Using Plug-in Hybrid Vehicles

to Drastically Reduce Petroleum-Based Fuel Consumption and Emissions

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WIDE-SCALE INTRODUCTION and utilization of specifically designed plug-in hybrid vehicles could reduce the use of oil to produce gasoline and diesel fuel by 50% to 75% without significantly degrading the performance and operability of these hybrids compared to similar standard automobiles and light trucks. The large-scale substitution of electricity produced by pollution-free power plants (nuclear and renewable energy) in place of gasoline and diesel fuel could drastically reduce oil imports, balance-of-payment deficits, and pollution emissions. Whether the life-cycle cost of introducing plug-in hybrids on such a massive scale is balanced by the benefits is dependent upon factors beyond the scope of this analysis. However, intuitively, any large-scale reduction in the use of petroleum-based fuels would improve the current energy, economic, and political situations of the United States. The plug-in hybrid vehicle approach discussed here is one of very few paths forward that appears feasible in the short- or medium-term. The benefits and challenges of using hybrid automobiles to reduce hydrocarbon fuel consumption drastically are discussed below in quantitative terms with the view to showing that the proposed approach is feasible, practical, compellingly rational, and worth implementing on a significant scale in the next decade.

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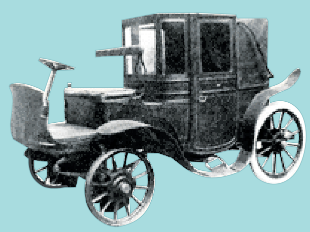
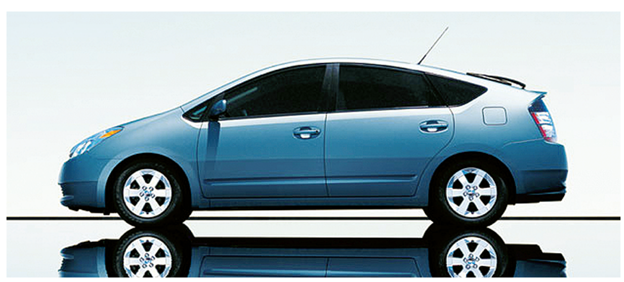


1903 gasoline and electrical hybrid

BACKGROUND

The hybrid vehicle is not a new concept. Hybrids were first conceived and vehicles constructed about 100 years ago. Even though it was demonstrated to be a viable concept technically, the hybrid vehicle received relatively little attention until the late 1960s when it was considered by some groups to be a possible way of meeting the newly established emission reduction requirements for automobiles. Early, but limited, research programs showed that emissions could be dramatically reduced by using a hybrid vehicle. However, the real stimulus for pursuing hybrids with an organized effort and significant funding came as a result of the petroleum embargo and resulting energy crisis of 1973-74.[1] Congress passed Public Law 94-413, the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976, which directed the newly established Department of Energy (DOE) to pursue, among other activities, the technologies associated with electric and hybrid vehicles. Through subsequent DOE funding, many studies were performed and many experimental components, systems, and vehicles were built and tested. While these activities were underway, the energy crisis subsided simultaneously with automobile manufacturers making dramatic improvements in conventional vehicle fuel efficiency and emission of pollutants. The introduction and wide spread deployment of engine-controlling microprocessors along with continued improvements in exhaust after-treatment have led to a near doubling of EPA fuel mileages and more than an order of magnitude reduction in exhaust emissions. As a result, there has been little corporate interest in pursuing the heavier, more fuel efficient, less polluting, more complex, and more expensive hybrid vehicles. Even so, the considerable work that had been completed showed that hybrids could simultaneously improve fuel efficiency and greatly reduce emissions compared to current



2005 Toyota Prius, a current hybrid

1. *The author's introduction to hybrids occurred in the early 1970s at the University of Florida where Dr. Vernon P. Roan Jr.* [FL A '58] *and his students built two hybrid vehicles: 1) a small hybrid using a Datsun chassis, a 14-hp Onan motor-generator, and eight automotive lead-acid batteries, and 2) a 24-passenger, 30-ft. urban transit bus using a 60-hp diesel engine driving two 15-kW generators charging two 1,600 lb. lead-acid batteries. The bus was loaned to the EPA for extensive testing of emissions and fuel usage* [Roan 1975, 1976].

conventional vehicles, and DOE continued supporting some hybrid-oriented research activities. The not-for-profit Electric Power Research Institute (EPRI) of the electric-utility industry is one of the few organizations that has continued an extensive research program for hybrids, with special emphasis on hybrid plug-in vehicles using batteries that are charged primarily with electricity generated by utilities.

