The Continued Design and Development of the University of California, Davis FutureCar

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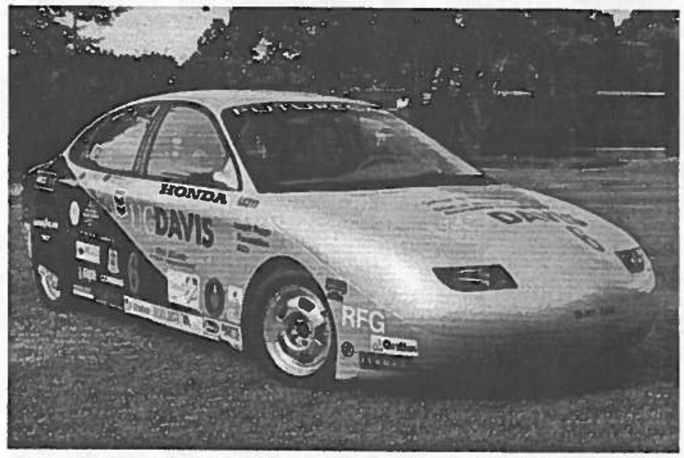
ABSTRACT

The UC Davis FutureCar Team has redesigned a 1996 Ford Taurus as a parallel hybrid electric vehicle with the goals of tripling the fuel economy, achieving California ultra low emissions levels (ULEV), and qualifying for partial zero emissions vehicle (ZEV) credits in California. These goals were approached using a highly efficient powertrain, reducing component weight, and improving stock aerodynamics. A charge depletion driving strategy was chosen to maximize energy economy and provide substantial all-electric operating capabilities. The UC Davis FutureCar couples a Honda 660 cc gasoline engine and a UNIQ Mobility 48 kW-peak brushless permanent magnet motor within a compact, lightweight, and reliable powertrain. The motor is powered by a 15.4 kWh Ovonic Nickel Metal Hydride battery pack. The body of the vehicle has been reshaped using carbon fiber composite panels to improve airflow characteristics and reduce weight. At the 1997 FutureCar Challenge, the vehicle achieved an equivalent fuel consumption of 5.64 L/100 km (41.7 mpg) on the federal urban driving schedule and 3.74 L/100 km (62.8 mpg) on the federal highway driving schedule for a combined fuel consumption of 4.79 L/100 km (49.1 mpg). This represents a doubling of the stock vehicle's fuel economy. Driving range exceeded 400 km on the combined driving schedules. The vehicle accelerates from 0 to 100 kph in 14.4 seconds and has an all-electric range of 105 km.

INTRODUCTION

The University of California, Davis, FutureCar Team was selected as one of twelve North American universities to participate in the 1996-97 FutureCar Challenge sponsored by the U.S. Department of Energy (DOE) and the U.S. Council for Automotive Research (USCAR). The competition challenges engineering students to redesign a mid-size sedan to achieve three times its current fuel economy without sacrificing performance, utility, or cost. Supplementing these goals, UC Davis focused on meeting anticipated California legislation which recognizes the significant emissions reduction capability of some hybrid electric vehicle designs. Innovations resulting from extensive research and prototype testing can help advance automotive technology while exposing emerging engineers to practical designs of future vehicles.

The UC Davis FutureCar Team set forth several goals, which are listed in Table 1, to win the 1997 FutureCar



Challenge. The magnitude of these tasks can only be met through significant revision of virtually every original Taurus system. The most critical areas for design considerations were identified as:

- powertrain configuration,
- reduction of vehicle weight,
- improvement of aerodynamic efficiency,
- optimization of control strategy,
- reduction of accessory system power loads, and
- extensive emissions controls.

	UC Davis FutureCar	Stock Ford Taurus
FUDS and FHDS Range	400 km HEV	600 km
Freeway Range	900 km	600 km
ZEV Range	130 km	0 km
0 to 100 kph Acceleration	12.0 sec (HEV)	12.5 sec
Emissions	California ULEV*	Federal Tier 1*
Equivalent Energy Efficiency	2.9 L/100 km (80 mpg)	9.4 L/100 km (25 mpg)
Curb Weight	1150 kg	1500 kg
Aero Drag: C_D	0.26	0.30
Passenger Capacity	5 passengers	6 passengers

* Note: California ULEV is a more stringent emissions standard than Federal Tier 1.

Table 1. UC Davis FutureCar design goals.

VEHICLE CONFIGURATION CHOICE

Three primary vehicle types were considered to meet the fuel economy, emissions, performance, and range goals for the UC Davis FutureCar. They are an internal combustion engine vehicle, an electric vehicle, or a hybrid electric vehicle.

The first choice is to maintain the same basic configuration as the stock Taurus—an internal combustion engine vehicle (ICEV). ICEVs can easily achieve the range goal, while the emissions goal can be met with advanced catalyst technology and engine controls. In order to meet the fuel economy goal, the vehicle would have to weigh about 600 kg, have very low aerodynamic drag, and require a small engine which sacrifices acceleration performance. Achieving the weight reduction and low aerodynamic drag through the conversion of a stock Taurus is impractical.

The second choice is an electric vehicle (EV). EVs can easily achieve the emissions goal and their overall powertrain efficiency is approximately three times greater than an ICEVs. However, they are limited by current battery technology to under 200 km range in a practical mid-size vehicle. The weight and packaging requirements of a large battery pack make achieving the fuel economy goal unrealistic when converting a vehicle.

The third choice is a hybrid electric vehicle (HEV). A HEV combines the best features of both the ICEV and the EV. A HEV utilizes two separate power sources to provide the power necessary for driving the vehicle, allowing each component to be used within its optimal efficiency range. The use of an internal combustion engine allows longer range with a smaller battery pack, while the electric motor enables a more efficient drivetrain with high performance and very low emissions.

Of the three vehicle choices considered, a HEV was chosen for its potential to best meet the UC Davis FutureCar goals. Two HEV configurations are possible—series or parallel. The choice between a series versus a parallel configuration is not straightforward. Many major automobile manufacturers are focusing on the series configuration with the expectation of a highly efficient fuel cell as the powerplant in the long term. But, in the short term or if fuel cells do not prove to be as efficient as hoped, the trade-offs become less obvious. This is evidenced by the fact that some companies are currently developing parallel hybrid vehicle concept cars and Toyota plans to market a parallel hybrid in 1998.[1]

SERIES HEV - A series hybrid provides all driving power to the wheels through an electric motor. When the state of charge of the batteries is above a certain threshold, they are the sole power source for the motor. As battery charge becomes depleted, an auxiliary power unit (APU)/generator set provides electricity to the motor and can simultaneously recharge the batteries.

One advantage of this configuration is that the APU is decoupled from the instantaneous demands of the road so that almost any power generating technology can be used. If the APU is an internal combustion engine, it can run in a narrow torque and speed range where its efficiency can be maximized while minimizing emissions. On the other hand, the high efficiency of the APU is compromised by the many energy conversions required to drive the wheels. When the APU is running, but not charging the batteries, the energy it produces is reduced by first converting the mechanical energy into electricity in the generator (at an efficiency of 90% to 95%) and then converting from electricity back to mechanical energy at the motor (at an average efficiency of 80% to 85%). SIMPLEV[2] simulations show that, depending on control strategy and APU sizing, up to 70% of the energy produced by the APU during on/off use will be stored in the batteries before reaching the motor. This net APU energy is further reduced by charge/discharge losses in the batteries (at an efficiency of about 80%). The overall affect of these losses is an energy conversion efficiency between the APU and the wheels of 60% to 67%.

The ability to recharge its batteries while driving allows the series HEV to have low electrical energy storage. Thus, a small battery pack can be used without limiting HEV range. However, constant recharging of the batteries to maintain this range has an emissions penalty. Analysis based on the California electricity generation mix (i.e. by coal, natural gas, oil, nuclear, etc.) shows that if the batteries were charged only from the electricity grid, the range accrued while operating without the engine would produce emissions an order of magnitude less than an engine running at California ULEV levels.[3] The small battery pack also reduces the ability of the HEV to operate in an EV mode for extended periods. This would diminish the incentive for people to drive the series HEV as an EV and lessen its overall emissions reducing capabilities.

PARALLEL HEV - A parallel hybrid provides the driving power to the wheels through a combination of an electric motor and an IC engine. Unlike the series configuration, the engine is mechanically coupled to the transmission. Because of this, technologies which do not have reasonable part load and/or rapid on/off capabilities (gas turbines, stirling engines) cannot be used.

