UNIVERSITY OF IDAHO FUTURETRUCK 2001

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EXECUTIVE SUMMARY

This final report details the development of the University of Idaho hybrid electric vehicle (UI-HEV) and gives an overview of the competition requirements, summarizes the design features of the UI-HEV and includes research results.

The objectives of the University of Idaho FutureTruck project were to

- Complete the conversion of the 2000 Suburban into a working hybrid electric vehicle ready for competition in June 2001
- Educate the public on the benefits of hybrid propulsion vehicles.
- Collect data on the performance of the FutureTruck in terms of power generated and energy efficiency.

The University of Idaho Advanced Vehicle Concepts Team (AVCT) was successful in designing and demonstrating the conversion of a 2000 Chevrolet Surburban to hybrid propulsion. Besides designing a vehicle to meet or exceed the performance requirements established by *FutureTruck 2001 Rules and Regulations*, the UI team focused on a series configuration that could complete an urban driving cycle in zero emission mode. The AVCT raised over $100,000 from various sponsors beyond the UTC funding and participated in several community outreach events to promote advanced vehicle technology. Special efforts were made to centralize control and monitoring functions in a programmable logic controller (PLC). Based on modeling results, the UI FutureTruck 2001 entry is predicted to achieve 21 km/L (50 mpg) during typical city driving and 13 km/L (31 mpg) for typical highway driving while maintaining emission levels lower than a comparable vehicle equipped with a 1.9 L diesel engine.

DESCRIPTION OF PROBLEM

FutureTruck 2001 is a competition sponsored by the U.S. Department of Energy and GM Corporation. The competition strives to improve the emission and fuel economy performance for the Chevrolet Suburban. In recent years, the popularity of the sport utility class of vehicles has caused concern for maintaining the nation's air quality. While steady advances in vehicle technology have been realized in recent years, the consumer's demand for performance has offset potential gains in vehicle emissions and fuel economy [1]. With the sport utility vehicle (SUV) market share predicted to increase beyond 19 percent of the total light vehicle market by the year 2005 [2], the Department of Energy and GM recognized the need for environmental improvements in SUVs and sponsored the FutureTruck 2001 competition.

Competition goals included a need to double the vehicle's fuel economy, reduce emissions, and maintain total vehicle functionality. Table 1 summarizes these goals. The competing schools were also required to raise additional funding, provide outreach to the general public to improve awareness of alternative vehicle technologies, successfully perform the conversion, and compete in June 2000 at the GM Desert Proving Grounds and in June 2001 at the GM Milford Proving Grounds.

Table 1. FutureTruck 2001 Competition Goals

- High-quality engineering educational experience
- Reduce total GHG emissions by 2/3 compared to stock vehicle
- Maintain fully functional power accessories and passenger comfort features
- Maintain 3,175 kg (7,000 lb.) towing capacity
- Provide seating for 8 and 1.294 cu. meters luggage capacity
- Build public awareness for improving efficiency and emissions of light duty vehicles

APPROACH AND METHODOLOGY

Our final approach was a modified series hybrid electric vehicle capable of completing the Urban Dynamometer Driving Schedule (UDDS) in electric mode with extended highway range. The series hybrid configuration is illustrated in Fig.1. Assuming the battery pack is fully charged, this vehicle allows a consumer to complete a typical commute through a congested urban area without the use of a combustion engine. The UI-HEV is solely propelled by a 150 kW (55 kW continuous) motor and controller. A Volkswagen 1.9L turbo direct injection (TDI) engine converts mechanical power into electrical power via a 35kW alternator. The power from the engine is stored as electrical energy in thirty 12V PC1200 Hawker Energy batteries.

There are several advantages of a series hybrid powertrain versus conventional internal combustion (IC) engine and parallel hybrid powertrains. One of the most significant advantages of a series HEV is the flexibility in operating modes. A series HEV can operate as either an all-electric vehicle during short trips or as an HEV during extended trips. An all-electric vehicle has zero tailpipe emissions, commonly called a zero emission vehicle (ZEV). Since the majority of American driving is short range, with an average commute to work of 18 km (11.2 miles) per day [3], significant reductions in tailpipe emissions can be gained by operating a series HEV.

A series HEV operating in hybrid mode commonly has lower tailpipe emissions compared to parallel and conventional vehicles. With a series HEV, the electric motor is the only

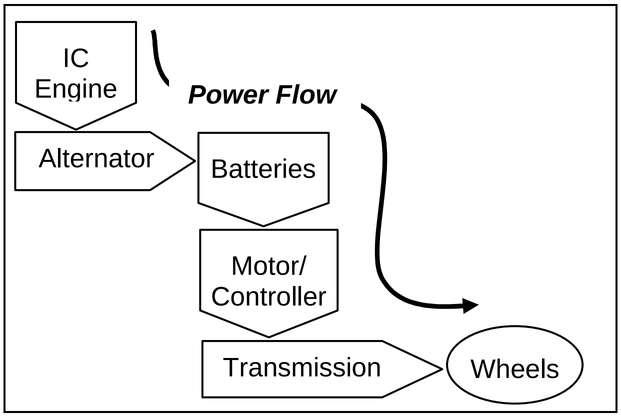

Figure 1. Series hybrid electric vehicle configuration.

component mechanically coupled to wheels, and the internal combustion (IC) engine operates at a near constant speed when required to charge the batteries. With a parallel HEV or conventional vehicle, the IC engine fluctuates over a broad operating range. High tailpipe emissions associated with transient operation of an IC engine can be significantly reduced with a series HEV.

