Design and Development of the UC Davis FutureTruck

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ABSTRACT

The University of California, Davis FutureTruck team redesigned a 2000 Chevrolet Suburban as a Hybrid Electric Vehicle to meet the following goals: reduce fuel cycle greenhouse gas emissions by 66%, increase vehicle fuel economy to double that of the stock Suburban, meet California's Super Ultra Low Emissions Vehicle standard, and qualify for substantial Partial Zero Emissions Vehicle credits in California. *Sequoia* meets these goals with an efficient powertrain, improved component systems, and an advanced control system.

Sequoia utilizes two independent powertrains to provide Four-Wheel Drive and achieve stock towing capacity. The primary powertrain combines a 1.9L gasoline engine inline with a 75 kW brushless DC motor driving the rear wheels. This powertrain configuration is simple, compact, reliable, and allows flexibility in control strategy. The secondary powertrain employs a 75 kW brushless DC motor to drive the front differential. Together, the two powertrains allow *Sequoia* to achieve high efficiency under normal operating conditions while matching stock vehicle performance at high load. A 29 kWh nickel metal hydride battery pack powers the electric motors, providing up to a 107 km all-electric range. *Sequoia's* superior fuel economy, low cost of operation, and performance, combined with aerodynamic innovations, telematics systems, and other consumer features make it a desirable and competitive vehicle in today's market.

INTRODUCTION

The University of California, Davis FutureTruck team is participating in the 2001 FutureTruck competition, sponsored by General Motors Corporation and the U.S. Department of Energy. In response to international concern regarding the adverse effects of Greenhouse Gas (GHG) emissions, the competition challenges student teams to redesign a medium-duty 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 focused on qualifying for 80% Partial Zero Emissions Vehicle (PZEV) credit under the California Low Emissions Vehicle II amendment. UC Davis will compete in the 2001 FutureTruck competition with *Sequoia*, a redesigned 2000 Chevrolet Suburban. Figure 1 illustrates the vehicle's configuration and Table 1 lists the team's design goals for 2001.

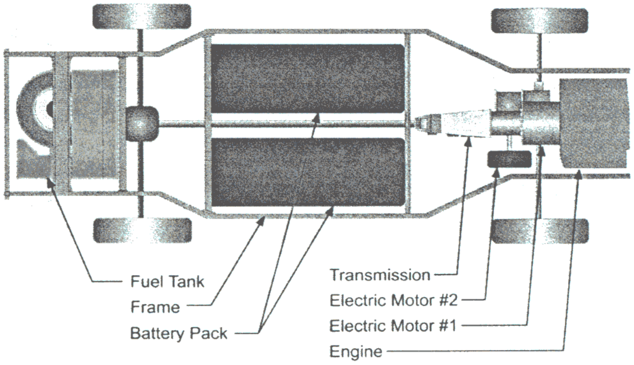

Figure 1. *Sequoia* Design Layout

Table 1. UC Davis FutureTruck Design Goals.

	Sequoia	Stock Suburban
Fuel Economy (L/100km)	7.6	15.0
Acceleration (0-100kph)	9.5 sec	9.8 sec
Range (km)	855	834
GHG Index (g/mi)	279	838
Curb Weight (kg)	2676	2587

The FutureTruck Challenge evaluates each vehicle design primarily by quantifying the total reduction in fuel-cycle greenhouse gas emissions. The emphasis on reducing greenhouse gases: CO_2, CH_4, and N_2O suggests the use of electricity as the primary fuel due to its low fuel-cycle emissions[1]. A charge-depletion control strategy maximizes electricity usage by using energy from off-board charging and regenerative braking. The vehicle automatically shifts to a charge-sustaining mode during extended use and towing operations. In addition to improved efficiency, *Sequoia* also demonstrates excellent acceleration, competitive towing capacity, an advanced driver interface, and Four-Wheel Drive (4WD) capability.

DESIGN PHILOSOPHY

CONFIGURATION SELECTION – The first step in *Sequoia*'s design was selecting the vehicle configuration. Evaluation of vehicle configuration was based on extensive modeling and research into published configuration efficiency results. A parallel hybrid configuration was chosen for its potential to deliver high powertrain efficiency. Direct power transfer to the wheels eliminates the energy conversions present in series and dual hybrid configurations. Well-executed shifting strategies and engine throttle control can still effectively isolate the engine from fluctuations in load, improving efficiency. The use of high torque, high power electric motors allows a significantly downsized Internal Combustion Engine (ICE), maximizing average engine thermal efficiency. A high power, high energy battery system further increases system efficiency by recovering vehicle inertia through regenerative braking.

UC Davis has used a unique charge-depletion strategy in previous vehicles, but the change from a mid-size sedan platform to a medium-duty truck platform required a reassessment of this control strategy. Vehicle simulations were used to demonstrate that even with the increased size and weight of the Suburban, charge depletion was beneficial on both the vehicle and fleet levels.

FUEL SELECTION – Reformulated Gasoline (RFG) and electricity were selected as *Sequoia's* fuels. Simulations indicate that electricity is the best available fuel for reducing vehicle greenhouse gas emissions. Current battery technology limits practical electric range. *Sequoia* uses gasoline to meet range targets. Gasoline and electricity are both commonly available transportation fuels. The market presence of four Super Ultra Low Emissions Vehicle (SULEV) gasoline vehicles in California demonstrates that extremely low emissions are possible.

VEHICLE OPERATION – *Sequoia* uses a combination of charge-depletion and charge-sustaining control strategies. During city driving at high battery State-of-Charge (SOC), *Sequoia* operates as an Electric Vehicle (EV). Upon reaching engine turn-on speed, the powertrain transitions from all-electric operation to assisted-engine operation. At highway speeds or at a low battery SOC, the vehicle uses the engine to decrease the rate of battery depletion. Typical highway driving occurs at speeds in the engine-assisted region, as illustrated in Figure 2. This strategy biases initial vehicle operation towards electricity, but maintains range by increasing gasoline usage as battery charge depletes. At 20% SOC, the vehicle shifts to charge-sustaining operation. Range is limited only by fuel storage capacity rather than battery storage.

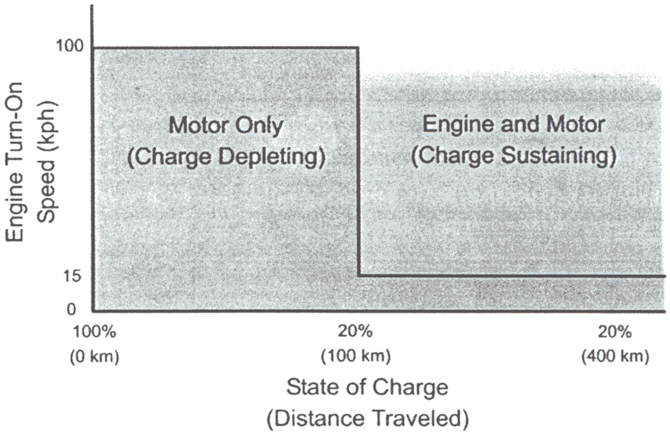

Figure 2. Engine Control Strategy.

The charge-depletion strategy shifts a significant percentage of vehicle miles from gasoline to grid energy. Eliminating engine idle, low-speed and light load conditions dramatically improves the average thermal operating efficiency of the ICE. As a result, tailpipe emissions and Greenhouse Gas emissions are greatly reduced. Models comparing *Sequoia* to a similarly equipped charge-sustaining vehicle show a reduction in greenhouse gas emissions of 53%.

Data from the 1995 National Personal Transportation Survey (NPTS) shows that using such a strategy could displace a significant portion of gasoline usage with electricity. Figure 3 indicates that *Sequoia* can accomplish approximately 70% of the total vehicle miles traveled in the United States using stored electric energy.[2] Figure 4 shows GHG weighted with the population distribution. These composite results demonstrate that a large fleet of HEV's like *Sequoia* would reduce GHG production significantly more than single vehicle performance indicates. A fleet of vehicles like *Sequoia* produces 71% less GHG than a fleet of conventional Suburbans while consuming only 29% of the gasoline.

An independent study using similar data found that a mid-sized charge depletion vehicle could operate for approximately 73% of its annual travel using stored electricity.[3] The California Air Resources Board (CARB) has recognized this reduction in gasoline consumption and revised the LEV II requirements based on National Personal Transportation Survey Vehicle Miles Traveled data.[4] CARB will award PZEV credits to vehicles that meet the SULEV standard at 200,000 km and have zero evaporative and refueling emissions. *Sequoia* is eligible for up to 80% PZEV credit under these regulations (CARB LEV II).

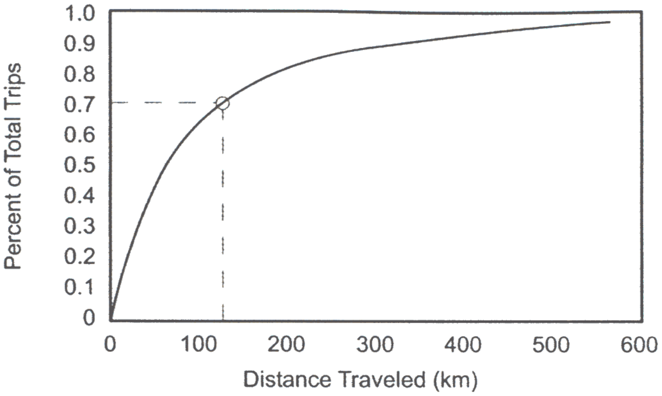

Figure 3. 1995 NPTS Data for Cumulative Daily Travel.

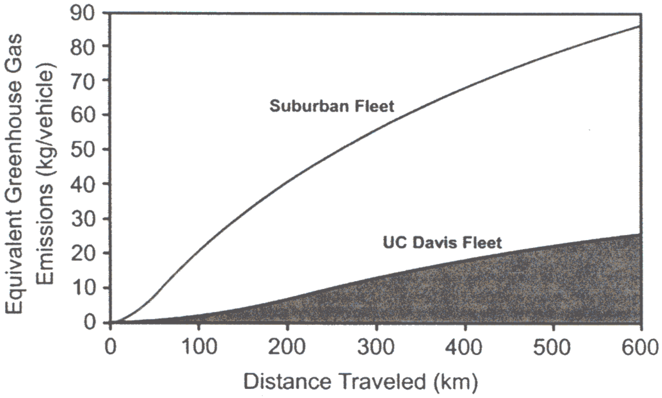

Figure 4. Daily GHGI of a Representative Fleet.

