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

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Working Paper
UCTC No. 375

The University of California Transportation Center

University of California
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The University of California Transportation Center

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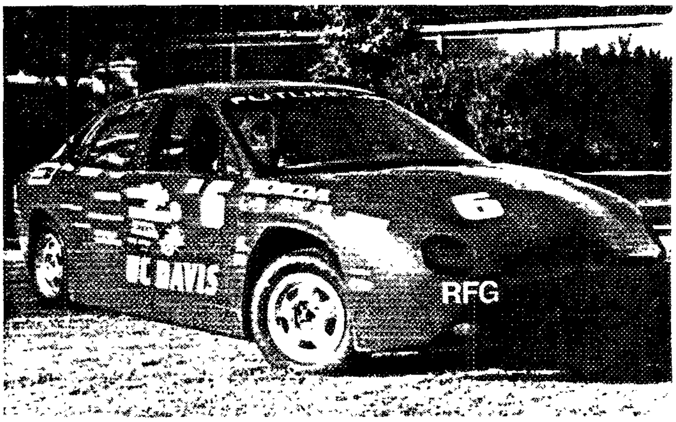
ABSTRACT

The UC Davis FutureCar team has redesigned a 1996 Ford Taurus as a 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 are to be achieved by using a highly efficient powertrain, reducing vehicle weight, and improving stock vehicle aerodynamics. A charge-depletion parallel hybrid 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. Each can provide torque to the wheels and are combined within a compact, lightweight, and reliable powertrain. The motor is powered by a 16.6 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 to reduce weight. Computer simulations indicate that the vehicle will achieve an equivalent fuel consumption of less than 4.7 L/100 km (53 mpg) and a range of 400 km on a combined federal urban and highway driving schedule. The vehicle is predicted to accelerate from 0 to 100 kph in 12 seconds and have an all-electric range of 95 km.



INTRODUCTION

The University of California, Davis Hybrid Electric Vehicle 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 UC Davis engineering students to redesign a 1996 Ford Taurus to achieve three times its current fuel economy without sacrificing performance, utility, or cost. In addition to this challenge, the UC Davis team has taken on the task of qualifying for partial ZEV credits in California. The California Air Resources Board (CARB) is proposing to credit hybrid electric vehicles for their ability to operate as ZEVs. The UC Davis FutureCar has been designed to qualify for 80% ZEV credit. In mass production, this would allow ten of these vehicles to equate to eight ZEVs to satisfy the CARB mandate.

Table 1 illustrates the goals set forth by the team to both win the FutureCar Challenge and qualify for partial ZEV credit. The magnitude of this task can be seen by comparing these goals to the Stock 1996 Taurus performance. The UC Davis FutureCar represents the same tripling of fuel economy as well as a significant reduction in emissions and the addition of a zero emissions capability. To achieve this, a new powertrain configuration is incorporated and the aerodynamic drag is reduced. However, significantly reducing the vehicle weight to achieve the weight goal has proven to be very difficult. This is due to the need to both add components and convert an existing vehicle which has not been optimized for low weight.

	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 seconds (HEV)	12.5 seconds
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	0.27	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 can be considered for their possibility of meeting the fuel economy, emissions, and range goals for the UC Davis FutureCar.

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 a very low aerodynamic drag coefficient and require a small engine which would sacrifice acceleration performance. Achieving the weight reduction and low drag coefficient through the conversion of a stock Taurus is impractical.

The second choice is an electric vehicle (EV). EVs can easily achieve the emissions goal, but are limited to under 200 km range in a practical mid-size vehicle using current battery technology. Electric vehicles have an advantage over ICEVs regarding overall powertrain efficiency, but 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). An HEV combines the best features of the ICEV and the EV. A hybrid electric vehicle utilizes two separate power sources to provide power for driving the vehicle. This allows each component to be used within its optimal efficiency range. The use of an internal combustion engine allows long range with a smaller battery pack, while the electric motor enables a more efficient drivetrain and very low emissions.

Once an HEV is chosen, two configurations are possible—series or parallel. The choice of a series versus a parallel configuration is not straightforward. The long term focus of many major automobile manufacturers is towards the series configuration with the long-term expectation of a highly efficient fuel cell as the powerplant. But, in the near term or if fuel cells do not prove to be as efficient as hoped, the trade-offs between series and parallel vehicles are complicated and it is unclear as to an obvious choice. This is evidenced by the fact that some companies are currently developing parallel hybrid vehicle concept cars.

