation of vehicle performance. Consequently, control strategies are more accurately modeled in PSAT, a forward-looking modeling system, than in Advisor.

PSAT component model and control strategy parameters were modified to better represent *Yosemite*. A single Simulink S-Function encapsulated the C language Vehicle System Control (VSC) code. This enabled rapid development of VSC 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 mandates use of an SI engine. There is currently little, if any published evidence that production CI engines can meet the strict SULEV standard in the near future, while several manufacturers already offer SULEV SI-powered models[4].

Simulations determined that a minimum engine power of 90 kW was required to meet steady-state grade and towing targets. Suitable engine candidates were identified and benchmarked on efficiency, emissions, availability, technical support, packaging, and weight. The final candidates were the Nissan 1.8L SULEV, Saturn 1.9L DOHC (Dual Overhead Camshaft), and the Ford 2.0L Zetec. Figure 2 compares the engine specifications based on the aforementioned criteria. Each candidate engine meets the target specifications, having similar efficiency, power output, packaging size, and weight. The 2.0L Zetec has the highest power, but each engine exceeded the 90 kW target for steady-state power while delivering high average efficiency for charge-sustaining operation. The Nissan 1.8L SULEV had a significant advantage in engine emissions. The deciding factor in favor of the Saturn 1.9L was the availability to UC Davis of the OEM engine calibration data, allowing the implementation of a custom engine controller calibrated to function as part of the UC Davis hybrid powertrain.

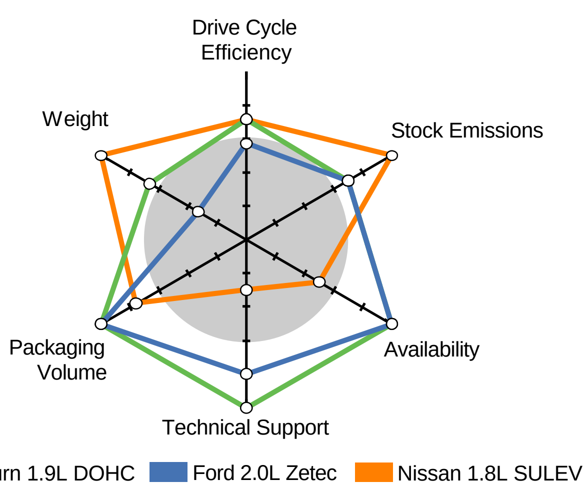


Figure 2. Engine specifications.

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 complete engine calibration for improvements in cold start emissions, high-load conditions with fast-response closed loop Lambda control using a Bosch LSM-11 wide band oxygen sensor.

ENGINE COOLING SYSTEM

The engine cooling system is 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 Saturn 1.9L, 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. Three of the system candidates are shown in Figure 3: UQM SR218N 75kW, Enova Systems Panther 60kW, and the AC Propulsion AC150. The UQM SR218N was chosen for the primary powertrain on the basis of efficiency and packaging.

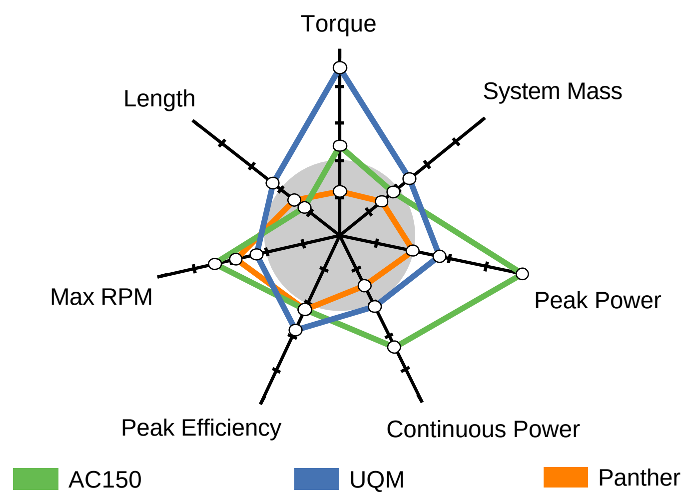


Figure 3. Primary electric drive selection chart.

A dual motor system (one per drive axle) provides 4WD capability, 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. The 60kW Panther was best suited for the front application as it offered a fully integrated system with electric motor, gear reduction, and differential in a transaxle configuration with a two-step 7.99:1 helical gear reduction. The system will deliver 1270Nm of wheel torque for both traction power and regenerative braking functions. The Enova motor control system includes integrated charging, battery management, and high voltage DC-DC down-converters for 12 and 42 volts.

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. The three candidates were the Borg-Warner T5, the Richmond 5-speed, and the New Venture 3550. Figure 4 shows the relative rankings of each transmission.

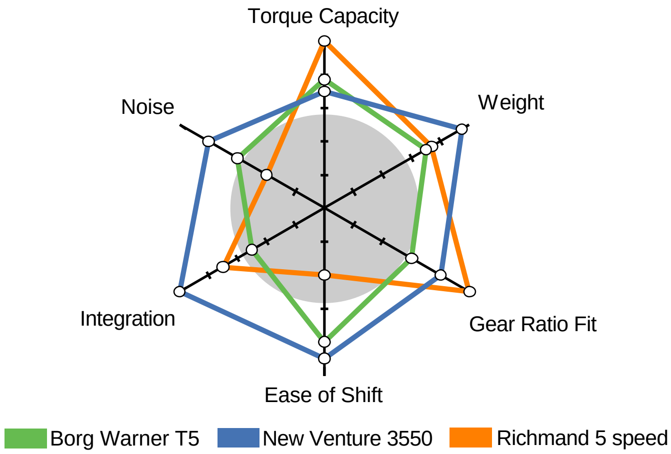


Figure 4. Transmission selection chart.

New Venture's 3550 five-speed manual transmission, with a 4.10:1 final drive met the vehicle selection criteria. Its torque capacity is sufficient to handle *Yosemite's* primary powertrain loads. The 3550 uses 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 5. The total rear powertrain output is 167kW at 6000rpm with a maximum rear axle torque of 6669Nm at 2500rpm in first gear.