The direct coupling of the engine and transmission eliminates losses which occur in the generator and motor in a series configuration. The penalty for avoiding these losses is that the engine must operate over a wider performance range which reduces the overall engine efficiency. However, this effect can be minimized by operating the engine within a window of torques and speeds where it is most efficient. This is achieved in three ways. First, the engine is sized only as large as is necessary to maintain highway speeds on a reasonable grade (usually one quarter to one third the power of a conventionally sized engine). Using a small engine reduces the time the engine operates at part throttle where it is least efficient. The torque lost by using the smaller engine is compensated by the electric motor. Second, part throttle engine use is further reduced by using the electric motor to drive the vehicle at lower speeds (where the torque requirements are low and the engine efficiency is poor). This also improves fuel economy by eliminating engine idle. Finally, a multi-gear transmission enables engine operation to be limited to the speeds where it is efficient. These strategies also help maintain engine operation within a region where the emissions levels are low.

While a parallel hybrid can be made to sustain the battery charge by using the motor as a generator, further efficiency gains can be made by never charging the battery from the engine.[4] Such a *charge depletion* parallel hybrid would be recharged only from the electricity grid which produces energy at thermodynamic efficiencies up to 45%.[5] As a result, the battery charge/discharge losses will not accrue to the engine, thereby increasing the overall vehicle efficiency.

The major challenge for the charge depletion parallel configuration is to achieve a long range during city driving where the electric motor is primarily used. To meet this challenge, a fairly large battery pack is used to increase hybrid and EV range. The longer all-electric range would allow the car to be used by most drivers in the EV mode, making a large impact on reducing emissions in polluted areas. Extending the urban HEV range is achieved by optimizing the vehicle control strategy. The lower the speed at which the engine turns on during city driving, the lower the energy supplied by the battery pack. The result is a need to balance between minimizing the window of engine operation to maintain high efficiency and maximizing that same window to provide long urban range.

CHOOSING A HEV CONFIGURATION - The series and parallel descriptions highlight the fact that there are advantages and disadvantages of each configuration. Using a FORTRAN vehicle simulation program to predict the efficiencies of nine different hybrid configurations[6], the choice becomes clear. Based on three major considerations: efficiency, all-electric operation, and implementation, the final decision of the UC Davis FutureCar Team was to pursue a charge depletion parallel hybrid.

Efficiency - In general, a charge depletion parallel hybrid should be more efficient because of fewer onboard energy conversions and access to energy at powerplant efficiencies over 40%. The FORTRAN simulation shows this style of hybrid to be 9.3% more efficient than an electric vehicle, 11.4% more efficient than a power-assist charge sustaining parallel hybrid, and 18.4% more efficient than the best series hybrid design simulated. These results are further corroborated by a National Renewable Energy Laboratory (NREL) study which asserts that a parallel charge sustaining design will be 4% better than a series hybrid with similar components.[7]

All-electric operation - The California Air Resources Board (CARB), the state government body sanctioning transportation environmental policy, mandates that by 2003, 10% of vehicles sold in California (approximately 100,000 vehicles) must be Zero Emissions Vehicles (ZEV). Battery-only electric vehicles qualify as a ZEV, but there is doubt due to range and battery cost of their ability to sell. As a result, hybrid electric vehicles have gained popularity. CARB is currently considering legislation which would allow hybrid electric vehicles to receive partial ZEV credit. To do so, a hybrid must meet a minimum all-electric driving range (80 km), use a battery with a minimum energy density (60Wh/kg), and have very low emissions (1/2 ULEV). The UC Davis FutureCar Team has anticipated the numerical values of the hybrid requirements. Sources within CARB indicate these requirements are still under development.

The UC Davis style of charge depletion parallel hybrid is ideally suited to meet the anticipated partial hybrid emissions credits.

Implementation - Previous experience and observation show that the true test of a vehicle lies in its implementation. A major hurdle in implementing a parallel configuration is the coupling of the engine and the motor. The UC Davis team has four years of experience with previous hybrid vehicles in both coupling and blending the torque of the two components. The team has also become very familiar with the control system required to successfully implement the parallel configuration. Information acquired from engine dynamometer and battery performance tests conducted on a previous powertrain provided insight towards optimizing the current design.[8]

VEHICLE CONTROL STRATEGY

The UC Davis charge depletion control strategy has two primary goals. The first is to maximize fuel economy and range and reduce emissions while maintaining or improving stock vehicle performance. The second is to provide a seamless interface between the driver and powertrain.

For the hybrid powertrain, the electric motor accelerates the vehicle from rest to a speed of 24 kph. At this speed, the engine is turned on when the driver shifts from first to second gear. Simulations show that fuel economy has a weak dependence on the speed at which the internal combustion engine is turned on. However, range increases greatly as the engine turn-on speed is decreased because vehicle operation is biased toward gasoline use. Once the engine is turned on, it can efficiently provide all the power required for driving at highway speeds up to 110 kph in 5th gear. It can also provide the power required to climb a 6% grade, though at lower efficiency and speed. To climb at higher speed requires assistance from the electric motor. The motor also supplements engine power for better acceleration performance. This vehicle control strategy allows the UC Davis FutureCar to achieve a 400 km range without recharging or refueling

The main advantage to turning on the internal combustion engine during the upshift is to deliver a smooth transition from all-electric operation to hybrid operation. With the clutch depressed, the powertrain is decoupled from the road and the impact torque of the engine startup is isolated from the passenger compartment. The engine is started using residual electric motor inertia, eliminating the need for a starter motor and further simplifying operation for the driver. The transition from electric to hybrid operation during the upshift from first to second gear is the best trade-off between driveability and range capability.

The internal combustion engine is turned off and disengaged from the transmission at speeds below 19 kph. This eliminates engine idle when the vehicle is at rest or driving in very slow traffic. As a result, fuel economy is increased and emissions are reduced.

In addition to the normal mode which implements the UC Davis control strategy, the vehicle has an EV mode. If drivers know that their daily driving needs will be less than the all-electric range, they can choose this mode to further reduce vehicle emissions. Moreover, drivers will be able to lower their operating costs due to the lower price of electricity per delivered kWh as compared to gasoline.

CONTROL SYSTEM IMPLEMENTATION - The heart of the control system is a Z-World Engineering "Little Giant" programmable microcontroller. This system operates at 9.2 MHz with 256k of RAM and a 64k EPROM to store the control algorithm. The Little Giant monitors accelerator pedal position, vehicle speed, status of engine (on or off), and clutch pedal position (depressed or released). Using this information, the microcontroller implements the UC Davis control strategy with outputs to the electric motor and gasoline engine. The microcontroller then provides feedback to the driver about the throttle requests to each powertrain component.

Accelerator input to the microcontroller is designed to maximize control resolution available to the driver through the various operating modes. The microcontroller's interpretation of accelerator pedal position depends first on engine status. While the vehicle is operating in the all-electric mode, the full range of pedal motion is interpreted as torque requests from the motor and is sent to the motor controller. Once the engine is turned on, the first 30% of pedal travel is interpreted as torque requests from the engine, while the remaining 70% is interpreted as torque requests from the motor. The torque requests for the engine are then sent by the microcontroller to a servo-motor attached to the engine throttle. The use of the microcontroller/servo-motor system limits the rate at which the throttle position changes. This reduces the high emissions levels associated with rapid transients in throttle position.

In addition to acceleration control, the control system provides a means for regenerative braking which increases energy efficiency by returning energy to the battery pack while braking. Although this feature could have been implemented in the program for the microcontroller, a separate electronic circuit was chosen instead for safety reasons. Should the microcontroller malfunction and lock the throttles in an open position, the driver's natural panic reaction would be to forcibly apply the brakes. This would automatically initiate regenerative braking through its separate circuit which would still be operational. Because of the built-in safety features of the motor controller, a regenerative braking signal overrides any throttle request to the electric motor. The braking provided by the electric motor also stops the IC engine. Having separate systems increases reliability because concurrent failure is less likely than a single system failure.

Another safety feature implemented in the control program is the use of an onboard watchdog timer. This is a hardware component that automatically restarts the control program if it does not reset the watchdog timer every 1.6 seconds. The control program normally resets the watchdog every few fractions of a second so that it will not trigger the automatic program restart. If the program crashes, it cannot reset the watchdog timer. The timer then resets the vehicle control program so the FutureCar remains operational.

VEHICLE PERFORMANCE REQUIREMENTS

Vehicle simulations were performed to determine cruising, climbing, and acceleration power requirements for the powertrain. These results aided in the selection of the engine, electric motor, transmission, and battery pack. The following table presents the guidelines used in designing the UC Davis FutureCar. The simulations are based on a 1500 kg vehicle test weight with a frontal area of 2.18 m^2, a drag coefficient of 0.27, and a rolling resistance coefficient of 0.007.