POWERTRAIN DESIGN

INITIAL DESIGN MODELING – Vehicle modeling of *Sequoia* was performed in two stages. Initial powertrain design was conducted during the first phase using Advisor. The second phase utilized PSAT, a forward-looking vehicle simulator, to develop specific powertrain control strategies.

Advisor Modeling - Advisor, a publicly available vehicle modeling platform produced by the National Renewable Energy Laboratory, was used to establish component sizes during the initial design stages. General power requirements were determined by running a series of cycles representing the performance of a competitive SUV. These simulation results are outlined in Table 2.

Table 2: Suburban Power Requirements.

Cycle	Peak Power
Golden to Vail	92 kW
Federal Urban Driving Schedule (FUDS)	61 kW
Highway Fuel Economy Test (HFET)	50 kW
0-100 kph in 9.5 sec	170 kW
5% Grade at 100 kph	74 kW
5% Grade at 100 kph with 7000 lb. trailer	100 kW
120 kph Constant Speed	49.8 kW
FutureTruck Towing Peak	181 kW
FutureTruck Towing Average	75.9 kW

Simulations show that combined fuel economy increases as the ICE's size decreases due to increased loading of the ICE. The smallest engine with sufficient steady state power to meet towing requirements was selected. The high efficiency of electric motors throughout their operating range allows them to efficiently meet transient power demands without the sacrifices in efficiency caused by the use of a larger ICE.

The power requirements above led to the component size goals listed in Table 3. These goals were used to direct the design of a reliable, efficient powertrain.

Table 3: Component Design Goals.

Component	Goal
Engine Power	100 kW
Motor Power	150 kW
Transmission Torque Capacity	410 N-m
Battery Energy Capacity for 100 km	28.8 kWh

ENGINE SELECTION – The choice of engine is crucial to meeting the efficiency and emissions requirements. The engine must operate efficiently under loads comparable to the road-load of the vehicle and utilize an effective after-treatment system to curb tailpipe emissions. The engine must also be light and compact, with readily available components and technical support.

Engine Specification - Engine research focused on recent, low-emission, high production models. In descending order of importance, the engines were compared on the basis of efficiency, stock vehicle emissions, availability, technical support, size and weight. The five engines considered were the Mitsubishi GDI 1.8L, Subaru 2.0L Boxer, Nissan 1.8L SULEV, Saturn 1.9L DOHC, and Saturn 2.2L DOHC.

Gasoline Direct Injection (GDI) engines are ideal for conventional cars and mild hybrids because of their high efficiency at partial load. Unfortunately, current lean burn NO_x catalyst technology requires varying load conditions to function properly. Because the engine in a charge-depletion hybrid runs almost exclusively at high load, a GDI engine would actually produce higher emissions. The Subaru 2.0L Boxer has higher peak efficiency than the other conventional engines, but its unconventional packaging (horizontal opposed cylinders) complicates integration into the Suburban platform. The Nissan 1.8L engine in the Sentra SULEV sedan has the lowest emissions of any production engine and met packaging requirements, but difficulties in communication and support would have limited the performance achievable for the competition. The Saturn engines are both readily available and have an attractive combination of high efficiency, low emissions, compact size, and low weight. Upon consideration of all engine options, the two Saturn engines best fit the given design constraints. Figure 5 compares the engines' specifications.

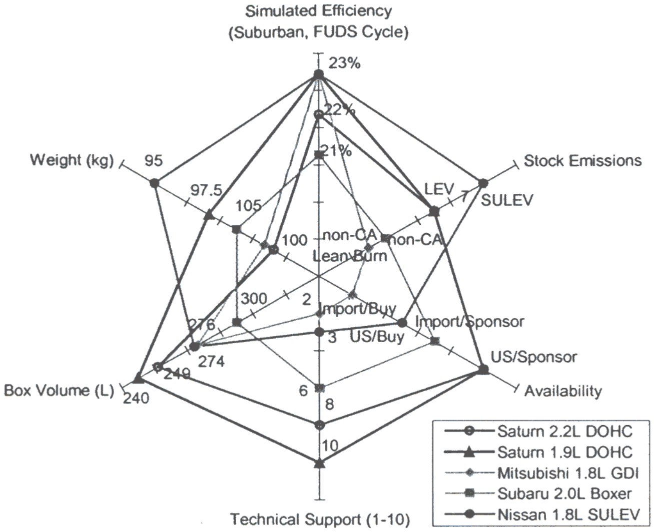

Figure 5: Engine Specification Comparison.

Both Saturn engines have similar efficiencies and emissions characteristics. The Saturn 1.9L DOHC is better sized for *Sequoia* because its peak efficiency is close to the steady state power demand reflected in the design goals. The engine also has sufficient reserve power for continuous operation at higher load. The engine weighs 99.8 kg and meets California Low Emissions Vehicle (LEV) standards in stock form.[5] Components, technical support, and engine operating data are readily available. The Saturn engine's fuel injection computer is reprogrammable, allowing for finer emissions control.

TRANSMISSION SELECTION – Efficiency, torque capacity, gear ratios, size, weight, and reliability were factors in selecting a transmission.

Both conventional planetary automatic transmissions and spur-gear manual transmissions satisfy the transmission design requirements. A manual transmission was chosen for its higher efficiency, low weight, compact package, and simplicity.[6]

The transmission was chosen for torque capacity, number of gears, and availability of optimal gear ratios. The primary powertrain is capable of producing a total of 405 N-m, eliminating most small transmissions from consideration. The final selection was an H pattern 6-speed Richmond Gear transmission. This transmission exceeds the powertrain's torque requirements, is available with a range of gear ratios, and is lightweight, compact, and reliable. The selected gear ratios provide substantial low-end torque and an even spread of ratios throughout the powertrain's useable region. An Advisor simulation helped optimize the gear and final drive ratio selection to provide the most efficient combination. The final system uses a 4.56:1 final drive resulting in the reductions shown in Table 4.

Table 4. Transmission Gear Ratios.

Gear	Ratio	Total Reduction
1st	4.41	20.11
2nd	2.45	11.17
3rd	1.57	7.16
4th	1.24	5.65
5th	1.00	4.56
6th	0.81	3.69

ELECTRIC MOTOR SELECTION – The vehicle's electric motors provide tractive force during transient operation and are used for electric power generation during regenerative braking and charge-sustaining operation. The limited availability of high-voltage electric motors capable of meeting the power requirements resulted in only two motor configurations being considered.

The first configuration uses an AC Propulsion AC-150 150 kW motor as the sole drive motor. The AC-150 could supply all the electric power required by the design goals, is lightweight, and has a built-in conductive charger and DC-DC converter. Zero-torque losses are minimal due to the inherent design of an AC motor. Unfortunately, the AC-150 would require a 2:1 speed reduction to match the operating speeds of the ICE. The air-cooled motor and inverter design results in package that is large and difficult to properly cool when used in close proximity to the engine. 4WD would require the use of a transfer case.

The second configuration employs two 75 kW brushless DC motors, one motor inline with the engine and transmission forming the primary powertrain, and the second motor driving the front wheels. This configuration eliminates the stock transfer case, allows on-demand four-wheel regenerative braking and eliminates additional speed match gearing.

The dual motor configuration emerged as the most promising solution for *Sequoia* electric traction system. The primary powertrain uses a Unique Mobility SR 218N 75 kW motor for its high efficiency and through-shaft design. The range of operating speeds closely matches the IC engine, allowing an in-line, pre-transmission configuration without requiring an additional reduction gear set. A PreMag 75 kW motor drives a 2001 General Motors S10 differential with outputs to the front wheels. This motor utilizes a unique winding design and small rotor volume, improving packaging in the engine compartment and reducing vehicle weight.

One disadvantage to this configuration is the drag torque losses associated with free spinning permanent magnet motors. Typical losses for this type of motor can approach 750 W at high rotor speeds. The zero-torque loss is reduced by disengaging the front motor during steady-state, low-power operation. Simulations show the significantly higher efficiency of a permanent magnet motor (compared with an AC induction machine) outweighs the drag torque losses over an average drive cycle. Figure 6 shows a comparison of the motor specifications and application considerations.

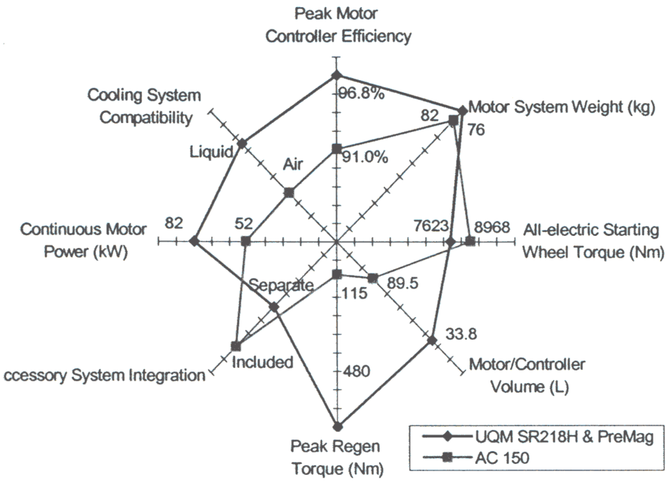

Figure 6: Electric Motor Specifications.

VEHICLE CONTROL STRATEGY

Sequoia's control strategy minimizes GHG and regulated tailpipe emissions. Four operating modes accommodate different driving needs: Normal, EV, Tow/Haul, and 4WD. Normal mode is optimized for maximum efficiency, since it is used for the majority of miles driven, whereas the other modes are designed for performance in specific situations. *Sequoia* is capable of both charge-depletion and charge-sustaining operation.

All modes use regenerative braking to recapture the kinetic energy from the vehicle. Simulations show that regenerative braking extends *Sequoia's* total range by 63 miles and increases city fuel economy by 17%.

NORMAL MODE – Normal mode primarily uses a charge-depletion control strategy. If the battery is sufficiently discharged, the controller switches to charge-sustaining mode. Normal mode focuses on minimizing energy usage and emissions through the use of an intelligent gear shifting strategy and emissions control system.

Gear Shifting Strategy - The electric motor provides transient drive power, allowing the engine to run at near steady-state conditions in a highly efficient region under typical use. *Sequoia* uses a transmission shifting strategy to achieve maximum efficiency during operation. The algorithm used to determine the optimum shift point was derived from UC Davis' experience with Continuously Variable Transmissions (CVTs), which require a precise definition of optimum power points. The methods developed for CVT operation were modified to allow selection of the optimal discrete ratio.