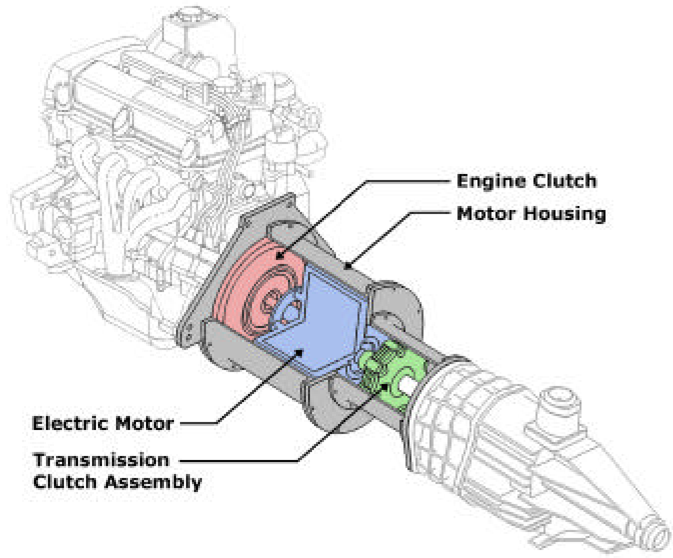


Figure 5. Primary powertrain diagram.

Design of the motor and clutch housing is based on a force and moment analysis under peak torque loading. A structural housing is 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 4140 chrome-moly steel. The housings and plates were manufactured from 6061-T6 aluminum.

To insure the rigidity of the assembled powertrain, a static analysis was performed with the powertrain treated as a simply supported beam. The analysis yielded the shear forces and bending moments on each component. These values were then used to analyze solid models, drawn in AutoDesk Inventor, and then transferred to CosmosWorks for finite element analysis (FEA). The results are provided in Table 3 and APPENDIX A.

Table 3. Primary Powertrain Design Results.

Component	Factor of Safety for Yield
Torque Tube	3.5
Clutch Housing	6.2
Trans. Mounting Plate	5.3
EM Mounting Plate	5.8
ICE Mounting Plate	14

ICE Coupling Shaft	2.7
EM Flywheel Flange	12

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. 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.

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.

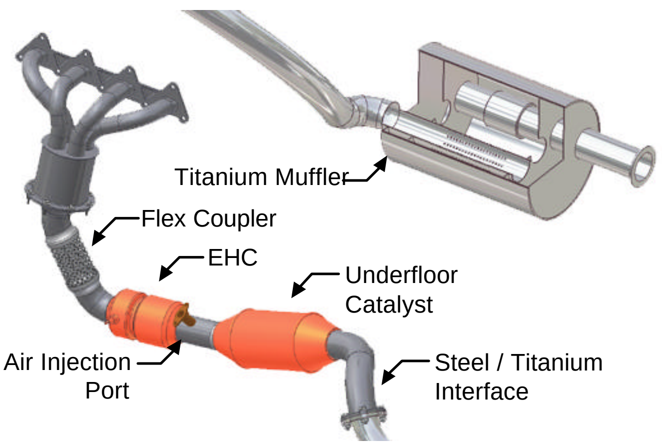


Figure 6. Exhaust system.

The exhaust system is shown in Figure 6. A flexible coupler was incorporated after the CCC to reduce powertrain-induced NVH (Noise Vibration and Harshness). The Electrically Heated Catalyst (EHC) follows the coupler and the air-injection port is positioned in front of the underfloor catalyst.

A titanium muffler system was designed and fabricated to complete the exhaust system. Using Bond Graph modeling, the muffler volume, resistance, and wall mass were tuned to suit *Yosemite's* ICE characteristics[5]. Figure 7 shows the flow ratio versus frequency of the stock and UC Davis designed mufflers. The new design demonstrates improved acoustic response while imposing essentially no change in backpressure.

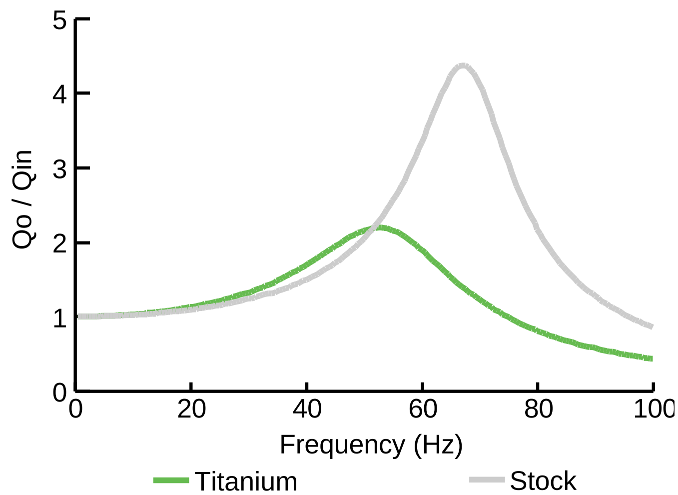


Figure 7. Flow ratio versus frequency.

ENGINE CONTROL HARDWARE

The Motec ECU manages the injection and ignition of an 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 are eliminated with the Motec calibration constants.

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 8. 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 motors for acceleration. The engine does not actively charge the battery in this region, so state-of-charge (SOC) generally decreases. PSAT and Advisor simulations show that regenerative braking, while recovering significant energy, is typically not enough to sustain SOC alone. Charge sustaining operation actively maintains SOC above 20% when required.

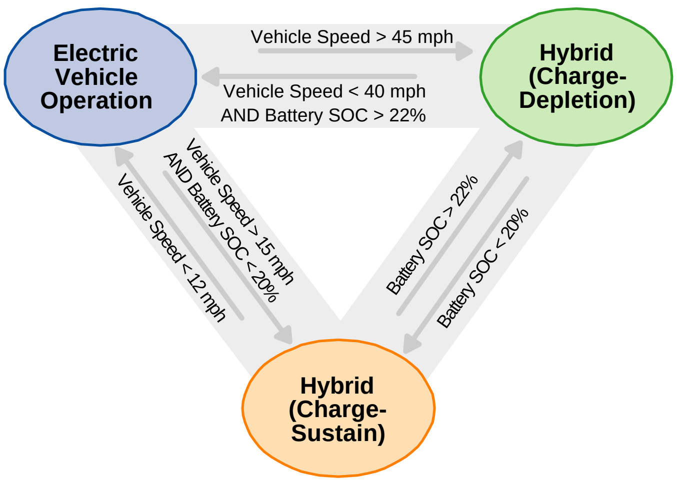


Figure 8. NORMAL mode operation.