Performance	Energy/Power Required
100 kph cruising power	12 kW
100 kph cruising power 6% grade	35 kW
65 kph cruising power	6 kW
65 kph cruising power 6% grade	22 kW
Peak power for 0-100 kph in 12 seconds	75 kW
Energy for 125 km ZEV range on FUDS	18 kWh
Energy for 95 km ZEV range on FUDS	14 kWh

Table 2. Vehicle design requirements.

SIMULATIONS AND TESTING - In simulating the car, two different computer models were used. The first, AVTE, was developed at the UC Davis Institute of Transportation Studies. It is a MATLAB based program which uses efficiency maps of the powertrain components to calculate fuel and electricity usage. The second, a FORTRAN program written by FutureCar Team members, uses fuel flow and loss maps to predict fuel and electricity consumption. Two different programs were used in order to check program validity. AVTE predicted 5.88 L/100 km (40 mpg) on a federal urban driving schedule and the FORTRAN program predicted 4.90 L/100 km (48 mpg), but the car actually obtained 5.39 L/100 km (44 mpg) on a dynamometer test.

AVTE and the FORTRAN program showed similar changes to fuel and power consumption with the same changes in vehicle driving strategy. Both programs agreed that improvement in gas mileage is relatively insensitive to improvement of the physical characteristics of the vehicle. Results from AVTE in Table 3 show the required reductions in any one physical characteristic of the vehicle in order to obtain a 5% increase in energy economy.

Physical Characteristic	Percent Reduction
Weight	13.1%
Rolling Resistance	25.7%
Drag Coefficient	18.7%
Frontal Area	18.6%

Table 3. Required improvement in any one physical characteristic to obtain a 5% increase in energy economy.

POWERTRAIN DEVELOPMENT

ENGINE SELECTION - The engine for the 1997 UC Davis FutureCar has certain criteria to meet. First, the engine must have sufficient power to maintain highway cruising speeds ensuring a highway range limited only by the gas tank size. The engine must also provide some power for hard accelerations and hill climbing. At 100 kph, the expected power requirement for the engine is 12 kW. Therefore, the engine needs to produce this power at a reasonable engine operating speed (2000 rpm to 3500 rpm). To meet the fuel economy and emissions goals, the engine must also operate with high efficiency and low emissions over a wide range of torques and speeds. Finally, the engine needs to be compact and lightweight.

Fuel Options - After specifying engine criteria, five fuel types were considered: methanol, ethanol, compressed natural gas (CNG), diesel, and reformulated gasoline (RFG). Methanol and ethanol have been suggested for use in reducing automobile emissions, but no significant advantage is apparent, especially when compared to RFG.[9] While the fuels allow for compression ratios higher than those of gasoline engines, this efficiency gain is offset by the inefficiencies in the actual production of the fuels.[10]

The advantages of CNG are very low emissions and the potential for efficiencies greater than a gasoline engine due to a higher compression ratio. The disadvantages of the fuel are storage size and storage weight as well as fuel availability. Since natural gas is a gaseous fuel, its volumetric energy density (kWh/L) is significantly less than that of liquid fuels. This can be improved by storing the gas at pressures of

20 MPa to 25 MPa (3,000 psi to 3,600 psi), but would still fall short of the densities of gasoline and diesel fuels. As a result of low energy density, the storage volume required to provide sufficient range would intrude into the passenger compartment or trunk space. Furthermore, the combination of a low gravimetric energy density (kWh/kg) and the mass of the high pressure tank adds significant weight to the vehicle. Finally, the infrastructure required to provide CNG for a mass fleet does not yet exist.

Diesel fuel has the advantages of fuel density, engine efficiency, and hydrocarbon and carbon monoxide emissions. The fuel has high volumetric and gravimetric energy densities which allow for lightweight and compact fuel storage. The cycle used to burn diesel fuel operates without throttling losses at a high compression ratio, resulting in a peak efficiency of 35% to 40%. Finally, the lean operating characteristics of the diesel engine result in low hydrocarbon and carbon monoxide emissions. One disadvantage of the lean operating characteristic is that the engine must be larger than a comparable spark ignition engine. Another disadvantage is that the high pressure, high temperature, and lean combustion environment leads to high nitrogen oxide (NO_x) emissions. This problem is exacerbated by the unavailability of catalysts which can reduce NO_x in a lean exhaust environment. Finally, the combustion of diesel fuel produces significantly more particulate emissions than gasoline.

Reformulated gasoline (RFG) has high volumetric and gravimetric densities which allow a small and lightweight fuel storage system. The reformulation of the fuel and stoichiometric operation of the engine produce low hydrocarbon, carbon monoxide, nitrogen oxides, and particulate emissions. Stoichiometric engine operation also allows a 3-way catalyst to be used to simultaneously reduce all three primary pollutants. Compared to diesel, the use of RFG results in an efficiency sacrifice (peak efficiencies are 30% to 32%) which is balanced by lower engine weight and simplified packaging. In addition, the lower particulate emissions are valuable in light of recent findings linking particulate emissions to long-term health effects. Aside from its chemical attributes, RFG represents the most established and widespread fuel infrastructure and is the most familiar fuel to consumers. The UC Davis FutureCar Team chose RFG after considering the various fuel types.

Engine Options - After specifying the engine characteristics and the fuel type, several specific spark ignition engines were considered for this powertrain. The first option was to convert a 1000 cc, three cylinder Otto-cycle engine to run on an Atkinson cycle. In order to do this, the effective compression ratio of the engine is increased and the valve timing changed so that less charge is drawn into the combustion chamber. This maintains the same compression ratio while increasing the expansion ratio. The overall effect is that the pumping losses are reduced and the volumetric and thermodynamic efficiencies are improved. While showing promise for improved efficiency, this option was not pursued due to the lead time required for development and testing.

The second option was to use a two-stroke engine from Orbital Engine Co. In this engine, air and fuel are injected directly into the cylinder. This reduces pumping/throttling losses, provides excellent fuel atomization, and eliminates the bypass of raw fuel from the intake to the exhaust common in two-stroke cycles. This engine is small and lightweight as well as efficient and clean burning. The Orbital engine was the team's first choice, but proved to be unavailable in the American market.

The chosen engine was a 660 cc, three cylinder water-cooled Honda engine. This engine provides accurate fuel management with a closed-loop, multi-port sequential fuel injection system. It has an overhead cam and four valve-per-cylinder valve-train configuration for proper air/fuel flow and combustion control. The exhaust is treated with a close-coupled catalytic converter which has a short heat-up time and high catalyst efficiency. The cast aluminum cylinder block and heads conform to the criterion to be lightweight.

The Honda engine is relatively small, very durable, and runs smoothly under part throttle, full throttle, and transient operation. The engine puts out 12.0 kW with its lowest fuel consumption at 2800 rpm and produces 34.3 kW at 6000 rpm which meets the necessary power requirements (Table 2). It also starts quickly which is necessary under the high-speed start-up characteristic of the FutureCar powertrain. The Honda engine gives the vehicle an efficient, low-emitting, and reliable internal combustion engine capable of fulfilling the needs of the parallel powertrain.

ELECTRIC MOTOR/CONTROLLER SELECTION - The primary criteria for selecting an electric motor were high efficiency, low weight, high power, and an operating voltage which matches that of the battery pack. The UNIQ 218G, Hughes Dolphin 50, and AC Propulsion AC-100 were considered. Table 4 provides specifications for these motors.

	UNIQ 218G	Hughes Dolphin 50	AC Propulsion AC-100
System Weight [kg]	58.6	90	77.1
Continuous Power [kW]	32	38	41
Peak Power [kW]	48	50	100
Peak Torque [N-m]	165	160	149
Maximum Speed [rpm]	6,000	9,000	12,000
Peak Sys. Efficiency [%]	95	93	91
Cooling Method	Liquid	Liquid	Air
Input Voltage [VDC]	180	300	336

Table 4. Electric motor options.

Both the Hughes and AC Propulsion systems are AC induction motors. These systems operate over a wide speed range with relatively high peak efficiencies. The Hughes system could provide the necessary power and torque for the UC Davis powertrain, but the weight was considered to be excessive and the high voltage requirement was incompatible with the battery pack. The AC-100 provides higher power than needed. This power capability would seldom be utilized, resulting in extended part load operation. In addition, the excess weight, lower efficiency, and high input voltage requirement of the motor eliminated it from consideration.

The UNIQ Mobility 218G brushless permanent magnet motor/controller system has the highest efficiency and is the lightest of the three considered. The peak power of 48 kW combined with 22 kW from the Honda engine at 4200 rpm provides the desired 70 kW for acceleration as (Table 2). The UNIQ motor is well matched to the Honda engine in that the highest efficiencies occur between 2500 rpm and 3200 rpm and the maximum speed is 6000 rpm. The UNIQ system was chosen for its power output, high efficiency, and low weight.