Algorithm Description - During vehicle operation, the powertrain controller evaluates the required drive power based on throttle position and powertrain speed. Efficiency maps, stored in the vehicle control computer, are used to determine the optimum gear for the commanded power level. If this new gear offers significantly better efficiency, the powertrain controller notifies the driver via dashboard indicators that a shift is required.

During all-electric operation, the shift points are set to operate the electric motor in its most efficient region; during assisted-engine operation, the combined efficiency of the ICE and electric motor is used. Figure 7 illustrates the decision-making process for a steady-state 30 kW demand on the ICE alone. If the vehicle were in either sixth or fourth gear, the driver would be notified to shift into fifth gear.

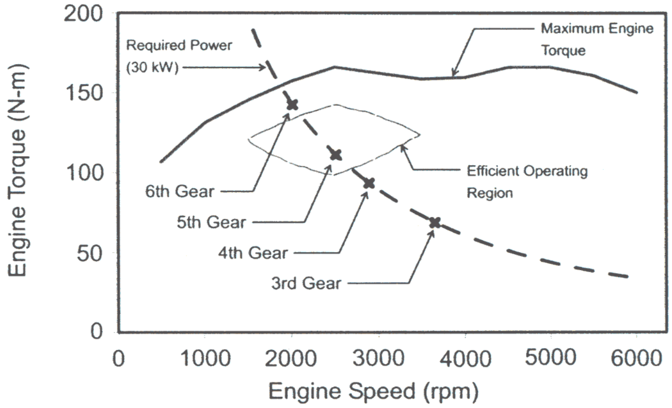

Figure 7: Illustration of Gear Shifting Strategy.

Drivability Concerns - The gear-shifting algorithm includes allowances to increase drivability and prevent frequent shift requests. The algorithm is designed with hysteresis to prevent oscillation near shift points; the power request signal is heavily filtered, reducing effects by transients. Both parameters are tuned to optimize efficiency and drivability but are driver adjustable.

Emissions Control – The electronic throttle controller avoids transient engine conditions by limiting the throttle position rate of change. The powertrain controller compensates for the slower engine throttle response by commanding electric motor torque.

EV MODE – The driver may select EV Mode to force the vehicle to operate on electric power only. Such operation may be desirable for local driving or commute travel that consists of highway driving within *Sequoia's* all-electric range. EV Mode utilizes the gear-shifting strategy of Normal Mode to minimize energy consumption. If the battery becomes depleted, the vehicle automatically switches to charge-sustaining Normal Mode.

TOW/HAUL MODE – *Sequoia's* powertrain produces sufficient power to match stock Suburban towing capacity. Tow/Haul mode is engaged by the driver when extended towing capability is needed. This mode uses a charge-sustaining control strategy to maintain sufficient reserve battery storage for hill climbing and acceleration.

The powertrain control system commands additional engine power while simultaneously regenerating with the primary electric motor if the battery SOC reaches its minimum threshold. The Normal Mode shifting strategy is used with this combined power command to maintain efficiency. Low engine throttle settings preclude charge-sustaining operation to prevent powertrain instability and avoid excessive regeneration during braking.

4WD MODE - The 4WD powertrain control strategy requires careful consideration because of *Sequoia*'s two separate powertrains. The rear powertrain operates with a multi-speed transmission while the front drivetrain utilizes a single gear reduction, causing the front and rear torque split to change as the transmission is shifted. Proportioning the torque command to provide equal front and rear output limits the maximum torque that can be applied at the wheels, but torque delivery is adequate in nearly all conditions. Both electric motors can apply maximum torque at zero speed, so the torque capacity is expected to exceed traction capability in off-road conditions. Reducing the accelerator pedal sensitivity at low settings eliminates the need for 4WD low gearing and low-speed clutching.

VEHICLE MODELING

Advisor's principal limitation for modeling dynamic systems is its underlying backwards-facing structure. In a backwards-facing simulation, the power required to meet the road load is calculated first and propagated back through the different model components. The input requirements are calculated from the known output. Since a control system determines the output based on a set of inputs, backward-facing models cannot correctly simulate the effects of control systems. To overcome these limitations, two forward-facing models were used. Initially, a model constructed by UC Davis in the MathWorks Simulink environment was used. Work then shifted to PSAT, a forward-facing model developed by Argonne National Laboratory. Both models allow the simulation of *Sequoia's* 4WD powertrain and aided the development of both charge-depletion and charge-sustaining control strategies.

TOW/HAUL MODELING – *Sequoia's* engine produces sufficient power to tow significant loads at steady speeds on moderate grades, but the electric motors are required during for acceleration and climbing steep grades. Modeling results of a mountain climb from Golden to Vail Colorado illustrate *Sequoia's* ability to tow a 3,180 kg trailer. This route has an average speed of 88.4 kph and a net elevation gain of 807 meters. The peak power on this cycle is 214 kW, within the power capacity of *Sequoia*'s powertrain. The key factor limiting the towing ability of a battery-dominant HEV is the *average* power requirements of the route. During three successive runs of this route, for a net elevation gain of 2,421 meters over a total distance of 260 miles, *Sequoia* finished the trip with a final battery SOC of 51% and an average ICE power of 45.2 kW. These results show that the ICE has sufficient reserve capacity for an extended, difficult towing cycle at near maximum vehicle carrying capacity.

PSAT MODELING – Data for selected vehicle components was imported into PSAT, allowing powertrain control strategies to be developed based upon chosen components. This section focuses on powertrain control strategy development using PSAT. A full explanation of the PSAT modeling efforts can be found in UC Davis' PSAT Final Report.

Control Strategy Development – The HEV powertrain control strategy provided by PSAT is intended for charge-sustaining vehicles only. Since *Sequoia* utilizes both charge-depletion and charge-sustaining strategies, a complete rewrite of the model's control algorithms was necessary. Instead of re-implementing *Sequoia's* entire control strategy in Simulink, *Sequoia's* C-language microcontroller code was imported directly into PSAT.

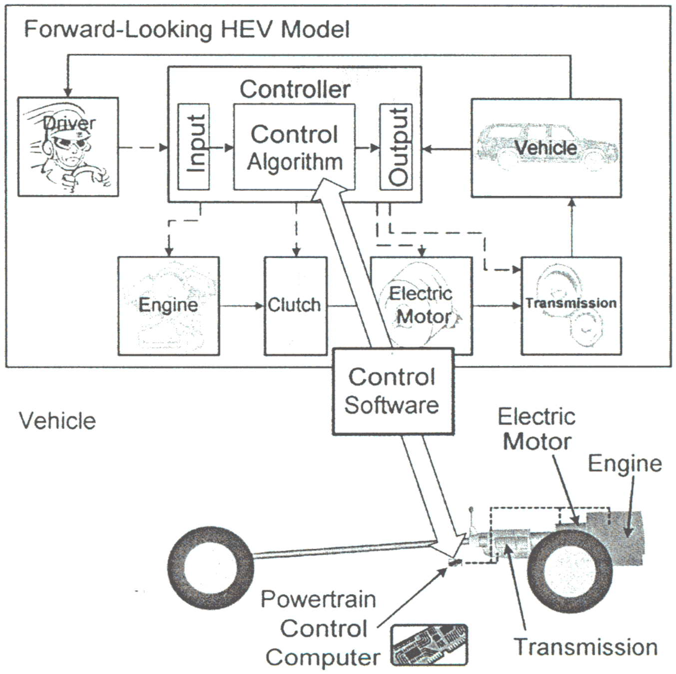

Figure 8. Development of Controller Code.

Within the PSAT software, the Input/Output (I/O) signals that are normally routed to a model of an HEV powertrain controller are instead mapped to variables in the UC Davis control code. During a simulation run, PSAT interfaces with the control code and executes it exactly as the vehicle's powertrain controller does. Instead of receiving input signals from vehicle controls and sensors, the control code reads information from other portions of the PSAT model. Likewise, the output commands that are normally sent to drive components and actuators are instead routed to command the respective component models within the PSAT simulation.

The implementation of C code within PSAT was beneficial in many ways. It allowed the team to further develop and test *Sequoia's* powertrain control strategy under PSAT using C code, allowing a direct transfer of the finalized code to the vehicle without translating from Simulink back to C. An illustration of the process is shown in Figure 8.

RESULTS OF STRATEGY DEVELOPMENT – Table 5 shows the fuel economy improvements achieved through the development of powertrain controller code within PSAT. The "Refined Strategy" results represent improvements in engine loading and gear shifting strategy compared to *Sequoia's* original control strategy. With the refined strategy, the model predicts a fuel economy improvement of 3% on the City cycle and 12% on the Highway cycle.

Table 5. *Sequoia* Fuel Economy.

	Fuel Economy (mpg)	
EPA Test Name	Original Strategy	Refined Strategy
City (FUDS)	27.9	28.6
Highway (HWFET)	27.6	31.0

GREENHOUSE GAS ANALYSIS - Table 6 provides an estimate of the greenhouse gas emissions of the GM Suburban and compares this value to two cases for *Sequoia*. The results for *Sequoia* are based on PSAT simulations. The first case represents calculations based on the FutureTruck rules, which derive results from a continuous 250-mile trip and national-average power plant emissions. This case shows a 53% reduction in GHG. The second example illustrates *Sequoia's* GHG emissions using long-term California power plant emissions and trip-length weighting based on NPTS driving statistics. This case indicates that up to 68% reduction in GHG is possible using *Sequoia's* design.

Table 6. Greenhouse Gas Index Comparison.

Vehicle Case	GHG Index (g/mi)	GHG Reduction
GM Suburban	828.1	N/A
Sequoia/FutureTruck	391.4	53%
Sequoia/California	262.7	68%

CONTROL HARDWARE

Sequoia employs a distributed control system and multiplexed network, simplifying wiring and signal condition, reducing weight, and improving system flexibility over a centralized system. The Powertrain Control Module (PCM), an Intel x86-based controller, executes high-level powertrain and vehicle control. A network of Motorola MC68HC-based control modules located throughout the vehicle perform low-level control and data acquisition.

VEHICLE CONTROL NETWORK – *Sequoia's* controllers communicate over two 250 kbps Controller Area Network (CAN) busses using the MC68HC on-board CAN controller. A dedicated bus connects the PCM with the Engine Control Module (ECM) and Secondary Motor Controller (SMC), providing an uncontested low-latency bus for drive-critical real-time communication. The remaining modules are connected to the secondary bus, with the PCM relaying data between busses as required. The control system architecture is illustrated in Figure 9 and a list of control modules is presented in Table 7.