WHAT MAKES HYBRIDS RESPONSIVE, EFFICIENT?

The reason that hybrid vehicles accelerate so well is that torque provides acceleration. Torque produced by a gasoline engine increases with engine speed from a low value at low rpm to a maximum in the 1,500-2,500 rpm range, after which it falls off somewhat. However, in an electric motor, torque is quite large; its maximum value occurs at zero rpm, and it remains relatively constant during acceleration. Hence, in hybrids, the combination of an electric motor and a gasoline engine together provides higher torque and better acceleration than is available in comparable conventional vehicles of equal horsepower, even though the hybrids usually weigh more and have smaller gasoline engines.

The reason that all hybrids are so fuel efficient is that the amount of fuel consumed per unit of energy output (specific fuel consumption—pounds or gallons per horsepower-hour) generally decreases with power level until it reaches a minimum at 75-85% of maximum power. Thus, a smaller engine running at a higher percentage of its full power is more efficient and more economical for a given load than a larger, heavier gasoline engine operating at a lower percentage of its maximum power. Furthermore, regenerative braking is used on almost all hybrids. Regenerative braking converts some of the kinetic energy of a moving vehicle to electrical energy and stores it in a battery for later use, rather than converting it to wasted heat by friction between the brake discs and brake pads.

TYPES OF HYBRID ELECTRIC VEHICLES

Over the years a wide variety of hybrid configurations has been tried, and many organizations and individuals have found their favorites. Both gasoline and diesel engines have been tested; both series and parallel-drive configurations have been used. The advent of digital-control systems to optimize the operation of the various components has led to more efficient, but usually more complex, hybrid systems. Today, four general types of hybrids are commonly recognized: 1) micro hybrids (sometimes called start-stop hybrids), 2) mild hybrids, 3) full hybrids, and 4) plug-in hybrids. These have many common components, such as regenerative braking, gasoline or diesel engine, electric motor, alternator, battery pack, and central digital-control system.

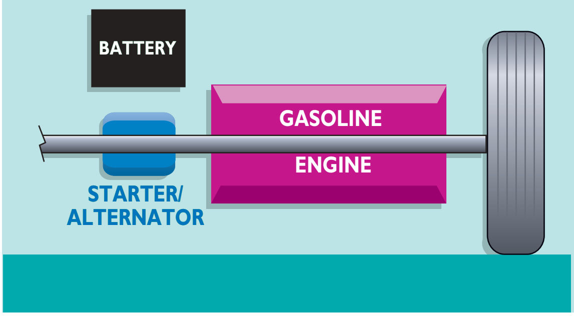
In the diagrams of the four types of hybrids on the next page, the size of the schematic representations of the primary components indicates their relative size. As we move from Figure 1 to Figure 4, the size of the electrical components become larger and their use increases, the gasoline or diesel engine becomes somewhat smaller, the performance (acceleration) increases, and the fuel economy increases. However, larger components are heavier, more complex, and more expensive. Furthermore, the decrease in the size of the gasoline engine is usually less than the increase in size of the electrical components. For these reasons, hybrids almost always out perform similar conventional vehicles. Drivers expect their automobiles to accelerate rapidly, yet be economical, and hybrids do provide the desired combination of performance and economy.