TRANSMISSION SELECTION - A manual transmission was chosen over an automatic transmission to take advantage of its higher operating efficiency and lower weight. The transmission must be rated for 140 N-m of torque and be compact and lightweight. In order to maximize engine efficiency at a freeway cruise speed of 100 kph, an overall fifth-gear ratio (including final drive) of approximately 3:1 is required. Transmissions from the following four production vehicles were considered for the UC Davis FutureCar: Toyota Paseo, Honda Civic EX, Mazda MX-3, and Geo Storm GSi. Their characteristics are shown in Table 5.

	Toyota Paseo	Honda Civic EX	Mazda MX-3	Geo Storm GSi
5th Gear Ratio	3.21:1	2.98:1	2.99:1	2.84:1
Max. Torque [N-m]	123	145	133	163
Weight [kg]	33.6	33.1	31.8	40.8
Width [m]	0.343	0.343	0.368	0.318

Table 5. Transmission options.

The Toyota and Mazda transmissions, while of appropriate physical size, were eliminated from consideration because their maximum torque ratings were too low for the powertrain. The size and torque ratings of the Geo transmission were more than adequate for this application, but the weight was excessive. The five-speed Honda Civic EX transmission was chosen because it provided the appropriate torque capacity and fifth-gear ratio within a lightweight, compact package.

POWERTRAIN CONFIGURATION - Within the parallel hybrid arrangement, the selected engine and motor could have been combined in two possible configurations. The first design locates the electric motor in-line between the transmission and engine. This would eliminate the need for a lateral belt or chain system between the two drive components for an offset design. Its implementation would be mechanically simpler and potentially more reliable, but this configuration could not be pursued due to the limited space available within the Taurus engine compartment. The second design considered and chosen offsets the electric motor from the engine and transmission. Figure 1 illustrates this design.

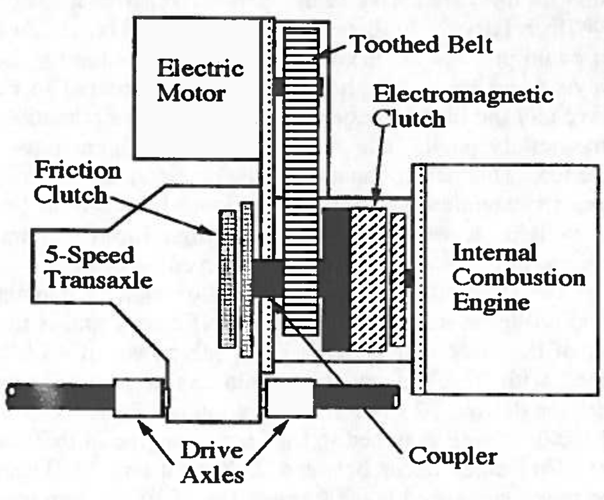


Figure 1. Powertrain configuration.

IMPLEMENTATION - After choosing the major powertrain components, the necessary coupling mechanisms between the engine, electric motor, and transmission were chosen. The offset design requires a belt or chain to link the electric motor to the transmission. A chain drive is attractive since it is narrower than comparable belt systems. However, to retain high efficiencies an oil bath would be required, adding complexity and maintenance to the system. Belts have the advantage of being highly efficient, lightweight, and virtually maintenance free. A Dayco RPP Panther series belt drive system was chosen for the vehicle. This system has the advantages of a typical belt system and produces less noise than other belts due to its reinforced, parabolic tooth profile.

For the UC Davis control strategy, the engine must be easily coupled and de-coupled from the transmission. A Pitts electromagnetic, automotive compressor clutch was chosen for this application. This clutch was selected for its relatively narrow size, low weight, and ability to transmit the engine torque up to the maximum speed of 6000 rpm. The clutch is rated for 160 N-m whereas the maximum torque of the engine is 55 N-m. The reduced inertia of the cut-down stock engine flywheel necessitated the over-rated clutch to prevent slipping from generated torque spikes as each cylinder fires. The Pitts clutch also uses a stationary field which requires only 60 W. The stationary field eliminates the need of brushes and the periodic maintenance of replacing them.

In constructing an efficient powertrain, it was important to maintain extremely close alignment between components. Misalignment leads to energy losses as well as reduced component life due to vibrations. Use of a coordinate measuring machine as well as a computer numerically controlled milling machine allowed higher accuracy to be achieved over standard machining practices. Another important tool used to align, size, and package the powertrain was a full scale mock-up of the Taurus' engine compartment. A simple steel box tube cage was made to represent the critical portions of the engine bay such as the main side beams and fire wall. This allowed complete accessibility to the powertrain from all angles during design and fabrication.

Simplicity, reliability, and low weight were the major objectives for the design of the powertrain hardware. Simplifications in the design were made by adapting existing automotive components. For example, an entire Civic clutch assembly (flywheel, spring plate, clutch disc, and slave cylinder) was used in conjunction with the Civic transmission. Greater reliability was realized through using systems that have been thoroughly tested for automotive use. Low weight was achieved by using high strength aluminum alloys (6061-T6 and 7075-T6) for the powertrain chassis. The alloys are fairly inexpensive, weldable, and easily machined to meet strict tolerances.

The powertrain design was kept mechanically simple by minimizing the number of power transmitting components. This provided for greater reliability as well as ease of manufacturing. A prime example of this concept is the coupler between the electromagnetic clutch and the transmission. This component transmits the torque from both the electric motor and the engine to the transmission. Vents placed in the outer surface of the coupler allow sufficient cooling of the electromagnetic clutch friction surface. The coupler is supported on the engine side by the single-row ball bearing of the electromagnetic clutch, and on the transmission end by another single-row ball bearing. The dynamic components of the powertrain are illustrated in Figure 2.

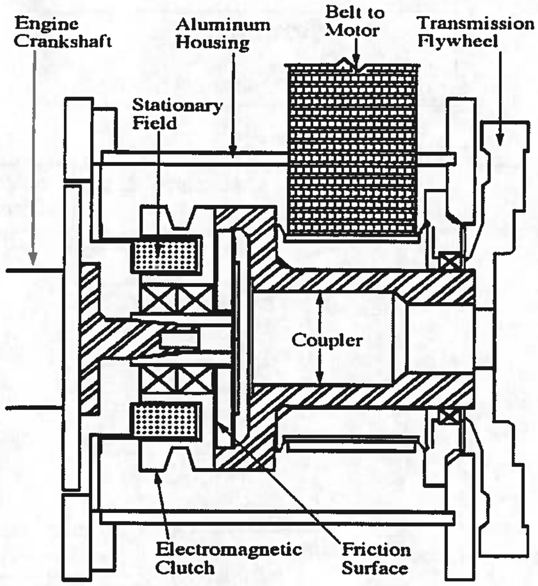


Figure 2. Powertrain internal components.

TRACTION BATTERY

BATTERY SELECTION - A critical component in the design of an efficient charge-depletion hybrid vehicle is the traction battery. It must have high energy density to minimize the weight required to provide sufficient energy storage for a long all-electric range. The battery must also have a high volumetric energy density to avoid large packaging requirements within the vehicle. This is especially important when converting an ICEV into a HEV. It needs a power density which will provide good acceleration performance. In addition to these performance characteristics, the battery should be maintenance free to avoid burdening the consumer.

Vehicle simulations show that an 18 kWh battery pack is required to achieve the all-electric range goal of 125 km. The battery pack must also provide 50 kW to accelerate from 0 to 100 kph in 12 seconds. With these pack and module specifics in mind, three batteries were considered for use in the FutureCar: the Electrosource Horizon SLA, the SAFT NiCd STM 5.100 and the Ovonic NiMH 13-EV-90. Table 6 shows the manufacture's specifications for each battery type and Table 7 shows the characteristics of an 18 kWh battery pack composed of each of the three batteries under consideration.

The Ovonic NiMH battery pack has the lowest mass, volume, and peak power. However, this relatively low peak power still meets the minimum requirement of 50 kW for the vehicle while at a significantly lower weight and volume. The Ovonic NiMH battery pack voltage is well matched with the UNIQ Mobility 218G motor/controller system so that the system's highest efficiency and power can be realized. The batteries are also sealed for maintenance-free operation. For these reasons, the Ovonic NiMH battery was chosen for use in the UC Davis FutureCar.

After becoming familiar with the charge/discharge characteristics of the Ovonic NiMH batteries, the fifteen-module pack was reduced to thirteen modules to ensure that the maximum motor controller voltage was not exceeded during charging or regenerative braking. This reduced the energy storage of the pack to 15.4 kWh which limits the all-electric range to 105 km. However, the pack is still able to provide the required peak power output of 50 kW.