NORMAL 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 the front powertrain and engine, 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 mode 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 as a generator 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 9 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.

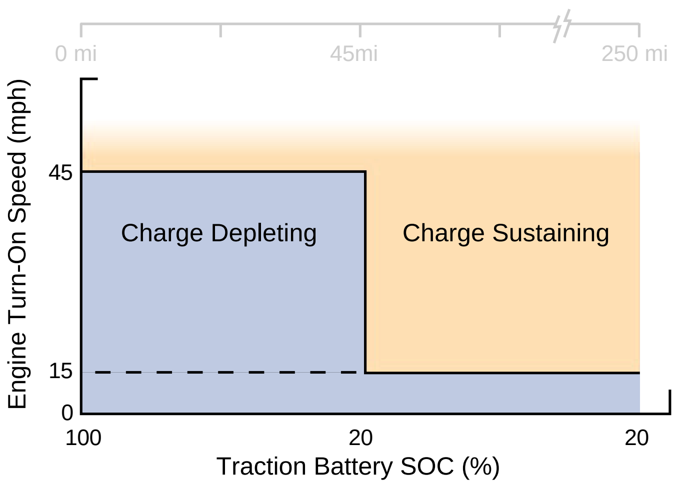


Figure 9. Charge sustaining, charge depletion regions.

GEAR SHIFTING STRATEGY

The powertrain controller 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, and refine 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[6]. 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 is 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[7]. 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. Table 4 describes each module in the vehicle.

Table 4. Control module summary.

Name	Platform	Description
PCM	MPC565	Powertrain control, vehicle energy management
ETC	HCS12	Electronic throttle actuation control
CAM	HCS12	Engine clutch actuation control
BMS	HCS12	Battery monitoring system
AEM	HC12	Active emissions control
CCM	HC12	Thermal management
HCM	HCS12	HVAC control
RCM	HCS12	Relay / accessory load control
BCM	HCS12	Body electronics control
IC	HC12	Instrument cluster
DLM	HCS12	CompactFlash data-logger
TEL	x86	Telematics / GUI / DAQ

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.

CAN HIGHER LAYER PROTOCOL

UC Davis has developed a Higher-Layer Protocol (HLP) to facilitate the structured exchange of information between modules. The UC Davis HLP (UCDHLP) software toolkit allows application code to interact with abstract named signals on the bus. No dependencies exist between application code and bus message addressing. During system integration, the UCDHLP toolkit generates driver code for each module. In this way, a module's hardware and software may be reused in multiple vehicles with different bus addressing layouts. The same toolkit automatically generates HTML documentation and an interactive GUI for a desktop PC. Figure 10 illustrates the system integration workflow using the UCDHLP toolkit.

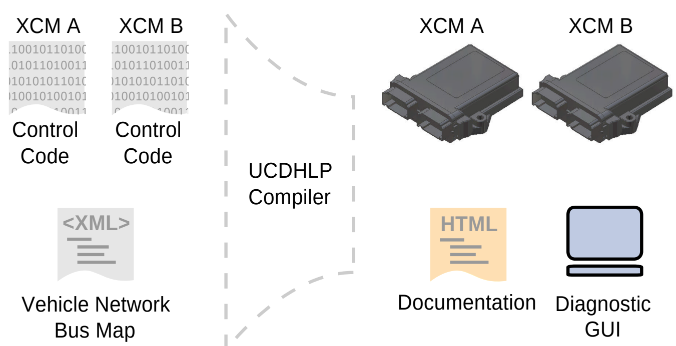


Figure 10. UCDHLP toolkit workflow.

BATTERY MONITORING SYSTEM

The UC Davis Battery Monitoring System (BMS) was designed to ensure the safety of the traction battery pack while transmitting pack state parameters and module data to the vehicle control network.

The decision to design and implement a custom BMS was the result of extensive analysis of third party BMSs. Existing BMSs are costly, limited in flexibility, and suffer from poor reliability and support. The commercial BMS systems evaluated lacked key functionality such as contactor control or a controlled "pre-charge" routine. The most significant drawback of these systems is their proprietary communication protocols that prevent full control system integration. A ground-up BMS design enhances the control system architecture, vehicle efficiency and safety.

The BMS hardware is composed of a single Host Controller and 24 Sense Modules, one for each battery module. The Host Controller is responsible for determining battery SOC and instantaneous power available. The Sense Modules are miniaturized, very low cost electronic sensors that transmit voltage and temperature data to the Host Controller over an open protocol. Intelligence for contactor control and pre-charge routine is integrated into the Host Controller.

UC Davis is working with the Cornell University FutureTruck team in an effort to jointly develop the control strategy and battery-specific algorithms necessary to accurately estimate key pack conditions at any point in a pack's lifetime.

The UC Davis BMS has been designed with safety as a top priority. The Host Controller continuously monitors the high voltage interlock and measures for ground. Pre-charge is disabled and contactors open if an interlock has been broken or a ground fault is detected. Finally, by providing critical pack parameters to the vehicle control system via the CAN bus, unsafe loads on the traction battery are prevented.

POWERTRAIN CONTROLLER

The PCM executes high-level vehicle control strategy. The controller is based on the Motorola MPC565 microcontroller, an automotive grade microcontroller using the 32-bit PowerPC architecture. The MPC565 has on-board floating-point hardware, executes instructions faster and consumes less power than the PC/104 286 used in previous years. It also integrates peripherals such as Queued Analog-To-Digital Converters (QADC) and Time Processor Units (TPU), allowing efficient, low overhead data collection and processing.