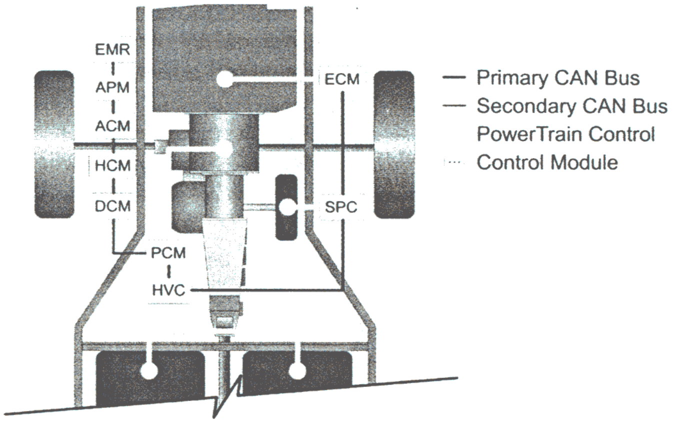

Figure 9. Control System Layout

Table 7. Controller Names and Functions.

Name	**Function**
Accessory Control Module (ACM)	Controls cooling & emissions systems
Accessory Power Module (APM)	Controls high voltage accessory systems
Dashboard Control Module (DCM)	Interfaces instrument cluster to UCD control network
High Voltage Controller (HVC)	Controls High-voltage systems including soft-start
HVAC Control Module (HCM)	Controls HVAC system
Powertrain Control Module (PCM)	High-level powertrain controller
Engine Control Module (ECM)	Actuates engine throttle, Interfaces with Saturn PCM
Secondary Powertrain Controller (SPC)	Controls the secondary powertrain

UC Davis developed a custom High-Level Protocol (UCD HLP) to abstract the details of network access from individual module high-level control algorithms, while maximizing filter efficiency in the Motorola CAN hardware. The UCD HLP employs a shared memory architecture: each node may "broadcast" values from its own address space, write values to remote nodes' address spaces, or query the values of remote nodes' addresses. All data on the CAN bus is transmitted at predefined intervals. Each controller implements a fail-safe protocol if a given data packet does not arrive when expected. Packet transmit and receive timing is handled by the UCD HLP implementation, freeing the module designer to deal exclusively with high-level control.

An Extensible Markup Language (XML) file for each module fully describes all data transmitted and received by that module along with the required encoding, frequency, engineering units, and other "metadata." Shared CAN source code is generated from this dataset, keeping network identifiers consistent between all modules. Additionally, an in-house utility dynamically builds a Graphical User Interface (GUI) capable of interacting with or simulating each module in the vehicle from the XML dataset. The GUI provides a unified interface for development, debugging, in-vehicle configuration, and data acquisition. When the XML data changes, the GUI immediately reflects the change.

A boot loader residing in each module allows new firmware to be updated remotely via the CAN network. Upon power up, the boot loader queries a known address for firmware revisions. The development team can load firmware by triggering a remote reset over the CAN bus or power-cycling the target module after placing the new firmware on the server.

UNIVERSAL CONTROLLER HARDWARE – The similarity in requirements between each control module prompted the in-house development of a universal board containing the microcontroller, support hardware, and I/O circuitry common to all modules. Daughterboards map I/O resources on the microcontroller to module connector pins via specialized signal conditioning hardware. Three generic daughterboard designs, shown in Figure 10, fulfill approximately 95% of the control modules' I/O requirements. This functionality includes performing any combination of RS232 and J1850 communication, digital input (with pull-up, pull-down, or voltage conditioning), digital output (short-to-ground), pulse generation, A/D conversion, and CAN I/O.

This custom universal controller platform, called the Extensible Control Module (XCM), is a leap in controller technology over application-specific hardware systems. Designers can draw on a cache of pre-designed signal conditioning blocks, dramatically cutting the time and effort required to build a new control module or incorporate changing requirements. In the event that no suitable daughterboards exist, only that specific block must be designed and built. Spare parts for control modules built on the XCM platform, shown in Figure 10, are easily shared between controllers, reducing maintenance costs and inventory size.

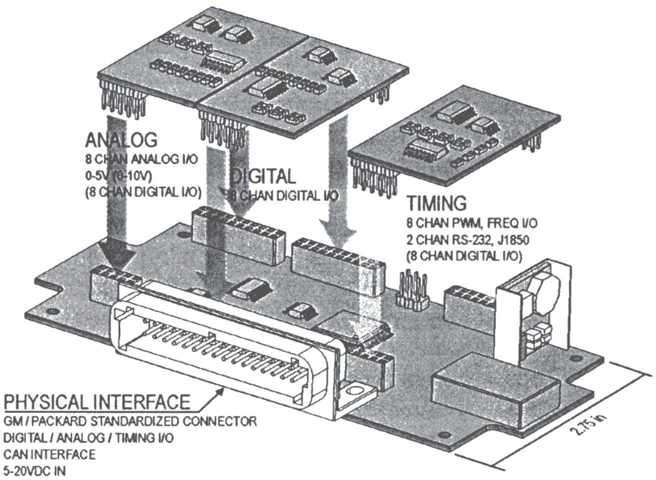

Figure 10. XCM Architecture.

POWERTRAIN IMPLEMENTATION

Integrating the engine, electric motors, their accessories, the fuel tank, and batteries required careful design and analysis. This implementation was accomplished through creative packaging based on solid modeling and Finite Element Analysis (FEA). This resulted in a vehicle powertrain system that is efficient, light, compact, and reliable.

PRIMARY POWERTRAIN – The primary powertrain, consisting of the 1.9L Saturn engine and the Unique Mobility SR218H electric motor, drives the rear wheels. The transmission changes the drive ratio of both the motor and engine. The maximum power output to the wheels of the primary powertrain is 167 kW (223 hp) at an engine speed of 6000 rpm and a maximum rear axle torque of 8044 N-m (5933 lb-ft) at 2500 rpm in first gear. The primary powertrain design configuration is shown in Figure 11.

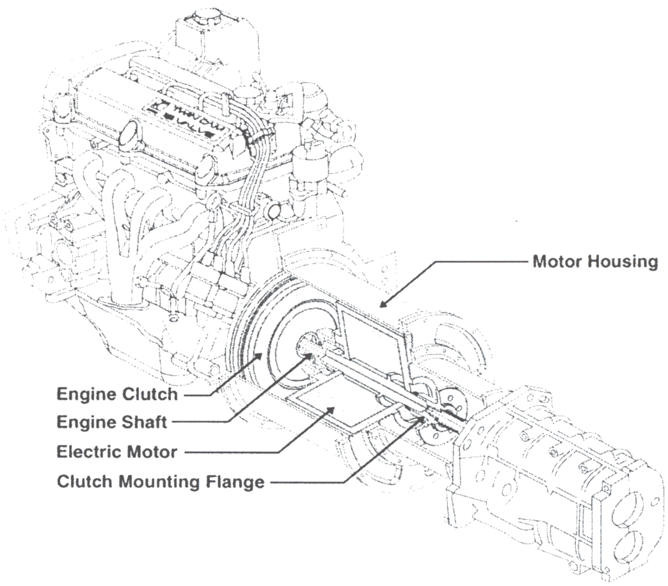

Figure 11. Primary Powertrain Design.

Loading restrictions on the motor case necessitated a housing to carry the reaction torque of the engine to the bell housing of the transmission. This effectively isolates the motor case, but introduces complications during shaft alignment. Careful manufacturing processes and the use of a working spline between the motor and engine addressed these complications. A fatigue analysis of the spline connections on both ends of the motor shaft ensures that the couplings would endure for well over 160,000 km, with a factor of safety of 2.6 for the working spline and 4.0 for the fixed spline.

The increased length of the overall assembly required that the mounting and resultant strength of the housing assemblies be thoroughly analyzed. The assembled system was treated as a beam to determine the shear and moment on the individual components. These loads were applied to SolidWorks models and analyzed using CosmosWorks, a FEA software package. Table 8 shows the resulting safety factors for the custom powertrain components. FEA results are presented in Appendix A.

Table 8. Primary Powertrain Design Results.

Component	Factor of Safety for Yield
Motor Housing	4.4
Trans. Bell-Housing	9.8
Trans. Mounting Plate	3.6
Motor Mounting Plate	4.7
ICE Coupling Shaft	2.8
Trans. Flywheel Flange	7.2

The inertial damping required to minimize engine torque spikes is provided by the engine's flywheel. Electric motor torque delivery does not require additional inertial damping, making a second flywheel unnecessary. A 16.5 cm diameter, two-plate clutch manufactured by Tilton eliminates the flywheel and decreases the bell housing size. The decreased diameter allows the powertrain to be mounted further inside the transmission tunnel than the stock system, freeing room in the engine bay.

Emissions Control – Meeting the SULEV emissions target requires a sophisticated aftertreatment system as well as fuel injection re-programming. A production 2001 Saturn SL2 with California emissions successfully meets the LEV target in EPA testing. The emissions performance of this engine in *Sequoia*, a vehicle with over twice the mass and road load of a Saturn sedan, requires a highly efficient aftertreatment system to meet SULEV standards.

The exhaust aftertreatment system of the stock 1.9L Saturn engine with California emissions includes an air injection pump, Close-Coupled Catalyst (CCC), and secondary catalyst. The stock system is supplemented by an active aftertreatment system consisting of a Hydrocarbon Trap (HC trap), and an Electrically Heated Catalyst (EHC) [7]. When the PCM calls for an engine-on condition, the ACM compares the temperatures of the CCC and EHC to each units specified light-off temperature. The Accessory Control Module (ACM) will then energize the EHC at a rate of up to 3.5 kW until light-off occurs. Unburned hydrocarbons will pass through the cold CCC and are temporarily absorbed by a Zeolitic coating on the HC Trap. The EHC is designed to reach peak conversion efficiency before the hydrocarbon trap begins desorbing hydrocarbons back into the exhaust flow[8]. The air injection pump then purges the hydrocarbon trap of any un-burned hydrocarbons[9]. The effects of this modified system are shown in Figure 12. *Sequoia* uses a metal foil EHC with a cell density of 1200 cells per inch (cpi) density. The metal foil wall thickness is only 0.05 mm, allowing for stable, rigid cell strength, low thermal mass and high surface area.