TODAY'S HYBRID VEHICLES

Most investigators consider the conventional internal-combustion-engine vehicle to represent a mature technology with further improvements being of an evolutionary nature. Thus for significant improvements in fuel efficiency and emissions, new technologies are needed. One such technology is the modern hybrid-electric vehicle that was introduced to the public as the Toyota Prius and Honda Civic and Insight hybrids. The success of the Prius, as evident by the long waiting time for delivery, has convinced the firm to schedule 100,000 Prius models for the U.S. market in 2005 and to introduce two additional hybrid models—the popular light SUV Highlander and a premium SUV, the Lexus RX400h. Toyota and Honda have clearly established that there is a market for hybrid automobiles in the U.S. The Prius and the new Ford Escape hybrid (using Toyota technology), are full-hybrids. The Civic and Insight models introduced in the late 1990s, the Honda Accord hybrid, and the Dodge RAM Diesel light-truck hybrid to be introduced in 2005 are mild hybrids. The Chevrolet Silverado and GMC Sierra are micro-hybrids that are to be introduced in 2005 [*Consumer Reports*, 2004].

Full-hybrids significantly improve gas mileage, but tend to cost 10%-15% more than other hybrids and conventional vehicles. Independent testing by *Consumer Reports* indicates overall fuel mileages of 44 mpg for the Prius, 36 mpg for the comparable sized Civic, and 51 mpg for the small two-seat Insight, somewhat less than the EPA-mileage numbers on their window stickers [*Consumer Reports*, 2004]. While these gasoline mileage increases are impressive, typically 40%-45% more for full-hybrids, 20%-25% more for mild-hybrids, and 10% for micro-hybrids, the differences are not sufficient to have a dramatic impact on the national consumption of hydrocarbon fuels. Hence, a different mode of operation and some redesign of full-hybrids will be required to save larger amounts of gasoline and diesel fuel. One manufacturer, DaimlerChrysler, in cooperation with EPRI, is testing the first of five hybrids (versions of its Sprinter vans) that are designed for the batteries to be charged by connection to a utility electrical supply[2] [*Economist*, 2004]. Two gasoline versions will be tested in California and a diesel version will be tested in Kansas [DaimlerChrysler, 2004]. As will be shown below, this approach, if implemented widely, could drastically reduce both fuel consumption and pollution emissions while significantly

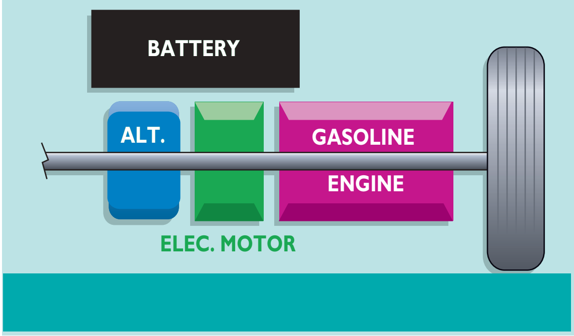
*FIGURE 1. MICRO HYBRID**



MICRO HYBRID

Engine cut-off – Whenever the vehicle stops, the engine is turned off to save gasoline.
Engine restart – When the driver pushes the accelerator, the integrated starter/alternator initiates acceleration of the vehicle and simultaneously starts the gasoline engine.
Acceleration – The integrated starter/alternator assists the gasoline engine in accelerating the vehicle until the desired speed is reached and during other short periods of acceleration.
Cruising – The gasoline engine alone propels the vehicle.
Fuel efficiency increase compared with non-hybrid: 10%.

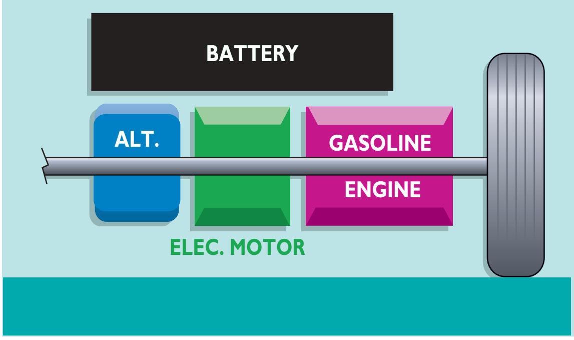
*FIGURE 2. MILD HYBRID**



MILD HYBRID

Electric motor assists gasoline engine – The main difference between the micro and mild hybrids is that the integrated starter/alternator is replaced with a separate electric motor and alternator that perform the same functions.
Gasoline engine dominates – In a mild hybrid vehicle, the electrical motor seldom propels the vehicle alone.
Larger electrical components – Compared with the micro hybrid, the electric motor, alternator, and the battery pack are larger and play a greater role in the operation of the vehicle.
Fuel efficiency increase compared with non-hybrid: 20-25%

