Hybrid-Electric Vehicle Technology (1990-2000)

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Abstract

Hybrid-electric vehicle technology has been reviewed and developments that have occurred in the period 1990-2000 highlighted with particular attention being given to their resultant effect on light-duty vehicle emissions and fuel economy. Electrical energy storage technologies (pulse batteries and ultracapacitors) are considered in depth and control strategies for series, parallel, and dual mode hybrid drivelines are described with emphasis on how the different strategies influence vehicle emissions and energy consumption. Hybrid vehicle operation for drivelines using various engines (fuel injected gasoline, diesel, and Stirling) and fuel cells (fueled with compressed hydrogen) is simulated for the Federal Urban and Highway driving cycles. The simulation results are utilized to compare the emissions and energy consumption of many hybrid vehicle designs with those of battery-powered electric and conventional ICE vehicles of equivalent size and performance. The emission comparisons are made based on full fuel cycle emissions starting at the powerplant, refinery, and hydrogen generation station for each of the vehicle types. Energy efficiency is described in terms of gasoline equivalent fuel economy and full fuel cycle CO2 emissions. The marketing and regulation of hybrid-electric vehicles are reviewed in light of the California ZEV Mandate and the initial experiences of auto companies in leasing and selling battery-powered and hybrid vehicles.

The technology review indicated that in the last ten years much progress has been made in the development of components for both battery-powered electric and hybrid-electric vehicles. The auto industry now has available technology for the design of ultra-clean vehicles utilizing several driveline options, including battery-powered and fuel cell electric and engine-powered hybrids with an electric range from zero to that close to a battery-powered EV. The mass-produced cost and customer acceptance of these various technology options is unclear at the present time and which of the options will be pursued in the near-term by the auto industry depends on their assessment of these factors.

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Introduction

Electric vehicles have a number of important and well-recognized advantages compared to conventional engine-powered, liquid-fueled internal combustion engine (ICE) vehicles. These advantages include zero exhaust emissions, very quiet operation, home refueling, a relatively simple, highly efficient driveline, and the possible use of non-fossil, renewable energy as the primary energy source for commercial and personal transportation. The main disadvantage of electric vehicles in the minds of many consumers and the auto companies is their limited range before it is necessary to recharge the batteries, which in most instances takes a number of hours. Even though the daily travel of most vehicle owners on the vast majority of days is much less than the present range of electric vehicles, most consumers are reluctant to purchase a limited range vehicle, which could not be used to meet all their needs. This is especially true if, as is likely when electric vehicles are first marketed, their price is higher than that of conventional ICE vehicles.

The limited range of the electric vehicle can be overcome by incorporating into the driveline of the vehicle the capability to generate electricity on-board the vehicle, when needed, from a chemical fuel. Such a vehicle is termed a hybrid-electric vehicle. It has the characteristics of both an electric vehicle and a conventional ICE vehicle and can be operated either on wall-plug electricity stored in a battery or from a liquid fuel (e.g., gasoline) obtained at a service station. Hybrid-electric vehicles can be designed that will operate only on wall-plug electricity most days for city commuting and yet offer the owner unlimited range without recharging the battery on those days when long distance travel (hundreds of miles) is needed. This type of hybrid-electric vehicle has all the advantages previously cited for the electric vehicle in city use for daily travel less than its battery range and could be marketed as a direct substitute for the conventional ICE vehicle to those consumers who feel they need an all-purpose vehicle. On those days that the hybrid-electric vehicle is operated on the battery alone, it is a zero emission vehicle and makes the maximum contribution to reducing air pollution in the urban area. On those days when the engine is operated to extend the range of the vehicle, the vehicle's exhaust emissions are not zero, but on an annual basis, as discussed later in the essay, the average emissions of the vehicle can be very low, much below that of ICE vehicles meeting the California Ultra Low Emissions Vehicle (ULEV) standards. Present hybrid-electric vehicle designs utilize a heat engine driven generator to convert a chemical fuel to electricity on-board the vehicle. Future designs can use a fuel cell rather than an engine to convert the chemical fuel to electricity. The fuel cell-powered vehicle would have lower emissions than the hybrid-electric vehicle with an engine.

A second type of hybrid-electric vehicle, which is more closely related to a conventional ICE vehicle, can be designed with the primary objective of significantly reducing the fuel consumption of the vehicle; in other words, to greatly increase its fuel economy. Such a vehicle must, of course, also meet or exceed the required exhaust emissions standards. The most stringent at the present time for ICE vehicles are the ULEV standards in California. These hybrid-electric vehicles would be powered by an electric motor, but all the electricity needed to power the vehicle would be generated on-board from a chemical fuel using either an engine or a fuel cell. In either case, a pulse power energy storage unit, such as a high power density battery or ultracapacitor, would be used to load level the engine or fuel cell permitting it to provide the average power needed to propel the vehicle in city and highway driving. Operating the engine or fuel cell at average power, rather than at highly varying transient powers as is the case in conventional ICE vehicles, results in a higher efficiency and thus lower energy consumption and higher fuel economy as well as lower emissions.

As noted in the previous discussion, hybrid vehicles can be designed with either minimum emissions or maximum fuel economy as the primary goal. Both emissions and fuel economy standards are available against which to compare the performance of particular vehicle designs. In the case of vehicle exhaust emissions, the most stringent standards (see Table 1) for the next ten years have been set by the California Air Resources Board (CARB). Standards are given for nonmethane organic gases (hydrocarbons HC), carbon monoxide (CO), and nitrogen oxide (NOx) emissions in terms of gm/mi on the Federal Urban Driving Schedule (FUDS). As shown in Table 1, CARB has defined several classes of vehicle emissions with the SULEV and Zero Emission Vehicle (ZEV) classes having the lowest emissions. Presently only electric vehicles satisfy the requirements for the ZEV class and hybrid-electric vehicles must meet the SULEV requirements, 0.01 gm/mi HC, 1.0 gm/mi CO, and 0.02 gm/mi NOx, when the vehicle is operated in the hybrid mode. It would be expected that the average annual emissions for hybrid-electric vehicles using significant wall-plug electricity would be well below the SULEV standards and the emissions from vehicles using fuel cells would be even lower than the emissions from battery-powered electric vehicles that are recharged using electricity from advanced generating powerplants. Only hybrid-electric vehicle designs that meet these extremely low emission standards should be considered for future development.

The energy consumption of passenger cars is expressed in terms of fuel economy (miles per gallon of gasoline equivalent). The fuel economy standard for auto manufacturers is set in terms of a Corporate Average Fuel Economy (CAFE) for all the new cars sold by the manufacturer in a given year. At the present time, the CAFE standard is 27.5 mpg for a combination of city and highway driving. There is currently a national debate as to whether and to what value the CAFE standard should be increased. The highest value that has been seriously considered is 40 mpg. Using conventional automotive driveline technologies, it will be difficult to reach the forty mpg value without a significant reduction in the weight of cars, which could have crash safety implications.

The fuel economy (composite of city and highway driving) of new cars in 1998 (Reference 1) varies from 40 to 45 mpg for subcompact cars to 25 to 30 mpg for full-size cars with the fleet average being about 28 mpg. There are strong indications that by using a hybrid-electric driveline the fuel economy of these same size cars can be nearly doubled to 85 and 50 mpg, respectively. The emissions from these vehicles could meet the SULEV standards or lower. The hybrid vehicles would likely use conventional ICE engines and gasoline as the fuel, but the engine would be much smaller (lower maximum power) and be loaded-leveled by the electric drive to increase its average operating efficiency and lower its emissions. In this way, a

CAFÉ standard in excess of 40 mpg could be met without a drastic downsizing of the size of cars and at the same time meet SULEV or more stringent emission standards.

Hybrid-Electric Vehicle Design Options

There are a large number of ways an electric motor, engine, generator, transmission, battery, and other energy storage devices can be arranged to make up a hybrid-electric driveline (Reference 2). However, most of them fall into one of two categories. These categories are the series and parallel configurations. In the series configuration (see Fig. 1), the battery and engine/generator act in series to provide the electrical energy to power the electric motor, which provides all the torque to the wheels of the vehicle. In a series hybrid, all the mechanical output of the engine is used by the generator to produce electricity to either power the vehicle or recharge the battery. In the parallel configuration (see Fig. 2), the engine and the electric motor act in parallel to provide torque to the wheels of the vehicle. In the parallel hybrid, the mechanical output of the engine can be used to both power the vehicle directly and to recharge the battery or other storage devices using the motor as a generator. In recent years, a third type of hybrid configuration, the dual mode, is being developed that is a combination of the series and hybrid configurations. As shown in Figure 3, the engine output can be split to drive the wheels (parallel mode) and to power a generator to produce electricity (series mode). The dual mode configuration is the most flexible and efficient of the hybrid configurations being developed, but it is also likely to be the most complex and costly.

A range-extended electric vehicle would most likely use the series configuration if the design is intended to minimize annual urban emissions. It would be designed for full-performance on the electric drive alone. The series hybrid vehicle can be operated on battery power alone up to its all-electric range with no sacrifice in performance. (acceleration or top speed) and all the energy to power the vehicle would come from the wall-plug. This type of hybrid vehicle is often referred to as a "California hybrid" as it most closely meets the ZEV requirement for most of its use. The engine would be used only on those days when the vehicle is driven long distances.

Hybrid vehicles designed to maximize fuel economy in an all-purpose vehicle could use the series, parallel, or dual configurations depending on the characteristics of the engine to be used and acceptable complexity of the driveline and its control. In general, parallel hybrid configurations will require frequent on-off operation of the engine, mechanical components to combine the engine and motor torque, and complex control algorithms to smoothly blend the engine and motor outputs as needed to power the vehicle efficiently. The parallel hybrid would likely be designed so that its acceleration performance would be less than optimum on either the electric motor or engine alone and require the use of both drive components together to have the desired fast acceleration characteristics (zero to sixty mph in 10-12 seconds). Such a hybrid vehicle would not function as a ZEV in urban/freeway driving unless the driver was willing to accept reduced acceleration performance. It is likely, however, that the parallel configuration can be designed to be more efficient (yield higher fuel economy) that the series configuration. A fuel cell hybrid vehicle would necessarily be a series hybrid as the fuel cell produces only electricity and no mechanical output. The dual mode hybrid is intended to maximize fuel economy and thus be designed like a parallel hybrid, but with a relatively small generator that could be powered by the engine when desired. The engine in the dual mode hybrid would operate in the on/off mode, but be cycled on and off less frequently than in the parallel configuration.

History and Present (CA 1998) Activities

The first hybrid vehicles were built in the early 1900s during the period of transition between the popular electric vehicles of those days and the newly developing engine-powered, gasoline-fueled vehicles coming on to the scene. As the gasoline-fueled vehicles became more reliable and fuel was more readily available, there was no need for the electric driveline and the conventional engine-powered vehicle as we know it came to completely dominate the vehicle market. Research and development (R&D) on hybrid vehicles was revived in the 1970s as a result of the oil crisis of the period. The hybrid vehicle was seen as a way of using electricity generated from non-petroleum sources to meet a significant fraction of the country's transportation needs. More recently (the 1990s), the hybrid vehicle is seen as a way to reduce the emissions from cars in urban areas by extending the range of electric vehicles-thereby making electric vehicles more marketable in large numbers.

