4 HYBRID VEHICLE SYSTEMS

401 INTRODUCTION AND SUMMARY

A hybrid-electric vehicle includes an internal combustion engine in addition to an electric propulsion motor and storage battery. There are many workable arrangements for sharing propulsion duties between engine and motor, giving rise to a broad spectrum of possible hybrids. At one end of this spectrum are hybrids much like pure EVs; they usually operate all-electrically, derive most of their energy from electric utilities, and employ their ICES only to extend range on long trips. At the other end of the spectrum are hybrids much like pure ICE vehicles; they derive all their energy from gasoline and employ their electric components simply to increase the average efficiency and reduce the average emissions of their ICES. In between are vehicles with many of the advantages, and disadvantages, of both electric and ICE propulsion.

Hybrids were conceived long ago in attempts to combine the best attributes of both electric and ICE propulsion. A patent granted in 1905, in fact, diagrams 'he hybrid configuration which today enjoys greatest popularity. A few hybrids were built and sold in the United States after 1910, but the combination of ICE, electric motor, and battery which eventually captured the entire motor vehicle market made no direct use of the electric motor for propulsion. Instead, the battery and motor were employed only to start the ICE, as Charles Kettering's 'self-starter" for the 1912 Cadillac. For most of the years since, market forces have favored no larger role for the electric motor and battery in motor vehicles.

Interest in hybrids was reawakened in the 1960s, when worsening air pollution forced a major reevaluation of the use of ICES for vehicular propulsion. The resultant consensus, however, was that hybrids were complex and costly. In 1967, a panel of experts convened by the Department of Commerce to investigate electrically-powered vehicles dismissed hybrids in a single paragraph as economically uncompetitive.[2] It is worth noting that the panel dismissed its assigned topic, electric vehicles, almost as briefly, and then went on with incisive foresight and broadened scope to recommend what has since come to pass (national air quality and emission standards clean-up of conventional vehicles) .

Hybrid R&D continued nevertheless with both government and industry sponsorship, and after 1973 its objectives shifted increasingly to conservation of petroleum. In 1976 an experimental program at Ford Motor Company showed potential fuel economy improvements of 30 to 100 percent with a hybrid configuration resembling a conventional ICE system with a much enlarged starter motor.[3] The electric motor was used for all vehicle movement up to 10 to 15 mph, not just to start the ICE; but because all battery recharge came from regenerative braking or the ICE, no use was made of electric utility power. Also in 1976, a small business described a hybrid with a larger electric motor which was used more extensively to assist a small ICE in propelling the vehicle. In this hybrid, recharge energy from electric utilities was deliberately used to supplant gasoline use.

Today, hybrid R&D is aimed at use of electric energy from utilities and at vehicles with sufficient all-electric capability to remain operable even in the complete absence of gasoline. Because of the resultant emphasis on electricity stored in batteries, these hybrids are nearly as dependent as pure electric vehicles on improved batteries with more energy per pound and much longer life. They also require most or all of the electric drive train components of the electric vehicle. Probably because of these factors, most developers have focused on the pure electric vehicle, postponing the hybrid (with the complication of its added ICE) until satisfactory electric vehicles become available as a starting point.

Despite their slower start in R&D, hybrids ultimately may prove superior to pure electric vehicles for many motorists. The ICE effectively can relieve the range limitation of the pure electric car, or raise its acceleration to equal that of ICE cars, or both. Yet the hybrid can simultaneously be no more expensive, and retain some or all of the electric vehicle's capability to electrify travel with energy from electric utilities.

A "range-extension" hybrid with almost all the desirable properties of the pure electric vehicle is derived from the all-electric vehicle by substituting a small ICE for part of the propulsion battery. The ICE is just large enough to power continuous cruising on the highway (15-25 hp). For simplicity and efficiency, it has a direct mechanical connection to the electric motor shaft. The ICE operates only for extended highway travel. In urban driving, it is disconnected and the vehicle operates electrically. This arrangement not only eliminates the range limitation which is the principal disadvantage of the electric car, but is also among the simplest of the hybrid configurations to build. In addition, it minimizes problems of controlling air pollutant and noise emissions, because the ICE would operate very little in urban areas.

With a useful electric range of 60 miles, the future range-extension hybrid could electrify about as much of the travel of a typical US auto as the pure electric car with 100-mile maximum range. Yet the hybrid could be both lighter and cheaper, with unlimited driving range on its ICE. Projected sticker prices for such hybrids using near-term lead-acid and nickel-zinc batteries are $7,700 and $8,000, about 5 percent under those of comparable electric cars (though still 65 to 70 percent above those of comparable ICE cars). Projected life-cycle costs for these hybrids are 23.5 and 26.0 cents per mile, 2 percent under those of the electric versions (but 10 to 20 percent above those of the comparable ICE cars) .

With the advanced lithium-metal sulfide battery and a useful electric range of 60 miles, the price of the range-extension hybrid might be about $6,200, 20 percent more than that of the comparable ICE vehicle. Life-cycle cost might be only 19.3 cents per mile, 11 percent less than that of the ICE despite low 1980 gasoline prices.

A "high-performance" hybrid differs from the range-extension hybrid in that it employs a larger ICE, a smaller electric motor, and a smaller battery. It is capable of all-electric operation at low speeds and accelerations, but makes the ICE instantly available when high acceleration and speed are demanded. The combined power of the ICE and the electric motor suffice for acceleration competitive with that of conventional ICE cars, and range on the ICE is unlimited. Yet the high-performance hybrid might be less expensive than either the pure electric car or the range-extension hybrid. Its drawbacks are reduced range and acceleration in all-electric operation, and increased use of gasoline in typical driving. Furthermore, the stop-start operation required of the ICE (to assist with acceleration whenever necessary in urban driving) imposes significant technical difficulties and risks exceeding those of the range-extension hybrid.

Development and construction of a high-performance hybrid was begun in 1980 for the Department of Energy by General Electric and Chrysler, the team which completed the all-electric ETV-1 in late 1979. The high-performance hybrid is designated HTV-1. In the preliminary design study preceding the HTV-1 development and construction contract, the acceleration capability of the GE/Chrysler design was estimated at O-56 mph in 12.6 seconds, equal to that of the ICE car chosen for reference, a five-passenger 1978 Chevelle Malibu V-6 updated to 1985 conditions. Price of the HTV-1 design in mass production was estimated to be 35 percent higher than that of the updated reference car, but life-cycle costs were projected to be about equal to those of the reference car. Range and acceleration of the GE HTV-1 preliminary design in all-electric operation were not reported in the summary of the design phase of the project, but would be below those of the all-electric and range-extension hybrid vehicles described in this report.[4]

Estimated fuel use of the preliminary high-performance hybrid design is 63 percent of[4] that which would be required by the reference car projected for 1985. The range-extension hybrid, with its greater reliance on electric drive and utility power, would use around 20 percent of the fuel required by the ICE car comparable to it.

This chapter first discusses hybrid vehicles and drive trains as an extension of the electric vehicle technology presented in Chapter 3. Then it describes and compares representative examples of projected future range-extension hybrids and projected future high-performance hybrids.

4.2 VEHICLE DESIGN

Hybrid Configurations

The series hybrid configuration is the most obvious of the major hybrid propulsion alternatives. It may be thought of as an electric propulsion system to which an auxiliary engine and generator are added. This is illustrated at the top of Fig. 4.1.