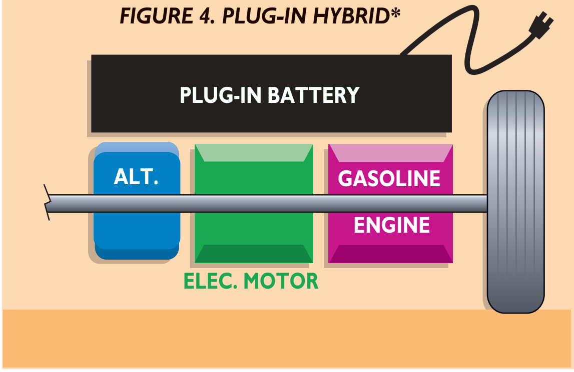
*FIGURE 3. FULL HYBRID**



FULL HYBRID

Larger electrical components – The configuration for the full-hybrid is essentially the same as for the mild-hybrid except that the electric motor, alternator, and battery pack are larger.
Full electric propulsion – The electric motor can and often does propel the vehicle alone, particularly in city (start-stop) driving.
Smaller gasoline engine – The gasoline engine may be smaller because the electric motor is larger.
Sophisticated control system – The control system is more complex in order to optimize the power management.
Fuel efficiency increase compared with non-hybrid: 40-45%

*FIGURE 4. PLUG-IN HYBRID**



PLUG-IN HYBRID

Electrical connection – The plug-in hybrid is similar to the configuration of the full-hybrid. The battery pack has a connection to an outside (utility) source of electrical energy for charging.
Larger electrical components – The battery pack, alternator, and electric motor are considerably bigger.
Smaller gasoline engine – The gasoline engine may be smaller.
Sophisticated control system – Control system must prevent charging of the battery by using the gasoline engine until the battery reaches the minimal level required for full-hybrid operation.
Fuel efficiency increase compared with non-hybrid: No gasoline is used at all while traveling within the range of the batteries. After that, fuel effieciency is comparable to that of full hybrids (above).

**The sizes of the colored blocks in the figures above represent the relative sizes of the components.*

reducing the cost of fuel for the average automobile owner. Perhaps most important, deploying hybrid vehicles does not require changes in driver behavior or fuel delivery infrastructure[2] [*Economist*, 2004].

U.S. LIGHT-VEHICLE TRANSPORTATION STATISTICS

Estimates based on extrapolated DOE-EIA data[3] from the 1990s indicate that in 2004 there were 225 million light-transportation vehicles in the U.S; 133 million were passenger automobiles and 92 million were light trucks (including SUVs, passenger minivans, pickup trucks, and delivery vans). It is further estimated that on any given day on average, 50% of U.S. vehicles are driven less than 20 miles. Using these statistics, we can develop a simple model to calculate the potential saving of fuel by the use of hybrids operating in a plug-in mode. The model assumes that only the electric motor, operating on batteries charged from electric-utility sources, is used to power a vehicle until the battery has discharged to about half of its stored energy (estimated to be 35 miles). Beyond that point, the gasoline or diesel engine and electric motor would operate together in the normal full-hybrid mode.

PLUG-IN MODE OF OPERATION

For purposes of this assessment, the standard automobiles and light truck vehicles are grouped and assumed to achieve an overall average of 20 miles per gallon of gasoline or diesel fuel.[4] Let us assume that all of the above vehicles are hybrids capable of the plug-in mode of operation in about three decades (i.e., 2035).[5] This mode involves charging the batteries of a hybrid overnight using electricity from an electrical outlet typically in the owner's garage. We assume that when batteries are fully charged, these hybrids can operate using only the electric motor for at least the first 35 miles.[6] For this type of operation, the controls of current full-hybrids would need to be modified so as not use the gasoline engine to recharge the batteries beyond the level necessary to sustain normal hybrid operation.