Battery Specifications	Electro-source Horizon	SAFT NiCd STM 5.100	Ovonic NiMH 13-EV-90
Specific Energy [Wh/kg]	50	45.7	70
Volumetric Energy Density [Wh/L]	103	85	166
Capacity [Ah]	112	100	90
Energy Content [Wh]	1344	600	1188
Peak Power @ 20% SOC [W/kg]	300	250	220
Voltage [V]	12	6	13.2
Mass [kg]	27	13	17.8
Volume [L]	13.1	7.0	7.5
Sealed	Yes	No	Yes

Table 6. Manufacturer's battery specifications.

Battery Pack Specifications [18 kWh]	Electro-source Horizon	SAFT NiCd STM 5.100	Ovonic NiMH 13-EV-90
No. of Modules	13	30	15
Mass [kg]	351	390	267
Volume [L]	170	210	113
Power @ 20% SOC [kW]	105	97.5	58.7
Voltage [V]	156	180	198

Table 7. 18 kWh battery pack characteristics.

THERMAL MANAGEMENT SYSTEM - The Ovonic NiMH battery is temperature sensitive and thus requires a thermal management system that will keep the batteries within the necessary operating temperature range. To accomplish this, the UC Davis Team designed a battery box which provides the recommended cooling air of 500 L/min per module. Referring to Figure 3, the numbered arrows indicate the cooling air flow path through the box. Cooling air from under the vehicle (1) enters the plenum located under the batteries through the holes on the sides of the box. The area of these holes is 25% greater than the open area between the batteries to ensure an adequate inlet volume of air. The air (2) then travels from the bottom air plenum to the top air plenum along the battery sides. The 6 mm gap between the batteries increases the velocity of the air to enhance heat removal. From the top plenum, the heated air (3) is drawn to the ends of the box by blowers and then expelled out the bottom of the box through the exhaust holes (4). The exhaust holes have the same area as the inlet holes and the top and bottom plenums have the same volume.

To further ensure that the batteries remain at the proper operating temperature, a battery monitoring system (BMS) has been developed to measure individual module temperatures, voltages, and current. This system works in conjunction with the microcontroller which manages engine and electric motor operation. Monitoring module temperatures allows the BMS to protect the battery pack from overheating while it is powering the vehicle, charging, or at rest. If the batteries reach 55°C while driving, the system signals the microcontroller to limit the power output of the electric motor until the batteries drop below 45°C.

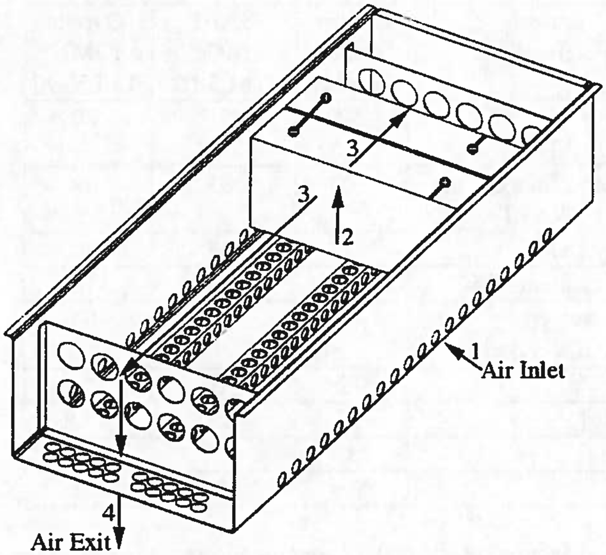


Figure 3. Battery box schematic.

The BMS signals the microcontroller to limit the power output of the electric motor if module voltage drops below 8 volts. This allows maximum use of the energy stored in the battery pack which in turn provides the 105 km all-electric range. Pack current is monitored to determine net Ah and kWh out of the battery pack. This information in conjunction with module temperature is used by the Magne Charge battery charger to optimize charging efficiency.

The UC Davis FutureCar Team designed the BMS to be a modular system capable of real-time measurements and communication. Each battery module has a separate board for measuring voltage and temperature. A modular design was chosen for ease of manufacture and simple replacement. Figure 4 illustrates the modular design. A flow chart of the BMS functions is shown in Figure 5.

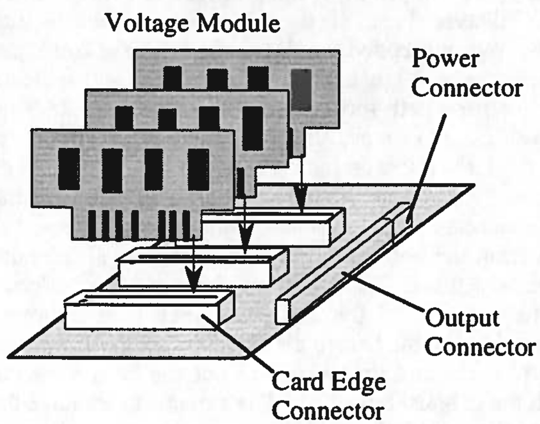


Figure 4. Modular plug-in boards.

In designing the BMS, the following problems had to be overcome: potential difference of up to 210 volts, output current up to 300 amps, physically rough and electronically noisy environment, and linearity and stability of the measurement throughout an adequate range.

Monitoring temperature - The use of thermistors provides a linear response of 10mV/°C. Voltage isolation and thermal conductivity is achieved through the use of nonconductive epoxy. The output signal required filtering since it is a triangular wave (f=43 Khz).

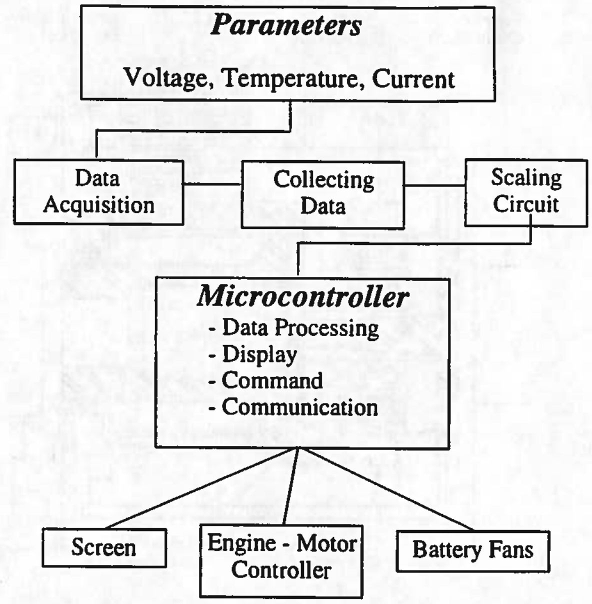


Figure 5. BMS function analysis.

Monitoring voltage - Reading voltage was the most challenging part of developing the BMS. To fulfill the requirements for isolation, a combination of fuse and optocoupler was used. Each voltage module is protected by a fast-acting fuse of .375 amps. Downstream, the optocoupler provides a galvanic isolation up to 2500 V_{RMS}. This chip, once integrated with a simple amplifying circuitry, provides a proportional voltage output using the light of a photodiode to drive a phototransistor. The output reading needed to be filtered as the output signal of the optocoupler is a square wave (f=230 KHz). For the selected battery module range of 8 to 17 volts, an accuracy of 1% was achieved by calibrating each voltage module.

Monitoring current - Hall effect probes provide full isolation while delivering an accurate linear response.

Data Processing - A Little Giant microcontroller is used together with four mutliplexers to simplify data acquisition and analysis and to command several systems. Temperature is sampled every 2 minutes and voltage and current are sampled every .1 second.

Providing power to the components - A fluctuating power supply adversely affected the accuracy of the voltage measurements. The optocouplers are powered by the battery modules. The remaining circuits receive power through a DC/DC converter which regulates the voltage supply to a stable 11.91 volts.

BATTERY BOX FABRICATION - The battery boxes were designed and fabricated to be strong, lightweight, compact, and provide protection to vehicle occupants. The boxes are constructed of 5052 aluminum sheet which has good strength, weldability, and bending properties. The batteries sit on three aluminum 6061-T6 C-channel sections which serve the dual purpose of increasing the stiffness of the box floor and raising the batteries to create the bottom plenum. Phenolic G10, a glass-fiber reinforced composite material with exceptional electrical properties, lines the aluminum box walls, floor, and top to electrically insulate the battery pack from the vehicle. Polycarbonate spacers which fit on the top and bottom of each module maintain the required 6 mm cooling gap and prevent battery movement in the box. Polycarbonate was chosen for its good electrical properties to prevent a high voltage leak (without these insulating materials, the non-isolated stainless steel cans which encase each NiMH cell could provide a high voltage path to the box walls). A rubber gasket completely seals the battery box from the vehicle occupants and improves cooling by only allowing air into the box from the designated inlets.