The UI-HEV was modeled with the Advanced Vehicle Simulator (ADVISOR) and the Program for New Generation of Vehicles Systems Analysis Toolkit (PSAT) to predict vehicle performance. ADVISOR, developed by the National Renewable Energy Lab (NREL), has been widely used and tested throughout the automotive industry. PSAT, a tool developed by Argonne National Laboratory, was offered to FurtureTruck 2001 teams. The UI team evaluated fuel economy and emissions predictions for three different vehicle configurations involving diesel engines: series, parallel, and conventional. Model results indicated that fuel economy during the UDDS for the series configuration was 21.4 km/L (50.4 mpg) while the parallel and conventional were 10 and 9.9 km/L (23.7 and 23.3 mpg), respectively.

The Highway Fuel Economy Driving Schedule (HFEDS) was used to model these same vehicles. The parallel configuration showed the best fuel economy with 14.2 km/L (33.8 mpg), whereas the series and conventional vehicles were 13.0 km/L and 12.6 km/L (30.7 and 29.7 mpg). Results of emissions modeling also favor the series configuration. The emissions results are presented in Table 10 in the modeling section. The major components used in each of these vehicles were comparable in size. Given these fuel economy and emissions results, the UI team concluded that a series configuration has advantages when used for urban driving.

The University of Idaho student team was organized into several sub-groups, each with its own leader and graduate student advisors. There were two types of groups, the goal-seeking groups and system design groups. Each of these teams had a captain, who was an experienced AVCT member. Throughout the year, the goal-seeking groups were assigned different tasks to research and develop. This gave team members the opportunity to study and work on several different systems. Two graduate students also worked with the teams as technical advisors. The graduate students completed modeling as part of their graduate work. The systems design groups included the following: Drive-Train/Chassis, Electrical/Controls, IC Engine, Modeling/Testing, Battery and Executive. Table 2 lists the various systems design groups and their responsibilities.

Table 1. UI-HEV System Design Groups for 2001

Group	Responsibilities
Drive-train/ Chassis	Implementation of the gear reducer, transmission calibration, and weight reduction
Electrical/ Controls	Electric controller upgrades, PLC programming, high voltage wiring
IC Engine	Startup logic, enhanced cooling, closed loop speed control
Modeling/ Testing	Instrumentation for data collection, ADVISOR and PSAT simulation, data analysis
Battery	Battery pack upgrade, battery box design, enhanced high voltage safety systems
Executive	leadership, organization, communication, fundraising, reporting, public education

During the past year, public education remained an important objective for the UI Team. Newspaper articles and television reports featured the UI FutureTruck, and the team visited area schools. Display and demonstration of the vehicle enabled people to visualize how an alternative vehicle can look and function like its stock counterpart. Table 3 summarizes the major public education activities.

Table 2. UI-HEV public education events.

Event	Month
NIATT Peer Panel Review	October 2000
Women in Engineering Day	November 2000
UI Legislative Field Trip	December 2000
Vandal Friday; University of Idaho	March 2001
Earth Day; North Idaho College	April 2001
Science Class' Moscow High School	April 2001
Engineering Design Expo	May 2001

Vehicle Design—Powertrain Configuration

The UI-HEV series hybrid configuration is shown in Fig. 2. The power required to move the vehicle comes from the electric motor, which is directly coupled to a gear reducer. The gear reducer multiplies the torque and reduces the speed of the electric motor to match the transmission input requirements for optimal vehicle performance. The drive shaft, differential, and axle are the original GM components.

The batteries are located on either side of the driveline between the frame rails. Two boxes mounted to the undercarriage hold 30 Hawker Energy batteries. Under the hood sits the IC Engine, alternator, and controller. The IC engine is situated in the same position as the stock IC engine but with an alternator mounted to the front. The controller is next to the IC engine on the passenger side of the vehicle.

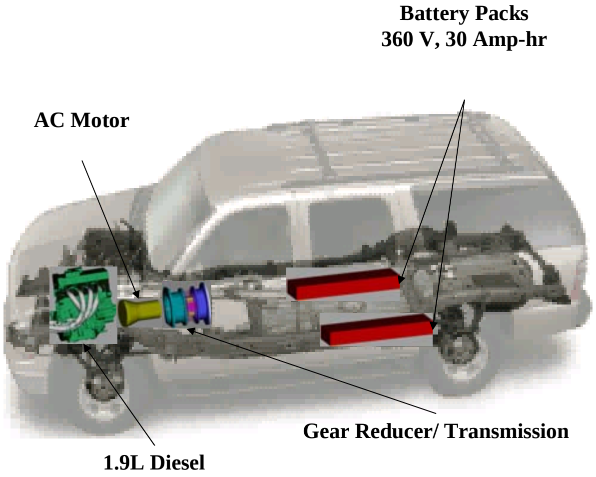

Figure 2. UI-HEV component layout.