The vehicles envisioned by the author for plug-in operation are those manufactured by companies to today's standards equipped with normal features such as automatic transmission, air conditioning, and power steering. Hence, a larger electric motor and better and larger batteries probably would be required, which could lead to the use of a smaller gasoline or diesel engine. Solid-state digital controls capable of optimizing performance and economy while minimizing the use of fuel should make the performance of these vehicles more than competitive with comparable standard vehicles.

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>
> *"This represents 74% of the estimated nine million barrels of oil per day now used to produce gasoline and diesel fuel for standard automobiles and light-truck vehicles."*

MODEL TO CALCULATE FUEL SAVED BY PLUG-IN MODE OF OPERATION

The model assumes that each day one-half of the 225 million light-hybrid vehicles operate only for 15 miles on batteries alone while the other half operate on batteries alone for their first 35 miles and then automatically switch to normal full-hybrid mode—in which gasoline or diesel fuel powers the vehicles for the remaining miles. This means that electrical energy provided to recharged batteries would fuel these vehicles for a grand total of 5.625 billion miles per day.[7]

If the comparable standard (non-hybrid) light vehicles average 20 miles per gallon, then 225 million light vehicles would use 281 million gallons of fuel to travel 5.625 billion miles per day. Hence, it is theoretically possible, based on this simple model, to replace 281 million gallons (6.7 million barrels) of fuel per day with electricity by using hybrid vehicles operating in the plug-in mode. This represents 74% of the estimated nine million barrels of oil per day now used to produce gasoline and diesel fuel for standard automobiles and light-truck vehicles.[8]

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2. *As shown later, large scale use of the plug-in hybrid vehicles would require additional power plants and transmission/distribution facilities to deliver additional electrical power throughout the U.S.*

3. *Unless otherwise indicated, data on U.S. vehicles is from the DOE energy information administration's statistics available on the internet.*

4. *DOE EIA data show that in 2003, automobiles averaged 22.3 miles per gallon and light trucks averaged 17.7 mpg.; hence, 20 mpg is a reasonable weighted-average value.*

5. *This may be an unrealistic assumption, but it does allow us to evaluate the total potential savings of fuel associated with using hybrids operating in the plug-in mode. Fuel savings will be reduced in relation to the percent of light vehicles that are not hybrids.*

6. *Because the range of electric vehicles is typically 75 miles, it is reasonable to assume that hybrid batteries have sufficient charge after 35 miles to allow proper operation in normal full-hybrid mode.*

7. *Supporting calculations for this and all other derived quantities are available from the author at ruhrig@utk.edu.*

Recent graphical data attributed to EPRI and Daimler Chrysler support this quantitative result [*Economist*, 2004]. Clearly reductions in both imported oil for transportation fuels and emitted atmospheric pollutants would be dramatic with widespread implementation of full-hybrids operating in the plug-in mode. However, realistically, some of the *saved* fuel would still be needed, because in the three decades needed for full implementation, the number of vehicles and the number of miles driven per vehicle in the U.S. could increase significantly—perhaps 25% to 50%.

FUEL-COST SAVINGS

At a price of $2.00 per gallon, the fuel cost is $0.10 per mile for standard light vehicles averaging 20 mpg. Because a gallon of gasoline contains 36.65 kWh of thermal energy, 1.833 kWh is used per mile. However, the efficiency of an internal combustion engine operating over a range of speeds plus energy losses in the transmission, drive, and tires results in an "overall gasoline thermal energy to miles traveled efficiency" of about 20%. Hence, the mechanical energy expended at the pavement driving the vehicle is only 0.367 kWh per mile. If the overall efficiency of the electric drive including charger, batteries, motor, generator, and drive is 70%, the electrical energy purchased from the utility is 0.524 kWh per mile. Because the proposed plug-in mode of operation would probably require larger batteries and a larger electric motor, adding several hundred pounds of weight to the vehicle, this value will be increased by 15% to 0.603 kWh per mile. At a price of $0.06 per kWh, the cost of electricity to drive a mile in a hybrid is only $0.0362. For the half of light hybrid drivers in our model who travel 15 miles per day (5,475 miles per year) using electricity, the savings would be $349 per year. For the other half of the light-hybrid drivers who travel 35 miles per day (12,775 miles per year) using electricity before shifting into hybrid mode, the savings would be $815 per year.