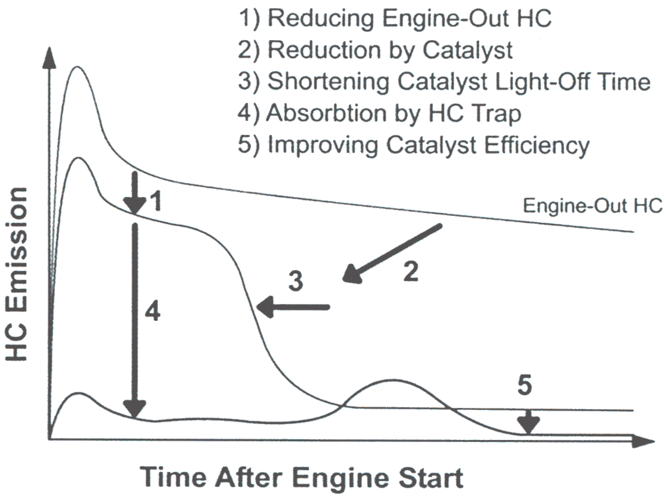

Figure 12. Exhaust System Modifications[10].

To increase the efficiency of the catalytic converters and reduce hydrocarbon emissions, the fuel injection computer was recalibrated to run stoichiometric under most operating conditions.

Engine Thermal System – The ICE cooling system serves the Saturn 1.9L engine and provides a source of heat for the HVAC heater core. A Davies-Craig Electric Water Pump (EWP) improves system efficiency by reducing parasitic drag on the engine. The pump speed is independent of engine speed, allowing control of engine operating temperature. The EWP is controlled by an external microprocessor that takes a signal from a coolant temperature sensor and adjusts the speed of the pump accordingly.

Electronic Thermal System – The electronic cooling system serves the primary and secondary electric motor/inverter units, the DC-DC voltage converters, and the HVAC controller. The cooling circuit operates independently of the ICE cooling system and employs a separate radiator, electric water pump, and thermostatic controller. An aluminum radiator is mounted in the passenger side of the front fascia, ensuring sufficient airflow and improving vehicle packaging by using space not practical for other components.

SECONDARY POWERTRAIN – The secondary powertrain uses a PreMag 75kW electric motor with a fixed gear reduction to provide extra power and torque during high load operation. The peak output is 75 kW (101 hp) with 2797 N-m (2063 lb-ft) of wheel torque at a motor speed of up to 3000 rpm. The motor can provide a continuous power output of 50 kW.

Due to packaging constraints, the motor is located on the passenger side with its axis parallel to the front axle. The motor is connected via a drive shaft to a ring and pinion bevel gear set with a reduction of 2.5:1. The ring gear is connected by a quill-shaft to the pinion input of a 2001 S-10 differential with a reduction of 3.73. This layout is shown in Figure 13.

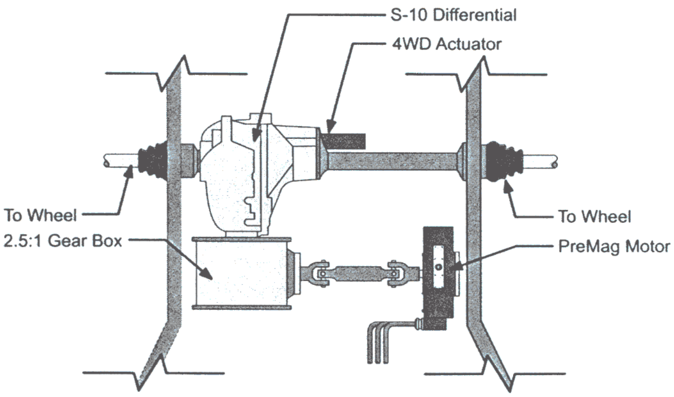

Figure 13. Secondary Powertrain Design.

The combined reduction of 9.325:1 provides substantial low-end torque while allowing a maximum speed of 100 kph. The S-10 differential is closely matched to the systems parameters, resulting in a smaller package with the simplicity and reliability of stock automotive designs. Table 9 shows the modeled safety factors of the major components and interfaces.

Table 9. Secondary Powertrain Design Results.

Component	Factor of Safety
Gearbox	3.5
Mounting Flange	4.2

FUEL SYSTEM

Simulations determined that a 15-gallon fuel tank is required to meet range and performance requirements. Although the stock fuel tank could have been adapted for use with the Saturn engine, its capacity and placement rendered it impractical. A lightweight 15-gallon fuel cell was constructed to replace the 33-gallon, original equipment plastic tank.

LOCATION – The new tank is designed to fit under the rear portion of the vehicle, directly behind the rear differential, between the frame rails. This offers crash protection for the tank as well as utilization of unused space. The tank's envelope design is shown in Figure 14 and allows it to fit around the spare tire without hindering the tire's mounting or accessibility.

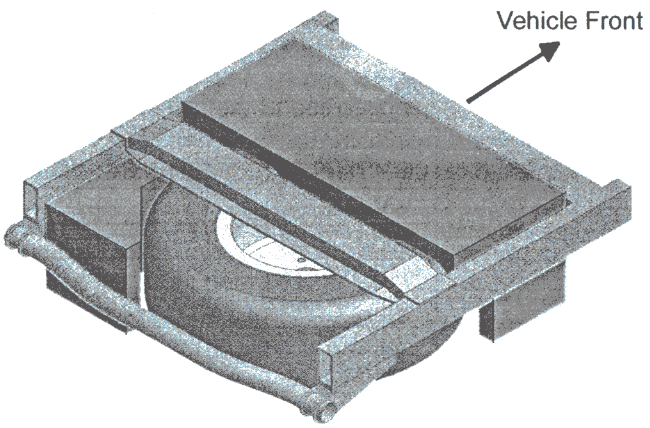

Figure 14. Fuel Tank Layout.

FUEL SYSTEM – The fuel cell, manufactured by ATL, consists of two parts, an aluminum outer shell and a Kevlar/rubber bladder. The bladder is rated to a minimum tensile strength of 4.45 kN. The new tank offers increased protection from puncture and leakage. The outer shell is designed to protect the bladder from surface abrasion and wear. The bladder is intended to prevent puncture and reduce evaporative fuel loss. The fill valve features an internal flap to prevent spillage in the event of vehicle rollover. The regulator supplies a constant pressure to the fuel rail feed via an aluminum fuel line. A fuel accumulator in the engine bay acts as a capacitive buffer to keep the rail supplied under sudden pressure changes.

TRACTION BATTERY

Traction battery selection and integration is important in maximizing the efficiency, emissions characteristics, and cycle life of an HEV. The battery requires high specific energy to provide sufficient energy storage for all-electric travel and high specific power for maximum recovery of regenerative braking energy and full-power accelerations at low states of charge. High energy density minimizes packaging and weight requirements, which helps to offset the weight addition to the vehicle associated with additional batteries. The battery should also typify a high cycle life and incorporate maintenance free operation to increase consumer acceptance.

BATTERY SELECTION – A Nickel Metal Hydride (NiMH) battery pack from Ovonic Battery Company was selected for its high energy and power densities and its sealed cell architecture.

UC Davis worked with Ovonic to develop a battery pack that is ideally suited to the operating characteristics of a charge-depleting HEV. The Ovonic HEVII battery has been optimized for both pulse and continuous power draws. Table 10 lists the physical and performance characteristics of a 60 and a 90 Ah module. Table 11 shows the properties of a 320 V nominal battery pack constructed out of these modules, which is required to match the nominal input voltage of the electric motor system.

Table 10. High-Power HEV NiMH Battery Specifications.

Battery Specifications	OBC 13.2-HEV-60	OBC 13.2-HEV-90
Nominal voltage	13.2 V	13.2 V
Nominal capacity	60 Ah	90 Ah
Mass	12.8 kg	18.4 kg
Specific energy	65 Wh/kg	66 Wh/kg
Energy density	150 Wh/L	180 Wh/L
Specific power (50% SOC)	420 W/kg	420 W/kg
Power density (50% SOC)	1000 W/L	1150 W/L
Module Internal Resistance (50% SOC)	8.4 mΩ	5.8 mΩ

Table 11. 320V Nominal Battery Pack Properties.

Pack Properties	OBC 13.2-HEV-60	OBC 13.2-HEV-90
Nominal voltage	317 V	317 V
Measured energy	19.8 kWh	29.6 kWh
Peak power (50% SOC)	130 kW	185 kW
Module Mass	306 kg	442 kg
Number of modules	24	24

Table 12 lists the results of vehicle simulations analyzing the trade-offs between these two battery packs, including weight, fuel economy, and all-electric range. A vehicle with the 90 Ah pack has greater all-electric range, resulting in a 7.2% reduction in GHG emissions over a 400 km trip construction. The 90 Ah battery pack was chosen for *Sequoia* to maximize partial ZEV credit while maintaining efficiency and performance.

Table 12. Vehicle simulation results for 60 Ah and 90 Ah battery packs.

Vehicle Performance	OBC 13.2-HEV-60	OBC 13.2-HEV-90
FUDS energy economy	8.2 L/100 km	8.2 L/100 km
HWFET energy economy	7.6 L/100 km	7.6 L/100 km
All-electric range (FUDS)	71.5 km	106.8 km
0-100 kph acceleration	12.1 sec	9.5 sec
PZEV Credit	0.65	0.79

BATTERY INTEGRATION – The batteries are split into two equal packs consisting of 12 modules each. This arrangement uniformly distributes the weight of the batteries over the vehicle centerline and allows other components to be more easily packaged around the two enclosures. Each pack is located between the drive shaft and respective frame rail. The boxes extend longitudinally from the front torsion bar to the rear frame rail stiffener, as shown in Figure 15. To maximize protection of the battery enclosures and to maintain the stock ground clearance, the lowest point of the enclosures was placed above the bottom plane of the frame rails, allowing the frame to serve as vertical and side impact protection.

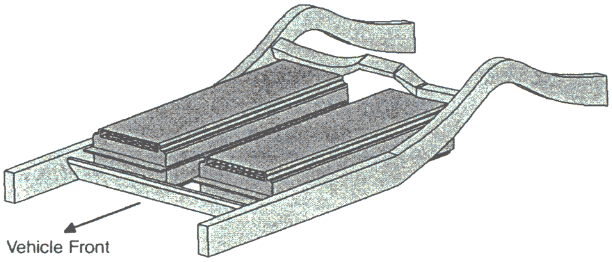

Figure 15. Battery Enclosure Location.

The battery enclosures are mounted directly to the frame's lateral cross members for maximum structural support. To ensure clearance during frame flexure, the enclosures are secured by flexible mounting points, while maintaining a minimum clearance of 2.5 cm between the enclosures and any body-mounted structure.