BATTERY PACK LOCATION - For a conversion vehicle, the location of the batteries requires careful consideration. Initially, the trunk may be considered a logical place to put the batteries. However, this would reduce consumer utility and bias the weight distribution to the rear. This bias would change the vehicle from an understeer car to an oversteer car which is both unsafe and unfamiliar for most drivers.

The UC Davis team located the batteries between the front and rear wheels, eight modules under the front seats and five under the rear seat. To do this, the stock front seats were replaced and the floor was lowered 90 mm. The replacement front seats are 8 kg lighter and retain original height. Lowering the floor created additional packaging space under the vehicle and changed the ride height to 125 mm. The weight distribution remained biased to the front and about the same as the stock Taurus. The low concentrated mass of the battery pack improved vehicle handling by reducing roll when cornering.

EMISSIONS AND FUEL SYSTEMS

The UC Davis FutureCar is capable of driving 105 km in ZEV mode, during which it produces no tailpipe emissions. For its hybrid mode, the powertrain control system was developed to minimize start-up, running, evaporative, and refueling emissions. The UC Davis team has modified the conventional emissions and fuel systems to ensure that these emissions are kept below California ULEV levels. These modifications are addressed below.

ENGINE START-UP - Start-up emissions are significantly reduced by the use of a time delayed engine start-up. This delay causes no loss in driveability since the electric motor is the primary power source for the vehicle at low speeds. Once the engine turn-on speed is reached, the microcontroller activates the engine start-up sequence which primes the fuel pump and activates a 12–volt Corning electrically-heated catalytic converter (EHC). After the EHC reaches its light-off temperature, the engine is started by closing the electro-magnetic clutch and powering up the engine control unit. If the catalytic converter is already hot from previous engine operation, the heating period is bypassed.

The cold-start emissions typical of a conventional engine have been further minimized by eliminating cold-start enrichment. This enrichment normally ensures smooth operation during engine warm-up. Since the engine is always operated at high torque, the enrichment is unnecessary. To eliminate the cold-start enrichment, the coolant temperature sensor is bypassed during the warm-up period. When the engine reaches normal operating temperature, the sensor is reconnected to the fuel injection computer and normal operation begins.

RUNNING EMISSIONS - The EHC, located between the Honda OEM close-coupled and primary catalysts, acts as the main exhaust treatment after engine start-up until the other catalysts reach their light-off temperatures. The close-coupled catalyst heats up quickly due to the high temperature exhaust gases. At the same time, the primary three-way catalyst from Car Sound Exhaust Systems heats up rapidly from the oxidation reactions occurring in the EHC. All three catalysts are located within 90 cm of the exhaust ports and are wrapped with insulating exhaust tape to prevent cool-down when the engine is off. The added EHC and primary three-way catalyst are designed for much larger engines with higher exhaust flow rates than the Honda. As a result, the added back pressure to the exhaust system is negligible to engine performance and the long residence time of the exhaust gases increases conversion efficiencies. This system is similar to the three-part catalytic converter used on a ULEV certified Honda Civic engine[11].

EVAPORATIVE EMISSIONS - The stock Taurus fuel system was redesigned to more effectively contain evaporative emissions during vehicle operation and non-use conditions. This system is completely sealed during normal operation (ambient air temperatures between -25°C and 50°C) to eliminate all evaporative emissions. This necessitated the design of a tank that withstands pressurization and protects vehicle occupants. Using a scaled down model of the sealed tank, the maximum pressure was found to be 240 kPa (35 psi) at 50°C. In the unlikely event of excessive pressure build-up in the tank, an over-pressure relief valve opens at 275 kPa (40 psi). This bleeds vapors into the engine intake manifold. The lightweight, cylindrical aluminum gas tank has passed a pressure test to 310 kPa (45 psi). A one-way check valve allows air to enter the tank if a vacuum develops. The sealed fuel tank is located under the vehicle between the frame rails and between the rear battery box and suspension mounts. This location should provide adequate protection to occupants in an accident or if the tank ruptures.

REFUELING EMISSIONS - Onboard refueling vapor recovery (ORVR) systems are being developed as a means of combating refueling emissions so that future emissions standards can be met. Compared to conventional systems, ORVR systems require larger carbon canisters, more vapor lines, complex nozzle seals, and mechanical pumps. This increases weight, cost, and complexity and makes failures more likely and difficult to repair.[12]

Fire safety concerns regarding ORVR systems have been raised by the National Highway Traffic Safety Administration (NHTSA). One example of NHTSA concerns is a simulation of a failed refueling vapor vent hose which, if accidentally disconnected or improperly installed, could result in a sustained flame .6-.9 meters in length.[13]

ORVR systems can also make refueling lengthy and troublesome in hot weather. One system, provided by the oil industry to prove the viability of onboard systems, repeatedly shut off during refueling and caused driveability problems for 10-15 minutes afterwards.[14] For these reasons, ORVR systems seem illógical and impractical for future vehicles.

Handling refueling emissions with increased usage of Stage II vacuum nozzles presents a better solution for collecting refueling emissions. Standards could be set and enforced sooner and more easily for gas station recovery systems. The effects of using Stage II nozzles would be realized much sooner than ORVR systems since it would be unnecessary to wait until a majority of the operating fleet consists of cars produced after a certain date[15]. Stage II nozzles affect all automobiles, not just new ones, and would not incur the increased repair and safety problems of ORVR systems.

The UC Davis team has developed a refueling system to be used with Stage II nozzles which minimizes refueling emissions. For this system, reformulated gasoline vapors are contained at tank pressure by a flapper valve when the filler cap is removed. The valve opens when the pump nozzle is inserted allowing the vapors inside the tank to be collected by the vapor recovery systems on Stage-II refueling nozzles currently found throughout California. This is a low cost, lightweight, simple solution to prevent refueling emissions. Figure 6 shows a schematic of this system.

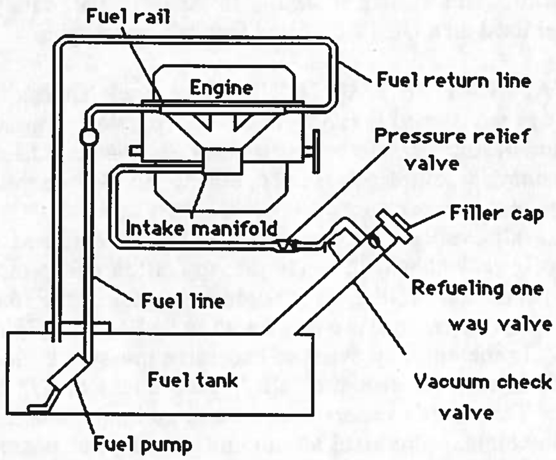


Figure 6. Fuel System Schematic.

Current laws concerning onboard vapor recovery systems for automobiles in the future may exclude the UC Davis fuel system since it does not collect refueling emissions. However, the laws represent only the latest round in the debate about whether refueling emissions should be collected by gas stations or by vehicles.

SUSPENSION AND BRAKING SYSTEMS

The primary goals of suspension modifications were to improve handling and reduce weight without changing the vehicle's ride. The stock rear springs were replaced with springs that are 20% stiffer to compensate for the altered front to rear weight ratio (the location of the batteries shifted the weight ratio from 60:40 to 58:42). The rubber rear sway bar bushings were replaced with polyurethane to help reduce the response time lag due to this weight shift. The components left unchanged were those in which no significant weight reduction or handling benefit could be accomplished. These parts include: the front cast aluminum steering knuckles, the front sway bar, the hollow rear sway bar, the composite front sway bar end links, and the stamped steel control arms.

The operation of the braking system has been redefined to include regenerative braking and mechanical brakes. Regenerative braking is now the primary braking system so that energy recovery is maximized. The purpose of mechanical brakes is then to provide braking power beyond regenerative braking and for emergency situations. The first 30% of the brake pedal throw varies the amount of braking torque provided by the motor. As the pedal is depressed beyond 30%, the hydraulic brakes add braking torque to the maximum provided by the electric motor. The use of variable regenerative braking produces a braking feel similar to a conventional vehicle while providing a more efficient use of the vehicle's kinetic energy.

To ensure the safety of the new braking system, the mechanical brakes are designed to stop the vehicle from 100 kph in 45 meters (0.83 g's) without the use of regenerative braking. Using this performance guideline and changing the brake duty cycle, the stock system was downsized to reduce weight. This is possible since the mechanical brakes are not required to sustain heavy extended braking periods when descending hills. Regenerative braking also eliminated the need for a power assisted mechanical system.