Vehicle Design—Component Selection

Table 4 summarizes key specifications for each of the powertrain components of the UI-HEV. The following subsections discuss the rationale for selecting and integrating each of these components.

<u>IC Engine</u> - The UI-HEV utilizes an internal combustion (IC) engine to produce electrical energy that is stored in batteries onboard the vehicle. The IC engine selected was a 1.9 L

Volkswagen TDI diesel. The engine meets Tier II federal emissions standards and has a peak thermodynamic efficiency of 43 percent. The IC engine, control computer, and accessories were removed from a 1996 Volkswagen Passat. The IC engine converts mechanical power to electrical power through a 35kW Fisher Electric alternator that is attached directly to the crankshaft.

Table 3. Major components in the UI-HEV

AC Propulsion Electric Motor
- Weight: 50 kg (110 lb)
- Size: 305 mm dia x 381 mm long (12” dia x 15” long)
- Type: 3-phase AC induction
- Peak power: 150 kW (200 hp)
- Continuous power: 55 kW (74 hp)
- Speed: 0-12000 rpm
- Max Torque: 220 N m (165 ft lb)

Gear Reducer
- 2.5 : 1.0 reduction
- Input speed : 8000 rpm
- Output speed: 3200 rpm
- Input torque: 223.7 N m (165 ft lb)
- Output torque: 558.6 N m (412 ft lb)

Volkswagen Diesel
- 1.9 Liter displacement
- 79.5 mm bore
- 19.5:1 compression ratio
- 95.5 mm stroke
- 202 N m torque at 1900 rp
- 66 kW output at 4000 rpm

AC Propulsion Controller
- Weight: 70 lb (32 kg)
- Size: 767 mm x 386 mm x 208 mm (30.2” x 15.2” x 8.2”)
- Voltage: 240 – 480 V
- Peak efficiency (battery to shaft): 91%
- Charging: 0-100 amps
- GM Transmission
- GM 4L60E
- TCI Computer controlled
- Phenolic Disk electric Isolation
- NGB246 Transfer Case

Hawker Energy Battery
- Weight: 16 kg (35.4 lb) each, 480 kg (1,062 lb) total
- Type: Sealed lead acid
- Resistance at 1 kHz @ 77°F: 4.5 m Ω
- Reserve capacity: 91 minutes
- Cold cranking amps: 630 amps
- Temp. range: -40°F (-40°C) to 176°F (80°C)

The IC engine was sized to deliver continuous power that would be sufficient for highway driving while maintaining optimum efficiency. An efficiency map for the IC engine is shown in Fig. 5. The most efficient operating point for the IC engine was chosen at an engine speed of 1800 rpm and a torque of 61 N-m. This translates to approximately 17 kW of power. A road load of 17 kW is equivalent to driving the UI-HEV at 88.5 km/h (55 mph) on level ground. At 88.5 km/h (55 mph) and under, the UI-HEV produces enough power from the IC engine and alternator to be charge sustaining.

Transmission and Gearing - The performance requirements of the FutureTruck 2001 competition were used to model the powertrain components. The FutureTruck 2001 requirements were to accelerate 0-97 km/h (0-60 mph) in less than 12 seconds and to maintain a minimum speed of 88.5 km/h (55 mph) pulling a 3175 kg (7000 lb) trailer up a 5 percent grade. The continuous power requirement of the UI-HEV was determined using the road load power equation during steady state operation over a flat road and over a 5 percent grade with and without towing a trailer. The road load is a sum of the power required to overcome rolling resistance, aerodynamic drag, hill climbing, and acceleration at a particular speed. Figure 6 plots the road load power and the power transmitted through the drivetrain to the wheels as functions of vehicle speed. The sawtooth curve in Fig. 3 represents the transmitted drivetrain power for each gear. At the point where the transmitted drivetrain power intersects the road load power, the vehicle has reached maximum speed. In the cases where the transmitted drivetrain power does not intersect the road load curve, the vehicle's speed is limited only by the maximum speed of the drivetrain. At a steady state speed of 88.5 km/h (55 mph), a road load of 17 kW is expected. When towing a trailer at 55 mph up a 5 percent grade, a road load of 135 kW is required.

Another model was developed to determine the shift points for the automatic transmission that would result in adequate acceleration. The UI-HEV drivetrain was designed to meet the competition acceleration goals. The results of the acceleration model are shown in Fig. 4, showing the speeds attained throughout each gear as a function of time. The model predicts the UI-HEV will accelerate from 0 to 97 km/h (60 mph) in approximately 10.8 seconds.

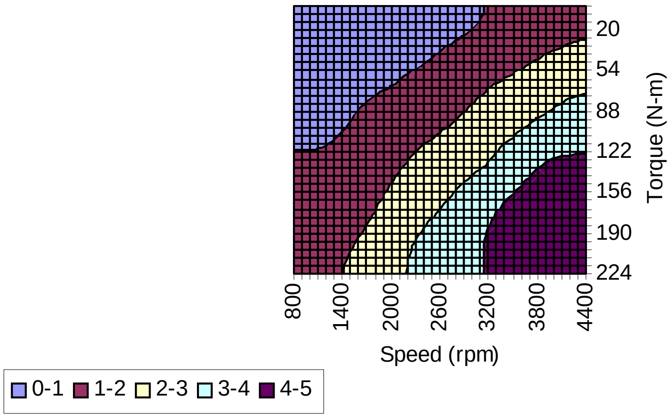

Figure 3. IC engine brake specific fuel consumption map in grams per second.