The PCM runs a UC Davis developed implementation of the Open Systems and the Corresponding Interfaces for Automotive Electronics (OSEK) operating system[8], an accepted standard in the automotive industry. The OSEK real-time operating system (RTOS) provides efficient CPU utilization and low event response latency. Alternatives such as Microsoft Windows and Linux are not real-time and therefore unsuitable for vehicle controls.

An online model of the vehicle running inside the MPC565 self-adapts and calibrates to actual sensor feedback. In this way, it is finally possible to create a truly adaptive control system that will not only optimize itself on dynamic powertrain data but will be able to compensate for component tolerances and wear over time. UC Davis expects a significant gain in vehicle reliability and performance from moving to this microcontroller.

EXTENSIBLE CONTROL MODULE

Automotive ECUs tend to use the same processor I/O peripherals (such as digital I/O, timing, and analog) with small variations in signal conditioning. The difference between each controller becomes the number and types of signals required. UC Davis recognized that significant redundant work went into custom-designing hardware for each ECU for every application. The eXtensible Control Module (XCM), a universal controller containing circuitry common to every ECU such as the microcontroller and power supplies, was designed to address this problem. Specialized daughterboards map processor I/O resources to pins on the physical connector. Configured daughterboards and custom firmware make up the completed controller design.

The XCM 2.0 is a major revision to the UC Davis XCM platform. The new design is powered by a Motorola MC68HC9S12DJ256 16-bit microcontroller, selected for its extensive on-chip I/O, mature CAN controller, and well-developed compiler support. Usability and flexibility were key design goals throughout evolution of the XCM. The XCM 2.0 now features interchangeable daughterboards, rugged and accessible enclosures, and improved I/O capability.

The universal nature of the XCM allows UC Davis to focus on a single robust hardware design that can be leveraged to meet the needs of most modules in the control system. By standardizing on a single set of components, spare XCMs can perform many different tasks. A malfunctioning XCM can be replaced by simply transferring its daughterboards and firmware to a new XCM.

A specialized version of the XCM, the Cooling Control Module (CCM), accommodates Pulse Width Modulation (PWM) switching of high-power inductive loads such as coolant pumps and fans. The module accommodates a standard XCM daughterboard to read thermistors or thermocouples.

CONTROL SOFTWARE

UC Davis designed a comprehensive set of software drivers for the 68HC12/HCS12 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 use the ICE to maintain the steady state load 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 ensure identical amounts of energy entering the engine, the following formulas describe the increase in fuel injected:

$$E_{injected,Gasoline} = (1L) * (33.0MJ/L) = 33.0MJ$$

$$E_{injected,E85} = (1.455L) * (22.6MJ/L) = 33.0MJ$$

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 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.

Multiple composite layers embedded in an epoxy matrix provide tank rigidity, while a high grade sealant ensures corrosion resistance. Carbon fiber layers provide structural integrity and a Kevlar layer provides puncture resistance and impact protection. Structural channels provide paths for fuel to flow into the sump area as well as add rigidity to the base of the tank. Safety foam in the sump area maintains a constant supply of fuel to the fuel pump, preventing starvation during dynamic maneuvers. The tank inlet, a 6061-T6-aluminum plate, incorporates a flush fill seal and is fastened and bonded onto the tank. To prevent E85 from corroding the fabrics, resin, and aluminum, the tank interior is a dichromate cured polysulfide sealant supplied by PPG (PR-1422A). This sealant is used in aircraft fuel systems for similar purposes.

EMISSIONS CONTROL

The stringent SULEV emissions standard requires a system approach to emissions control. The *Yosemite* emissions control strategy combines a sophisticated engine management system, high level hybrid systems control strategy, and a sophisticated exhaust aftertreatment 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 aftertreatment system consists of a CCC, a metal foil EHC, and a larger underfloor catalyst, all shown in Figure 6.

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[9,10]. 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.

The thermal design of the exhaust manifold and CCC improve heat retention, reducing the need for active EHC heating during warm stop-start operation. Advanced coatings on the CCC and EHC assist in NO_x reduction at the higher relative engine loads seen by the 1.9L engine. Modal emissions testing determined that cold-start CO emissions are small compared to steady-state CO at higher engine loads. To reduce steady-state CO emissions air-injection occurs only at the underfloor catalyst, where the excess oxygen will not interfere with NO_x reduction at the upstream catalysts. The after-treatment effects of the system are shown in Figure 11.

Ethanol, a renewable fuel and oxygenate, is capable of high combustion efficiency and reduced engine-out emissions relative to reformulated gasoline. Figure 12 shows modal emissions data from *Yosemite* during hybrid operation on the EPA test cycles.

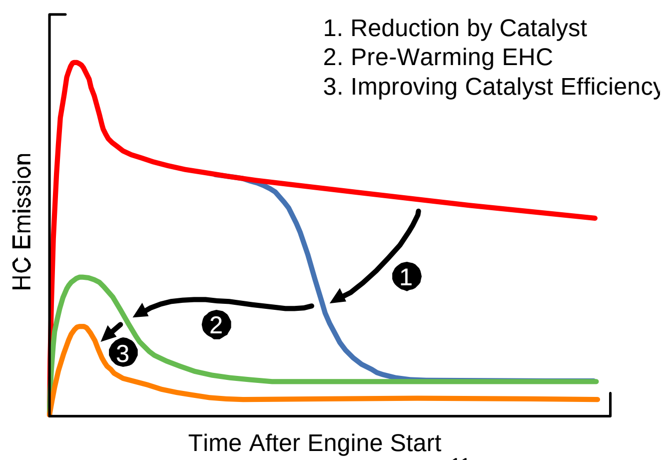


Figure 11. Modal emissions reduction[11]

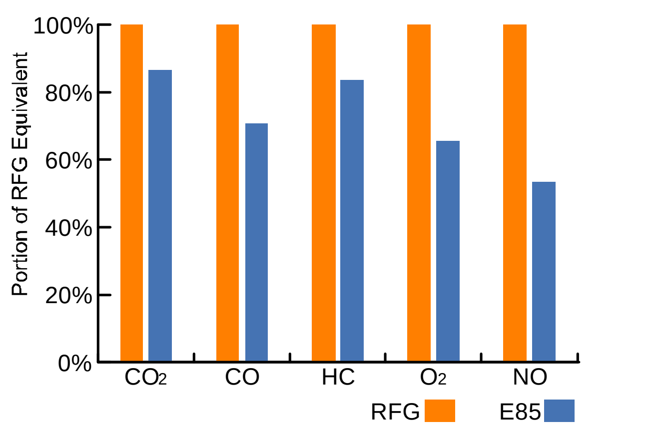


Figure 12. RFG vs. E85 emissions test data.