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 the batteries become 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, since the APU is decoupled from the instantaneous demands of the road, almost any power generating technology can be used. In addition, the APU 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 first by converting the mechanical energy into electricity in the generator (at an efficiency of 90% to 95%) and then from electricity back to mechanical energy at the motor (at an average efficiency of 80% to 85%). SIMPLEV[1] 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 90%). The overall effect of these losses is an energy conversion efficiency between the APU and the wheels of 67% to 75%.

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 instead 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[2]. The small battery pack also reduces the ability of the HEV to operate in an EV mode for city trips or with reasonable acceleration. 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, sterling 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 the engine must operate over a wider performance range which will reduce the overall engine efficiency. This effect can be minimized by operating the engine within a window of torques and speeds where it is 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 third to one quarter the power of a conventionally sized engine). Using a small engine reduces the amount of time the engine would spend at part throttle where it is least efficient. The torque lost by using the smaller engine is compensated by the electric motor. Second, the operating range where the engine would be at part throttle 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 further 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.[3] Such a "charge-depletion" parallel hybrid would be recharged only from the electricity grid which produces energy at thermodynamic efficiencies up to 45%.[4] 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 used for the majority of driving. The first strategy to meet this challenge is to use a fairly large battery pack. This provides higher power for acceleration and increases hybrid and EV range. The longer all-electric range would increase the incentive for people to utilize the EV mode, potentially making a large impact on reducing emissions in polluted areas. Extending the urban HEV range is also 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 CONFIGURATION - The previous descriptions highlight the fact that there are advantages and disadvantages of each configuration. A more detailed analysis of the trade-offs could provide further insight. SIMPLEV could have been used to model several series hybrid designs, but an equivalent simulation program for parallel hybrids was unavailable and precluded such an analysis. The final decision of the UC Davis team to pursue a charge-depletion parallel hybrid was made based on three major considerations: efficiency, all-electric operation, and implementation.

Efficiency - Achieving high efficiency while using energy from the engine to drive the wheels is more likely for the parallel configuration due to fewer energy conversions. Achieving high efficiency while operating on battery power depends primarily on electricity generation and energy storage efficiencies. With powerplant efficiencies already over 40%, the charge-depletion parallel hybrid should have access to a more efficient energy supply. The energy storage efficiency of ultracapacitors could improve the efficiency of a series hybrid, but they are not yet available in the required size.

All-Electric Operation - As a California school in an air quality non-attainment region, UC Davis is very aware of the problems caused by the emissions produced from automobiles. The charge-depletion parallel hybrid configuration relies on powerplant electricity for a significant portion of its driving range. On the other hand, a charge-sustaining series configuration depends on electricity generated on-board for most of its driving range. CARB has recognized these issues and has set limits to the amount of ZEV credit which could be obtained. These limits are based on the all-electric range of the vehicle (higher all-electric range receives more credit) and the potential for the engine to continuously recharge the batteries (the credits are cut in half unless it can be proven that the driver will not rely on the APU to keep the batteries charged).[5] As a result, the charge-depletion parallel hybrid has the potential for receiving the highest value of ZEV credits since it has the longer all-electric range and does not produce electricity on board.

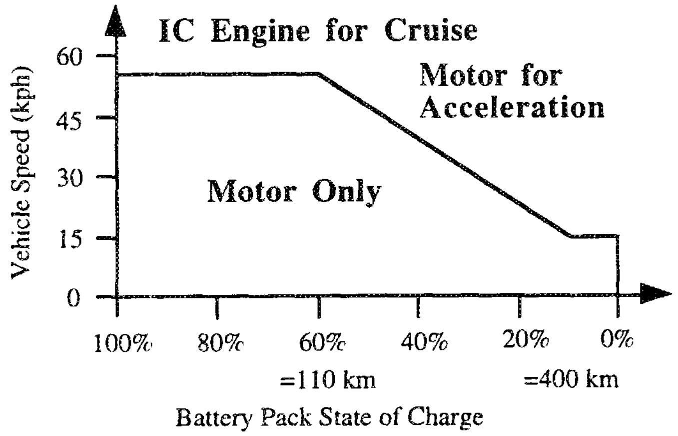


Figure 1. Schematic of vehicle control strategy.

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 three years of experience from 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. Finally, the information acquired from engine dynamometer and battery performance tests conducted on a previous powertrain provided insight to optimize this year's design.[6]

VEHICLE CONTROL STRATEGY

The primary foci of the UC Davis charge-depletion control strategy are as follows:

- Maximize fuel economy and reduce emissions while maintaining or improving stock vehicle performance.
- Provide a seamless interface between the driver and power systems.