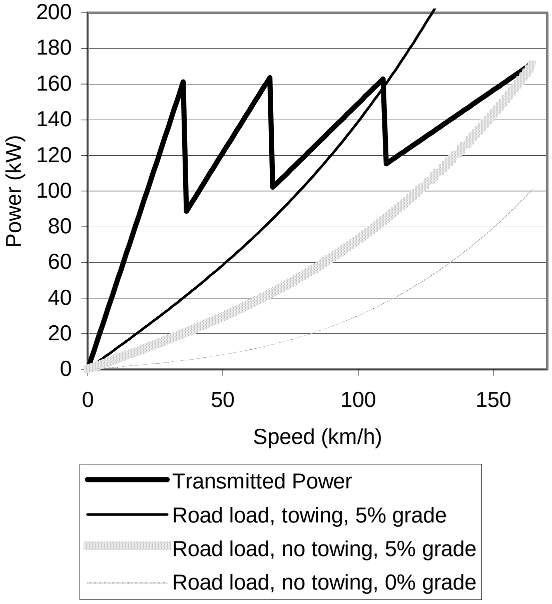

Figure 4. UI-HEV speed and power requirements.

A star speed reducer converts the high electric motor speeds ranging from 7000 to 12000 rpm to a low transmission input speed ranging from 1000 to 3000 rpm. This reduction multiplies the electric motor torque by 2.5. With input speeds and torque similar to that of the stock gasoline engine, the rest of the powertrain was left unchanged except for location. A TCI after-market transmission controller [5] allows the UI-HEV to shift much like the stock Suburban and enables the UI Team to adjust and calibrate the transmission for optimum performance.

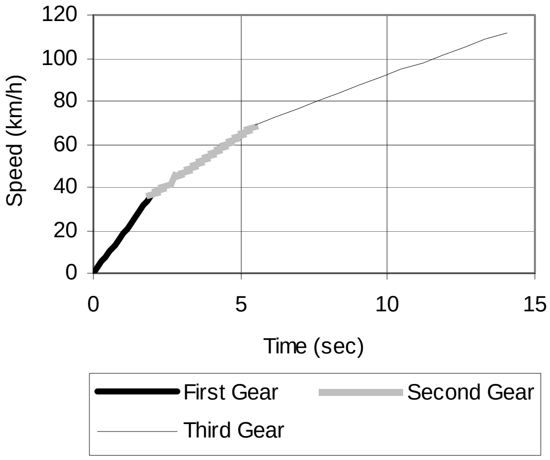

Figure 5. Acceleration performance (0-97 km/h).

Universal Technical Systems software was used to size the gear set based on the required gear reduction, required torque, and electric motor speeds [6]. The gear reduction is 2.5:1. A maximum input speed of 8000 rpm and 224 N-m (165 ft-lb) is reduced to 3200 rpm and 558 Nm (412 ft-lb) at the transmission. The epicyclic gear set consists of one central external gear (sun) meshed with four external "planet gears." The planet gears then mesh with an internal ring gear. The pitch diameter is 0.254 m (10 in.) with a 20° pressure angle and 0.044 m (1.75 in) face width. A Pro/Engineer CAD software was used to design and fabricate the gear reducer according to AGMA gear design standards [5].

Power Electronics: Motor/Controller - The main drive system for the UI-HEV is an AC-150 motor/controller from AC Propulsion, Inc. The AC-150 motor/controller is a three-phase, AC Induction motor rated at 150 kW peak power and 55 kW continuous power. The power electronics unit (controller) receives a scaled voltage signal from the accelerator pedal and converts it to a variable frequency signal that controls the motor power output. The AC-150 high voltage drive system was chosen for its combination of high performance, high efficiency, and rapid and convenient charging capabilities.

The stock Suburban requires signals to control safety operations. The two key signals, vehicle speed and throttle position, have been substituted in the conversion. The vehicle tachometer signal is returned to the stock control system by conversion of the electric motor speed from a 256 pulse/revolution signal to the required 24 pulse/revolution. The throttle position sensor is required for safety procedures related to acceleration pedal malfunction. The AC-150 system has a built-in acceleration malfunction safety scenario. If the accelerator behaves erratically, the controller senses high voltage and de-energizes the five-volt accelerator input. The vehicle will coast to a stop or be slowed by operation of the brake pedal. In the case of a mechanical malfunction, the key switch can be turned off, or the emergency disconnect switch can be depressed. This switch disables the high voltage system, which is the only source of propulsion. The emergency disconnect switch is a safety component required by the competition rules. If activated, it removes the high voltage system, forcing the electric controller to shut down the propulsion system. If a component of the electric controller system fails from high voltage, a ground fault may occur, and the high voltage system will disengage.