Before 1990, most of the R&D on hybrid vehicles was funded by the United States Department of Energy (DOE), but some privately funded work was done by automobile companies in the United States, Europe, and Japan. Except for Volkswagon, no automobile company seriously considered marketing a hybrid vehicle, because of the relatively low cost of gasoline and the expected high cost of the hybrid vehicle. The work in the period 1975 to 1990 did, however, indicate the technical feasibility of designing and building hybrid vehicles that would be attractive from a performance point of view to the motoring public and thus lead to the high level of work on hybrid vehicles in the 1990s.

The main driving forces for the work on hybrid vehicles in the 1990s were the EV Mandate in California and the establishment of the Partnership for a New Generation of Vehicles (PNGV) by the Clinton administration in the United States. As a result of the EV Mandate, the large automotive companies spent considerable resources on electric drivelines and batteries and became convinced that the range limitations and the high cost of batteries would make marketing battery-powered electric vehicles in large quantities difficult. The auto companies began to propose hybrid/electric vehicles with relatively small electric range (much less than 20 miles) as an alternative to EVs and hoped that California would give such vehicles EV credits (see Table 2). In that way, the auto companies felt they could more easily satisfy the EV Mandate for 10 percent of the sales in 2003. The Clinton administration created in 1993 the PNGV program with the expressed aim of keeping the US auto industry competitive with the auto industries in Japan and Europe as the companies in those countries develop new technologies to reduce greenhouse gases from passenger cars. The goal of the PNGV program was to develop passenger cars that had three-times (80 mpg) the fuel economy of cars currently being marketed. Studies by the auto industry and others indicated that in addition to a significant weight reduction, the use of a hybrid/electric driveline was needed to reach that fuel economy goal using conventional gasoline and diesel engines and, of course, electric drivelines are needed to utilize fuel cells. Hence, all the auto companies worldwide established hybrid vehicle programs that by the year 2000 will be producing prototype hybrid vehicles that are nearly ready for marketing (Toyota and Honda) or being displayed as concept cars in the annual auto shows. In addition, the US Department of Energy (DOE) and the Society of Automobile Engineers (SAE) established an annual competition between selected colleges and Universities in North America for the design, fabrication, and testing of hybrid vehicles intended to reach the 80 mpg target of the PNGV program. These college competitions were known as the HEV Challenge (1994-96) and the

Future Car Challenge (1997-1999). Thus in the late 1990s, there have been many prototype hybrid vehicles built even if only the Toyota Prius in Japan (1997) has been sold or leased to consumers. Photographs of some of the recent hybrid vehicles are shown in Figures 4 through 7. The characteristics of these and many other vehicles are given in Table 3. It seems likely that before 2005 most automobile companies will be marketing hybrid vehicles in order to reduce emissions and to increase fuel economy.

Component Technologies: Status and Prospects

Motor and Electronics

Recent advances in both motor and inverter electronics technologies have important implications for the design of high performance hybrid vehicles. The characteristics of state-of-the-art (1998) components are shown in Table 4. The size and weight of the motor and the electronics combined are now significantly smaller (by a factor of two to three – see Table 8 for engine characteristics) than that of an engine and transmission of the same peak power. The size advantage of the electrical components will be even larger as the operating voltage of the electrical drive system is increased above the 300-400V that is common today. This means that in packaging the hybrid driveline under the hood of a vehicle, the electric drive components take up only a small fraction of the space available and finding room for the mechanical components, such as the engine, transmission or torque coupler, can present a difficult challenge.

Electrical Energy Storage

The key component in the hybrid driveline that permits it to operate more efficiently than the engine/transmission in a conventional car is the electrical energy storage unit. It must store sufficient energy (kWh) to provide the all-electric range of the vehicle or to permit the engine or fuel cell to operate near the average power required by the vehicle (in a load-leveled mode). It must also have sufficient power capability to meet on demand the peak power of the motor/electronics for vehicle acceleration or regenerative braking. In most cases, the energy storage unit in a hybrid vehicle is sized by the peak power requirement. Since the size (weight and volume) of the energy storage unit (often a battery) in the hybrid vehicle is smaller than the battery in a battery-powered electric vehicle (EV), the power density (W/kg and W/liter) requirements of the energy storage unit in the hybrid vehicle are greater than for the battery in an electric vehicle. For example, power densities of 200-300W/kg are satisfactory for use in an EV, but power densities of 500-1000W/kg are needed for hybrid vehicles. As indicated in Table 5, considerable progress has been made in the development of high power batteries (often referred to as pulse batteries) of various types. In hybrid vehicles, the energy density of the energy storage unit is usually of secondary importance and compromises in energy density have been made to reach the high power density of pulse batteries. For example, nickel metal hydride batteries designed for EVs have an energy density of 70Wh/kg and a power density of 250 W/kg, while those designed for hybrid vehicles have an energy density of 40-45Wh/kg and a peak power density of 600-700W/kg. Another important consideration for energy storage units for use in hybrid vehicles is the need to minimize the losses associated with transferring energy into and out of the unit, because in the hybrid, a reasonable fraction of the electrical energy produced onboard the vehicle is stored before it is used to power the vehicle. In order to minimize the energy storage losses, the round-trip efficiency (energy out/energy in) should be at least 90 percent. This means that the useable peak power capability of the energy storage unit is much less that its peak power density at which the efficiency of the transfer is less than 50 percent. From Table 7, it is seen that the useable power is only about 20 percent of the peak power capacity. This is another reason that the design of energy storage units for hybrid vehicles is much more difficult than for pure electric vehicles and energy storage technology is often described as the enabling technology for hybrid vehicles.

A new energy storage technology that is well suited for hybrid vehicles is the electrochemical ultracapacitor – often referred to as the double-layer capacitor. As shown in Figure 8, the construction of an ultracapacitor is much like a battery in that it consists of two electrodes, a separator, and is filled with an electrolyte. Unlike a battery the two electrodes are identical and there is no chemical reaction between the active material and the electrolyte. The electrodes have very high surface area (1000-1500 m2/gm) with much of the surface area in micropores of diameter 20 Angstroms or less. The energy is stored in the double-layer (charge separation) formed in the micropores of the electrode material. Most of the ultracapacitors presently available (1998) use activated carbon as the electrode material. Photographs of several ultracapacitors are shown in Figure 9. The cell voltage is primarily dependent on the electrolyte used. If the electrolyte is aqueous (sulfuric acid or KOH) the maximum cell voltage is 1V; if an organic electrolyte (propylene carbonate) is used, the maximum cell voltage is 3V. As in the case of batteries, high voltage units (300-400V) can be assembled by placing many ultracapacitor cells in series. Ultracapacitors for vehicle applications have been under development since about 1990. A discussion of the various technologies being developed is given in Reference 3. A summary of the current (1998) status of the technology is shown in Table 6. Comparing Table 5 for batteries and Table 7 for ultracapacitors, it is seen that batteries have much higher energy density and capacitors have much higher power capacity. Hence the technical challenge for developing ultracapacitors for vehicle applications is to increase the energy density (Wh/kg and Wh/liter) to a sufficiently high value that the weight and volume of a pack to store the required energy (500 Wh for a passenger car) is small enough to be packaged in the vehicle. Power density and cycle life is usually not a problem with ultracapacitors. The cost ($/Wh) of ultracapacitors is presently too high – being about $100/Wh – and it must be reduced by at least an order of magnitude (a factor of 10) before this new technology is used in passenger cars. Nevertheless, ultracapacitors are a promising new technology for electrical energy storage in hybrid vehicles.

Engines and Auxiliary Power Units

The characteristics of engines for hybrid vehicles are shown in Table 8. Most of the hybrid vehicles designed and built have used four stroke gasoline or diesel engines. Nearly all gasoline engines are now fuel-injected and both gasoline and diesel engines are computer controlled. Continuing improvements are being made in these engines in terms of size, weight, efficiency, and emissions. These improvements and the common use of computer control make it fairly easy to adapt the conventional engines to hybrid vehicle applications. The major difficulty in this regard is to find an engine of the appropriate power rating for the hybrid vehicle application. Most automotive engines have power of 55kW (75hp) and greater, which is too large for use in most hybrid vehicle designs. Experience has shown that good sources of engines for hybrid vehicles are the minicars designed for the small car markets in Japan and Europe.

There have been several advanced engines developed especially for hybrid vehicles. These include a high-expansion ratio gasoline engine (Atkinson cycle) developed by Toyota (Reference 4) for their Prius hybrid vehicle which they started to market in Japan in 1997. Stirling Thermal Motors (STM) under contract to General Motors (GM) designed and fabricated a Stirling engine (30kW) for use on GM's series hybrid vehicle built as part of the US DOE hybrid vehicle program (Reference 5). Capstone Technology developed a 25kW recuperative gas turbine engine (Reference 6) for use in a flywheel hybrid vehicle built by Rosen Motors (Reference 7). The characteristics of these engines are indicated in Table 8. The most successful of these engine development projects was the Prius engine of Toyota. The other two engines were found to be too large and did not have sufficiently high efficiency to warrant their further development for hybrid vehicle applications. The new Toyota engine in the Prius is a four cylinder (1.5 liter), four stroke gasoline engine that utilizes variable inlet valve timing to vary the effective compression ratio from 9.3 to 4.8 in an engine having a mechanical compression ratio of 13.5. Varying the effective volume of air during the intake stroke permits operation of the engine at part load with reduced pumping and throttling losses. This results in a higher engine efficiency. The expansion ratio at all times is set by the high mechanical compression ratio of the engine. This new engine was optimized for operation in the hybrid mode and had a brake specific fuel consumption of about 235 gm/kWh for output powers between 10 and 40kW. This corresponds to an efficiency of 37 percent, which is very high for a four stroke gasoline engine. In terms of size and weight, the Prius engine is equivalent to a conventional engine of the same peak power rating.

The engine output in a hybrid vehicle can be utilized to generate electricity on board the vehicle or to provide torque to the driveshaft of the vehicle. In the first case, the engine output torque drives a generator and the combination of the engine and the generator is termed an auxiliary power unit (APU). The generator can be either an AC induction or a brushless DC permanent magnet machine. The size of the generator for a given power rating depends to a large extent on the voltage of the system and the RPM at which the generator rotates. For a 400V system and a maximum RPM of 8000-10000, the size and weight of the APU are 0.7kg/kW and 0.8 liter/kW, respectively, including the electronic controls. The efficiency of the generator system will vary between 90 to 95 percent depending on the power output. The losses associated with the production and storage of the electrical energy onboard the vehicle as in a series hybrid are significant (10 to 20%) and can not be neglected in predicting the fuel economy of the vehicle.