The vehicle control strategy was fine tuned using a vehicle model recently made available to the team. The model, ADVISOR, which was developed by the National Renewable Energy Laboratory (NREL), has the capability to robustly simulate parallel hybrid vehicles. UC Davis has modified the battery algorithms and incorporated the charge-depletion control strategy and component models to predict realistic performance characteristics of the vehicle.

The vehicle control strategy will allow the UC Davis FutureCar to achieve a 400 km range while operating the engine in its high efficiency window. The engine is turned on based upon a combination of vehicle speed and battery state of charge (SOC) (Figure 1). When the SOC is high, the engine is turned on at 56 kph. Once the SOC declines to 60%, the engine begins to turn on at lower vehicle speeds to maintain performance over a long urban driving range. The initial engine turn-on speed was chosen such that, above that speed, the engine is operating near its peak efficiency. The higher engine turn-on speed at high SOC is also intended to bias the initial operation of the vehicle towards electricity. The point where the turn-on speed begins ramping down and the endpoint (16 kph) at which the batteries are considered depleted is based on a balance between maintaining the high efficiency of the engine and achieving the required range of 400 km.

Once the engine is turned on, it can efficiently provide all the power required for driving at highway speeds. It can also provide the power required to climb a 6% grade, but at a lower efficiency. This allows the vehicle to have a highway range limited primarily by fuel storage. The electric motor is only used above the engine turn-on speed to provide power for good acceleration performance.

The control strategy allows the highest efficiency and lowest emissions to be achieved during short trips (up to 100 km). The 1990 National Personal Transportation Survey data shows that over 80% of trips are under 100 km.[7] Assuming that people will maintain a high SOC by opportunity charging and completely recharging their vehicle each night, a large portion of a person's yearly mileage should accrue while operating on electricity.

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.

CONTROL SYSTEM IMPLEMENTATION - The heart of the control system is a Z-World 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, battery SOC, and the status of the engine (on or off). Using this information, the microcontroller implements the UC Davis control strategy through outputs to the electric motor and engine. The microcontroller also provides information to the driver about the operating characteristics of each powertrain component.

The microcontroller's interpretation of accelerator pedal position depends on the engine status. This allows the microcontroller to maximize the control resolution available to the driver. 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 vehicle reaches the engine turn-on speed, the first 30% of pedal travel is then 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 combination limits the rate at which the throttle position changes. This reduces the high emissions levels associated with rapid transients in the throttle position.

A flowchart of the control system is shown in Figure 2. This figure also illustrates the back-up control system which replaces the microcontroller in the event of a malfunction. While the primary system has been designed to be robust, the nature of prototype vehicles is that systems can sometimes fail. The backup system provides direct servo-motor and motor controller inputs from the pedal. In addition, a simple back-up control circuit has been incorporated which can monitor the vehicle speed and turn on/off the engine if the microcontroller ceases to function.

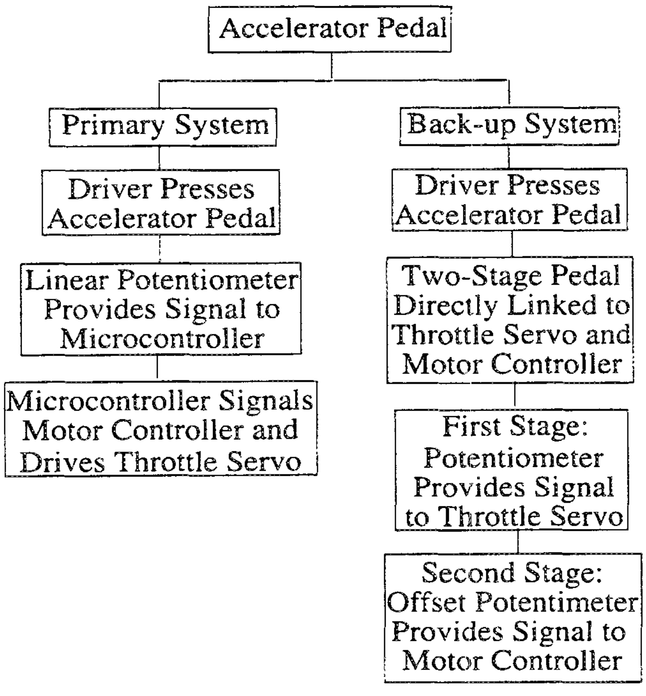


Figure 2. Vehicle Control Systems.