Power and torque curves for the AC-150 motor are shown in Figure 6. Maximum torque is produced immediately and is maintained throughout the first half the motor's speed range. This flat torque curve is important for vehicle performance. Unlike conventional IC engines, high torque is available at low motor speeds. The high torque gives the UI-HEV the accelerations needed to meet the competition requirements. Relatively high efficiency is maintained throughout much of the operating range of the AC-150 motor/controller. The efficiency of the AC-150 is 90-95 percent. In contrast, parallel hybrids and conventional vehicles operate at optimum efficiency over a narrower speed range.

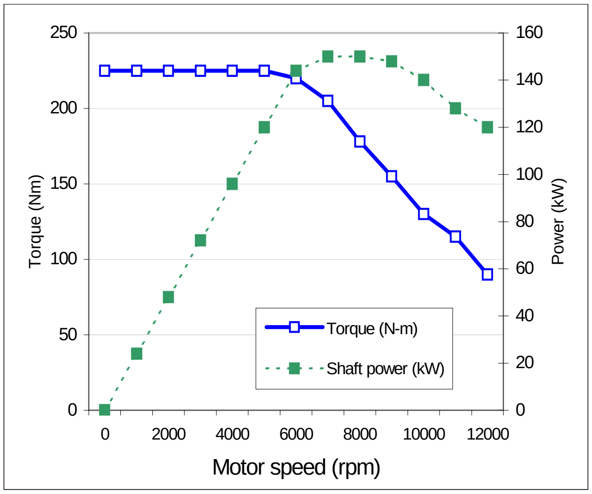

Figure 6. AC-150 motor power and torque.

The charging and discharging capabilities of the AC-150 controller provide flexibility and performance for the UI-HEV. The controller converts DC power from the battery pack to AC power for the motor. The controller can accept a range of voltages from 240 to 420 volts DC. The battery pack was sized to provide power throughout this voltage range. In addition, the controller provides charging from either a 110 or 220-volt outlet with in-rush power rated as high as 20 kW. This adds tremendous convenience for charging of the battery pack.

<u>Power Electronics: Batteries</u> - The requirements for a battery pack are to safely store a large amount of energy while maximizing power density. Other factors considered when selecting batteries were cost, energy management capabilities, maintenance requirements, specific power, and temperature range. Two different batteries have been implemented in the UI-HEV. The battery used in the UI FutureTruck 2000 vehicle was the Hawker PC680. Using

30 pairs in series, 60 batteries total, the PC680 batteries supplied 11.5 Amp-hours (30-minute discharge rate) of energy, while weighing only 399 kg (880 lb).

For the UI FutureTruck 2001 vehicle, batteries with increased energy storage were needed to ensure a 22-kilometer (12-mile) range of the UI-HEV while operating in ZEV mode. Hawker PC1200 batteries were selected. Although heavier then the PC680, the PC1200 supplies 30.4 Amp-hours at a 30-minute discharge rate. The total increase in battery weight compared to the PC680 batteries was 68 kg (150 lb). For the new configuration, 30 12-volt PC1200 batteries were connected in series resulting in a pack voltage of 360 volts. Figure 7 shows the maximum battery power and current that can be sustained from a single battery for a given time period. During this time period, the battery voltage will decrease from 12.84 V to 10.02 V.

To determine whether or not the Hawker PC1200 batteries provide sufficient energy storage for a 22 km (12-mile) range, data from Fig. 11 and Fig. 6 was used. Assuming 30 minutes of electric motor operation is required for a 22-kilometer (12-mile) commute, the bank of 30 batteries could provide 24 kW as shown in Fig. 11. (Draw a vertical line from 0.5 hours, intersect the power curve at 800 watts, and multiply 800 watts by 30.) The power for the 22 km (12-mile) driving range can be determined from Fig. 6, which shows that approximately 8 kW would be required at an average speed of 44 km/hr (24 mph) for driving without towing on a 0 percent grade. This allows sufficient margin for powertrain losses and vehicle acceleration.

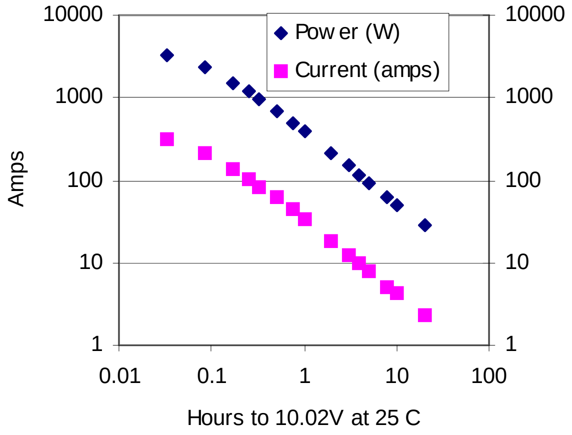

Figure 7. Constant current and power as a function of discharge time for a single battery.

The battery containment system consists of two aluminum boxes, located between the two frame rails of the vehicle on either side of the driveline. To electrically isolate the batteries from the aluminum, the boxes were coated with a durable spray-on rubber coating. In addition, protective covers isolate each terminal to ensure the packs are safe if conductive objects fall in the boxes during maintenance. For added vehicle safety, an emergency high voltage-disconnect system was added. This is located on the passenger side battery box before the high voltage cables connect to the controller. In the event of an accident, two large slam switches can be pressed to isolate the batteries from the rest of the vehicle. Also for safety reasons, all high voltage with the exception of the alternator is contained within the battery boxes.