Mechanical Components

The transmission, clutch, and other mechanical components needed in a hybrid vehicle to combine the output of the engine with the electric motor and generator and the main driveshaft of the vehicle are critical to the efficient and smooth operation of parallel and dual mode hybrid vehicles. The design of these components is relatively straightforward and not much different than that for similar components for conventional engine-powered vehicles. In a parallel hybrid (see Figure 2), the engine torque is connected to the drive shaft through a clutch that opens and closes as the engine power is needed. The speed ratio between the engine and the wheels is determined by the gear ratios in the transmission. Mechanical design of the engine clutch such that it has a long life and smooth operation is one of the critical tasks in the development of a parallel hybrid vehicle. Many hybrid vehicles are built with manual transmissions, because automatic transmissions with a torque converter have unacceptably high losses. A recent development is the use of a continuously variable transmission (CVT) in a parallel hybrid driveline (References 8, 9). The operation of the CVT is like an automatic transmission from the driver's point-of-view with the advantages of lower losses and a wider range of continuous gear ratios, which result in efficient driveline operation in both the electric and hybrid modes. The disadvantages of the CVT are that control of the system is more difficult than with a manual transmission and the steel belt used in the CVT is much less tolerant of abuse (sudden changes in speed and torque). Nevertheless, it appears that in future years CVTs will have application in parallel hybrid drivelines.

There are several arrangements of the dual mode hybrid driveline. In the simplest (see Figure 3), the generator can be used as a motor to start the engine and/or to supplemental torque of the traction motor to drive the vehicle. In this dual mode configuration, the batteries can be recharged either by the generator or by the traction motor acting as a generator. This simple dual mode system does not require a transmission. A second dual mode system (Figure 10) utilizes a planetary gear set to couple the engine, generator, and main driveshaft. In this arrangement, the speed ratio between the engine and main driveshaft depends on the fraction of the engine power that is applied to the generator. This second arrangement is used by Toyota in the Prius hybrid car. This system is less flexible and likely is less efficient than the first system in which the engine and generator are directly connected on the same shaft, but it does not require a clutch, which must be opened/closed smoothly and reliably under computer control. Operation of the Toyota dual mode hybrid driveline has proven to be smooth and reasonably efficient in practice (Reference 10).

Fuel Cells

Fuel cells can be utilized in electric-hybrid vehicles as the means of converting chemical fuel to electricity on-board. Rapid progress (References 11, 12) has been made in the development of fuel cells, especially Proton Exchange Membrane (PEM) fuel cells, for transportation applications. This progress (see Table 9) has resulted in a large reduction in the size and weight of the fuel cell stack and as a result, there is now little doubt that a fuel cell of the required power (20-50kW) can be packaged under the hood of a passenger car. The primary question regarding fuel cells in light duty vehicles is presently how they will be fueled. The simplest approach is to use high pressure hydrogen as has been done in the most successful bus demonstrations to date (Reference 13). This approach is satisfactory for small test and demonstration programs, but since the development of the infrastructure for using hydrogen as a fuel in transportation is likely to be many years in the future, considerable work (References 14, 15) is underway to develop fuel processors (reformers) to generate hydrogen on-board the vehicle from various chemical fuels (ex. methanol or hydrocarbon distillates). Most of the hydrogen used for industrial and transportation applications is presently generated by reforming natural gas using well developed technology. A promising approach to fuel processing to hydrogen (H^+ and electrons) on-board the vehicle is direct oxidation of methanol within the fuel cell stack itself (References 16, 17). When technology for the efficient, direct conversion of a liquid fuel to hydrogen within the PEM fuel cell is developed, the commercialization of fuel cells in light duty vehicles is likely to occur rapidly.

Control Strategies

Control Strategies for Series Hybrid Vehicles

In general, the intent of the control strategy is to maintain the state-of-charge of the energy storage unit within a prescribed range regardless of the driving cycle and the resultant power demand on the driveline. This should be done such that the on-board electrical generator (engine/generator or fuel cell) is operated at high efficiency and low emissions. This is done more easily when the energy storage capacity is reasonably large as with a battery than when it is small as using ultracapacitors. The strategy used for vehicles having a significant all-electric range is to discharge the battery to a prescribed state-of-charge (20 to 30%) and then to turn-on the engine to maintain the battery within 10 to 20 percent of that condition. Electrical energy is generated at a rate slightly greater than the average power demand of the vehicle to account for losses associated with storing the energy. In the case of an engine/generator, a minimum power level is set such that the engine is never operated below it. Proper selection of this minimum power can have an important effect on fuel economy. When the battery charge reaches the maximum permitted, the engine is turned off and it remains off until the battery state-of-charge falls to the engine turn on state-of-charge. When the series hybrid is operated such that the battery is permitted to discharge to a relatively low state-of-charge, it is termed a **charge depleting** hybrid. If the battery is maintained at a high state-of-charge (80%), it is termed a **charge sustaining** hybrid and the battery is seldom, if ever, recharged from the wall-plug. A significant fraction of the energy used by **charge depleting hybrid vehicles** is from the wall-plug and their average annual emissions and energy consumption are dependent on use pattern of the vehicle and how the electricity used to recharge the batteries is generated.

Control Strategies for Parallel Hybrid Vehicles

The control strategies for parallel hybrid vehicles are more complicated than those for series hybrids primarily because they are dependent on both vehicle speed and energy storage unit state-of-charge and should include a criteria for splitting the driveline torque between the engine and the electric motor. In general, the intent of the strategy is to permit the electric motor to provide the torque if it can at vehicle speeds below a prescribed value and permit the engine to provide the torque at higher speeds. If the vehicle is operating in the all-electric mode, the motor provides the torque and the engine is not turned on regardless of the torque demand or vehicle speed. Since the all-electric range of a hybrid vehicle is usually less than 80 km, operation of the vehicle should change automatically to the hybrid mode when the all-electric range is exceeded. The control strategy in the hybrid mode can be either **charge sustaining** or **charge depleting**. In the case of **charge sustaining**, the battery state-of-charge is maintained at a near constant value by a control strategy using electrical energy produced by the engine and the motor acting as a generator and consequently little electrical energy is used from the wall-plug. For the **charge depleting** case, the control strategy permits the battery state-of-charge to decrease as the vehicle is driven and the battery is then recharged from the wall-plug at night. Parallel hybrids usually have a multi-speed transmission so the control strategy must also include a gear shifting algorithm that depends on whether the motor or engine or both are producing torque. A continuously variable transmission (CVT) would be particularly attractive for use in a parallel hybrid driveline (Reference 18).

In order to achieve high fuel economy with a parallel hybrid, it is necessary to avoid engine operation below some minimum engine torque (or effective throttle setting) where the engine brake specific fuel consumption(gm/kWh) is relatively high and to manage engine turn on and off carefully to minimize emissions and wasted fuel. In urban driving (such as on the Federal Urban Driving Schedule), the control strategies for parallel hybrids often result in the engine being turned on and off frequently as the vehicle speed and power demands vary rapidly in stop-and-go driving. The effects of this on-off engine operation on fuel usage and emissions for the parallel hybrids are neglected in most simulations at the present time, so further analysis and vehicle testing is needed to determine whether the high fuel economy and low emissions projected for parallel hybrids can be attained in practice for actual vehicles having good driveability.. The control strategies for parallel hybrids are necessarily more complex than those for series hybrids and the uncertainty in the simulation results for parallel hybrids are greater.

Control Strategies for Dual Mode Hybrid Vehicles

In general, the control strategies for dual mode hybrid vehicles are a combination of those used for series and parallel hybrids. Since there are so many possible hardware arrangements and associated control strategies, it is not possible to summarize them in a simple manner as was the case for series and parallel hybrids. The objective of the dual mode operation is to use the possibility of battery charging simultaneously with the use of the engine and electric motor to power the vehicle as a means of maintaining engine operation at high efficiency at all times. At highway speeds, the engine can be used directly to power the vehicle with the engine operating at high efficiency. This mode of operation is essentially that of a parallel hybrid. At low vehicle speeds, when the battery does not need charging (that is state-of-charge greater than a specified value), the driveline would operate in an electric only mode if the electric motor can provide the power required by the vehicle. If the power demand is greater than that available from the electric motor, the engine is turned on to assist the electric motor. At low speeds when the battery requires charging, the engine output is split between powering the generator and the vehicle. The possibility of splitting the engine output in this way at low vehicle speeds is the distinguishing feature of the dual mode hybrid configuration. In principle, this permits the engine to be operated near its maximum efficiency at all times and the battery to be recharged when needed regardless of the vehicle speed and power demand. The dual mode arrangement also reduces the need for on/off engine operation as required in the series and parallel control strategies. Dual mode hybrids are operated with the battery state-of-charge maintained in a narrow range **(charge sustaining)** and thus require no recharging of the battery from the wall-plug. The Toyota Prius hybrid vehicle uses this dual mode operating strategy.

Performance of Hybrid Vehicles

The added complexity of the various hybrid vehicle designs relative to battery-powered electric vehicles and conventional engine-powered vehicles is evident. In order to justify this added complexity, hybrid vehicles must be more marketable than pure electric vehicles and have higher fuel economy and lower emissions than conventional engine-powered vehicles. The performance (acceleration, range and refueling time, fuel economy, and emissions) of the different vehicle design options are compared in this section as the first step in comparing their relative attractiveness to potential purchasers. All the vehicle types (electric, hybrid, and conventional) can be designed to have the same acceleration performance and top speed by the proper selection of the driveline components. Acceleration times of 0-100 km/hr in less than 8 seconds and top speeds in excess of 120 km/hr for passenger cars have been demonstrated for both pure electric and hybrid vehicles. It is also true that range and refueling time (time to recharge the battery) are a clear disadvantage of pure electric vehicles. The range of an electric vehicle with a practical size and cost of battery is probably limited to 325 km (200 miles) even with advanced lithium batteries (150Wh/kg) and except with special fast charging equipment and battery thermal management systems, the time to recharge the battery would be several hours compared to several minutes to fill the gasoline tank in a conventional engine-powered vehicle. The primary advantage of the hybrid vehicle compared to the electric vehicle is that its range and refueling time can be the same or better than the conventional vehicle because it is refueled in the same manner – at the fuel pump. Hence the key comparisons of interest are the fuel economy and emissions of hybrid and conventional vehicles. As of 1999, there is very limited test data available for fuel economy and emissions of hybrid vehicles so most comparisons will be made based on computer simulation results.

A recent detailed study of the fuel economy and emissions of series and parallel hybrid vehicles using a wide range of component technologies is summarized in Reference 19. Most of the results cited in this report are taken from that reference. Computer simulations were performed for both mid-size and compact, light-weight vehicle designs for driving on the Federal Urban Driving Schedule (FUDS) and the Federal Highway Driving Schedule (FHWDS). These driving cycles (speed vs. time) are intended to simulate vehicle operation in city and highway driving, respectively. The characteristics of the two vehicle types studied are shown in Table 10. For each vehicle type, computer simulations were run using gasoline fuel injected engines, diesel engines, and Stirling engines. Electricity was generated on board the hybrid vehicles by coupling the engines to a generator or by utilizing a fuel cell fueled using compressed hydrogen. In all cases, electrical energy was recovered into the energy storage unit during braking using the traction motor as a generator. The control strategies used in the simulations were essentially those previously discussed in the Section on **Control Strategies.** In all cases, the engines and fuel cell were operated in an on/off mode to maintain the energy storage unit in the state-of-charge range specified by the control strategy. The minimum power setting of the engines and fuel cell when they were "on" were set so their efficiency was near the maximum value.

