UNIVERSITY OF ILLINOIS HYBRID ELECTRIC VEHICLE: AN ELECTRIC VEHICLE FOR TODAY

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PAP-TR-94-4
May 1994

Power Affiliates Program
Department of Electrical and Computer Engineering
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ABSTRACT

Hybrid electric vehicles offer a next step in controlling fossil fuel emissions. A hybrid vehicle combines electric traction with an internal combustion engine to gain emissions advantages while maintaining long range. A team of 250 students at the University of Illinois, Urbana, has produced a practical hybrid vehicle using advanced industrial-grade off-the-shelf technology. This car has 30 mile zero emission range, coupled with over 400 miles of ultra-low emission range. This performance is accomplished through design innovations such as: preheated catalyst, tuned-port fuel injection, removable battery pack, high efficiency ac traction system and distributed microcontroller network. The estimated cost increase is $2,000 for mass production, compared to the Ford Escort on which the conversion is based.

INTRODUCTION

With legislation in California and other states requiring two percent of new automobile sales to be zero-emission vehicles in 1998, many automobile manufacturers are scrambling to produce marketable vehicles that satisfy these requirements. The University of Illinois at Urbana-Champaign has established a Hybrid Electric Vehicle (HEV) Program to address emissions concerns through hybrid architectures. The UIUC Team holds the philosophy that an economically viable hybrid electric vehicle that meets or exceeds the performance characteristics of a conventional car is attainable using off-the-shelf industrial technology, coupled with innovative solutions for design optimization, and backed by thorough engineering. Although an HEV is not a true zero emission car it offers a realistic stepping stone toward fully electric vehicles, while providing better short-term emissions reduction. For example, a 90% reduction in internal combustion emissions can be obtained in hybrid operation compared to an equivalent conventional vehicle. The fact that HEVs do not compromise operating performance, it is expected that hybrids are more marketable than purely electric vehicles. Deep emissions reductions, combined with improved marketability, mean that hybrids are likely to have a greater effect on pollution than anticipated zero-emission cars.

The UIUC Team goal is to produce a practical vehicle that is within economic reach of the public and one that meets the intent of the recent zero emission mandates. This philosophy guided the team through the design stages, influencing decisions such as the choice of electric drive motor and the selection of the internal combustion engine. However, design decisions are ultimately backed by engineering principles, and the following design categories are discussed: power requirements, regeneration and braking strategy, battery packaging, suspension and structural modifications, hybrid control strategy, emissions, climate control, and driver interface. Of course, safety, manufacturability, reliability, and serviceability permeate all of these categories.

DESIGN CONSIDERATIONS

The UIUC vehicle utilizes a series HEV architecture, which combines an electric drive with a small engine-generator auxiliary power unit (APU). The electric drive provides excellent dynamic performance without emissions, while the APU provides long range with substantial emissions reduction. The ICE has no mechanical connection with the drive axles. The engine's operation can be optimized as necessary independent of the vehicle operating state for emissions, efficiency, or other requirements. To minimize emissions, the vehicle can be operated in a zero-emissions, all-electric mode for daily commuting and switched to hybrid mode for extended travel.

The design was implemented through conversion of a 1992 Ford Escort Station Wagon. This vehicle was refitted with an ac electric traction system, a 22 HP water-cooled engine-generator set, and a unique lead-acid battery package. See General Layout of HEV Components in Appendix.

Power Requirements

The electric drive system determines dynamic performance, and its power level was selected to match acceleration capabilities of the stock Escort. The system has a peak rating of 62kW (83 HP), and should be able to accelerate slightly faster than the stock car's 13.2 0-60 time. Figure 1 shows the measured road power requirements for the Escort. The drive system continuous rating is 22kW (30HP), and allows extended operation at speeds in excess of 110 km/hr. The APU is sized to provide cruising power on the highway. At 104 km/hr (65 mph), the Escort uses about 18 kW. An APU capable of 18kW output will allow freeway cruising at
the legal speed limit, with range limited only by fuel tank volume. Thus, APU specifications are based on steady state vehicle performance in this architecture, while transients such as acceleration determine traction motor specifications.