Power Electronics: Alternator - A Fisher Electric alternator rated at 35kW continuous power is used to charge the battery pack. The alternator is mounted directly to the IC engine using a modified bell housing. The performance specifications of the alternator make it the optimum choice for the UI-HEV.

The alternator was sized to completely charge the battery pack in approximately 15 minutes. At the 15-minute discharge rate, the Hawker PC1200 batteries provide approximately 104 amps of continuous current. The 104 amps of current at the nominal battery pack voltage of 360 V results in 37 kW of power. The power output of the alternator is approximately 37 kW at a speed of 1850 rpm. At a speed of 1850 rpm, the alternator is approximately 93 percent efficient. As mentioned previously, the IC engine also operates at a maximum efficiency near 1850 rpm. Fisher Electric provided all data for the alternator.

Modifications To Chassis, Brakes, Suspension – Major changes in this area included powertrain mounting, battery box integration, electric power steering, and suspension enhancements. The mounting scheme for the electric motor/gear reducer/transmission assembly was modified to place the assembly further toward the rear of the vehicle. The assembly is suspended between two cross members. The front member was fabricated from 2 x 2 x 0.094-inch 6061-T6 aluminum tubing to minimize weight. The rear mount of the assembly also supports the torsion rods. The original torsion bar mount was modified to accommodate the added bending and shear load of the transmission. A 3G load from the transmission and the maximum moment from the torsion bars was applied to the member and analyzed in the FEA package, RISA 3D Demonstration. The vibration isolation bushings that mount the rear cross member to the frame rails were redesigned with a polyurethane bushing to accommodate the increased load.

The battery boxes were designed to withstand 20G lateral and 8G downward loads. The boxes were fabricated from 6061-T6 aluminum. Finite element analysis was performed in RISA 3D demonstration on both the boxes and their mounts for each scenario. Plate elements were used to model the mounts and boxes. The mounting system designed for the boxes provides distributed support along the front, the back, and the side along the vehicle frame. The distributed support system was used to minimize the local stresses around the fastener locations. The rim of each box rests on a cantilever mount and a set of side supports. The rear mounts are suspended from the rear cross member. The boxes were secured in place with ¼ inch grade 8 bolts. The endurance limit for one bolt was found to be 648 Mpa (94 ksi). Assuming only four bolts hold the load of an 8G-battery weight, the stress in each bolt would be 255 Mpa (37 ksi). This is well below both the endurance limit and the 827 Mpa (120-ksi) minimum proof stress.

<u>Advanced Control Strategies</u> - Due to the large number of separate systems on board the UI-HEV, a central control system was developed. A programmable logic controller (PLC) was used as the backbone to this system. Relay ladder logic (RLL) was used to program the PLC controls system. RLL was programmed and tested on a PC and then uploaded to the PLC for controls implementation. All necessary subsystems, sensors, and inputs are routed to the PLC.

To minimize user interaction, a starting control system was designed so the IC engine turns on automatically when the batteries reach a state of 50 percent discharge and shuts off at 90 percent charge. An E-meter was used to monitor the state of charge (SOC).

To maintain the IC engine speed at steady state (1800 rpm), a voltage feedback speed control system was designed. Maintaining constant engine speed during a generation cycle reduces emissions and also regulates the output voltage at the rectifier. While the emissions benefits result from reduced acceleration, this strategy also dampens voltage surges higher than the rated amount to protect the electric motor controller.

To control engine speed the PLC implements a Proportional-Integral-Derivative (PID) control loop. The control loop uses battery pack voltage as a process variable while outputting a 0-5 Volt signal to the engine computer that controls engine speed along with two binary outputs that were switched at certain throttle positions. These signals replaced the need for a throttle position sensor and allowed the PLC to control engine speed. Under normal control conditions the engine speed was set to hold the pack voltage at 420 Volts during charging. Advantages of this system are reduced number of components, reduced mass in the vehicle, and ease of modification.

FINDINGS; CONCLUSIONS; RECOMMENDATIONS

To date, the performance and emission evaluation of the UI-HEV has been based primarily on computer modeling. Fuel economy, acceleration, and handling have been verified by driving the vehicle around a 2.5-mile loop that resembles an urban cycle.

DATA ACQUISITION - The data acquisition system was completely revamped for the FutureTruck 2001 competition. Since all major components are either controlled or monitored through the PLC, a communication network was established between a laptop PC and the PLC for data acquisition. DSData Server software, provided by the PLC manufacturer, was used to communicate between the PLC and a laptop. This enabled the laptop to download all necessary data from the PLC without designing a separate data acquisition system.

The PLC monitors and responds to various vehicle components. Data from each of the components are stored in memory locations in the PLC. These memory locations are linked to a VisualBasic application via the DSData Server software. The VisualBasic application runs on a laptop and provides information to the user during vehicle operation through a Windows based graphical interface. Data are logged and saved to a file on the laptop.