ELECTRICITY TAX IMPACT ON COST/MILE

It is inevitable that if electricity becomes a significant source of energy for automotive and light-truck travel, it will be taxed by an amount sufficient to recover the tax revenue lost on petroleum-based fuels by governmental authorities at the national, state, and local levels. If we assume that the current total tax on these fuels is about $0.35 per gallon and the estimated total consumption of fuel is 103 billion gallons per year (281 million gallons per day), the total tax would be $36 billion per year. Using information provided earlier, the calculated total kWh of electricity consumed in the plug-in mode would be 1,238 billion kWh per year. The equivalent tax is about $0.029 per kWh, thereby increasing the cost of electricity used on the road from $0.06 to $0.089 per kWh. Hence, the fuel

[8] *Tinkering with assumptions in the model will give slightly different numerical results, but will not impact the overall conclusion that it is possible to save a large majority of the petroleum fuel used for light vehicles today through the wide-scale use of plug-in hybrid vehicles.*

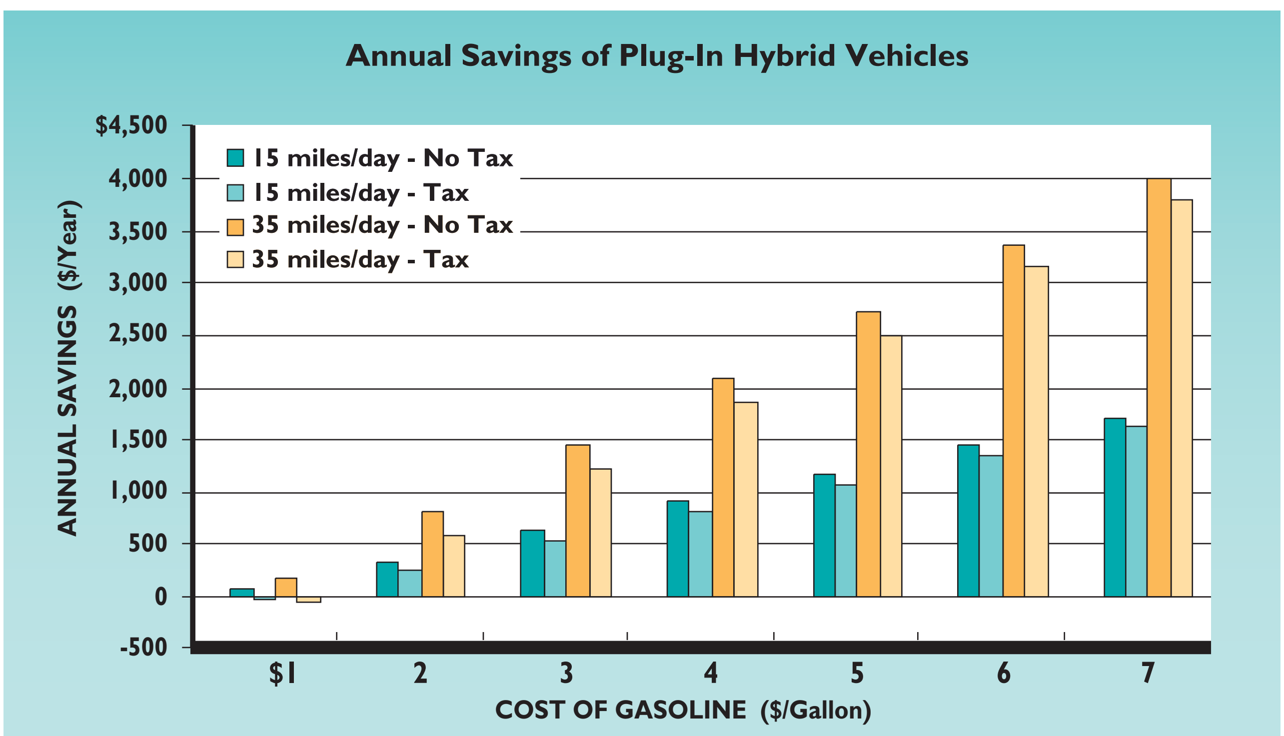

Figure 5. Savings for plug-in hybrids with and without taxes (electricity costs $0.060/kWh without tax and $0.089/kWh with tax).