Expected road load -
Measured motor input -

Fig. 1 Road Power vs. Speed

Battery Selection and Packaging
An extensive search for high-performance, rechargeable batteries revealed that few types are readily available as production parts. Lead-acid, nickel-cadmium, nickel-metal-hydride and other technologies were compared. As discussed in [1], lead-acid batteries offer the best compromise between availability, low cost, easy maintenance, recyclability, specific energy and power ratings, cycle life, and other environmental considerations. An HEV normally has a smaller battery pack than an all-electric vehicle, but it has similar power requirements. Specific power density is especially important in an HEV. Thus, Johnson Controls UPS 12-95 batteries were selected for use in the vehicle. This is a sealed glass-mat, lead acid battery intended for interruptable power supply applications. It shows excellent power density, good energy density, requires no maintenance, and will not disperse dangerous acids if opened.

Twenty-six sealed lead acid batteries weighing 11.8 kg each (totaling about 307 kg) provide a total of 8.58 kW·hr of energy at a three hour discharge rate. The batteries are placed on their sides and connected in series with a split ground that yields equal positive and negative DC busses with a nominal voltage 156 VDC per rail for a total battery nominal voltage rating of 312 VDC. Pressure plates are placed between individual batteries to distribute pressure on the center of the battery walls. The pressure prevents the electrolyte matting from separation with the plate structure and increases battery capacity by approximately ten percent. Foam springs maintain constant pressure and provide an insulation barrier to help maintain an equal cell temperature profile.

Battery Pack
All batteries are contained in an aluminum enclosure which is mounted between the rear floorpan and the rear suspension crossmember. The battery mass shifted the weight distribution from 60%/40% front/rear to 45%/55%. The effect on handling is discussed in Suspension Modification. The placement of the battery box is space-efficient and allows for maximum cargo space because it is in an area used for only the spare tire mounting and the fuel tank in the original vehicle. The spare tire is relocated behind the rear wheel well and mounted vertically. In a severe accident, the box is designed to separate from the vehicle and travel underneath the car. The battery pack is supported in front, rear, and side so the pack will not experience a pendulum affect.
Power System Design

Overall electrical system architecture is illustrated in Fig. 2. Overcurrent protection is provided by two 250 VDC rated fuses sized at 250 amps. One fuse is installed in each bus for total overcurrent protection. A maintenance disconnect switch function is provided by a 250 amp, 250 VDC Class, 2-pole molded case circuit breaker and is wired to the output of the battery pack immediately before the fuses. The circuit breaker is opened remotely through a shunt trip. The shunt trip is powered indirectly from the main battery pack via an onboard 312/12 VDC switchmode power supply. To assure shunt trip operation in the advent of 12 VDC supply failure, a capacitive energy storage circuit has been implemented. Shunt trip operating locations are in the vehicle dashboard and underhood, with the underhood switch operable from outside the vehicle. Both the circuit breaker and the fuses are mounted within the main traction drive inverter enclosure for improved volumetric efficiency. The vehicle high voltage power system is grounded to the chassis at a single point through a silver plated copper bar. All electrical items added by the UIUC Team are connected to this ground bar, which is in turn connected to the vehicle chassis through a single #8 AWG conductor. This configuration prevents any chassis conducted currents from occurring under normal operating conditions other than those designed into the stock Ford Escort 12 VDC electrical system. It should also be noted that all loads connected to the high voltage DC system are operated between the positive and negative supply busses; there are no loads connected between bus and ground. Thus, only during a bus to ground fault will current flow through the high voltage power system ground. This arrangement permits the use of a hall effect based ground fault current sensing with milli-ampere sensitivity.

Hybrid Control Strategy

In order to emulate the look, feel and operation of the original car, a number of functions must be controlled automatically. For this purpose the vehicle features a distributed microcontroller system consisting of four Motorola 68HC11-based microprocessors. These microcontrollers are configured to monitor battery state of charge, control APU while in operation, control commanded traction motor torque, and control the on-board LCD. Information is shared between the microcontrollers via an RS-485 network. Control reliability is ensured with the distributed control architecture by minimizing the affects of controller failures.