A global positioning system (GPS) has been installed in the vehicle to download vehicle position, elevation, and speed. These data are used to build local driving cycles and monitor the vehicle’s energy consumption over a wide range of driving conditions. Data from the GPS is also sent to the PLC touch screen for driver information such as latitude, longitude, elevation and heading. The GPS is a Garmin GPS 35HVS device specifically made for OEMs. It connects to the PLC via a 9-pin serial plug using RS-232 compliant protocol. A BASIC program parses the GPS sentences and saves the vehicle data to appropriate memory locations in the PLC data memory. The GPS system does not require driver interaction and powers up automatically whenever the PLC is turned on.

While the data acquisition system has the ability to log vehicle data for later analysis and interpretation, a touch screen was added into the vehicle. This provides real time vehicle data to the driver and passengers. The touch screen displays information such as GPS data

(See Fig. 19), data from the IC engine, battery pack SOC, and other useful vehicle information. Similar to the DAQ system, the touch screen operates as a peripheral device of the PLC, and has read/write access to the PLC memory locations. Currently, the majority of the touch screen interface is designed for read only operation to minimize the modification of sensitive operating parameters. In the future, the interface could be modified to allow the operator to modify settings such as charging controls and IC engine parameters.

Modeling

Modeling tools have been an integral part of the design and development of the UI-HEV. PSAT and ADVISOR have been the primary vehicle simulators used to predict fuel economy and emissions. A vehicle performance application developed in MatLab was used to predict vehicle acceleration, component sizes and transmission shift points. In addition, a senior laboratory design project was conducted to determine vehicle energy use during a local driving cycle. University of Idaho students developed a vehicle performance model, also using MatLab. The senior laboratory projected involved the collection of real-time voltage, current, and vehicle speed data, which was used in the Clean Vehicle Energy Management Model (CVEM), developed by a UI graduate student.

ADVISOR was used during preliminary studies of fuel economy and emissions for various vehicle configurations. The major components in each vehicle were kept the same and were selected to most closely match the components in the UI-HEV. Table 5 lists these vehicle components. The series configuration has an added generator; however the transmission is greatly simplified, which results in a slightly lighter vehicle than the parallel configuration. The conventional vehicle is considerably lighter because of fewer overall components.

PSAT was also used to simulate vehicle performance. A similar arrangement of three vehicles was developed for the model. Again, the vehicle components were selected to most closely represent the UI-HEV. The PSAT simulation results contained inaccuracies and are not presented in this paper. As PSAT is further developed, it should offer additional insight into the development of hybrid electric vehicle operation and will be incorporated into the UI FutureTruck vehicle designs.

Table 4. Vehicle component specifications for fuel economy and emissions modeling.

Component	Series	Parallel	Conventional
Engine	67kW CI	67kW CI	67kW CI
Batteries	30-12V, 30.4 Ah	30-12V, 30.4 Ah	N/A
Generator	32kW	N/A	N/A
Transmission	1-Speed	4-Speed, auto.	4-Speed, auto.
Chassis	SUV	SUV	SUV
Electric Motor	59kW continuous	59kW continuous	N/A
Accessory Load	700 W	700 W	700 W
Weight	3109 kg	3135 kg	2735 kg

Component data files were required for both the ADVISOR and PSAT simulations. The data for the IC engine was taken from the Oak Ridge National Laboratory (ORNL) small engine test facility. ORNL tested a similar Volkswagen 1.9L TDI. The operating conditions were different from typical on-road driving; however efficiency and emissions maps were generated throughout the engine's torque and speed range. Transmission data was obtained from GM and incorporated in the transmission file for the simulation. The alternator and motor/controller files were not modified; default sizes were chosen to most closely match the components in the UI-HEV. The data files for the batteries were modified to match the 30.4 amp-hour capacity of the Hawker PC1200. The charging and discharging efficiencies were not modified. These data are from slightly smaller capacity Hawker batteries.

The vehicle performance application developed by the UI team was used to size vehicle components and to determine vehicle-operating limits. The road load power equation was used to determine the power demand on the UI-HEV under various operating conditions. The UI-HEV was modeled with and without towing a trailer on a flat grade and on a 5 percent grade. The results from these analyses are given in the Table 6.

Table 5. Power and speed predictions under different operating scenarios

Scenarios	Power(kW)	Speed (km/h)
Towing trailer, 5% grade	159	110
No trailer, 5% grade	170	165
No trailer, 0% grade	105	165

The local driving cycle, devised during the senior laboratory project, simulated an urban environment. The driving cycle was mapped and vehicle speed, time, and elevation were logged. These data were then used in CVEM, which determines vehicle energy consumption. The local driving cycle profile is depicted in Fig. 7. The driving cycle is 2.9 miles long with a maximum grade of 3 percent.

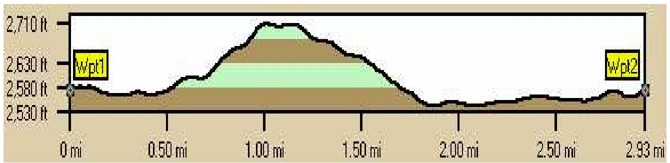

Figure 8. Elevation profile of local driving cycle.