Fuel Economy

Fuel economy simulation results for various engines in series hybrids are compared in Table 11 for the FUDS and FHWDS driving cycles. For both the mid-size and compact cars, fuel economy depends significantly on the technology used in the driveline. The use of diesel engines results in the highest fuel economy (miles per gallon of diesel fuel); however, from the energy consumption (kJ/mi) and CO2 emission (gm CO2/mi) points-of-view, the advantage of diesel engine relative to gasoline-fueled engines should be discounted to reflect the higher energy and the carbon content per gallon of diesel fuel compared to gasoline. These discount factors are 15 to 20 percent. The simulation results also indicate that for the same type of engine, the fuel economy can be 10 to 20 percent higher using ultracapacitors in place of batteries as the energy storage device. The highest fuel economics are projected for vehicles using fuel cells. The fuel economies (gasoline equivalent) of the fuel cell vehicles using compressed hydrogen are about twice those of hybrid vehicles with direct injected gasoline engines and about 80 percent higher than vehicles with diesel engines. All the fuel cell vehicle designs utilized a fuel cell load-leveled with a nickel metal hydride battery permitting it to operate at high efficiency at all times.

Comparisons between the fuel economies of conventional passenger cars and those using series hybrid drivelines are shown in Table 12. The hybrid vehicles have the same weight and road load as the conventional cars. The utilization of the hybrid driveline resulted in about a 50 percent improvement in fuel economy for the FUDS cycle and about a 10 percent improvement on the FHWDS (highway cycle)

The fuel economy of the conventional cars was taken from the EPA Fuel Economy Guide (Reference 1) corrected by 10 percent for the FUDS and 22 percent for the highway cycle. These corrections were made, because the actual dynamometer fuel economy test data had been reduced by those factors in order that the published fuel economies would be in better agreement with values experienced in real world use of the vehicles. The small improvement on the highway cycle relative to FUDS cycle is due to the higher average power on the highway cycle and the lack of opportunity for energy recovery in regenerative braking on that cycle. Comparing the fuel economy results in Table 11 for port injected gasoline engines with those in Table 12, one can conclude that for the FUDS cycle most (about 75%) of the fuel economy improvement is due to the use of the hybrid driveline not the reduction in road load of the hybrid vehicles, but that on the highway cycle, most of the fuel economy improvement of the hybrid vehicle is due to the reduced road load.

The fuel economy of series and parallel hybrid vehicles are compared in Table 13 for both the compact, lightweight and mid-size cars. The series hybrids are assumed to operate only in the **charge sustaining** mode (no battery recharging from the wall plug), but the parallel hybrids can operate in either the **charge sustaining** or **charge depleting** mode. In the case of the parallel hybrid in the **charge depleting** mode, the fuel economy is given for gasoline alone and at the powerplant including energy needed to recharge the batteries from the wall-plug. For hybrid vehicles using gasoline engines (port injected), the fuel economy of the parallel hybrid vehicles in the **charge sustaining** mode (batteries charged from the engine - not from the wall plug) is 9 to 12 percent higher than that of the series hybrids; for the powerplant efficiency (33%) assumed in the calculations, the parallel hybrids operating in the **charge depleting** mode (battery charged only from the wall plug) had only 1 to 4 percent higher equivalent fuel economy that the same vehicle operating in the **charge sustaining** mode. If the batteries were recharged using electricity from a higher efficiency powerplant, the fuel economy advantage of the parallel hybrid in the **charge depleting** mode would be higher. For hybrid vehicles using the swirl chamber diesel engine, the differences in the fuel economy of series and parallel hybrids are smaller than for vehicles using gasoline engines; the differences between parallel hybrids in the **charge sustaining** and **charge depleting** modes are also smaller using the diesel engine (see Table 13). These differences between the gasoline and diesel engine results are due to the higher efficiency of the diesel engine (closer to the powerplant efficiency) and the smaller variation of the efficiency of the diesel engine with output power. In terms of the effect of driveline configuration and operating mode on fuel economy, the advanced engines can be expected to be like the diesel engine,

Full Fuel Cycle Emissions

The full fuel cycle emissions of the hybrid vehicles are the total of all the emissions associated with the operation of the vehicle and the production, distribution, and dispensing of the fuel and electricity to the vehicle. The total emissions can be calculated for all the vehicle designs utilizing as inputs the vehicle simulation results for the electricity consumption, fuel economy, and exhaust emissions in the all-electric and hybrid modes and the upstream refueling, evaporative, and fuel production emissions based on energy usage – both fuel and electricity. Both regulated emissions (NMOG, CO, NOx) and CO2 emissions can be calculated.

Regulated Emissions

The total NMOG, CO, and NOx emissions for the FUDS and FUDSWAY driving cycles are given in Table 14 for **charge depleting** and **charge sustaining** operation of the various hybrid vehicle designs. Results are also shown for electric vehicles and conventional ICE vehicles for comparison with those for the hybrid vehicles. The results shown in the tables are for a baseline use pattern of 7500 miles per year random travel and a round-trip to work of 15 miles. Hybrid vehicles operated in the **charge depleting** mode (battery charged from the wall plug) have total emissions comparable to those of electric vehicles if their all-electric range is fifty miles or greater. Hybrid vehicles operating in the **charge sustaining** mode have much greater NMOG emissions than electric vehicles when the refueling and evaporative emissions are included. The calculated total emissions of the electric vehicles are close to the California EZEV standards when the battery charging is done in the LA basin.

Hybrid vehicles in the **charge sustaining** mode that use gasoline engines can have total emissions at or near ULEV standards if the refueling and evaporative emissions are zero, but much above the EZEV standard. Hybrid vehicles operating in the **charge sustaining** mode using diesel engines have NMOG (excluding refueling and evaporative emissions) and CO emissions at or below ULEV, but their NOx emissions are well above ULEV primarily because of the relatively low conversion efficiency of their catalyst for NOx.

Total emission results are also shown in Table 14 for fuel cells using hydrogen produced by reforming natural gas. All the emissions are due to the production of the hydrogen, because the regulated exhaust emissions from the fuel cell powered vehicles are zero. The total NMOG and NOx emissions shown are close to the SULEV standards or lower. These emissions are based on the hydrogen production emissions of 9.5 gm NMOG/GJ H2 and 8.6 gm NOx/GJ H2. There is considerable uncertainty regarding the hydrogen production emissions as they depend on the technology used and the scale of the production plant.

Total CO2 Emissions

The total CO2 emissions (gm/mi) for the various vehicle designs, including conventional gasoline engine powered (ICE) and electric (EV) vehicles, are shown in Table 15 for both **charge depleting** and **charge sustaining** operation of the hybrid vehicles. The all-electric range of the **charge depleting** hybrid vehicles is 60 miles. The range of the electric vehicles is 80-120 miles. All the vehicles are operated on the baseline use-pattern (7500 miles random miles and a 15 mile round-trip to work). The results in Table 15 indicate that the difference in the CO2 emissions between operating a hybrid vehicle in **charge depleting** and **charge sustaining** modes, regardless of its all-electric range, is not large using nickel metal hydride batteries. This was not the case for the regulated emissions which were lower when the hybrid vehicle was operated in the **charge depleting** mode. The CO2 emissions of the gasoline and diesel engine powered hybrids do not vary (only about 25%) as much as might be expected based on the differences in their fuel economies, because of the higher energy content and the higher carbon to hydrogen ratio of the diesel fuel. The CO2 emissions in the **charge depleting** mode depend primarily on the all-electric range of the hybrid and the type of batteries used.

The CO2 emissions for fuel cell powered, electric, and ICE powered vehicles are also shown in Table 15. The fuel cell powered, hydrogen fueled vehicles are projected to have the lowest CO2 emissions by 25 to 30 percent when compared to the most efficient of the engine powered vehicles even when the hydrogen is produced by reforming natural gas. The CO2 emissions of the conventional ICE vehicles are directly proportional to their fuel economy, which is projected to be significantly less than the hybrid vehicles. ICE powered vehicles will have low CO2 emissions only when their fuel economy is greatly increased. The CO2 emissions of the electric vehicles are dependent on the type of battery used, but can be expected to be comparable to the engine powered hybrids, but significantly higher than the fuel cell powered vehicles. For electric vehicles, careful attention must be given both to the energy consumption at the battery (vehicle road load and driveline efficiency) and battery recharging efficiency (battery overcharge and charger efficiency) to achieve low CO2 emissions. In general, the results shown in Table 15 indicate that the CO2 emissions of vehicles are highly depended on the technologies used to power them and can vary by a factor of at least two for the same size and weight of vehicle. The CO2 emissions factor used for hydrogen production from natural gas was 110 kg CO2/GJH2.

Testing of Hybrid Vehicles

Testing of hybrid vehicles to determine their fuel economy and emissions is different from testing conventional engine-powered vehicles because the hybrid vehicles have an electrical storage unit on-board that can be charged and discharged during the test. The energy storage unit is not usually at the same state-of-charge at the beginning and end of the test, which can have a significant effect on the measured fuel economy and emissions. For example, if the energy storage unit experienced a net discharge during the test, the measured fuel economy would be higher than would have been the case if there had been no change in the state-of-charge of the unit. Much of the work (Reference 20) to establish test procedures for hybrid vehicles has dealt with how to properly correct the measured data for any change in the state-of charge of the on-board energy storage unit that occurred during the test.

There have been relatively few tests of hybrid vehicles in recent years (1990s). One example of such tests is that of the Toyota Prius by the United States EPA (Reference 21). Special care was taken in those tests to account for changes in the net state-of-charge of the batteries on the vehicle. The test results for the Prius are summarized in Table 16. Also shown in the table are computer simulation results for fuel economy of the Prius on the FUDS and Highway test cycles. The simulation results were obtained at UC Davis using the same hybrid vehicle simulation program used to obtain the fuel economy projections given in Table 11. Note that there is good agreement between the measured and calculated fuel economies for the Prius. The EPA emissions data indicate that the CO and NOx emissions of the Prius are well below the California ULEV standards and that the NMHC emissions are only slightly higher than the 0.04 gm/mi ULEV standard for HC. Table 15 also indicates that the fuel economy of the Prius on the FUDS cycle (in city driving) is 56 percent higher than a 1998 Corolla (equipped with a 4-speed lockup automatic transmission) and 11 percent higher for highway driving. These improvements in fuel economy for a hybrid/electric car compared to a conventional ICD car of the same size are consistent with those discussed earlier in the Section on **Fuel Economy**.

Regulatory Considerations

Technologies have been and are being developed that permit the design of hybrid-electric vehicles that have much lower total emissions of both regulated pollutants and CO2 than present passenger cars. When vehicles utilizing these technologies will be marketed depends both on consumer demand and government incentives and regulations. There is little doubt that consumers would welcome vehicles with double the present fuel economy and much lower air quality related emissions, but bringing such vehicles to the market at costs comparable to current prices will require very large investments by the auto industry. These investments are not likely to occur in the foreseeable future without government regulations that require much higher fuel economy than needed to meet the present CAFE standard of 27.5 mpg. The state of California has low emission standards (ULEV) in place and is considering even tighter standards (SULEV) for the future. Recent advances in emission control technologies for engines seem to indicate that even SULEV exhaust emission standards can be met with ICE powered cars, especially those using gasoline engines. These cars would likely have CO2 emissions essentially the same as present cars unless diesel engine technology is developed that can meet the ultra-clean emission standards. Hence it does not appear that tighter regulated emission standards will be the driving force for the introduction of the hybrid-electric technologies. The driving force for their introduction will be a significantly higher CAFÉ standard and/or a significantly higher fuel price either due to an increase in the cost of oil or a higher fuel tax.