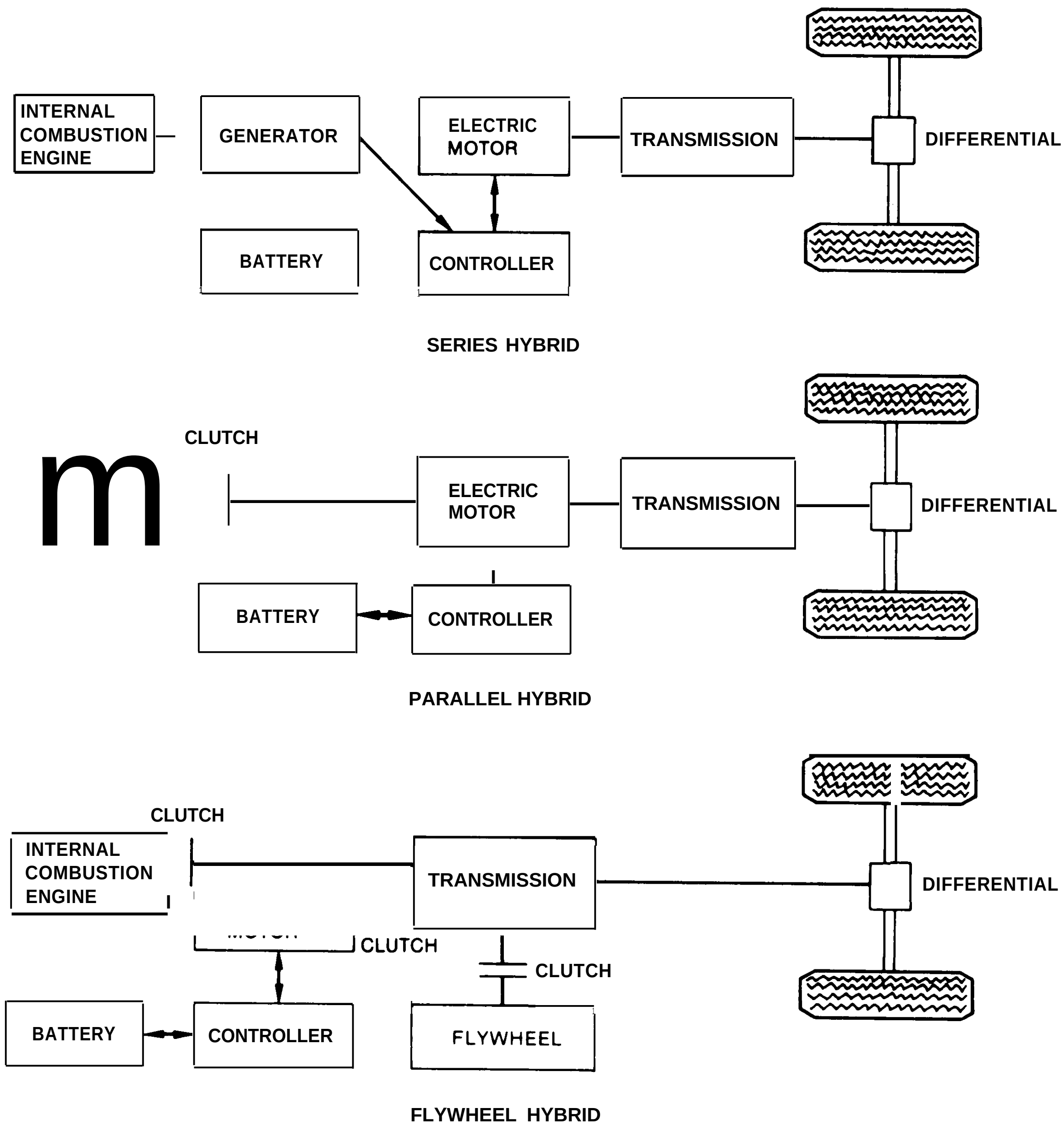


Figure 4.1 **Basic** Hybrid Configuration

The role played by the engine and generator in the series hybrid depends on their size. An engine-generator set with sufficient output to drive the electric motor at its maximum rated power make the battery unnecessary, and reduce the electrical equipment to performing functions ordinarily assigned to the transmission. This is the arrangement now used in diesel-railroad locomotives; it was introduced in highway vehicles as long ago as 1908. With smaller engine generator sets, the battery becomes necessary to meet peak electricity demands of the propulsion motor. Very small engine generator sets lead to vehicles approaching the pure electric vehicle in capability. In any of these arrangements, recharge power for the battery may be derived either from electric utilities or the on-board generator. The larger the battery, the more use may be made of electric utilities.

The advantages of the series configuration include:

- Capability for all-electric operation.
- Regenerative braking.
- Constant-power ICE operation with high consequent ICE efficiency and low pollutant emissions.

The disadvantages include:

- The high weight and cost of an ICE and generator in addition to an electric motor large enough to meet all propulsive power requirements.
- The high losses in passing all power from the ICE through both a generator and a motor before it reaches the driven wheels.

The parallel hybrid configuration is the principal alternative to the series configuration. The parallel configuration provides direct mechanical paths between the driven wheels and both the ICE and electric motor. This eliminates the weight and cost of the generator in the series configuration, as well as electrical losses in transmitting power from the ICE to the driven wheels. In general, however, it also eliminates the possibility of operating the ICE at constant speed and load, which tends to reduce ICE efficiency and increase pollutant emissions.

The parallel hybrid may be regarded as an ICE drive train with an electric motor added to assist the ICE with maximum power demands and to provide regenerative braking. Alternatively, this same configuration may be regarded as a complete electric drive train with an ICE added to assist the electric motor and battery with both power for high acceleration and energy for long-range cruising. The configuration is illustrated at the center of Fig. 4.1. Just one version is shown; in others the locations of the electric motor and ICE may be interchanged, or the

ICE and motor may be given separate inputs to the transmission so they may run at different speeds, or the transmission may be used between the ICE and motor while the motor drives the differential directly. All these arrangements offer the essential feature of the parallel hybrid: a direct mechanical path from both ICE and motor to driven wheels.

The advantages of the parallel hybrid configuration include:

- Capability for all-electric operation.
- Regenerative braking.
- High efficiency from the ICE to the driven wheels.

The disadvantages include:

- ICE operation at varying speed and load.
- Simultaneous control of ICE and motor are generally necessary

A flywheel hybrid is sometimes distinguished as a separate hybrid-electric configuration. It amounts to a parallel hybrid in which a flywheel is added as a short-term energy store. This is illustrated at the bottom of Fig. 4.1. A successful flywheel and associated transmission could also do much to improve either a pure electric or pure ICE drive.

The advantage of the flywheel approach is high power capability at high efficiency. With peak power demands met from a flywheel, both ICE and electric motor could be smaller in the flywheel hybrid than in the simpler parallel hybrid. Regeneration efficiency might be improved by avoiding the electrical losses in the round-trip of braking energy through the electric motor, controller, and battery. The disadvantages of the flywheel hybrid are the extra weight, cost,[5] complexity, and technical risk associated with the flywheel subsystem.

Given today's needs for increasing reliance on utility electricity rather than gasoline to propel vehicles, the parallel hybrid configuration is generally preferred. In the Phase 1 design competition of DOE's Near-Term Hybrid Vehicle Program, all four contractors chose parallel hybrid configurations.[4] Such alternatives as the flywheel hybrid (or a similar hybrid with a hydraulic accumulator) were rejected as technically uncertain or insufficiently beneficial, or both. The flywheel hybrid, in particular, provides net benefits if--and only if--the necessary flywheel and transmission can be sufficiently light, long-lived, reliable, and inexpensive. A flywheel subsystem for this sort of application is being developed for DOE'S Electric Test Vehicle ETV-2, but has encountered serious setbacks in testing. The ETV-2 development lags behind that of the companion ETV-1 discussed in Chapter 2.