An additional feature of the primary microcontroller system is that the transition period between electric motor operation and engine start-up can be smoothed out. The engine is started by the electric motor while the vehicle is driving, momentarily reducing the torque output of the electric motor to the wheels. The slight hesitation that would be felt by the driver during engine start-up is avoided by momentarily increasing the torque command to the motor as the engine is started.

POWERTRAIN PERFORMANCE REQUIREMENTS

To aid in powertrain component selection and vehicle design, simulations were performed to determine basic operating requirements. The following table represents 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 2.0 m^2, a drag coefficient of 0.27, and a rolling resistance coefficient of 0.007.

Performance	Energy/Power Required
100 kph cruising power	15 kW
100 kph cruising power 6% grade	35 kW
65 kph cruising power	9 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	19 kWh
Energy for 95 km ZEV range on FUDS	14 kWh

Table 2. Powertrain operating requirements.

POWERTRAIN DEVELOPMENT

ENGINE SELECTION - The engine used for the 1996 UC Davis FutureCar had to meet certain criteria. First, the engine must have sufficient power to maintain highway cruising speeds to ensure 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 15 kW. Therefore, the engine must produce 15 kW at a reasonable engine operating speed (2000 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 were not chosen for the vehicle because they did not show promise for any substantial improvements over traditional petroleum fuels. 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.[8] Methanol and ethanol have been suggested for use in reducing automobile emissions, but no significant advantage is apparent, especially when compared to RFG.[9]

The advantages of CNG are very low emissions and the potential for efficiencies greater than a gasoline engine due to a high compression ratio. The disadvantages of the fuel are storage size and weight as well as fuel availability. Since natural gas is a gaseous fuel, its volumetric energy density (kWh/liter) 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 to 3,600 psi), but would still fall short of the densities of gasoline and diesel fuels. As a result, 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 add significant weight to the vehicle. Finally, the infrastructure required to provide CNG for vehicles does not yet exist.

Diesel fuel's advantages are in the areas 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 at a high compression ratio and without throttling losses, 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. Additionally, 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) was selected because it maintained many of the advantages of diesel fuel while avoiding the disadvantages. 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. The use of RFG results in an efficiency sacrifice (peak efficiencies are 30% to 32%) which is balanced by lower 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.

Engine Options - After specifying the engine characteristics and the fuel type, several specific spark ignition engines were considered for this powertrain. The first 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 is 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 need 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 15.0 kW at 2800 rpm and 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 considerations for selecting an electric motor were high efficiency, low weight, high power, and an operating voltage which matches that of the battery pack. Table 3 provides the specifications for the examined 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 3. 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 used in the vehicle. The AC-100 provides higher power than needed. The power capabilities would never be fully utilized, resulting in extended part load operation. In addition, the excess weight, lower efficiency, and high voltage requirements eliminated this motor from consideration.

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

TRANSMISSION SELECTION - A manual transmission was chosen over an automatic 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. The transmissions considered for the UC Davis FutureCar are shown in Table 4 below.

	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 4. Transmission Options.

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. 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.

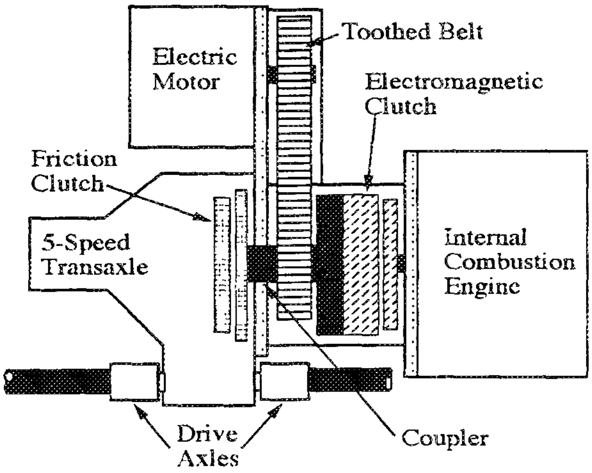


Figure 3. Powertrain Configuration.

POWERTRAIN CONFIGURATION - Within the parallel hybrid arrangement, the selected engine and motor could have been combined in two possible configurations. The first design considered was to locate the electric motor between the transmission and engine. This would eliminate the need for a lateral belt or chain system between the two drive components. Its implementation would also be mechanically simpler and potentially more reliable. This configuration could not be pursued due to the limited space available within the Taurus engine compartment. The second design considered and chosen was to offset the electric motor from the engine and transmission. Figure 3 illustrates this design.