Battery Enclosure Fabrication – The battery enclosures were designed and fabricated to provide maximum strength and safety while minimizing weight and volume. These enclosures are constructed from composite materials to provide a stiff, lightweight structure that is electrically isolated.

The box consists primarily of graphite fiber, fiberglass, and honeycomb core material. Figure 16 illustrates the composite formation of the enclosure's symmetrical cross-section. The inside surface is constructed from fiberglass to electrically isolate the batteries from the rest of the enclosure. Four carbon fiber box beams were added to the floor of the bottom section to support the batteries, increase enclosure stiffness, and promote airflow in a constrained volume. Composite U-section strips are attached to these beams in order to constrain the batteries under high reverse loading and vibrations.

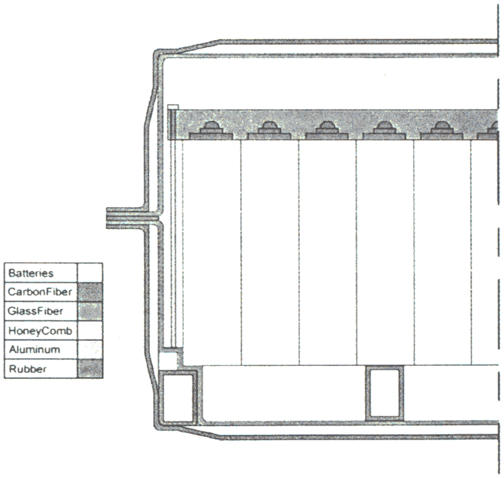

Figure 16. Battery Enclosure Construction.

Thermal Management – The batteries are cooled convectively by airflow between the modules. Top-to-bottom airflow was chosen over cross flow, increasing enclosure height, but providing more effective, uniform cooling. Inlet cooling air is drawn from the high-pressure region at the base of the windshield and ducted to the front of the pack. This raises the inlet duct significantly above the road, allowing the inlet air to be conditioned by the HVAC system during high discharge/charge periods or extreme ambient temperature conditions. The enclosure outlet ducts direct the ventilation air to a low-pressure region at the rear of the vehicle.

The twelve modules are arranged laterally inside the box, spaced 9mm apart. These gaps were specifically chosen to insure that they are the dominant airflow restriction, ensuring uniform vertical airflow throughout the modules. The resulting flow pattern is represented in Figure 17. The exhaust chamber volume is slightly larger then the inlet volume to ensure that the pressure drop along the enclosure length is negligible.

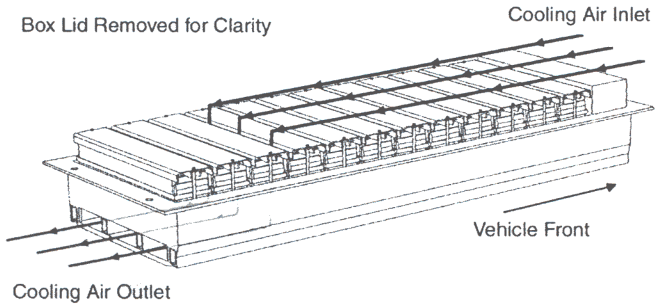

Figure 17. Battery Enclosure Airflow.

Airflow through the enclosures is controlled by a thermal management system located in each box. The temperature and voltage of each module is measured and used to control the speed of the cooling fans. If module temperature increases rapidly or if ambient inlet air temperatures are too high, the HVAC system will activate an evaporator to increase heat rejection. During extreme conditions or system malfunction, the powertrain control module will limit battery current to prevent module damage.

BATTERY CHARGING – The 90 Ah battery pack charges from 20% to 100% SOC in six hours using a standard inductive charging system found in every major metropolitan area throughout California and Arizona. In light of recent power crises, the possibility of bi-directional charging from this type of battery pack could offer additional benefit to the consumer. Coordinating charge time with off-peak power generation can help stabilize the demand on local power grids, illustrated in Figure.18. The off-peak electricity purchased by vehicle owners will load level power plant operation, increasing their efficiency and profitability, while helping fund additional generating capacity.

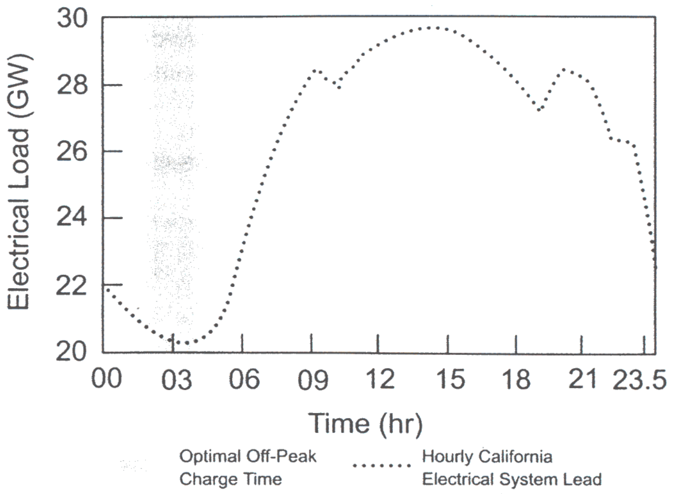

Figure 18. California Independent System Operator (ISO) Plot of a Daily State Electrical Load.

DRAG REDUCTION

The aerodynamic performance of a bluff-bodied vehicle like the Suburban is important to vehicle performance and fuel economy. Decreasing mass, coefficient of rolling resistance, C_{RR}, or the coefficient of aerodynamic drag, C_D, can significantly reduce total vehicle drag. Decreasing vehicle frontal area would also reduce drag, but this would unacceptably compromise vehicle utility.

WEIGHT REDUCTION – The most significant weight reductions were achieved by replacing existing steel panels with plastic/composite parts. The original 32 kg steel hood was replaced with a 7 kg composite hood. Composite fender skins reinforced with sandwiched sheet aluminum-composite substructures saved an additional 13 kg. The rear differential has an aluminum housing and fiberglass composite cover. Total weight savings from powertrain components totaled 54 kg and new radiator assemblies saved 12 kg. All original steel frame mounts that were not used in the redesign were removed to reduce weight and to free up unused space.

ROLLING RESISTANCE – Rolling resistance is caused by tire deformations due to the vehicle's weight. Coast-down testing the stock Suburban yielded a C_{RR} of 0.0125 for the stock tires. *Sequoia* is equipped with special high-pressure tires from Goodyear with a C_{RR} of 0.0065 at 42 psi and a load of 683 kg per tire. The lower C_{RR} yields a constant decrease in vehicle drag force. The effect of this decrease is more pronounced at low speeds where rolling drag makes up a larger proportion of the total drag force.

AERODYNAMIC MODIFICATIONS – Body modifications to improve vehicle aerodynamics were based on existing literature, research, faculty consultation, and coast-down tests. Mockups of each proposed modification were coast-down tested on a stock Suburban. The results of each test were compared to the baseline vehicle to quantify the effects of proposed designs.

The after-body drag on a bluff body such as *Sequoia* is a large contributor to aerodynamic drag. *Sequoia* features an active aerodynamic drag reduction system to decrease after-body drag. This system automatically extends a pair of boat-tail plates at the rear of the vehicle. Each boat-tail is broken into an upper and lower section. The upper section consists of a titanium fan structure that remains recessed in the rear D-pillar. The lower section is integrated into the rear liftgate. The boat-tail plates are not visible to the driver and do not interfere with the function of the rear window or liftgate.

The boat-tails reduce the low-pressure wake by entraining the airflow inwards as it passes the rear of the vehicle. Both the upper and lower sections are deployed when the vehicle reaches 80 kph and retract when the vehicle slows to 50 kph. Coast-down tests with a prototype design showed a 10% reduction in C_D (ΔC_D=0.047) and are in agreement with published results on the aerodynamic effects of boat-tails[11]. Figure 19 shows the results of coast down tests with and without the boat tail modifications.

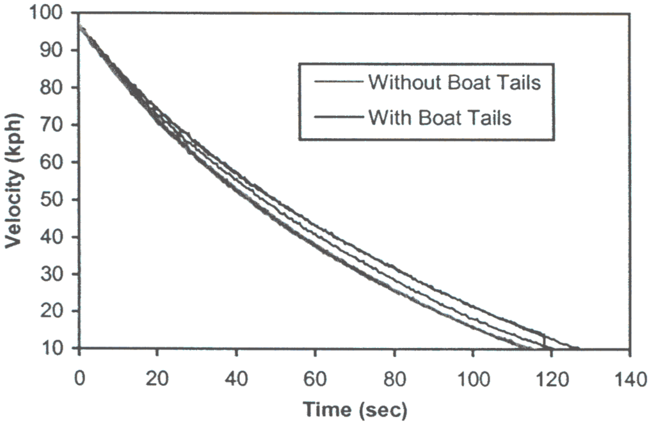

Figure 19. Coast Down Results of Boat-Tail Effects

The radiators were moved to a lower position below the front grill. The resulting front fascia is more streamlined. The front bumper was integrated into the front fascia to promote laminar flow over the front of the vehicle. Underbelly panels covering the entire underside of the vehicle were added to reduce the turbulence level beneath the vehicle. Design considerations for the underbelly panels included provision of drainage under the engine bay, easy removal for maintenance, and protection of the battery enclosures, external wiring, and fuel lines. The aerodynamic modifications provide an estimated drag reduction from the stock value of 0.47 to 0.378, a 19.6% reduction. The predicted contributions of the aerodynamic modifications are summarized in Table 13.

Table 13. *Sequoia* Drag Parameter Improvements.

Modification	**ΔC_D**	**ΔC_{RR}**
Initial	0.470	0.0100
Front Fascia	-0.020	N/A
Belly Pans	-0.020	N/A
Boat-tail	-0.042	N/A
Radiator Ducting	-0.010	N/A
Goodyear Tires	N/A	-0.0035
Total	0.378	0.0065

ACCESSORY SYSTEMS

AVIS – Driver and passenger safety, comfort, and convenience are the driving forces behind the Advanced Vehicle Information System (AVIS) shown in Figure 20. AVIS consists of two subsystems: a telematics platform, providing AM/FM/MP3 audio, navigation, vehicle systems monitoring and internet access, and a passenger entertainment system providing multiple channels of video to passenger displays.