cost per mile for the light-hybrid vehicles increases from $0.0362 to $0.0537 per mile, which is still little more than half the $0.10 per mile for standard vehicles using $2/gallon gasoline.

The annual savings for gasoline at $2 per gallon are substantial, but they may not be large enough to justify the additional cost of a plug-in hybrid vehicle. However, if the cost of gasoline increases to $4 or $5 per gallon, prices that are common in Europe today and a realistic possibility in the U.S. if oil imports are not drastically reduced, the savings become quite large. These annual savings with and without taxes for gasoline prices ranging from $1 to $7 per gallon are shown in Figure 5.

HOME ELECTRICAL SERVICE REQUIRED

Now let us look at the electrical supply aspects of this system. Light-hybrid vehicles that travel 35 miles per day on electricity would use 21.1 kWh per day. If batteries are to be charged in eight hours at night using a 220-volt system, the required capacity would be about 12 amps. However, charging batteries requires more current when the batteries are deeply discharged, so the peak currents could be double this value. Even so, it seems reasonable that most modern homes with 200 to 300 amp electrical service would have adequate spare capacity to provide 24 amps at 220 volts during the night.

ELECTRICAL GENERATION CAPACITY

Even though it is anticipated that battery charging would occur at night when we expect to have excess electrical generating capacity (an expectation that proves to be false), it is important to know the total electrical generating capacity required. Multiplying the miles per day for all the light hybrids using electricity times the kWh per mile results in 3.39 billion kWh per day. Charging the batteries in eight hours would require 424 million kWe or 424 GWe. This equals the output of 424 power plants of 1,000 MWe size. Because the entire U.S. generating capacity today is 850 GWe, it is clear that there would not be sufficient spare capacity available at night or any other time to charge the batteries of all the hybrids projected in 2035. While not all charging would occur in the same eight-hour period because of time zones and some help could be provided by existing excess capacity, significant new generating capacity—perhaps 200 new 1,000 MWe nuclear or other non-polluting plants—would have to be built to charge the batteries. New transmission and distribution lines and substations would be needed to deliver the electrical power. Building 200 1,000 MWe power plants and associated power delivery facilities in three decades would be a daunting task, but certainly feasible.

UTILITY ISSUES

Clearly, utilities have a key role in the implementation of the proposed plug-in hybrid electric-vehicle transportation system because they must generate the needed electrical energy. A study by Atomic Energy of Canada Limited [Miller 2003] of the cost for electricity on the Alberta open market for 2002 showed an average price of $0.0293/kWh with peaks as high as $0.60/kWh. Further study showed that the price was less than $0.06/kWh for 95% of the time and that the average price was $0.0224/kWh. Such a situation is well suited for *interruptible* supply mode of operation in which the utility could interrupt the supply of electricity to charge batteries for short time periods in exchange for a reduced price for the customer. In most cases, the customer's additional cost would be the cost of a small amount of fuel. The utility would be relieved of meeting peak demands to recharge batteries when traditional utility loads such as air conditioning and heating are high. This means that a utility could delay adding additional generating capacity until its average load increases. It is a *win-win* situation because hybrid-vehicle owners would get reduced electric rates that offset the costs of any extra fuel needed.