IMPLEMENTATION - After the three major components of the powertrain were selected, the necessary coupling mechanisms could be 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 that they are 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 where as the maximum average 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 as torque spikes are generated 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 significant 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. A greater reliability is 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 double-row ball bearing of the electromagnetic clutch, and on the transmission end by a single-row ball bearing. The dynamic components of the powertrain are illustrated in Figure 4 below.

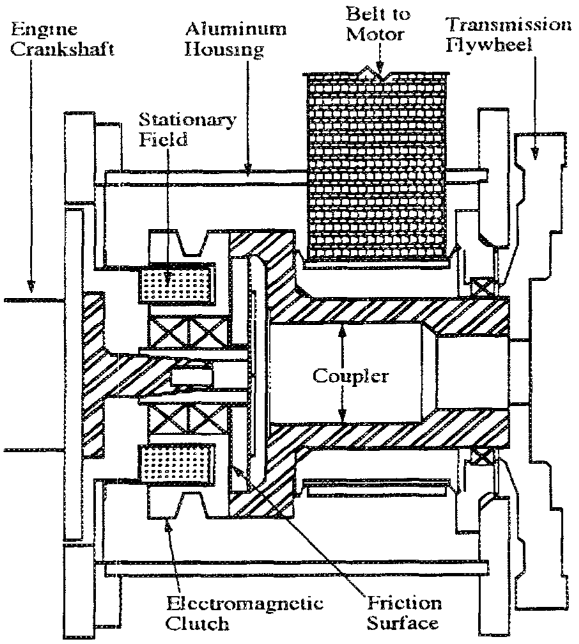


Figure 4. Powertrain internal components.

TRACTION BATTERY

BATTERY SELECTION - Another 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 an 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 130 km. The battery pack must also be able to provide 50 kW to achieve a 0 to 100 kph acceleration time of 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 5 shows the manufacture's specifications for each battery type and Table 6 shows the characteristics of an 18 kWh battery pack composed of each of the three batteries under consideration.

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 5. 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 6. 18 kWh battery pack characteristics.

The Ovonic NiMH battery pack has the lowest mass and volume as well as 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 learning more about the charge/discharge characteristics of the Ovonic NiMH batteries, the fifteen-module pack was reduced to fourteen modules to ensure that the maximum input voltage to the motor controller was not exceeded. This reduced the energy storage of the pack to 16.6 kWh which limits the all-electric range to 110 km. However, the pack is still able to provide the required peak power output of 50 kW.

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 5, 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.

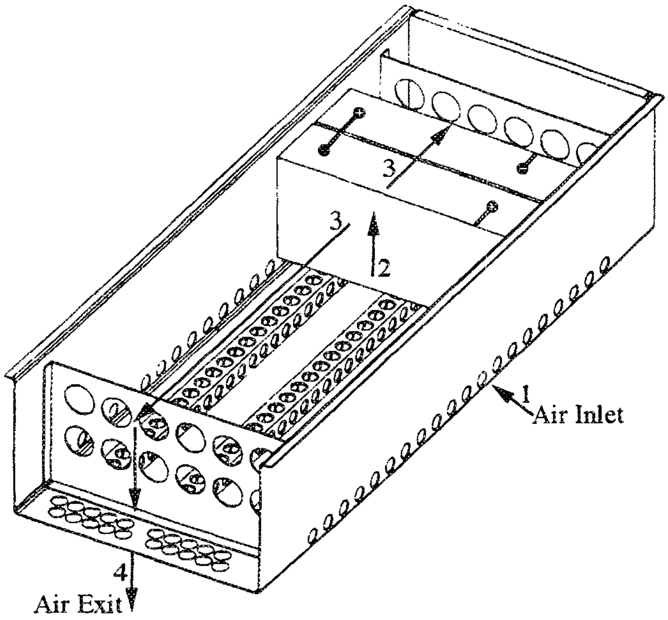


Figure 5. Battery Box Schematic.

To ensure that the batteries remain at the proper operating temperature, a battery monitoring system is being 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 the temperature of the modules allows the system to protect the battery pack from overheating while it is powering the vehicle, charging, or at rest. The blowers are always on while the vehicle is being driven or the pack is being charged and the monitoring system can turn on and off the blowers while the vehicle is not in use. 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.

The battery monitoring system also guarantees that no module voltage drops below the limit of eight volts. When this limit is reached, the system signals the microcontroller to limit the power output of the motor. This allows maximum use of the energy stored in the battery pack which in turn provides the 110 km all-electric range. Pack current is also monitored by the system to calculate Ah as a means of determining state of charge. Accurate SOC information is critical for the UC Davis FutureCar to achieve the desired range, fuel economy, and emissions since it is used to determine the engine turn-on speed.