Costs of Hybrid Vehicles and Marketing Strategies

The societal advantages of the hybrid-electric vehicles will come to fruition only when they are marketed on a large scale. This can occur only when a significant fraction of vehicle purchasers decide to buy one of them. This will occur if the purchase of the hybrid vehicles makes economic sense to them and the vehicle meets their needs. Otherwise vehicle buyers will continue to purchase conventional ICE -powered vehicles. The key to any workable marketing strategy is the availability of hybrid driveline technologies that make the transition from engine-based to electric-based drivelines manageable and attractive to the consumer with only modest financial incentives. The state of development of the new driveline technologies at the time of introduction must be such that vehicles meet the needs of the first owners and they find the vehicles to be reliable and cost-effective to operate. Otherwise the market for the new technologies will not increase and the introduction of the new technologies at that time will be counterproductive. Even after the technical and economic feasibility of a new technology is shown in prototype vehicles, a large financial commitment by industrial companies is needed to perform the preproduction engineering and testing of the vehicles before the vehicles can be introduced for sale.

Electric vehicles in California in 1998-99 are in a limited-production phase of introduction with several car manufacturers offering to lease to the public three hundred to six hundred vehicles over a three year period. The vehicles are well engineered and reliable, but the lease rates ($400-$600 per month) are high and the response of the public has been less than enthusiastic for that reason. Starting in the fall of 1997, Toyota offered for sale in Japan the Prius Hybrid at a price close to that of the comparable conventional car (Reference 22). The initial response of the public was enthusiastic and the production rate quickly rose to more than one thousand vehicles per month. Toyota is planning to introduce a redesigned Prius in the United States in the fall of 2000. Honda has announced (Reference 23) that they will offer for sale a subcompact hybrid/electric car in the United States in the fall of 1999 at a price of less than $20,000, which is only several thousand dollars higher than the Honda Civic. The fuel economy of the Honda hybrid car is expected to be 70-75 mpg.

During 1998-99, there have been a number of announcements (References 24) by auto companies in the United States, Europe, and Japan that they intend to start limited production of fuel cell powered electric cars by 2004. No prices for these vehicles have been stated and large reductions in the cost of the fuel cells are required before those vehicles can be priced close to conventional cars. In addition, it is uncertain as to how the first large group of fuel cell powered cars will be fueled.

The auto companies around the world have shown much more interest in marketing hybrid vehicles than battery-powered electric vehicles and seem more willing to offer hybrid vehicles than electric vehicles at prices close to those of conventional cars during the early years after initial introduction. This important difference in the marketing strategy for hybrid vehicles seems to indicate that the auto industry sees a long term growth potential for the sales of hybrid vehicles and not for battery-powered electric vehicles.

Prius Test Results from EPA

	FUDS (mpg)		Highway (mpg)	
Vehicle	**EPA guide**	**Uncorrected**	**EPA guide**	**Uncorrected**
1998 Corolla (2750 lbs.)	28	31.1	36	46.2
Hybrid Prius (3000 lbs.)		48.6 (46.8*)	(Net Ah into/out battery = 0)	51.4 (51.6*)
Percent increase in MPG		56.2		11.3

Prius Emissions

FUDS 0.05 gm/mi NMHC, 0.4 gm/mi CO, 0.05 gm/mi NOx

Highway 0.01 gm/mi NMHC, 0.2 gm/mi CO, 0.05 gm/mi NOx

Acceleration Time 0-60 mpg 14 sec when battery fully charged

(Dynamometer tests) 19 sec when battery needs charging

* - UC Davis simulation results for the Prius

(9506 words in document)

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The Driveline Schematic and Engine for the Toyota Prius Hybrid Vehicle

Table 1: California Exhaust Emission Standards for New 2004 Passenger Cars and LightDuty Trucks

	Mass Exhaust Emissions (gm/mi)			
Category	NMOG	CO	NOx	Diesel particulates(2)
TLEV(1)	.125	3.4	.4	.04
LEV(1)	.075	3.4	.05	.01
ULEV(1)	.04	1.7	.05	.01
SULEV(2)	.01	1.0	.02	.01
ZEV	0	0	0	0
EZEV	.004	.17	.02	-

(1) 50,000 mi durability

(2) 120,000 mi durability

Table 2: Summary of the ZEV Credits for Various Vehicle and Fuel Choices (as of November 1998)

1. EV Mandate – 10% of sales to be ZEVs in 2003
2. Pure ZEVs must account for at least 40% of the 10% of sales
3. Partial ZEV credits can account for up to 60% of the 10% of sales
4. Vehicles receive partial ZEV credits based on total emissions (exhaust plus refueling and evaporative), all-electric range, and fuel used (see summary below).
5. Minimum requirement for ZEV credit is that the vehicle meet the SULEV emissions standard for 120,000 miles

Summary of ZEV Credits for Various Vehicle and Fuel Choices

Vehicle Type	Primary Fuel	Secondary "Fuel"	ZEV Credits
Conventional SULEV	Gasoline or Diesel*	None	0.2
	Methanol	None	0.2/0.4
	CNG	None	0.4
Charge Sustaining SULEV HEV	Gasoline or Diesel*	Electricity	0.2 to 0.6
	CNG	Electricity	0.4 to 0.7
Charge Depleting SULEV HEV	Gasoline or Diesel*	Electricity	0.6 to 0.85
BEV with trailer	CNG, Gasoline or Diesel*	Electricity	0.6 to 1.0
FCV	Direct Methanol	None	0.8/1.0
	Off-board Gasoline Reformer	None	0.8
	Off-board CNG Reformer	None	1.0
	On-board Reformer	None	0.2 to 0.4**

*Diesel may not meet baseline requirements

**It is unlikely that on-board reformers will eliminate tailpipe emissions. Unless they do, they will not qualify for AEV range credits

Table 3: Summary of the Characteristics of Various Hybrid Vehicle Designs (1980-1997)

Vehicle						Battery		Performance	
Developer	Year	Type	P/S/D(1)	Motor (kw)	Eng./Gen. (kw)	Type	Wgt. (kg)	Electric Range (km)	Fuel Econ. C/H (2)
DOE/JPL/GE (HTV-1)	1980	Full-size	P	33	55	Lead-acid	340	48	17/33
General Motors (HX3)	1990	Mid-size	S	90	40	Lead-acid	380	70	-
Volkswagen (Chico)	1992	Sub-compact	P	6	40 (diesel)	Lead-acid	215	25	31
Volvo (ECO)	1992	Mid-size	S	70	41 (gas turbine)	NiCd	300	85	-
UC Davis(3) (AfterShock)	1995	Sub-compact	P	45	13	NiCd	380	160	39/74
UC Davis(3) (Joule)	1997	Mid-size	P	48	36	NiMtHy	240	115	42/63
Univ. of West Virginia(3)	1997	Mid-size	S	55	93 (nat. gas)	Lead-acid	180	0	41/53
Virginia Tech. Univ.(3)	1997	Mid-size	S	85	41 (propane)	Lead-acid	180	0	26/39
Toyota (Prius)	1997	Compact	D	30	44	NiMtHy	40	0	48/54
Conventional ICE car	1998	Mid-size	-	-	115 kw	-	-	-	22/36
Conventional ICE car	1998	Sub-compact	-	-	65 kw	-	-	-	38/50

(1) P = parallel, S = series, D = dual mode
(2) C/H: C = city, H = highway, gasoline equivalent including electricity from the powerplant
(3) Hybrid vehicles from the DOE/SAE university student competitions

Table 4: Volume and Weight Characteristics of the Motor and Electronics in an Electric Driveline

	System Rating/ Voltage	Motor		Inverter		System		
Type/Developer	kW/v	kg/kW	L/kW	kg/kW	L/kW	kg/kW	L/kW	Efficiency (%)
AC Induction/AC Propulsion	100/336	.46	.28	.32	.59	.78	.87	90/93
AC Induction/General Electric	75/336	.79	.2	.30	.51	1.09	.71	89-94
Brushless D.C. PM/Unique Mobility	60/200	.83	.30	.30	.75	1.13	1.05	85-90

Table 5: Characteristics of Pulse Power Energy Storage Devices

	Pulse Batteries			
Characteristic	Lead-Acid (Thin-Film)	Ni Mt Hydride (Thin-Plate)	Electrochemical Capacitors (organic-3V/cell	Composite Fly-Wheel
Energy Density				
Wh/kg	20	50	5-10	15
Wh/l	50	135	6-12	25
Fraction Energy Used	.1-.2	.1-.2	.75	.75
Power Density				
W/kg	1000	500	1000	1500
Round-trip Efficiency (%)	90	55	90	90
Life	-	-	>10 yrs.	>10 yrs.
Status of Development	Prototype Devices	Prototype Devices	Prototype Devices	Lab Testing

Table 6: Summary of Ultracapacitor Technology (1998)

Country	Company or Lab	Funding	Description of the Technology	Device Characteristics	Energy Density Wh/kg	Power Density W/kg	Status/ Availability
Carbon Particulate Composites							
Japan	Panasonic	Private	Spiral wound, particulate with binder, organic electrolyte	3V, 800-2000 F	3-4	200-400	Commercial
France/US	Saft/Alcatel	U.S. DOE/Private	Spiral wound, particulate with binder, organic electrolyte	3V, 130 F	3	500	Packaged Prototypes
Australia	Cap – xx	Private	Spiral wound & monoblock, particulate with binder, organic electrolyte	3V, 120 F	6	300	Packaged Prototypes
Japan	NEC	Private	Monoblock, multi-cell, particulate with binder, aqueous electrolyte	5-11V, 1-2 F	0.5	5-10	Commercial
Russia (Moscow)	ELIT	Russian Gov't/ Private	Bipolar, multi-cell, carbon with sulfuric acid	450V, 0.5 F	1.0	900-1000 >100,000 cycles	Commercial
Carbon Fiber Composites							
United States	Maxwell	U.S. DOE/Private	Monoblock, carbon cloth on aluminum foil, organic electrolyte	3V, 1000-2700 F	3-5	400-600	Commercial
Sweden/Ukraine	Superfarad	Private	Monoblock, multi-cell, carbon cloth on aluminum foil, organic electrolyte	40V, 250 F	5	200-300	Packaged Prototypes
Aerogel Carbons							
United States	PowerStor	U.S. DOE/Private	Spiral wound, aerogel carbon with binder, organic electrolyte	3V, 7.5 F	0.4	250	Commercial
Conducting Polymer Films							
United States	Los Alamos National Lab	USDOE	Single-cell, conducting polymer (PFPT) on carbon paper, organic electrolyte	2.8V, 0.8 F	1.2	2000	Laboratory Prototype
Mixed Metal Oxides							
United States	Pinnacle Research Institute	U.S. DOE/Private	Bipolar, multi-cell, Ruthenium oxide, on Titanium foil, Sulfuric acid	15V, 125 F 100V, 1 F	.5 - .6	200	Packaged Prototypes
United States	US Army, Fort Monmuath	U.S. DOD	Hydrous Ruthenium oxide, bipolar, multi-cell, Sulfuric acid	5V, 1F	1.5	4000	Unpackaged lab prototype
Hybrid							
United States	Evans	Private	Double-layer/electrolytic, single cell, monoblock, Ruthenium oxide/Tantalum powder dielectric, Sulfuric acid	28V, .02 F	.1	30,000	Packaged Prototype
Russia (Moscow)	ESMA	Russian Govt./Private	Double-layer/Faradaic, monoblock, multi-cell modules, carbon/nickel oxide/KOH	1.7V cells/17V modules/20 Ah (50,000 F)	8 – 10 Wh/kg	80-100 (95% discharge effic.) Cycle life 10-20 K cycles	Commercial