Effective manual brakes proved feasible by altering key parameters in the braking system. The mechanical advantage of the pedal was increased from 3:1 to 5:1 to generate the required pedal force of 335N. The master cylinder diameter was decreased from 25 mm to 20 mm for increased line pressure. New brake calipers were then chosen for their piston diameters to self-proportion the braking forces. The front OEM single piston calipers were replaced with four piston aluminum calipers for a weight reduction of 7.0 kg. The rear drum brakes were converted to disk brakes using lightweight Honda CRX calipers with an integrated, cable-actuated parking brake. All four rotors were constructed with aluminum wheel mounts and ceramic coated titanium alloy rotor surfaces. The combination of the titanium base material, ceramic coating, and the harder brake pad material performs with a higher coefficient of friction, better strength to weight ratio, and better thermal properties over cast iron and mild steel rotors. The redesigned braking system resulted in a 9.0 kg (or 70%) reduction over the OEM front rotors and an additional 3.8 kg savings by replacing the rear drum brakes.

AERODYNAMICS AND BODY DESIGN

Two key methods for improving vehicle efficiency are reducing aerodynamic drag and vehicle weight. To achieve this, the body was redesigned and built with several primary goals. They are to reduce the coefficient of drag (C_D) to .26 from .30, fabricate stiff lightweight panels, and maintain driveability, visibility, and accessibility of powertrain compartment, trunk, and wheels. The final body design resulted from aerodynamic testing of the 1996 Taurus, literature research, and consultation with professional aerodynamicists.

TESTING OF STOCK TAURUS - The aerodynamics of the original vehicle were analyzed to determine areas where improvements could be made. This analysis was done on several levels. Coast-down tests were conducted using a Datron speed sensor and data acquisition system. The vehicle was tested both in the stock configuration and with several temporary body modifications. These modifications included: covered radiator cooling inlets, faired rear wheels, faired windshield wipers, covered rear door handles, and removed side-view mirrors. Unfortunately, the results of the coast-down tests were inconclusive due to irrepeatable and erratic values for each run. However, the modifications to the body did provide useful insight into how the final body might be shaped.

Qualitative information on the vehicle aerodynamics was gathered by running several *tuft* tests. To help visualize the airflow over the surface of the body, several hundred 5 cm pieces of string were attached to one side of the vehicle. While driving at 100 kph, the pattern and behavior of the tufts were recorded on videotape. Runs were conducted with the unmodified body and the modified body (i.e., faired rear wheels, no side-view mirrors, covered rear door handles, etc.). The videotapes showed the direction and characteristics of the air flow along the surface of the vehicle. In areas where the flow was attached, the tufts laid flat against the body and did not flutter. In areas where the flow was separated and disturbed, the tufts fluttered erratically.

Several areas on the unmodified body were observed to exhibit separated flow: behind the unfaired front and rear wheels, around the side-view mirror, behind the A-pillar of the front side window, and at the base of the rear window. For the modified body, the flow behind the removed side-view mirror and faired rear wheel appeared less turbulent.

BODY MODIFICATIONS - For an automobile, the overall drag force is dominated by pressure effects such as the separation observed in the tuft tests, rather than skin-friction effects. Therefore, the majority of the changes made in the body shape were aimed at reducing the size of the vehicle's pressure wake. This was accomplished by reducing or eliminating the separation caused by discontinuities in the body such as wheels, wheel wells, mirrors, and door handles. In addition to reducing the pressure wake, the shape of the vehicle body was modified to create a pressure gradient which promotes attached flow along the entire length of the body.

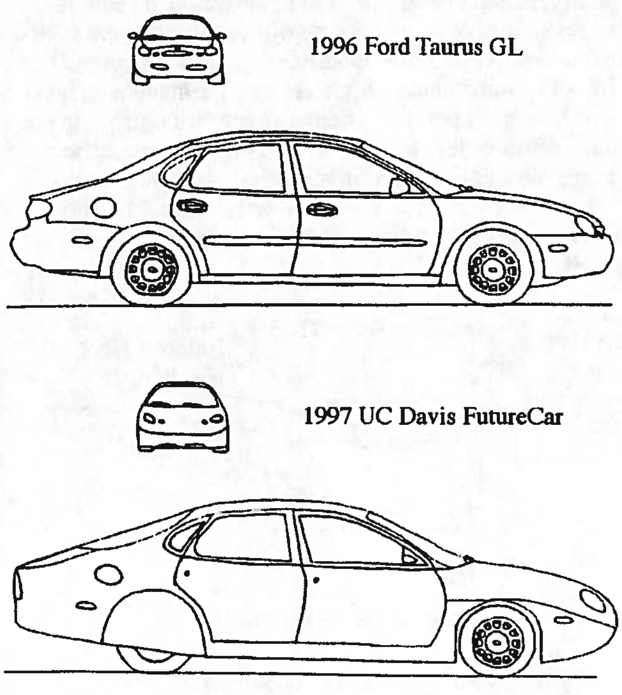


Figure 7. Vehicle Body Modifications.

The nose and hood of the vehicle were altered to reduce separation and encourage smooth airflow. The radiator cooling inlets were moved to the underside of the nose. The headlights and turn signals have been covered with polycarbonate lenses formed to the shape of the nose. The front hood seam was moved below the stagnation point on the nose, creating an undisturbed surface extending to the base of the windshield. The hood gaps above the front fenders have been lowered to run along the tops of the wheel well openings. This provides a continuous surface for the air flowing along the sides of the nose toward the A-pillars. With these changes (see Figure 7), the entire top half of the nose is smooth and seamless, and should support a laminar boundary layer. A two-dimensional flat-plate approximation indicates that the flow may be laminar over the entire length of the hood.

Wheels and wheel wells add as much as 0.07 to 0.09 to the drag coefficient of a *basic body shape*.[16] This is due to the interference of the unsteady flow entering and exiting unfaired wheel wells with the basic body flow. The rear wheel wells have been covered with wheel fairings to minimize separation along the sides of the vehicle. The bottom of the wheel wells are also closed off as much as possible to decrease entering air.

The underside of the vehicle has been covered with a smooth surface from nose to tail to greatly improve airflow. In contrast, the powertrain, exhaust, fuel tank, spare tire, etc. created a very irregular surface for the airflow on the stock Taurus which increased drag.

At the base of the rear window, the separation was due to the increasing window slope and the onset of a concave section just before the trunk lid. The result was that the air flow did not have enough energy to remain attached to the surface. This separation has been minimized by reshaping the rear window and trunk lid in order to reduce the rear window angle and eliminate the concave section. Figures 8 and 9 explicitly show the difference in air flow over the rear window for the unmodified and modified Taurus body.

Figure 8. Tuft testing of stock 1996 Ford Taurus.

Figure 9. Tuft testing of UC Davis FutureCar.

These changes keep the air flow attached to the body from the nose to the rear edge of the trunk. This edge has been sharpened on the top and bottom to provide a distinct separation point for the trailing vortices. The sharp edge avoids the varying separation points of a curved trailing edge. These variations lead to unsteady aerodynamic characteristics and a larger pressure wake.

The tail of the vehicle has been extended so that the trunk now ends at the rear edge of the bumper. The lengthened taper of the sides of the tail created a smaller rear area and reduced the pressure wake. In addition to the extension, the back surface of the tail has been hollowed-out in the center. This cavity caused a tumbling effect in the trailing wake and further reduced the size of the pressure wake.

As a final change, the side-view mirrors have been replaced with CCD cameras using small externally-mounted lenses. The lenses are 15% the size of the stock mirrors. Small flat-screened monitors placed on either side of the steering wheel make drivers aware of their surroundings without significant head movement. In addition to improving aerodynamics, removing the mirrors eliminated the blind spot because the cameras have a 78° field of view.

BODY PANEL MANUFACTURING - To implement the aerodynamic improvements, the shape of the Taurus had to be radically changed. The stock Taurus body was used as a reference point for the body modifications. A mold was built on the front and rear of the original body with foam and body filler. The mold was shaped and smoothed until the final body shape was obtained. Tools were formed on the front and rear molds using a fiberglass chopper-gun to obtain exact negatives of the body shape. Next, the honeycomb core and pre-impregnated carbon fiber sheets were laid-up in the tools forming the laminated composite panel structure. The panels were then vacuum-bagged to draw out trapped air and cured in McClellan Air Force Base's autoclave at 150°C and 70 kPa (10 psi). In the final step, the panels were trimmed, mounted, smoothed, and painted.