BATTERY BOX FABRICATION - The battery boxes were designed and fabricated to be strong, lightweight, and compact. 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 increase the stiffness of the box floor and raise the batteries to create the bottom plenum. Phenolic G10, a glass-fiber reinforced epoxy 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 over the top and bottom of each module were machined to maintain the required 6 mm cooling gap and prevent battery movement in the box. Polycarbonate was chosen for its good electrical properties which further ensures against 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.) Seven 12 V, 5 Watt, 1400 L/min blowers mounted on the ends of the two battery boxes provide cooling and ventilation. A rubber gasket completely seals the battery box from the vehicle occupants as well as improves cooling by only allowing air into the box from the designated inlets.

BATTERY PACK LOCATION - Locating the batteries in a conversion vehicle 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. Nine modules were placed under the front seats and five under the rear seat. The replacement front seats which are 8 kg lighter than the stock ones remained at stock height. But to do this, the floor was lowered 90 mm. This changed the ride height to 100 mm and created additional packaging space under the vehicle. 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. Trunk volume was only minimally reduced by placing a small gas tank between the rear wheels just behind the rear seat. The original tank had been under the rear seat.

EMISSION AND FUEL SYSTEMS

The UC Davis FutureCar control strategy allows for extended operation in all-electric mode where the vehicle will produce no tailpipe emissions. But, the spark ignition engine results in the potential for start-up, running, and hot-soak emissions. The UC Davis team has modified the conventional emissions and fuel systems to ensure that these emissions are kept below California ULEV levels.

ENGINE START-UP - Start-up emissions are significantly reduced by the use of a time delayed engine start-up sequence except near full-throttle operation. Since the electric motor is the primary power source in the vehicle at low speeds, the IC engine start-up can be delayed without a significant loss in drivability. Once the engine turn-on speed is reached, the microcontroller activates the engine start-up sequence. This first primes the fuel pump and activates a 12-volt Corning electrically-heated catalytic converter (EHC) located downstream of the OEM close-coupled catalyst. If the catalytic converter is already hot from previous engine operation, the catalyst heat-up is bypassed. Once the EHC is at its light-off temperature, the engine is started by closing the electromagnetic clutch and powering up the engine control unit. The EHC then acts as the primary exhaust-treatment catalyst until the higher-efficiency close-coupled catalyst heats up.

The cold-start emissions typical in a conventional engine have been further minimized by eliminating cold-start enrichment. This enrichment normally ensures smooth operation during warm-up. Since the engine is always operated at high torque, the enrichment needed to maintain drivability is unnecessary. To eliminate the cold-start enrichment, the coolant temperature sensor has been 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.

HOT SOAK EMISSIONS - Hot soak emissions are due to fuel vapors escaping from the engine intake, fuel lines, and fuel tank. These emissions are minimized with a sealed fuel tank and by storing fuel vapors in a charcoal canister when the engine is not in use. Figure 6 is a schematic of this system.

When the door covering the fuel filler cap is opened, a solenoid valve between the charcoal canister and tank is opened to purge the vapors from the tank into the canister. When the filler cap is removed, the tank is at atmospheric pressure, and the only vapors emitted to the environment occur during refueling. During engine operation, the solenoid valve between the charcoal canister and engine intake manifold is opened to purge the canister of stored vapors into the intake manifold.

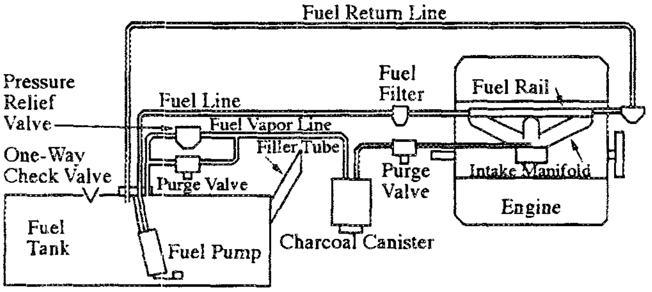


Figure 6. Fuel System Schematic.