In addition to exporting the battery state of charge data to the network for transmission and display in the instrument cluster, the state of charge calculator will also send messages to the APU controller to turn on and turn off the APU. Turn on and turn off thresholds are set at 40% and 80% respectively. The APU is also turned on when vehicle speed exceeds 45 MPH continuously for 3 minutes or instantaneously once the vehicle reaches 55 MPH. Once the APU controller is given the signal to start, it first turns on the catalyst preheater, then starts the engine and finally loads the generator.

There are three basic modes of operation: Zero Emission Vehicle (ZEV), Automatic Hybrid Electric Vehicle (AHEV) and Manual Hybrid Electric Vehicle (MHEV). In the ZEV mode, the APU will not start and the vehicle operates on battery power alone. This mode would be used primarily by the commuter, as she would know if the vehicle range is adequate for her daily requirements. In the AHEV mode, the APU operates automatically based on battery SOC and vehicle speed as described above. This mode would be used during normal driving other than commuting. The MHEV mode is primarily for use in emergencies or out of the ordinary driving conditions where the APU must be operated.

Instrumentation

The on-board LCD is located in the dashboard and serves to monitor vehicle parameters that cannot be accommodated in the instrument cluster, such as motor winding temperature and battery current and voltage. Also displayed are menus for the presettable cruise control, component temperatures and individual battery voltages. The LCD display obtains this information by interrogating the RS-485 network for periodic updates. In addition, the LCD display is used to provide complete alarm annunciation and system self-diagnosis for a large variety of foreseen vehicle failures. A keypad is provided to allow the motorist to change displayed parameters, adjust cruise control settings and acknowledge alarms.

After evaluating commercially available energy meters, a decision was made to develop a suitable meter internally. The algorithm utilized for the UI-UC HEV is a modification of the TVA method [2], which is based on averaged discharge currents to compensate for the rated amp-hour capacity of the battery pack. As can be seen in Fig. 3, lead-acid battery capacity is a strong function of temperature. Consequently, the algorithm used to calculate battery capacity has been modified to compensate for temperature derating. The primary advantage of the modified TVA method is high accuracy (median accuracy is approximately 5%) with a relatively simplistic processing algorithm.

![Fig. 3 Battery Capacity vs. Temperature](image-url)
Auxiliary Power Unit -- Engine

An exhaustive search was conducted of small internal combustion engine manufacturers for an engine which would meet the vehicle power requirements as well as maximize specific power and minimize volume, brake specific fuel consumption, emissions, and noise. The APU internal combustion engine is a 37 kg Kawasaki FD620D that is liquid-cooled, V-twin, aluminum block, and fuel injected. This engine has a displacement of 620 cc with a maximum rated power of 17 kW at 3300 rpm. Brake specific fuel consumption values are excellent at a nominal 280 g/kW·hr using gasoline. Testing shows that this rated value is at a rich condition and stoichiometric running results in values as low as 265 g/kW·hr. The engine already meets California’s 1995 emissions standards for off-road vehicles and extensive testing shows that emissions at stoichiometric air fuel ratio are excellent.

The University of Illinois team modified the stock Kawasaki engine in several different ways. The stock engine has an uneven fuel distribution between cylinders. To further decrease emissions and increase fuel economy, a tuned port fuel injection system was designed, fabricated and installed. Through dynamometer testing, we have demonstrated an increase in power of 20%. In addition to a new intake system, a complete fuel injection computer was designed and built to control each cylinder separately. This computer accounts for changes in coolant and air temperature, air density, manifold pressure, exhaust oxygen composition, and fuel composition. The new computer allows the system to be variable fuel. The engine will run on any combination ethanol, methanol, or gasoline. This system has demonstrated an equivalent of 70 miles per gallon using gasoline.

The team designed an 11 gallon safety fuel cell system located directly under the battery pack. The fuel cell was fabricated by ATL.