INCENTIVES FOR OWNERS AND OTHERS

Current IRS and some state regulations provide several tax incentives for current buyers and operators of hybrid and electric vehicles. Given the large petroleum fuel and pollution reductions of the plug-in hybrids described above, additional incentives, such as reduced or no taxes on electricity used to charge batteries at home, would seem appropriate—at least in the early years of implementation. The federal government has a large vested interest in promoting any technology that drastically reduces the consumption of transportation fuels, thereby reducing importation of petroleum. Governmental agencies with fleets of light vehicles could be required to increase their percentage of plug-in hybrid electric vehicles on a progressive schedule during a phase-in period, thereby providing a market and incentive for manufacturers to develop and continuously improve plug-in hybrids.

PROBLEMS WITH IMPLEMENTATION

Current full-hybrid designs would require modifications for the proposed plug-in mode of operation for several reasons:

1) the size of current electric motors operating alone may not be large enough for satisfactory performance under battery power alone,
2) present batteries may not be large enough to provide the desired power and range for operation with only the electric motor,
3) a larger electric motor and batteries will increase the cost and weight of a hybrid vehicle,
4) most batteries are designed for operation in a near fully charged condition, and deeper discharge might harm the battery,
5) battery life could be shortened under the proposed mode of operation, and
6) adequate power will be needed for standard desired accessories of today's light vehicles—air conditioning, automatic transmission, and power steering.

These are engineering design problems that are a significant challenge to the manufacturers, but they do not appear insurmountable.

A human-factors issue to be addressed is connecting an electrical source to a vehicle every time it enters a garage. It is unlikely that a homemaker returning from shopping with merchandise and small children will give top priority to reconnecting the power cord to the vehicle. Hence, an automatic docking station that engages an electrical connection would undoubtedly be an important feature. Furthermore, an inductive coupling device that avoids mechanical contact would also seem to be a reasonable and appropriate feature of a docking station. Docking stations would also be required for vehicle owners who do not have garages.

Perhaps the biggest impediment to the proposed implementation of plug-in hybrids is time. It takes time to design and introduce even the relatively simple, but needed, changes in the current full hybrids. It takes time for people to accept the changes in operating hybrids compared to their current vehicles. It takes a decade or more for a majority of the vehicles in the U.S. to be replaced. Higher sticker costs are impediments to purchasing new vehicles, even when life-cycle costs may actually be lower. The 30-year period used in this analysis for complete conversion may be unrealistic unless the cost of imported oil remains stable. Temporary reductions of imported oil prices in the past three decades have impeded relatively successful efforts to increase mileage, such as the CAFE (corporate average fuel economy) standards for automobiles.

CONCLUSIONS

Given the projected uncertainty in both cost and availability of petroleum, the possibility of replacing up to three quarters (or even half) of the gasoline and diesel fuel needed for automobiles and light trucks in the U.S. with electricity by 2035 is extremely compelling. This proposed approach to reducing our need for petrochemical fuel appears to be significantly simpler and could be accomplished sooner and much more inexpensively than any other approach presently under consideration. Indeed, it is probably the only technology that could be implemented quickly enough to have a significant near-term impact on oil imports—e.g., 10% to 20% reduction in a decade.

While the 30 years until 2035 may seem like a long time, we are reminded that the 1973 OPEC oil embargo and subsequent energy crisis occurred more than 31 years ago and that little has been done since then to resolve the oil supply situation. Indeed, imports have doubled from one-third to two-thirds of our total needs in this period.

Unless the United States move ahead decisively to reduce our use of petroleum by all practical and reasonably economic means, our importation of petroleum-based energy that is a critical driving-force in our economy will be a far greater problem in 2035 than 2005. The use of hybrid vehicles operating in the plug-in mode is a rational and reasonable alternative that could be implemented in less time than almost any other alternative and should be explored with all deliberate speed. Nothing less than the economic well-being and security of the United States are at stake.

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Dr. Uhrig was a vice president at Florida Power & Light Company during 1973-86. He served as dean of engineering at the University of Florida during 1968-73, and was appointed dean emeritus in 1989. Previously, he was deputy assistant director for research for the Department of Defense in1967-68. He chaired the department of nuclear engineering sciences at UF, was an associate professor and an engineer for the Atomic Energy Commission's Ames Laboratory at Iowa State University, and taught at the U.S. Military Academy while on active duty with the U.S. Air Force.

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