E85 is low in fossil carbon content, resulting in lower fuel cycle greenhouse gas emissions. The GHG index is determined by measuring fuel cycle production of CO_2, CH_4, and N_2O and applying the following formula based on the relative warming contribution of each species.

$$GHGI = CO_2 + 21*CH_4 + 310*N_2O$$

N_2O and CH_4 emissions levels can be controlled through aftertreatment. N_2O generation occurs at low catalytic temperatures (150°C to 400°C, peaking around 200°C) [12]. CH_4 is relatively easy to oxidize in a sufficiently warm catalyst. In both cases, the EHC and CCC are important to maintaining high catalyst temperatures, minimizing both N_2O and CH_4 emissions.

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 13. The battery pack consists of 24 11-cell modules. Module capacity is 50 Ahr and pack voltage is 317V.

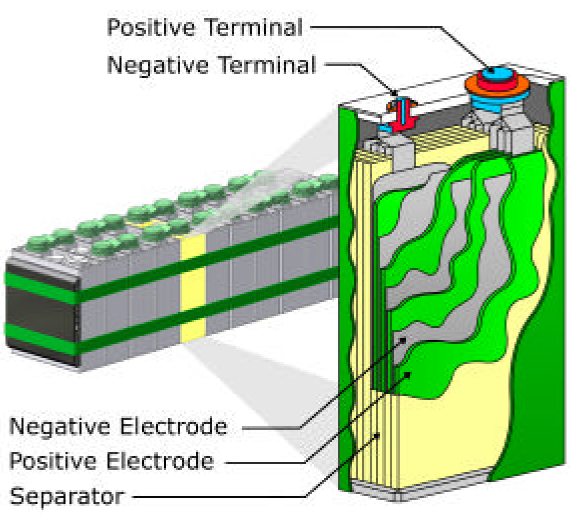


Figure 13. Ovonic NiMH battery cell[13].

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 and Figure 16. 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 14. 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.

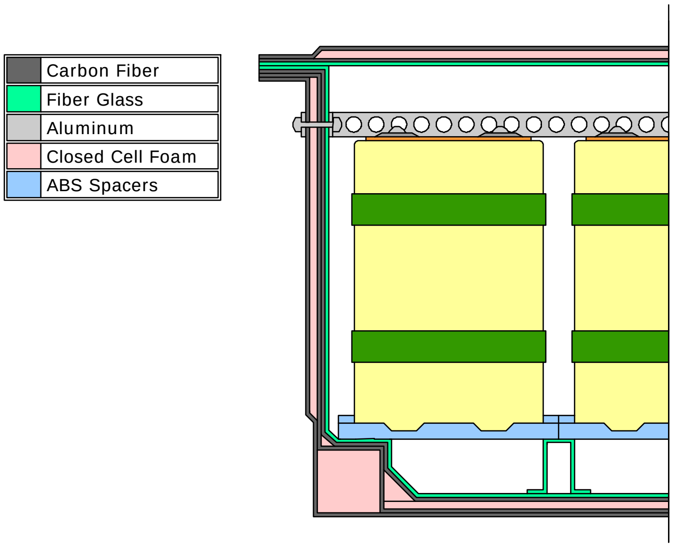


Figure 14. Battery enclosure cross section.

FEA ANALYSIS

CosmosWorks was used to perform an FEA on the battery enclosures by using the material properties of 45-45 carbon fiber weave to approximate our complete structure. Static loading showed the location of stress concentrations on the enclosure walls and was used in designing and reinforcing the composite layering. The enclosures were simulated dynamically under an 8.5G load. Both models indicated that failure was unlikely for the design under known loading conditions.

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

The Enova drive system incorporates a 6.6kW 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. The Enova Systems electric motor control unit is a key element of the system, providing integrated charging and DC-DC down-converters. A central high voltage distribution box supplies power to each load. Fusing is located within the battery box to ensure complete isolation during serious short 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[14].

Integration of the new instrument panel was simplified by using the stock IC housing and designing a new graphic overlay with the same dimensions. 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 formally 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.

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 [15]. 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 like conventional heater cores.

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.

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.

BRAKE LIGHTS

Center High Mounted Stop Lamps (CHMSL) have been standard equipment on all new passenger vehicles since 1994. The purpose of CHMSL is to safeguard a car or light truck from being struck in the rear by another vehicle. Brake lights on contemporary vehicles only indicate whether or not the brakes are being applied. UC Davis has improved the CHMSL by modulating the visual pattern to indicate the intensity of braking. Panels on the CHSML light progressively as braking intensity increases.

Ten special Light Emitting Diodes (LEDs) with higher luminous flux than standard LEDs illuminate the ten panels. Several factors affected the number of LEDs required: retaining the stock lens and enclosure compliance with SAE minimum illumination area of $29cm^2$ and maximum luminous intensity of 130 candela[16]. Four circuits containing four, two, two and two LEDs respectively compose the final system.

CONSUMER FEATURES

TELEMATICS SERVICE PLATFORM

A cyclic dependency is preventing the acceptance of next-generation network connected telematics systems in the consumer automotive market. The lack of a single dominant platform upon which to build and deliver services has failed to motivate the development of a “killer-app.” A dominant platform will only emerge with consumer demand, which is itself dependent on the availability of compelling applications and services. Entry into the telematics market is a risky business endeavor until this situation is resolved.

UC Davis’s solution is a software framework that permits the deployment of cross-platform services to a heterogeneous fleet of vehicles. Telematics terminals complying with the UC Davis Telematics Service Platform (TSP) will be able to run services developed in the future. Furthermore, the platform itself is inherently upgradeable to remain compliant with future versions of the TSP. The platform is built on industry standard technologies such as the Java programming language and the Open Services Gateway Initiative (OSGi) service management framework specification.