Within the parallel hybrid configuration, there remains a wide spectrum of possible designs. At one extreme, the ICE would run continuously much as in a conventional car, with occasional help from the electric motor to provide high acceleration and possibly high speed. At the other extreme, the electric subsystem would be used alone for most travel, with occasional assistance from the internal combustion engine to meet driving demands beyond the sole capability of the electric subsystem. Most hybrid work of the late 1960s and early 1970s used the electric drive to help a small, continuously-running ICE, an arrangement which decreased the load fluctuations on the ICE and thereby improved its operating efficiencies and pollutant emissions. In the late 1970s, this approach has been replaced by the alternative in which the ICE only operates occasionally to help a basic electric propulsion system. This arrangement provides greater opportunities for supplanting gasoline use with electricity from utilities, and gives a basic electric operational capability even when gasoline is unavailable.

In hybrids wherein the ICE intermittently assists a basic electric drive, there are two alternatives distinguished by important functional and technical differences: the range-extension and the high-performance hybrid.

In a range-extension hybrid, the ICE is used only to extend the range of the vehicle beyond that provided by the battery and electric drive alone. The electric drive gives adequate acceleration for all types of driving, and adequate range for most full-day travel requirements. It alone would suffice for almost all urban driving, with all the attendent advantages of electric propulsion for reducing petroleum use and vehicular emissions of air pollutants. The ICE would be relatively small, with one-third to one-half the power output of the electric motor. It would be used mostly in highway driving, operating over a relatively narrow speed range near its maximum power. These are favorable conditions for high efficiency and low emissions. During highway cruising the ICE would provide enough extra power beyond that needed to propel the vehicle to recharge slowly the propulsion battery. This would ensure availability of electric power for occasional bursts of acceleration and higher speed or for climbing hills.

In a high performance hybrid, the ICE would be used not only to extend range beyond that of the basic electric drive, but to provide power for higher acceleration whenever the driver demanded it. Reliance on the ICE for acceleration leads to designs in which ICE output may be up to twice that of the electric motor. It also requires that the ICE operate in a stop-start mode in urban driving, contributing high power almost instantly when the driver depresses the accelerator pedal, and stopping when the pedal is released in order to conserve fuel. ,

Because the high-performance hybrid uses a larger ICE with larger load fluctuations for more driving conditions, it generally requires more gasoline than the range-extension hybrid. It also poses more difficult control and drivability problems because the ICE must be abruptly started and stopped and its high power output smoothly combined with that provided by the electric drive. In the range-extension hybrid, the ICE is smaller, less frequently operated, and more easily managed as a result. Its low power output could be entirely diverted, if necessary, by the electric drive to battery recharging, so that throttling of the ICE is not necessary during deceleration and stops. Starting could be manually controlled because it need not be sudden and would probably not be required at all on most travel days.

Aside from control and drivability problems, the stop-start ICE operation of the high-performance hybrid raises significant problems of engine wear and life. Two important causes of engine wear are erosion and corrosion. Erosion results from metal-to-metal contact due to inadequate lubrication. Corrosion results from chemical attack of metal surfaces by moisture and corrosive products from the combustion process. Both mechanisms are accelerated by stop-start operation, which leads to more frequent cold starts and lower average operating temperatures. During startup, especially cold startup, insufficient lubrication may be available at the pistons and piston rings, a condition exacerbated by rich fuel mixtures resulting from choking of the engine to improve cold drivability. Engines operated intermittently, with consequent low cylinder wall temperatures, tend to build up accumulations of corrosive combustion products which attack metal surfaces. Eventually, combustion products may contaminate engine oil to the point at which cold-engine sludges begin to coagulate, separate, and accumulate where oil flow is slow or restricted, further interfering with engine operation.

In short, the technical challenges posed by the high-performance hybrid exceed those of the range-extension hybrid.

Examples of Hybrid Design

Only a few hybrids have been built recently, in comparison with the much larger number of all-electric vehicles constructed. Whereas the Department of Energy has supported a number of electric vehicles for limited production and has completed the sophisticated **ETV-1, it** has not supported a range-extension hybrid and has only begun on a sophisticated high-performance hybrid. A recent development from industry, however, illustrates the status of the less-demanding approach, and the preliminary designs for the DOE Hybrid Test Vehicle HTV-1 reveal what may be expected from a sophisticated high-performance hybrid by the end of 1982.

The Briggs and Stratton Corporation completed a hybrid electric car in late 1979. Developed entirely on company funds, the car illustrates the potential role of the small engines manufactured by Briggs and Stratton in hybrid-electric automobiles. It is shown in Fig. 4.2.

Figure 4.2 The Briggs and Stratton Hybrid-Electric Car

The Briggs and Stratton hybrid is based on a 6-wheel electric vehicle chassis from Marathon Electric Vehicle Company of Quebec (Fig. 4.3). The two extra wheels support the batteries in a 'captive trailer" behind the conventional rear driving wheels. The heart of the drive train is the front mounted electric motor, which drives the rear axle through a manual clutch, 4-speed manual transmission, and differential. The free front end of the electric motor shaft can be driven by a two-cylinder gasoline engine through a one-way clutch.

The Briggs and Stratton hybrid may be operated all-electrically or with the combined power of both the motor and the ICE, at the discretion of the driver. It carries two adults, two children, and packages. Its curb weight is 3,200 pounds including a propulsion battery assembled from 12 production golf-car batteries weighing about 800 pounds which are carried in the 200-pound captive trailer. The maximum electric motor output, 20 horsepower, is reported to accelerate the car from 0 to 30 mph in 10.5 seconds and suffice for driving at speeds up to 40 mph in urban areas. All-electric range is 30 to 60 miles. The 18-horsepower

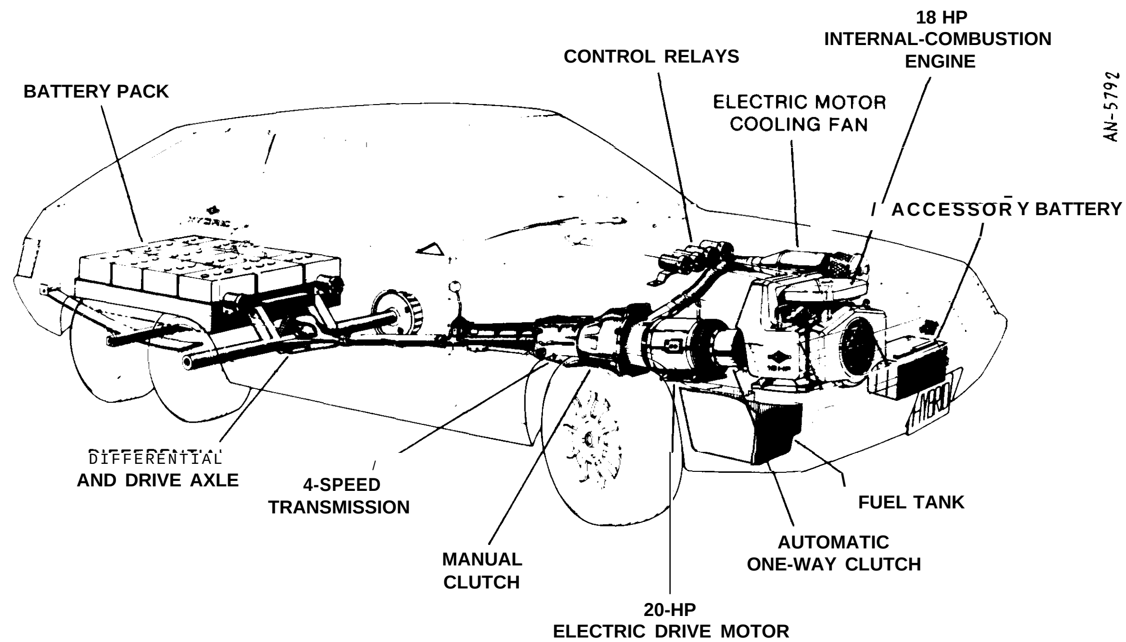


Figure 4.3 Schematic of the Briggs and Stratton Hybrid Electric Car

ICE alone gives the car unlimited cruising range at speeds up to a maximum of 45 mph. Motor and engine together allow 55-mph speed. Fuel economy on the ICE is 25-40 mpg. The controller is a simple contactor device which does not provide regeneration during braking or battery recharging frOm the ICE.