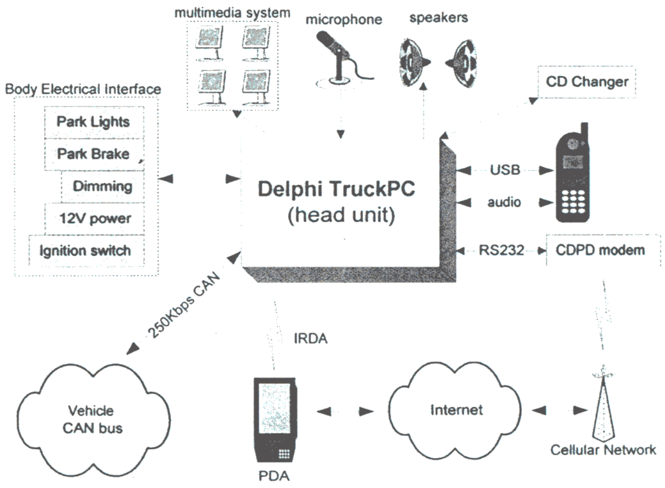

Figure 20. Telematics System Architecture.

Telematics – The telematics system is built upon Delphi Delco's TruckPC platform, a single-DIN automotive computer running Microsoft Windows CE. The TruckPC incorporates a 320 X 80 pixel electro-luminescent display for limited visual display to the driver. The primary driver interface uses voice synthesis and recognition. The voice interface allows the driver to control the audio and navigation systems, initiate, answer, and carry on phone calls, or hear and compose email without ever having their eyes leave the road.

This platform allows for full integration with the vehicle's control network. *Sequoia's* telematics system displays a real-time representation of the hybrid powertrain on an external color display integrated into the rear-view mirror, along with battery pack state-of-charge and estimated mileage pertaining to various drive configurations. A charging station database integrated with the navigation system will alert the driver to convenient charging locations along their route of travel if necessary.

Sequoia's telematics system employs a Cellular Digital Packet Data (CDPD) wireless internet connection for an optimal combination of bandwidth, operational cost, and service availability. Domestic wireless carriers are rapidly nearing deployment of 2.5G and 3G wireless systems that will provide significantly faster and more reliable data service. When these services are available, upgrading will only require a simple component swap.

The AVIS system integrates an infrared (IrDA) transceiver, allowing it to synchronize phone numbers, email addresses, and even vehicle status (e.g. charge, estimated range, etc.) with personal digital assistants (PDAs). The wireless internet connection allows the user to remotely monitor and manipulate vehicle systems from any wireless device with a web browser, such as a PDA or cellular phone. This could be used to activate the air conditioning system on a hot day and cool the interior before arriving at the vehicle.

Network-connected telematics systems in grid-connected HEVs allow the possibility of driver-approved bi-directional charging. When the vehicle is plugged into the grid and a request is received from the local power company to buy back power, the telematics system will page the user's PDA or cell phone. Using a browser-based interface, the user will interact with AVIS system to accept, decline, or modify the offer.

Entertainment System – *Sequoia's* entertainment system is designed to maximize entertainment and convenience while minimizing driver distraction. The system distributes up to five channels of video and stereo audio to passanger displays throughout the vehicle.

A UC Davis-designed digital video-on-demand system provides one channel of entertainment. The player contains approximately eight hours of MPEG-2 digitally compressed video recorded by a support appliance in the driver's home. When parked at home, *Sequoia's* entertainment system wirelessly downloads new recordings, providing on-demand access vehicle occupants' favorite recordings. A DVD player and TV tuner provide additional entertainment sources. The video output from the telematics platform and a rear-view camera provide the remaining two video channels. This architecture accommodates different programs on each display in the vehicle.

A dedicated 2.8" LCD display is integrated into the rear-view mirror. The driver's display shows the telematics video output during normal operation, and automatically switches to the rear view camera when the vehicle is shifted into reverse. The driver's screen may not view any of the multimedia entertainment sources.

HVAC – *Sequoia's* Heating, Ventilation, and Air-Conditioning (HVAC) system retains the plumbing, ducting, and heat exchanger of the stock vehicle. An electric compressor manufactured by Sanden replaces the engine-driven compressor to provide cooling in all operating modes.

The HVAC Control Module (HCM) replaces the stock Suburban HVAC controller. The Sanden compressor is not coupled to the powertrain like the stock, engine-driven unit, and is capable of variable speed operation. The HCM reads the front HVAC control panel and cabin, ambient, and duct air temperature sensors. A control algorithm actuates the mixer doors and controls the speed of both the blower motor and Sanden compressor. The HCM is connected to the CAN network, allowing remote modules to monitor the function of the HVAC system and display system activity and statistics such as cabin and ambient temperatures to the vehicle occupants.

DFMEA

The results of the Design Failure Mode and Effects Analysis (DFMEA) performed on *Sequoia* are presented in Appendix B. DFMEA is used to address 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

All advanced vehicles must overcome cost barriers, both real and perceived, if they are to succeed commercially. The most significant barrier to commercialization of a hybrid electric vehicle is the expensive battery pack. Other factors affecting cost include the power electronics, high performance electric traction motors, use of lightweight materials, and downsizing of the ICE and other related accessories.

BATTERY COST – Issues of advanced battery specific energy and power, manufacturing cost, and durability have been the dominant concerns facing the development of battery electric and hybrid vehicles. Currently available designs like the NiMH pack in the UC Davis FutureTruck provide sufficient power and energy to achieve the design targets, including a 60 mile all-electric range, two-thirds reduction in greenhouse gases, and performance surpassing that of the stock vehicle.

The impact of battery cost on the Manufacturer's Suggested Retail Price (MSRP) of an HEV Suburban requires four initial assumptions, including:

1. Battery manufacturing cost at production volumes
2. Battery lifetime, both cyclical and annual
3. Secondary pack use value
4. Recycled value of battery materials

Current estimates place the cost of NiMH batteries in volume production at between $200 and $400 per kWh [2,12,13]. A figure of $250/kWh was chosen for battery module cost, a figure favored by many analysts for high-volume production[1415].

In *Sequoia*, the ICE buffers the battery system, protecting it from dangerously deep discharges and thermal stress. NiMH batteries are already highly reliable. Southern California Edison reports only six module replacements after three million miles for their EV fleet[14]. Analysis of existing battery life cycle data and consultation with industry experts indicates that mature NiMH technology should withstand approximately 1750 full discharges to zero SOC[16] with an annual life exceeding seven to ten years[12,14,15,17]. The cycle life of NiMH batteries is highly dependent on energy throughput. Discharging the pack to 50% between charges will, at a minimum, double the cycle life[13]. Conservatively assuming a linear dependence of cycle life on depth of discharge, the battery pack in *Sequoia* would last for a minimum of (1750 cycles x 66 miles/cycle) 115,500 miles of all electric travel. Constructing a rough estimate of total gasoline and electric miles based NPTS data results in total vehicle mileage of approximately 165,000 miles. This figure exceeds the design life of some conventional vehicles, so battery replacement is not considered in this cost analysis.

After 1750 cycles, the battery is assumed to have degraded to 80% of original capacity and is replaced. The used modules are still superior in capacity and cycle life to stationary lead acid batteries costing $200-$300/kWh[15]. Estimates for this secondary value (in present day dollars) range from $50-200/kWh. The UC Davis battery pack also contains over 200 kg of high-value recyclable materials and is assigned an end-of-life value of $600 per pack. The residual value of the old battery, added to the lower operating time on the internal combustion engine and related systems will help mitigate the cost of battery replacement, if it becomes necessary during the life of the vehicle.

UC DAVIS HEV COST SUMMARY – A cost analysis was used to determine the price differential to the consumer of a production vehicle like *Sequoia*. Each added or deleted vehicle component carries an OEM cost and a markup factor used to arrive at the contribution to vehicle MSRP. Individual component costs are estimated by assigning a value as a percentage of the vehicle MSRP[11,16]. Components and systems manufactured by the automaker are given a markup of 2.0. Components and systems assumed to be provided by an outside vendor are assigned a lower value of 1.5, reflecting the warranty, capital, and development costs borne by the vendor. The battery modules are assigned a markup of 1.15 based on studies of battery integration and its costs to the OEM[11,12,17].

In addition to the battery pack, *Sequoia* requires two DC traction motors, a power electronics module and a battery enclosure. These costs are estimated below in Table 14. The power electronics module incorporates both motor drives, DC-DC converters for accessory loads, and battery charging/monitoring. There are additional off-board charging component and installation costs to the owner. The stock 5.3L V8 engine, including accessories, is replaced by a 1.9L Saturn engine assembly. Each ICE system cost includes and differences in exhaust, cooling, accessories, and required components. The 4WD transfer case and front axle assembly are deleted in favor of one of the DC motors and a front gear drive assembly. The automatic transmission is replaced with a lower cost, lower capacity manual transmission to reflect the lower torque and peak power of *Sequoia*'s primary powertrain.

The cost of the lightweight materials used in *Sequoia* was not considered in this analysis. The application of aluminum and Fiber-Reinforced Polymer (FRP) materials is not confined to advanced vehicles. For example, the stock 2000 Suburban uses an aluminum liftgate and reinforced plastic dashboard and running boards.

Table 14: Component Cost Estimates

System or Component	OEM	Markup	MSRP
NiMH Pack (29 kWh)	$ 7,250	1.15	$ 8,338
Electric Drive Motors (2)	$ 1,140	1.5	$ 1,710
Power Electronics Module	$ 1,596	1.5	$ 2,394
1.9L Saturn Engine	$ 2,209	2.0	$ 4,418
Front Drive Assembly	$ 225	2.0	$ 450
Battery Enclosure and Hardware	$ 400	1.5	$ 600
Charger and Installation	$ 550	1.5	$ 825
Total Added HEV Components	$13,370		$ 18,735
5.3L Engine Assembly	$ (4,049)	2.0	$ (8,098)
4WD Equipment	$ (1,350)	2.0	$ (2,700)
Auto Trans(cost premium)	$ (450)	2.0	$ (900)
Total Stock Deleted Components	$ (5,849)		$(11,698)
Total HEV Cost Increment			$ 7,037

The hybrid electric powertrain and battery system of *Sequoia* added $18,735 to the MSRP of the vehicle. Deleting the stock powertrain components decreased the cost by $11,698. The resulting net cost increment to the buyer is $7,037. Table 15 shows this cost premium compared with other high-efficiency or premium powertrain options available throughout the truck industry. This study does not consider currently available incentives for alternative fuel vehicles. It also does not consider the value to the OEM due to positive environmental advertising, Corporate Average Fuel Economy (CAFE) credits, and ZEV mandate or other regulatory compliance. It is highly likely that these benefits would lower the cost increment to the consumer.