Emissions

Ethanol is used as fuel for the APU primarily for emissions considerations: higher heat of vaporization implies a lower peak flame temperature, reducing nitrous oxide emissions. Additionally, recent advancements in membrane separation and distillation techniques may allow for more efficient production of ethanol, resulting in an effectively closed carbon cycle with CO₂ produced during combustion and recovered during plant photosynthesis. Also, ethanol is typically non-corrosive, indicating relatively simple conversion from gasoline operation to ethanol operation.

Dynamometer testing of rpm, manifold pressure, load, emissions, air to fuel ratio, and fuel consumption have been performed in an effort to determine an optimization between low emissions and high power output of the APU. Running the engine lean reduces CO emissions and decreases brake specific fuel consumption. Dynamometer testing has shown emission levels on the order of ULEV levels. CO levels were reduced to .08 g/mile. Unburned HC were reduced to .02g/mile and NOx levels were reduced to .10g/mile.

The exhaust system for the APU includes the exhaust manifold, the catalytic converter, a catalyst preheater to reduce cold-start emissions, and a muffler. The team designed and built a catalyst preheater system. This system incorporates a properly sized 3-way catalyst enclosed in a preheater chamber which heats the initial air charge to allow the catalyst to reach light off temperature more quickly. This is incorporated into the control strategy to allow for a 20 second preheat and a 3 second postheat. This system is well suited for a series hybrid electric vehicle because the driver will not experience any changes in vehicle operation. The exhaust system upstream of the catalyst is made of stainless steel to further increase the rate of catalyst warm-up. Evaporative emissions use the production vapor recovery system of the 1992 Escort. Further reductions of evaporative emissions are achieved through the higher latent heat of vaporization of the ethanol fuel.

Auxiliary Power Unit -- Generator

One of the basic premises for the APU sizing and selection is that the system, when activated operates at 100% rated output. Consistent with prior work with hybrid and electric vehicles[3], the induction and permanent magnet synchronous machines stand out as candidates for the generator. Both machines have good efficiency. The induction machine has excellent robustness and relatively low cost, while the synchronous machine has slightly higher efficiency. Both types of APU systems have been developed by the UIUC Team for use in the vehicle. The generator is coupled to the internal combustion engine via a Gates GT Gilmer pulley system.

Traction Motor Selection

Desirable characteristics for traction motors in passenger vehicles are high torque, low mass, and high efficiency for improved range. In a series HEV, traction motor efficiency is more critical since all the vehicle’s energy is transferred through the motor to the wheels. Referring to Table II, an induction motor yields the best balance between efficiency, robustness, and cost. Although alternatives were evaluated, available PM synchronous machines suffer from very high cost and questionable reliability; standard DC machines suffer from high cost, mass, and maintenance when compared to a squirrel cage AC induction motor; switched reluctance machines offer substantial gains in efficiency and cost, but torque characteristics from currently available models are inadequate for this application.

Two constraints influence the size and rating of the motor. The motor should be able to accommodate continuous cruising power. In general, this constraint is not demanding, considering that the 1992 Escort station wagon typically uses about 18 kW at freeway speeds. It should provide high momentary power for acceleration or regenerative braking. This constraint is more limiting since typical over torque capability for a standard NEMA Design B motor is only 250%. This implies that the motor rating should be selected primarily based on peak requirements, which closely parallels how automotive gasoline engines are currently rated.