The Briggs and Stratton hybrid is essentially a range-extension hybrid with the low acceleration of present all-electric vehicles. With improved batteries capable of higher power output and a larger electric motor, use of the ICE could be unnecessary to reach freeway speeds. It could then be operated purely for range extension. A lower-drag body with a slightly larger engine would allow cruising at 55 mph on the ICE alone.

Other recent hybrids have been even more dependent on the ICE for assisting the electric drive in all but the least demanding urban conditions. One example is the Volkswagen Hybrid Taxi, derived from the familiar VW van by addition of an electric motor and batteries to the standard rear engine-transaxle drive train.[8] Another is the Daihatsu 1.5-ton truck developed several years ago in Japan. The major objectives of this design are quiet, emission-free operation at low speeds in crowded urban areas. The drive train configuration, shown in Fig. 4.4, is identical to that of the Briggs and Stratton hybrid except that a controller using both armature and field choppers is employed. The maximum speed of the truck on the 85-horsepower diesel ICE is about 50 mph, while on the 40-horsepower motor it is about 35 mph.[9]

The Hybrid Test Vehicle HTV-1, a high-performance design under development for the Department of Energy by a team headed by General Electric, is illustrated in Fig. 4.5. The HTV-1 is a five-passenger

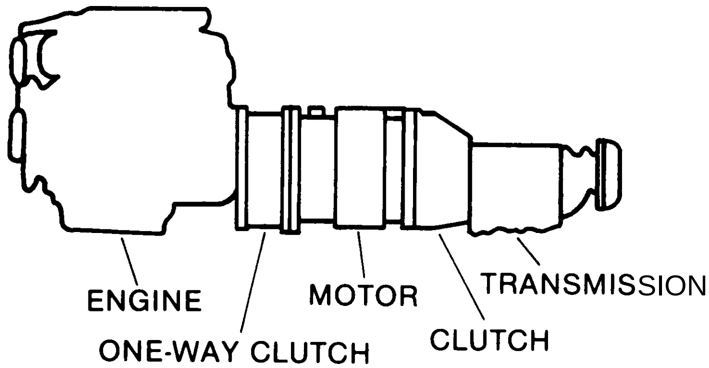


Figure 4.4 Power Train of Daihatsu 1.5-ton Hybrid Truck

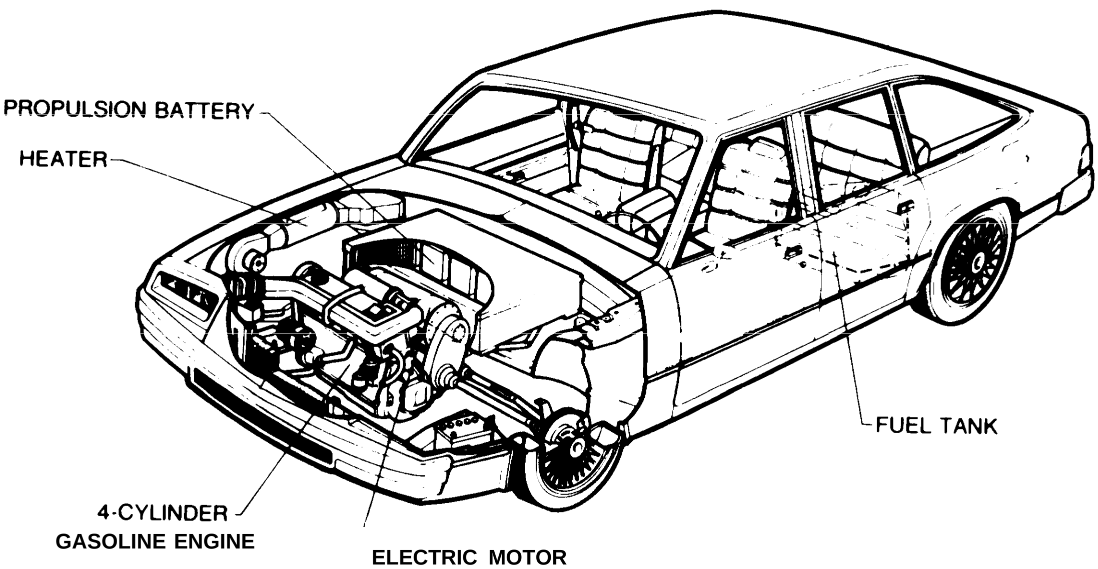


Figure 4.5 Schematic of DOE's Hybrid Test Vehicle HTV-1

intermediate-size car comparable in both performance and accommodations to conventional ICE cars. The entire hybrid drive train and propulsion battery are placed in the front of the car. The car is expected to weigh about 3,950 pounds, some 800 pounds more than a comparable conventional car. Its ten lead-acid batteries will weigh 770 pounds; they will be improved stat-of-the-art batteries expected from the DOE Near-Term Battery Program.[4]

The electric motor of the HTV-1 is a DC machine controlled by a field chopper and battery switching, with 44 horsepower peak output. It will power the 'primary-electric" mode of urban driving at speeds below 31 mph. A 4-cylinder, 60-horsepower fuel-injected ICE will operate on demand for bursts of high acceleration during the primary-electric mode, and will provide the primary capability for higher-speed driving. The front wheels of the HTV-1 preliminary designs are driven by both engine and motor through a 4-speed, automatically-shifted gear box. **Maximum** acceleration using both engine and motor was estimated for the preliminary HTV-1 design at 0-31 mph in 5 seconds and O-56 mph in 12.6 seconds, implying capability for accelerate g from O to **40** mph in 7 to 8 seconds. Top speed was estimated at 93 mph.[4]

Petroleum use for the preliminary **HTV-1** design was projected to be 63 percent of that for the comparable conventional vehicle.[4] More recently, General Electric has indicated that performance of the final design may be slightly reduced, an automatic 3-speed transmission substituted for the 4-speed gear box, and petroleum use de eased to 45-60 percent of that for the comparable conventional car.[10]

Design Tradeoffs

In the range-extension hybrid, increasing battery size increases range on electricity alone and thus increases the portion of total travel on electricity rather than gasoline. AS in the electric vehicle, however, increasing battery size also increases vehicle weight, sticker price, energy use per mile, and life-cycle cost.

For the range-extension hybrid, then, the crucial design tradeoff is between expense and independence of the gasoline pump. The critical design parameter is range on electricity alone, as in the pure electric vehicle. The importance of long electric range is much less for the hybrid, however, because it can ordinarily continue beyond its electric range using its ICE. Short electric ranges do not limit mobility, as in the case of the electric car. Furthermore, the electric range of the hybrid can be fully utilized on all long trips, including trips too long to be undertaken by the electric car. For such trips, the owner of the electric car would have to substitute an ICE car for the entire distance.