BRAKING SYSTEM

The stock Taurus braking system was redesigned to significantly reduce weight, incorporate variable regenerative braking, and provide comparable performance to the original power braking system. All major components of the mechanical system were replaced with lighter more efficient substitutes. The OEM front calipers were replaced with four-piston aluminum calipers for reduced weight (7.0 kg lighter) and increased braking force. The cast iron rotors and spacers were replaced with steel rotors and aluminum spacers for a weight savings of 7.0 kg or 50%. The rear drum brakes were converted to disk brakes using lightweight Honda CRX calipers which have an integrated cable-actuated parking brake. The rear brake rotors are of identical construction to the front rotors with an eleven inch diameter for good braking torque. In addition to the 3.6 kg weight savings of the rear disk brakes, braking efficiency was improved by reducing brake fade to which drum brakes are prone as they heat up. The mechanical advantage of the brake pedal was increased to 4.5:1 from 2:1 to eliminate the need of the vacuum booster.

Variable regenerative braking was added to the UC Davis FutureCar. The first 30% of the brake pedal throw varies the braking torque request from the motor. As the pedal is depressed beyond 30%, the hydraulic brakes add braking torque to the maximum provided by the electric motor. The regen signal is sent directly from the brake pedal to the motor controller to ensure reliability. The use of variable regenerative braking enables a braking feel similar to a conventional vehicle while providing a more efficient use and recovery of the vehicle's kinetic energy.

AERODYNAMICS AND BODY DESIGN

Two key components to improving vehicle efficiency are reducing aerodynamic drag and weight. To achieve this, the body was redesigned and built with these primary goals:

- Reduce the coefficient of drag, C_D, to approximately 0.27 from 0.30.
- Fabricate stiff, lightweight panels.
- Maintain driveability, visibility, and accessibility of engine bay, trunk, and wheels.

TESTING OF STOCK TAURUS - The aerodynamics of the original vehicle were analyzed to determine areas where improvements could be made. Coast-down tests were conducted using a Datron speed sensor and data acquisition system. The vehicle was tested 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.

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 (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. Laminar flow will be attached and create less skin friction drag compared to the typical turbulent flow.

Wheels and wheel wells add as much as 0.07 to 0.09 to the drag coefficient of a *basic body shape*.[10] This is due to the interference of the unsteady flow entering and exiting unfaired wheel wells with the basic body flow. All four wheel wells have been covered with wheel fairings to minimize separation along the sides of the vehicle (Figure 8). 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.

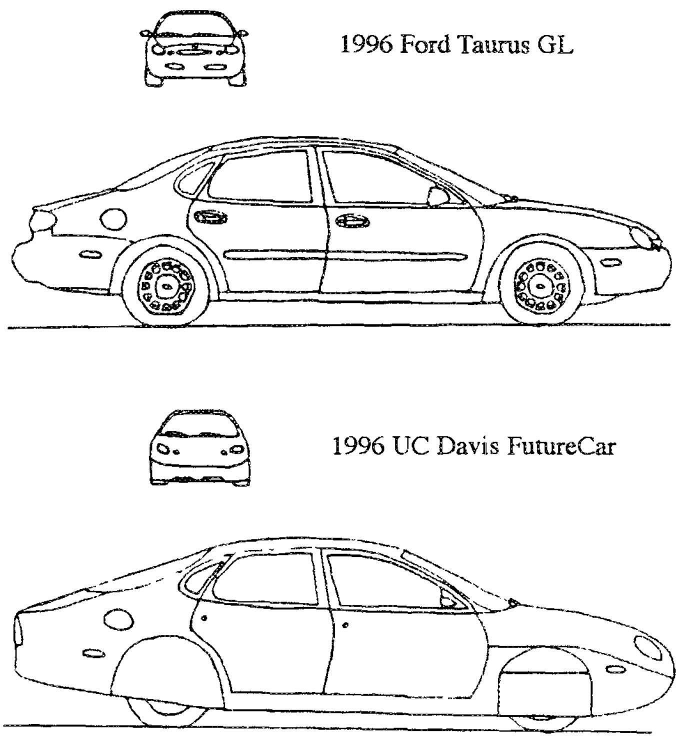


Figure 7. Vehicle Body Modifications.

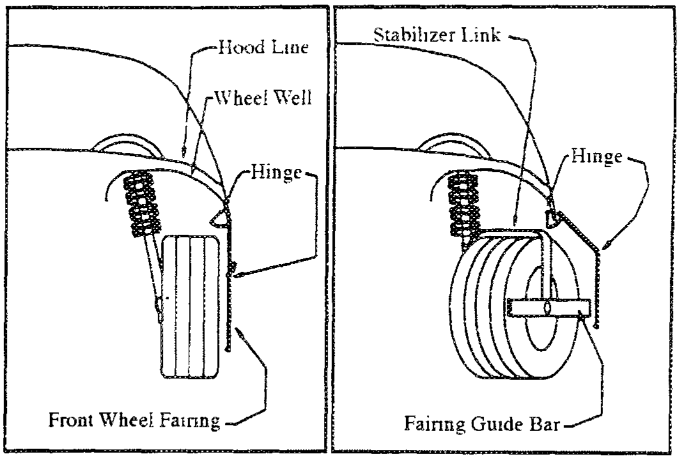


Figure 8. Front Wheel Fairings.