Performance ratings for the UIUC traction motor are given in Table I.
### TABLE I
Traction Motor Performance Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>60 Hz Base Ratings</th>
<th>180 Hz Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>67 VAC L-L</td>
<td>200VAC-L-L</td>
</tr>
<tr>
<td>Current</td>
<td>88 A</td>
<td>264 A</td>
</tr>
<tr>
<td>Breakdown Torque</td>
<td>103 Nm</td>
<td>103 Nm</td>
</tr>
<tr>
<td>Power Factor</td>
<td>0.83</td>
<td>0.83</td>
</tr>
<tr>
<td>Power</td>
<td>7.5 kW</td>
<td>22.4 kW</td>
</tr>
<tr>
<td>Slip</td>
<td>3%</td>
<td>2%</td>
</tr>
<tr>
<td>( \eta ) at Peak Torque</td>
<td>89%</td>
<td>90%</td>
</tr>
<tr>
<td>( \eta ) at 10% Torque</td>
<td>74%</td>
<td>76%</td>
</tr>
<tr>
<td>Rated RPM</td>
<td>1800</td>
<td>5400</td>
</tr>
<tr>
<td>Cost</td>
<td>$600</td>
<td>$7000</td>
</tr>
<tr>
<td>Mass</td>
<td>55 kg</td>
<td>60 kg</td>
</tr>
</tbody>
</table>

The traction motor is mated to the stock Ford Escort transaxle via a flexible coupling. When driven at maximum torque through the standard transmission, the HEV has a 0-100 km/hr acceleration time that is 5% better than the stock Ford Escort Wagon.

### Variable Frequency Traction Motor Drive

The traction motor drive is based on a 98% efficient commercially available PWM variable frequency inverter. The drive is a state of the art component featuring 400 amp IGBT switching devices controlled by a 32 bit microprocessor. Judicious repackaging reduced the mass by approximately 41 kg while providing an enclosure that satisfies IP42 specifications for environmental protection for improved reliability. The entire enclosure is shock mounted to the vehicle firewall for vibration isolation. The rating of the traction drive was selected to permit the motor to develop its maximum over-torque capability. Since power electronic devices are sized based on current ratings, the drive was selected with a 200% overcurrent capability matching over-torque capacity of the traction motor.

### Induction Motor Torque Control & Clutchless Shifting

The traction motor drive was originally designed for industrial applications requiring speed control, but it has been modified to operate as an induction motor torque control. Extensive testing of a prototype HEV with similar design architecture determined that the motor speed control alone will not yield a satisfactory driver interface. Thus, motor torque control has been implemented by developing an interfacing controller to accept driver inputs corresponding to accelerator and brake pedals position and generates motor slip commands to the traction drive. Also, pedal signals are conditioned through a buffer circuit to provide safe failure modes. This technique also uses machine rotor speed feedback using a variable reluctance magnetic pickup and current feedback via a Hall effect sensor implemented around a standard scalar V/f control algorithm. The method is similar to conventional techniques [4], and a block diagram is shown in Fig. 4. This control strategy is in direct contrast to more sophisticated indirect flux vector sensing torque control techniques that are typically utilized for induction motor control. For high performance applications such as induction servo motors, flux vector control is necessary. However, for a traction application such as the HEV, very high performance flux vector control is excessive particularly when vehicle reaction time constants are taken into consideration. In addition, for direct or indirect flux vector control to operate reliably, an extensive knowledge of the induction machine parameters is required in order to ensure error term cancellation for stable motor operation. Since these parameters often vary with time, there is some evidence to suggest that flux vector control may not be robust enough to ensure satisfactory motor control over the projected life of the vehicle. On the other hand, scalar V/f control will provide sufficient performance with the additional benefit of providing a more robust control due to its insensitivity to changes in machine parameters.

The original clutch and fly wheel were removed to reduce weight, and a clutchless shifting system was installed. The clutchless shifting involves a unique procedure made possible by the rapid response of the electric motor. A micro switch from a Porsche auto-stick clutchless shifting mechanism is incorporated into the shifter to determine when a shift is initiated by registering any force applied to the shifter. This force instantaneously drops the motor torque to zero allowing the gear to disengage. The intended gear is determined by shifter column position and force direction while in neutral. For example, if the shift lever is in the 3rd-4th column and there is a forward force on the lever, the motor speed is matched to the correct rpm for 3rd gear based on the present vehicle speed. As the gear is engaged, torque is returned to zero until force is removed from the shifter, resulting in smooth, clutchless shifting.