U.S. DOE – U.S. Department of Energy
CEC – Commission of European Communities

Table7: Performance Characteristics of Various Ultracapacitors

Ultracapacitor Device	V	Ah	Wgt. kg	Resistance mΔ	wh/kg	$(w/kg)_{max}$ 95% Disch. Effic.	Matched Imped. Disch.
Maxwell Ultracapacitor							
2700 F	3	2.25	.85	.5	4.0	593	5294
1000 F	3	.83	.39	1.5	3.1	430	3846
Panasonic							
800 F	3	.67	.32	2.0	2.6	392	3505
2000 F	3	1.67	.57	3.5	4.4	127	1128
Superfarad (250 F)	50	3.4	16	20	5.4	219	1953
Saft (mfg. data)							
Gen 2 (144 F)	3	.12	.030	24	6.0	350	3125
Gen 3 (132 F)	3	.11	.025	13	6.8	775	6923
PowerStor (10 F)	3	.0083	.015	10	.833	1680	15000

Table 8: Characteristics of Engines for Hybrid Vehicle

				Emissions (gm/kWh) (Nominal)			
Engine Type	kg/kW	l/kW	Maximum Efficiency (%)	HC	CO	NOX	Manufacturer/Developer
Spark Ignition							
Valve Injection	2.0	4.0	32	3.0	20	8.0	Auto Companies
Direct Injection	2.5	4.1	38	5.0	4.0	3.5	Auto Companies
Rotary	.8	1.0	30	3.0	4.0	5.0	Moller International
Two-Stroke	1.0	1.75	30	3.0	3.0	6.0	Orbital
Diesel							
Prechamber/Turbo	2.6	4.2	35	.1	1.0	3.0	Auto Companies
Direct Injection/Turbo	3.0	4.4	42	1.0	1.0	15.0	Auto Companies
Gas Turbine							
Metal							
With Recup.	2.5	5.3	30	.08	.30	.03	Capstone
Incl. generator					(catalytic combustion)		
Ceramic							
with Recup.	2.0	4.0	40	.08	.30	.03	Allison
					(catalytic combustion)		
Stirling							
H_2 Working Fluid/ Wobble Plate Drive	2.7-3	2-2.5	30-35	.01	.15	.22	Stirling Thermal Motors

Table 9: Progress in PEM Fuel Cell Stack Weight and Volume Characteristics (1990-1996)

Fuel Cell Stack Characteristic	Year of Technology*		
	1990-1	1992-3	1995-6
Output (kW)	5	13	30
Weight (kg)	40	40	32
Power Density			
kW/kg	.125	.325	.94
kW/l	.156	-	1.0
Efficiency(%)	47	-	55%

*Based on reported characteristics of Ballard fuel cell stacks.

Table 10: Hybrid Vehicle Design Characteristics used in the Vehicle Simulations

Vehicle Type	Test Weight (kg)	C_D	$A_f(m^2)$	Rolling Resistance	Accessory Load (W)	AC Induction Electric Drive (kW)	Regen. Breaking Ratio	Engine/ Generator (kW)
Mid-Size, 1995 Materials	1400-1580	.27	2.0	.006	250	84	.65	40
Compact-Size, Light-Weight Materials	750-850	.24	1.85	.006	200	32	.65	25

Table11: Summary of Hybrid Vehicle Fuel Economy Results on the FUDS and Highway Driving Cycles using Various Engines and a Fuel Cell

			Miles Per Gallon (1)	
Vehicle	**Engine**	**Energy Storage**	**FUDS**	**Highway**
Mid-size	Honda Gasoline	Ni. Mt. Hy. Bat.	36.1	45.4
	Direct Injection Gasoline	↓	47.3	56.0
	Sw. Ch. Diesel		49.7	56.8
	Direct Injection Diesel		60.5	71.1
	Stirling		50.0	57.2
	Honda Gasoline	Capacitor	44.3	47.3
	Sw. Ch Diesel	Capacitor	62.3	65.7
	Fuel Cell (H_2)	Ni. Mt. Hy. Bat.	89.2	105.0
Light-weight Compact	Honda Gasoline	Ni. Mt. Hy. Bat.	69.6	71.4
	Direct Injection. Gasoline	↓	82.9	84.9
	Sw. Ch. Diesel		98.2	95.6
	Direct Injection Diesel		107.3	110.4
	Stirling		89.5	92.7
	Honda Gasoline	Capacitor	81.4	75.5
	Sw. Ch. Diesel	Capacitor	109.8	104.0
	Fuel Cell (H_2)	Ni. Mt. Hy. Bat.	16.3	17 9

(1) mpg diesel fuel for diesel engine and mpg gasoline equivalent for fuel cell powered vehicles

Table 12: Comparisons of the Fuel Economy of Conventional ICE and Series Hybrid Vehicles

Vehicle(1)	Test Weight (kg)	Transm.	City(2)	Highway(2)
Mid-size				
Conventional ICE (Ford Taurus)	1668	A4	22	36
Series Hybrid (gasoline engine, charge sustaining)	1655	-	33.9	38.6
Sub-compact				
Conventional ICE (Geo. Metro)	958	A3 M5	33 43	44 55
Series Hybrid (gasoline engine, charge sustaining)	956	-	56.3	57.0

(1) Conventional and Series Hybrid Vehicles had same weight, C_DA, and fr

(2) Fuel economy of ICE Vehicles were taken from the 1997 EPA Fuel Economy Guide corrected by 10% for FUDS and 22% for highway

Table 13: Comparisons of the Fuel Economy for Series and Parallel Hybrid Vehicles

	Fuel Economy (mpg) Gasoline Engine		Fuel Economy (mpg) Swirl Chamber Diesel(1)	
Vehicle	FUDS	Highway	FUDS	Highway
Small, light-weight				
Series Hybrid Charge sustaining	62.4	71.1	75.7	85.2
Parallel Hybrid Charge Sustaining	68.2	79.5	75.9	88.8
Charge Depleting gasoline alone	90.1	86.1	95.6	94.0
including pp	71.1	80.5	75.8	88.1
Mid-size (1995 materials)				
Series Hybrid Charge sustaining	39.2	48.2	47.9	58.5
Parallel Hybrid Charge Sustaining	42.8	54.1	48.0	60.6
Charge Depleting gasoline alone	55.3	56.6	59.0	62.3
including pp	45.4	54.7	49.1	60.6

(1) Fuel economy shown for diesel engines is gasoline equivalent

Table 14: Summary of the Regulated Emissions) of Hybrid Vehicles Using Various Engines and a Fuel Cell (based on simulations)

		Emissions (gm/mi)				
		NMOG		CO	NOx	
Vehicle	**Engine/Fuel**	**Exhaust**	**Total**	**Total**	**Total**	
Mid-size	**P.I./gasoline**					
	Ch. Depl.	.001	.006	.026	.024	LA Basin
			.01	.04	.155	LA Total
	Ch. Sust.	.02	.06	.14	.095	
	D.I./gasoline					
	Ch. Depl.	0	.009	.04	.162	
	Ch. Sust.	.025	.057	.02	.056	
	D.I./diesel					
	Ch. Depl.	.001	.009	.04	.206	
	Ch. Sust.	.032	.042	.003	1.87	
	Stirling/gasoline					
	Ch. Depl.	0	.009	.04	.163	
	Ch. Sust.	.001	.033	.014	.124	
	Fuel Cell/H_2					
	Ch. Depl.	-	-	-	-	
	Ch. Sust.	0	.003	.022	.047	
Compact, light-weight	**P.I./gasoline**					
	Ch. Depl.	0	.003	.014	.014	LA Basin
			.005	.021	.10	LA Total
	Ch. Sust.	.015	.035	.10	.06	
	D.I./gasoline					
	Ch. Depl.	0	.005	.021	.10	
	Ch. Sust.	.014	.032	.012	.032	
	D.I./Diesel					
	Ch. Depl.	0	.005	.021	.10	
	Ch. Sust.	.017	.023	.018	1.07	
	Stirling/gasoline					
	Ch. Depl.	0	.005	.021	.098	
	Ch. Sust.	0	.017	.009	.067	
	Fuel Cell/H_2					
	Ch. Sust.	0	.002	.012	.024	

All-electric range = 60 miles
Evaporative emissions = 0

LA total (exceptions noted)
P.I. = port injected (valve inlet)
D.I. = Direct injected (cylinder)

Ch. Depl. = Charge Depleting
Ch. Sust. = Charge Sustaining

Table 15: Total Full Cycle CO2 Emissions for ICE, Electric, and Hybrid Vehicles using Various Engines and a Fuel Cell

		gm CO_2/mi	
Vehicle	Engine	Depl.	Sustain.
Mid-size	Honda Gasoline	179	226
	Direct Injection Gasoline	187	182
	Sw. Ch. Diesel	190	197
	Direct Injection Diesel	190	163
	Stirling	187	176
	Fuel Cell	-	119
Light-weight Compact	Honda Gasoline	117	130
	Direct Injection Gasoline	117	110
	Sw. Ch. Diesel	121	110
	Direct Injection Diesel	121	101
	Stirling	117	102
	Fuel Cell	-	68
Mid-size	EV-Pb. Acid		148
	EV - Ni. Mt. Hy.		210
	EV - Li - ion		108
	ICE - ULEV (27.5 mpg)		347
	ICE - SULEV (35 mpg)		268
Light-weight Compact	EV - Pb. Acid		108
	EV - Ni. Mt. Hyd.		136
	EV - Li - ion		69
	ICE - ULEV (40 mpg)		234
	ICE - SULEV (75 mpg)		125

Table 16: EPA Chassis Dynamometer Test Data for the Toyota Prius Compared with Computer Simulation Predictions

	FUDS (mpg)		Highway (mpg)	
Vehicle	**EPA guide**	**Uncorrected**	**EPA guide**	**Uncorrected**
1998 Corolla (2750 lbs.)	28	31.1	36	46.2
Hybrid Prius (3000 lbs.)		48.6 (46.8*)	(Net Ah into/out battery = 0)	51.4 (51.6*)
Percent increase in MPG		56.2		11.3

Prius Emissions

FUDS	0.05 gm/mi NMHC, 0.4 gm/mi CO, 0.05 gm/mi NOx	
Highway	0.01 gm/mi NMHC, 0.2 gm/mi CO, 0.05 gm/mi NOx	
Acceleration Time	0-60 mpg	14 sec when battery fully charged
(Dynamometer tests)		19 sec when battery needs charging