Though available travel data are less than definitive, it appears that a range-extension hybrid with a useful electric range of 100 miles would be able to accomplish electrically about 85 percent of the distance travelled annually by the average US car. For shorter electric ranges, decreases in electrification of travel would at first be slow: with 60-mile useful range, the hybrid could still electrify about 80 percent of average annual car travel. At still shorter ranges, however, electrification would drop rapidly (see Fig. 4.6). Useful range is the distance which would be driven on electricity before starting the ICE of the hybrid. It would probably be limited to 80 percent of the maximum

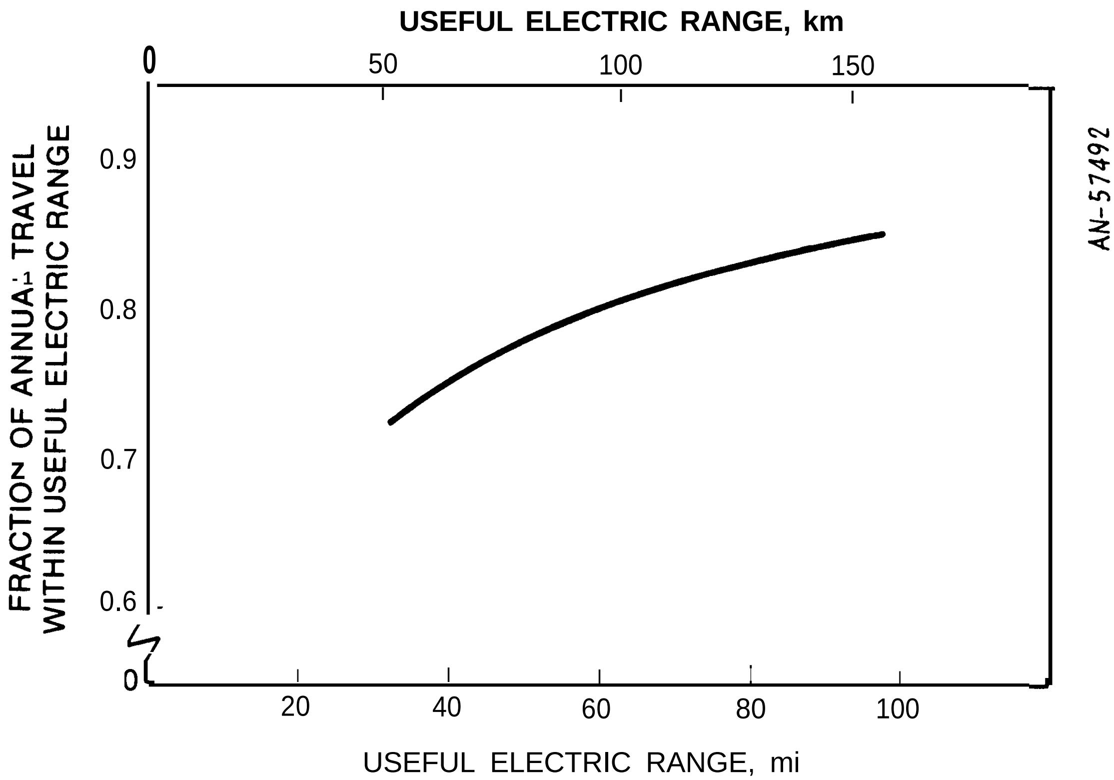


Figure 4.6 Annual Travel on Electricity Versus Useful Electric Range of Hybrid Cars

electric range, in order to leave sufficient battery capability available for assisting the ICE with electric power for bursts of acceleration.

To project the costs which must be weighed against the benefits of increasing electrification, key characteristics for future range-extension hybrids were projected using the same methods and assumptions employed to project characteristics for pure electric vehicles (see Appendix). The projections were made for near-term hybrids with lead-acid and nickel-zinc batteries. Depending on battery size, the projected four-passenger cars with near-term batteries could offer:

- 45-105 miles useful urban range on electricity alone.
- Sticker prices of $7,000 to $10,000.
- Annual fuel usage from 70 gallons per year for the short-range cars to 50 gallons per year for the long range cars (for annual travel of 10,000 miles).

The initial and life-cycle costs of the comparable ICE vehicle are projected to be $4,470 and 21.4 cents per mile. Maximum battery weights assumed were 32 percent of vehicle test weight for lead-acid batteries, and 28 percent for nickel-zinc batteries. The minimum battery weight was 23 percent of test weight for lead-acid battery vehicles and about 19 percent for nickel-zinc vehicles. At any given range, the cars with nickel-zinc batteries are considerably lighter, about equal in sticker price, and roughly 28 percent more expensive on a life-cycle basis than the cars with lead-acid batteries due to the shorter life projected for the nickel-zinc battery.

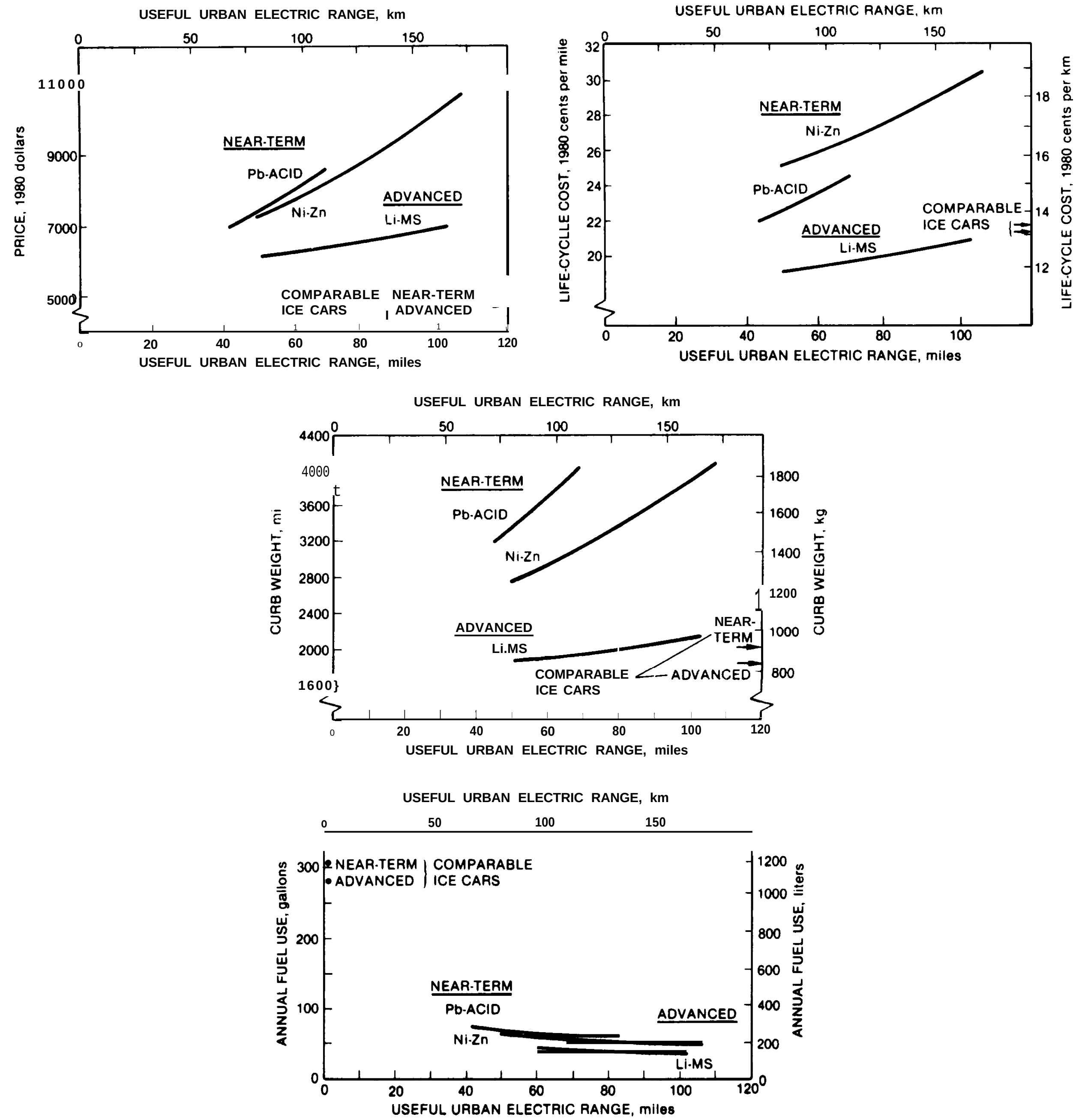
Projections were also made for four-passenger range-extension hybrids using advanced lithium-metal sulfide batteries. Depending on battery size, the projected cars would offer:

- 50 to 100 miles urban range on electricity alone.
- $6,100-7,000 sticker price.
- 19-21 cents per mile life-cycle cost.
- 45 gallons per year gasoline use at the shortest range to 35 gallons per year at the longest range (for annual travel of 10,000 miles) .

The comparable conventional car would offer a sticker price of $5, 140, a life-cycle cost of 21.7 cents per mile, and an annual petroleum use of 280 gallons, approximately.

Figure 4.7 further illustrates the tradeoffs between cost and petroleum use. The projections do not, however, include hybrids with the nickel-iron or zinc-chlorine batteries employed in projections for electric cars. This is because the versions of these batteries now under development have insufficient power output per pound to permit hybrid designs with relatively small batteries and short ranges. For those battery types to be used in range-extension hybrids, versions designed for higher power in relation to energy are desirable. Present design goals are better suited to pure electric vehicles, for which a lower relative level of power output is satisfactory.

A more complicated set of design tradeoffs arises for the high-performance hybrid because the designer has an additional degree of freedom: shifting acceleration power requirements from the electric motor to the internal combustion engine. In the high-performance hybrid, the ICE can be started at any time to meet acceleration requirements, even during the primary-electric operating mode. With the ICE's power instantly available, the designer is free to reduce the electric motor size and battery size at will. This makes the high-performance hybrid less expensive, but more dependent on petroleum fuel, i.e., more like an ICE car and less like an electric car.



Assumptions: Mid-1980 dollars
Useful electric range equals 80% of maximum electric range
Acceleration Capability: 0-40 mph in 10 seconds
Driving Cycle: SAE J227a, Schedule D

Source: General Research Corporation

Figure 4.7 Design Tradeoffs for Four-Passenger Range-Extension Hybrid Cars

For the near term, ICES large enough to provide from half to two-thirds of maximum available acceleration power are favored for high-performance hybrids.[4] The design tradeoffs behind such choices were developed by four independent contractor teams during the study and preliminary design phase of the DOE near-term hybrid vehicle program. The contractors' reports detailing this work, however, are not yet generally available.

4.3 REPRESENTATIVE FUTURE HYBRID VEHICLES

Hybrid designs offering low electric range and electric acceleration capability are generally cheapest to buy and to operate over their life, at least given today's gasoline and electricity prices. By the time hybrids are marketed in high volume, however, it is likely that a spectrum of designs will be offered, including many with more than minimum electric capability. Especially if petroleum shortages and price increases recur, many buyers may prefer range-extension hybrids with long electric range and low dependence on petroleum fuels. Many others, however, may still prefer hybrids with lower prices and less electric capability or with performance as high as that of large conventional cars, despite greater petroleum use and less operational capability when it is unavailable. This section addresses both possibilities.

Range-Extension Hybrids

A maximum range of 75 miles on battery power alone is a reasonable choice for representative future range-extension hybrids. This leads to a useful electric range of 60 miles before the ICE would ordinarily be started, at 80 percent depth of battery discharge. This would be enough for electrification of about 80 percent of the annual travel by the average US automobile. This is the same level of electrification that the 100-mile all-electric car would achieve, as discussed further in Chapter 6.

Near-term four-passenger range-extension hybrids with 60-mile useful ranges and lead-acid or nickel-zinc batteries would offer:

- Sticker prices of about $8,000 or $7,800, slightly less than the prices of about $8,500 or $8,100 projected for electric cars with the same types of batteries but 69 percent or 64 percent greater than the $4,740 price of the comparable ICE car.

- Life-cycle costs of 23.5 or 26.0 cents per mile, less than the figures of 23.9 or 26.6 cents per mile estimated for all-electric versions but 5 percent or 20 percent greater than the 21.4 cents per mile for the comparable ICE car.

- Annual fuel use in average travel of about 66 or 60 gallons per year, only 22 percent or 20 percent of the 300 gallons per year projected for the comparable ICE car.

A four-passenger hybrid with advanced lithium-metal sulfide battery and 60 mile useful electric range might offer a price just 20 percent above that of the comparable ICE car, a life cost 11 percent lower, and a fuel use of only 45 gallons per year, just 16 percent of the 280 gallons per year projected for the comparable ICE car (see Table 4.1).

The range-extension hybrids weigh less and cost less than their electric counterparts because they offer less electric range and therefore require a smaller battery. The reductions in battery weight and cost exceed the weight and cost added by their ICE systems. In addition, the weight and cost of the necessary electric propulsion system and the remainder of the car are slightly reduced. For the near-term four-passenger car with nickel-zinc battery, for example, 200 pounds of expensive battery is replaced by 150 pounds of less expensive ICE system (Table 4.2).

Like pure electric vehicles, the range-extension hybrids are more expensive to buy than comparable ICE cars because of the weight and cost of their batteries and electrical equipment. On a life-cycle basis, they are more expensive due to battery depreciation and the extra costs of capital, which exceed the savings they bring on repairs and maintenance, and on energy. Further details are given in Table 4.3.

Fuel costs projected for the comparable ICE cars are about 4 cents per mile. Thus doubling the assumed gasoline price (to $2.50 per gallon) would add 4 cents per mile to the life cycle costs of the ICE cars. If gasoline prices rose from $1.25 to about $2.00 per gallon (in 1980 dollars) and other costs remained unchanged, the near-term range-extension hybrid with lead-acid battery would be no more expensive (in terms of life cycle cost) than the comparable ICE car. For the hybrid with nickel-zinc battery, the corresponding gasoline price is $2.70 per gallon. Because of the very high performance and long life projected for the lithium-metal sulfide battery, plus a low off-peak price for electricity, the advanced range-extension hybrid is already cheaper on a life-cycle basis than the comparable ICE car, even at 1980 gasoline prices.

If petroleum alone were used to generate recharge energy, the energy requirements of the lead-acid and nickel-zinc hybrids would be equivalent to those of conventional cars getting 31 to 33 mph (miles per gallon) in urban driving. The car with advanced lithium-metal sulfide batteries would increase this equivalent fuel economy to about 42 mpg. This is competitive with the projected conventional cars offering the same passenger space and acceleration, built with the same materials, and using conventional ICE drive trains, which might get 33 to 36 mpg in urban driving. If coal alone were used to generate electricity and produce synthetic gasoline, however, the near-term hybrid cars would offer the equivalent of 53 and 58 mpg, and the advanced battery car 73 mpg. This results from the inefficiencies of using coal rather than petroleum to produce gasoline. Table 4.4 summarizes these projections.