The choices of materials and manufacturing processes used for constructing the UC Davis FutureCar body were tailored to the capabilities of available facilities. Carbon fiber composite panels were chosen because of their light weight, high strength, and ease of shaping. However, in mass production, these panels could be replaced with Sheet Molded Composite (SMC)[17], Structural Reaction Injection Molding (SRIM)[18] composites, or Glass-mat thermoplastics. SMC and SRIM composites, currently found on production vehicles, use thermoset resins and are only partially recyclable. Glass-mat thermoplastics surpass SMC technology because they absorb between 2.5 to 3 times more impact energy and are 100% recyclable.[19]

POWERTRAIN COOLING - The cooling-air inlet commonly placed in the vehicle nose is a major source of aerodynamic drag. Because of this, the engine and electric motor radiators were moved underneath the front of the nose. Fans draw air through an inlet that is flush with the belly pan. This location avoids the drag associated with the stagnation of a large volume of air against the flat surface of the intake. It also allows the nose to be optimally shaped to encourage laminar flow. Finally, because the air must now be drawn into the vehicle at all times, the degree of engine cooling is more closely matched to the actual cooling requirements and issues such as overcooling at high speeds are avoided.

HEATING, VENTILATION, AND AIR CONDITIONING

The UC Davis team focused on innovative and efficient heating, ventilation, and air conditioning (HVAC) designs to satisfy varying occupant comfort requirements. Reversible heat pumps, solid state thermoelectric devices, and refrigerator cooling systems were researched. System design criteria included total energy consumption, conditioning ability, weight, packaging, and component availability. A reversible heat pump HVAC system showed the best potential for meeting the design criteria.

Based on a concept introduced by Department of Defense research on personnel cooling, the HVAC system was designed to give the occupants the perception of feeling cool without cooling the entire cabin. A two speed, squirrel cage fan blows conditioned air across occupants' bodies towards their heads through vents in the center console. A vent is directed at each front passenger and two vents condition the rear passengers. The fan is dual wound which eliminates the energy losses associated with drop-down resistors typically used for variable speeds in conventional HVAC systems.

Localized heating and cooling allows the HVAC system capacity and component sizes to be reduced. A Sanden TRS050 scroll compressor and Showa condenser are used from a Honda Today. This condenser acts as the exhaust exchanger. Two high efficiency, flat pack blowers draw air through this condenser and direct it out under the car. A tubular condenser was also used for the interior heat exchanger since both exchangers experience high fluid pressures. A bi-flow expansion valve was not available at the time of production, so dual one-way expansion valves were used with dryers and check valves to control flow direction. A four-way reversing valve is used to direct the refrigerant (R-134a) for the desired interior conditioning. The compressor is driven by a high efficiency, high voltage permanent magnet motor. Outlet air temperature is determined by controlling the motor and compressor speed. This allows more efficient temperature control over conventional systems because compressor power consumption is directly related to cooling load. The reversible heat pump plumbing schematic is shown in Figure 10.

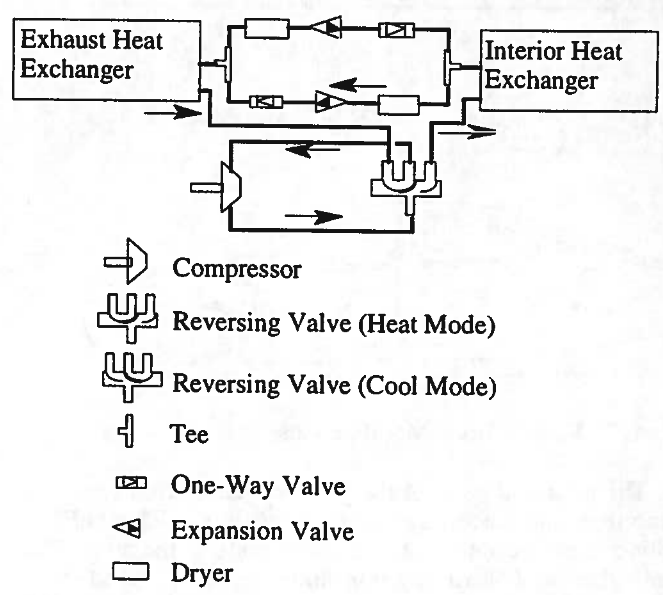


Figure 10. Heat pump plumbing schematic for heat mode.

Duct length minimization and packaging restrictions determined the system location. If behind the dashboard as in conventional vehicles, long duct lengths are needed for outlets to the rear seats. The dashboard was also considered as an ideal location for protecting the vehicle's control system hardware. As a result, the system was placed underneath the rear passenger seat floorboard. Light weight, smooth carbon fiber air ducts enclose both HVAC heat exchangers. Recirculated air flows with low losses through short ducts to pass through the interior exchanger and exit the vents. The exhaust exchanger takes air from and returns air to the vehicle's underside with minimal increase in aerodynamic drag.

Overall system weight and energy consumption have been reduced from conventional HVAC systems. Future extensions of the system include window tinting, an electrically heated windshield for efficient defrosting, and photo-voltaic solar cells for powering fans to lower interior temperature when the car is unoccupied.

CONCLUSION

The UC Davis FutureCar Team has redesigned a 1996 Ford Taurus as a parallel charge depletion hybrid electric vehicle. The UC Davis FutureCar incorporates a blend of advanced and conventional automotive technologies to produce a highly efficient vehicle which could help reduce the environmental impact of future transportation systems. This vehicle may also qualify for partial ZEV credit in California under the anticipated hybrid regulations.

The UC Davis FutureCar won First Place Overall in the 1997 FutureCar Challenge by scoring 830 out of 1020 points, 111 points ahead of the second place finisher. The UC Davis FutureCar also won the following awards:

- Most Energy Efficient Vehicle
- Lowest Vehicle Driving Losses
- Best Application of Advanced Technology
- Best Development & Application of Advanced Materials
- Best Technical Report
- Best Dynamic Performance

A performance summary of the UC Davis FutureCar and stock Ford Taurus is shown in Table 8. The FutureCar doubled the Taurus' fuel economy by achieving 5.64 L/100 km (41.7 mpg) on the FUDS and 3.74 L/100 km (62.8 mpg) on the FHDS. This fuel economy was verified on a test drive from Davis, CA to Salt Lake City, UT. The increase in fuel economy resulted from the significant reduction in aerodynamic drag and the increased efficiency of the parallel hybrid powertrain operating under a charge depletion control strategy. The FutureCar's acceleration was slightly slower than the Taurus, but handling was much improved due to the lowered center of gravity and suspension modifications. Both vehicles have approximately the same weight and driving range.

The UC Davis FutureCar reached only two of the team's ambitious goals, the FUDS and FHDS combined range and the reduction of aerodynamic drag. The team's effort now turns to achieving the other goals listed in Table 1. A ZEV range of 130 km can easily be attained by increasing the battery pack energy storage. To meet the acceleration performance of 0 to 100 kph in 12 seconds, the electric motor must be able to produce 75 kW. The desired weight reduction for the current UC Davis FutureCar is impractical so future hybrid development will be based on an aluminum framed vehicle. The final goal of 2.9 L/100 km (80 mpg) will only be possible if all other goals are met and the parallel powertrain and charge depletion control strategy are optimized.

	UC Davis FutureCar	Stock Ford Taurus
FUDS and FHDS Range	550 km HEV	600 km
ZEV Range	105 km	0 km
0 to 100 kph Acceleration	14.4 sec (HEV)	12.5 sec
Equivalent Energy Efficiency	4.8 L/100 km (49 mpg)	9.4 L/100 km (25 mpg)
Curb Weight	1524 kg	1515 kg
Aero Drag: C_D	0.26	0.30
Passenger Capacity	5 passengers	6 passengers

Table 8. Vehicle performance summary.

ACKNOWLEDGMENT

The authors wish to thank and congratulate all of the members of the UC Davis FutureCar Team, otherwise known as Team Fate, for their hard work and perseverance in developing a winning UC Davis FutureCar. The leadership and knowledge of Dr. Andrew Frank who won the NSF Faculty Award and Dr. Andrew Burke make this project possible. Dave Hook and Michael Akahori provided design and manufacturing assistance. Eric Chattot, Lothlorien Redmond, Eric Galambos, Jonathan Isaac, and Scott Sutorius significantly contributed to the editing of this paper.

[1] Press release from Toyota at the beginning of April.

[2] SIMPLEV is a program developed by INEL to model series hybrids.

[3] State of California Air Resources Board, Proposed Amendments to the Low-Emission Vehicle Regulations to Add an Equivalent Zero-Emission Vehicle (EZEV) Standard and Allow Zero-Emission Vehicle for Hybrid-Electric Vehicles, July, 1995.

[4] A. A. Frank, "A True Electric Vehicle Option: A Charge Depletion Hybrid," presented at the 1995 NESEA Conference on Sustainable Energy, Providence, RI, November, 1995.

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