Table 15: Premium Powertrain Cost Delta

Powertrain Option	Incremental Cost (MSRP)
GM 6.5L Duramax Diesel	$ 4,810
Ford 7.3L Turbo Diesel	$ 4,720
Dodge Cummins 5.9L 24V Turbo Diesel	$ 5,225
UC Davis HEV Option	$ 7,037

OPERATIONAL COST, USE, AND BENEFITS

There are numerous benefits to the owner of a grid-connected hybrid vehicle like *Sequoia*. In addition to clear environmental benefits, the owner of *Sequoia* will experience lower operating costs, time saved by reducing trips to the gas station, and the ability to counter periodically higher gasoline prices with charging. An ongoing consumer focus study conducted by the Electric Power Research Institute indicated that majority of drivers had a favorable opinion of an HEV that they plugged in at home or at work[16].This was especially true of younger drivers who are already using a number of devices that require daily charging such as cellular phones, palm computers, and laptop computers[18].This data is supported by a recent survey of 134 electric vehicle owners and operators where only a single respondent indicated that they would not lease an EV again[19].

Advisor simulations were used to calculate an approximate cost of operation based on certain styles of vehicle driving and energy costs of 5.5 cents/kWh for off-peak electricity and $1.50 per gallon of gasoline. A driver operating *Sequoia* as purely an electric vehicle would pay 2.4 cents/mile to fuel the vehicle. Using NPTS data and a nominal all-electric range of 66 miles, the cost of electricity and gasoline for *Sequoia* is 3.9 cents/mile. The stock Suburban costs 10.1 cents/mile to fuel, enabling the driver of *Sequoia* to save over $7,000 in fuel costs over the life of the vehicle battery pack.

ORGANIZATION

The UC Davis FutureTruck Team is a group of students undertaking extraordinary challenges in advanced vehicle design as an extracurricular activity. It is crucial for the team structure to be responsive to the needs of the students, whose primary focus is completing an academic degree. The team is organized into four primary groups: Body Chassis (BCG), Powertrain (PTG), Electronics and Controls (ECG), and Management and Administration (MAG). Figure 21 lists the responsibilities of each group. Leadership responsibilities are highly distributed among the experienced members of the team, with multiple backups for each task or position. Group members are highly interdisciplinary and often cross over to support critical activities in other groups. The team advisors assist with the group organization, supply technical insight, and provide valuable engineering coursework and credit while encouraging an atmosphere conducive to student learning and development.

Effective communication is an essential tool for accomplishing the group's objectives. In addition to traditional meetings, the team employs a variety of networking and email tools to promote the exchange of information to meet the timeline laid out by Figure 22. The team budgets financial support for opening the lab and machine shop on Saturdays, enabling the entire group to spend one day per week working concurrently. A large block of Nextel™ handsets combined with personal cellular phones allows team members to stay in close contact, facilitating instant consultations with students currently not in the lab. These techniques, combined with distributed leadership roles and clear, achievable objectives help the FutureTruck project fit the needs and resources of the student team members.

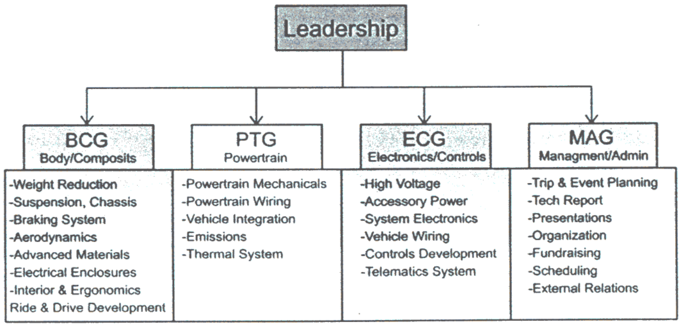

Figure 21. Team Organization

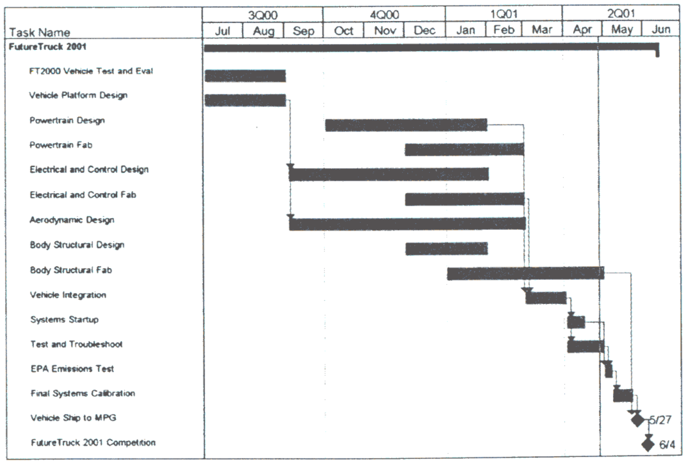

Figure 22. Team Timeline

CONCLUSION

The UC Davis FutureTruck team has redesigned a 2000 Chevrolet Suburban as a hybrid-electric vehicle to significantly reduce greenhouse gas and other tailpipe emissions. The vehicle design centered on a charge-depletion philosophy but includes charge-sustaining capability to provide extended range and towing capacity. This enables the HEV to maximize efficiency when possible and still retain the convenience and performance that accompanies its conventional counterpart. The powertrain has been redesigned to greatly increase efficiency; body sections have been remanufactured to incorporate aerodynamic improvements and weight savings, and certain component systems have been reengineered for improved performance.

The result is *Sequoia*, a sport utility vehicle that features California SULEV emissions, qualification for 79% partial ZEV credit in California, up to a 68% reduction in greenhouse gases, and improved performance when compared to the stock Suburban. The cost increment of *Sequoia* over the Chevrolet Suburban is projected to be $7,037. Although the initial cost increment appears significant, the fuel cost savings over the life of the vehicle will likely compensate for the additional cost. As a result, the lifecycle cost of *Sequoia* is equal to or lower than the stock model. This combination of efficiency, performance, and cost benefits makes *Sequoia* an environmentally friendly, sporty vehicle with significant mass-market potential.

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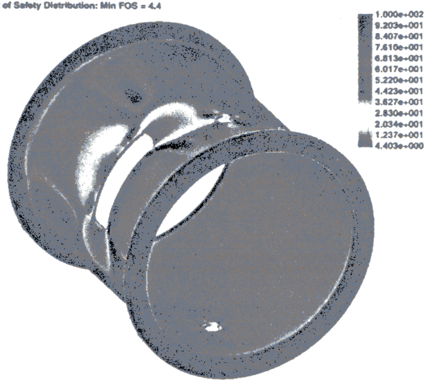
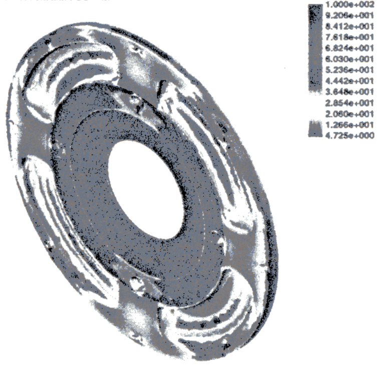
APPENDIX A

Finite Element Analysis: Factor of Safety results

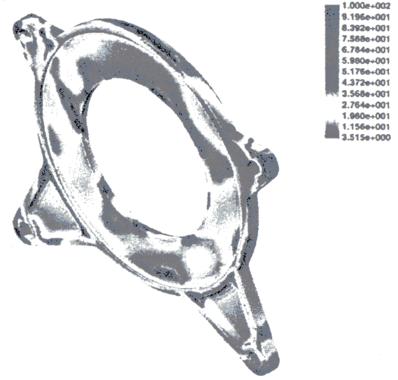
Torque Tube: Design Check Criterion: Max von Mises Stress
Factor of Safety Distribution: Min FOS = 4.4



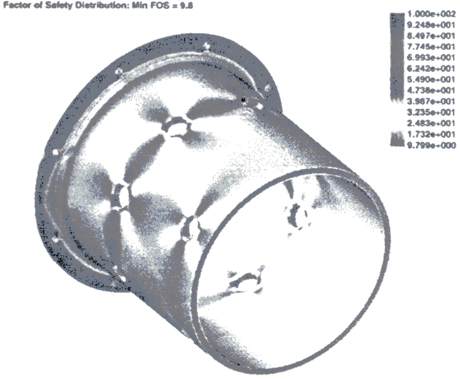
Motor Mounting Plate: Design Check Criterion: Max von Mises Stress
Factor of Safety Distribution: Min FOS = 4.7



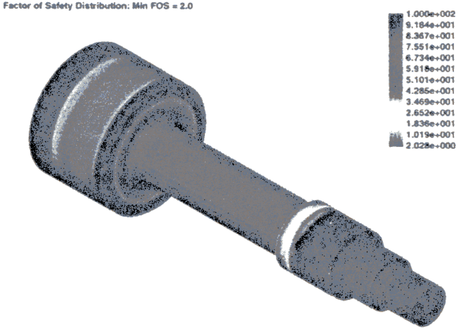
Transmission Mounting Plate: Design Check Criterion: Max von Mises Stress
Factor of Safety Distribution: Min FOS = 3.6



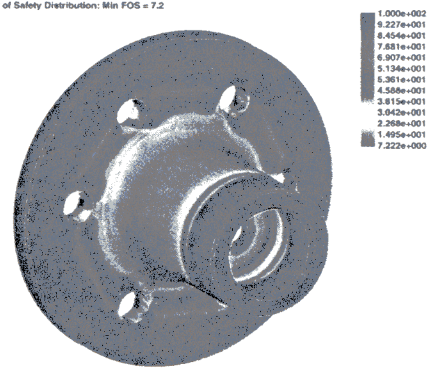
Transmission Bell Housing: Design Check Criterion: Max von Mises Stress
Factor of Safety Distribution: Min FOS = 9.8



Engine Shaft: Design Check Criterion: Max von Mises Stress
Factor of Safety Distribution: Min FOS = 2.0



Torque Tube Flange: Design Check Criterion: Max von Mises Stress
Factor of Safety Distribution: Min FOS = 7.2



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	7	4	3	84	-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	-Keep replacements on hand -Simplify replacement
Engine Coupling Shaft	7	2	6	84	-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	7	3	3	63	-Overheat -Thermal runaway	-Battery damage -Decreased capacity -Fire	-Underestimated pressure drop in cooling airflow	-Robust design -Experiments -Design review	
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	1	6	60	-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	
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	