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**Fig. 4. Traction Motor Control Block Diagram**
Regeneration and Braking Strategy

To increase vehicle efficiency and electric range, it is desirable to recover energy that would otherwise be dissipated as heat in the brakes. This energy can be recovered with regenerative braking. Simulations of the EPA city cycle show that a 24 percent range increase can be realized using this regeneration strategy.

The UIUC team developed a safe regeneration strategy that basically involves adding free-play to the brake linkage. As the brake pedal is depressed, the spring-loaded pedal arm activates a potentiometer, and braking is accomplished entirely through reverse torque on the motor, resulting in regeneration. The controller determines the torque to be applied by the motor based on potentiometer position and the current state of the transmission. The reverse torque applied is proportional to potentiometer position and inversely proportional to transmission gear ratio to achieve a constant ratio between wheel braking torque and pedal position. When the brake pedal is further depressed, mechanical braking is introduced at a deceleration rate greater than 0.3g, and will operate even in the case of a total regeneration system failure. This design prematuresly locks-up the front wheels. Due to this situation, an Anti lock Regenerative Braking System (ARBS) has been developed. Sensors at the rear wheels and controls determine if the front wheels lock up before the rear. A situation like this is easily realized on a relatively slick road surface with regenerative brakes. Upon premature lockup of the front wheels, the ARBS decreases regeneration until the front and rear wheels turn at the same speed.

Structural Modifications

The rear structure of the vehicle requires modification to accommodate the battery pack. This involves modification to the bottom section of the tailgate, the rear seat mounts, the cross member to which the rear suspension attaches, and removal of the spare tire well. All chassis modifications result in greater moment of inertia at the modified area. Both the original and modified rear cross member were tested for structural integrity, and the results are shown in Fig. 5, Fig. 6, and Fig. 7.

From the figures, one can see that the testing shows that the modified cross member is stiffer than the original in the loading configurations tested. This is assumed to imply greater strength although yield testing was not performed due to the high cost of prototype fabrication. This is the most significant structural change.

Suspension Modifications

In order to match original ride characteristics, the natural frequencies of the front and rear of the vehicle were used as design parameters to be matched. With the changes to the mass of the front and rear of the vehicle, one can alter the respective spring rate to keep the natural frequency constant. Thus, with knowledge of both the original and modified vehicle mass distributions, one can calculate the new spring rates and make the necessary changes. Constant natural frequency implies that the ride height remains constant with no changes to spring free length.

However, with modified mass distributions, the front/rear cornering bias of the vehicle is altered as well. Specifically, the weight added to the rear of the vehicle increases the weight transfer at the rear end, resulting in a tendency toward an oversteering vehicle. To compensate for this, the diameter of the front anti-roll bar is increased until neutral to understeering characteristics were achieved. Moreover, tire pressures on the low rolling loss Goodyear Invicta GLR tires are biased higher to the rear to increase stability.
Battery Charging

An external outlet is provided to permit battery recharging from an AC line. The DC outlet is installed in under the body mold trim in the front quarter panel. When the molding is lifted, the plug is revealed. The plug and fuel fill port are located on the same side of the vehicle for consistency. DC current is provided from a 220 VAC single phase line source by a regulated power supply system. This system is configured with three commercial power supplies, each rated at 150 V and 20 amps.

The power supplies are oversized to permit an increase in the main battery pack capacity without having to redesign the battery charging system. The three Sorenson DCS 150-25 power supplies are connected in series and controlled via a GPIB bus computer interface interconnected to a personal computer. The computer system permits constant current/constant voltage, or constant power charging algorithms, in addition to data logging of charging amps and voltage. The constant power algorithm enables the batteries to be charged aggressively without exceeding the 30 ampere limit imposed on line current draw by the HEV Challenge Rules. A kilowatt-hour meter is included to permit tracking of energy consumed during charging. The power supplies were not installed into the car to permit charging directly from an AC line input due to weight constraints. Charging is time limited to 6 hours, but in practice the batteries are recharged in 3 to 4 hours. Single phase true power factor correction may be added in the near future. Efficiency is rated at approximately 83% and claimed power factor is 0.68.