* - UC Davis simulation results for the Prius

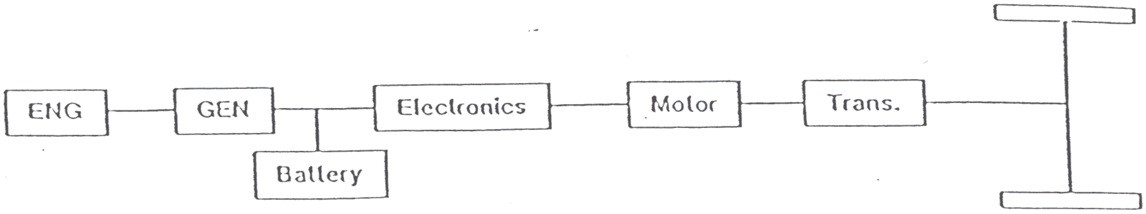


Figure 1: Series Hybrid Vehicle Driveline Schematic

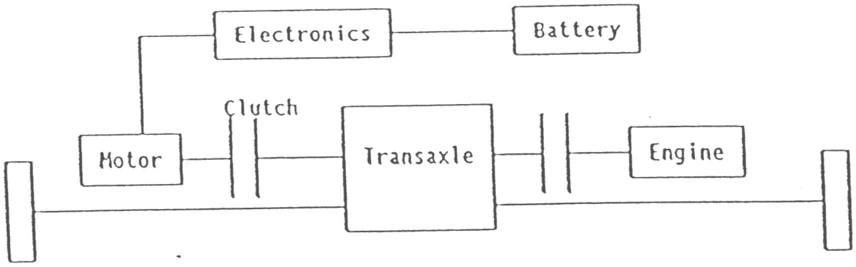
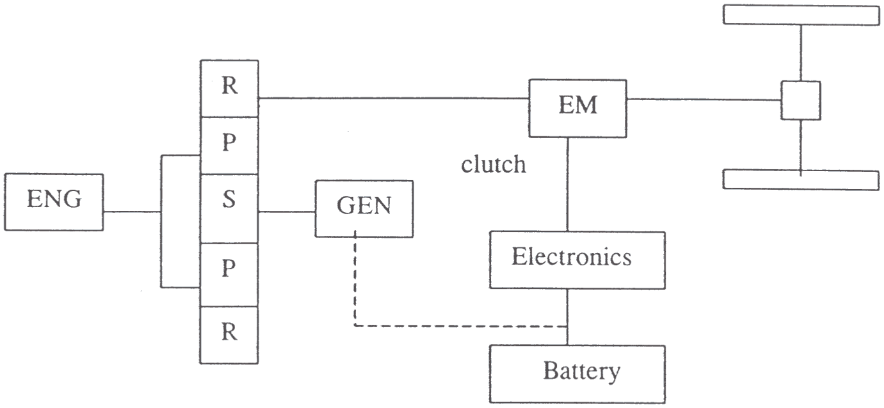
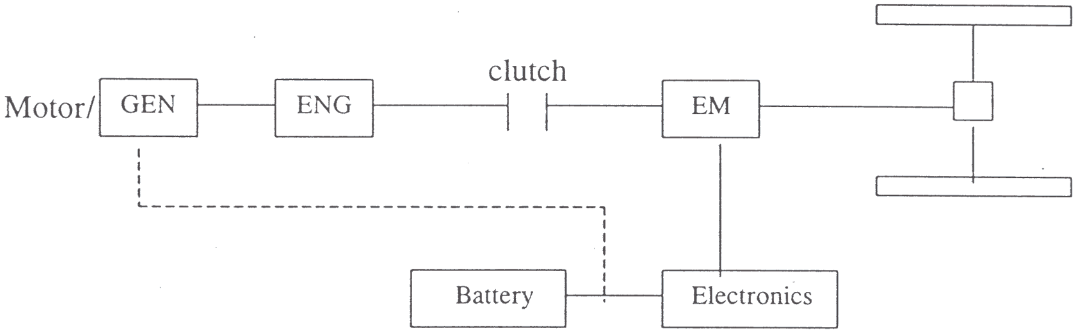


Figure 2: Parallel Hybrid Vehicle Driveline Schematic

Planetary Gear Torque Coupling



Clutch/Shaft Torque Coupling



clutch open - series

clutch closed – parallel/dual mode

Figure 3: Dual Mode Hybrid Vehicle Driveline Schematics

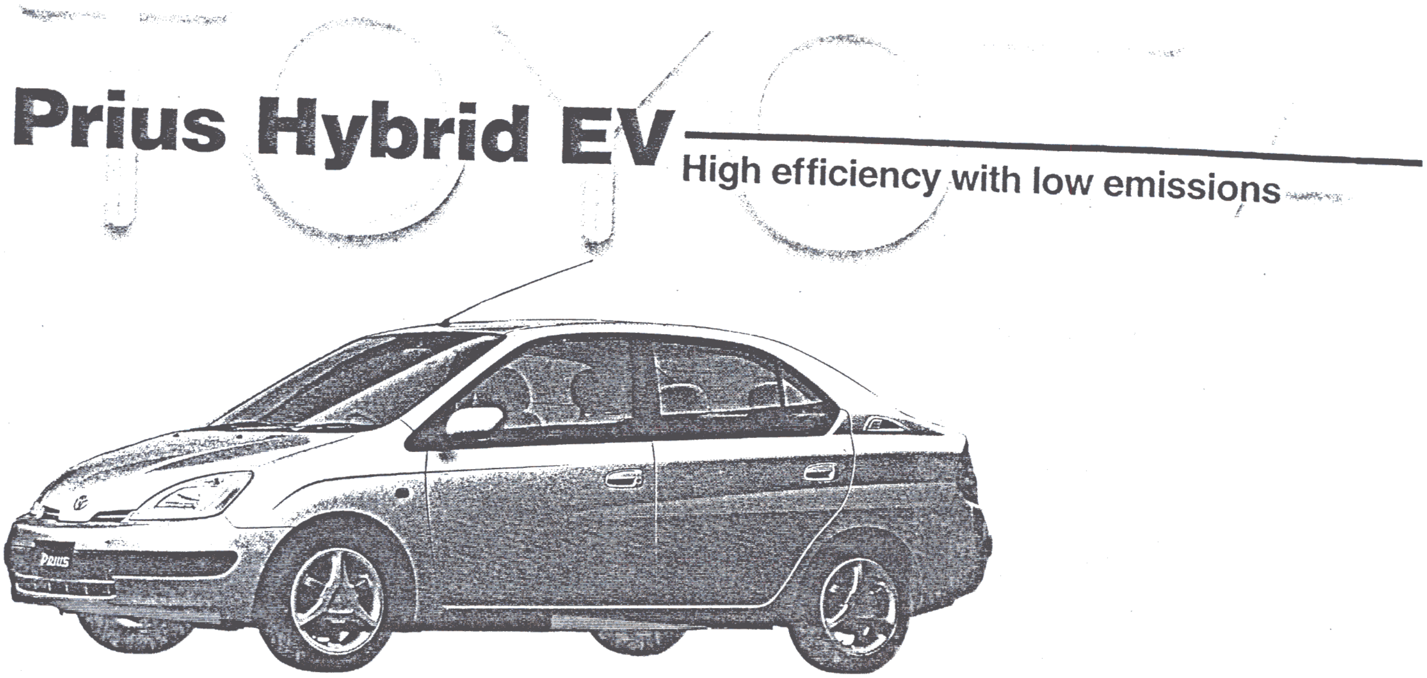


Figure 4: Photograph of the Toyota Prius

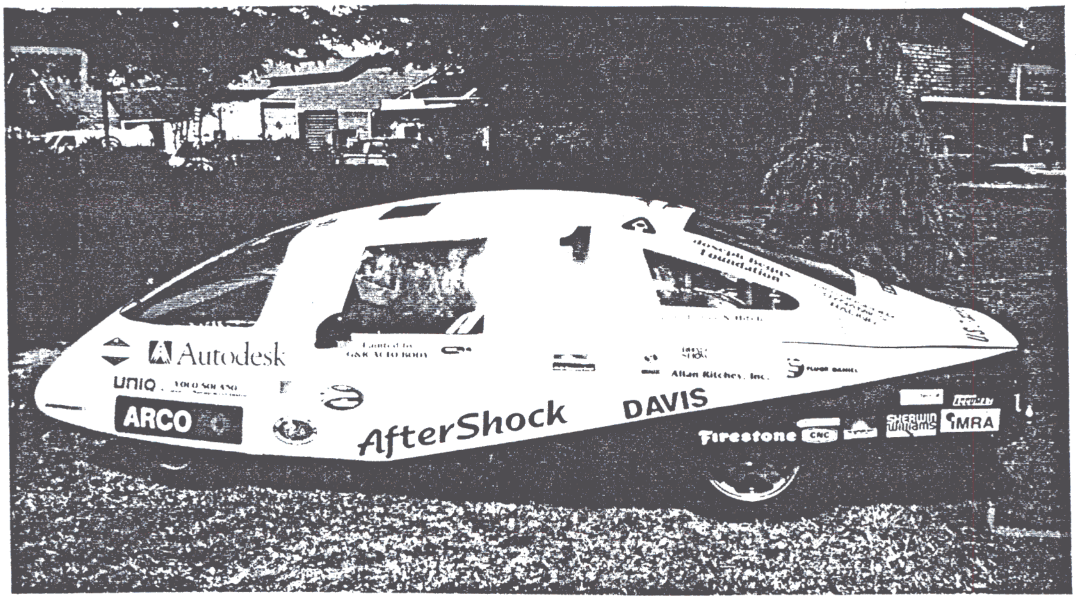


Figure 5: Photograph of the UC Davis AfterShock

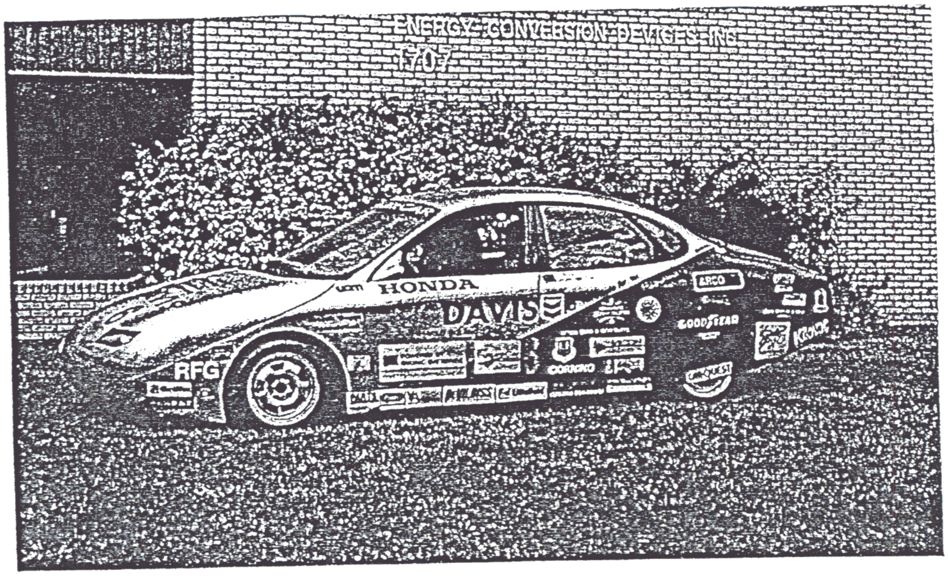


Figure 6: Photograph of the UC Davis Future Car I (Joule)