TABLE 4.1

REPRESENTATIVE FUTURE RANGE-EXTENSION HYBRID CARS

	Near-Term			Advanced	
	Pb-Acid	Ni-Zn	(ICE)	Li-MS	(IcE)
Battery Specific Energy, Wh/lb	22.7	31.8		68.0	
Useful Electric Range, mi	60	60		60	
Curb Weight, lbs	3750	2960	2010	1910	1810
Sticker Price, mid-1980 dollars	8020	7770	4740	6200	5140
Life-Cycle Cost, cents per mi	23.5	26.0	21.4	19.3	21.8
Electricity Use, kWh/mi	0.38	0.37		0.27	
Fuel Economy, mpg	31	34	33	45	36
Annual Fuel Use, gal/yr	66	60	304	45	282

Assumptions:		
	Electricity Price	$0.03 per kwh
	Gasoline Price	$1.25 per gallon
	Hybrid Vehicle Life	12 years
	ICE Vehicle Life	10 years
	Annual Travel	10,000 mi
	ICE Use in Hybrids	20 percent
	Urban Driving Cycle	SAE J227a, Schedule D, for hybrid cars Federal Urban Driving Cycle for ICE cars
	Acceleration Capability	0-40 mph in 10 seconds
	Passenger Capacity	Four persons plus luggage

Source: General Research Corporation. Performance and cost estimates for all vehicles were made with the ELVEC and EVWAC computer models. Costs are in mid-1980 dollars and are based on mass production of all vehicles (300,000 units or more per year).

TABLE 4.2

WEIGHT AND COST BREAKDOWNS FOR REPRESENTATIVE FUTURE ELECTRIC AND RANGE-EXTENSION HYBRID CARS

	Electric		Hybrid		Change	
	Weight, lbs	cost, $	Weight, lbs	cost, $	Weight, lbs	cost, $
Battery	890	2410	700	1880	-190	-530
ICE Propulsion			150	250	150	250
Electric Propulsion	340	1020	330	1000	-lo	-20
Basic Vehicle	1800	4700	1780	4640	-20	-60
Total	3030	8130	2960	7770	-70	-360

Assumptions: Near-Term Technology
Nickel-Zinc Battery
Nominal Maximum Electric Range: 100 miles - electric car
75 miles - hybrid car
Electric Propulsion Rating (Short-Term):
47 hp - electric car
46 hp - hybrid car
ICE Propulsion Rating (continuous) - 18 hp
ICE Fuel Tank Size: 7.3 gal

Source: General Research Corporation

TABLE 4.3

INITIAL AND LIFE-CYCLE COSTS OF REPRESENTATIVE FOUR-PASSENGER RANGE-EXTENSION HYBRID CARS

	Near-Term			Advanced	
	Pb-Acid	Ni-Zn	(ICE)	Li-MS	(ICE)
Initial Cost, dollars	8020	7770	4740	6200	5140
Vehicle	6410		4740	5300	5140
Battery	1410			900	
Life-Cycle Cost, cents per mi	23.7	26.0	21.4	19.4	21.8
Vehicle	5.0	4.4	4.3	4.0	4.7
Battery	2.3	5.7		1.4	
Repairs & Maintenance	2.0	2.0	3.9	2.0	3.9
Replacement Tires	0.6	0.5	0.4	0.4	0.4
Insurance	2.2	2.2	2.2	2.2	2.2
Garaging, Parking, Tolls, etc.	3.1	3.1	3.1	3.1	3.1
Title, License, Registration, etc.	0.7	0.6	0.5	0.5	0.5
Electricity (per electric mile)	2.2	1.9		1.5	
Fuel and Oil (per ICE mile)	4.3	3.9	4.0	3.0	3.7
Cost of Capital	5.2	5.2	3.0	4.0	3.3

All costs are in mid-1980 dollars.

Assumptions:

Electricity Price	$0.03 per kWh
Gasoline Price	$1.25 per gallon
Hybrid Vehicle Life	12 years
ICE Vehicle Life	10 years
Annual Travel	10,000 miles
Travel Using ICE	20 percent
Car and Battery Salvage Value	10 percent
Cost of Capital	10 percent per year

Car and battery purchases are 100 percent financed over their useful lives.

Repair and Maintenance cost equal to that of an electric vehicle for all-electric travel, and equal to that of an ICE vehicle for travel using ICE.

Electricity cost includes a road use tax, equal to that paid by typical gasoline vehicles of equal weight via state and federal gasoline taxes.

Source: General Research Corporation. Cost categories and many entries, such as tires, insurance, garaging, etc., are based on periodic cost analyses by the Department of Transportation (see Ref. 11). All costs shown were computed by tile Electric Vehicle Weight and Cost Model (EVWAC), Ref. 12.

TABLE 4.4

EQUIVALENT FUEL ECONOMIES OF FOUR-PASSENGER RANGE-EXTENSION HYBRID CARS RECHARGED FROM PETROLEUM OR COAL RESOURCES

	Equivalent Miles per Gallon*	
	Oil	Coal
Near-Term Cars		
Lead-Acid	31	53
Nickel-Zinc	33	58
(Comparable ICE Car)†	(33.0)	(33.0)
Advanced Cars		
Lithium-Metal Sulfide	42	73
(Comparable ICE Car)†	(35.6)	(35.6)

Assumed Conversion Efficiencies:

Crude oil to gasoline	- 89%	Coal to gasoline	- 53%
Crude oil to electricity	- 28%	Coal to electricity	- 30%

Efficiencies include losses and energy inputs in extraction of the energy resource from the ground, transportation and conversion to its final form for vehicular use, and delivery to the vehicle. Source: Ref. 13

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*Equivalent miles per gallon is the urban fuel economy of an ICE car requiring the same use of petroleum (for gasoline) or coal (for synthetic gasoline) as would be needed to generate recharge electricity for the hybrid car.

†The comparable ICE cars offer the same passenger compartments and acceleration capability as their hybrid counterparts, are built with the same materials, and use conventional ICE drive trains. Their fuel economies are projected for urban driving.

The range of the range-extension hybrid during all-electric operation would be as sensitive to head winds, grades, and other driving conditions as the ranges of all-electric cars. The importance of this sensitivity to motorists would be much less, however, because the availability of the ICE would insure against premature battery depletion before the end of a planned trip. An electric air conditioner or an electric heat pump for both cooling and heating would be attractive for the range-extension hybrid for this same reason: trip completion would not be threatened by premature battery depletion. A gasoline heater would also be facilitated by the availability of the gasoline on board for the ICE.

Comparisons between larger hybrid cars and comparable conventional cars, or between hybrid and conventional light trucks, would be like those drawn here for four-passenger cars. That is, if the sticker price of the four-passenger hybrid were 70 percent above that of the four-passenger ICE car, the sticker prices of other hybrid vehicles would also be about 70 percent above the prices of the comparable ICE vehicles.

Because of its low reliance on its ICE, the range-extension hybrid poses few technical problems beyond those of the electric vehicle on which it is based. The availability of the ICE enhances the dependability of the vehicle, since it is disconnected from the basic electric drive in most driving but can be engaged to provide propulsive power not only after battery discharge, but in the event of typical electrical system failures. Excessive ICE operation in urban areas, with attendant petroleum use and pollutant emissions, is unlikely: the driver might thus improve acceleration capability or avoid electrical recharge from utility power, but the ICE is too small to add greatly to acceleration, and operation on gasoline is considerably more expensive than on electricity. Furthermore, plugging in the car for overnight recharge at **home will generally be more convenient than making stops at the filling** station for gasoline.