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.

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 edges avoid 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 creates 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 is projected to encourage a tumbling effect in the trailing wake and further reduce 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 since 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 steel body panels on the nose and tail of the vehicle have been replaced with composite panels. These panels are formed from a carbon fiber and Nomex honeycomb sandwich. They are 7.5 mm thick and have a very high strength-to-weight ratio. Composite panels were chosen because of their weight, strength, ease of shaping, and available manufacturing facilities.

The original body of the stock Taurus was used as a reference point for the body modifications. A buck was built on the front and rear of the original body with foam and body filler. The buck was shaped and smoothed until the final body shape was obtained. The buck was then used to form tools which were exact negatives of the body shape. The four tools were formed on the front and rear of the buck using a fiberglass chopper-gun. The left and right halves of both the front and rear tools were joined and the seams sealed. Next, the honeycomb core and pre-impregnated carbon fiber sheets were laid-up in the tools forming the laminated 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. In the final step, the panels were trimmed, mounted, smoothed, and painted.

COOLING - The cooling-air inlet commonly placed in the vehicle nose is a major source of aerodynamic drag. While this is partially offset by the ability of the ram effect to reduce cooling fan energy consumption, the UC Davis team opted for an alternative location which showed promise for further reductions in aerodynamic drag. The radiators for the engine and motor have been moved underneath the front of the nose and utilize fans which draw air through an inlet 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.

The efficiency of the cooling-air intake was further improved by minimizing the total cooling load and the power required to draw cooling air into the vehicle. To reduce the total cooling load, the hot air in the engine compartment is ducted around the exhaust pipe and out the bottom of the car. The cooling system uses thermostaticly controlled, low power electric fans to draw air through the radiators. This avoids the need to mechanically couple the fans to the drivetrain. The hot air is ducted to the wheel wells to take advantage of their low pressure which aids in drawing the air through the system. The ducts are smooth-walled with relatively direct paths to minimize friction losses.

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 can win both the FutureCar Challenge competition and qualify for partial ZEV credit.

The UC Davis version of NREL's ADVISOR vehicle simulation program was used to predict the performance of the UC Davis FutureCar. The following table shows the results of this analysis.

HEV FUDS/FHDS equivalent gasoline fuel consumption	4.2 L/100 km (56 mpg)
HEV FUDS/FHDS range	410 km
HEV acceleration: 0-100 kph	11.5 seconds
ZEV FUDS range	95 km
ZEV FHDS range	95 km
ZEV acceleration: 0-100 kph	19 seconds

Table 6. Projected vehicle performance.

Over the next year, the primary focus of the team will be to reduce the vehicle weight, refine the control strategy, incorporate a high efficiency HVAC system, and minimize accessory loads. These modifications will enable the team to both improve vehicle fuel economy and satisfy a broad range of consumer needs.

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

[2] 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.

[3] 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.

[4] While the current national average is around 32%, technologies such as gas turbine combined cycles which can produce electricity at over 45% are becoming more widespread. M. A. DeLuchi, Emissions of Greenhouse Gasses from the Use of Transportation Fuels and Electricity, Volume 2: Appendixes A-S, Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, Illinois, 1993.

[5] Ibid. State of California Air Resources Board, 1995.

[6] This work was performed under contract from the National Renewable Energy Labs.

[7] Ibid. State of California Air Resources Board, 1995.

[8] M. A. DeLuchi, Emissions of Greenhouse Gasses from the Use of Transportation Fuels and Electricity, Volume 1: Main Text, Center for Transportation Research, Energy Systems Division, Argonne National Laboratory, Illinois, 1993.

[9] D. Sperling, M. A. DeLuchi, Is Methanol the Transportation Fuel of the Future?, published in *Alternative Transportation Fuels: An Environmental and Energy Solution* , D. Sperling, ed., Quorum Books, New York, 1989.

[10] Fabijanic, John, "An Experimental Investigation of Wheel-Well Flows," SAE 960901. Note: the *basic body shape* refers to a generic vehicle shape with a smooth underbelly and without wheels, mirrors, or any other protrusions.