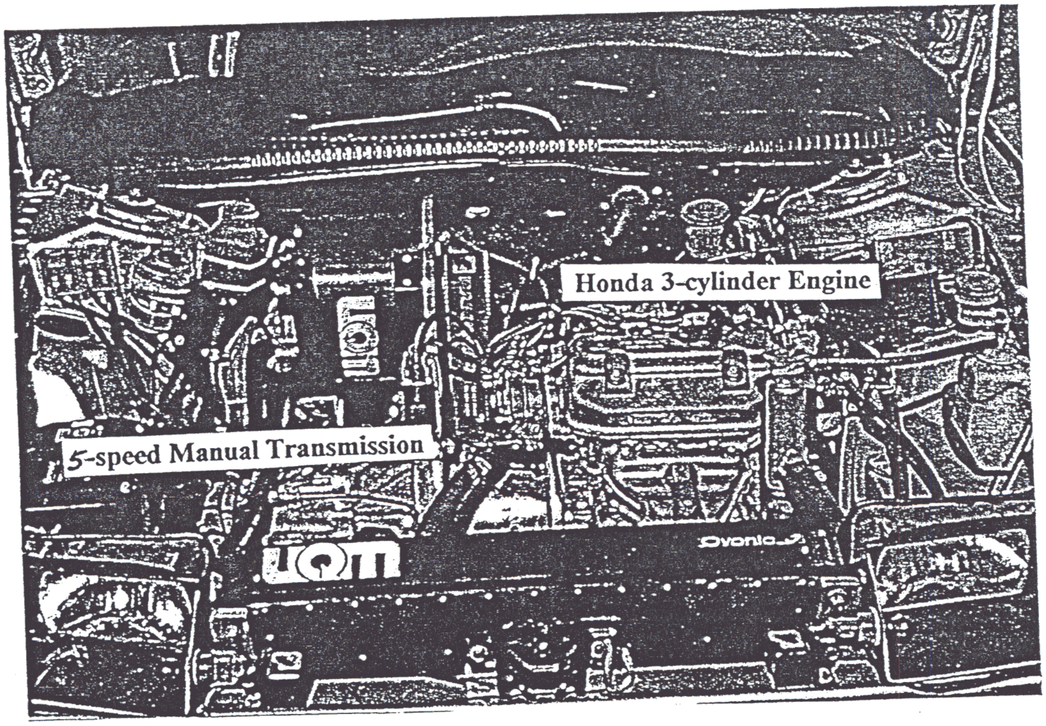


Figure 7: Photograph of the Parallel Driveline in the UC Davis Future Car I

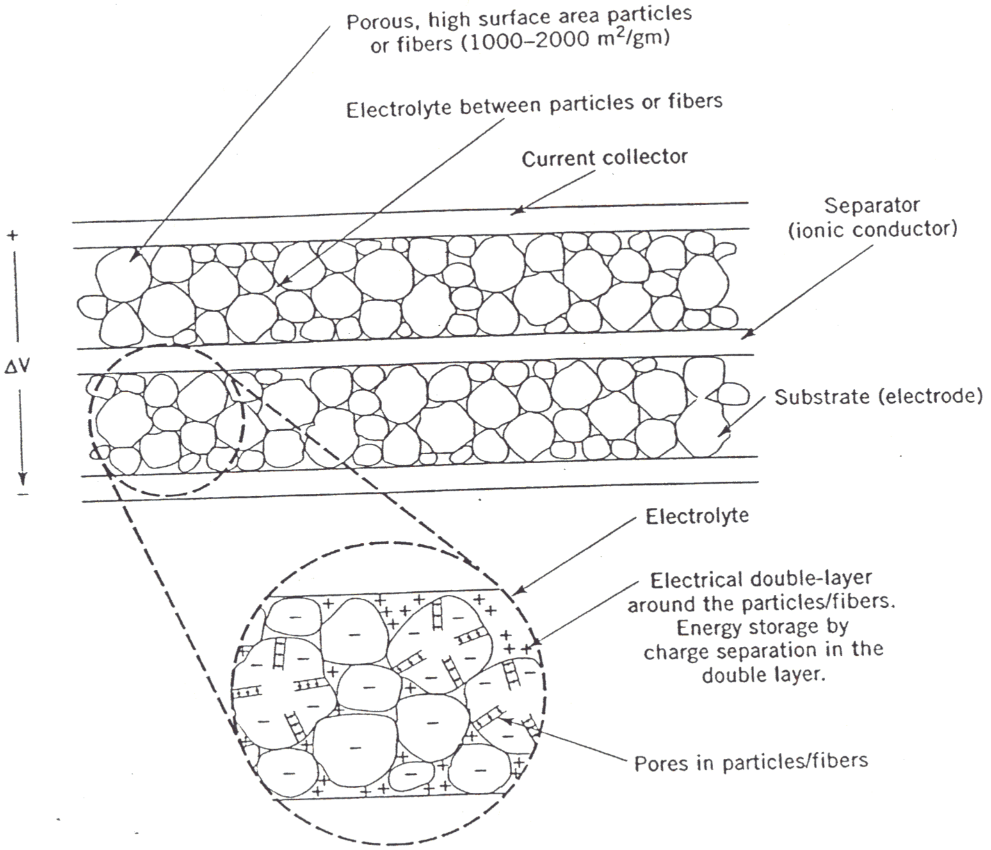


Figure 8: Schematic of the Construction of an Ultracapacitor

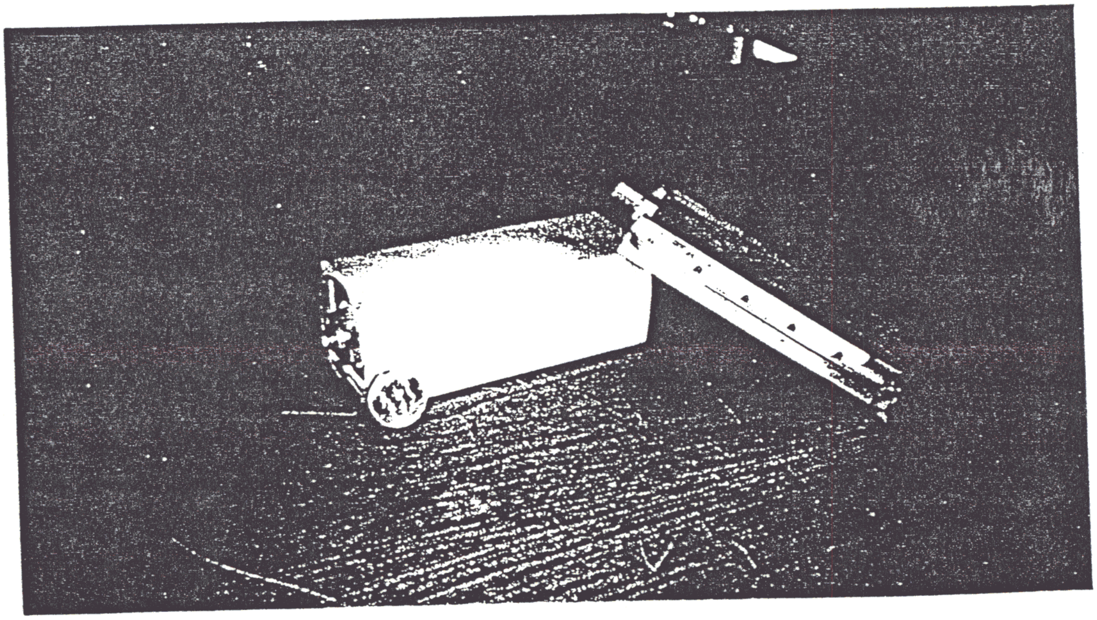


Figure 9: Photograph of Ultracapacitors from Maxwell Energy Products

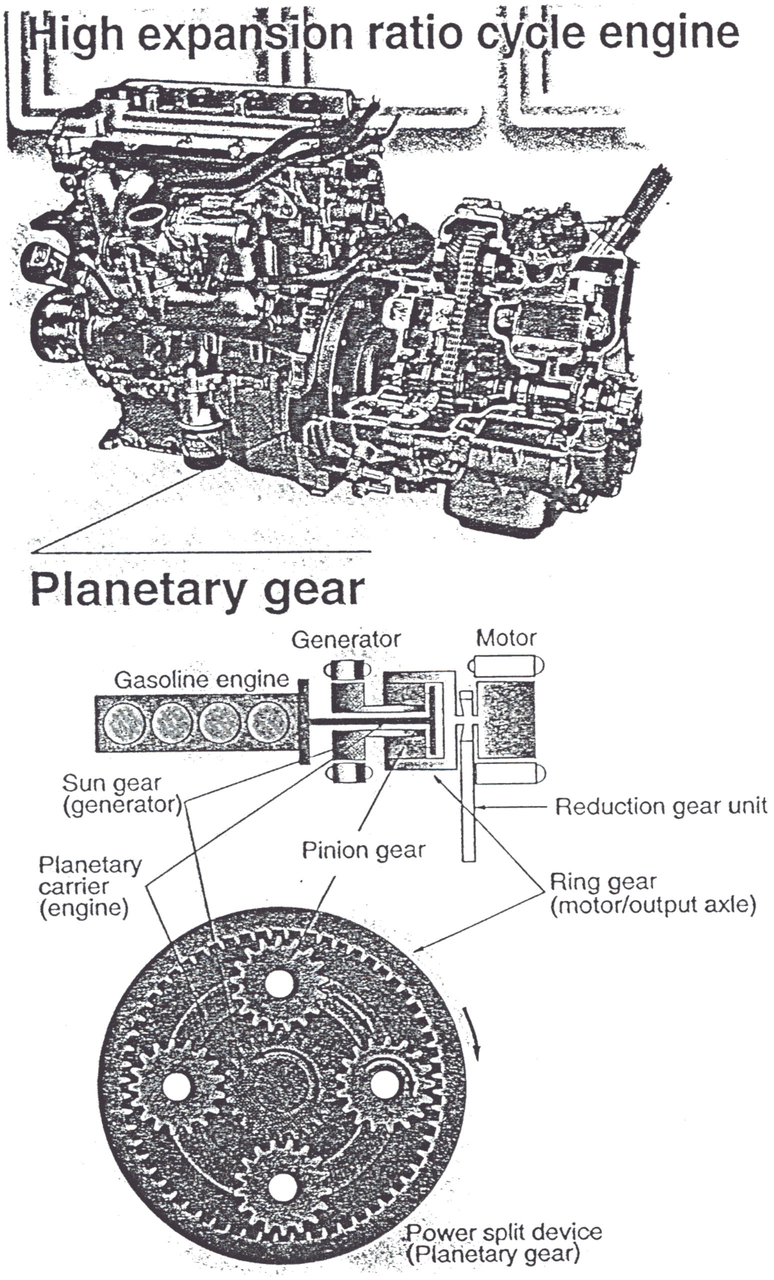


Figure 10: The Driveline Schematic and Engine for the Toyota Prius Hybrid Vehicle