Climate Control

Approximately 80 percent of vehicles sold in the U.S. today have air conditioning, indicating that climate control is necessary for a marketable vehicle. Climate control system efficiency is crucial, because the power requirements for operation are significant (around six horsepower for the original refrigeration system) and energy storage is a fundamental limitation to electric mode operation. This problem is exacerbated by the drive motor producing insufficient heat to warm the passenger compartment. Climate control in the UIUC HEV is achieved through a vapor compression cycle which utilizes a reversing valve to toggle between refrigeration and heat pump operation modes. This system is illustrated in Fig. 8. It implies that only one system is needed for both refrigeration and heating.

Refrigerant 134a is used due to its environmentally safer composition. Extra evaporator volume is needed to accommodate the heat pump function, slightly increasing total system volume. The compressor is powered from the drive motor.

Manufacturability

Manufacturability is addressed throughout the component selection process by the choice of slightly modified off-the-shelf technology. Structural modifications are accomplished with the use of materials which match the original structure, allowing high volume manufacture with a simple change in die geometry at low cost. In production, all aluminum fabrications could easily be replaced by die castings resulting in a low marginal component cost. The entire drive train and APU system could be installed as one unit with the sub-frame consistent with modern assembly-line standards. The battery box could also be converted to a stamped and spot-welded assembly.

![Figure 8 Climate Control System Schematic](image)

Team Organization

The project has brought together over 250 graduate and undergraduate students in the last two years to carry out all aspects of production. Students are responsible for designing the architecture, developing selection criteria for components, modifying parts, writing codes, and fund raising. The project fosters student leadership and promotes "Green Engineering". The HEV program is now completely integrated into the University's curriculum through ECE and M&IE courses. Students are able to enroll in the HEV project through senior design classes, independent study, MS thesis and on a volunteer basis. Students have gained project management experience that normally requires years of work in industry.

An integrated, team-based concept is utilized to better prepare students with realistic training. Although there are two faculty advisers, the project is entirely student run. Two graduate students, one is a mechanical engineer and the other is an electrical engineer, form and supervise task teams to complete the development of the HEV. Tasks teams use concurrent engineering to assure that the prototype will be successful. An MBA student manages the fundraising and publicity efforts of the project. Most students admit that this program is the most rewarding experience they have had in college.

CONCLUSIONS

The manufacturability of the UIUC HEV is achieved, in part, using off-the-shelf technology. With this state-of-the-art, readily available technology, the University of Illinois
Hybrid Electric Vehicle Team believes that a marketable vehicle can be produced by 1998.

The final operational vehicle is the result of 24 months of design, analysis, iteration, and fabrication involving over 250 people at the University of Illinois. One objective of the design is to produce a vehicle capable of winning the Hybrid Electric Vehicle Challenge. However, the team also has an earnest desire to produce a safe, environmentally friendly vehicle.
Appendix

General Layout of HEV Components

Battery Pack Open for Inspection

Stock Ergonomics
Summary of specifications and characteristics of
University of Illinois College of Engineering Hybrid Electric Vehicle

Basic outline: The University of Illinois (UIUC) Hybrid Electric Vehicle was prepared for the Ford/Dept. of Energy/SAE 1993 Hybrid Electric Vehicle Challenge. It is a converted 1992 Ford Escort station wagon. The UIUC car was the only one in the Challenge to retain the complete five-passenger interior structure of the stock car.

System arrangement: Series hybrid, with full ac electric traction drive system. The electric system is supplemented by a small fueled engine-generator set.