Open telematics standards such as the UC Davis TSP decouple the hardware platform from application development, attracting cutting-edge innovation – a prerequisite for commercial success. Examples of telematics services that could be developed and deployed to TSP-compliant vehicles include: real-time collection and dissemination of traffic data, intelligent traffic-aware navigation and routing, vehicle-to-grid charge/discharge control, anti-theft lockouts, or remote vehicle control and monitoring.

TELEMATICS IMPLEMENTATION

Yosemite’s telematics system provides a flexible and user-friendly interface to on-board vehicle systems and dynamic TSP services. This includes powertrain, energy storage, and entertainment systems. The vehicle is equipped with a MOST fiber optic multiplexed digital entertainment network. The MOST subsystem consists of an AM/FM tuner, CD player, and can accommodate additional audio and video sources via plug-and-play upgrades.

The core of the telematics system, illustrated in Figure 15, is a Pentium-class PC/104 computer. A 19.8cm transflective (part reflective, part transmissive) Liquid Crystal Display (LCD) provides a crisp backlit display in low-light situations while retaining excellent visibility in sunlight. A surface acoustic wave touch screen provides excellent tactile feedback. These items are packaged in the stock radio location.

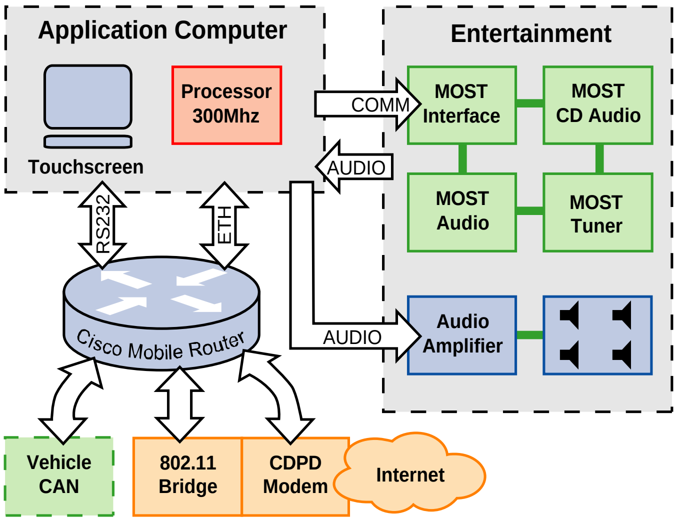


Figure 15. *Yosemite* telematics system architecture.

A Cisco PC/104 router provides IP connectivity to the vehicle's local IP network. The router implements IP Mobility to seamlessly maintain connectivity while roaming in between 802.11b wireless Ethernet networks or on a low-speed Cellular Digital Packet Data (CDPD) modem. Together, the two supply nearly full-time data coverage with high-speed capability in many areas. An embedded GPS module provides positioning data. A CAN-to-ethernet bridge allows the telematics system and PC-based diagnostic tools to simultaneously interact with the vehicle's control network.

A soft-key user interface ensures safe operation by the driver by placing touch-sensitive areas of the screen near tactile cues at the edge of the screen. A speech synthesis and recognition interface provides access to basic functionality without taking the driver's attention from the road. Dynamically loaded telematics services may present interfaces via the visual/tactile interface, the speech interface, or some combination thereof.

VISION AUGMENTATION

Cameras behind each side view mirror and under the rear bumper cover the driver's blind spots. A small LCD screen embedded in the rear view mirror displays the appropriate camera image when the turn signals are engaged or the vehicle is shifted into reverse. At other times, the display is off. The selected camera may be manually overridden through the telematics interface.

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, hood hinges, and fuel tank. The composite components are able to provide the strength and rigidity required, at a much lower mass than their 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 afterbody drag at the rear of the vehicle is a significant factor in total drag. Reductions in afterbody drag can improve overall vehicle drag coefficient by up to 9%[17].

Yosemite employs an active afterbody drag reduction system. The system consists of three small actuator-driven body panels that deploy at the rear of the vehicle at speeds above 50mph (80.5km/hr). When deployed, the panels are securely positioned perpendicular to the liftgate along its top, left, and right edges. Vortices form at the outer surface of each panel, entraining the flow inwards to reduce the low pressure area immediately behind the liftgate. Field testing of the system verified a 1.13mpg increase in fuel economy at freeway speeds. The movable panels are not visible to the vehicle occupants and are retracted flush to the vehicle body at lower speeds.

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 16.

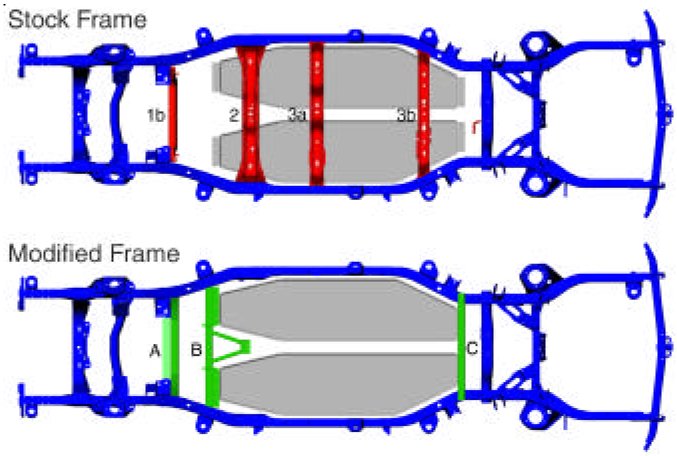


Figure 16. Frame modifications.

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. A custom made torsion bar was installed as a replacement. The design utilizes a tubular torsion bar with adjustable rod ends to reduce weight and replicate stock spring rates.

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 which supplies a constant vacuum to the brake booster.

DFMEA

The results of the Design Failure Mode and Effects Analysis (DFMEA) performed on *Yosemite* appear in APPENDIX B. DFMEA addresses potential design flaws rather than failures due to problems introduced after the design phase. Risk assessment factors were assigned to potential failures based on three criteria: likelihood of detection by design control (D), severity of effect (S), and probability of occurrence (O). The R, S, and O values were multiplied to create the Risk Priority Number (RPN). Items with RPN values higher than 75 are deemed at risk for failure and require action.