High Performance Hybrids

Working independently, four design teams completed thorough trade-off studies and preliminary designs for high-performance hybrids for the US Department of Energy in late 1979. The four teams were headed by Fiat (the Italian auto maker), General Electric, and two small firms: Minicars and South Coast Technology, both of Santa Barbara. The trade-off studies considered typical driving needs against the performance capabilities, costs, and risks of a wide variety of future technological alternatives to choose the components and operating strategies for the preliminary designs. The General Electric study and design led to selection of the GE team for final design and construction of DOE's Hybrid Test Vehicle **HTV-1, which is to be completed** about the end of 1982 (see Fig. 3.5). The results of the preliminary design work have been reported by the Cal Tech Jet Propulsion Laboratory (JPL), manager of the work for the Department of Energy.

The performance projected for the four preliminary designs is much like that of recent intermediate and full-size US sedans, and much higher than that of electric vehicles:

- Acceleration from O to 31 miles per hour in 4.3-5.0 seconds, compared with about 9 seconds for the DOE Electric Test Vehicle ETV-1 and 6-7 seconds for the range-extension hybrids and future electric cars projected elsewhere in this report.

- Acceleration from O to 56 miles per hour in 12.6-13.9 seconds, compared with 25-30 seconds for the ETV-1 and about 20 seconds for the range-extension hybrids and future electric cars.

The preliminary designs of the high-performance hybrids also provided cruising speeds from 55 to 80 miles per hour, maximum speeds from 80 to 110 miles per hour, and seating for either 5 or 6 passengers.

The costs of the preliminary high-performance hybrid designs exceed those of the comparable ICE cars projected by the individual study teams, but they are generally below those of range-extension hybrids and pure electric cars in this report:

- Retail prices are projected to be 20 to 60 percent above those of comparable ICE cars, whereas sticker prices of the range-extension hybrids were estimated to be 65 to 70 percent higher (with near-term batteries).

- Life-cycle costs were estimated to range from slightly less to about 25 percent above life-cycle costs for the comparable ICE cars.

Estimated fuel uses for the preliminary high-performance hybrid designs are substantially higher than those for the range-extension hybrids: 30 to 60 percent of the fuel usages projected for the comparable ICE cars, versus 20 percent for the range-extension hybrid (see Table 4.5).

Though all the preliminary designs of the high-performance hybrids employ the parallel configuration, they differ considerably in battery and drive train choices. The Fiat preliminary design places much more reliance on electric power than the others: its electric motor almost equals its ICE in power output, whereas the others use ICES providing up to twice the power of the electric motor. The high reliance of the Fiat design on electricity is based on selection of the high-performance nickel-zinc battery. Two of the other designs employed future lead-acid batteries instead because of the higher risks foreseen in obtaining

TABLE 4.5

PROJECTED PERFORMANCE, COST, AND FUEL USE OF PRELIMINARY DESIGNS FOR HIGH-PERFORMANCE HYBRID CARS

	Fiat	GE	Minicars	SCT
PERFORMANCE				
Acceleration time, sec				
0-31 mph	5.0	5.0	5.0	4.3
O-56 mph	13.8	12.6	13.0	12.9
Speed, mph				
Cruise	75	81	55	81
Maximum	81	93	112	103
Passenger Capacity	6	5	5	6
COST (relative to ICE car*)				
Retail price, %	121	135	140	161
Life cycle cost, %[t]	102	99	123	127
FUEL USE (relative to ICE car), %	31	63	44	52

Source: JPL (Ref. 4)

* The comparable 1985 ICE car for each design, as projected independently by each individual contractor.

[t] Based on prices (in 1980 dollars) of $1.38 per gallon of gasoline and 5.4 cents per kilowatt-hour of electricity.

nickel-zinc batteries with satisfactory life and overall cost. One design used nickel-iron batteries, considered intermediate in both performance and risk. Both designs not based on lead-acid batteries provided alternatives for backup use of lead-acid batteries.

Only the Fiat design, with its high electric capability, was capable of following the Federal Urban Driving Cycle without use of its ICE. This was made possible not only by the nickel-zinc battery and large electric motor, but also by assumptions of very advanced tires and low aerodynamic drag. Tire rolling resistance was assumed to be 0.45 percent, under half that assumed for other designs. The aerodynamic drag coefficient was projected to be 0.3, about 25 percent less than coefficients estimated for the other designs. The high reliance of the Fiat design on electricity led to the lowest projected annual usage of petroleum fuel, 31 percent of that for the reference ICE vehicle, whereas the other preliminary designs require up to 63 percent of the petroleum used by the reference vehicle.

Two of the designs use electric controllers which do not include expensive armature choppers. The GE design combines a field chopper with battery switching and a four-speed gear box with automatic shift, an arrangement also appropriate for near-term range-extension hybrids. The other three designs also include multispeed transmissions.

Table 4.6 offers additional details of battery and drive train characteristics for the preliminary high-performance hybrid designs. Comparison of the four preliminary designs shows clearly how projections of electric and hybrid vehicle characteristics can vary, even with clear-cut basic assumptions and groundrules, and even for periods as short as five years. The four contractors who independently produced these preliminary designs all worked towards--and met--the same minimum performance and payload requirements. All were required to utilize components and fabrication techniques within the state of the art by 1980 or earlier and amenable to mass production by the mid-1980's. They nevertheless differed to the extent of choosing nickel-zinc rather than lead-acid batteries, and projecting tires with rolling resistances differing by a factor of two. All the contractors were required to design vehicles with purchase prices competitive with those of reference ICE cars, and life costs equal to those of the reference ICE cars. None eventually projected a purchase price less than 20 percent above the projected price of the reference ICE car, but two projected life-cycle costs which were approximately equal to those of the reference ICE cars.

The high-performance hybrid approach has special advantages for application in light trucks and vans. These are basically load-carrying vehicles, and though they often serve as passenger cars with very little

TABLE 4.6

PROJECTED WEIGHT AND DRIVE TRAIN CHARACTERISTICS
OF PRELIMINARY DESIGNS FOR HIGH-PERFORMANCE HYBRID CARS

	Fiat	GE	Minicars	SCT
Curb Weight, lbs	3,580	3,940	3,850	4,110
Maximum Power Ratings				
ICE, hp	50	60	65	71
Electric Motor, hp	47	44	32	40
Controller				
Battery Switching		x		
Field Chopper	x	x		x
Armature Chopper	x			x
Transmission Type	C V T	4-speed gear box	3-speed auto	4-speed auto
Battery Type	Nickel-Zinc	Lead-Acid	Lead-Acid	Nickel-Iron
Battery Fraction, percent[4]	18	18	18	13

Source: JPL (Ref. 4)

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[1]Continuously variable transmission.

[2]With lock-up torque converter.

[3]Automatically shifted.

[4]Battery weight as a percent of vehicle test weight (with 300-lb payload).

load, they are called upon to move large and heavy loads with surprising frequency even in personal rather than commercial service.[14] Electrification of heavily-loaded vehicles is unattractive because battery weight (and expense) must be increased in proportion to load weight in order to maintain range and performance. The ICE in the high-performance hybrid could much more effectively supply the extra power for adequate acceleration and range during heavily-loaded operation of light trucks and vans, yet leave unloaded and undemanding travel to the electric drive and to energy from electric utilities.

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