Summary of major components:

<table>
<thead>
<tr>
<th>System element</th>
<th>Description</th>
<th>Capability or Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main drive motor</td>
<td>Three-phase ac squirrel-cage induction motor with forced-air cooling.</td>
<td>82 HP peak at 6500 RPM. 0-9000 RPM speed range.</td>
</tr>
<tr>
<td>Mechanical drive system</td>
<td>Stock Ford Escort arrangement, with elimination of clutch.</td>
<td>5 speed clutchless manual transmission, stock transaxle</td>
</tr>
<tr>
<td>Engine for E-G set</td>
<td>V-twin fuel-injected four-stroke water-cooled engine. Fuel adjustment for ethanol, gasoline, or any mixture.</td>
<td>26 HP at 3600 RPM.</td>
</tr>
<tr>
<td>Generator for E-G set</td>
<td>Three-phase ac squirrel-cage induction motor, or three-phase permanent magnet ac synchronous generator.</td>
<td>15 kW output continuous, 7200 RPM for induction machine. 18 kW continuous, 5000 RPM for synchronous machine.</td>
</tr>
<tr>
<td>Inverter for electric drive</td>
<td>Constant volts per hertz system with slip control.</td>
<td>100 A continuous output. IGBT inverter system.</td>
</tr>
<tr>
<td>Brakes</td>
<td>Dual regenerative and power-assist standard Escort brakes.</td>
<td>Regeneration for all normal braking action. Mechanical brakes are applied when sufficient pedal travel appears.</td>
</tr>
<tr>
<td>Batteries</td>
<td>26 sealed glass-mat lead-acid units from computer backup supply application, connected in series.</td>
<td>312 V nominal (split for ± 156 V), 8.8 kW-hr at 3 hour discharge rate, 307 kg.</td>
</tr>
<tr>
<td>Battery pack</td>
<td>Enclosed flat pack mounted externally in place of stock fuel tank and spare tire.</td>
<td>Fully enclosed plug-in pack system, with slide-in mount method. Dimensions: approx. 15 cm high, 80 cm wide, 145 cm long.</td>
</tr>
<tr>
<td>Displays</td>
<td>Stock dashboard. Stock display (from Mazda Protege) with LED graph used to show battery state-of-charge.</td>
<td>Separate LCD display added for diagnostics and testing.</td>
</tr>
<tr>
<td>12 V system</td>
<td>Dc-dc converter from main battery bus.</td>
<td>Up to 1200 W output, 12.0 V, fixed output as battery voltage decreases.</td>
</tr>
<tr>
<td>Electronics</td>
<td>Microcomputer network with multi-task operating system, for displays, diagnostics, and battery monitoring.</td>
<td>Complete vehicle control retained if computer network is nonfunctional.</td>
</tr>
<tr>
<td>Charging interface</td>
<td>Dc port in front fender. Electronic safety interlock.</td>
<td>Up to 20 A charge current at full dc input.</td>
</tr>
<tr>
<td>Charger</td>
<td>Switching power supply unit, garage mounted.</td>
<td>Input source: standard 208-240 V 30 A or 50 A outlet. Output: dc for battery pack, with interlock.</td>
</tr>
<tr>
<td>Interior</td>
<td>No modifications to interior space except roll cage required by Challenge Rules.</td>
<td>Complete five-passenger interior space retained. Cargo space, seats, dashboard, and accessories per stock Escort.</td>
</tr>
</tbody>
</table>
Performance characteristics:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Test basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration</td>
<td>100 m in 9.1 s (0.25 g). 0-50 mph in 9.3 s.</td>
<td>Measured at 1993 HEV Challenge competition.</td>
</tr>
<tr>
<td>Top speed</td>
<td>95 mph (estimated)</td>
<td>92 mph achieved in early tests.</td>
</tr>
<tr>
<td>Range, electric</td>
<td>33 miles, 45 mph</td>
<td>Measured on highways near campus.</td>
</tr>
<tr>
<td>Range, hybrid</td>
<td>&gt;400 miles, 45 mph</td>
<td>Limited only by fuel tank size. Batteries do not discharge in hybrid mode at 50 mph. Actual 100 mile test achieved.</td>
</tr>
<tr>
<td>Charging</td>
<td>90% of charge restored in 4 hours from 30 A, 208 V outlet. Full charge in approx. 6 hours.</td>
<td>Multiple charge cycles with full discharge.</td>
</tr>
</tbody>
</table>

Other characteristics:

Curb weight 3240 lb.

Date of first operation: June 2, 1993
REFERENCES