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 accurately determine. Two significant efforts to understand and develop cost models for calculating Retail Price Equivalent (RPE) for advanced vehicles were undertaken by Cuenca, et al[18]. and Graham, et al[3]. 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 2003 dollars, assumes a production volume of roughly 100,000 vehicles. Figure 17 shows the component price relationships for engines, transmissions, and electric drive systems used in the conventional and hybrid Explorer. 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 [19]. 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.

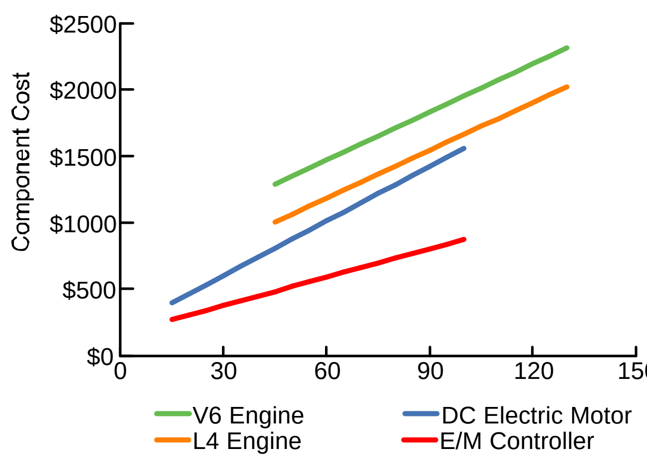


Figure 17. Component cost relationships.

Table 5. 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 in any way.

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 2006 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 18 and Table 6 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.

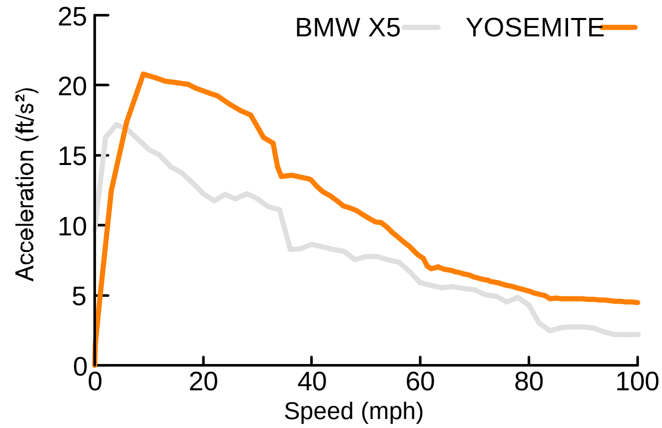


Figure 18. Acceleration comparison with BMW X5.

Table 6. 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.

ORGANIZATION

The UC Davis FutureTruck Team is a group of students undertaking extraordinary challenges in advanced vehicle design as an extracurricular activity. The team structure must be sensitive to the needs of the students, whose primary focus is completing an academic degree. The team is organized into four primary groups: Body and Chassis (BCG), Powertrain (PTG), Electronics and Controls (ECG), and Management and Administration (MAG). Figure 19 details the responsibilities of each group. Leadership roles are distributed between the experienced team members with backups for each task or position. Group members are cross-functional and often support critical activities in other groups. The team advisor assists with the conceptual and technical insight while providing an atmosphere conducive to learning.

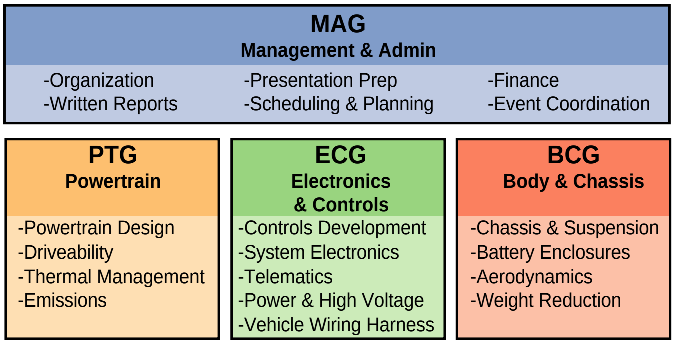


Figure 19. Team organization.

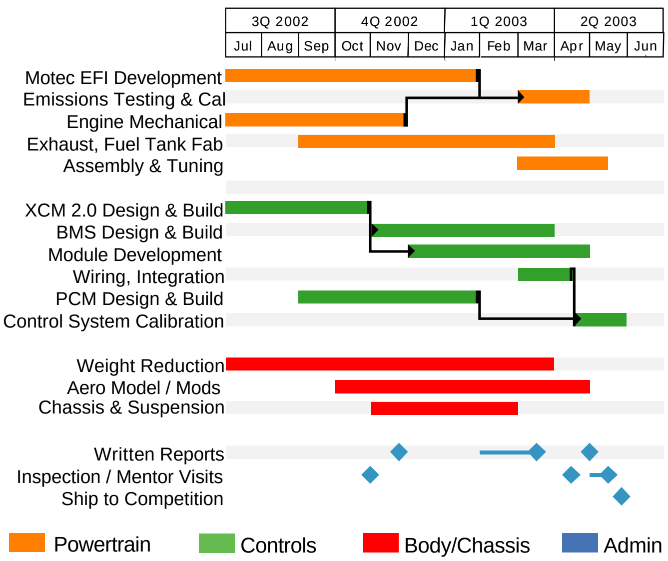


Figure 20. Vehicle design, build, and test schedule.

Effective communication is essential to promote the teamwork necessary for accomplishing the group's objectives as laid out by the vehicle development schedule in Figure 20. In addition to traditional meetings, the team employs a variety of cellular, email, and electronic messaging tools to promote the exchange of information and facilitate instant consultation with group members when they are away from the lab. The team organizes Saturday workdays, enabling the entire group to spend one day per week working concurrently. These techniques combined with clear, achievable objectives contribute to the success of the FutureTruck project.

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 7 below.

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.

Table 7. 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

Yosemite's EV range of 45 miles can account for over 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 promising market potential.