Efficiency and Emissions

Modeling results of the three different vehicles are summarized in Table 7. Each vehicle was modeled over a city and highway driving cycle. The city driving cycle used was the UDDS and the highway cycle was the HFEDS. Each vehicle was modeled over one cycle. The fuel economy predictions for the series vehicle show a significant improvement in fuel economy over the parallel and conventional vehicle for urban driving.

Table 6. Fuel economy and emissions comparisons for series, parallel and conventional vehicle configurations.

	Vehicle Configuration		
	Series	*Parallel*	*Conventional*
Fuel Economy-City (mpg)	50.4	23.7	23.3
Fuel Economy-Hwy (mpg)	30.7	33.8	29.7
Emissions-City (gm/mile)			
HC	0.042	0.09	0.098
CO	0.081	0.192	0.221
NOx	1.499	2.977	2.576
PM	0.092	0.101	0.101
Emissions-Hwy (gm/mile)			
HC	0.047	0.06	0.058
CO	0.084	0.085	0.076
NOx	2.574	2.785	2.684

In addition to the ADVISOR simulations, the UI-HEV was tested over a local driving cycle to determine total energy consumption. Using a global positioning system a local driving cycle was mapped. Speed, elevation, and distance were logged along a 4.7-km (2.9-mile) route. Voltage and current from the battery pack was logged at 0.15 sec intervals along the local drive cycle. The product of voltage and current at each time interval was numerically integrated to obtain the total energy consumed during one driving cycle. This procedure was repeated four times and the results averaged. The UI-HEV consumed 11.0 MJ with a standard deviation of 0.98 MJ at an average power draw of 23.0 kW. The average speed along the local driving cycle was 40 km/h (25 mph).

The VW TDI diesel incorporates state-of-the-art emissions after treatment. This includes use of exhaust gas recirculation (EGR) to control NOx, as well as fuel injection before the catalytic converter under lean conditions to maintain chemical equilibrium for optimal catalytic oxidation of carbon monoxide and particulates. This system should be sufficient to keep vehicle emissions below Tier II standards. Further reduction in NOx emissions would be possible with selective catalytic reduction (SCR). This would involve placement of a SCR catalyst upstream of the oxidation catalyst. Urea injection in the hot exhaust is necessary to achieve the correct stoichiometry for efficient nitrogen reduction. However, this is not allowed by FutureTruck 2001 rules that prohibit use of “unusual fluid.s.” Urea is not a hazardous chemical. In fact, urea is the active ingredient in agricultural fertilizer. Hopefully subsequent FutureTruck competitions will allow teams to showcase promising emission control concepts that involve aqueous solutions of environmentally friendly compounds.

Consumer Acceptance

A design requirement for this project was to maintain the original safety, convenience, and function features of the stock Suburban.

To confirm the braking safety of the modified vehicle, tests were conducted on a Stock Suburban. A VC-2000 accelerometer system was used to gather data on initial velocity, braking distance, braking time, average G force and peak G force. Two series of tests were conducted, the first with the Suburban weight at 2630 kg (5800 lbs), and the second with the addition of 454 kg (1000 lbs) to simulate the conversion weight. The tests were simulations of emergency stops from approximately 97 km/h (60 mph). At 3084 kg (6800 lbs), stopping distance averaged 46 m (150 feet) in 3.5 seconds. The standard deviation indicates less variation in the average G with the additional weight. This is consistent with operator observations that ABS activation was less pronounced at 3084 kg (6800 lbs.). Increased frictional forces between the tire and the road for the heavier vehicle can explain these results.

Design failure mode effects analysis (DFMEA) was used to improve the level of safety associated with the UI-HEV. DFMEA is a systematic approach intended to recognize potential failures in a design, determine the effects those failures would have on the operators, and identify actions to reduce the potential for failure. The DFMEA process involved prioritizing potential failures based on the likelihood of detection, the severity of the failure mode, and the predicted frequency of occurrence. A rating system from one to five was used to score the importance of each consideration, a score of five being the highest priority and one being the lowest. Table 8 shows the ratings for each potential failure along with a risk priority, which is a mathematical product of the three ratings. Refer to the Vehicle Design section for a discussion of the actions taken to reduce the potential for each of the identified failures. These design considerations and the resultant modifications combined with the safety systems of the stock Suburban create a comprehensive failure mode buffer**.**

Table 7. DFMEA matrix.

Potential Failure	Detection	Severity	Occurrence	Risk Priority
Battery Boxes	3	3	1	9
High Voltage	3	5	3	45
Power Steering	3	5	5	75

For reasons of consumer comfort, convenience, and pride of ownership, the exterior and interior of the UI-HEV appear to be original. Roominess and storage space are unchanged and all important vehicle accessories are functional.

The UI's series hybrid is an effective and clean alternative for today's transportation. The series design offers the ability to complete a typical commute in an urban area with zero emissions while minimizing complicated control issues associated with a parallel hybrid configuration. The vehicle has been shown to competitively meet or exceed all FutureTruck 2001 requirements. Over the last two years, the UI-HEV has been used in conjunction with a variety of laboratory and design projects within the mechanical and electrical engineering departments. The FutureTruck project at the University of Idaho has also been highly successful in training future transportation engineers and in generating public awareness about alternative vehicle technology.

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