REFERENCES

[1] .California Air Resources Board, "Description and Rationale for Staff's Additional Proposed Modifications to the January 10, 2003 ZEV Regulatory Proposal," March 5, 2003.

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

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

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

[5] Margolis, Donald, Personal Communication, March 2003.

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

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

[8] OSEK Group (2001), OSEK/VDX Operating System Specification 2.2 Available at: http://www.osek-vdx.org/mirror/os22.pdf

[9] 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

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

[11] Nishizawa, Kimiyoshi, et al., "Development of New Technologies Targeting Zero Emissions for Gasoline Engines", SAE Paper 2000-01-0890

[12] Meffert, Michael, et al, "Analysis of Nitrous Oxide Emissions from Light Duty Passenger Cars", SAE Paper 2000-01-1952

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

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

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

[16] Society of Automotive Engineers, "J1957: Center High Mounted Stop Lamp Standard for Vehicles Less than 2032 mm Overall Width", March 2000.

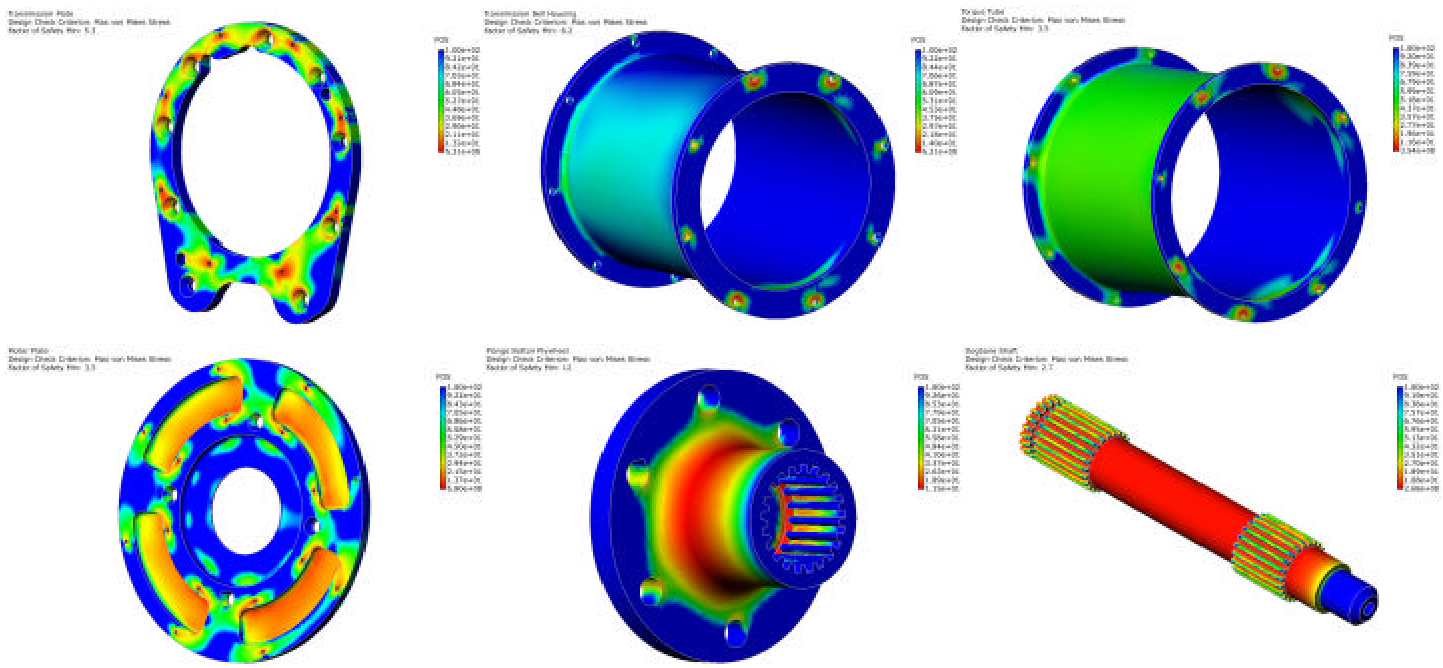
[17] Lansesr, W., Ross, J. Kaufman, A. "Aerodynamic Performance of a Drag Reduction Device on a Full-Scale Tractor/Trailer." SAE 912125

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

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

APPENDIX A

Finite Element Analysis:
Factor of Safety results



APPENDIX B

Table of DFMEA results

Item	S	D	O	RPN	Potential Failure Mode	Potential Effects of Failure	Potential Causes/ Mechanisms of Failure	Current Design Controls	Actions
Engine	8	2	2	32	-Overheat -Blown head gasket -Warp head	-Engine failure	-Incorrect heat production of engine -Incorrect heat rejection of radiator	-Design review -Experiments -Robust design -Worst case analysis	-
Engine Coupling Shaft	8	3	3	72	-Over-torque Fracture of shaft	-Engine non-op	-Lower Grade Material -Neglected Dynamic effects	-Robust design -FEA -Design review	-Make multiple backups -Simplify replacement
Battery System	9	3	3	81	-Overheat -Thermal runaway -Breech of Enclosure	-Battery damage -Decreased capacity -Fire	-Underestimated pressure drop in cooling airflow	-Robust design -Experiments -Design review	-Implement a secondary cooling circuit -Improve vehicle isolation -Simplify enclosure replacement
Powertrain Mounting	10	2	3	60	-Mount tear -Bracket failure	-Powertrain non-op -Transmission damage	-Incorrect stress calculations -Lower grade component -Neglected dynamic effects	-Robust design -Design review	-
High Voltage Wiring	10	2	5	100	-Ground fault -Short	-Shock -HV electrical non-op -Fire	-Incorrect insulation grade -Improper insulation of conductive surfaces -Inadequate abrasion resistance	-Robust design -MegaOhm-meter testing -Fuses -Ground fault detection -Interlock loop	-Make multiple backups -Implement testing nodes for MegaOhm -Simplify schematic documentation
Powertrain Housing	8	2	2	32	-Crack propagation from openings	-Vehicle non-op -Engine damage -Motor damage -High voltage short	-Neglected dynamic effects	-Robust design -FEA -Design review	-